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# Design of Inertial Measurement Module for UAV Based on ARM

Luyu Yang, Fengshuo Dong, Anxuan Li, Zhongmin Xiao

Civil Aviation University of China, Tianjin 300300, P.R. China

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*Abstract: With the wide application of unmanned aerial vehicles, the precision of its inertial measurement data is more and more demanding. However, the basic data collected and returned contains a lot of noise and interference. Therefore, an unmanned aerial vehicle (UAV) inertial measurement module based on ARM is designed. It can work with the UAV controlled by the computer at the same time and improve the accuracy of the data, so as to control the unmanned aerial vehicle in real time. The module is designed with STM32F103 as the processing unit, and is designed with the MEMS three axis acceleration sensor, the three axis magnetic force sensor and the three axis angular velocity sensor. In this paper, a simple and effective complementary filtering algorithm is used to solve the attitude calculation, which effectively improves the accuracy of attitude measurement. It is proved by the test that the attitude information obtained by the inertial measurement module has high precision. And it can satisfy the design and development of the general prototype system.*
*Keywords: STM32, attitude calculation, complementary filter, MEMS inertial sensor*

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## 1. INTRODUCTION

Inertial measurement system is an important part of the UAV flight control system. It provides the current attitude information for the UAV flying in the air, and guides the control system to control the aircraft attitude accurately. At present, the basic attitude data of the UAV flying in the air is from gyroscope, accelerometer and magnetometer data. Then, after preprocessing, fusion and correction, it can be applied in practice. This process will take some time, and the data can not be processed in time, so there are errors. With the development of microelectronic technology, integrated circuit technology and processing technology, MEMS sensor has been widely used in automotive, aerospace, weapon guidance and other military and civilian fields because of its high cost performance.

In summary, a special module for the UAV inertial measurement system is designed based on ARM to make it work with the UAV control computer at the same time. In addition, a simple and effective complementary filter algorithm is used to calculate the attitude of the aircraft. Compared with the traditional Calman filtering algorithm, the algorithm has the advantages of fast response speed, less computation, and no precise system model and noise variance.It effectively improves the accuracy of attitude measurement and meets the requirements of the general UAV attitude measurement.

## 2. PRINCIPLE OF INERTIAL MEASUREMENT FOR UAV

### 2.1 MEMS Inertial Sensor

2.1.1 Three-Axis Accelerometer

The MEMS acceleration sensor is similar to the spring, where $F$ is the external force, $m$ is the mass, and $a$ is the acceleration. Known by Newton's second law and Hooker's law:

$$F = ma = kx \tag{1-1}$$

Where $x$ is the distance and $k$ is the inherent coefficient in the range of spring's elasticity. Therefore, according to the measured distance, mass of the object and coefficient of the spring, we can get the value of acceleration.

Triaxial acceleration is obtained by using three uniaxial acceleration sensors perpendicularly placed to each other. Although the MEMS accelerometer can be used to measure the acceleration in motion, it will bring big errors when measuring displacement. In practical applications. In practical applications, it is generally used to measure the tilt angle of the object in a static or quasi-static condition, thereby estimating the degree of tilt in three-dimensional space. However, triaxial accelerometer cannot completely determine the orientation of the object in three-dimensional space, and magnetometer is required to determine the azimuth angle.

2.1.2 Three Axis Magnetometer

Magnetic sensor is subjected to geomagnetism to output the current position. When it is applied to a compass, the compass is usually located on a horizontal plane. The magnetic sensor will measure the horizontal component of the geomagnetic field, and the azimuth angle is

$$\gamma = \arctan\left(\frac{H_y}{H_z}\right) \tag{1-2}$$

In this case, the compass is required to be in the horizontal plane. In practical applications, it often needs to be applied to the non - horizontal state, and the formula (1-2) can not be used to calculate the azimuth. At this time, the three axis acceleration sensor and the three axis magnetic sensor can be used to calculate any azimuth in the three-dimensional space. Therefore, it is necessary to use the inclination angle to correct the coordinate of the magnetic force sensor. Assuming that the three axis magnetic sensor is in the same direction with the acceleration sensor, that is, the magnetic sensor $X-Y-Z$ coordinates with the three axis acceleration sensor $X-Y-Z$ . According to the output of the three axis acceleration sensor, the dip angle can be obtained. At the same time, the formulas (1-3) and (1-4) are given for the corrected geomagnetic vector.

