Automated magnetic field reconstruction stand for mobile robot navigation algorithms debugging which use magnetometer data

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Abstract. An important addition to the inertial navigation system are magnetometers. Areas with magnetic field anomalies serve to determine the reference points. But the magnetometers are influenced from both the electrical equipment of the robot itself and robot's parts configuration. Compensation of the robot's self-influence on the readings of the magnetometers is carried out by computer tools. In order to obtain the initial data, live experiments are required in a natural enviroment. For simplifying data acquisition about the behavior of magnetometric systems of a mobile robot an facility is used, which allow to compensate the Earth's magnetic field in a working space and to create an artificial magnetic field that varies according to a predetermined algorithm and simulates a magnetic field in the intended environment of application of the robot. The facility features: a working space, sufficient to place the mobile robot; a coil temperature drift correction; uniformity of the frequency response in operating frequency range; compensation of power supply interference and similar disturbances; sensitivity equalization of control channels; compensation of misalignment coordinate systems of the sensor and coil system. An nteractive Simulink model designed and evaluated. The automated stand created as experimental facility, its parameters proove proposed model adequacy.

1. Introduction

SLAM based on magnetometer data is a rapidly growing field in the robotics [1] – [8]. The unperturbed natural Earth's magnetic field (EMF) is used to determine the orientation of the mobile robot, and local anomalies (disturbances) of the EMF are used as features for positioning and navigation algorithms [4], [6]. Magnetometer data based algorithms and methods for navigation and mapping are especially relevant for indoor usage and for usage in urbanized environment. Such areas have a large number of objects perturbing the EMF, which in the mobile robots operation areas is expected to be homogeneous and stable. Modern researches create systems for building maps of magnetic environment along with maps based on data from lidars and cameras. For magnetic environment map building single- or multi-axes magnetometers (electronic compass) of magnetometer systems, integrated with exterior receptive sensor system of the mobile robot are used.

Even a carefully calibrated magnetometer system, in combination with sensors of spatial position estimation (accelerometers) is subject to the influence of static, folding, retractable and other elements of the robot, as well as its flowing currents. Distortion of magnetometer estimations caused by such influence may be compensated by algorithms based on machine learning with redundant data, which is recorded by proprioceptive mobile robot sensor system [9]. The quality of compensation depends on the model of formation and propagation of disturbances. The perturbation model is created in a special environment called "magnetic silence", which significantly excludes external, i.e. not related to the

robot, influences on magnetometers. Such influences are caused by different objects like indoor engineering networks (power supply – first). Even the influence from reinforced concrete beams and metal coated floor may be significant. For model evaluation in [9] authors were obliged to build experimental site in the Utah desert.

2. Magnetometers calibration stand

For magnetometers calibration it is a common practice to use facilities based on the Helmholtz coil system (or other similar coil systems) and functional generators. These facilities allow creating the artificial magnetic field (MF), comparable with EMF. These systems form a homogeneous MF which is constant or varies according to a given function, with or without simultaneous compensation of the EMF, as well as its perturbations of both anthropogenic nature and magnetic storms. The control channel is implemented both open [10] and closed [11].

The authors used this approach while designing an automated stand for reconstructing the MF for solving the problem of determining perturbations caused by mobile robot elements. A mobile robot is placed in the test zone of a three-component contour system, where a series of experiments is performed using various operating modes of its executive subsystems. The reproducible MF is either constant or changing according to the function which were specified in a dedicated editor (e.g., simulating rotations of a mobile robot). The prerecorded set of magnetic induction vectors serves as a training set for designing and evaluating various models which are invariant to the self-influence of the robot. Another task of automated stand consists in representing variation of the MF vector along the real route to the robot, which is situated in the contour system, with further benchmark of the features recognition algorithms. The MF parameters may be previously recorded using precision three-component magnetic induction sensor.

