Microprocessor system for calibrating the antenna position sensor*

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Abstract

A method for joint calibration of an antenna system position sensor is proposed, consisting of an accelerometer, magnetometer, GPS receiver, and microprocessor. The joint calibration significantly improves the accuracy of measuring the components of the Earth's gravitational acceleration and magnetic field vectors, which ensures better targeting of the mobile antenna system. A prototype device and microprocessor software for calibration have been developed.

Keywords

calibration, accelerometer, magnetometer, antenna system, microprocessor

1. Introduction

When positioning satellite communication antenna systems in space, it is necessary to orient them along two coordinates — azimuth and elevation. Typically, these calculated coordinates are available in tables for geostationary satellites or are computed in real-time based on orbital parameters. In the case of mobile (moving or portable) antenna systems, it is crucial to determine their current position at any given moment. The most convenient way to do this is by using a position sensor installed on the movable part of the antenna, which needs to be spatially oriented.

The sensor should consist of the following components: a magnetometer and an accelerometer mounted on a single platform, rigidly connected to the movable part of the antenna, as well as a satellite positioning signal receiver and a microprocessor board that processes their signals and controls the antenna's operation. The magnetometer determines the direction of the Earth's magnetic field and, accordingly, the magnetic azimuth. The accelerometer makes it possible to determine the spatial orientation of the antenna in the Earth's gravitational field, which defines its tilt relative to the Earth's surface (elevation angle). The satellite positioning signal receiver (GPS or similar) is used to determine the current location of the antenna system for calculating the pointing coordinates and correcting the magnetic azimuth during satellite tracking sessions, including when mounted on a moving object. One possible case of such a positioning system is discussed in [1].

The magnetometer calibration method was investigated for two-axis and three-axis systems without an accelerometer [2, 3, 4, 5, 6, 7]. To improve the positioning accuracy of the antenna using this sensor, it becomes necessary to calibrate it and store the calibration table for both the magnetometer and accelerometer in the microprocessor's memory. The calibration processes for both sensors are interdependent. In the first stage, the accelerometer is calibrated by assuming that the Earth's gravitational acceleration vector is directed vertically downward, perpendicular to the Earth's surface at the calibration point. In the second stage, the magnetometer is calibrated based on the calibrated accelerometer values.

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The aim of this research is to develop a joint calibration algorithm for the magnetometer and accelerometer to achieve the required accuracy in determining the spatial orientation of the antenna system and controlling it in real-time operation mode.

2. Main Section

The sensor consists of an accelerometer and magnetometer rigidly fixed to a non-magnetic platform and precisely aligned with each other so that their X, Y, and Z axes are aligned. In this case, when the platform mounted on the antenna is rotated, the coordinates of both devices and the projections of the gravitational force vector and the magnetic field will change synchronously according to the calculated dependencies, considering that the natural components of these vectors in the stationary reference frame on the Earth's surface remain constant at the chosen point.

Let us examine the vector components in the coordinate system of the magnetometer and accelerometer, as shown in Figures 1 and 2.

