Attitude Solution of Quadrotor UAV

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Abstract

In this paper, the attitude solution of a quadcopter UAV is introduced, and the integrated circuit designed by the UAV is verified. The angular velocity data and acceleration data required for this solution are provided by two modules: gyroscope and accelerometer. In this attitude control, three values are used: quaternions, rotation matrices, and Euler angles. Through data algorithm analysis, integrated circuit design and program design, the feasibility of the attitude algorithm is prove. On this basis, the problem of combining two systems: attitude flight and fixed height and fixed point is solved.

Keywords: Attitude solution, quaternion, Euler Angle, rotation matrix, gyroscope

1. Introduction

In order to do the attitude solution, we need to understand the basic idea of the solution. The data required for the calculation is provided by the following modules: Quad copter aircraft, also known as quad rotor aircraft, whose four propellers are simple mechanisms with motors directly connected. The cross-shaped layout allows the aircraft to obtain the force of rotating the fuselage by changing the motor speed, so as to adjust its own attitude.

Generally speaking, attitude means that we stand on the ground to observe the pitch/roll/heading state of the aircraft. The aircraft needs to know its current attitude in real time so that it can control its next actions as needed, such as keeping steady and rolling.

Mathematical model: Attitude is used to describe the angular position relationship between the fixed coordinate system and the reference coordinate system of a rigid body (attitude Angle), there are some mathematical representation methods. The common ones are Euler angles, quaternions, matrices, axis angles.

Applying the above mathematical model to the attitude description of aircraft, the reference coordinate system corresponds to the navigation coordinate system is fixed. We usually use the frame R. The fixed coordinate system corresponds to the body coordinate system, denoted by the coordinate system r. Then we can use Euler Angle, quaternion and other mathematical methods to describe the angular position relationship between r and R. This is the mathematical model for the attitude solution of the vehicle.

The core of the attitude solution of the quad copter is the control rotation. We generally use quaternion to represent the rotation. After obtaining the quaternion, it will be converted into Euler Angle and then input into the attitude control algorithm. In the design process of the quadcopter, we used the gyroscope and other inertia elements. Attitude calculation through this method is also a relatively complicated part of the control quadcopter.

In order to simplify the complexity of the technology, we apply MPU6050, which uses hardware DMP to read the quaternion directly. In other words, MPU6050 has a built-in function module, which can correct and process the original data before output [1].

This paper will study the quadcopter based on STM32 control center carrying MPU6050, and analyze from the aspects of hardware, algorithm and circuit design.

2. Attitude solution

2.1. *Basic idea of solution*

The gyroscope, which measures angular velocity, has high dynamic characteristics. It is a device for measuring angles indirectly. It measures the derivative of the Angle, the angular velocity, and you integrate the angular velocity over time to get the Angle. Due to the influence of noise and other errors, it accumulates continuously under the action of integration, and finally leads to the low frequency interference and drift of the gyroscope.

The direction the accelerometer outputs the current acceleration (including the gravitational acceleration). The high frequency signal sensitivity caused by the measurement principle makes the high frequency interference of the accelerometer in the vibration environment. Therefore, we can conclude that the gyroscope is sensitive to low frequency disturbance and the accelerometer is sensitive to high frequency disturbance. The gyroscope can be trusted in a short time, and the accelerometer needs to be trusted in a long time, so the idea is to hold the attitude calculated by the accelerometer to correct the gyroscope. Namely, complementary fusion, using the acceleration vector and the gyroscope angular velocity vector as the cross product, if there is no change between the two attitudes, the cross product result should be 0, but if there is a change, then the result can be used as the correction of the gyroscope angular velocity. Adding variables Kp and Ki can be used for PI correction to quickly correct the angular velocity value. A relatively accurate attitude value can be obtained by updating the quaternion with the compensated angular velocity.

The fusion of complementary proposed in this paper is shown in Fig.1.

