

TILT COMPENSATED ECOMPASS

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Abstract

This paper describes implementation of a tilt compensated electronic compass and calibration method of the used sensors. Firstly describes used hardware and then focus on the method of sensor calibration parameters. The eCompass uses a three-axis accelerometer and three-axis magnetometer. The compass heading is a function of all three accelerometer readings and all three magnetometer readings. The accelerometer measures the components of the earth gravity and provide pitch and roll angle information which is used to correct the magnetometer data. The magnetometer measures the components of earth's magnetic field to determine the heading angle to the magnetic north.

Keywords: eCompass; MEMS; Accelerometer; Magnetometer; Calibration



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1. Introduction

The first compass was probably a magnetized stone, that when suspended, would always point the same way. Today's all non-electronics compasses use a magnetized steel needle, supported in the middle. The important points of a compass are North, East, South and West; always read clockwise around the circle. North is found at 0° (which is also 360°). [1]

The compass points to the magnetic north, not true geographic North Pole. The compass therefore points a little to the side of the geographic North Pole, and this varies depending on where you are on Earth, and also with time. In fact, the magnetic pole migrate over time, it moves about 55 km a year, and the movement has speeded up recently [2].

The Earth acts like a large spherical magnet: it is surrounded by a magnetic field. That changes with time and location. At any point and time, the Earth's magnetic field is characterized by a direction and intensity which can be measured.

The intensity of the magnetic field is about 0.25 to 0.65 gauss (25000 - 65000 nT) and has a component parallel to the earth surface that always points toward the magnetic North Pole. In the northern hemisphere this field point down. At the equator it points horizontally and in the southern hemisphere it points up. This angle between the earth's magnetic field and horizontal plane is defined as an inclination angle. Another angle between the earth's magnetic north and geographic north is defined as a declination angle in the range of $\pm 20^\circ$ depending on geographic location [3], see Fig. 1 [8]. A magnetic compass needle tries to align itself with the magnetic field lines. However, near the magnetic poles, the fields are vertically converging. The strength and direction tend to "tilt" the compass needle up or down into the Earth.