$$H_x = H_x' \cos\theta + H_y' \sin\psi - H_Z' \sin\theta\cos\psi \tag{1-3}$$

$$H_y = H_y' \cos\psi + H_z' \sin\psi \tag{1-4}$$

2.1.3 Three Axis Angular Velocity Sensor

The angular velocity sensor is a gyroscope. The common angular velocity sensor or gyroscope is called Gimbal Gyroscope, of which three vertical rings are called gimbal. The outside gimbal is usually fixed, and the middle gimbal has 1 degrees of freedom, and the inside gimbal has 2 degrees of freedom. So the whole gyroscope has 3 degrees of freedom. By measuring three rings, the angular velocity of three-dimensional space can be obtained.

However, the bulky volume of Gimbal Gyroscope bound its further application. Hence the MEMS angular rate sensor. This sensor is mainly based on the principle of Coriolis force. By measuring the Coriolis force, angular velocity can be obtained. When angular velocity is obtained, the angle is

$$\theta = \theta_0 + \int \omega dt \tag{1-5}$$

In which $\theta$ is for current angle calculated, $\theta_0$ is for initial angle, and ω is for angular velocity in motion process.

**2.2 Azimuth Description of Three-Dimensional Space**

Based on the measured values given by the inertial measurement unit, the azimuth in the three-dimensional space can be provided. Commonly used 3D spatial orientation representation methods are Euler angle and four element method.

2.2.1 Euler Angle, Euler Matrix and Four Element Number

According to Euler angle rotation theorem, any rotation can be described as a rotation around a certain axis. Assuming that axis vector is $V = [x, y, z]$ , rotation angle is $\theta$ , and rotation is described as the Euler angle. The formula is

$$x = \theta V \tag{2-1}$$

Although Euler angle can describe the rotation change in three-dimensional space, it is not suitable for describing continuous rotation in three-dimensional space, so it is usually expressed by Euler matrix or four element number. The rotation matrix is used to describe the three-dimensional azimuth change. There will be a gimbal deadlock problem. That is to say, the rotation matrix will have a singular solution, so it is expressed by Hamilton four element number. The definition of four elements is

$$q = (q_1, q_2, q_3, q_4) \tag{2-2}$$

When the vector $V_1$ rotates the vector U around angle of $\theta$, it is the vector $V_2$. The formula is

$$V_2 = qV_1q^{-1} \tag{2-3}$$

2.2.2 The Calculation of Attitude

At present, the usual method of attitude calculation is still dominated by classical Calman filtering or extended Calman filtering, but Calman filtering requires precise system model and noise variance. At the same time, because of its complex algorithm and high requirement for processors, multi-dimensional Jacobi matrix processing is needed. If it is not handled properly, it will cause severe data delay and is very unfavorable for real-time control.

The attitude calculation is mainly based on information measured by gyroscope and accelerometer. Gyroscope measures the rotation speed of the carrier relative to the inertial coordinate system. Accelerometer measures the acceleration of the carrier relative to the inertial coordinate system. The gyroscope itself is excursion, and the accuracy is high in a short time. However, the acceleration of accelerometer is not very precise in a short time, but its measurement error does not accumulate with time. Using the complementary characteristics of the two in frequency, a complementary filtering algorithm for data fusion between the two can improve the accuracy and dynamic response of the attitude measurement.

Taking the Bachmann based Gauss-Newton complementary attitude filtering algorithm as an example. The acceleration, magnetic force and angular velocity used in the algorithm are represented by the number of four elements, which are as follows:

Acceleration unit vector:

$$h = [0 \quad h_1 \quad h_2 \quad h_3] \tag{2-4}$$

Unit vector of magnetic force:

$$b = [0 \quad b_1 \quad b_2 \quad b_3] \tag{2-5}$$

Angular velocity unit vector:

$$w = [0 \quad p \quad q \quad r] \tag{2-6}$$

The measurement vector:

$$\mathbf{y_0} = [h_1 \quad h_2 \quad h_3 \quad b_1 \quad b_2 \quad b_3]^T \tag{2-7}$$

Estimation vector:

$$\mathbf{y_0}(\hat{q}) = \left(\hat{q}^{-1} m \hat{q}, \hat{q}^{-1} n \hat{q}\right) \tag{2-8}$$

