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[1]O. A. Sushchenko,
[2]Y. M. Bezkorovainyi,
[3]V.O. Golitsyn

RESEARCH OF PRECISION OF NON-COLLINEAR INERTIAL MEASUREMENT DEVICES

Faculty of Air Navigation, Electronics and Telecommunications, National Aviation University, Kyiv, Ukraine
E-mails: [1]sushoa@ukr.net ORCID 0000-0002-8837-1521, [2]yurii.bezkor@gmail.com, [3]vova.gol@ukr.net

Abstract**—***The non-collinear measurement devices based on the inertial triaxial devices, and structural units such as the triangular, and quadrangular polyhedrons are presented. The corresponding matrices of guide cosines are obtained. In contrast to the known non-collinear measurement devices, the measurements of all sensors that are part of the triaxial devices are taken into account. A description of the relative position of the measurement axes of the individual sensors in the proposed measurement devices is given. Theoretical estimation of non-collinear measurement devices of MEMS-sensors on the basis of uniaxial and triaxial angular velocity meters using correlation matrices of measurement errors is obtained. The obtained results are useful because they are aimed at providing high-precision and reliable measurements that is important for unmanned aerial vehicles, which are currently widely used in Ukraine.*

Index Terms—Cosine guides; inertial sensor; non-collinear measurement device; measurement error; precision.

I. INTRODUCTION

Today, sensors based on microelectromechanical systems (MEMS sensors) are widely applied in the fields of navigation and motion control. Among these destinations, it is worth mentioning the control units of unmanned aerial vehicles and missiles designed to launch small artificial satellites into orbit. It should be noted that features of these applications are high requirements for precision and reliability of measurements. Given the use of modern MEMS sensors, ensuring these requirements requires additional measures.

Improving the reliability and precision of measurements can be provided through redundancy. It is known that it is possible to reserve both sensors of kinematic parameters (angular velocities, accelerations) of a moving object, and measurement bases. In the first situation, a triaxial orthogonal coordinate system is applied and the measurement axes of the sensors are oriented along the axes of this system. With this approach, the failure of two sensors can lead to the failure of the navigation system as a whole. The redundancy of measurement bases is based on the orientation of the measurement axes of the sensors along axes of a geometric shape.

The use of non-collinear measurement devices to increase the reliability and precision of measurements has a history [1]. Detailed descriptions of such measurement devices are contained in [2], [3]. The use of non-collinear redundant measurement devices of inertial navigation information meters based on MEMS sensors has some advantages. First, such measurement devices reduce the zero offset. It should be noted that the presence of zero offset is one of the important problems of functioning modern MEMS sensors. Therefore, the use of non-collinear redundant measurement devices increases the precision of navigation information measurements. Secondly, the reliability of measurements is significantly increased due to redundancy. Third, in this measurement device it is possible to place more sensors within the structural unit with the same dimensions. This advantage is useful even with the miniaturization of modern inertial sensors. An additional advantage is the ability to increase the fault tolerance of navigation systems. The urgency of work in this direction is due to the need to ensure high precision and reliability of navigation data in the motion control systems of unmanned moving objects.

II. ANALYSIS OF LITERATURE AND PROBLEM STATEMENT

Due to the recent development of unmanned aerial vehicles, the use of excessive, including non-collinear measurement devices of inertial sensors, has received considerable attention. Thus, in modern scientific periodicals it is noted that the use of excessive fault-tolerant inertial measurement units leads to a significant improvement in the precision and reliability of navigation measurements [4]. Accordingly, such measurement devices can be used to create inertial navigation systems, as presented in [5]. In unmanned aerial vehicles, it is advisable to apply inertial measurement units based on non-collinear measurement devices and this is justified in

