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[1]V. O. Golitsyn,
[2]O. A. Sushchenko

METHODS OF PROCESSING DATA IN MEASURING INSTRUMENT WITH NON-ORTHOGONAL ORIENTATION OF INERTIAL SENSORS

Faculty of Air Navigation, Electronics and Telecommunications, National Aviation University, Kyiv, Ukraine
E-mails: [1]vova.gol@ukr.net, [2]sushoa@ukr.net ORCID 0000-0002-8837-1521

Abstract**—***The paper deals with improving methods of processing data in measuring instruments with non-orthogonal orientation of inertial sensors. The method of processing measuring information based on neural networks is represented. The method for searching failures of separate sensors in the redundant non-orthogonal measuring instrument based on neural networks is proposed. The method for widening the dynamic range of redundant non-orthogonal measuring instrument is described. The appropriate calculating procedures are represented in details. Description of the represented methods is accompanied by representation of modelling results. The proposed approach ensures improving accuracy and reliability of measurements. The obtained procedures can be especially useful for designing measuring instruments assigned for application in unmanned aerial vehicles.*

Index Terms—Non-orthogonal measuring instrument; inertial sensor; neural network; search of failures; dynamic range.

I. INTRODUCTION AND PROBLEM STATEMENT

One of the important problems in the development of inertial sensors is the processing of redundant information. Solving this problem leads to an increasing in the accuracy of navigation information and, accordingly, the successful functioning of moving objects, in particular UAVs.

Designing low cost inertial measuring instruments with improved operating characteristics is one of the most important trends in modern device-building. One of the most efficient ways to improve accuracy and reliability of measuring information in navigation and motion control systems is usage of functional redundancy [1] – [3]. In this case, the maximum accuracy and reliability of measuring can be achieved for non-orthogonal configuration of inertial sensors [4] – [6]. Such an approach is especially useful for application in unmanned aviation.

One of the most important issue in the above-mentioned approach is processing redundant information. Using different methods, is possible to improve accuracy and reliability of navigation data by algorithmic means.

There are traditional methods of processing information in measuring instruments based on non-orthogonal configurations of inertial sensors. They are based on the theory of statistical solutions and mathematical statistics. The method of maximum likelihood is convenient to use for known probable characteristics of measuring errors. In this case, the covariation matrix of errors is determined on the basis of experimental data. The least square method is usually used in situations, when a priori data about properties of estimated parameters and their measuring errors are absent.

There are different methods for improving navigation information, for example, optimal recurrent Kalman filtration. But using such methods requires a priori information about dynamic characteristics of the system. In practical situations, this information, usually, is not available. This decreases reliability of the obtained estimates. It is convenient to use new methods of information processing.

The goal of the article is developing methods of processing data in measuring instrument with non-orthogonal orientation of inertial sensors based on neural network technologies. Using functional redundancy ensures also the possibility to improve resistance to failures and to widen functional possibilities of the measuring instrument.

II. THE METHOD OF PROCESSING MEASURING INFORMATION BASED ON NEURAL NETWORKS

Improvement of measurement procedures can be implemented based on the use of non-linear mathematical models of measurement objects and modern optimization algorithms, such as genetic algorithms, fuzzy logic, evolutionary programming, and neural networks. Neural network technology is one of the most developed from the point of view of software implementation [7], [8]. Therefore, it is most applicable in such practical situations as signal measurement, algorithms for processing redundant information, diagnostics of failures in engineering systems, etc. The efficiency of the neural network depends on its assimilation during navigation information processing. The main goal of the method is to ensure the minimum measurement error at the output of the neural network.