Most of emergency mobile robots are fit in space about 1 m^3, but building a coil system with such test zone space caused a series of problems. By increasing test site space we decrease the current transmission coefficient. Compensation of the coefficient drop by increasing the number of coil turns causes an increase in inductance of the coils and a narrowing of the operating frequency range consequently. Increasing the control currents in its turn requires non-trivial solutions for their formation, with preserving low levels of interference. In addition, it results in the fact that it is no longer possible to neglect changes in currents caused by the temperature drift of the coil resistance, which further leads to deviations of the MF, comparable in magnitude with the EMF. The MF stabilization in the test site space is impossible without using of a closed loop system. Feedback can be realized either with a separate MF sensor or with the robot on-board sensor. The coaxial arrangement of the sensor and the Helmholtz coil circuit system also ensures correct operation of the closed loop control system. The mechanical arrangement of the coordinate systems cannot be sufficiently accurate because mobile robots usually are not equipped with tools for precise orientation estimation. In addition, in a sequence of experiments, a robot is not always installed in a similar way, but takes many different positions. The residual misalignment should be compensated by the program setting of the test site.

3. Automated stand model

Let us dwell on details of solving the problem of stabilizing the MF in the test site volume, compensating for the residual misalignment of the coordinate systems of the sensor and the contour system, eliminating power supply interference, and the influence of temperature drift of the ring resistances.

The proposed solution is explained using the Simulink model, convenient from the point of view of interactive verification of the automated stand for the reconstruction of the MF is shown in figure 1.
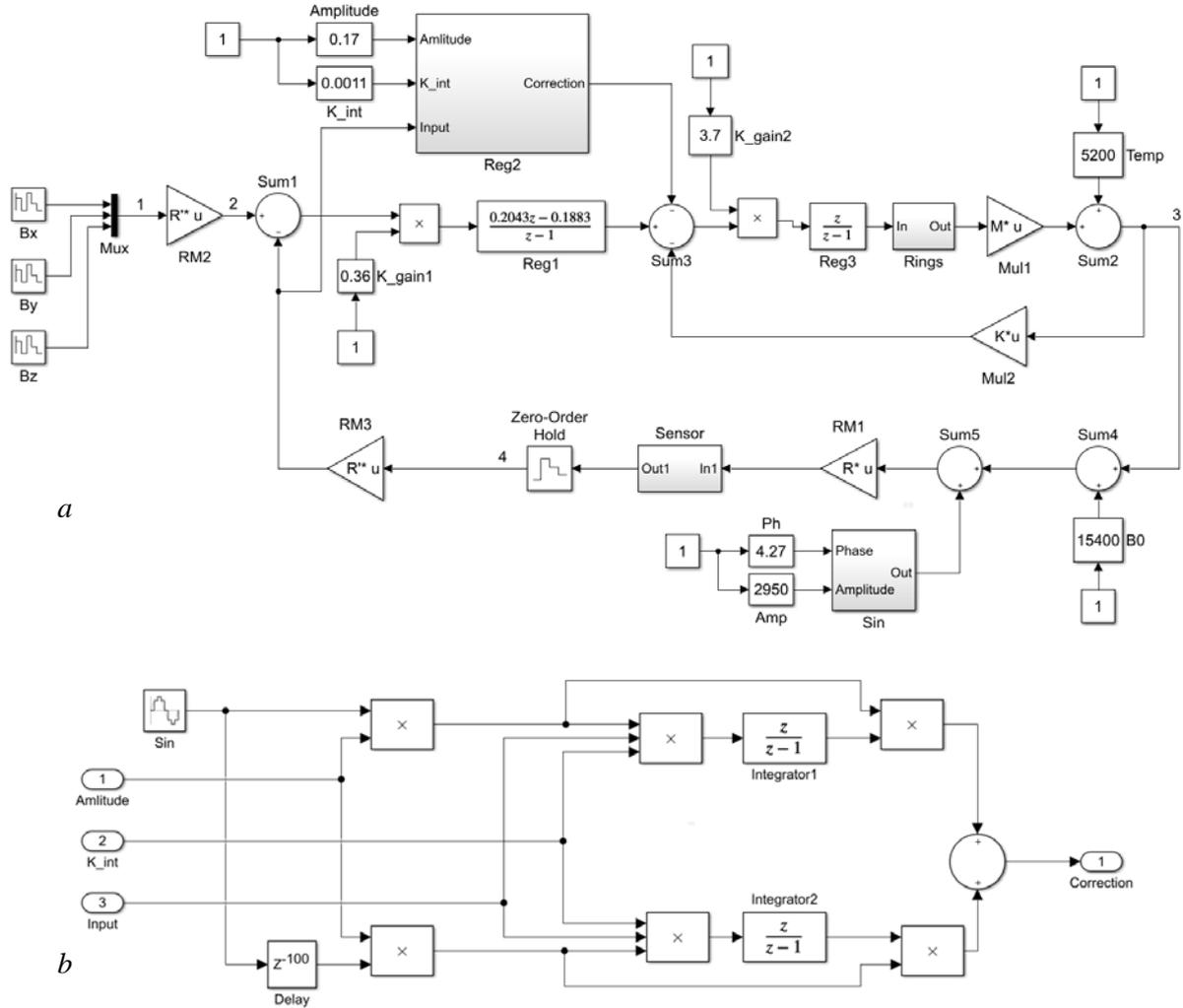
Figure 1. a – Simulink-model of the automated stand for the reconstruction of the magnetic field, b – the structure of the adaptive regulator Reg2.