[6]. Non-collinear redundant measurement devices of one-axis inertial sensors are presented in [7]. Theoretical assessment of precision and the corresponding comparative analysis of different non-collinear measurement devices are given in [8]. In the above-mentioned works, non-collinear devices include based on one-axis sensors [4] – [6], or on equally oriented inertial measurement units [7], [8]. Non-collinear measurement devices based on triaxial inertial measurement units with full use of measurement redundancy require further study. The problem of improving navigation precision is especially important for the control of unmanned moving objects, such as unmanned aerial vehicles, as justified in [9]. Possibilities of application of excessive measurement devices in fault-tolerant navigation systems are investigated in [10]. Using the redundancy of inertial meters (accelerometers), it is even possible to determine the spatial orientation of a moving object without the use of high-speed rate gyros, as it is represented in [11]. Sometimes redundant measurement data arises in accordance with the principle of operating the navigation meter. This situation occurs in the Coriolis vibration gyroscope [12]. But it is usually necessary to form excessive measurement devices of inertial sensors. In general, works [9], [11], [12] confirm the fact of the relevance of the use of redundancy of navigation measurements in the motion control systems of unmanned moving objects. The non-collinear measurement device of single triaxial MEMS sensors based on a triangular polyhedron is given in [13]. Approaches to the formation of such measurement devices on the basis of triangular and quadrangular polyhedrons and inertial measurement blocks are given in [14]. Thus, the study of issues related to the assessment of the possibility of using non-collinear redundant measurement devices for navigation applications, and the development of more reliable and accurate measures of primary navigation information should be considered promising. Improving the precision of inertial measurement units is of both scientific and practical importance due to their widespread use in unmanned aerial vehicle navigation facilities.

The objective of the researching is to estimate the precision of non-collinear measurement device based on both uniaxial inertial sensors and triaxial inertial measurement units using triangular and quadrangular polyhedrons as structural elements achieving the goal requires solving the following tasks interconnected problems:

- to research the measurement devices of MEMS sensors based on uniaxial inertial meters;- to present the results of research of non-collinear measurement device of MEMS-sensors on the basis of triaxial inertial measurement blocks using triangular and quadrangular polyhedra as structural units and to determine guide cosines for designed non-collinear measurement devices including inertial sensors;
- to describe the peculiarities of researching the precision of measurement the angular motion of the object using non-collinear excessive inertial meters;
- to perform theoretical and experimental evaluations of non-collinear measurement devices including MEMS sensors.

III. Features of Non-collinear Inertial Measurement Devices

There are several ways to create non-collinear measurement devices based on excessive measurement bases [2], [3]:

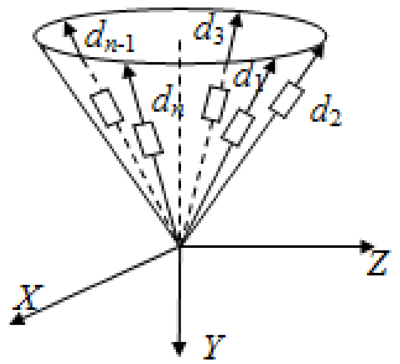
1) the use of the cone as a figure of geometric shape and the direction of the measurement axes of the MEMS sensors on the generators of the cone, as it is given in Fig. 1a;

2) the usage of the cone as a geometric shape which provides symmetry and the orientation of the measurement axes of the MEMS sensors on the generators of the cone and the symmetry axes in accordance with Fig. 1b;

3) the orientation of the measurement axes of the sensors perpendicular to the sides of the polyhedra in accordance with Figs 1c and d.

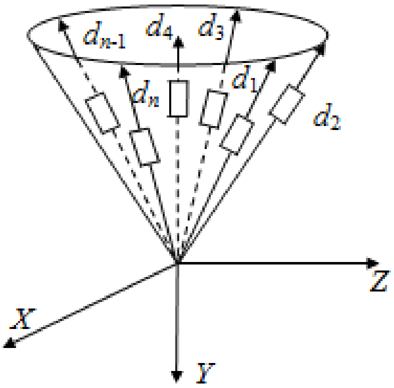
One of the main characteristics of non-collinear measurement devices of inertial sensors is the matrix of guide cosines. The angular velocity projections of a moving object on the axis of the navigation coordinate system can be indicated by ω_x, ω_y, ω_z.