The object of research is a redundant non-orthogonal measuring instrument based on MEMS inertial sensors. This device uses the tetragonal pyramid as a structural element and five three-axis measuring units, i.e. 15 single-axis inertial sensors, respectively [9]. Therefore, to determine the projection of the angular velocity of a moving object in the traditional way, it is necessary to perform calculations using the 15×15 dimension conversion matrix. It is possible to increase the accuracy of processing navigational information by methods for processing redundant information. The use of an information processing method based on neural networks allows you to identify three inertial sensors that are characterized by the highest accuracy. Namely, these sensors are further used for navigation calculations. This approach avoids intricate calculations associated with the use of matrices. Next, the angular velocity projections of the moving object in the navigation system can be determined based on the measurements of the chosen inertial sensors. The implementation of such a method ensures a reduction in measurement error and information processing time.

The output information of the non-orthogonal measuring inertial unit can be presented in the following form

$$\begin{aligned} \hat{\omega}_x &= k_x \omega_x + \omega_{x0} + k_{tx} \Delta t, \\ \hat{\omega}_y &= k_y \omega_y + \omega_{y0} + k_{ty} \Delta t, \\ \hat{\omega}_z &= k_z \omega_z + \omega_{z0} + k_{tz} \Delta t, \end{aligned} \qquad (1)$$

where ω_i is the projection of the angular rate, the indices x, y, z correspond to the projections of the angular velocity on the axis of the $Oxyz$ navigation coordinate system; ω_{i0} are zero signals; k_i are transfer constants; Δt is the temperature increment; k_{ts} are temperature coefficients.

The block diagram of the neural network corresponding to the mathematical model of the measuring inertial unit (1) is shown in Fig. 1.

The neural network shown in Fig. 1 consists of three layers, including input, hidden and output ones. The data for the input layer of the neural network are the temperature and readings of the inertial measurement unit. The internal hidden layer implements the information processing procedure of individual triaxial inertial measurement units. The outer output layer determines the resulting projections of the measured angular velocity vector of the moving object on the axis of the orthogonal navigation coordinate system.

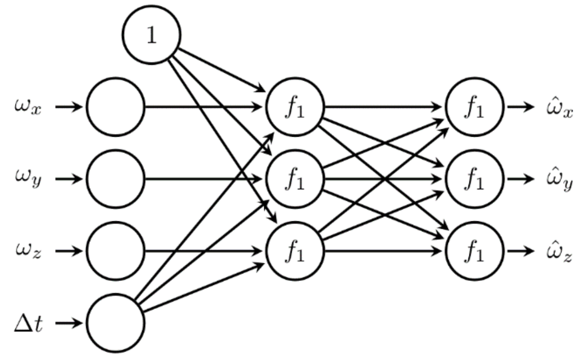

Fig. 1. Block diagram of the neural network of the triaxial inertial measuring unit

The structure of a neural network for processing information from an excessive non-orthogonal measuring instrument based on MEMS inertial sensors is presented in Fig. 2 [10].