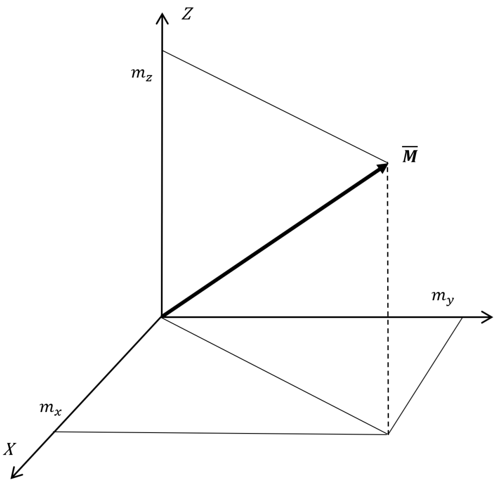

Figure 1: Projections of the Earth's Magnetic Field Vector

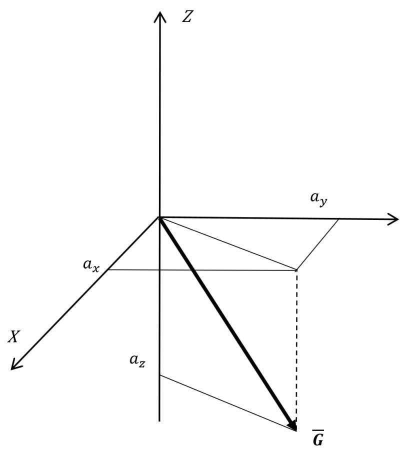

Figure 2: Projections of the Earth's Gravitational Force Vector

By measuring the component values of vectors provided by the magnetometer and accelerometer, it is easy to determine the direction of the corresponding vector. The challenge lies in the fact that due to manufacturing inaccuracies of the devices, as well as the presence of nearby objects that can distort the magnetic field, calibration is necessary. This calibration process involves several steps to determine both the sensitivity coefficients for each coordinate and the corresponding offset of the zero point for the gravity acceleration and magnetic field vector sensors. The obtained calibration coefficients are stored in the microprocessor’s non-volatile memory and are subsequently used for positioning and controlling the operation of the antenna system. If necessary, this process can be repeated in the event of replacing the accelerometer or magnetometer.

The following section describes the recommended calibration process using the sensor’s built-in microprocessor.

The sensor platform is mounted onto a rotating device with axes aligned as shown in Figure 3. A slow rotation is performed with a set increment around the horizontal axis, which corresponds to the Z-axis of both devices. The microcontroller periodically captures readings from both the accelerometer and magnetometer, storing them in RAM for further processing. In this configuration, the X and Y components of the accelerometer vector change, while the Z-axis reading remains low, primarily determined by the offset of the Z-axis channel.

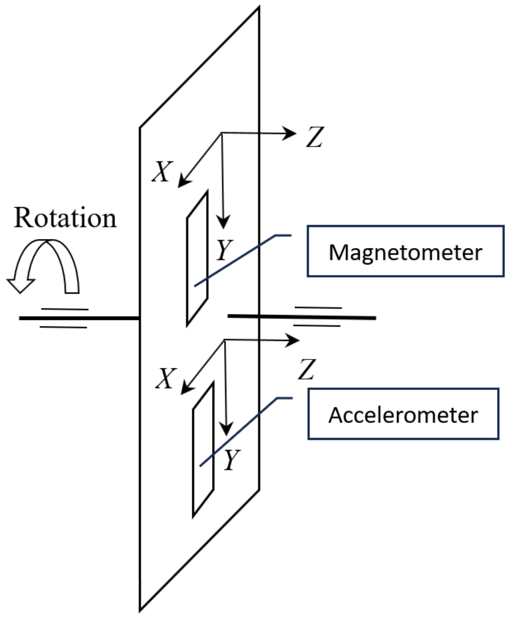

Figure 3: Platform rotation around the Z-axis.

Next, the platform is repositioned so that the horizontal rotation axis aligns with the Y-axis of both devices (Figure 4). The same slow rotation and data recording process into the microcontroller memory is repeated. In this orientation, the X and Z values change similarly to the previous setup, and the Y-axis signal remains low.

Clearly, the amplitude of the X-axis signal in both tests should be similar, and the values in the inactive (zero) channels should be minimal, indicating correct measurement procedures. If distortions are observed, calibration results are unreliable, and the cause must be identified and the calibration repeated.

The datasets obtained through this process represent real, synchronously recorded raw (uncalibrated) values from the accelerometer and magnetometer.

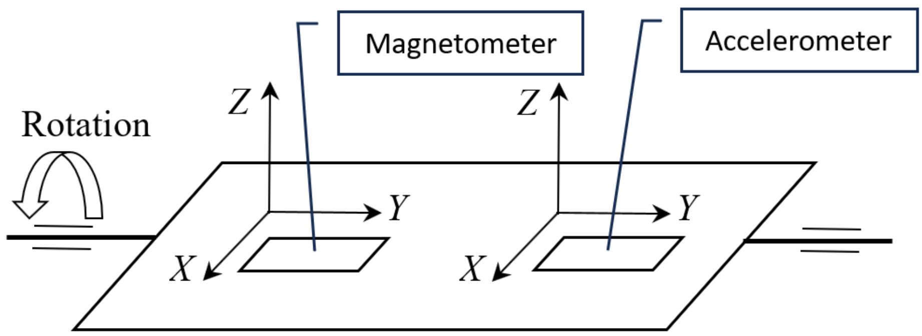

Figure 4: Platform rotation around the Y-axis.