The number of angular velocity projections on the axis of the measurement coordinate system is defined by the quantity of sensors in the device. The projections for a measurement device consisting of six sensors $d_1 - d_6$ can be denoted accordingly.



a)

Fig. 1. Non-collinear measurement devices: (a) is along the cone-forming; (b) is along the axis of symmetry and forming a cone; (c) is perpendicular to the sides of the tetrahedron; (d) is perpendicular to the sides of the dodecahedron



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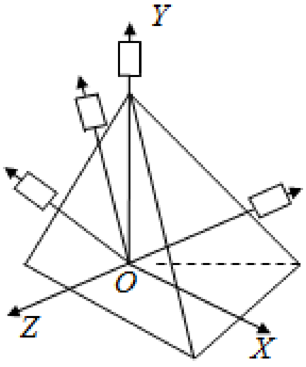

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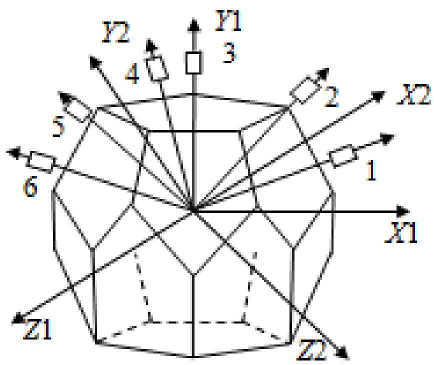


d)

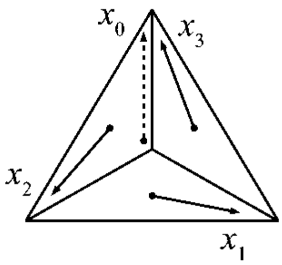
Fig. 1. Ending. (See also p. 70)

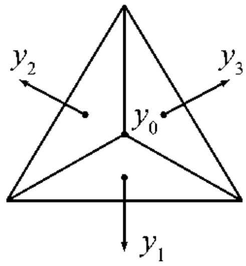
Guidance cosine matrices are needed to transform navigation information when determining the spatial orientation of a moving object. Therefore, the analysis of different non-collinear redundant measurement devices of MEMS sensors should include consideration of guide cosine matrices

IV. Guide Cosines

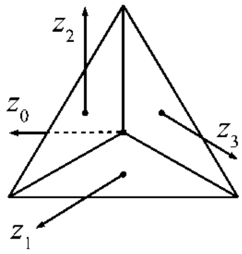
To determine the navigation information using non-collinear inertial meters, it is necessary to determine the navigation coordinate system *xyz* and the corresponding measurement coordinate systems. Typically, the axes of the navigation coordinate system along which the projections of the angular velocity with regard to the longitudinal, normal, and lateral axes of the aircraft are measured, are determined as follows. The y-axis is directed along the axis of symmetry of the polyhedron and is directed upwards. The *x*, *z* axes of the navigation coordinate system coincide with the corresponding axes of the inertial measurement device developed with using such a geometrical figure as the polyhedron.

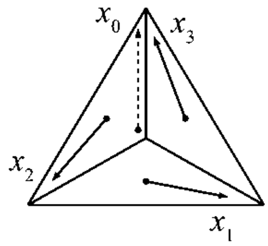
The orientation of the measurement axes is opposite to each other in order to increase the reliability of navigational information. These orientations are defined so that the angles between the axes are the largest. This reduces the zero offset when obtaining the angular rate projections onto navigation axes. The relative location of the axes of the measurement coordinate systems for individual inertial measurement blocks for such a structural unit as a triangular polyhedron is shown in Fig. 2.





a) b)





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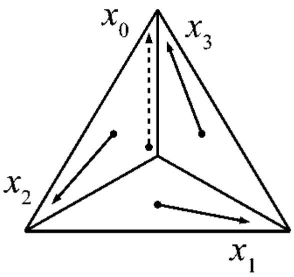

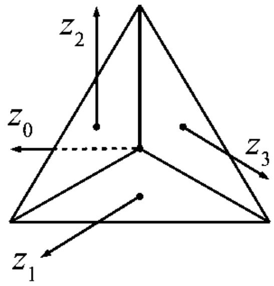

e) f)

