COMPUTER-AIDED DESIGN SYSTEMS

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BASIC PROBLEMS OF DESIGN OF REDUNDANT NONCOLLINEAR CONFIGURATIONS WITH INERTIAL SENSORS

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Abstract—*The paper deals with basics tasks of the design of redundant noncollinear inertial measuring units based on the technology of micrielectromechanical systems. Analysis of noncollinear configurations of inertial sensors is represented. The approach to the creation of the mathematical model of the inertial sensor is given. The basic problems of redundant information processing are discussed. The problem of optimal orientation of inertial sensors sensitivity axes in noncollinear configurations is studied. The approaches to conversion of redundant measuring information into projections of moving vehicles kinematical parameters are represented. The possibility to use the criterion of maximum a posteriori probability and least-squares method is considered. The ways to solve the above-mentioned problems are proposed. The obtained results can be useful for the design of inertial measuring units of the wide class.*

Index Terms—Inertial sensor; information processing; noncollinear configuration; rate gyroscope; redundancy.

I. INTRODUCTION

Importance of presented researches is caused by the necessity to increase the quality of navigation of unmanned moving vehicles.

Redundant configurations of inertial sensors are widely used in inertial navigation systems. Redundancy is a way to improve the accuracy and reliability of navigation measurements. There are some known types of reliability such as parametric, mode, structural, time and functional [1]. The latter type of redundancy is the most applicable in topicality of control of moving vehicles. In this case, we can say about the redundancy of inertial measuring instruments using for determination of angular rates and accelerations of a moving vehicle.

Redundant configurations of inertial sensors can be classified by a number of measuring axes in a single unit including uniaxial inertial sensors, and also biaxial and triaxial inertial measuring units. There are also collinear and noncollinear redundant configurations of both inertial sensors and inertial measuring units (biaxial or triaxial).

As a rule, kinematical parameters of a moving vehicle are vectors, for example, vectors of angular rate and acceleration. To obtain necessary information about a vector, it is necessary to use a definite number of sensors. Sensitivity axes of redundant sensors are collinear in configurations of the first type. So, vectors of sensitivity axes are linear dependent. Respectively, sensitivity axes of redundant sensors are noncollinear in configurations of the second type. And vectors of sensitivity axes are not linear dependent and therefore more informative [1].

Application of noncollinear inertial measuring instruments has a definite history. Gyroscopic angular rate vector meters have been operated in for many years in systems of control of orientation and stabilization for spacecraft of different purposes. The above-mentioned measuring instruments have been developed on the basis of sensitive elements of the different type such as float gyroscopes, dynamically tuned gyroscopes, and fiber-optic gyroscopes. Nowadays gyroscopic angular rate vector meters on the basis of two-degrees-of-freedom float gyroscopes with the gas-dynamic suspension and magnetic centering of the float are used in these applications. Measuring instruments using these devices provide the orientation of the spacecraft in the inertial space with accuracy no more than 0.1° and stabilization of spacecraft angular motion $(10^{-5}\ldots10^{-4})$°/s [2].

Development of unmanned aviation has renewed interest to noncollinear configurations of inertial sensors based on the technology of microelectromechanical systems (MEMS) able to improve accuracy and reliability of navigation measurements on unmanned aerial vehicles (UAVs)

[3], [4]. It is known that determination of the vector in the three-dimensional space requires using measuring instrument with sensitivity axes forming a three-dimensional measuring basis. So, application of noncollinear configurations leads to functional redundancy. The vector of kinematical parameters can be measured by different combinations of inertial sensors or as a result of processing a redundant number of inertial sensors [1]. An additional advantage of such a configuration is the possibility to identify faults of separate sensors.

The above-mentioned arguments prove the issue of the day and importance of research of redundant noncollinear configurations of inertial sensors and inertial measuring units.

II. PROBLEM STATEMENT

The generalized structural scheme of navigation system using redundant noncollinear configuration of inertial sensors is represented in Fig. 1.