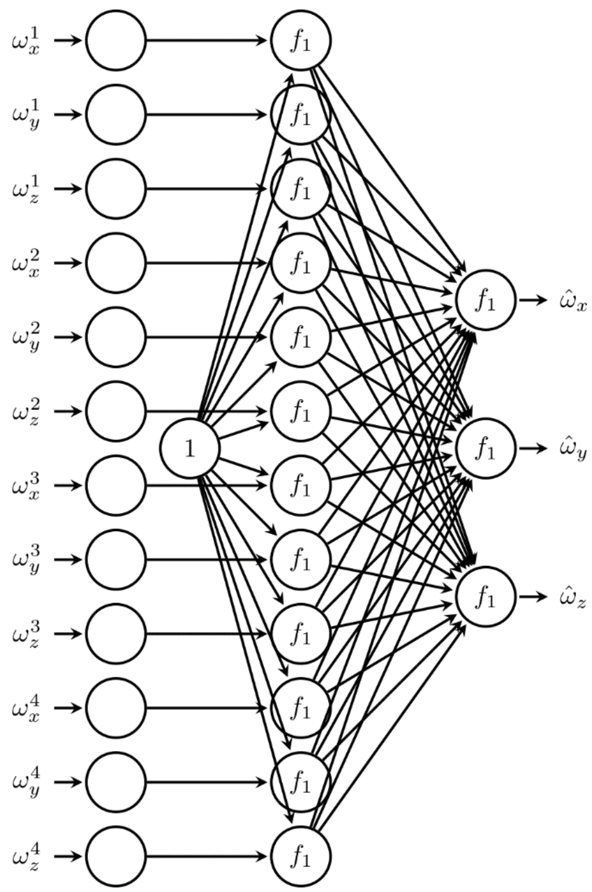

Fig. 2. The neural network of non-orthogonal measuring instrument

Usually, inertial measurement units based on MEMS gyroscopes have a built-in thermal stabilization system. Therefore, the temperature drift can be reduced to a minimum value, and the connections of the neural network that determine the temperature dependence can be omitted for simplicity. The process of learning a neural network for processing the information of a- redundant non-orthogonal measuring instrument based on three-axis MEMS sensors for the z-axis of the navigation coordinate system is presented in Fig. 3.

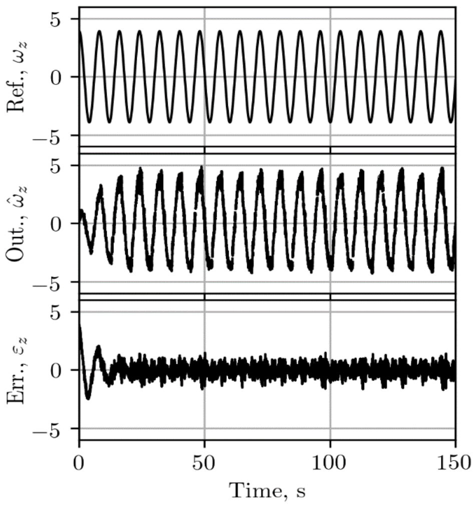

Fig. 3. Learning of a neural network during the determination of projections angular velocity on *z* axis

In Figure 3, the following notations are used: Ref is the reference signal at the output of the neural network; Out is the output signal that changes during the learning process; Err represents the error of the output signal.

A graphic representation of the change in the connection coefficients of the neural network during its learning is presented in Fig. 4. The application of the proposed information processing method ensures the choice of the best three-axis MEMS sensors from the point of view of achieving minimum root mean square errors. As a result of the application of the developed information processing method based on a neural network, inertial sensors were chosen, which ensure the maximum accuracy of determining the projections of the angular velocity of a moving object on the axis of the navigation coordinate system.

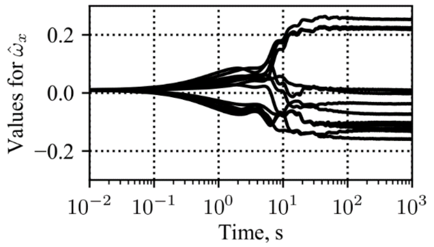

Fig. 4. Determination of angular velocity projections on the axis of the navigation coordinate system

The use of the developed information processing algorithm significantly speeds up the process of determining the angular velocity of a moving object. It should be noted that the standard information processing procedure requires complex calculations caused by the need to take into account the matrix of transformations between the measurement and navigation coordinate systems. The coefficients of the measurement equation in most applications are determined by linear dependencies (1) and can be determined using the method of least squares. However, the application of the least squares method requires significant computing resources, including the RAM capacity for storing reference values and intermediate calculation results, and execution time. Neural networks do not have such disadvantages and can be implemented based on a microcontroller with limited resources.

III. The Method of Searching Failures Based on Neural Networks

Consider a neural network, taking into account the fact that a set of n inertial sensors is combined in an excessive non-orthogonal configuration. For certainty, let's focus on an inertial device designed to measure the angular velocity of a moving object.

The structural diagram of such a neural network is presented in Fig. 5 [11].

The measurement error for each inertial sensor can be defined as

$$\Delta_i = \Omega_i - \Omega, \qquad (2)$$

where Δ_i is the measuring error; Ω_i is the projection of the angular rate; Ω is the reference value.