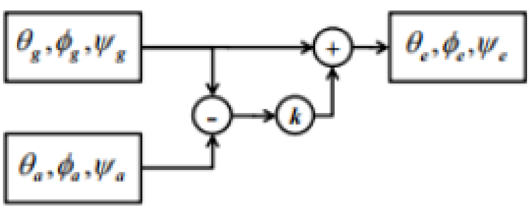

Fig.1 Fusion of complementary

2.2. *Quaternion,rotation matrix and Euler Angle*

In attitude control, we need to know three values: quaternion, rotation matrix and Euler Angle .

The relationship between quaternion, rotation matrix and Euler Angle proposed in this paper is shown in Fig.2.

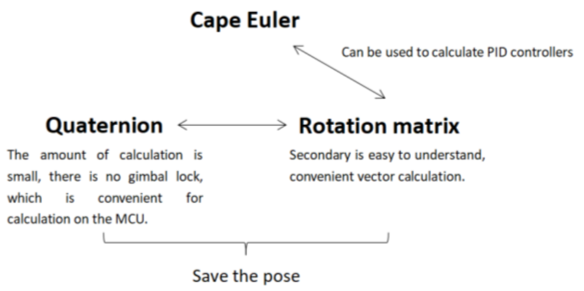

Fig.2 Quaternion rotation matrix and Euler Angle

(1) Definition of quaternion [2]

Quaternions were proposed by the Irish mathematician William Rowan Hamilton in 1843. Any rotation of three-dimensional space can be represented by an Angle rotated around an Axis of three-dimensional space, namely the so-called axis-angle representation method. In this representation, Axis can be represented by a three-dimensional vector (x,y,z), θ can be represented by an Angle value, and intuitively, a four-dimensional vector (θ,x,y,z) can represent any rotation in three dimensions. Note that the three-dimensional vector (x,y,z) here is used only to represent the orientation of the axis, so a more compact representation would be to use a unit vector to represent the direction axis and the length of that three-dimensional vector to represent the Angle value θ. Thus, a three-dimensional vector (θ*x,θ*y,θ*z) may be used to represent any rotation in three-dimensional space, provided that (x,y,z) is a unit vector.This is the way the Rotation Vector is represented, which is used extensively in Open CV to represent rotation (see rvec in the Open CV Camera Calibration section) [3].

(2) Euler Angle [4]

Static definition

Three independent coordinate variables are required to describe the configuration of a fixed point rotating rigid body. To describe the configuration of a fixed axis rotating rigid body requires an independent coordinate variable, namely the Angle. The process of fixed point motion is decomposed into three independent angles, namely Euler Angle, which is composed of nutation Angle, precession Angle and rotation Angle. The basic idea of Euler Angle is to decompose angular displacement into a sequence of three rotations about three mutually perpendicular axes. Euler Angle is used to describe the orientation of a rigid body in three-dimensional Euclidean space. For a frame of reference in three dimensions, the orientation of any coordinate system can be represented by three Euler angles. A frame of reference, also known as a laboratory frame of reference, is stationary. The coordinate system is fixed to the rigid body and rotates as the rigid body rotates.

Dynamic definition

There are two different dynamic definitions. One is the composition of three rotations about the coordinate axis fixed to the rigid body. The other is a composite of three rotations around the laboratory reference axis. Note that the XYZ axis is the rotating rigid body axis, while the xyz axis is the stationary laboratory reference axis.

Rotation about the XYZ axis: Initially, the axes of the two coordinate systems xyz and XYZ overlap, starting with a rotation of α about the Z axis, then a rotation of β about X, then a rotation of γ about the Z axis.

Rotation about the xyz axis: Initially, the axes of both coordinate systems xyz and XYZ overlap, starting with a rotation of gamma Angle about the z axis, then a rotation of alpha Angle about x, and finally a rotation of beta about the z axis.

When using Euler Angle, we need to know another concept: Gimbal Lock, referred to as gimbal lock or gimbal lock, is caused by the fact that two axes of the three gimbal joints overlap and will lose one degree of freedom. Result: Because of the existence of universal lock, Euler Angle cannot realize spherical smoothing interpolation. The solution is to use quaternion spherical linear interpolation [5].

