R. HOLYAKA, T. MARUSENKOVA, D. FEDASYUK

SIGNAL MODEL FOR SPATIAL POSITION SENSORS IN MAGNETIC TRACKING SYSTEMS

The **subject** of research is the process of forming signals in magnetic tracking systems including those used for spatial position calculation within the concepts of Industry 4.0 and Industrial Internet of Things. Such systems are based on calculating the spatial position of objects upon measurements of reference magnetic fields in low-frequency electromagnetic radiation spectrum. The **goal** is to develop and verify a signal model for spatial position calculating in magnetic tracking systems. The signal model is developed upon experimentally obtained dependencies of the informative signals on the distances and angles between sensor and actuator coils. **Objectives**: analysis of signals in magnetic tracking systems, development of tools for experimental study, mathematical interpretation of the research results along with development of the signal model, verification and use of the developed model. General scientific **methods** were used, including experiment, measurement, analysis, synthesis, probabilistic and statistical methods. We have obtained the following **results**: The structure of a signal chain of the programmable magnetic tracking systems and its implementation on the basis of PSoC of 5LP Family by Cypress Semiconductor has been disclosed. Experimental results obtained at different distances and angles between the actuator and sensor coils have been presented. For spatial positions calculation signal models that describe distribution of magnetic fields and signals of sensor coils are used. We have analyzed typical inaccuracies and ways of their minimization. For verification of the introduced signal model we propose to use the mean square deviation of normalized signals. **Conclusions**. A signal model for the mutual position of actuators and sensors in magnetic tracking systems has been developed. The model describes functional dependencies whose main parameters are the distances and angles between coils. Further development of the presented results implies the proposed signal model to be used when solving problems of developing and specifying algorithms of spatial position calculation, system debugging and rapid analysis, optimization of calibration procedures.

Keywords: Industry 4.0 devices; magnetic tracking; signal model; programmable system-on-chip.

Formulation of the problem

This paper deals with the problem of creating spatial position sensors (near spatial navigation) in the concepts: Industry 4.0 (Industry 4.0), Industrial Internet of Things (IIoT), Virtual (VR – Virtual Reality) and augmented (AR - Augmented) Reality) Reality, the 5th generation of mobile networks (5G – 5 Generation of Digital cellular networks) [1]. In addition to optical ambient recognition devices and inertial sensors, MT – Magnetic Tracking [2] are considered effective sensors. The magnetic tracking method is based on determining the spatial position of objects by the measurement of the vector of induction of the reference magnetic fields in the low-frequency spectrum of electromagnetic radiation. Measurements are made using inductive coils, which form a system of interrelated pairs of actuators and sensors. The actuator coils form the magnetic fields of the low-frequency spectrum, and the sensory ones generate the electromotive force caused by these fields. Therefore, another name for this method is EMT (Electromagnetic Tracking) [3]. Magnetic tracking systems are used in industry, robotics, animatronics, game consoles, spatial navigation of instruments in minimally invasive surgery, etc.

Let's consider the development trends and examples of scientific work in this area.

Analysis of recent research and publications

The development of information and communication technologies in industry, in particular in the concepts of Industry 4.0 [4] and IIoT [5], involves the solution of a wide range of tasks to create a new generation of means of interaction with the surrounding world. Virtual technologies [6] and augmented [7] reality play a decisive role in these concepts. Significant progress has been made towards the creation of a new generation of information and communication tools that integrate a variety of measuring devices [8].

One of the most important tasks of such measuring devices is spatial navigation, in particular based on optical systems (Visual Navigation) [9] and Global Positioning System (GPS) [10]. The further development of spatial navigation devices involves the combination of GPS technologies and local navigation sensors, in particular based on Inertial Navigation System (INS) and their basic components - Inertial Measurement Unit (IMU) [11].

Magnetic tracking is a promising direction for the development of spatial navigation tools [12]. A significant advantage of magnetic tracking systems over optical tracking systems is the ability to operate outside the direct vision area. With respect to inertial tracking systems, the advantages of magnetic tracking systems are the ability to accurately measure the coordinates of the sensors relative to the formed matrix of actuators of the coordinate system and the absence of errors due to the time drift of the accelerometers [13] and gyroscopes [14]. Modern solutions of magnetic tracking systems are: universal framework (framework) ARIoT in the concepts of augmented reality and Internet of things [15]; the concept of Data Fusion in medical imaging devices [16]; navigation devices for surgical instruments in medical apparatus [17]; biomedical engineering technologies, in particular for the monitoring of face kinematics [18]; means of mechatronics of flexible robots [19], etc.

Formulating the purpose of the article

The information signals of the relative position in the "actuator-sensor" pairs of magnetic tracking systems are described by functional dependencies, the main arguments of which are the distance between the coils and their

inclination relative to each other. To calculate the spatial position, mathematical models of the distribution of the generated magnetic fields are used. These models are synthesized on the basis of theoretical assumptions and results of experimental studies. A variety of mathematical models are signal models that describe the dependence of the formed measuring system of signals on the values of measuring values [20].

The purpose of this work is to develop and verify a signal model for calculating the spatial position of objects in magnetic tracking systems. The signal model is developed on the basis of experimentally obtained families of dependencies of informative signals on the distance and angles between the sensor and actuator coils. The results are part of a comprehensive work on the creation of integrated magnetic tracking software - Magnetic Tracking System Integrated Development Environment (MTS IDE), conducted by our team in a number of scientific and applied projects.

Materials and methods

The principle of operation of sensor-based magnetic tracking systems is based on the determination of the spatial position of objects by the measurement of the vector of induction of the reference magnetic fields in the low-frequency spectrum of electromagnetic radiation. Preferably, sensors and actuators in such measurement systems are small-sized coils and their two-dimensional 2D (2-Dimension) or 3D (3-Dimension) assemblies (fig. 1). Examples of 3D collections of commercially available magnetic tracking coils are Premo's 3DV series [21, 22].
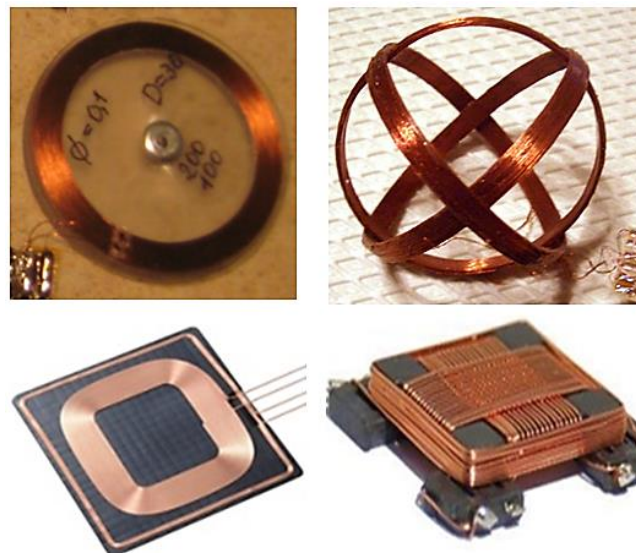

Fig. 1. Planar (1D) and 3D (3D) coils of magnetic tracking systems

The spatial distribution of the Actuator coil magnetic field and the placement of the Sensor coil in the 2-Dimension plane are shown in fig. 2, and the relative placement of these coils – in fig. 3. The supporting and moving coordinate system is considered. The reference coordinate system is defined by the spatial position of the actuator, and the movable sensor sensor coils. To simplify the analysis below, we restrict ourselves to the consideration of two-dimensional 2D (plane) coordinate systems. The plane of the actuator coil is arranged parallel to the X_A axis, and its normal N_A coincides with the Y_A axis. The slope of the plane of the sensor coil relative to the moving $X_S Y_S$ coordinate system is determined by the angle α. At $\alpha = 0$, the plane of the P_s of the sensor coil coincides with the X_S axis, and its normal plane – with the Y_S axis.

