The Design of Strapdown Inertial AHRS Based on MEMS

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***Abstract*—A method of low cost strapdown inertial Attitude and Heading Reference System based on MEMS is implemented in this paper. Based on the analysis of the modules, the proper selection of the core processor and the inertial devices, the hardware components of the system is presented; Using the gradient-descent algorithm which is based on quaternion, it can finish the calculation of the attitude; This AHRS can realize the real-time extraction, calculation and the output of the information.**

Keywords-MEMS; AHRS; Gradient-descent algorithm

I. INTRODUCTION

Inertial navigation [1] is a kind of independent navigational method which is used to calculate the attitude, speed and position parameter of the moving object. It depends on the carrier entirely to finish navigation task independently and has no contact with the outside world in the type of light or electricity. So the character of concealment is very good and the works have no restrictions with the environment conditions. These unique characteristics make it widely used in aerospace, aviation, navigation and geodetic survey, etc.

Inertial navigation system can be divided into strapdown inertial navigation system and platform inertial navigation system [2] according to the installation method of inertial measurement unit. The strapdown inertial navigation system (SINS) comes from the development of the platform inertial navigation system. Due to delete the mechanical and electrical platform, SINS is simple in structure, small in size, light in weight, reliable and cheap. It also shortens the system startup-time and eliminates the error related to the platform system.

This paper proposes a Strapdown Inertial Attitude and Heading Reference System which meets the requirements of low and medium grade in precision based on the requirements of INS in the areas mentioned above. This system is based on the ARM processor and made of the three-axis gyroscope, three-axis accelerometer and three-axis magnetometer.

II. THE OVERALL DESIGN OF SYSTEM

This system is composed of MEMS devices, navigation processor and external monitoring computer, etc. The MEMS devices include three-axis accelerometer, three-axis gyroscope and three-axis magnetometer collecting acceleration, angular rate of the carrier which the sensors in and the intensity of earth's magnetic field respectively. The navigation processor calculates the Euler angles of the carrier after processing the informations what it received and then the external monitoring computer displays the attitude of the carrier. The gyroscope, accelerometer and magnetometer we have chosen have the I2C digital interface. They are hanging in the I2C bus of the navigation processor.

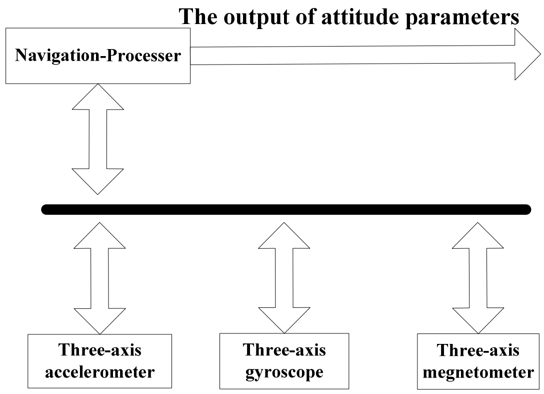

Figure 1. The structure of attitude and heading measurement module.

A. *The Selection of Navigation Processor*

AHRS need to measure the real-time information including the acceleration, angular rate of carrier and the intensity of earth's magnetic field about the x, y and z axes of senor frame and then the attitude and heading of carrier can be calculated by using SINS algorithm. So it is an embedded information processing system [3] which is strong in real-time, intensive in operation and high in accuracy actually. ARM processor is becoming the synonym of the embedded processor which is high performance, low power consumption and low cost because of its excellent performance and significant advantages. So it has been widely used in the areas of 32-bit embedded applications. In this paper, taking stm32F407 processor produced by Samsung Company as the navigation computer becomes a good choice undoubtedly. Stm32F407 processor is a kind of 32-bit microprocessor with high-performance and low power consumption. It has independent instruction set and data memory interface which make the processor taking the instruction and reading or writing data simultaneously possible; it increases the clock frequency and parallel processing ability by using five stage pipelines. It also supports the functions such as LCD. These characteristics meet the requirements of real-time calculating and storing data fast. So this paper chooses stm32F407 as navigation processor.

