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Magnetometer Error Models of Low-Cost Land Vehicle Navigation System

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***Abstract*—This article implies a method of magnetometer error determination. Using solid-state magnetic sensors, vehicle odometer and GPS sensor, low-cost complex navigation system for land vehicles can be realized. The methods and algorithms of magnetometer calibration are shown. Results of magnetometer calibration experiments and possibility to detect magnetometer error parameters in process of car driving are analysed. To acquire vehicle heading output, navigation system described here is developed.**

***Index Terms*—Magnetometers; error analysis; models; course correction; Global Positioning System.**

I. INTRODUCTION

The design of low-cost integrated land vehicles navigation systems becomes a more and more actual problem. Core to the integration is concept of fusing measurements from GPS sensor and inertial measurement unit using linear or nonlinear estimation techniques [1]. Nowadays, the magnetometers and odometers are also used in low-cost integrated land vehicles navigation systems for dead recognition (DR) attitude determination during GPS outage [2].

The proposed navigation system consists of a GPS, an odometer, a map and a magnetic course sensor (Fig. 1) and provides the position and heading angle. The odometer filter estimates the velocity of the land vehicle, the heading filter estimates the heading angle (true course) using information about GPS true course magnetic variation and corrected magnetic course, and the position filter estimates the position, velocity and the heading of the complex GPS and DR system. All filters use Kalman filtering for data preprocessing.

Odometer filter provide scale factor error of odometer (SF_{od}) [3]

$$SF_{od} = \frac{\Delta V_{od}}{V_{od}}, \tag{1}$$

where $\Delta V_{od} = V_{od} - V_{GPS}$.

GPS sensor errors are widely described, for example in [4], [5]. GPS receiver supports navigation system with position data, heading angle and land vehicle horizontal velocity. Position filter is described in papers [1], [3].

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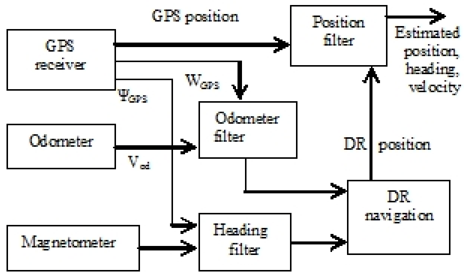

Fig. 1. GPS and DR navigation system structure.

In this paper we analyse only magnetic course sensor errors and their compensation with heading filter.

II. MAGNETOMETER TYPES AND STANDARD CALIBRATION METHODS

The magnetometers are used for absolute heading determination with reference to local magnetic north, where the heading is derived from the horizontal force of the magnetic field. If the magnetometer was aligned with the local horizontal plane, the heading ψ, would be calculated as (2).

$$\psi = arctg(My(\psi)/Mx(\psi)), \tag{2}$$

where M_x and M_y represent the horizontal magnetic field components of the Earth [6].

Nowadays, there are many types of magnetic field sensors, including fluxgate sensors, AMR sensors, search coil sensors, GMR sensors, Hall Effect sensors, and other magnetic field sensors.

One of the most popular magnetic field sensors is the anisotropic magneto resistive (AMR) sensor. AMR effect in ferromagnetic materials is the dependence of the electrical resistivity on the angle between the direction of the electrical current and the magnetization. When a magnetic field is applied to the sensor, magnetic field data will be received. AMR sensors can be used for the quantitative measurement of magnetic field, for instance, AMR sensors are used in electronic compasses [7]. MEMS technology allows manufacturers to fabricate sensors with a size of a few millimetres [8].

Unfortunately, any slight distortion of the Earth's magnetic field can affect output of the magnetometer. It is crucial to remove unwanted distortions caused by the external magnetic field before the start and in the process of navigation. Otherwise, using these results, false heading (true course) will be determined, thereby affecting the whole inertial navigation solution. Furthermore, noises, drift error, sensor axis misalignment error must be taken into account.

There are several techniques to compensate distortions caused by the external magnetic field. The simplest way to calibrate a magnetometer for hard and soft iron distortions is to use ellipsoid fitting algorithm.