The condition for making a decision about a choice of the measuring channel looks like

$$|\Delta| < \varepsilon . \qquad (3)$$

The expression (2) can be described in the following way

$$\Delta_i = \Omega_i - h(i,1)\omega_x - h(i,2)\omega_y - h(i,3)\omega_z . \qquad (4)$$

To simplify the calculation procedure, condition (3) can be divided into two linear functions

$$\Delta_i < \varepsilon \text{ and } \Delta_i > -\varepsilon \text{ or } \varepsilon - \Delta_i > 0 \text{ and } \varepsilon + \Delta_i > 0 . \qquad (5)$$

The function of the first layer of the neural network is to estimate the deviation of the measurement results from the probably measured values. At the same time, this layer of the neural network performs normalization of measurement estimates using the sigma function.

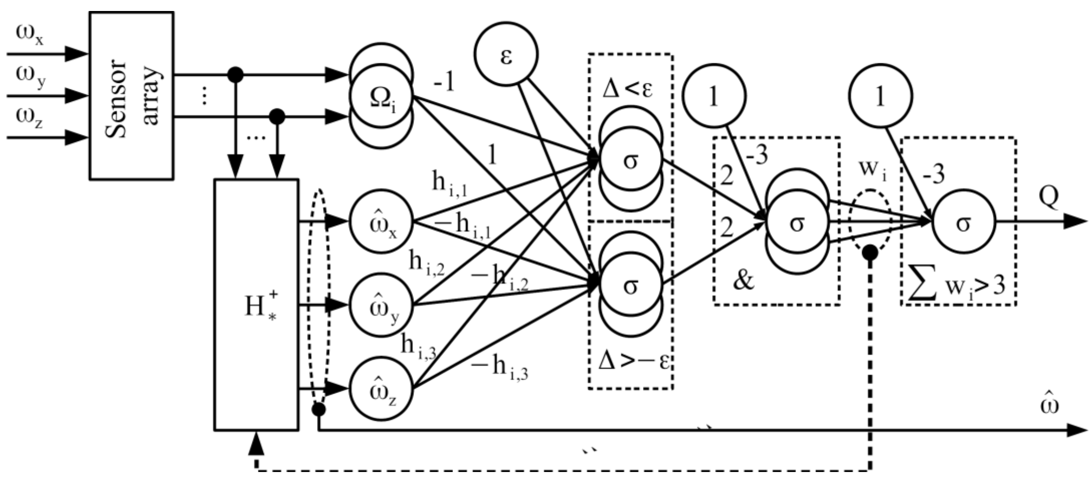

Fig. 5. Implementation of the neural network

The second level of the neural network, shown in Fig. 6, implements the logical AND function. In this way, it is possible to determine the error of the measuring channel, which does not exceed the permissible limits. At the same time, it allows you to define a weighting function for a given measuring axis.

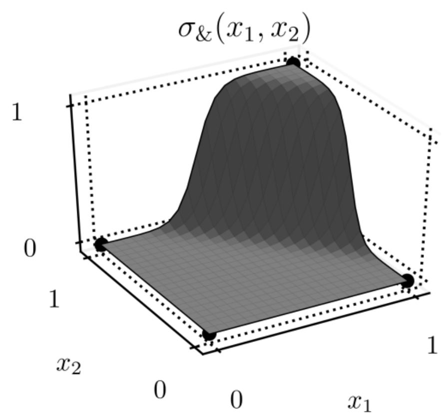

Fig. 6. Graphical representation of the transfer function of the second level of the neural network that implements the function of logical AND

The effectiveness of the proposed approach to fault finding on the basis of expressions (4), (5) is proven by the simulation results presented in Fig. 7.