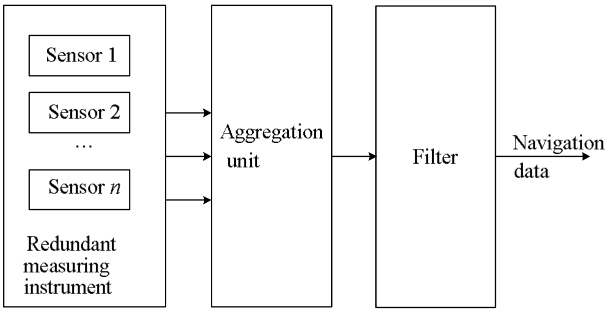

Fig. 1. The structrural scheme of a navigation system with the redundant noncollinear measuring instrument

The main goal of the research is to improve the accuracy and reliability of the determination of moving vehicle kinematical parameters based on redundant noncollinear configurations of inertial measuring units.

For achieving this goal it is necessary to solve some complicated problems.

1) To analyze different redundant noncollinear configurations of inertial sensors and inertial measuring units for formulating recommendations about the choice of the type of configuration.

2) To solve a problem of optimal orientation of measuring (sensitivity) axes in redundant noncollinear configurations based on requirements to accuracy and reliability.

3) To develop mathematical models of an inertial sensor and inertial measuring unit and also redundant noncollinear configuration.

4) To create the algorithm of information processing including calibration.

5) To develop the algorithm of the determination of faults.

II. REVIEW OF PUBLICATIONS AND RESEARCHES

Nowadays the significant attention is paid to the application of nonorthogonal configurations of inertial sensors by reason of development of unmanned aviation. It is marked in modern scientific periodicals that application of redundant fault-tolerant inertial measuring units leads to significant improvement of accuracy and reliability of navigation measurements [4]. Respectively, such configurations can be used for the development of inertial navigation systems as was shown in [5]. It is expedient to use inertial measuring units based on nonorthogonal configurations in unmanned aviation as was grounded in [6]. Nonorthogonal redundant configurations of uniaxial inertial sensors are represented in [7]. The theoretical assessment of accuracy and appropriate comparative analysis of different nonorthogonal configurations are given in [8]. The nonorthogonal redundant configurations consisting of triaxial MEMS sensors based on the triangular and tetragonal pyramids are represented in [9]. Theoretical and experimental assessments of such a configuration are presented in [10].

III. ANALYSIS OF DIFFERENT NONCOLLINEAR CONFIGURATIONS

Choice of orientation of sensitivity axes of single sensors in redundant noncollinear configuration requires solving two basic tasks. The first task is a choice of the orientation parameters, which define a position of sensitivity axes of an inertial sensor relative to the inertial reference frame. In other words, these orientation parameters determine a mutual position of measuring and inertial reference frames.

As parameter orientation can be used directional cosines, Euler angles, Hamilton Rodrigue parameters (quaternions), Cayley–Klein parameters.

There are four ways to form redundant noncollinear configurations of inertial sensors using a cone as symmetry figure [1]:

1) All n sensors are oriented along a cone's generatrices and symmetry axis along the measured vector. In this case, sensitivity axes are oriented along cone's generatrices through equal angles $\alpha = \frac{2\pi}{n}$ (Fig. 2).

2) The orientation of one of the sensors is located along cone's symmetry axis, and other (n – 1) sensitivity axes are located through equal angles $\alpha = 2\pi/(n-1)$ (Fig. 3).

3) Multi-cone location of the sensitivity axes with the integrated symmetry axis.

4) Multi-cone location of the sensitivity axes with the symmetry axes different for every cone.