In the above definition, $m = [0 \quad 0 \quad 0 \quad 1]$ is a unit vector of gravity in the earth's coordinate system, and $n = [0 \quad n_1 \quad n_2 \quad n_3]$ is the unit vector of the geomagnetic field in the earth coordinate system. The algorithm minimizes the discriminant function by using the Gauss-Newton method. The correction of four element number is as follows:

$$\Delta q_{full} = \left[X^T X^{-1}\right] X^T \varepsilon(\hat{q}) \tag{2-9}$$

The $X$ matrix is defined as:

$$X_{ij} = \left[\frac{\partial y_i}{\partial q_j}\right] \tag{2-10}$$

In the discrete time domain, the formula for updating the optimal four element number $\hat{q}$ is obtained as follows:

$$\begin{aligned} \hat{q}_{n+1} &= \hat{q}_n + \frac{1}{2}\hat{q}^B \omega \Delta t + \alpha \left[X^T X\right]^{-1} X^T \varepsilon(\hat{q}_n) \\ &= \hat{q}_n + k \Delta t \Delta q_{full} + \hat{q}_{measured} \Delta t \end{aligned} \tag{2-11}$$

In this way, the three-dimensional spatial orientation of the four elements can be obtained.

## 3. DESIGN AND IMPLEMENTATION OF INERTIAL MEASUREMENT MODULE

### 3.1 The Design of System Structure

According to the complementary characteristics of the above three axis acceleration, the three axis magnetic force sensor and the three axis angular velocity sensor, an inertial measurement module with 6DoF in three-dimensional space is designed.Based on the data output of the module, the azimuth of three-dimensional space can be obtained by using the above complementary attitude algorithm. The measurement module uses UART serial output to meet the development and application of the common experimental development environment system or prototype system.

Figure 1 gives the structure diagram of the inertial measurement module. The module includes the sensor part and the MCU part. The sensor part includes the three axis accelerometer, the three axis magnetic force sensor and the three axis angular velocity sensor. The MCU part is responsible for collecting the data of three kinds of sensors and sending the converted data to the UART port.

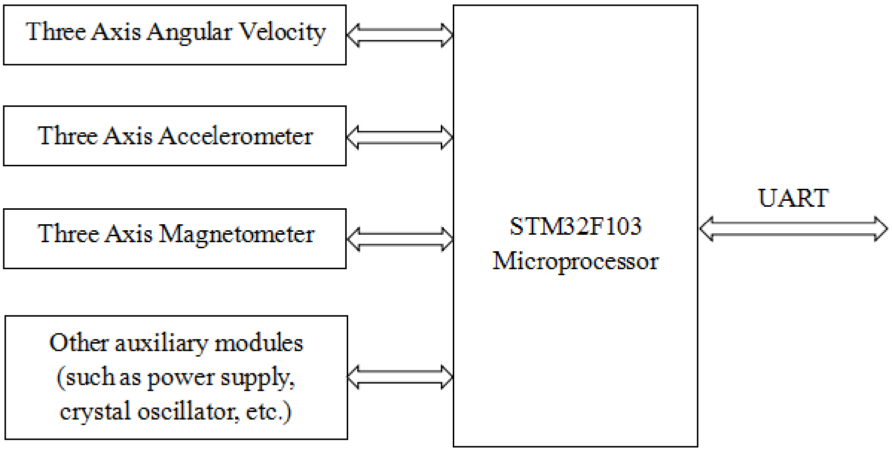


Figure1. The system diagram of the inertial measurement module

**3.2 The Design of Hardware**

3.2.1 Processor Module

The processor module is the core of the whole inertial measurement module. The main task is to collect data from each sensor, process the data and calculate the attitude of the aircraft. Thus the precise control of the attitude and direction of the aircraft is realized. This module uses the STM32F103ZET6 microprocessor of Italy Semiconductor Company as the main control chip. The micro processor uses a new ARM Cortex-M3 as the kernel. It can maintain low power consumption while ensuring high performance operations. In addition it also has multiple timers that can generate multiple PWM signals at the same time. These signals can drive a variety of executing agencies. Therefore, the processor provides rich peripherals to facilitate the development and expansion of the system.