The input signals entering the three-axis inertial measurement sensors are normalized sinusoids Fig. 7(a, b, c). Additive random noise with an amplitude of 0.075 (normalized value) is added to the sensor outputs. In the scenario, the third sensor of the excessive meter fails for a short time. In the first layer of the neural network, the deviation of the sensor readings from the weighted average value was determined (Fig. 7d, e). With the help of the second layer of the neural network, a logical signal of the sensor's weight coefficient was formed. (Fig. 7f). The conversion matrix is formed by the matrix of weighting coefficients of three sensors. In the future, this matrix is used to form the output signal. In the absence of correction of the weighting coefficients, the output signal of the meter (Fig. 7g), formed by averaging the output signals of individual sensors, will be distorted, as shown in Fig. 7h. Such a measuring system with a neural network implements the functions of the quorum element.

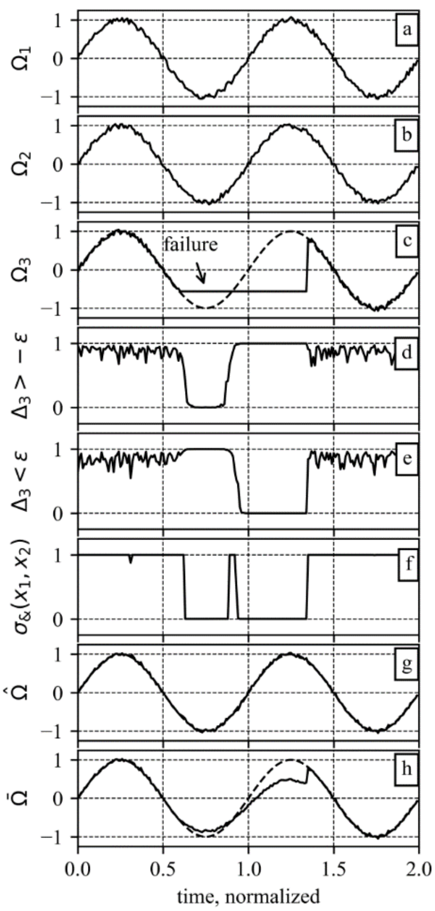

Fig. 7. Results of simulation

IV. THE METHOD OF WIDENING DYNAMIC RANGE

As mentioned earlier, measuring the angular velocities of a moving object requires the use of two coordinate systems, and the inertial and measurement coordinate systems. Projections of the angular velocities of a moving object are measured relative to the inertial coordinate system. The axes of the measuring coordinate system coincide with the axes of the sensor's sensitivity. The relative arrangement of two biaxial MEMS sensors is shown in Fig. 8. In this figure, the axes of the inertial coordinate system ($Ox_1y_1z_1$) coincide with the measurement axes of the first MEMS sensor. The scheme presented in Fig. 8, provides measurement in the horizontal plane.

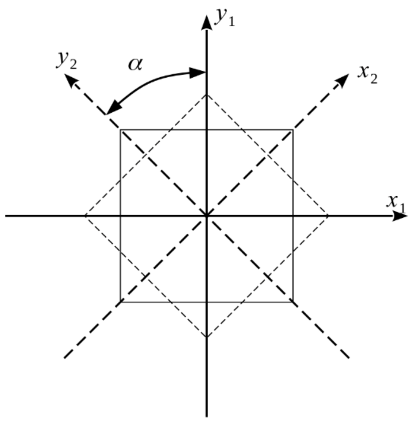

Fig. 8. Increasing range of measurements due to mutual location of two MEMS inertial sensors

It should be noted that solving this problem is of great importance for controlling the movement of various types of objects.

There are various methods of increasing the accuracy of non-orthogonal measuring devices, for example, calibration taking into account the influence of magnetic course deviations [12], [13]. But this article proposes to increase the range of measurements in a non-orthogonal configuration using information processing algorithms. The advantage of this approach is that it does not require additional testing.

The operation of the redundant inertial measuring instrument can be described by a vector equation [1], [14]

$$\mathbf{\Omega} = \mathbf{H}\boldsymbol{\omega}, \tag{5}$$

where $\mathbf{\Omega} = \begin{bmatrix} \omega_1 & \omega_2 & \omega_3 & \omega_4 \end{bmatrix}^{\mathrm{T}}$ is the vector of projections of angular rate onto measuring axes $\boldsymbol{\omega} = \begin{bmatrix} \omega_x & \omega_y \end{bmatrix}$.

