

# Attitude solver algorithm based on MUP6050 and HMC5883L

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**Abstract.** In aircraft control, getting the current aircraft attitude is foundation that we can control the flight of aircraft. In this paper, MUP6050 and HMC5883L sensors are used to measure aircraft attitude. As time goes on, the accumulation of integral error is growing, when the gyroscope is used to solve aircraft attitude; In the static, we can receive relatively stable attitude, but in large acceleration, the attitude will be interfered by large acceleration, when using accelerometer solver; Accuracy of attitude data be lost in strong magnetic of motor, when using the electronic compass solver. Data of gyroscope, accelerometer and electronic compass is used to solve attitude by Interpolation method in this paper.

## 1. Introduction

In recent years, MEMS sensors are more and more mature, widely used as a low-cost attitude measurement device of best choice, so the sensors used in this project are all MEMS sensors. Among them MUP6050 sensor integrated three-axis gyro and three-axis accelerometer that can measure angular velocity and acceleration of the aircraft; HMC5883L sensor has the capable of detecting the geomagnetic field vector. We can analysis and processing this data collected by the two sensors and finally come to an aircraft attitude data, namely aircraft Euler angles.

## 2. sensor calibration

### 2.1. gyroscope calibration

For gyroscope stationary output is 0 sensor, it can be easily corrected bias. The sensor is fixed, then the output value is averaged to give the A this is bias, such as (1). In practical use, the measured value minus bias resulting value is the correction. Practical applications formula such as (2), A is zero offset value,  $3 \times 1$  matrix, unit: LSB; Y is calibrated value,  $3 \times 1$  matrix, unit: rad/s;  $X_i$  is the measure of the original value, unit: LSB; gain is the conversion factor, unit: (rad / s) / LSB, given by the sensor data sheet.

$$A = \frac{1}{n} \sum_{\tau=0}^n X_{\tau} \quad (1)$$

$$Y_i = (X_i - A) \cdot \text{gain} \quad (2)$$

### 2.2. Accelerometer and electronic compass calibration

Accelerometer and compass sensors can measure the value of a vector field where the Sensor location. In the static accelerometers can measure equivalent gravitational field, electronic compass is measured geomagnetic field. The following describes only the accelerometer calibration, electronic compass calibration equally.

Acceleration measured object is gravity, which is the vector sum of gravity and motion acceleration. When stationary, the motion acceleration is 0. The equivalent value of the accelerometer measuring is acceleration of gravity, so we can make use of this feature to correction accelerometer. Accelerometer calibration method is: translation and scaling the measured value, and the measured value is fitted to the acceleration of gravity. Therefore correction tasks: to find the best translation and scaling parameters, make overall measurement data closer to the gravitational acceleration.

Note the measured value  $[x_m, y_m, z_m]$ , the corrected value  $[x_c, y_c, z_c]$ , translational parameters  $[o_x, o_y, o_z]$ , scaling parameter  $[g_x, g_y, g_z]$ , the relationship between them is (3).

$$\begin{cases} x_c = (x_m + o_x) \cdot g_x \\ y_c = (y_m + o_y) \cdot g_y \\ z_c = (z_m + o_z) \cdot g_z \end{cases} \quad (3)$$

Define error U is square difference of the measured value and gravitational constant G, such as (4).

$$u = x_c^2 + y_c^2 + z_c^2 - G^2 \quad (4)$$

The (3) into (4), we get:

$$u = g_x^2 x_m^2 + o_x^2 g_x^2 + 2x_m o_x g_x^2 + g_y^2 y_m^2 + o_y^2 g_y^2 + 2y_m o_y g_y^2 + g_z^2 z_m^2 + o_z^2 g_z^2 + 2z_m o_z g_z^2 - G^2 \quad (5)$$

Let the objective function U, weighed the overall error, here with the sum of squares of single error.

$$U = \sum u^2 \quad (6)$$

Correction tasks: U get the minimum. the minimum of U gets in extreme pole, namely first-order partial derivatives is 0.