In order to construct sensory devices of magnetic tracking, it is necessary to establish analytical regularities of the spatial distribution of values of the normal B_N and tangential B_T projections of the magnetic field induction vector. These projections are determined by the field induction module $B_M = \sqrt{B_N^2 + B_T^2}$ at the distance L_{SA} between the sensor and actuator coils and the angle θ between the vector connecting the centers of these coils and the plane of the actuator coil. The maximum values of normal B_N projection and zero values of tangential B_T projection occur along the Y_A axis. Instead, there are zero values of B_N and maximum values of B_T along the X_A axis.

The induction of the actuator field is characterized by a magnetic moment $M_A = N_A I_A A_A$. Its value is given by the product of the number of turns, the current I_A and the area A_A of the actuator coil [23]. With this parameter, the normal B_N and tangential B_T projections of the magnetic field induction are determined by the inverse cubic function of the distance L_{SA} between the sensor and actuator coils and the angle θ [24]:

$$B_N = \frac{K_{SA} M_A}{L_{SA}^3} \cos(\theta), \; B_T = \frac{K_{SA} M_A}{2 L_{SA}^3} \sin(\theta), \quad (1)$$

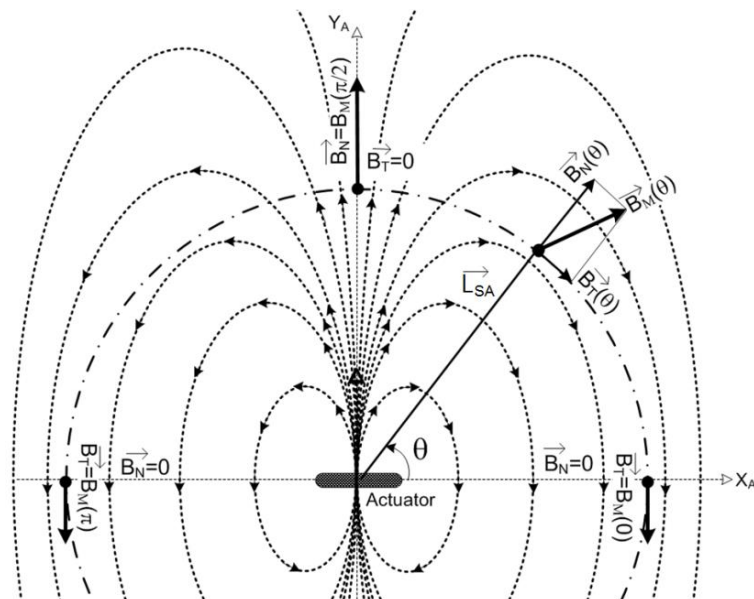where K_{SA} is a coefficient of proportionality.

7

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Fig. 2. Spatial distribution of the magnetic field in the plane
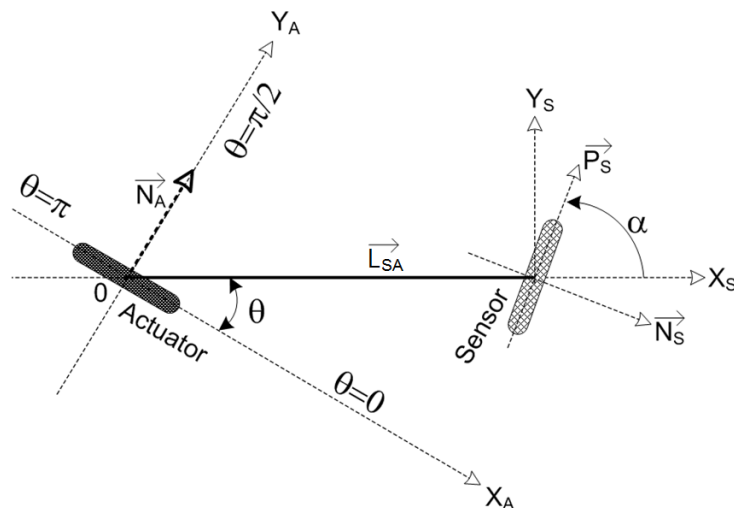

Fig. 3. Mutual arrangement of coils in the plane

The spatial position information signal in magnetic tracking systems is obtained by selectively measuring the useful component voltage generated at the leads of the sensor coil and determined by the above-mentioned spatial distribution of the reference magnetic field. Selective measurement involves amplification of the sensor coil voltage, its synchronous detection, filtering and subsequent conversion by digital signal processing. Magnetic tracking systems are multichannel hardware containing 1D, 2D and 3D sensor and actuator coils, analog front-end units, switches, analog-to-digital converters, microprocessors, etc. optimized for a specific task. The number and relative positioning of the coils in these kits should enable the calculation of the spatial position with the specified accuracy and measurement range.

The problems of this work are due to the need to create software for calculating the coordinates of the spatial position of objects, taking into account the characteristic (specific) errors in the measurement of signals that occur in sensor systems of magnetic tracking.

Such errors are caused by the deviation of the values of the real signals from their nominal values determined by the signal model. In magnetic tracking systems, such errors can be classified into four types (fig. 4): ER1 – amplitude or/and phase mismatch; ER2 – electromagnetic interference; ER3 – base-level off-set; ER4 – signal restriction.

The reason for ER1 errors is the deviation of the coil parameters from their nominal values, in particular the number of turns, area, shape, etc. In 2D and 3D assemblies, these errors are caused by the deflection of the coil rotation angles. Nominal coils in assemblies should be placed at right angles. The problem of minimizing errors is solved by improving the accuracy of fabrication and refining the parameters in the calibration process.

ER2 errors are caused by electromagnetic interference from third-party (parasitic) radiation sources, mainly power lines and transformers, secondary power converters, radio devices, and the like. The level of this type of error is determined by the signal-to-noise ratio. Given that the amplitude of the information signal in