To restore the vector of input signals, it is necessary to use the inverse matrix

$$\mathbf{H} = \begin{cases} \mathrm{diag}\{p_1, \dots, p_4\}\mathbf{H} & \text{if} \quad \sum_{i=1}^{4} p_i \geq 2, \\ \mathbf{H} \quad \text{if} \quad \sum_{i=1}^{4} p_i < 2, \end{cases}$$

$$\begin{cases} p_i = 1 & \text{if} \quad x_{\min} < |\mathbf{P}_i| \leq x_{\max}, \\ p_i = 0 & \text{otherwise.} \end{cases} \tag{6)}$$

Since the matrix **H** is not square in the general case, the Moore–Penrose algorithm must be used to determine the pseudo-inverse matrix

$$\mathbf{H}^{+} = (\mathbf{H}^{\mathrm{T}}\mathbf{H})^{-1}\mathbf{H}^{T}. \tag{7}$$

Based on (5) and (7), it is possible to write down the algorithm for determining the input vector of measurements

$$\boldsymbol{\omega} = \mathbf{H}^{+}\mathbf{\Omega}. \tag{8}$$

To estimate the accuracy of restoring the input vector, it is possible using the error correlation matrix

$$\mathbf{D} = (\mathbf{H}^{\mathrm{T}}\mathbf{H})^{-1}. \tag{9}$$

Modeling was carried out using expressions (6), (8) and (9). Figure 9 presents information on angular velocities measured by two MEMS sensors, including all measurement axes of the navigation coordinate system [15], [16]. Analysis of simulation results shows that direct use of formula (6) leads to sufficient distortion of measurement results. This situation is caused by the phenomenon of saturation. To compensate for this phenomenon, it is necessary to exclude from the calculations all measurements that belong to the saturation region.

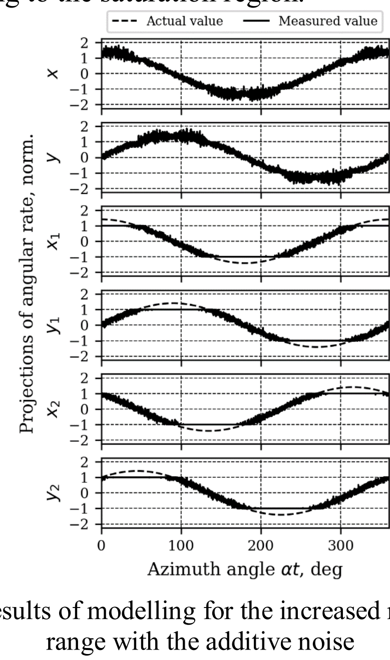

Fig. 9. Results of modelling for the increased measuring range with the additive noise

V. CONCLUSIONS

A neural network based on learning samples is considered. Such an approach reduces the calibration time, including the preparation of learning samples, in comparison with the algorithm based on the least squares method. The learning process of the neural network is shown. The simulation results proved the efficiency of the proposed method are represented.

An improved algorithm based on a neural network is proposed, which provides a current analysis of the accuracy of the measuring channels and a generalized assessment of the performance of the inertial redundant measuring instrument. The algorithm ensures searching failures in the device.

The possibility of increasing the dynamic range of the redundant measuring instrument due to the non-orthogonal configuration has been studied. The simulation results have been showed that the proposed structure of the inertial measuring unit and the information processing algorithm make it possible to increase the measurement range by 1.44 times with the same reduction of errors for measuring parameters in the given range.

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Golitsyn Volodymyr. Post-graduate.
Faculty of Air Navigation, Electronics and Telecommunications, National Aviation University, Kyiv, Ukraine.
Education: National Aviation University, Kyiv, (2018).
Research area: information-measurement devices.