### 3.Data Fusion

First introduced "attitude interpolation method", the process of this method is divided into two parts: First, if known initial attitude, we can use the integral gyro, constantly calculate the next attitude, this part of the dynamic performance is highperformance, but the error will accumulate; second, the accelerometer and electronic compass can be directly calculated a attitude, the attitude of expectation is correct, but as stated above, this attitude has noisy and unstable. In order to combine the advantages of both systems, the results of the two systems can be interpolated, the value obtained as the current posture.

Deeper, attitude is actually a rotation transformation, showing the rotating relationship between the body's coordinate system and the geographic coordinate system, here defined an attitude that converts from the geographic coordinate system to body coordinate system. In this article, the matrix in bold capital letters, such as  ${}^E_A \mathbf{R}$  the upper left and lower left icon indicates transformation from the body coordinate system (Aircraft) to the geographic coordinate system (Earth); Quaternions in bold lowercase letters, such as  $\mathbf{q}$  upper and lower icon standard meaning with the same as transformation matrix; Vector with arrowed bold lowercase letters, such as  ${}^A \vec{v}$ , upper left A represent vector coordinate values in the body coordinate system. Because attitude is essentially a rotational transform, according to Euler's theorem of rigid finite rotation, rotation transformation can be connected in series, a gesture may be subjected to a rotational transform into another attitude. Concepts analogy points and vectors, attitude equivalent point, rotate the equivalent vector, point by the vector into another point. If quaternion represents rotation, by quaternion multiplication to implement rotating series. Quaternion represents the rotation, computation of rotation in combination is less than other methods, so whether in the fields of computer graphics, rigid body rotation, aircraft control, quaternion has a pivotal position <sup>[1]</sup>.

Here to talk "attitude interpolation method" of calculation. The first is the first part - gyroscope integral calculates attitude. Gyroscope output Time discrete angular velocity, integrated over time to get the angle. The gyro output is angular velocity  $\vec{\omega} = [\omega_x, \omega_y, \omega_z]^T$  units: rad / s, the sampling interval  $\Delta t$ . Assuming that the sampling interval is sufficiently short, in a sampling time interval, an angular velocity constant, and the angle is small enough, trigonometric higher order terms are ignored, the mutual influence between the respective axes is negligible, in the interval the rotation can be represented by quaternion as:

$$\frac{A_{n-1}}{A_n} \mathbf{r}_n = \left[ \sqrt{1 - \frac{\Delta t^2}{4} (\omega_x^2 + \omega_y^2 + \omega_z^2)} \quad \frac{\Delta t \cdot \omega_x}{2} \quad \frac{\Delta t \cdot \omega_y}{2} \quad \frac{\Delta t \cdot \omega_z}{2} \right]^T$$

(7)

the attitude of Before updating  ${}^E_{A_{n-1}}\mathbf{q}$ ,  ${}^{A_{n-1}}_{A_n}\mathbf{r}_n$  is rotated on the basis of  $\mathbf{q}$ , put them multiplied to obtain the new current attitude. Quaternion multiplication symbol is  $\otimes$ .

$${}^E_{A_n}\mathbf{q}_{gyr} = {}^E_{A_{n-1}}\mathbf{q} \otimes {}^{A_{n-1}}_{A_n}\mathbf{r}_n \quad (8)$$

Then talk about the second part. Attitude is defined as a rotation transform two coordinate systems, so long as we know the two pairs in the two coordinate systems corresponding vector, you can find out the attitude. Two pairs of variables are acceleration and magnetic field strength, the measured acceleration and magnetic field strength is in the body coordinate system and the geographic coordinate system acceleration and magnetic field is constant, there is a rotation, acceleration and magnetic field strength in the body coordinate system can convert to corresponding constants coincides with in the geographic coordinate system, the rotation is the desired attitude. Due to the impact of sensor system error, noise, etc., the angle is not constant value measured acceleration and magnetic field, and it is impossible to precisely rotate and constants, so we can only seek the closest rotation. The closest in principle be set as follows: First, after rotating four vectors coplanar; second, make bisector of after rotation acceleration and magnetic field angle coincide with bisector of constant.