(3)Matrix of rotation [6]

Rotations in three dimensions are more complex than in two dimensions. You need to specify the rotation Angle and axis. If the three coordinate axes xyz of the coordinate system are taken as the rotation axis, then the point actually only makes a two-dimensional transformation on the plane of the vertical coordinate axis, and the three-dimensional transformation matrix can be derived by using a two-dimensional formula. Stipulation: In the right hand coordinate system, the positive direction of rotation is the right hand spiral direction, that is, from the positive half axis of the axis to the origin of the counterclockwise direction.

The rotation matrix relation proposed in this paper is shown in Fig.3.

绕z轴旋转：

$$(x',y',z') = (x,y,z,1)\begin{bmatrix}\cos\gamma & \sin\gamma & 0 & 0\\ -\sin\gamma & \cos\gamma & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

绕x轴旋转：

$$(x',y',z') = (x,y,z,1)\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & \cos\alpha & \sin\alpha & 0\\ 0 & -\sin\alpha & \cos\alpha & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

绕y轴旋转：

$$(x',y',z') = (x,y,z,1)\begin{bmatrix}\cos\beta & 0 & -\sin\beta & 0\\ 0 & 1 & 0 & 0\\ \sin\beta & 0 & \cos\beta & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

绕任意轴旋转公式((a,b,c)表示旋转轴，θ表示旋转角度)：

$$\begin{bmatrix}a^2+(1-a^2)\cos\theta & ab(1-\cos\theta+c\sin\theta & ac(1-\cos\theta)-b\sin\theta & 0\\ ab(1-\cos\theta)-c\sin\theta & b^2+(1-b^2)\cos\theta & bc(1-\cos\theta)+a\sin\theta & 0\\ ac(1-\cos\theta)+b\sin\theta & bc(1-\cos\theta)-a\sin\theta & c^2+(1-c^2)\cos\theta & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

Fig.3 Rotation matrix relation

Rotation matrix, Euler Angle, quaternion comparison

Rotation matrix, Euler Angle, quaternion are mainly used for: vector rotation, conversion between coordinate systems, angular displacement calculation, azimuth smooth interpolation calculation.

Different azimuth representations are suitable for different situations:

Euler angles are the easiest to use. Euler angles can greatly simplify human-computer interaction when it comes to specifying the orientation of objects in the world, including typing the orientation directly from the keyboard, specifying the orientation in code (such as setting the camera for rendering), and testing during debugging.

If you need to convert vectors between coordinate systems, choose the matrix form. Another approach is to use Euler angles as a "master copy" of the azimuth, but maintain a rotation matrix that is updated whenever Euler angles change.

Euler angles or quaternons are used when large amounts of azimuth data (such as animations) need to be stored. Euler angles take up 25% less memory, but are slower to convert to the matrix. If animation data requires nested connections between coordinate systems, quaternons may be the best choice. Smooth interpolation can only use quaternions. In other forms, you must go to the quaternion, and then go back after interpolation.

2.3. *Attitude update frequency and practical application*

In the calculation, we are actually updating the attitude, and then put the result of Euler Angle into the controller to calculate the control result of the motor.

The process involved in this article is shown in Fig.4.

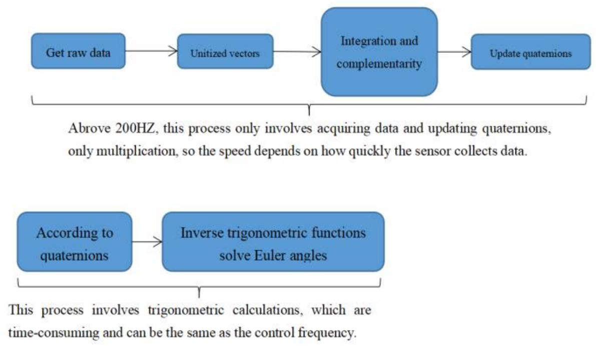

Fig.4 Actual application process

3. UAV programming

3.1. *Complete Framework Introduction*

For the complete framework of the entire flight control source code, we can get the following information according to the following figure:

The remote control input rudder information into the controller, at the same time, the controller can also give itself control rudder, in line control and other programs often use this function;

The sensor can input the attitude values of the accelerometer, barometer and gyroscope into the IMU solving unit, so that we can get a relatively accurate position of the UAV in space;

After the IMU is solved, the controller will control the motor according to the settlement result returned by it.