magnetic tracking systems is determined by the inverse cubic function of the distance L_{SA} between the sensor and actuator coils, the signal-to-noise ratio sharply decreases with increasing L_{SA} distance. It is this circumstance that limits the range of magnetic tracking. In part, the problem of increasing the range is solved by increasing the magnetic moment of the coils and methods of noise-immunity synchronous detection.
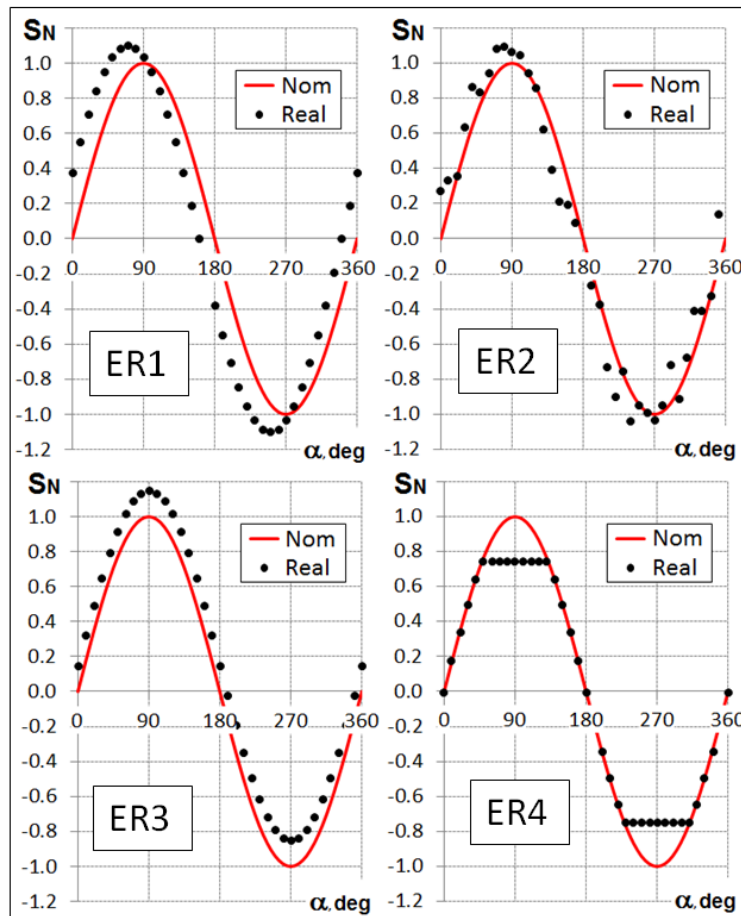

Fig. 4. Characteristic errors of signal measurement in magnetic tracking systems

ER3 errors are caused by a parasitic relationship between the input and output signal circuits of the sensor system. Given that in magnetic tracking systems, the ratio between the actuator coil output and the sensor coil input is up to six orders of magnitude higher, the problem of minimizing the parasitic relationship is of great relevance. Partial solution to this problem is based on the quality shielding of the signal circuits and the electromagnetic isolation of the earth circuits of these circles.

ER4 errors are caused by the signal amplitude limitation at short distances between the sensor and actuator coils. The level of such limitation is determined by the permissible voltage range in the signal circuits and is typically no more than a few volts. Especially the problem of signal limitation is relevant in the latest sensor equipment that satisfies the power requirements of low-voltage (3V or less) unipolar power supplies. In particular, these are devices in the concept of the Internet of Things. Partial solution to this problem is based on the dynamic switching of the input gain and the use of analog signal compression by logarithmic amplifiers.

Thus, signal analysis in magnetic tracking sensor systems, taking into account their characteristic errors, is important for improving the accuracy of these systems. Such an analysis, in turn, requires the creation of a signal model and the use of this model to establish regularities between the accuracy of measuring the spatial position and the distance between the sensor and actuator coils. The signal model presented in the paper is based on the results of experimental studies, which will be discussed further.

Means and results of experimental studies

Experimental studies were carried out using the MTS IDE integrated magnetic tracking software. A simplified block diagram of the signal path of a programmable magnetic tracking system (EM Programmable System) based on one pair of coils is shown in fig. 5, where: Sensor Coil, Actuator Coil – sensor and actuator coils; Amplifier – amplifier; Synchro Detector - synchronous demodulator (detector); LF Filter – low frequencies filter; Actuator Driver – actuator driver; Control Unit - control module; ADC is an analog-to-digital converter. Signal path implementation for coil sets involves the use of signal multiplexers on analog switches.
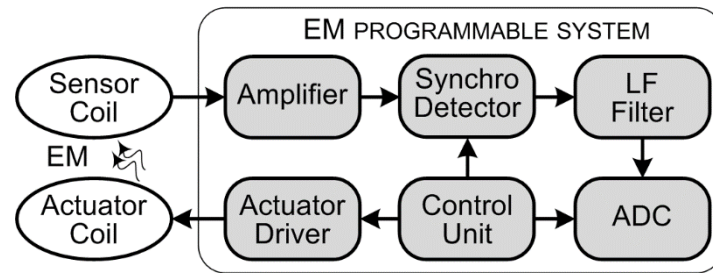
9

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Fig. 5. Block diagram of the signal path of the sensor system of magnetic tracking

Taking into account the requirements for modern microelectronics, the signal path of the magnetic tracking sensor system is implemented on the concept of programmable systems on a chip, in particular, on the PSoC 5LP Family of Cypress Semiconductor Corporation [25]. The PSoC structure includes digital and analog system nodes, microprocessor nodes, power-dependent and non-volatile memory matrices, system resources, as well as programming and power management nodes. The basis of digital nodes is a matrix of universal digital blocks, specialized digital blocks, in particular for implementing interfaces, timers, pulse-width modulators, and the like. PSoC analog nodes are blocks on switching capacitors and blocks with continuous signal conversion, in particular: operational amplifiers, Comparators, reference voltage sources based on the forbidden zone,

analog multiplexers, and so on. Nodes are connected by a programmatically configured network of signal lines. The synthesis scheme, its configuration and the implementation of the specified measurement algorithm is implemented in the PSoC Creator IDE.

A fragment of the PSoC Creator work windows and the main components of a programmable magnetic tracking system are presented in fig. 6. The software management of these components is performed using sets of appropriate API (Application Programming Interface) functions. The implementation of the system is based on CY8C58xxLP module CY8CKIT-059 [26] and a small number of external passive components (mostly RC signal filter circuits). A photo of the model layout of the system is shown in fig. 7, and an example of an oscilloscope study of the input and signal detector highlighted in fig. 8.
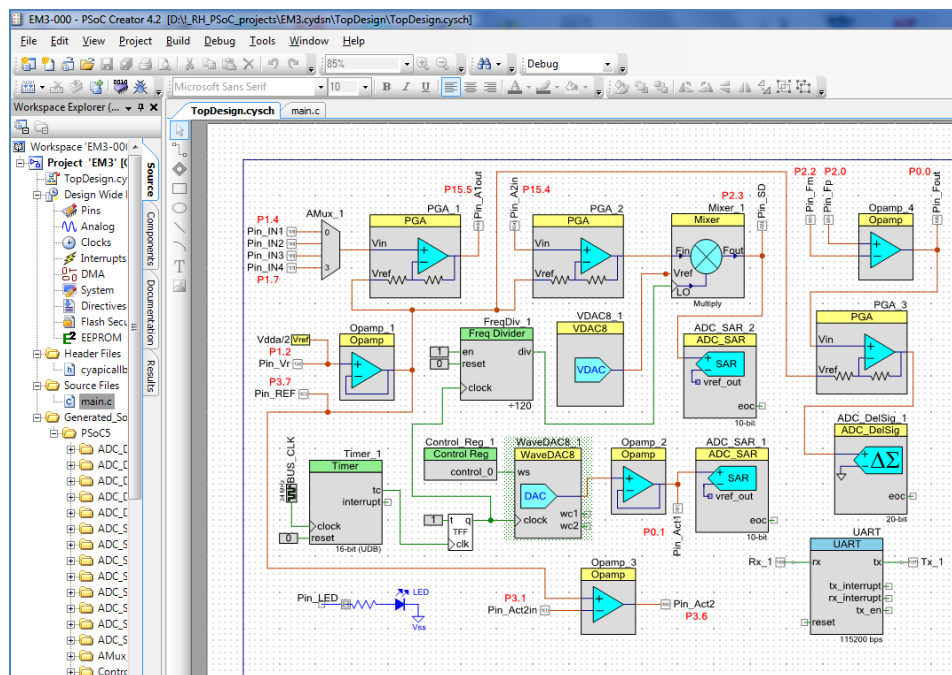