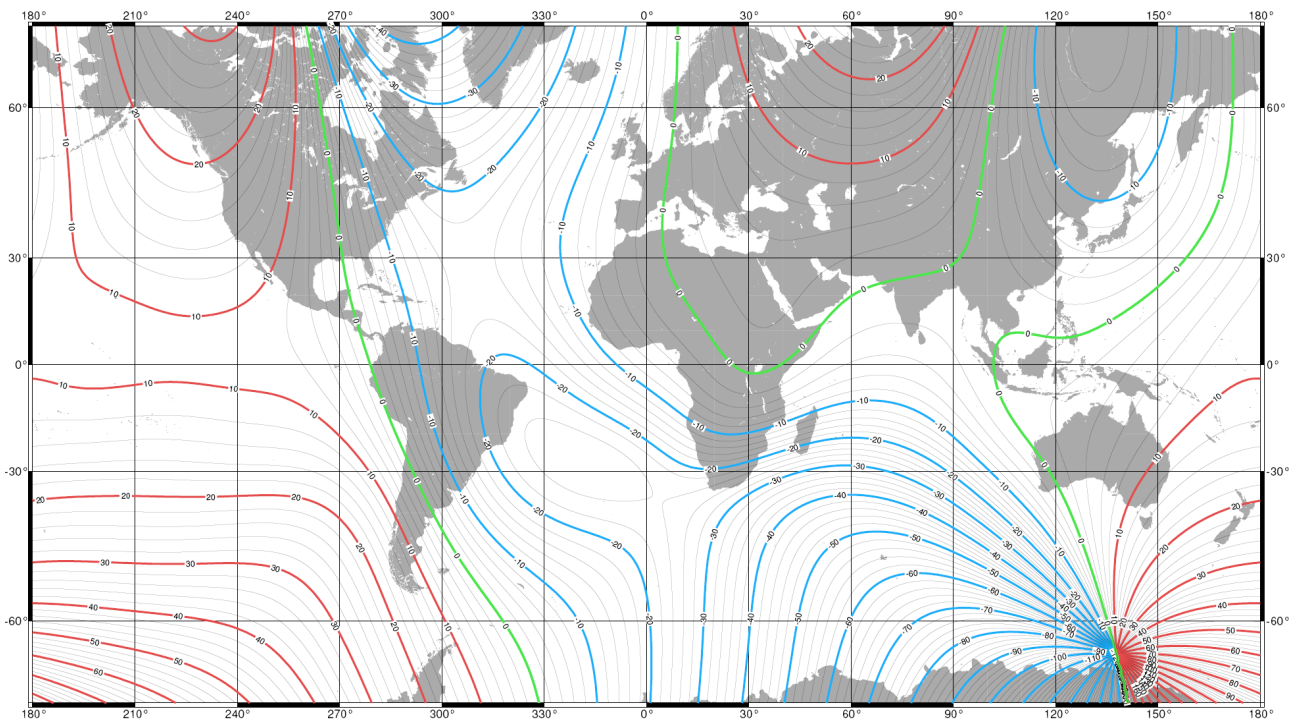


Fig. 1. Magnetic field declination [8]

A tilt compensated electronics compass system uses a three-axis accelerometer sensor and three-axis magnetic sensor. The accelerometer is used to measure the tilt angles of pitch and roll for compensation. The magnetic sensor is used to measure the earth's magnetic field. Then it is possible to calculate the compass heading angle (yaw) with respect to the magnetic north. The declination angle at the current geographic location should be used for compensation of the heading to obtain true geographic North Pole. The Fig. 2 shows coordinate system which uses the industry standard "NED" (North, East, Down) to label axes on the device [3]. The XD axis of the device is the eCompass pointing direction, the YD axis points to the right and ZD axis points downward. Positive yaw angle is defined to be a clockwise rotation about the positive ZD axis.

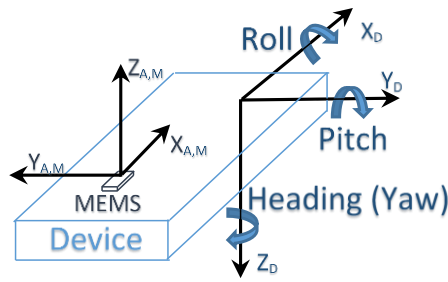


Fig. 2. eCompass coordinate system [3]

Similar, positive pitch and roll angles are defined as clockwise rotations. When MEMS is installed in a device as shown in Fig. 2 then the sign of $Y_{A,M}$ and $Z_{A,M}$ from the sensor measurements needs to be reversed to make the sensing axes the same direction as the device axes [3, 5].

2. Accelerometer

2.1. Physical principles and structure

An accelerometer is an electromechanical device that measures acceleration static and dynamic forces. There are many types of accelerometers and there are many different ways to make an accelerometer. Some accelerometers contain microscopic crystal structures that get stressed by accelerative forces use the piezoelectric effect. Another sensing changes in capacitance. Capacitive sensing has excellent sensitivity.

Typical MEMS accelerometer is composed of movable proof mass with plates that is attached through a mechanical suspension system to a reference frame. A MEMS accelerometer differs from integrated circuits in that a proof mass is machined into the silicon. Any displacement of the component causes this mass to move slightly according to Newton's second law, and that change is detected by sensors. Usually the proof mass disturbs the capacitance of a nearby node; that change is measured and filtered. Movable plates and fixed outer plates represent capacitors. The deflection of proof mass is measured using the capacitance difference. The free-space (air) capacitances between the movable plate and two stationary outer plates C1 and C2 are functions of the corresponding displacements. [6]

The most important specification is the number of axis. The MEMS proof mass can measure only one parameter in each available axis, so a one axis device can sense acceleration in a single direction. Three axis units return sensor information in the X, Y, and Z directions.

Accelerometer sensors measure the difference between any linear acceleration in the accelerometer's reference frame and the earth's gravitational field vector. The earth's gravitational field is defined by a force vector that points directly down towards the Earth's core. In the absence of linear acceleration, the accelerometer output is a measurement of the rotated gravitational field vector and can be used to determine the accelerometer pitch and roll orientation angles. The orientation angles are dependent on the order in which the rotations are applied. The most common order is the aerospace sequence of yaw then pitch and finally a roll rotation. [4]

Three-axis accelerometers supplied for the consumer market are typically calibrated by the sensor manufacturer using a six-element linear model comprising a gain and offset in each of the three axes. This factory calibration will change slightly as a result of the thermal stresses during soldering of the accelerometer to the circuit board. Rotation of the accelerometer package relative to the circuit board and misalignment of the circuit board to the final product will also add small errors. The original factory accelerometer calibration is adequate for the majority of consumer applications. However, own calibration improve accuracy for high-accuracy applications.