3.2.2 Attitude Sensor Module

MS5611 air pressure sensor is a high resolution pressure sensor launched by MEAS (Switzerland). It has I2C and SPI digital output, and its resolution can reach 10cm. The sensor module includes a high linearity pressure sensor and an ultra-low power 24 bit sigma ADC. MS5611 provides an accurate 24 bit digital pressure and temperature value and different operation modes, which can improve conversion speed and optimize current consumption. The high resolution temperature output can achieve the function of the altimeter/thermometer without additional sensors. It can be connected to almost any micro controller. The communication protocol is simple without programming in the device's internal registers. The size of MS5611 pressure sensor is only 5.0mm * 3.0mm * 1.0mm, so it can be integrated into mobile devices.

The single-chip MPU-6500 integrates a 3-axis accelerometer, a 3-axis gyroscope, and an on board Digital Motion Processor™ (DMP) in a small, 3.0mm * 3.0mm * 0.9mm QFN package. It provides digital-output of 6-axis Motion Fusion data and 9-axis fused data from Motion Processing Library. The three-axis angular rate sensor has a sensitivity up to 131LSBs/dps and a full-scale range of ±250, ±500, ±1000, and ±2000dps. And the three-axis accelerometer has a programmable full scale range of ±2g, ±4g, ±8g and ±16g. Therefore, the settling effects and sensor drift by elimination of board-level cross-axis alignment errors between accelerometer and gyroscope can be reduced. The VDD Supply voltage range of MPU-6500 is 1.71~3.6V. It provides 400kHz fast mode I2C or up to 20MHz SPI serial host interfaces.

The LSM303D is a system-in-package featuring a 3D digital linear acceleration sensor and a 3D digital magnetic sensor. The various sensing elements are manufactured using specialized micromachining processes, while the IC interfaces are realized using a COMS technology that allows the design of a dedicated circuit which is trimmed to better match the sensing element characteristics. The LSM303D has a linear acceleration full-scale of ±2g/±4g/±6g/±8g/±16g and a magnetic field full-scale of ±2/±4/±8/±12 gauss. All full-scale available are fully selectable by the user. The LSM303D includes an I2C serial bus interface that supports standard and fast mode (100kHZ) and fast mode (400kHz) and SPI serial standard interface. The system can be configured to generate an interrupt signal for free-fall, motion detection and magnetic field detection. Thresholds and timing of interrupt generators are programmable by the end user on the fly. Magnetic and accelerometer parts can be enabled or put in power-down mode separately. The LSM303D is available in a plastic land grid array package(LGA), and is guaranteed to operate over an extend temperature range from -40℃ to +85℃.

The schematic diagram of the inertial measurement module is shown in Figure 2.

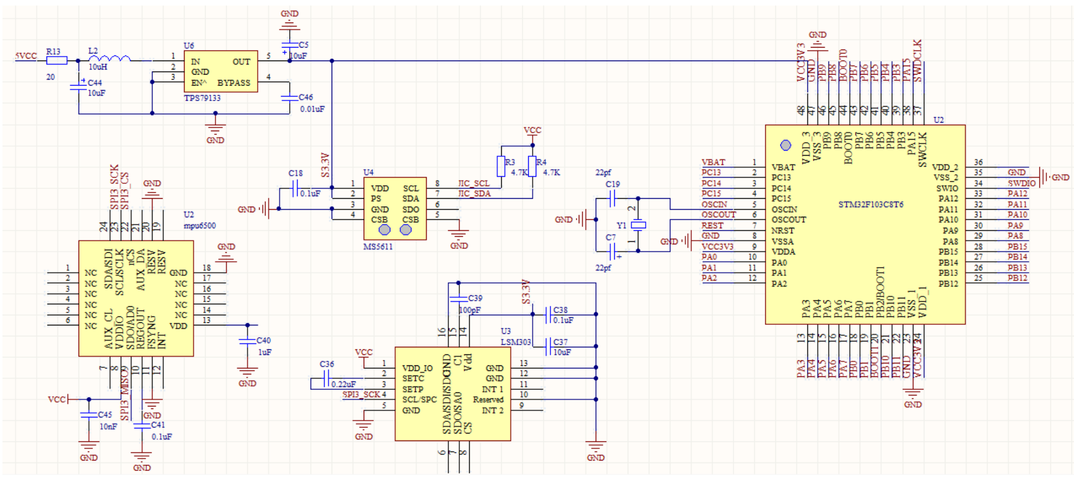

Figure 2. The schematic diagram of the inertial measurement module

Figure 3 shows the physical map, which shows that the designed plate is made up of several module chips connected by circuit. The small volume of the plate can not only be applied to the attitude measurement of UAV, but also can be applied to the development of various systems.