The flow chart covered in this paragraph is shown in Fig.5.

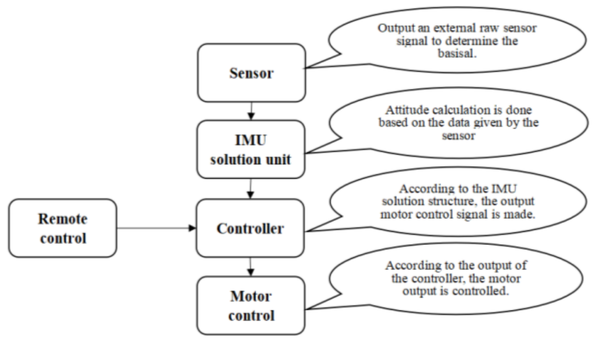

Fig.5 flow chart

3.2. *Remote control module frame*

According to Fig.6, we can learn the framework information about the remote control module.

In the attitude mode, the engine rudder directly controls the speed of the motor and flies high as much as it pushes.

In the fixed-point mode, the engine rudder only controls the flight altitude information.

The Pitch rudder controls the pitch Angle;

The Roll rudder controls the roll Angle;

The Yaw rudder controls the direction of the drone.

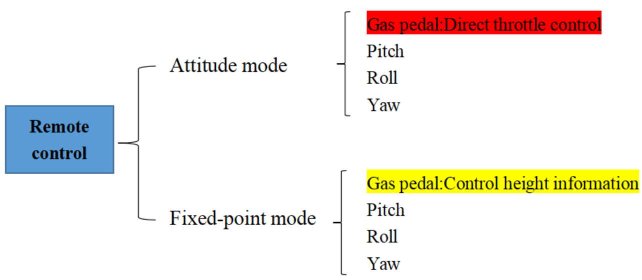

Fig.6 The frame information of the remote control module

3.3. *Sensor module frame*

According to Fig.7, we can see the information of the sensor module framework.

The attitude sensor used in IMU calculation is MPU6050;

The height sensor uses infrared laser sensor (measuring range of about 2m, recommended flight 1m~1.5m) and barometer.Data are prone to inaccuracies.

The horizontal sensor uses the optical flow sensor to measure the velocity value of the UAV in all directions, which can be combined with the IMU solution.

The unit measures more accurate horizontal velocity values;

The module used by the line sensor is OpenMV (more functional than other similar modules on the market).

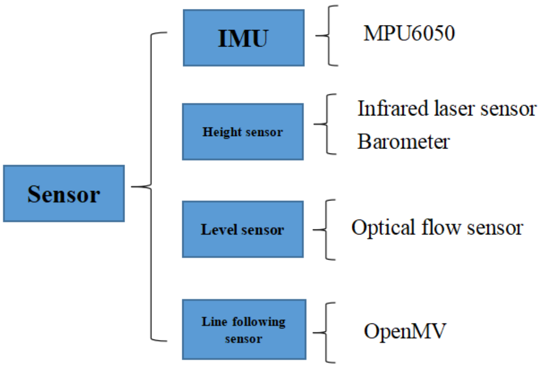

Fig.7 Sensor module frame information

3.4. *Introduction to IMU solution unit framework*

According to Fig.8, we can obtain the following information about IMU solving unit:

Acceleration information is used to correct gyroscope;

Gyroscope information is used to be calibrated;

The temperature information is used for thermostatic control.

