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Calibration and data fusion solution for the miniature attitude and heading reference system

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Abstract

Development, calibration and alignment of a miniature magnetic and inertial measurement unit, which is used as an attitude and heading reference system, are presented. Several guidelines were followed during the design process to make the magnetic and inertial measurement unit suitable for various kinds of applications, thus the system is designed both as small as possible but still modular, consisting of three inertial sensor units, a magnetic sensor unit and a control unit.

Complete calibration and alignment procedure is described and an adaptive Kalman filter concept for fusing various sensors' attitude and heading data is introduced and discussed. The characteristics of the magnetic and inertial measurement unit as an attitude and heading reference system are evaluated. The algorithm showed remarkable performance in the orientation determination as the average root mean square error was less than 1.2° over the entire appliable operating range.

Keywords: Inertial measurement unit; Electronic compass; Sensor calibration; Data fusion; Kalman filter

1. Introduction

The progress in micro electro-mechanical system (MEMS) and anisotropic-magnetoresistive (AMR) technology has enabled engagement of inertial MEMS and magnetic AMR sensors in broad spectrum of consumer market applications. Nowadays, a small-size inertial measurement unit (IMU) and electronic compass with of-the-shelf sensors are found in variety of applications, such as unmanned aerial [1] and underwater vehicles [2], handheld navigation devices, human motion tracking [3] and many more.

Despite highly automated production process, the parameters of the contemporary low-cost MEMS and AMR sensors may deviate from a piece to a piece. In our case, the vendor's data of the chosen sensors' sensitivity deviations are ±10% for the MEMS rate gyroscope [4] or even ±25% for the AMR magnetic sensor [5]. Therefore great concern must be paid to the calibration and alignment of the sensors on one side and on the other side advanced sensor data fusion concepts must be applied to achieve desired performance.

The scope of this paper is to present methods, how to build, calibrate, align and maximize the performance of such a low-cost sensor system. For this reason, a miniature magnetic and inertial measurement unit (MIMU) has been developed. The unit was calibrated and aligned according to methods from [6,7] and [8] but modified and adapted to suit the unified accelerometer, gyroscope and magnetometer sensor model. To compute the attitude and heading an effective adaptive Kalman filter data fusion technique was developed and implemented. The whole system was tested as an attitude and heading reference system (AHRS) and the performance was evaluated using an optical kinematic measurement system.

2. Theoretical background

2.1. Orientation representation

Attitude and heading (the orientation) of a rigid body expressed in the inertial coordinate frame can be represented in different ways such as direction cosine matrix (DCM), Euler angles or quaternions.

The DCM is the straightforward method to present the orientation, but the weakness of this approach is that nine parameters

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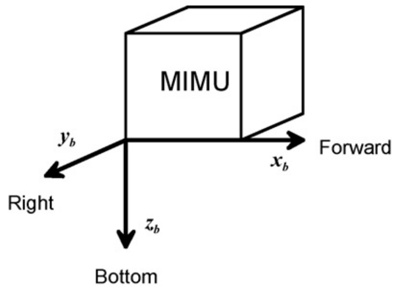

Fig. 1. Body frame fixed to the MIMU's casing.

are needed. If the quaternions are used, only four parameters are required, however, the quaternion representation of the orientation needs to be transformed before it can be displayed in easily understood format. For the orientation representation in our case the aerospace sequence Euler angles (ψ-heading, ϑ-elevation, ϕ-bank) are used [9]. This parameterization is chosen because of its intuitive nature, despite the singularities and nonlinearity of kinematic equations. Additional motive was the simple data fusion algorithm design, since the orientation information provided by the accelerometers and the electronic compass is represented in this way.

The body coordinate frame is fixed to the MIMU's casing, the x_b-axis points in the forward direction and it is aligned with the roll axis, the z_b-axis (yaw axis) points to the bottom of the MIMU and the y_b-axis (pitch) rounds up the right-handed orthogonal coordinate system (Fig. 1). The inertial coordinate frame is so called North, East, Down (NED) frame. The axes x_i and y_i lie on the local level tangent plane. The x_i-axis points to the north and the y_i-axis to the east. The z_i-axis completes the frame by pointing to the Earth's centre (Fig. 2).