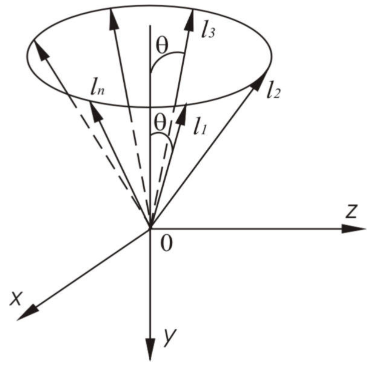

Fig. 2. Orientation of sensitivity axes along cone's generatrices through equal angles $2\pi/n$

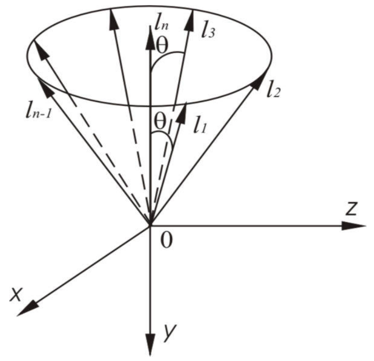

Fig. 3. The orientation of sensitivity axes along cone's generatrices through equal angles $2\pi/n$

It is known also the orientation of sensor measuring axes perpendicularly to facets of regular polyhedrons [1].

III. OPTIMAL ORIENTATION OF SENSORS IN REDUNDANT CONFIGURATIONS

Optimal orientation of redundant configurations of inertial sensors can be determined based on extremum of a chosen criterion. The approach to the choice of a criterion is achieving the highest accuracy, reliability, and also resistance to faults.

A number of equations using for optimization of the orientation of single sensors in the redundant configuration can be determined by the formula [1]

$$K = l/(n/n_0), \tag{1}$$

where l is a number of orientation parameters; n is a number of sensors; n_0 is a dimension of the inertial reference frame.

In the case of using such orientation parameters as directional cosines in the three-dimensional reference frame, the quantity of equations necessary for optimization in accordance with (1) is

$$K_{\text{opt}} = 3n.$$

For Euler angles this quantity on the basis of (1) becomes

$$K_{\text{opt}} = n.$$

The quantity of optimized equations decreases due to constraint caused by the necessary orthogonality of sensitivity axes in separate triples of sensors.

In the case of quaternions using and the three-dimensional reference frame, the number of equations necessary for optimization taking into consideration (1) can be represented in the form

$$K_{\text{opt}} = 4n/3.$$

It should be noted that in the case of quaternions, it is necessary to use four parameters for the determination of the orientation of every sensor.

To simplify the process of optimization of orientation is possible using two ways. The first way is using the symmetrical orientation of sensors relative to each other and the inertial reference frame. The second way to simplify the problem of optimal orientation of sensors in redundant configurations is using symmetrical schemes with the common origin of a sensor's sensitivity axes.

The problem of optimal orientation of sensors in redundant configuration can be solved on the basis of estimated variances of components of the measured vector in the inertial reference frame.

Optimal orientation of a sensor's sensitivity axes can be determined based on minimization of errors. The correlation matrix of errors can be determined as [1]

$$\mathbf{R} = (\mathbf{H}^{\mathrm{T}}\mathbf{H})^{-1}\mathbf{H}^{\mathrm{T}}. \tag{2}$$

One of the possible criteria of achieving accuracy can be the trace of the matrix (2), which represents a sum of its diagonal elements or variances of errors

$$\mathrm{tr}(\mathbf{R}) = \sum_{i=1}^{n} r_{ii}, \tag{3}$$

where r_{ii} are diagonal elements of the matrix $\mathbf{R}$; n is a number of sensors.

The expression (3) allows determining of optimal orientation of inertial sensors sensitivity axes in the noncollinear configuration.

IV. EXAMPLES OF ORIENTATION OF SENSORS IN REDUNDANT CONFIGURATIONS

Conversion by means of a matrix of directional cosines can be described by the expression

$$\mathbf{l} = \mathbf{H}\boldsymbol{\omega}, \tag{4}$$

where $[l_1\, l_2 \ldots l_n]^{\mathrm{T}}$ is the vector of projections of the angular rate, measured in the measuring reference frame; $\left[\omega_x\; \omega_y\; \omega_z\right]^{\mathrm{T}}$ is the vector of projections of the angular rate in the navigation reference frame; n is a number of sensors in the measuring instrument. The matrix $\mathbf{H}$ is called the matrix of transformation between the navigation reference frame and the redundant measuring frame.