In order to achieve the closest principle, the amount handled converted from the acceleration and magnetic field strength to their plane normal and angular bisectors. Remember accelerometer output is  ${}^A_{\mathbf{a}_m}$ , compass output is  ${}^A_{\mathbf{h}_m}$ , standardized equivalent gravitational acceleration is  ${}^E_{\mathbf{a}_c} = [0 \ 0 \ 1]^T$ , standardized geomagnetic field strength  ${}^E_{\mathbf{h}_c} = [0 \ y_{\mathbf{h}_c} \ z_{\mathbf{h}_c}]^T$ .

Plane normal vector and diagonal vector of acceleration and magnetic field strength:

$${}^A_{\vec{c}_m} = \frac{{}^A_{\vec{a}_m} \times {}^A_{\vec{h}_m}}{|{}^A_{\vec{a}_m}| |{}^A_{\vec{h}_m}|} \quad (9)$$

$${}^A_{\vec{d}_m} = \frac{{}^A_{\vec{a}_m}}{|{}^A_{\vec{a}_m}|} + \frac{{}^A_{\vec{h}_m}}{|{}^A_{\vec{h}_m}|} \quad (10)$$

Equivalent gravitational acceleration constant and the geomagnetic field strength constant plane normal vector and diagonal:

$${}^E_{\vec{c}_c} = {}^E_{\vec{a}_c} \times {}^E_{\vec{h}_c} \quad (11)$$

$${}^E_{\vec{d}_c} = {}^E_{\vec{a}_c} + {}^E_{\vec{h}_c} \quad (12)$$

Define a function for converting the rotation axis and rotation is converted into quaternion:

$$\mathbf{r} = \text{quaternion}(\vec{\omega}, \theta) \begin{cases} w_r = \cos(\frac{\theta}{2}) \\ x_r = \frac{x_{\vec{\omega}}}{|\vec{\omega}|} \sin(\frac{\theta}{2}) \\ y_r = \frac{y_{\vec{\omega}}}{|\vec{\omega}|} \sin(\frac{\theta}{2}) \\ z_r = \frac{z_{\vec{\omega}}}{|\vec{\omega}|} \sin(\frac{\theta}{2}) \end{cases} \quad (13)$$

Then define a function for acquiring a quaternion that make vector rotate to another vector:

$$\mathbf{r} = \text{rotate}(\vec{\mathbf{f}}, \vec{\mathbf{t}}) = \text{quaternion}(\vec{\mathbf{f}} \times \vec{\mathbf{t}}, \arctan(|\vec{\mathbf{f}} \times \vec{\mathbf{t}}|, \vec{\mathbf{f}} \cdot \vec{\mathbf{t}})) \quad (14)$$

The first rotation, the plane normal rotation to coincide:

$$\mathbf{q}_1 = \text{rotate}({}^A\vec{\mathbf{c}}_m, {}^E\vec{\mathbf{c}}_c) \quad (15)$$

After the first rotation, the four vectors have coplanar ,diagonal vector of acceleration and magnetic field strength becomes:

$${}^A\vec{\mathbf{d}}_m' = R(\mathbf{q}_1) \cdot {}^A\vec{\mathbf{d}}_m \quad (16)$$

Then the second rotation, make diagonal overlapped:

$$\mathbf{q}_2 = \text{rotate}({}^A\vec{\mathbf{d}}_m', {}^E\vec{\mathbf{d}}_c) \quad (17)$$

The combination of two rotations, is the attitude of the second part seeking .

$${}^E_A\mathbf{q}_{acc\&mag} = \mathbf{q}_2 \otimes \mathbf{q}_1 \quad (18)$$

Two parts attitude interpolation, we can get the current attitude.Because the two parts of the small difference between the calculated attitude,we can use ordinary linear interpolation. $\alpha$  is the interpolation coefficient, the range [0,1], closer to 0, the first part of the attitude the weight accounting is larger, and generally value close to zero.

$${}^E_{A_n}\mathbf{q} = \frac{\mathbf{t}}{|\mathbf{t}|} \quad \mathbf{t} = \alpha \cdot {}^E_A\mathbf{q}_{acc\&mag} + (1-\alpha) \cdot {}^E_{A_n}\mathbf{q}_{gyr} \quad (19)$$

Turn quaternion into Euler angles. There are many ways to define the Euler angles, defined here as the x-axis positive direction is heading, around the z-axis rotation angle is yaw angle (yaw), around the the y-axis is the pitch angle (pitch), around the x-axis angle is roll angle (roll), rotation order is the ZYX.