As the platform rotates, each accelerometer channel completes a full cycle, registering values from minimum to maximum, corresponding to the constant known value of Earth's gravitational acceleration. Therefore, the maximum and minimum values of each channel should, in absolute terms, equal the same gravitational acceleration. Any deviations require compensation (calibration).

The zero-point offset of each channel along its respective axis can be determined using known mathematical relationships:

$$X_{0a}=\frac{\left(X_{a\,min}+X_{a\,max}\right)}{2},$$

$$Y_{0a}=\frac{\left(Y_{a\,min}+Y_{a\,max}\right)}{2};$$

$$Z_{0a}=\frac{\left(Z_{a\,min}+Z_{a\,max}\right)}{2};$$

where $X_{a\,min}$, $X_{a\,max}$ – are the minimum and maximum reference values for the channel X respectively;

$Y_{a\,min}$, $Y_{a\,max}$ – are the minimum and maximum reference values for the channel Y respectively;

$Z_{a\,min}$, $Z_{a\,max}$ – are the minimum and maximum reference values for the channel Z respectively.

The calibration coefficients along the axes are determined based on the condition that the maximum calibrated value equals the acceleration due to gravity g:

$$A_x=\frac{g}{X_{a\,max}-X_{0a}};$$

$$A_y=\frac{g}{Y_{a\,max}-Y_{0a}};$$

$$A_z=\frac{g}{Z_{a\,max}-Z_{0a}}.$$

Thus, the actual values of the acceleration vector components along the corresponding axes of the accelerometer, taking calibration into account, are determined by the following formulas:

$$a_x=A_x\left(X_a-X_{0a}\right);$$
$$a_y=A_y\left(Y_a-Y_{0a}\right);$$
$$a_z=A_z\left(Z_a-Z_{0a}\right);$$

where - X_a, Y_a and Z_a – are the current reading values from the corresponding accelerometer channels.

The second step of the calibration process involves determining the coefficients for the magnetometer. We assume that the direction of the magnetic field is unknown, but that both the magnitude and direction of its vector remain constant during the calibration procedure. During rotation, as shown in Figures 3 and 4, the components of the magnetic field aligned with the axis of rotation remain constant, while the other two coordinates vary from minimum to maximum values. Similar to the accelerometer, the zero-point offsets for the magnetometer channels are represented as:

$$X_{0m}=\frac{\left(X_{m\,min}+X_{m\,max}\right)}{2},$$

$$Y_{0m}=\frac{\left(Y_{m\,min}+Y_{m\,max}\right)}{2};$$

$$Z_{0m}=\frac{\left(Z_{m\,min}+Z_{m\,max}\right)}{2};$$

where $X_{m\,min}$, $X_{m\,max}$ – are the minimum and maximum reference values for the channel X respectively;

$Y_{m\,min}$, $Y_{m\,max}$ – are the minimum and maximum reference values for the channel Y respectively;

$Z_{m\,min}$, $Z_{m\,max}$ – are the minimum and maximum reference values for the channel Z respectively.

To determine the sensitivity coefficients for each channel of the magnetometer, we use the array of measured data, taking into account the compensation for zero-point offsets. For each measurement (Figures 3 and 4), we identify the data point where the current value of a particular channel is zero, and the value of another channel is at its maximum. In these instances, the magnitude of the magnetic field vector can be determined using only the two non-zero components. As a result, we obtain four equations (two for each measurement, corresponding to different combinations of vector projections) to calculate the magnitude of the magnetic field vector *M*:

$$M^2=\left[M_x\left(X_{m\,max}-X_{0m}\right)\right]^2+\left[M_z\left(Z_{mc}-Z_{0m}\right)\right]^2;$$
$$M^2=\left[M_y\left(Y_{m\,max}-Y_{0m}\right)\right]^2+\left[M_z\left(Z_{mc}-Z_{0m}\right)\right]^2;$$
$$M^2=\left[M_x\left(X_{m\,max}-X_{0m}\right)\right]^2+\left[M_y\left(Y_{mc}-Y_{0m}\right)\right]^2;$$
$$M^2=\left[M_y\left(Y_{mc}-Y_{0m}\right)\right]^2+\left[M_z\left(Z_{m\,max}-Z_{0m}\right)\right]^2;$$

where $Y_{mc} \wedge Z_{mc}$ – are constant values of the corresponding channels that are aligned along the axis of rotation,