2.2. Accelerometer calibration

The relation between corrected accelerometer output and accelerometer raw measurements can be expressed as

$$\begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} = [Am_{xyz}]_{xyz} \begin{bmatrix} \frac{1}{S_x} & 0 & 0 \\ 0 & \frac{1}{S_y} & 0 \\ 0 & 0 & \frac{1}{S_z} \end{bmatrix} \begin{bmatrix} R_x - O_x \\ R_y - O_y \\ R_z - O_z \end{bmatrix} \quad (1)$$

Where:

A is the corrected reading in X, Y and Z axes.

A_m is the 3x3 misalignment matrix between sensor axes and device axes.

S is the sensitivity of each channel.

R is the raw data from the accelerometer.

O is the accelerometer's zero-g level.

The sensitivities and offsets are constants, so the matrix can be simplified to:

$$\begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} \cdot \begin{bmatrix} R_x \\ R_y \\ R_z \end{bmatrix} + \begin{bmatrix} C_{10} \\ C_{20} \\ C_{30} \end{bmatrix} \quad (2)$$

It is possible rewrite (2) as

$$\begin{bmatrix} A_x & A_y & A_z \end{bmatrix} = \begin{bmatrix} R_x & R_y & R_z & 1 \end{bmatrix} \cdot \begin{bmatrix} C_{11} & C_{21} & C_{31} \\ C_{12} & C_{22} & C_{32} \\ C_{13} & C_{23} & C_{33} \\ C_{10} & C_{20} & C_{30} \end{bmatrix} \quad (3)$$

The main goal of accelerometer calibration is to determine 12 parameters [10] from C_{10} to C_{33} . This is typically done using the least squares method [3, 4, 5].

The original 6-parameter (gain and offset in each channel) factory calibration can be recomputed to correct for thermal stresses introduced in the soldering process. Used 12 parameter linear calibration model can correct for accelerometer package rotation on the circuit board and for cross-axis interference between the accelerometer's x, y and z channels [7, 10, 11]. It is possible substitute (3) as

$$Y = w \cdot X \quad (4)$$

Where:

Matrix X is calibration parameters. Matrix w is raw data from the accelerometer collected at 6 stationary positions (when device lays on each side of the device and normalized gravity vector is zero in two axis). For better accuracy is possible add more stationary positions. Matrix Y is the known normalized gravity vector.

Finally, calculation of 12 calibration parameters by least squares method can be written as

$$X = [w^T \cdot w]^{-1} \cdot w^T \cdot Y \quad (5)$$

3. Magnetometer

A magnetometer is a type of sensor that measures the strength and direction of the local magnetic field. The magnetic field measured is a combination of both the earth's magnetic field and any magnetic field created by nearby objects. The accuracy is highly dependent on the calculation and subtraction in software of stray magnetic fields both within, and in the vicinity of, the magnetometer on the PCB (Printed Circuit Board). By convention, these fields are divided into those that are fixed (termed Hard-Iron effects) and those that influence or distort geomagnetic field (termed Soft-Iron effects).

Hard-iron interference magnetic field is normally generated by ferromagnetic materials with permanent magnetic fields. These materials could be permanent magnets or magnetized iron or steel, for example the metal chassis or frame of the device, any actual magnets attached such as speakers etc. This interference pattern is unique to the device and is constant (time invariant). The unwanted magnetic fields are superimposed on the output of the magnetic sensor measurements of the earth's magnetic field. The effect of this superposition is to bias the magnetic sensor outputs. If we consider the magnetic data circle (the magnetic field strength in one horizontal direction), hard iron interference shift the entire circle away from the origin by some amount [9]. The amount is dependent on different factors and can greatly exceed the geomagnetic field.

A soft-iron interference magnetic field is generated by the items inside the device. They could be current carrying traces on the PCB or magnetically soft materials. They generate a time varying magnetic field that is superimposed on the magnetic sensor output in response to the earth's magnetic field. The effect of the soft-iron distortion is to make a full round rotation circle become a tilted ellipse. The distortion in this case depends on the direction that the compass is facing. Because of this the distortion cannot be calibrated out with a simple offset. Devices

without strong soft-iron interference can simplify calculation, by comprising only the hard-iron offsets and the geomagnetic field strength.