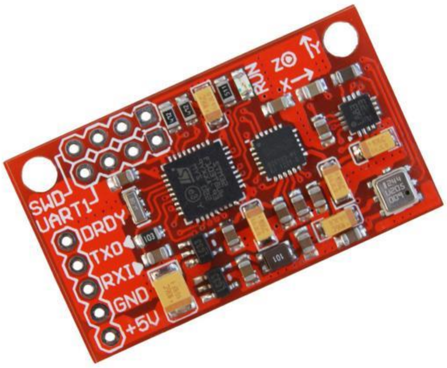


Figure 3. The diagram of the inertial measurement module

## 4. VERIFICATION OF HARDWARE PLATFORM

The performance test of inertial measurement module is achieved by depicting the change curve of UAV's heading angle. That is to make the module rest at a certain angle, then it will revert to the previous angle after a certain angle. The measurement results are sent to the ground station by the wireless communication module of the airborne circuit, and then sent to the PC terminal by the USB serial line of the ground station to the host computer serial port software. In the serial port software, we can see and analyze the measured data output from the measurement module in real time, and describe the measured data with curves. The measuring and changing curves of heading and attitude angles are shown in the figure.

### 4.1 The Pitching Angle

Figure 3 is the 0° - 90° -0° curve of the pitching angle. It can be seen from Figure 3 that when the pitch angle of aircraft changes, the module can accurately measure data in a few seconds. Moreover, the random error is less than 0.04, and the calculated data is relatively stable.

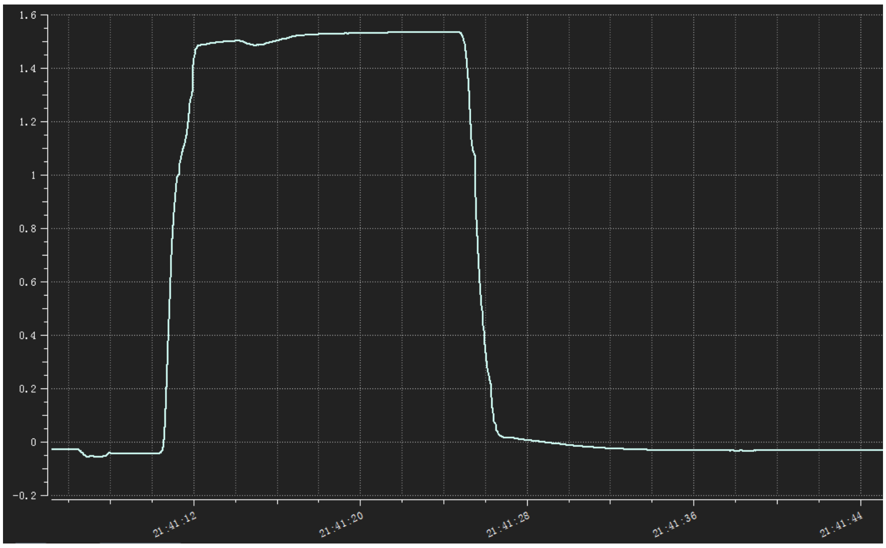


Figure 3. The change curve of pitch angle of 0° - 90° - 0°

### 4.2 The Roll Angle

Figure 4 is the curve of the change of the roll angle 0° - 90° - 0°. It can be seen from the graph that the rolling angle of the aircraft has a stable curve. When the angle changes, the speed and accuracy of data measurement is very high. Moreover, the error between the same angles is very small, which basically coincides with the standard line. It can meet the requirements of measurement.