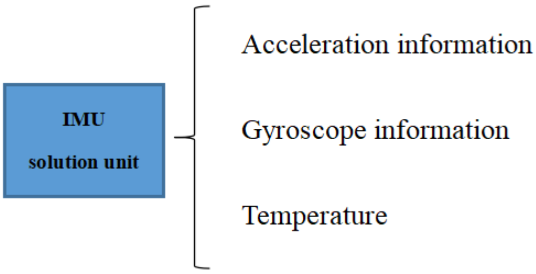

Fig.8 IMU solves the information of the unit

3.5. *Controller module framework*

According to Fig.9, information about the controller can be obtained as follows:

Attitude controller is the most basic controller to ensure the UAV has a relatively stable flight. It is a controller with two ring PID.

The height controller controls the height stability of the UAV when the height is fixed.

The horizontal controller controls the stability of the UAV in the horizontal direction;

The line controller uses the data from OpenMV to control the flight of the line.

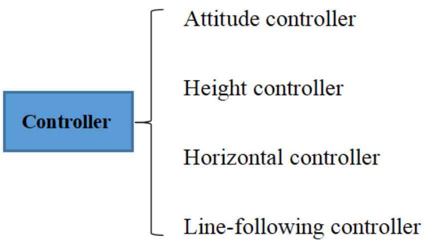

Fig.9 Controller Information

3.6. *Motor control module frame*

According to Fig.10, we can get the following information about motor control:

In UAV control, we use 400HZ PWM wave to control the motor (because the solution speed is not less than 100HZ, not more than 200HZ).

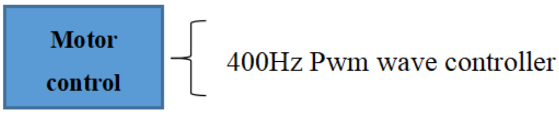

Fig.10 Information on motor control

4. Algorithm analysis [7]

In the design, the MCU timer peripheral output PWM signal to the electric modulation, the electric modulation control motor rotation to produce lift, so that you can fly. If the motor and the frame are completely symmetric without any error, it is a linear system. The diagonal of the motor rotates in the same direction, and the main and auxiliary diagonal lines will generate torsion forces in opposite directions to each other. It is assumed that the quadrotor is a linear system. You increase the voltage and you increase the lift and you fly. In theory, only a pair of diagonal motors can fly. However, the vehicle will rotate in one direction. Then the movement of the quadrotor is very simple, increase the speed of the motor 12, produce pitching motion, pitch forward, increase the speed of the motor 14, produce roll motion, roll to the right, increase the speed of the motor 13, is to produce yaw motion, clockwise yaw. Quadrotor aircraft can not be a linear system, there will be deviation, so we need to use the sensor to measure the deviation, as the system observation quantity, and then through the control algorithm of the flight control code to achieve control.

The difficulty in achieving attitude flight and altitude fixing is actually the combination of these two systems, which requires fitting together the offset data of these sensors on the XYZ axis. The fixed height point corresponds to three axes in the navigation coordinate system. The data of the data accelerometer, optical flow, gyroscope, accelerometer and gyroscope on the X-axis and Y-axis are mapped to the navigation coordinate system. After optical flow rotation, the fused data on the XY axis can be obtained by fitting the data of the accelerometer. Similarly, on the Z-axis, the laser ranging module can simply obtain the height information through the differential pressure method. After fitting with the Z-axis data of the accelerometer, the Z-axis data after fusion can be obtained. The fusion uses a third order complementary filtering method. Take the z-axis of the accelerometer as an example. If the complementary filtering method is not used, the system is an open-loop system. The position information can be obtained after two integrations of the Z-axis accelerometer. The poles under pure integration are zero, and the system is divergent and cannot be stabilized. The system block diagram of the third-order complementary filtering shown in the figure below is the position, velocity and acceleration respectively, with three appropriate values. And here are three third-order complementary systems, the XYZ axis.

The above flow chart is shown in Fig.11.