To perform this calibration method, 360 degrees' rotation magnetic field data on horizontal plane must be acquired. To compensate distortions, two scale factors X_{sf} and Y_{sf} can be determined by (3) to change the ellipsoid response to a circle. Offset values X_{off} and Y_{off} can then be calculated by (4) to center the circle around the 0,0 origin [2]:

$$\begin{cases} X_{sf} = \max\left(1, \dfrac{Y_{\max} - Y_{\min}}{X_{\max} - X_{\min}}\right), \\ Y_{sf} = \max\left(1, \dfrac{X_{\max} - X_{\min}}{Y_{\max} - Y_{\min}}\right), \end{cases} \quad (3)$$

$$\begin{cases} X_{off} = \left(\dfrac{X_{\max} - X_{\min}}{2} - X_{\max}\right) \times X_{sf}, \\ Y_{off} = \left(\dfrac{Y_{\max} - Y_{\min}}{2} - Y_{\max}\right) \times Y_{sf}, \end{cases} \quad (4)$$

$$\begin{cases} M_x = X_{sf} \times X_{reading} + X_{off}, \\ M_y = Y_{sf} \times Y_{reading} + Y_{off}, \end{cases} \quad (5)$$

Using scale factors (X_{sf}, Y_{sf}) and the zero offset values (X_{off}, Y_{off}), calibrated magnetic field values M_x and M_y can be determinate by (5) [2].

III. MAGNETOMETER CALIBRATION EXPERIMENT

The main device used in the tests was Xsens MTi-G GPS/MEMS IMU navigation system.

MTi-G has thin film magneto resistive onboard magnetometer [9]. Even this magnetic field sensor was considered as a primary sensor in the experiment to test it's ability to determine course. also GPS data (latitude, longitude, velocity) were collected.

The true course reference data were acquired from HOLUX GPS receiver using GPS data logger software (VisualGPS) and synchronized to Xsens MTi-G experimental data. Data processing was made by high-level scripting language MATLAB.

MTi-G device was mounted to the roof rack of vehicle absolutely aligned with reference to vehicle body frame. It is worth to mention that all test drives were performed on asphalt surface road containing sections of parking zones and real-time traffic conditions.

First of all, the vehicle was driven along a circular route trajectory to collect magnetic field data for calibration. Despite the fact, that Xsens MTi-G supports specialized magnetometer auto-calibration procedure, ellipsoid fitting algorithm was used to calibrate magnetometer.

Figure 2 shows the result before and after magnetometer calibration using ellipsoid fitting algorithm. As we can see, after calibration process, magnetometer values are shifted to the origin.

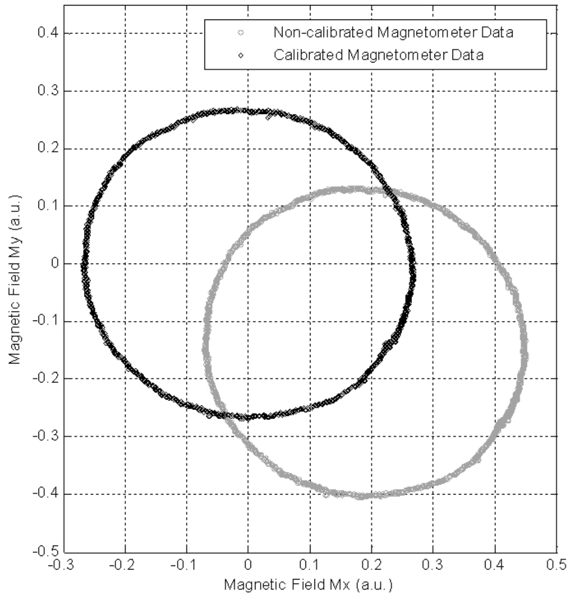

Fig. 2. Non-calibrated 2D magnetic field data points (red) and calibrated 2D magnetic field data points (blue).

Calculated parameters values (shown in Table I) suggest that mainly hard iron distortions were observed.

TABLE I. MAGNETOMETER CALIBRATION PARAMETERS.