The relationship between the normalized vector and the magnetic sensor raw data can be expressed as [3]:

$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} Mm_{xz} \\ Mm_{yz} \\ Mm_{zx} \end{bmatrix}_{3 \times 3} \begin{bmatrix} \frac{1}{S_x} & 0 & 0 \\ 0 & \frac{1}{S_y} & 0 \\ 0 & 0 & \frac{1}{S_z} \end{bmatrix} \cdot \begin{bmatrix} Ms_{xz} \\ Ms_{yz} \\ Ms_{zx} \end{bmatrix}_{3 \times 3} \cdot \begin{bmatrix} R_x - O_x \\ R_y - O_y \\ R_z - O_z \end{bmatrix} \quad (6)$$

Where:

M is the corrected reading in X, Y and Z axes.

Mm is the 3 x 3 misalignment matrix between sensor axes and device axes.

S is the sensitivity of each channel.

R is the raw data from the magnetometer.

Ms is the 3x3 matrix caused by soft iron distortion.

O is the offset caused by hard iron distortion.

The main goal of the magnetometer sensor calibration is to determine parameters to the normalized values could be obtained at any measurement position [3, 4, 7].

4. eCompass heading calculation

The accelerometer readings provide pitch and roll angle information which is used to correct the magnetometer data. This allow accurate calculation of the compass heading (yaw) when the device is not held flat. The pitch and roll angles are computed on assumption that the accelerometer readings result entirely from the compass orientation in the earth's gravitational filed. . Fast acceleration (or low-g conditions) influence pitch and roll calculation, so the accuracy of an electronic compass means static accuracy when the device is without high acceleration. If the PCB remains flat, then the compass heading could be computed from the arctangent of the ratio of the two horizontal magnetic field components. In general, the PCB has an arbitrary orientation, the compass heading is a function of all three accelerometer readings and all three magnetometer readings [5].

Pitch and roll can be calculated by equations [3, 5]:

$$Pitch = \rho = \arcsin(-A_x) \quad (7)$$

$$Roll = \gamma = \arcsin\left(\frac{A_y}{\cos \rho}\right) \quad (8)$$

Pitch is defined as the angle between the XD axis and the horizontal plane. Roll is defined as the angle between YD axis and the horizontal plane. The acrsin function has good linearity between about -45° to +45°, so accuracy degrades when pitch or roll angles exceed this range [3]. All accelerometers are completely insensitive to rotations about the gravitational field vector and cannot be used to determine such a rotation. The unknown yaw angle represents the device rotation from magnetic north. Its determination requires a magnetometer sensor.

For he heading calculation, magnetometer measurements need to be normalized by applying calibration parameters and then by tilt compensation. Tilt compensated magnetic sensor measurements can be obtained as [3, 5]:

$$M_{x2} = M_{x1} \cos \rho + M_{z1} \sin \rho \quad (9)$$

$$M_{y2} = M_{x1} \sin \gamma \sin \rho + M_{y1} \cos \gamma - M_{z1} \sin \gamma \cos \rho \quad (10)$$

Where M_{x1} and M_{y1} are normalized magnetic sensor measurements with applied calibration correction. This components can be used for heading angle calculation (yaw angle) [3, 5]:

$$Heading = \Psi = \arctan\left(\frac{M_{y2}}{M_{x2}}\right) \quad (11)$$

Equation (11) is valid for positive values of M_{x2} and M_{y2} . When M_{x2} is positive and M_{y2} component is negative then a negative result is summed with 360° . For the negative value of M_{x2} need to be add 180° to heading. Zero value of the M_{x2} means that device points to East ($90^\circ - M_{y2}$ is negative value) or West ($270^\circ - M_{y2}$ is positive value). Finally, value should be corrected by declination which is valid at the current location, see Fig. 1.

5. Conclusion

The objective of this work has been to describe an implementation of a tilt compensated eCompass using accelerometer and magnetometer. The accelerometer sensor output is used by the tilt compensated eCompass algorithms to compute the roll and pitch angles. These allow tilt correction of the magnetometer data. The magnetometer readings must be corrected for hard-iron and soft-iron effects. Although, all MEMS are factory calibrated for common using, it is recommended to perform own calibration to reach a better accuracy. In future, techniques of calibration can be extended to include temperature dependence by performing the recalibration at several temperatures and interpolating the fitted calibration parameters to the actual temperature [11].

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