The Rings block defines the model of the contour system as a transmission function $W(s) = \dfrac{1.4406}{0.0008s + 0.8}$ for each reproducing channel. This transmission function is obtained as a result of identification of a real Helmholtz coil having a diameter of 2 m with seven turns of copper wire with a cross-sectional area of 2 mm^2. The Mul1 block determines the differences in the current transmission coefficients of the coils by multiplying the input signals by the matrix. $M = \begin{bmatrix} 0.9 & 0 & 0 \\ 0 & 1.0 & 0 \\ 0 & 0 & 1.1 \end{bmatrix}$. The Sensor module simulates the transmission function of a three-component magnetic induction transducer $H(s) = \dfrac{1}{0.000514^2 s^2 + 0.0019s + 1}$ for each of the channels $H(s)$ as an estimate of the transmission function of the serial sensor HB0302.61A, the time step of the measurement data is 1 ms and is defined by the Zero-Order Hold block. It should be noted that the sampling interval of the entire Simulink model is 50 µs, therefore, the channel for reproducing the MF

is 20 times faster than the measuring channel. The signals of the magnetic induction vector B_x, B_y, B_z assigned for reproduction are combined by the Mux block into a vector signal, therefore all other signals of the Simulink model are three-component ones. The RM1 block specifies the misalignment of the contour coordinate systems and the magnetic induction sensor by multiplying the coil current vector $\begin{bmatrix} I_x & I_y & I_z \end{bmatrix}^T$ by the rotation matrix $R = \begin{bmatrix} 0.9998 & -0.0118 & 0.0146 \\ 0.01 & 0.9933 & 0.1152 \\ -0.0158 & -0.115 & 0.9932 \end{bmatrix}$. Identification of this matrix in practice is performed using the formula $R = DS^T \left(SS^T \right)^{-1}$, where D – the matrix of N test current vectors sequentially fed to the contour system, S – the corresponding matrix of the components of the magnetic induction vectors measured by the sensor $\begin{bmatrix} B_x & B_y & B_z \end{bmatrix}^T$. For an accurate estimation of R it is necessary to reproduce currents close to the borders of the ranges of the test MF, without causing saturation of the coils with respect to the current. It is necessary to take into account the displacement of the dynamic ranges of the channels by the magnetic induction, which is connected with the presence of a constant EMF in the region of system installation.

The main feedback loop for the MF sensor closes on Sum1, the input signals of which are firstly multiplied by the matrix R^T (in Simulink notation R') by the blocks RM2 and RM3. These blocks are designed to compensate axis misalignment of the sensor and the contour system.

The difference signal from Sum1 is fed to the regulator Reg1 with a transmission function $V(z) = \dfrac{0.2043z - 0.1883}{z - 1}$, whose amplification factor is interactively tuned with the K_gain1 block. In addition to K_gain1 block there are also Amplitude, K_int, Ph, Amp, K_gain2, Temp and B0 interactive tuning blocks. All of them are built using the standard Simulink block – Slider Gain.

The background MF level and its perturbations is interactively set by the B0 block and is added by Sum4 block to the field created by the coil system. The Sum5 block introduces a change in the MF into the coil system caused by power supply interference. It is a 50 Hz sine wave, set by the Sin block with interactively arranged amplitude (Amp block) and phase (Ph block).

The main feedback loop compensates a constant and slowly changing external MF, but it does not satisfactorily compensate the power supply interference. That's why we introduced another feedback loop with the regulator Reg2, built as a modification of the adaptive rejection filter for suppressing this interference [12]. The regulator structure is represented in figure 2b.