Parameter	Result
Scale factor (X_{sf})	1.028845
Offset (X_{off})	-0.194795
Scale factor (Y_{sf})	1
Offset (Y_{off})	0.136472

Figure 3 presents calculated magnetic course data while circular route trajectory was performed. The mean absolute error is 24.87°. Result reveals that potentially huge heading error could be possible, for instance, when performing bend road trajectory without magnetometer calibration.

Also three experimental test drives were made - straight road trajectory test, right bend trajectory test and left bend trajectory test.

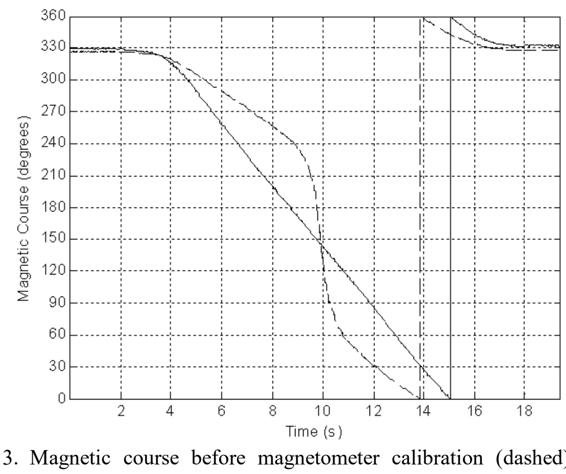

Fig. 3. Magnetic course before magnetometer calibration (dashed) and after magnetometer calibration (continuous).

Figure 4 illustrates estimated navigation solution for straight road trajectory test in Universal Transverse

Mercator (UTM) coordinate system. Position was estimated by using two methods: 1) GPS speed value and calibrated magnetometer readings, 2) another GPS data (Xsens GPS). The declination angle was compensated using information from National Oceanic and Atmospheric Administration homepage World Magnetic Model (WMM) data. In Riga declination angle is 7.41 degrees (16.12.2015).

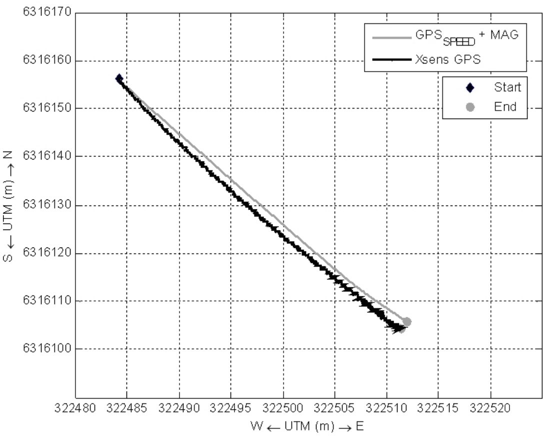

Fig. 4. Straight road trajectory test.

To compare true course results, linear interpolation was applied to approximate values of HOLUX GPS receiver data because of GPS update rate 1 Hz, while MTi-G magnetometer sampling frequency 100 Hz. Experimental results (Fig. 4) show that magnetometer error cause growing in time position error.

In the same manner as before, navigation solution for right and left bend trajectory tests are displayed in Fig. 5 and Fig. 6.

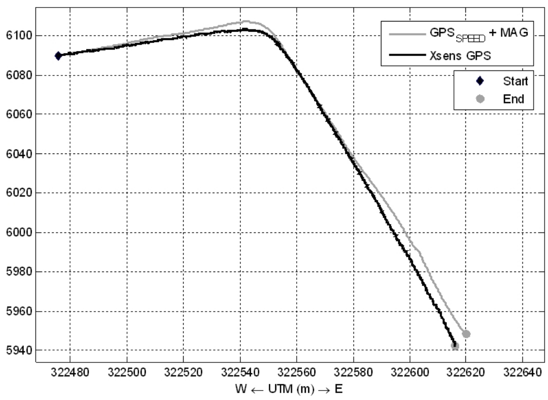

Fig. 5. Right bend trajectory test.