Taking into consideration (4), the formula for angular rate determination can be represented in the following form [4]

$$\boldsymbol{\omega} = \mathbf{H}_{\mathrm{con}}^{-1}\mathbf{l}\,. \tag{5}$$

The expression for the pseudoinverse matrix $\mathbf{H}_{\mathrm{con}}^{-1}$ based on the Moore–Penrose algorithm can be written as follows

$$\mathbf{H}_{\mathrm{con}}^{-1} = \mathbf{R} = (\mathbf{H}^{\mathrm{T}}\mathbf{H})^{-1}\mathbf{H}^{\mathrm{T}}\,. \tag{6}$$

The expressions (5), (6) can be used for determination of the angular rate by means of a redundant noncollinear configuration of inertial sensors.

Using the basic laws of the analytic mechanics for Euler angles, the expressions for determination of directional cosines of the nonorthogonal configuration based on such a construction unit as the triangular pyramid can be described by the following expressions [9]

$$\begin{aligned} \mathbf{D}_1 &= \mathbf{A}_x, & \mathbf{D}_2 &= \mathbf{A}_{y1}\mathbf{A}_z\mathbf{A}_y, \\ \mathbf{D}_3 &= \mathbf{A}_{y2}\mathbf{A}_z\mathbf{A}_y, & \mathbf{D}_4 &= \mathbf{A}_{y3}\mathbf{A}_z\mathbf{A}_y, \end{aligned} \tag{7}$$

here $\mathbf{D}_1, \mathbf{D}_2, \mathbf{D}_3, \mathbf{D}_4$ are matrices of directional cosines between axes of the navigational reference frame and the reference frame of the inertial measuring unit. The matrix $\mathbf{A}_x$ in the formula (7) defines axes of the inertial measuring unit located at the base of the triangular pyramid. The matrix $\mathbf{A}_x$ characterizes tilt of inertial measuring units located on the side faces relative to the horizontal plane. Matrices $\mathbf{A}_{y1}, \mathbf{A}_{y2}, \mathbf{A}_{y3}$ in (7) define a location of axes of inertial measuring units relative to previous axes. The matrix $\mathbf{A}_y$ in (7) is defined by axes of inertial measuring units located on the side faces along their medians.

V. MATHEMATICAL MODEL OF INERTIAL SENSOR

During simulation of inertial sensors based on MEMS technology, it is convenient to use a model in the form of the transfer function [11]

$$W(p) = \frac{\omega^2}{p^2 + 2\xi\omega p + \omega^2}, \tag{8}$$

here ω is a frequency of the bandwidth; ξ is the damping coefficient.

The model of MEMS sensor must include transfer function (8), saturation by measuring range and the error of the scale factor 1% by means of gain variation 1.01 (0.999)

The model also includes random errors of measurement, which are based on the white noise, that is signal with the constant spectral density $S(\omega) = N$. In this case, the variance of the random signal can be represented in the form $D = N\Delta\omega$, here $\Delta\omega$ is the bandwidth. The spectral density of signal power can be determined based on the formula $N = D/\Delta f$. To determine a random error due to input noise the following parameters are used $\mathrm{PSD} = \frac{\sigma^2}{\Delta\omega}$, here PSD is the power spectral density; σ is root-mean-square measured in degree per second; $\Delta\omega$ is the bandwidth, Hz. Sample time is defined as $1/\Delta\omega$. It should be noted that a developer usually represents a value of the output noise of MEMS-gyros in terms of standard deviation (σ). This simplifies the representation of the error in the model.

The studied model must also take into consideration a random error caused by the output noise, bias, coefficient of temperature bias (for temperature increment 1 $^{\circ}$C).

Modern inertial navigation systems use digital sensors. Therefore the general model of the inertial sensor must include quantizer. Nowadays the high-precision sensors with the high information capacity (32 bits) are produced. In this case, we can neglect with quantizer without decrease of reliability of simulation results.

The model of an inertial sensor based on performances of the rate gyroscope ADIS16488 (Analog Devices) is represented in [12].

VI. PROCESSING OF REDUNDANT INFORMATION

There are three basic stages of redundant information processing such as conversion of the primary information, noise filtering, and search of faults.