Publications: 6.
E-mail: vova.gol@ukr.net

Sushchenko Olha. ORCID 0000-0002-8837-1521. Doctor of Engineering. Professor.
Faculty of Air Navigation, Electronics and Telecommunications, National Aviation University, Kyiv, Ukraine.
Education: Kyiv Polytechnic Institute, Kyiv, Ukraine, (1980).
Research area: systems for stabilization of information-measurement devices.
Publications: 250.
E-mail: sushoa@ukr.net

В. О. Голіцин, О. А. Сущенко. Методи оброблення інформації вимірювача з неортогональним розташуванням інерціальних датчиків

У статті розглянуто вдосконалення методів обробки даних у вимірювальних приладах з неортогональною орієнтацією інерціальних датчиків. Представлено метод обробки вимірювальної інформації на основі нейронних мереж. Запропоновано метод пошуку відмов окремих датчиків у надмірному неортогональному вимірювачу на основі нейронних мереж. Описано метод розширення динамічного діапазону надмірного неортогонального вимірювача. Представлено відповідні обчислювальні процедури. Опис представлених методів супроводжується поданням результатів моделювання. Запропонований підхід забезпечує підвищення точності та надійності вимірювань. Отримані методики можуть бути особливо корисними для проектування засобів вимірювальної техніки, призначених для використання в безпілотних літальних апаратах.
Ключові слова: неортогональний вимірювач; інерціальний датчик; нейронна мережа; пошук відмов; динамічний діапазон.

Голіцин Володимир Олександрович. Аспірант.
Факультет аеронавігації, електроніки та телекомунікацій, Національний авіаційний університет, Київ, Україна.
Освіта: Національний авіаційний університет, Київ (2018).
Напрям наукової діяльності: інформаційно-вимірювальні прилади.
Публікації: 6.
E-mail: vova.gol@ukr.net

Сущенко Ольга Андріївна. ORCID 0000-0002-8837-1521
Доктор технічних наук. Професор.
Факультет аеронавігації, електроніки та телекомунікацій, Національний авіаційний університет, Київ, Україна.
Освіта: Київський політехнічний інститут, Київ, Україна, (1980).
Напрям наукової діяльності: системи стабілізації інформаційно-вимірювальних пристроїв.
Кількість публікацій: 250.
E-mail: sushoa@ukr.net

В. А. Голицын, А. А. Сущенко. Методы обработки информации измерителя с неортогональным расположением инерциальных датчиков

В статье рассмотрено усовершенствование методов обработки данных в измерительных приборах с неортогональной ориентацией инерциальных датчиков. Представлен метод обработки измерительной информации на основе нейронных сетей. Предложен метод поиска отказов отдельных датчиков в чрезмерном неортогональном измерителе на основе нейронных сетей. Описан метод расширения динамического диапазона избыточного неортогонального измерителя. Представлены соответствующие вычислительные процедуры. Описание представленных методов сопровождается представлением результатов моделирования. Предлагаемый подход обеспечивает повышение точности и надежности измерений. Полученные методики могут быть особенно полезны для проектирования средств измерений, предназначенных для использования в беспилотных летательных аппаратах.
Ключевые слова: неортогональный измеритель; инерциальный датчик; нейронная сеть; поиск отказов; динамический диапазон.

Голицын Владимир Александрович. Аспирант.
Факультет аэронавигации, электроники и телекоммуникаций, Национальный авиационный университет, Киев, Украина.
Образование: Национальный авиационный университет, Киев, (2018).
Область научных исследований: информационно-измерительные приборы.
Публикации: 6.
E-mail: vova.gol@ukr.net

Сущенко Ольга Андреевна. ORCID 0000-0002-8837-1521. Доктор технических наук. Профессор.
Факультет аэронавигации, электроники и телекоммуникаций, Национальный авиационный университет, Киев, Украина.
Образование: Киевский политехнический институт, Киев, Украина, (1980).
Направление научной деятельности: система стабилизации информационно-измерительных устройств.
Количество публикаций: 250.
E-mail: sushoa@ukr.net