By means of the MIMU the attitude and heading can be determined by either of two complementary approaches. A triad of rate gyros or a combination of a tri-axis accelerometer and an electronic compass can be used. Since each approach has its advantages and disadvantages, the combination of both approaches leads to the highest fidelity and accuracy of the orientation estimation.

2.2. Rate gyro approach

Rate gyro is used to compute the orientation by the integration of the rigid body kinematic equations. Roll, pitch and yaw angular rates (ω_x, ω_y, ω_z) measured by gyros in MIMU's body frame

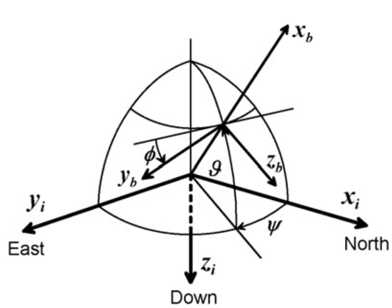

Fig. 2. Orientation of the body frame expressed in the inertial frame.

are transformed into the reference frame Euler angle rates: $\dot{\psi}$, $\dot{\vartheta}$ and $\dot{\phi}$ (Eq. (1)). The Euler angle rates are afterwards numerically integrated and orientation is obtained. Due to the drift of the null bias point and the presence of the noise in the gyro output signal, there is a considerable amount of the error accumulating in the gyro-derived orientation. The most important concern is that this accumulating error is unbounded in time, so only the short-term accuracy can be achieved using the rate gyro measurements.

$$\begin{bmatrix} \dot{\psi} \\ \dot{\vartheta} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} 0 & \sin\phi\sec\vartheta & \cos\phi\sec\vartheta \\ 0 & \cos\phi & -\sin\phi \\ 1 & \sin\phi\tan\vartheta & \cos\phi\tan\vartheta \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \tag{1}$$

2.3. Accelerometer and electronic compass approach

Tri-axis accelerometer or a triad (three orthogonally mounted sensors) of single-axis accelerometers is measuring the resultant of all accelerations acting on the MIMU expressed in the body frame (a_x, a_y, a_z). If the MIMU is not moving and the Coriolis acceleration due to the Earth's rotation is neglected then the gravity is the only acceleration affecting the accelerometer triad. Under these conditions the attitude (elevation-ϑ_{ACC} and bank-ϕ_{ACC}) can be established as stated in Eq. (2) and Eq. (3). Since accelerometer is used as an inclinometer a static activity detection algorithm must be implemented.

$$\vartheta_{ACC} = \text{arctg}\left[\frac{a_x}{\sqrt{a_y^2 + a_z^2}}\right] \tag{2}$$

$$\phi_{ACC} = \text{arctg}\frac{a_y}{a_z} \tag{3}$$

Electronic compass data are used for the heading calculation. In the first place the measurements must be electronically gimballed (Eq. (4)) i.e. the magnetic field vector measured in the body frame (m_x, m_y, m_z) is compensated for the elevation and bank angle to obtain its transform in the inertial frame (m_{xi}, m_{yi}, m_{zi}). Afterwards the heading—ψ_{MAG} is computed using Eq. (5).

$$\begin{bmatrix} m_{xi} \\ m_{yi} \\ m_{zi} \end{bmatrix} = \begin{bmatrix} \cos\vartheta & \sin\phi\sin\vartheta & \cos\phi\sin\vartheta \\ 0 & -\cos\phi & -\sin\phi \\ -\sin\vartheta & \sin\phi\cos\vartheta & \cos\phi\cos\vartheta \end{bmatrix} \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} \tag{4}$$

$$\psi_{MAG} = \text{arctg}\frac{m_{yi}}{m_{xi}} \tag{5}$$

Heading information provided by the electronic compass is valid only in the homogeneous and undisturbed Earth's magnetic field. If any anomalies in the magnetic field absolute value or in the magnetic field dip angle are noticed then the measurement uncertainty is increased or the current measurement is even invalid.

3. Hardware design process

Since various applications require a specific configuration of sensors, the flexibility of the system design is an important issue. Therefore we have developed a modular system, where more detachable sensor units are connected to a central control unit.