B. *The Selection of MEMS Sensors*

The MEMS sensors we have chosen include three-axis accelerometer, three-axis gyroscope and three-axis magnetometer. Because the errors of the MEMS inertial devices are the main error source of strapdown inertial navigation system, so the selection of devices is a very important step in the strapdown inertial navigation system. We choose the module of mpu6050 as gyroscope and accelerometer which integrates the three-axis gyroscope and three-axis accelerometer to calculate attitude. This module is the first component in the world which integrating 6 axis motion processing. Compared with the solutions using many components, this choice solves the problem of inter-axial differential by the combination of gyroscope and accelerometer and reduces a lot of packing space. Figure 2 is the circuit diagram of it. The gyroscope has the maximum range of 2000 degrees/s which can be configured and the accelerometer has the maximum range of 16g which can be configured. All of them have the I2C digital output interface.

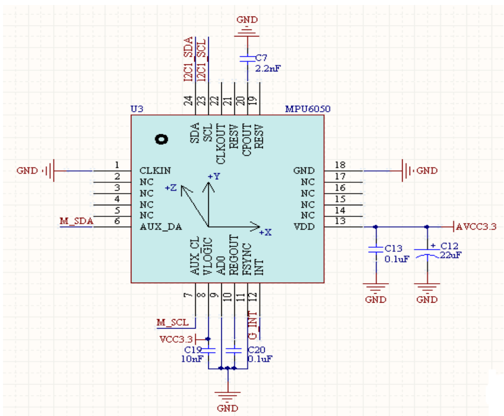

Figure 2. The circuit diagram of mpu6050.

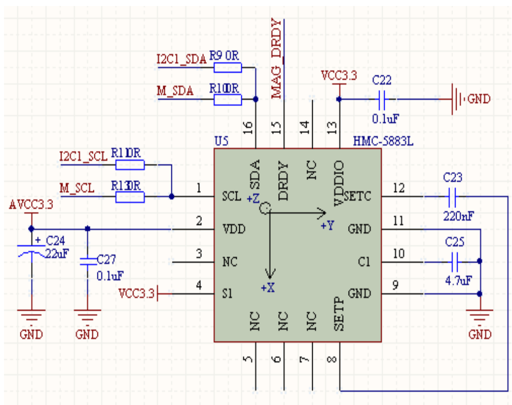

Figure 3. The circuit diagram of HMC5883L.

HMC5883L chip [4] produced by Honeywell company has been chosen as the magnetometer in this paper. Figure 3 is the circuit diagram of it. It is a chip which is LCC packaged. It includes our state-of-the-art, high-resolution HMC118X series magneto-resistive sensors plus an ASIC containing amplification, automatic degaussing strap drivers, offset cancellation, and a 12-bit ADC that enables 1° to 2° compass heading accuracy. The I2C serial bus allows for easy interface.

III. THE ALGORITHM OF ATTITUDE ESTIMATION

Acceleration and angular rate in the sensor frame are measured through using three-axis accelerometer and three-axis gyroscope respectively. The three-axis magnetometer can measure intensity of earth's magnetic field in x, y and z axes which are mutually orthogonal sensitive axes. The method confirming the attitude of carrier in the earth frame is which using the accelerometer and magnetometer data into an optimized gradient-descent algorithm [5] to compute the direction of the gyroscope measurement error as a quaternion derivative. Then the estimate orientation of the sensor frame relative to the earth frame and Euler angles can be calculated.

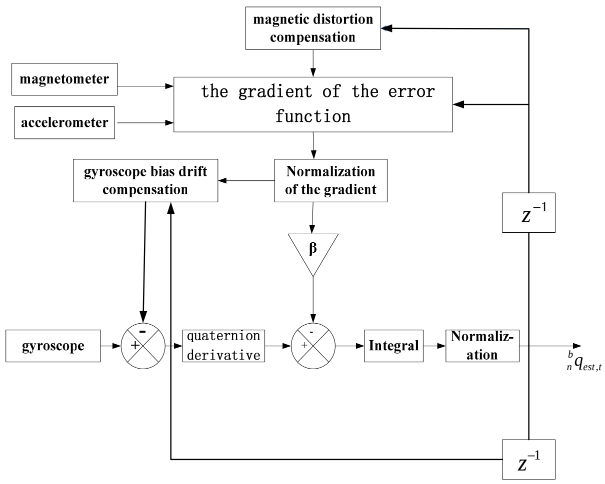

Figure 4. The block diagram of attitude detection based on MEMS.