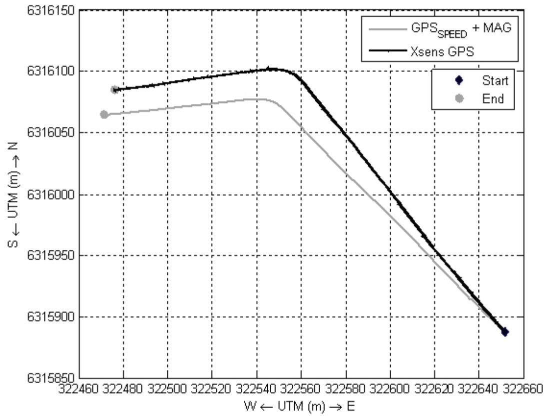

Fig. 6. Left bend trajectory test.

Clearly, we can see that a deviation of trajectory is observed when curves of the vehicle are driven. For magnetometer error compensation in driving process authors develop method which will be described in next part.

IV. MAGNETOMETER ERROR MODELS

As it was described above, the magnetic field shift Δx and Δy and scale factor for orthogonal magnetic field sensors ks_x and ks_y are important to course measurement precision. Error model analysis begins with field shift errors. In this case magnetic field M_x and M_y values are (6):

$$\begin{cases} M_x(\psi) = X_{\max} \times \cos(\phi) + X_{\max} \times \Delta x, \\ M_y(\psi) = Y_{\max} \times \sin(\phi) + Y_{\max} \times \Delta y, \end{cases} \tag{6}$$

where ψ is magnetometer determinate value of magnetic course, but φ is true value of magnetic field angle. The value of magnetic course is calculated according to (2).

Calculated value ψ include error $\Delta\psi_{sh}(\varphi)$. In Fig. 7 it is shown $\Delta\psi_{sh}(\varphi)$ graphic if Δx = -0.1 and Δy = -0.05. Formula for shift error compensation $\Delta sc(\varphi)$ can be written in form of (7). This error of hard iron effects is known as single-cycle errors. Shift errors compensation for all values of angle φ are shown in Fig. 7 if Δx = -0.1 and Δy = -0.05.

$$\Delta sc(\phi) = \sqrt{\Delta x^2 + \Delta y^2} \times \sin\phi - arctg(\Delta y / \Delta x). \tag{7}$$

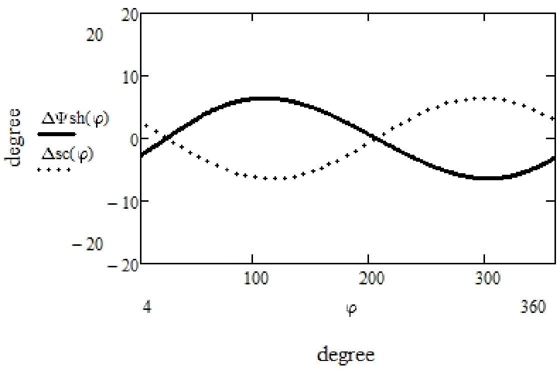

Fig. 7. Measured course error due to shift magnetic field $\Delta\psi_{sh}(\varphi)$ and its compensation curve $\Delta sc(\varphi)$.

Corrected course can be determined by summing measured value of magnetic course ψ with compensation value for course φ calculated from GPS data ψ_{GPS}.

Very important is that from $\Delta sh(\varphi)$ value for constant φ, using formula (7), the shift values Δx and Δy can be calculate in driving process. For this procedure iteration method can be used, with starting values Δx_0 and Δy_0, obtained from magnetometer data. In GPS outage mode compensation value $\Delta sh(\varphi)$ can be known for all drive angles and can be summed with magnetometer data for course calculation.