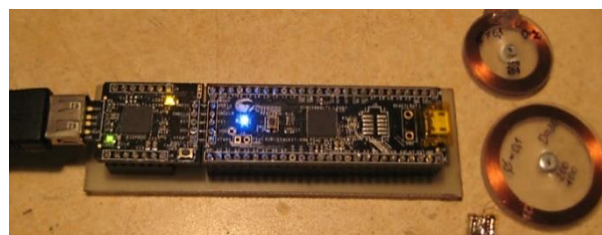**Fig. 6.** Fragment of PSoC Creator work windows

Fig. 7. Photo of a model sample of the magnetic tracking system

10

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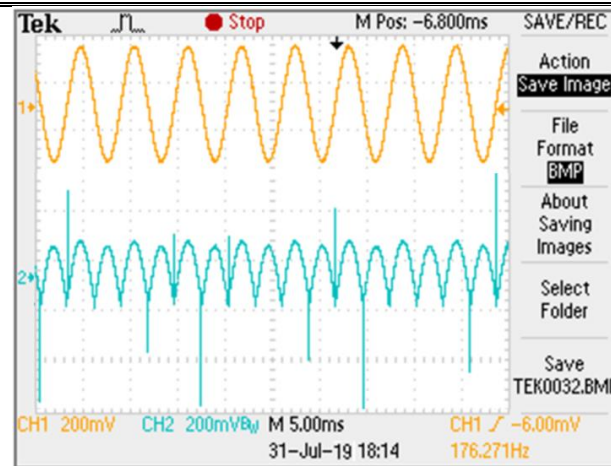
Fig. 8. Waveforms of the input (top) and the detector (bottom) selected signals

The equipment used for experimental investigations of the dependences of the information signals on the distance L_{SA} between the sensor and actuator coils and the angles θ, α, is presented in fig. 9, and examples of families of such dependences for the three distances are shown in fig. 10 (L_{SA} = 50 cm), fig. 11 (L_{SA} = 100 cm) and fig. 12 (L_{SA} = 15 cm). The output signals are represented by the voltage V_S at the output of the signal path of the aforementioned programmable magnetic tracking system. The gain was selected by V_S (L_{SA} = 50 cm) ≈ 100 mV. The rotation of the sensor coil (fig. 3) is relative to the X_S axis, coinciding with the vector L_{SA} (the radius of its rotation relative to the plane of the actuator coil).
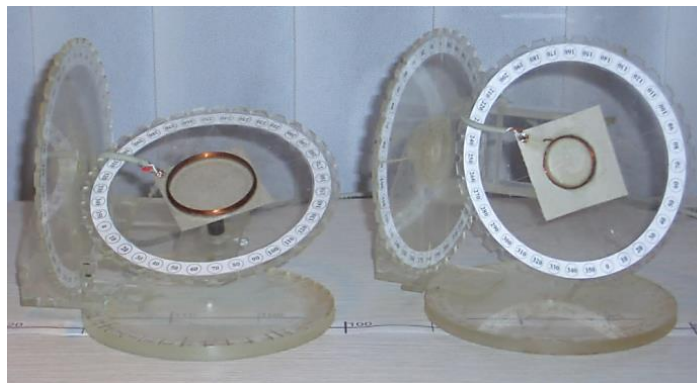

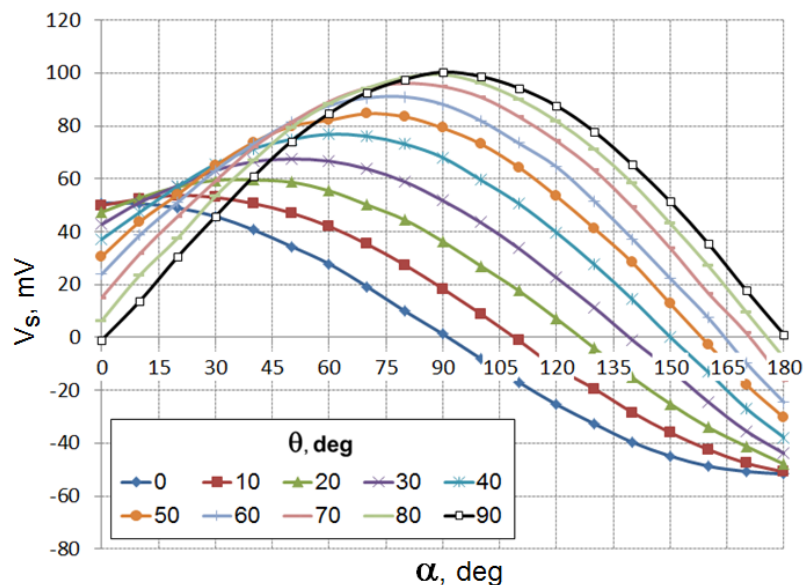**Fig. 9.** Equipment for spatial orientation of the coils

Fig. 10. The signal family V_S = f(L_{SA}, θ, α) at L_{SA} = 50 cm
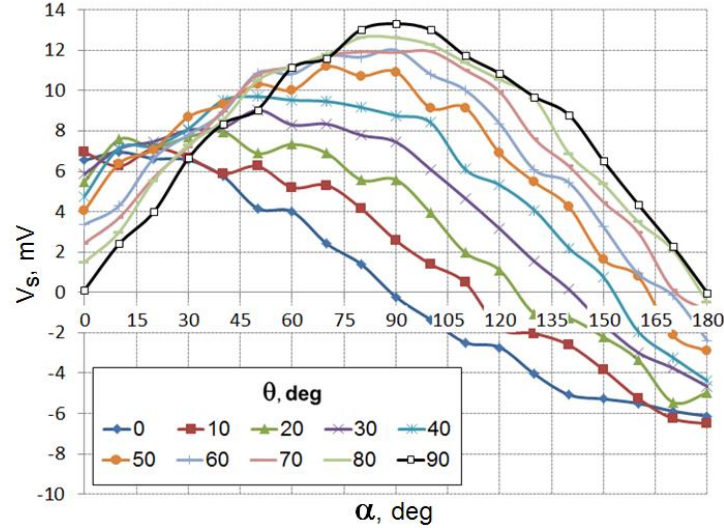
11

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Fig. 11. The signal family V_S = f(L_{SA} , θ, α) at L_{SA} = 100 cm