The first stage can be implemented in two ways. Firstly, the problem of redundant information conversion of n sensors can be written as the definition of n components of measured vectors [1]

$$\mathbf{V}_e = \mathbf{C}\mathbf{V}_m + \boldsymbol{\varepsilon}, \tag{9}$$

where $\mathbf{V}_e$ is a vector of estimated projections of dimension n; $\mathbf{C}$ is a conversion matrix of dimension $n \times n$; $\mathbf{V}_m$ is a vector of measured values; $\boldsymbol{\varepsilon}$ is a vector of errors of dimension n.

Estimation of vector components (9), for example, projections of the angular rate or acceleration, can be carried out based on dependences

$$\begin{aligned} \hat{V}_x &= f(V_{1x}, V_{2x}, \ldots, V_{nx}), \\ \hat{V}_y &= f(V_{1y}, V_{2y}, \ldots, V_{ny}), \\ \hat{V}_z &= f(V_{1z}, V_{2z}, \ldots, V_{nz}). \end{aligned} \tag{10}$$

To solve the task (10) is possible using some approaches, for example, determination of a mean value, a weighted mean value, and a median.

In the case of the determination of a mean value, an algorithm of information processing looks like [13]

$$\hat{V}_{ij} = \frac{1}{n} \sum_{i=1}^{n} V_{ij}, \qquad j = x, y, z. \tag{11}$$

It is possible to improve accuracy of the algorithm (11) by means of weighting coefficients

$$\hat{V}_{ij} = \sum_{i=1}^{n} \lambda_i V_{ij},, \tag{12}$$

where $\lambda_i = \frac{1/D_i}{\sum_{i=1}^{n} 1/D_i}$, D_i is variance of ith sensor.

In some practical situations, it is convenient to use averaging by means of the median algorithm

$$V_1 < V_2 < \ldots < V_{(n+1)/2} < \ldots < V_{n-1} < V_n. \tag{13}$$

The first approach to processing of redundant information foresees division of redundant vector space into separate nonredundant measuring instrument as follows from relationships (11) – (13).

Secondly, processing information about vectors can be used. In the general case, the number of measured values is greater than the number of estimated values. Hence, a number of unknown variables is less than a number of equations. This situation can be explained in the following way. The dimension of the measured vector exceeds the dimension of the estimated vector. Therefore the unique solution is absent in the generalized case. Nevertheless, a unique solution can be obtained on the basis of some chosen criterion, which provides achieving a solution optimal for the above-mentioned criterion.

One of the most widespread criteria applicable for processing of redundant information is maximum of a posteriori probability and maximum likelihood function. It should be noted that using this approach requires known a posterior probability density.

In the particular case, for the normal distribution law and known a priori information, the formula for estimation of vector components on the basis of likelihood function becomes [14]

$$\hat{V}_j = \frac{1}{n} \sum_{i=1}^{n} V_{ij}. \tag{14}$$

Another way is usy of the least-squares method. A solution can be represented in the following form [14]

$$\hat{\mathbf{V}} = \mathbf{H}_{\text{inv}} \mathbf{V}, \tag{15}$$

where $\mathbf{H}$ is the pseudo-inverse Penrose Moore matrix (2).

It should be noted that the least-squares method has some disadvantages. For example, it has restrictions on attenuated noise such as zero mean, Gaussian noise, equal variances of the noise. To improve this situation it is possible using the weighted least-squares method

$$\hat{\mathbf{V}} = (\mathbf{H}^{\mathrm{T}} \mathbf{R}^{-1} \mathbf{H})^{-1} \mathbf{H}^{\mathrm{T}} \mathbf{R}^{-1} \mathbf{V}. \tag{16}$$

The relationships (14) – (16) represent algorithms of redundant information processing.

The search for faults can be implemented on the basis of neural networks. In this case, the three-layered perceptron can be used as a neural network. Learning of the perceptron can be implemented by means of measurement results.

The neural network scheme is given in Fig. 4.