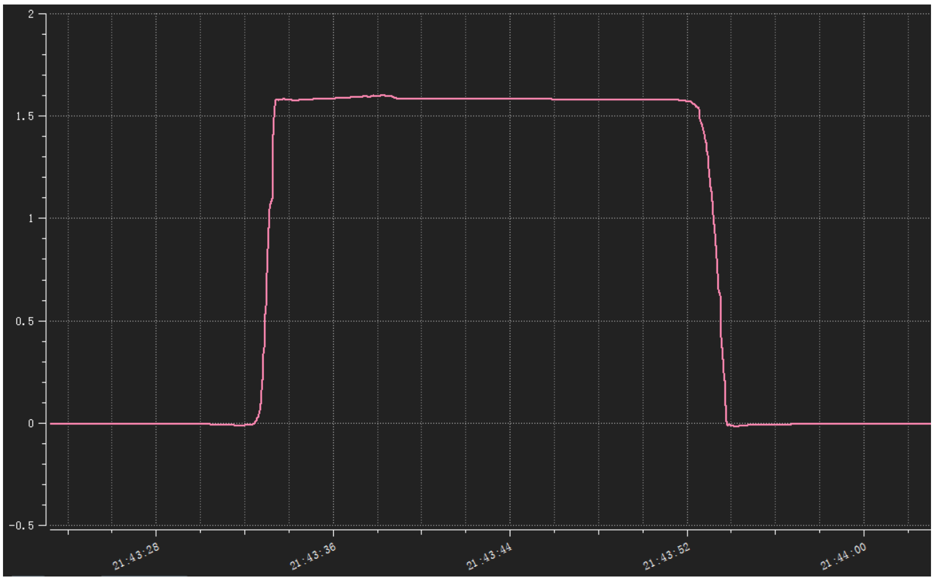


Figure 4. The change curve of roll angle of 0° - 90° - 0°

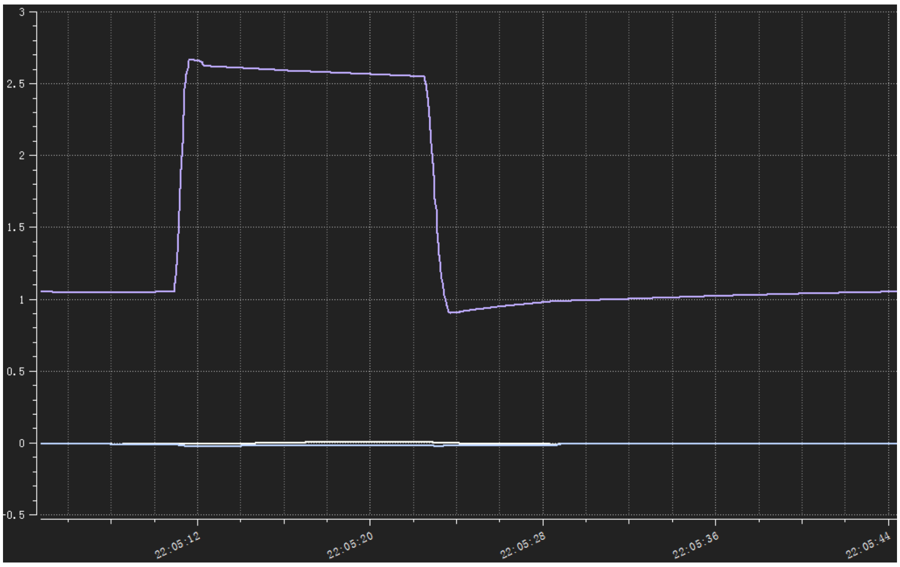


Figure 5. The change curve of yaw angle of 0° - 90° - 0°

### 4.3 The Yaw Angle

Figure 5 is the 0° - 90° - 0° curve of the yaw angle. It can be clearly seen from the diagram that when the angle changes suddenly, though the peak appears, the measurement results can be stabilized very quickly. And the random error of the measured data is not more than 0.1. The accuracy and stability of data solution can meet the general requirements.

## 5. CONCLUSION

In this paper, a ARM based UAV inertial measurement module is designed, which is simple and practical, with stable performance and high accuracy. The inertial measurement module uses the complementary filtering algorithm, which uses the complementary characteristics of the gyroscope and accelerometer on the measured frequency, and improves the accuracy and dynamic response of the attitude measurement data. The original data collected by a variety of sensors are processed and fused systematically, then the attitude is calculated, and the attitude information of the UAV is obtained. Finally, the results of the measurement are output and displayed. The experimental test shows that the module can systematically process and fuse the original data collected by various sensors, then calculate the attitude of the UAV, obtain the attitude information of the UAV, and finally output and display the results of the measurement, and meet the requirements of the general UAV attitude measurement. Therefore, the module can work in parallel with the flight control computer, reduce the vibration interference and the calculation load of the flight control computer, make the obtained data more accurate and stable, reduce the data error, so that the stable flight of the UAV can be controlled better.

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