${}^E_{A_n}\mathbf{q}$  is a quaternion, so  ${}^E_{A_n}\mathbf{q} = [x_q \ y_q \ z_q \ w_q]$ , see the specific conversion formula (29).

$$\begin{cases} y_a = \arctan 2(2w_q z_q + 2x_q y_q, 1 - 2y_q^2 - 2z_q^2) \\ p_a = \arcsin(2w_q y_q - 2z_q x_q) \\ r_a = \arctan 2(2w_q x_q + y_q z_q, 1 - 2x_q^2 - 2y_q^2) \end{cases} \quad (20)$$

#### 4.the algorithm verification

In the static state, attitude fusion idea is: gyro-based, accelerometer and compass correct the error, so the dynamic performance depends on the gyro, and static performance depends on the accelerometer and compass, so static situation is best way to reflect attitude fusion algorithms the merits. Figure 1 is a calculated roll angle, which took 1,000 consecutive samples with time sampling each 5s .As can be seen from the figure, the static drift is about 0.15 degrees, and gradually decreases over time, the attitude interpolation static effect is ideal. Then verify dynamic performance.Data shown in Figure 2, the light green curve is calculated using the accelerometer and compass gesture, equivalent to the second part attitude of attitude interpolation method, the red curve is the gyroscope, accelerometer and compass data by interpolation method fusion.Because dynamic performance determines by the gyro, and the angle of tens of degrees relative to the movement, the noise is almost negligible, which is also taking continuous samples of 1000, can be seen by the dynamic effect of the interpolation method is good.

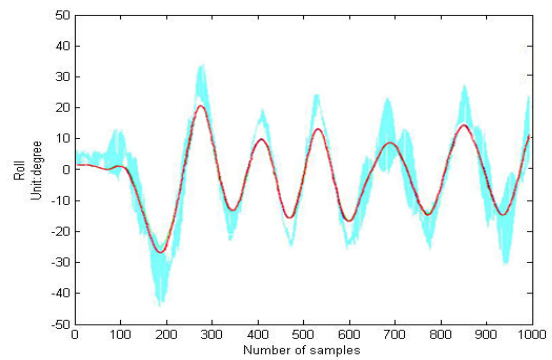
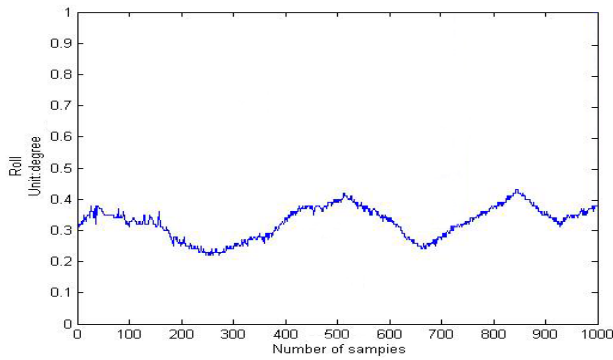


Fig. 1 under static system output data curve      Fig. 2 dynamic system output data curve

## 5. conclusion

By interpolation method makes gyroscopes, accelerometers and electronic compass data fusion, thereby improving the long-term accumulation of errors gyroscope, improve accelerometer influenced by external acceleration and improved electronic compass magnetic interference of motor and other. Actual test results show that in the static state and dynamic state data are very stable, low data zero drift, stable dynamic performance, precision can reach 0.01 degrees, the effective resolution of 0.1 degrees, even at 5 g acceleration, the solver data remain stable. But the amount of calculation is little large, low computing power microcontroller computing speed is slow. In this paper we use is based on the cortex-M3 core STM32F103ZET6 controller.

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