A. *The Original Alignment of AHRS*

The roll angle and pitch angle can be calculated by the data of accelerometer and the yaw angle can be calculated by the data of magnetometer. When the System is started, the roll angle, pitch angle and yaw angle should be calculated according to the data from accelerometer and magnetometer. The Euler angles are defined by equations (1), (2) and (3).

$$\gamma = \arctan\left(\frac{a_y}{a_z}\right) \tag{1}$$

$$\theta = \arcsin(\frac{a_x}{-g}) \quad (2)$$

$$\varphi = \arctan\left[(m_z * \sin\gamma - m_y * \cos\gamma) / \left(m_x * \cos\gamma + m_y * \sin\gamma + m_z * \sin\theta * \cos\gamma\right)\right] \quad (3)$$

γ represents the roll angle, θ represents the pitch angle and φ represents the yaw angle in the above equations. a_x, a_y, a_z represent the data of accelerometer in the sensor frame and m_x , m_y , m_z represent the data of magnetometer in the sensor frame respectively.

The initial value of the quaternion can be calculated by using the equations (4), (5), (6), (7):

$$q0 = \cos\frac{\gamma}{2} * \cos\frac{\theta}{2} * \cos\frac{\varphi}{2} + \cos\frac{\gamma}{2} * \sin\frac{\theta}{2} * \sin\frac{\varphi}{2} \quad (4)$$

$$q1 = -\cos\frac{\gamma}{2} * \sin\frac{\theta}{2} * \sin\frac{\varphi}{2} + \sin\frac{\gamma}{2} * \cos\frac{\theta}{2} * \cos\frac{\varphi}{2} \quad (5)$$

$$q2 = \cos\frac{\gamma}{2} * \sin\frac{\theta}{2} * \cos\frac{\varphi}{2} + \sin\frac{\gamma}{2} * \cos\frac{\theta}{2} * \sin\frac{\varphi}{2} \quad (6)$$

$$q3 = \cos\frac{\gamma}{2} * \cos\frac{\theta}{2} * \sin\frac{\varphi}{2} - \sin\frac{\gamma}{2} * \sin\frac{\theta}{2} * \cos\frac{\varphi}{2} \quad (7)$$

Converting the quaternion to attitude Euler angles:

$$Eular\_\gamma = arc\tan(\frac{2.0f * (q0 * q1 + q2 * q3)}{1.0f - 2.0f(q1 * q1 + q2 * q2)}) \quad (8)$$

$$Eular\_\theta = \arcsin(-2.0 * (q1 * q3 - q0 * q2)) \quad (9)$$

$$Eular\_\varphi = arc\tan(\frac{2.0f * (q1 * q2 + q0 * q3)}{1.0f - 2.0f(q2 * q2 + q3 * q3)}) \quad (10)$$

Stop here, the initial alignment of AHRS is finished.

B. The Updating Algorithm of AHRS

1) Using the angular rate measured by three-axis gyroscope calculate the quaternion derivative:

$$^{b}\omega = \begin{bmatrix} 0 & ^{x}\omega & ^{y}\omega & ^{z}\omega \end{bmatrix} \quad (11)$$

$$^{b}_{n}\dot{q}_{w,t} = \frac{1}{2}\, ^{b}_{n}q_{est,t-1} \otimes {}^{b}\omega_t \quad (12)$$