$M_x, M_y \wedge M_z$ – are sensitivity coefficients for the corresponding magnetometer channels that need to be determined..

To determine the angular parameters of the magnetic field vector's direction, it is sufficient to know the ratios between its vector components, without taking into account the actual magnitude of the magnetic field vector. Therefore, we can arbitrarily assume that the coefficient $M_x=1$. By equating the first two equations, we have obtained:

$$M_y=\frac{X_{m\,max}-X_{0m}}{Y_{m\,max}-Y_{0m}}.$$

From the last two equations, we will determine:

$$M_z=\frac{X_{m\,max}-X_{0m}}{Z_{m\,max}-Z_{0m}}.$$

The calculated values of the magnetic field vector components, accurate up to a constant multiplier, can be expressed as follows:

$$m_x=M_x\left(X_m-X_{0m}\right);$$
$$m_y=M_y\left(Y_m-Y_{0m}\right);$$
$$m_z=M_z\left(Z_m-Z_{0m}\right);$$

where - X_m, Y_m and Z_m – are current reading values from the corresponding magnetometer channels.

After calibration, the direction of the true gravitational acceleration vector g and the magnetic field vector M in the coordinate system associated with the platform can be determined using the direction cosine formulas, in the form [8]:

$\cos\alpha_x=\frac{a_x}{g};\cos\alpha_y=\frac{a_y}{g};\cos\alpha_z=\frac{a_z}{g}$ – for accelerometer;

$\cos\beta_x=\frac{m_x}{M};\cos\beta_y=\frac{m_y}{M};\cos\beta_z=\frac{m_z}{M}$ – for magnetometer;

where $M=\sqrt{m_x^2+m_y^2+m_z^2}$ – is the magnitude of the magnetic field vector.

Accordingly, taking into account the properties of the scalar (dot) product of vectors, the angle δ between these vectors is determined by the formula:

$$\cos\delta = \frac{a_x m_x + a_y m_y + a_z m_z}{gM}.$$

At the same time, regardless of how the platform with the accelerometer and magnetometer rotates, the angle between the vectors remains constant at a given point on the Earth's surface. This means that there is a rigid interdependence between the vector projections on the coordinate axes:

$$a_x m_x + a_y m_y + a_z m_z = gM\cos\delta = const;$$

which can serve as an additional source for calibration verification during system operation and provides the ability to filter out random disturbances during measurements, particularly those typical for magnetic field sensors.

3. Discussion

The obtained components of the Earth's gravitational acceleration and magnetic field vectors make it possible to calculate the direction of the antenna system using the methodology described in [1]. The microcontroller-based system, built on a microprocessor, performs calibration, acquires current signals from the sensor, and calculates the antenna's orientation, taking into account the satellite's trajectory and the actual geographic position of the antenna system. This system does not require position sensors for the axes of the antenna's azimuth-elevation mechanism, relying solely on the actual orientation of the antenna. This is particularly important for mobile or dynamic antenna systems, where traditional position sensors may be impractical or unreliable.

To verify the proposed methodology, a prototype calibration device was developed along with a software program for calculating calibration coefficients for the embedded microprocessor. The program includes sensor signal filtering methods, although these are not detailed in this work. The calibration results were tested in the field using geodetic instruments. The achieved accuracy is within ±1.5 degrees, which is sufficient for small satellite-band antennas.

4. Conclusions

The proposed calibration method for the antenna system's position sensor improves the pointing accuracy of the antenna system and reduces manufacturing costs by eliminating the need for precise angular position sensors on the azimuth-elevation unit. Additionally, it removes the requirement for precise initial setup of the antenna, which is especially important for mobile and portable antenna systems.

Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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