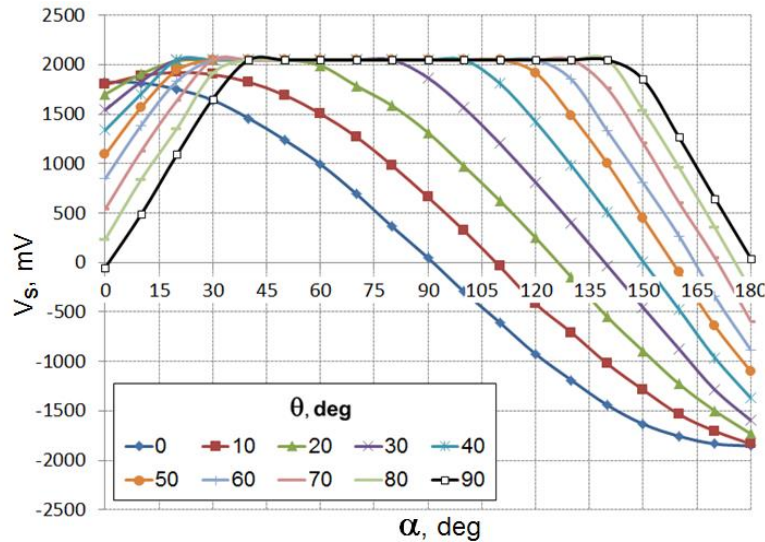**Fig. 12.** The signal family V_S = f(L_{SA} , θ, α) at L_{SA} = 15 sm

Two types of errors are observed, namely, electromagnetic interference (ER2) at L_{SA} = 100 cm and signal limitations (ER4) at L_{SA} = 15 cm. The other two types of errors, namely, amplitude or phase inconsistency (ER1) and base level bias (ER3), were minimized as much as possible during debugging of the signal path of the magnetic tracking system, and therefore, for further parametric analysis, are not determinative.

The following patterns are typical for all received signal families:

- at θ = 0° the maximum signal level is observed at α = 0°, and minimum –at α = 90°;

- at θ = 90° the maximum signal level is observed at α = 90°, and minimum –at α = 0° та 180°;

- the maximum value of the normal projection B_N of magnetic field induction (at θ = 90) is twice the maximum value of the tangential projection B_T (at θ = 90°).

At L_{SA} = 50 cm, the signal families have virtually no deviation from the nominal sine functions. At L_{SA} = 100 cm, the signal level drops 8 times (maximum voltage V_S ≈ 13 mV), which coincides with the nominal dependence of the magnetic field on the distance (inverse cubic function of the distance L_{SA} between the sensor and actuator coils). At L_{SA} = 100 cm, the signal-to-noise ratio significantly deteriorates. On the other hand, at L_{SA} = 15 cm, noise is practically not observed, however, the signal is limited to ≈ ±2000 mV. These limits are determined by the maximum allowable voltage level in the signal circuit.

Signal model.
According to the experimental data obtained, the maximum value of the normal B_{NM} projection of the magnetic field induction is twice the maximum value of the tangential B_{TM} projection. So let's write down their values in the normalized form:

$$B_{NM} = B_N\left(\theta = \frac{\pi}{2}\right) = 1.0 \; ; \quad B_{TM} = B_T\left(\theta = 0\right) = 0.5 \; . \quad (2)$$

Innovative technologies and scientific solutions for industries. 2020. No. 1 (11)

Having determined the trigonometric functions of the spatial distribution of these projections

$$B_N(\theta) = B_M(\theta)\sin(\theta), \quad B_T(\theta) = B_M(\theta)\cos(\theta). \quad (3)$$

let'swrite down the expressions of dependencies of the module BM the induction vector and the contribution angle ψ of its slope

$$B_M(\theta) = \sqrt{B_N^2(\theta) + B_T^2(\theta)}, \quad \psi = arctg\frac{B_T(\theta)}{B_N(\theta)}. \quad (4)$$

An illustration of the dependencies $B_N(\theta)$), $B_T(\theta)$) and $B_M(\theta)$ is presented in fig. 13.
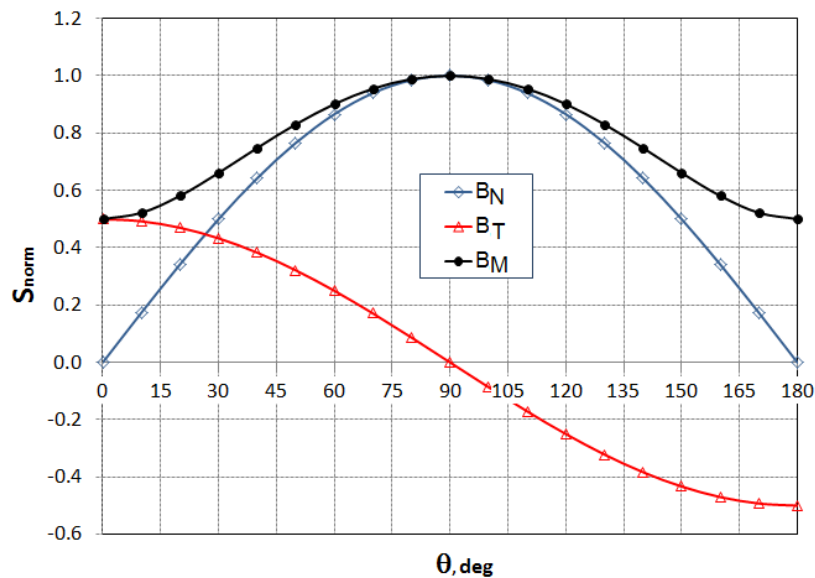

Fig. 13. Dependencies $B_N(\theta)$), $B_T(\theta)$) and $B_M(\theta)$

Next let's consider the angles of inclination of the sensor coil $\alpha_0(\theta)$ at which its plane coincides with the field induction vector. At these angles there is zero level of informative signal. Further

$$V_S = 0 \ @ \ \alpha(\theta) = \alpha_0(\theta) = \theta - \psi. \quad (5)$$

The @ symbol in the formula means "when". Instead, the maximum signal level occurs when the plane of the sensor coil is rotated by π/2 relative to the field

induction vector (the sensor coil normal coincides with the field vector)

$$V_S = V_{MAX} \ @ \ \alpha(\theta) = \alpha_{MAX}(\theta) = \theta - \psi + \frac{\pi}{2}. \quad (6)$$

An illustration of the dependencies $\alpha_{MAX}(\theta)$ та $\alpha_0(\theta)$ is presented in fig. 14.

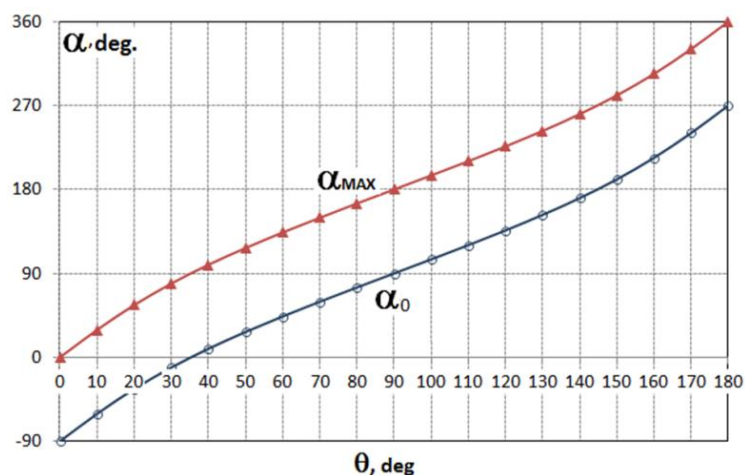**Fig. 14.** Dependencies $\alpha_{MAX}(\theta)$ та $\alpha_0(\theta)$