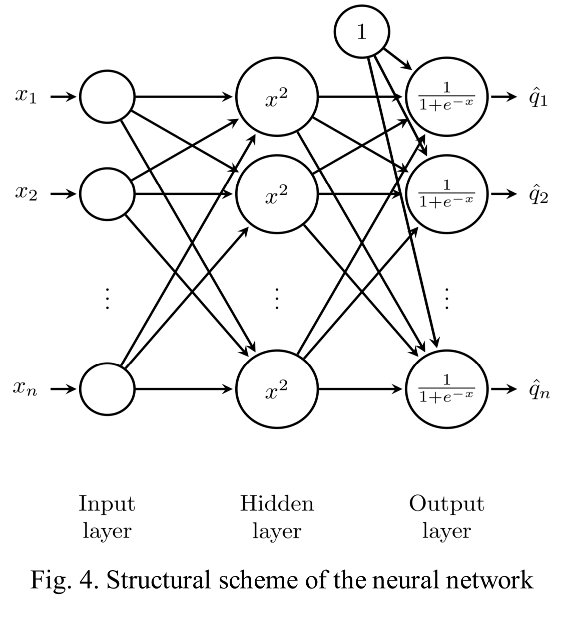

Fig. 4. Structural scheme of the neural network

An assessment of *i*th measured value can be done on the basis of expression

$$\Delta_j = x_j - \frac{1}{n-1}\sum_{\substack{i=1\\ i\neq j}}^{n} x_i . \tag{17}$$

Based on (17) it is possible to choose a quadratic criterion ε, for which $\Delta_j^2 - \varepsilon^2 \leq 0$. This criterion provides an assessment of the threshold value. As activation function the sigma function $f(x) = \dfrac{1}{1+e^{-x}}$ can be used.

VII. CONCLUSIONS

The basic problems of design of redundant noncollinear configurations are formulated. The basic approaches to solving these problems are given. The ways of determination of sensors axes sensitivity axes in the redundant noncollinear configuration are analyzed. The algorithms of determination of kinematical parameters based on the maximum of a posteriori probability density and least-squares method are represented.

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О. А. Сущенко, В. О. Голіцин. Основні проблеми проектування надмірних неколінеарних конфігурацій інерціальних датчиків

В статті представлено основні проблеми проектування надмірних неколінеарних інерціальних вимірювачів на основі мікроелектромеханічних технологій. Представлено аналіз неколінеарних конфігурацій інерціальних датчиків. Надано підхід до розроблення математичної моделі інерціального датчика. Обговорено основні проблеми оброблення надмірної інформації. Досліджено проблему оптимальної орієнтації чутливих осей інерціальних датчиків в неколінеарних конфігураціях. Представлено підходи до перетворення надмірної вимірювальної інформації в проекції кінематичних параметрів рухомих об’єктів. Розглянуто можливості використання критеріїв максимуму апостеріорної ймовірності і найменших квадратів. Запропоновано шляхи вирішення вищезгаданих проблем. Отримані результати можуть бути корисними для інерціальних вимірювальних пристроїв широкого класу.

Ключові слова: інерціальний датчик; обробка інформації; неколінеарна конфігурація; швидкісний гіроскоп; надмірність.

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О. А. Сущенко, В. А. Голицин. Основные проблемы проектирования избыточных неколлинеарных конфигураций инерциальных датчиков

В статье представлены основные проблемы проектирования избыточных неколлинеарных инерциальных измерителей на основе микроэлектромеханических технологий. Представлен анализ неколлинеарных конфигураций инерциальных датчиков. Дан подход к разработке математической модели инерциального датчика. Обсуждены основные проблемы обработки избыточной информации. Изучена проблема оптимальной ориентации чувствительных осей инерциальных датчиков в неколлинеарных конфигурациях. Представлены подходы к преобразованию избыточной измерительной информации в проекции кинематических параметров подвижных объектов. Рассмотрены возможности использования критериев максимума апостериорной вероятности и наименьших квадратов. Предложены пути решения упомянутых выше проблем. Полученные результаты могут быть полезными для инерциальных измерительных устройств широкого класса.

Ключевые слова: инерциальный датчик; обработка информации; неколлинарная конфигурация; скоростной гироскоп; избыточность.

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