The additive mixture of the useful signal and the power supply interference from the main feedback loop output is fed to the input of the adaptive regulator Reg2. The reference 50 Hz sine wave is generated by the Sin generator with 50 µs sampling interval of the Simulink model. The reference signal with 100 sampling intervals delay, created by the Delay block is converted into a signal shifted in phase by 90°. The reference signal and its shifted copy are multiplied with the input signal of the regulator Reg2, the resulting products are fed to the digital integrators Integrator1 and Integrator2. The corresponding integration results are the weight coefficients of the adaptive regulator. The weighted reference signal and its shifted copy are summed, resulting in the regulator output, which is subtracted from the output signal of the main regulator Reg1. Adjustable weighting values allow changing the reference signal in amplitude and phase by any method necessary to suppress the power supply interference. The interactive amplitude adjustment of the reference sine wave and the integration factor, which is common for both integrators using the Amplitude and K_int blocks, affects the adaptation speed.

The temperature stabilization loop includes system blocks associated with Helmholtz coil's currents generation. The output value – the coil current for each of the spatial axes – is converted with the scale factor (defined by Mul2 block) and is fed to the summation point Sum3. A signal compensating for the power supply interference also enters this point. The feedback transfer ratio depends on the parameters of the coils and the electronics of the regulated current source, so it must be selected during the initial system calibration.

The regulator in the direct transfer circuit (Reg3) eliminates the residual steady-state error of the control channels, and the block K_gain2 allows interactively changing the parameters of the current generating unit. The temperature error is modeled by the interactive Temp block and is summed with the current signals of the loop system.

In figure 2 the results obtained by using the Simulink model at points 1, 2, 3 and 4 are presented. For an effective demonstration of the proposed solution, let us designate three sawtooth signals offset from each other as changes in the component of the magnetic induction vector (point 1). The sawtooth signals at point 2 are no longer parallel to each other and show the degree of misalignment of the sensor and the contour system. At time $t = 0.5$ s the amplitude and phase of the sine wave of the power supply interference are abruptly changed, and at the time $t = 7.75$ s the level of the background MF is abruptly changed. Transient processes as a result of these disturbances may be estimated on the graph of the field reproduced by the coils (point 3) and superposition of this field and perturbations at the sensor output (point 4).
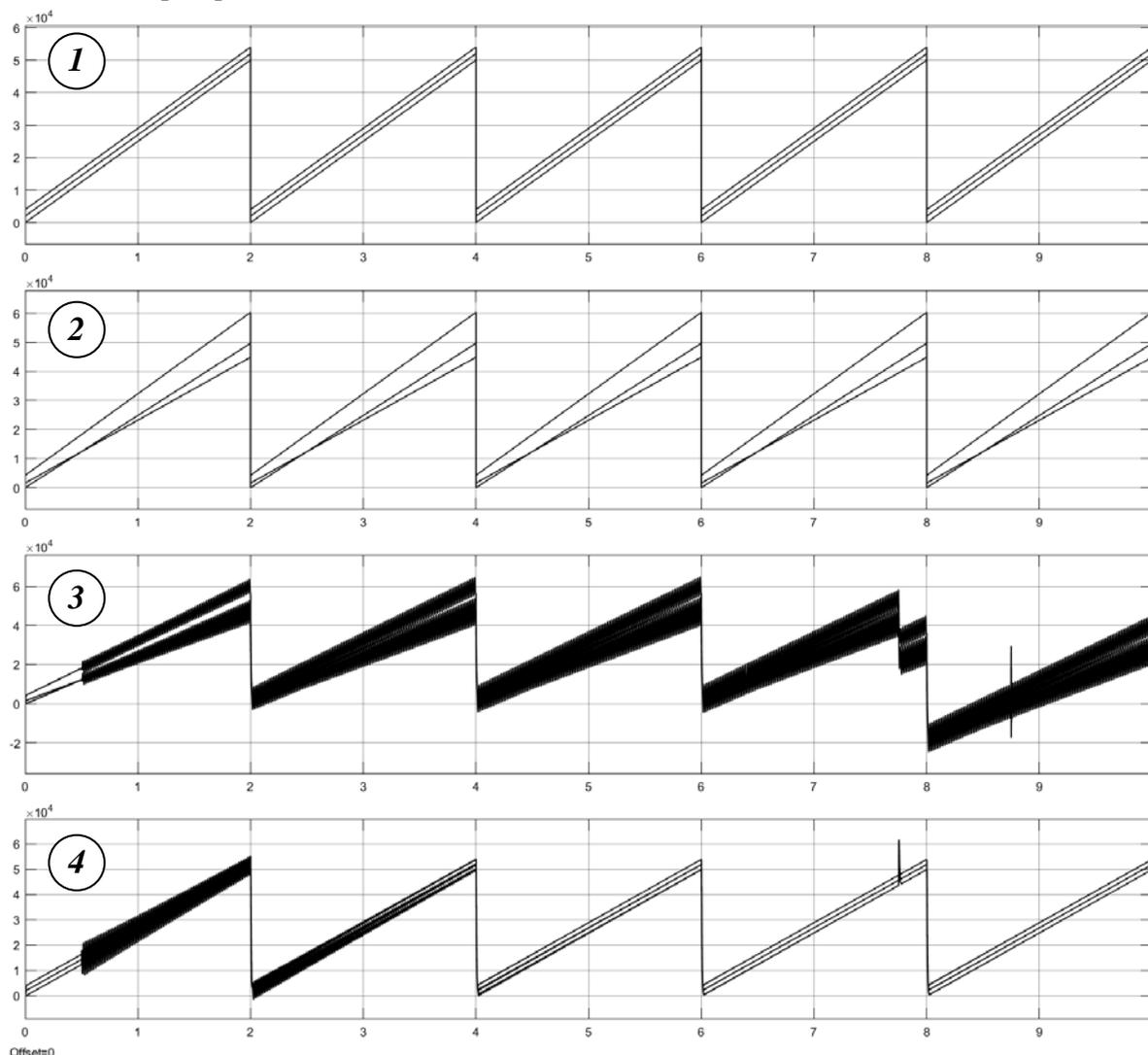