From the point of view of calibration of the magnetic tracking system and the use of signal model data for calculating the spatial position of the sensor coil, it is

advisable to consider two characteristic variants of its rotation. In the first variant, the rotation is performed relative to the axis OX_A in the coordinate system of the

actuator coil. Then the family of normalized signals of the sensor coil is defined by the expression

$$V_{SN1}(\theta,\alpha) = B_M(\theta)\cos(\alpha - \alpha_{MAX}(\theta)). \qquad (7)$$

But in the second variant, the sensor coil is rotated relative to the X_S axis, which coincides with the L_{SA} vector (the radius of rotation relative to the plane of the actuator coil). This option coincides with the turns according to fig. 3 and shown in fig. 10 – fig. 12

according to experimental data. Then the family of normalized signals of the sensor coil is defined by the expression

$$V_{SN2}(\theta,\alpha) = B_M(\theta)\cos(\alpha + \theta - \alpha_{MAX}(\theta)). \qquad (8)$$

Families of normalized signals are constructed using these expressions $V_{SN1}(\theta,\alpha)$ (fig. 15) and $V_{SN2}(\theta,\alpha)$ (fig. 16).
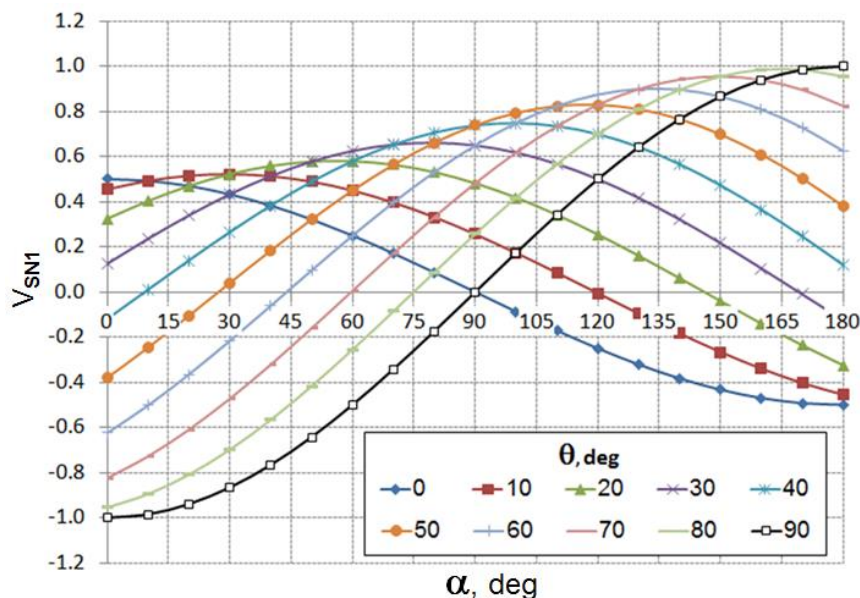
Fig. 15. The family of normalized signals $V_{SN1}(\theta,\alpha)$
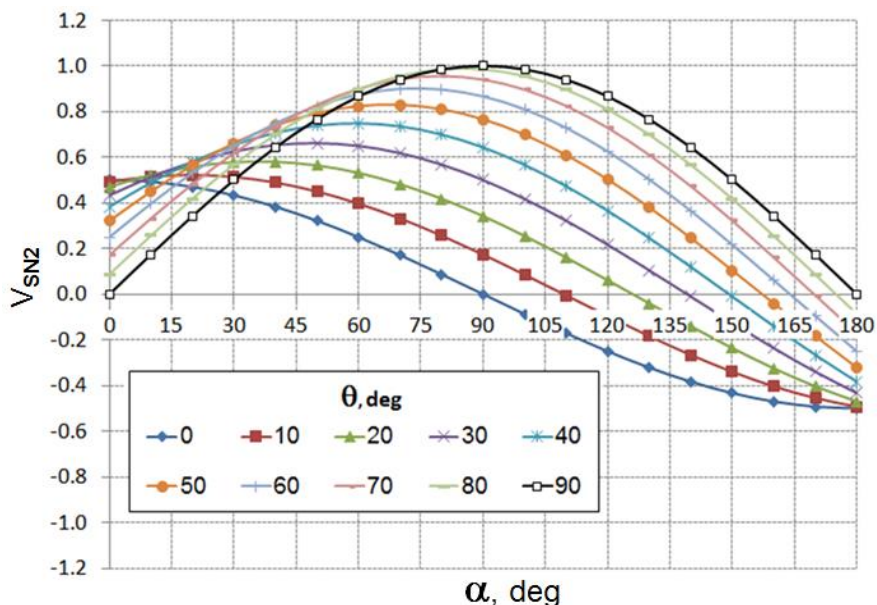
Fig. 16. The family of normalized signals $V_{SN2}(\theta,\alpha)$

The results of the verification of the signal model and their discussion

To verify the above signal model, we will compare the families of its normalized signals with the normalized signals of experimental measurements. An example of

such a comparison, which used data from the family of signals $V_S = f(L_{SA}, \theta, \alpha)$ at $L_{SA} = 50$ cm (fig. 10), is shown in fig. 17. You can see, at least at the level of qualitative analysis within a few percent, good agreement of these data.

14

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Fig. 17. Comparison of model (mod) and experimental (exp) data

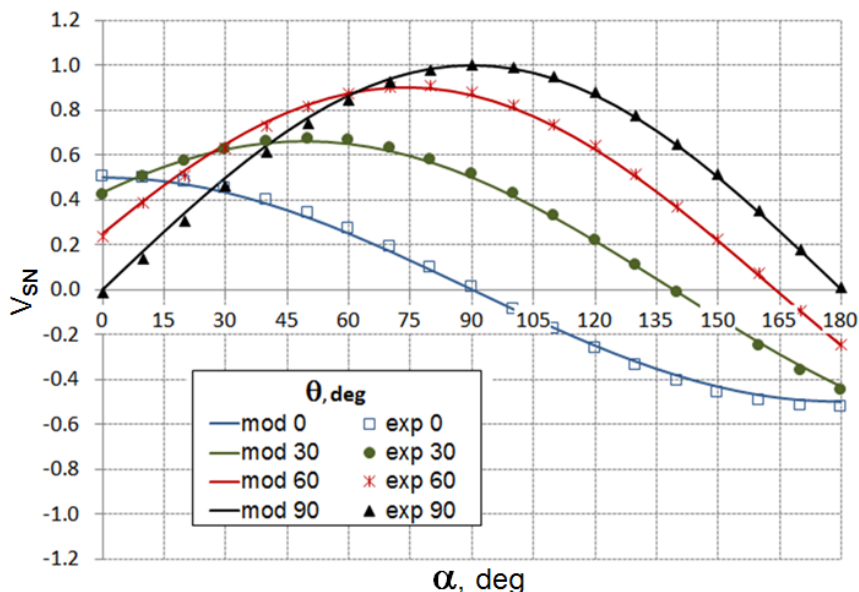To quantify the accuracy of the proposed signal model, numerous experimental studies of the signal families $V_S = f(L_{SA}, \theta, \alpha)$ have been performed with different sets of sensor and actuator coils. In particular, these studies used actuator coils with a diameter of $D_A = 50$ mm at the number of turns $N_A = 100$ and sensor coils with a diameter of $D_S = 30$ mm, 35 mm, 40 mm, 45 mm and 50 mm at the number of turns $N_S = 300$. The signal

path gain was selected for each set according to the criterion V_S ($L_{SA} = 50$ cm) ≈ 100 mV.