Second factor which causes error is scale factor for orthogonal magnetic field sensors ks_x and ks_y. If $ks_x \neq ks_y$, then $X_{max} \neq Y_{max}$. We can write that $X_{max} = ks_x \times X_{max0}$ and $Y_{max} = ks_y \cdot Y_{max0}$. In this case magnetic field orthogonal parts are (8):

$$\begin{cases} M_x(\psi) = X_{\max} \times \cos(\phi), \\ M_y(\psi) = Y_{\max} \times \sin(\phi). \end{cases} \tag{8}$$

For error determination use $X_{max0} = Y_{max0} = 1$, $ks = (1 + ks_y)/(1 + ks_x)$. From (8) we can write (9)

$$tg(\psi) = ks \times tg(\varphi) = tg(\varphi + \Delta\varphi). \quad (9)$$

Solving (9) for error $\Delta\varphi$ we must use Taylor series at point φ for small $\Delta\varphi$. Solving result gives (10)

$$\Delta\phi = \frac{ks-1}{2}\sin(2\phi). \quad (10)$$

Figure 8 shows this kind of course measuring error $\Delta\varphi m(\varphi)$ and compensation error compensation parameter $\Delta\varphi(\varphi)$ for all angles φ, for $ks = 1.091$. This error due to soft iron effects is known as two-cycle error. Determination of error for one driving course gives possibility to calculate ks and all values of compensation curve for random driving angles.

In real use magnetometer one-cycle and two-cycle errors discard measurements together. Practical filter realization shows, that first shift error and then scale factor error must be compensated.

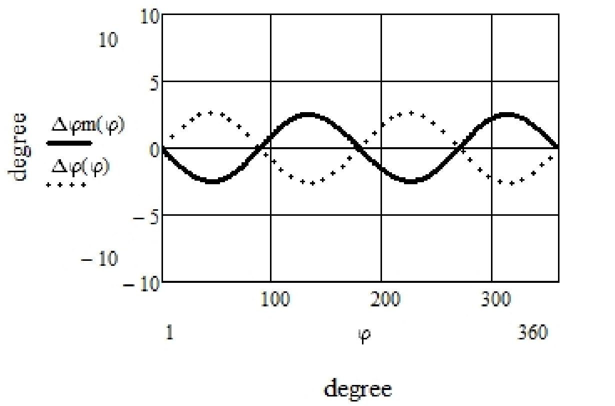

Fig. 8. Measured course error due to scale factor $\Delta\varphi m(\varphi)$ and its compensation curve $\Delta\varphi(\varphi)$.

Vehicles driving course is changing all time, and it is possible to use various headings for error calculation. In this case two equations for shift values Δx and Δy determination may be used. By using GPS data, it is possible to write equations for course error (n) determination, as follows:

$$\begin{cases} n_1 = \Delta x \times \sin(\varphi_1) - \Delta y \times \cos(\varphi_1), \\ n_2 = \Delta x \times \sin(\varphi_2) - \Delta y \times \cos(\varphi_2). \end{cases} \quad (11)$$

By solving equation system, we can extract shift values Δx (12) and Δy (13):

$$\Delta x = \frac{n_1 + \Delta y \times \cos(\varphi_1)}{\sin(\varphi_1)}, \quad (12)$$

$$\Delta y = \frac{n_2 \times \sin(\varphi_1) - n_1 \times \sin(\varphi_2)}{\cos(\varphi_1) \times \sin(\varphi_2) - \cos(\varphi_2) \times \sin(\varphi_1)}. \quad (13)$$

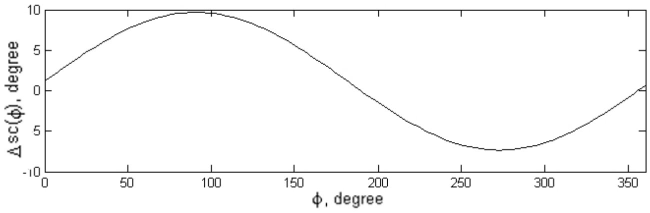

Fig. 9. Shift error compensation Δsc(φ) for right bend trajectory test.

Estimated formulas are used for right bend trajectory test mentioned before; thereby we can calculate shift error compensation for all courses (Fig. 9).

V. CONCLUSIONS

Modelling and experimental results show that using solid-state magnetic sensors, vehicle odometer and GPS sensor low-cost complex navigation system for land vehicles can be realized. After calibration is made magnetometer error is growing rapidly and must be eliminated. In this article we provide a method for magnetometer error correction in kinematics by using GPS heading data. Experimental results show possibility to detect magnetometer error parameters in process of car driving and increase performance of low-cost integrated land vehicle navigation system.

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