In the equations (12), *n* represents the earth frame and *b* represents the sensor frame. $^{b}_{n}\dot{q}_{w,t}$ represents the quaternion derivative calculating by gyroscope and describes change rate of orientation from the earth frame to the sensor frame at time *t*. $^{b}_{n}q_{est,t-1}$ represents the previous estimate of orientation at time *t-1*. $^{b}\omega_t$ represents angular rate in the x, y and z axes of the senor frame at time *t*. The equation (12) is the differential equation of quaternion [6]. It can be changed to the matrix form as equation (13).

$$\begin{bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & -\omega_x & -\omega_y & -\omega_z \\ -\omega_x & 0 & -\omega_z & -\omega_y \\ -\omega_y & -\omega_z & 0 & -\omega_x \\ -\omega_z & -\omega_y & -\omega_x & 0 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \quad (13)$$

In the process of quaternion's updating, attitude matrix may turn to non-orthogonal matrix because of the existence of calculating error. So orthogonal processing is needed to eliminate the error that caused by non-orthogonal. The method to solve the problem is normalized processing described as equation (14).

$$q_i = \frac{q_i}{\sqrt{q0^2 + q1^2 + q2^2 + q3^2}} \quad (14)$$

2) Using gradient-descent algorithm to compute the direction of the gyroscope measurement error as a quaternion derivative:

$$\mathrm{f}(^{b}_{n}\mathrm{q}, {}^{n}\mathrm{d}, {}^{b}\mathrm{s}) = {}^{b}_{n}q^{*} \otimes {}^{n}\mathrm{d} \otimes {}^{b}_{n}q - {}^{b}\mathrm{s} \quad (15)$$

In the equation (15), $\mathrm{f}(^{b}_{n}\mathrm{q}, {}^{n}\mathrm{d}, {}^{b}\mathrm{s})$ represents the difference between the estimated value calculating from the vector defined in the earth frame and the measured value from the sensor frame. The sensors rotate from earth frame to sensor frame and $^{b}_{n}q$ defines the rotation. Other vectors also defined, such as predefined reference direction in the earth frame, $^{n}d = \begin{bmatrix} 0 & d_x & d_y & d_z \end{bmatrix}$, the measured direction of the field in the sensor frame, $^{b}s = \begin{bmatrix} 0 & s_x & s_y & s_z \end{bmatrix}$. $\nabla f = J^T f$ can compute the gradient of the objective function and J is its Jacobian matrix. ${}_n^b\dot{q}_{\varepsilon,t}$ is the direction of the error of ${}_n^b\dot{q}_{est,t}$ which can be calculated by equation ${}_n^b\dot{q}_{\varepsilon,t} = \frac{\nabla f}{\|\nabla f\|}$. Combining these equations with equation (16):

$$ {}_n^b\dot{q}_{est,t} = {}_n^b\dot{q}_{w,t} - \beta\, {}_n^b\dot{q}_{\varepsilon,t} \quad (16) $$

${}_n^b q_{est,t}$ can be acquired easily. At last an on line magnetic distortion compensation algorithm and gyroscope bias drift compensation are needed.

The under figures are the experiment result which we can see in the monitoring computer using the gradient-descent algorithm.

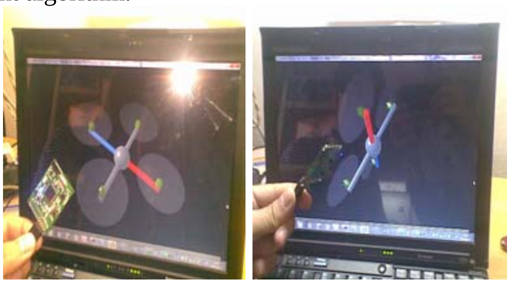

Figure 5. The picture of attitude displaying

IV. CONCLUSION

This system is useful in attitude detection of flight body mainly and we design it for the detection of firefighters in the fire, so the outside world can monitor the information of firefighters to make sure whether they are safe. We will design the SINS next step which is based on this system. For the error of MEMS devices are the main error of INS, INS can not meet the requirements of long-time and long-distance navigation. To improve the navigation precision, MEMS should be combined with the other types of navigation system, for example, GPS. The combination which will make mutual complement each other and form a kind of more excellent navigation system is in progress.

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