First, a comparison was made of the nominal (Nom) and experimental (variants – R1, R2, R3, R4, R5) dependencies of the maximum voltage V_{MAX} on the distance L_{SA} (fig. 18). The data of nominal (model) dependencies were determined by the inverse cubic function of the distance L_{SA} between the sensor and actuator coils.
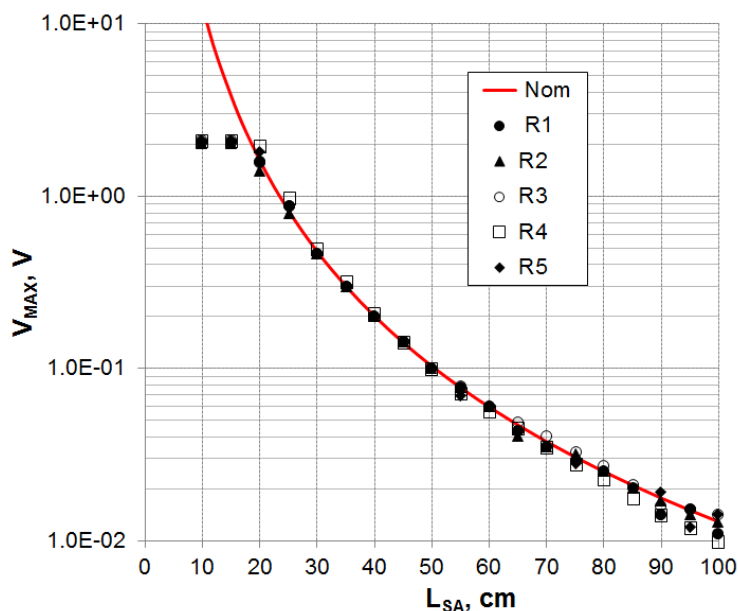
Fig. 18. Nominal (Nom) and experimental (R1… R5) V_{MAX} voltage dependencies on L_{SA} distance

It can be seen that in the range of distances from L_{SA} = 30 cm L_{SA} = 60 cm, the discrepancy between the experimental data and the nominal data is practically not observed. When the L_{SA} distance increases > 60 cm, the experimental data variation also increases, which is

caused by errors of the ER2 type (electromagnetic interference).

On the other hand, when the L_{SA} distance decreases by < 20 cm, there is an error of the ER4 type (signal limitation). In the range of 20 cm < L_{SA} < 30 cm, there is a certain deviation from the nominal experimental data,

which is caused by the "proximity" effect. There are two reasons for this effect. The first of them is the proportionality of the coil diameters with the distance between them, which leads to more complex functional dependencies based on the integration of the field over the area of the coils. The second reason is the emergence of an inductive relationship between the sensory and actuator coils.

For a more accurate analysis of the signal model, it is proposed to use the integrated standard deviation indicator S_{RMS}, calculated for families of normalized signals. For this purpose, a two-dimensional array [N M] is formed, where N and M are, respectively, the number of signal values when rotating at angles α and θ. Then, in this array, the values of experimental studies $S_{RE}(\theta,\alpha)$ and model calculations $S_{MO}(\theta,\alpha)$ are compared. The integrated indicator of this comparison is the standard deviation

$$S_{RMS} = \sqrt{\frac{1}{MN}\sum_{j=1}^{M}\sum_{i=1}^{N}\left(S_{REij}(\theta,\alpha)-S_{MOij}(\theta,\alpha)\right)^2} ,(9)$$

calculated for each distance L_{SA} value.

An example of the thus obtained dependence of the root mean square deviation of the S_{RMS} of the experimental data families from their model values is shown in fig. 19.

It can be seen that the obtained dependencies of the integrated S_{RMS} deviation qualitatively reproduce the preliminary analysis data at the maximum voltage V_{MAX}. In particular, in the range of distances from L_{SA} = 30 cm to L_{SA} = 65 cm, the minimum values of the integrated indicator are observed – S_{RMS} <0.01. The patterns of increase in S_{RMS} beyond this range and the reasons for this increase are similar to the above.
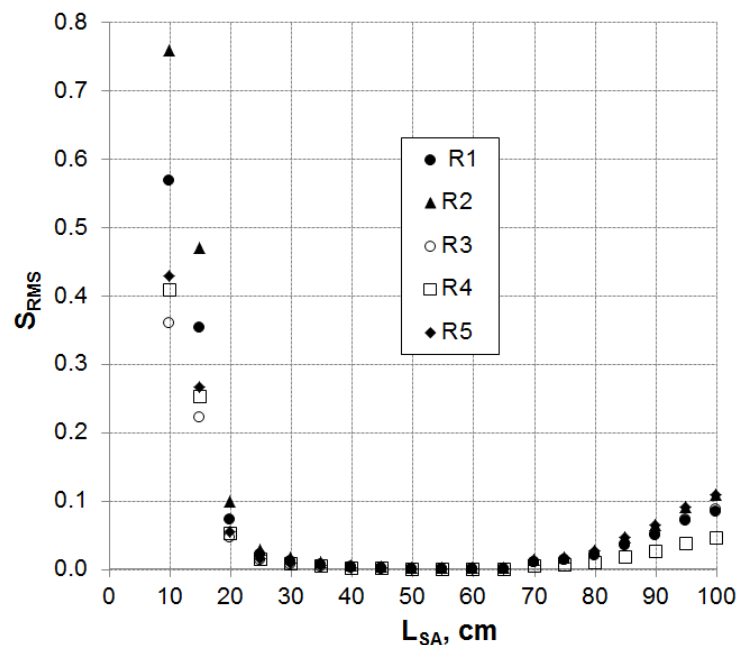

Fig. 19. Dependencies of the S_{RMS} of the experimental data families on their model values

The level of S_{RMS}, as a whole, is determined not only by the accuracy of the model presented, but also by the parameters of the coils and signal converter of the magnetic tracking system. Such parameters are the size and magnetic moment of the coils, noise immunity and the dynamic range of the signal path, the bit of the analog-to-digital converter, the accuracy of calibration and so on. In particular, noise immunity is enhanced by the optimization of bandpass filters, and dynamic range expansion by logarithmic gain schemes. These issues are beyond the scope of this publication.

Conclusions and prospects for further development

The principle of functioning of magnetic tracking systems and problems that arise in the process of development of these systems are considered. The spatial position of the objects is calculated by measuring the vector of induction of the reference magnetic fields in the low-frequency spectrum of electromagnetic radiation. Preferably, sensors and actuators in sensor-based magnetic tracking systems are small-sized coils and their 2D or 3D assemblies. The structure of the signal path of the programmable magnetic tracking system and its implementation based on the PSoC of the 5LP Family Cypress Semiconductor Corporation are disclosed. The results of experimental studies of the signal family when changing the distance between the L_{SA} coils and the angles of their relative positions θ, α are presented. Typical errors are analyzed and methods of their minimization are analyzed.

Taking into account the principle of operation and data of experimental studies, a signal model has been developed that describes the functional dependencies of

informative signals, namely the voltage $V_S = \mathrm{f}(L_{SA}, \theta, \alpha)$.