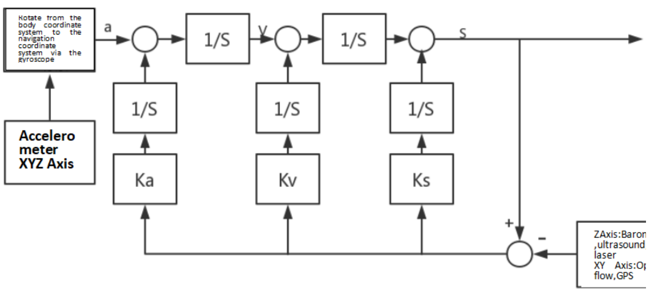

Fig.11 Flow chart

The controller used in this design is a cascade PID controller, the input is the ideal flight height, the output is PWM, drive motor, because the quadrotor is not a linear system, in order to minimize the possible deviation of the aircraft, using the current height minus the expected height is the deviation, the deviation is fed back to the input and mapped to the PWM output, forming a closed-loop system. Adjust these three parameters, you can achieve a stable state. We can use MATLAB simulation debugging, in fact, is to make the system transfer function stability of the optimal solution. We understand the unipolar system, then the cascade system is very simple, is the output of a PID controller as the input of another PID controller, the final output control quantity to the controlled object, the PID controller inside belongs to the inner ring, the outer controller belongs to the outer ring, that is, the output of the outer ring as the input of the inner ring, the final output of the inner ring to the controlled object. In a cascade system, the parameters of the inner ring are more important than those of the outer ring. If the parameters of the inner ring are properly adjusted, the parameters of the outer ring are relatively easy to solve.

The above flow chart is shown in Fig.12.

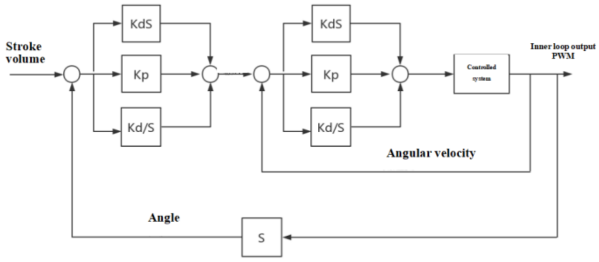

Fig.12 Flow chart

The following is the program design block diagram of this research. We adopt the timer time division multiplexing method, which is called in different time threads according to the update time required by different peripherals, different algorithms and different sensors.

The above flow chart is shown in Fig.13.

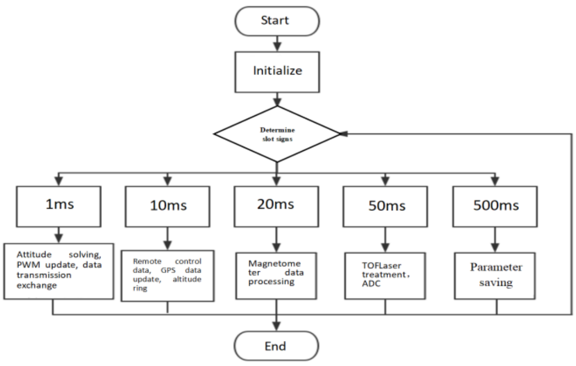

Fig.13 Flow chart

Acknowledgments

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Authors Introduction

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He will receive his bachelor's degree from Tianjin University of Science and Technology in China in 2024. His research interests include robot dynamics and attitude calculation of unmanned aerial vehicles.

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His bachelor's degree is in intelligent science and advanced manufacturing, School of Electronic Information and Automation, Tianjin University of Science and Technology, majoring in artificial intelligence, proficient in C language, proficient in using Solid works, CAD and other software, very interested in machine vision research.

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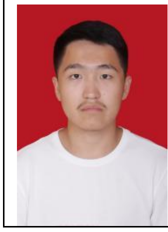

He participated in the American College Mathematical Contest in Modeling as a modeler and data analyst in early 2022 and won the s Award. During his freshman year, he published one international CPCI paper. In 2022, I will attend the "Hi cool" Global Entrepreneur Summit with my mentor.