Figure 2. Signals at points 1, 2, 3 and 4 of the Simulink model. X-axes in seconds, Y-axes in nanotesla.

Adaptation to the new value of the external field performed in 4 s, and the elimination of power supply interference ended after 30 ms. Transient process as a result of temperature step change located

on the graph of the field reproduced by the coils (point 3) at 8.85 s. System stabilization took about 15 ms. At point 4 temperature disturbance is imperceptible due to sensor sampling rate. Taking into account that these are not stressful effects typical for practice, the values obtained can be considered sufficient for solving the tasks set. The restored parallelism of the sawtooth signals at point 4 indicates that the compensation of misalignment of the sensor and the contour system is performed. Resulting MF magnitude (point 4) equivalent the programmed one (point 1).

4. Automated stand implementation

The automated stand for the MF reconstruction was made as an experimental facility, is presented in figure 3. The facility performance result is proved the adequacy of the proposed Simulink-model. A small number of independent variables of the model made it possible to abandon the analytical search for stability and the selection of parameters close to optimal values of regulators in favor of their interactive tuning. Effectiveness of proposed solution in a variety of mobile robots and magnetometers used as research objects was shown in practice.

The automated stand is used to perform experiments to evaluate the robot self-influence on the magnetomer system following the way described in [9], but without searching for a special "magnetic silence" terrain. To do this, first, a field that simulates the EMF is created in the empty coil system. For creating the initial MF, a separate sensor or robot on-board sensor or both can be used. The currents flowing through the coils are fixed as reference values. At the second stage, the robot is installed in the coil system and its magnetometer is used as a feedback sensor. Distortions of the MF caused by the self-influence of the robot, leads to other values of the control currents. The difference of the reference and observable currents serves as the basis for a training set for self-influence compensation algorithms.

The second use case is the determination of the frequency characteristics of the magnetometers. Simulink model point 1 switches on the automatic identification block. After transmitting a test sinusoidal signal with a linear frequency modulation to the coil system and simultaneously maintaining the specified amplitude of the coil currents, the unit will perceive all the frequency properties of the Sensor block.

Figure 3. Automated stand for reproducing magnetic field: on the left – a three-component coil system of Helmholtz coils, on the right – a functional block.

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