In the process of verification of the developed model, an array of the integrated standard deviation standard deviation of the SRMS families of normalized signals is calculated.

Further development of the results presented in this paper involves the application of the proposed signal model in the problems arising in the development of magnetic tracking systems. In particular, this is the development and specification of algorithms for calculating the spatial position, debugging and express evaluation of the accuracy of the system functioning, optimization of calibration procedures.

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17

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Відомості про авторів / Сведения об авторах / About the Authors

Голяка Роман Любомирович – доктор технічних наук, професор, Національний університет "Львівська політехніка", професор кафедри електронних засобів інформаційно-комп'ютерних технологій, Львів, Україна; email: holyaka@yahoo.com; ORCID: https://orcid.org/0000-0002-7720-0372.

Голяка Роман Любомирович – доктор технических наук, профессор, Национальный университет "Львовская политехника", профессор кафедры электронных средств информационно-компьютерных технологий, Львов, Украина.

Holyaka Roman – Doctor of Sciences (Engineering), Professor, Lviv Polytechnic National University, Professor of the Department of Electronics and Information Technology, Lviv, Ukraine.

Марусенкова Тетяна Анатоліївна – кандидат технічних наук, доцент, Національний університет "Львівська політехніка", доцент кафедри програмного забезпечення, Львів, Україна; email: tetyana.marus@gmail.com; ORCID: https://orcid.org/0000-0003-4508-5725.

Марусенкова Татьяна Анатольевна – кандидат технических наук, доцент, Национальный университет "Львовская политехника", доцент кафедры программного обеспечения, Львов, Украина.

Marusenkova Tetyana – PhD (Engineering Sciences), Associate Professor, Lviv Polytechnic National University, Associate Professor of the Department of Software, Lviv, Ukraine.

Федасюк Дмитро Васильович – доктор технічних наук, професор, Національний університет "Львівська політехніка", професор кафедри програмного забезпечення, Львів, Україна; email: fedasyuk@gmail.com; ORCID: https://orcid.org/0000-0003-3552-7454.

Федасюк Дмитрий Васильевич – доктор технических наук, профессор, Национальный университет "Львовская политехника", профессор кафедры программного обеспечения, Львов, Украина.

Fedasyuk Dmytro – Doctor of Sciences (Engineering), Professor, Lviv Polytechnic National University, Professor of the Department of Software, Lviv, Ukraine.

СИГНАЛЬНА МОДЕЛЬ СЕНСОРІВ ПРОСТОРОВОГО ПОЛОЖЕННЯ В СИСТЕМАХ МАГНІТНОГО ТРЕКІНГУ

Предметом дослідження в статті є процеси формування сигналів в системах магнітного трекінгу, зокрема для задач визначення просторового положення в концепціях - Індустрія 4.0 та Індустріальний Інтернет Речей. Такі системи базуються на визначенні просторового положення об'єктів за результатами вимірювання вектора індукції опорних магнітних полів у низькочастотному спектрі електромагнітного випромінювання. **Метою** роботи є розроблення та верифікації сигнальної моделі для розрахунку просторового положення об'єктів у системах магнітного трекінгу. Сигнальна модель розробляється на основі експериментально отриманих сімейств залежностей інформативних сигналів від відстані та кутів між сенсорною та актуаторною котушками. **Завдання**: аналіз сигналів в системах магнітного трекінгу, розроблення засобів проведення експериментальних досліджень, математична інтерпретація результатів досліджень з розробленням сигнальної моделі, верифікація та застосування цієї моделі. Використовуються загальнонаукові **методи**: експеримент, вимірювання, аналіз, синтез, методи теорії ймовірностей і статистики Отримано такі **результати**. Розкрита структура сигнального тракту програмованої системи магнітного трекінгу та його реалізація на основі PSoC сімейства 5LP Family Cypress Semiconductor. Представлені результати експериментальних досліджень сімейства сигналів при зміні відстані між котушками та кутів їх взаємного положення. Для розрахунку просторового положення використовують сигнальні моделі, які описують розподіл сформованих магнітних полів та сигналів сенсорних котушок. Проведено аналіз типових похибок та способів їх мінімізації. Для верифікації розробленої сигнальної моделі пропонується використання інтегрованого показника середньоквадратичного відхилення сімейств нормованих сигналів. **Висновки**. Розроблена сигнальна модель взаємного положення актуаторів та сенсорів в системах магнітного трекінгу. Модель описує функціональні залежності, основними аргументами яких є відстань між котушками та кути їх взаємного нахилу. Подальший розвиток представлених в роботі результатів передбачає застосування запропонованої сигнальної моделі в задачах розроблення та специфікації алгоритмів розрахунку просторового положення, відлагодження та експрес-оцінки точності функціонування системи, оптимізації процедур калібрування.

Ключові слова: пристрої Індустрії 4.0; магнітний трекінг; сигнальна модель; програмована система на кристалі.

СИГНАЛЬНАЯ МОДЕЛЬ СЕНСОРОВ ПРОСТРАНСТВЕННОГО ПОЛОЖЕНИЯ В СИСТЕМАХ МАГНИТНОГО ТРЕКИНГА

Предметом исследования в статье являются процессы формирования сигналов в системах магнитного трекинга, в частности, для задач определения пространственного положения в концепциях Индустрия 4.0 и Индустриальный Интернет Вещей. Такие системы основываются на определении пространственного положения объектов по результатам измерения вектора индукции опорных магнитных полей в низкочастотном спектре электромагнитного излучения. **Цель** работы – разработка и верификация сигнальной модели для расчета пространственного положения объектов в системах магнитного трекинга. Сигнальная модель разрабатывается на основе полученных экспериментальным путем семейств зависимостей информативных сигналов от расстояния и углов между сенсорной и актуаторной катушками. **Задания**: анализ сигналов в системах магнитного трекинга, разработка средств проведения экспериментальных исследований, математическая

18

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интерпретация результатов исследований с разработкой сигнальной модели, верификация и использование этой модели. Используются общенаучные **методы**: эксперимент, измерение, анализ, синтез, методы теории вероятностей и статистики. Получены следующие **результаты**: Раскрыта структура сигнального тракта программируемой системы магнитного трекинга и его реализация на основе PSoC семейства 5LP Family Cypress Semiconductor. Представлены результаты экспериментальных исследований семейства сигналов при изменении расстояния между катушками и углов взаимного размещения. Для расчета пространственного положения используют сигнальные модели, которые описывают распределение сформированных магнитных полей и сигналов сенсорных катушек. Проведен анализ типичных погрешностей и способов их минимизации. Для верификации разработанной сигнальной модели предлагается использование интегрированного показателя среднеквадратического отклонения семейств нормированных сигналов. **Выводы**. Разработана сигнальная модель взаимного положения актюаторов и сенсоров в системах магнитного трекинга. Модель описывает функциональные зависимости, основными аргументами которых являются расстояние между катушками и углы их взаимного наклона. Дальнейшее развитие представленных в работе результатов предполагает использование предложенной сигнальной модели в задачах разработки и спецификации алгоритмов расчета пространственного положения, отладки и экспресс-оценки точности функционирования системы, оптимизации процедур калибровки.

Ключевые слова: устройства Индустрии 4.0; магнитный трекинг; сигнальная модель; программируемая система на кристалле.

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