Fig. 2. Location of measurement axes on sides of the triangular polyhedron: (a) is the view of axes x_0, x_1, x_2, x_3 from front; (b) is the view of axes y_0, y_1, y_2, y_3 from front; (c) is the view of axes z_0, z_1, z_2, z_3 from front; (d) is the view of axes x_0, x_1, x_2, x_3 from above; (e) is the view of axes y_0, y_1, y_2, y_3 from above; (f) is the view of axes z_0, z_1, z_2, z_3 from above

There are two ways to determine the matrices of the guide cosines. The first method is to determine the projections of a single vector based on geometric transformations. The second method is to determine the guide cosines between the navigation coordinate system and the measurement coordinate systems based on successive rotations at certain angle. The first method is based on fewer conversions and calculations, accordingly. The advantage of the second method is clarity. The additional complication of the operations of the second method is decreased by the automating the calculations using the MatLab system.

Based on the basic laws of analytical mechanics, the expressions for determining the guide cosines of the non-collinear measurement device on the basis of such a structural block as a triangular polyhedron are as follows

$$\mathbf{B}_1 = \mathbf{M}_X, \qquad \mathbf{B}_2 = \mathbf{M}_{Y1}\mathbf{M}_Z\mathbf{M}_Y,$$
$$\mathbf{B}_3 = \mathbf{M}_{Y2}\mathbf{M}_Z\mathbf{M}_Y, \quad \mathbf{B}_4 = \mathbf{M}_{Y3}\mathbf{M}_Z\mathbf{M}_Y, \qquad (2)$$

where $\mathbf{B}_1$, $\mathbf{B}_2$, $\mathbf{B}_3$, $\mathbf{B}_4$ are appropriate matrices of guide cosines between the axes of the navigation coordinate system and the axes of the coordinate system of the inertial meter. The matrix $\mathbf{M}_X$ defines axes of the inertial measurement device for such a geometry figure as a triangular polyhedron. The matrix $\mathbf{M}_Y$ characterizes the inclination of the measurement axes of inertial measurement blocks situated on the sides of the polyhedron in the horizontal reference frame. Matrices $\mathbf{M}_{Y1}$, $\mathbf{M}_{Y2}$, $\mathbf{M}_{Y3}$ define the location of axes of inertial measurement device with regard to the previous axes. The matrix $\mathbf{M}_Z$ defines axes of inertial sensors situated on lateral sides relatively medians at the slope of 120.0°. For a triangular polyhedron, the angle between the base and the side is 70.5°. The matrices that are parts of expression (1) can be written in this representation

$$\mathbf{M}_X = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix}, \ \mathbf{M}_Y = \begin{bmatrix} \cos\delta_0 & 0 & -\sin\delta_0 \\ 0 & 1 & 0 \\ \sin\delta_0 & 0 & \cos\delta_0 \end{bmatrix},$$

$$\mathbf{M}_{Y_i} = \begin{bmatrix} \cos\delta_i & 0 & -\sin\delta_i \\ 0 & 1 & 0 \\ \sin\delta_i & 0 & \cos\delta_i \end{bmatrix}, \ \mathbf{M}_Z = \begin{bmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{bmatrix}, \qquad (2)$$

where $i = 1,2,3$; $\alpha = 180°$; $\delta_0 = 120°$; $\delta_1 = 0°$; $\delta_2 = 120°$; $\delta_3 = 240°$; $\beta = 70.5°$; α is determined for the base of the polyhedron; δ_i determine angles of turn of lateral sides; δ_0 determines a slope of normal axes to the sides; β is the angle of the side slope.

Substituting the matrices (2) into expression (1), you can determine the relative position of the navigation and measurement coordinate systems. The table of guide cosines between the navigation coordinate system and the coordinate measurement systems of inertial blocks situated on the sides of the triangular polyhedron takes the form presented in Table I.

The position of the axes of the measurement systems of the coordinates of individual inertial measurement devices for such a structural element as a quadrangular polyhedron is presented in Fig. 3.

The guide cosines of a non-collinear measurement device based on a quadrangular polyhedron can be obtained as described above, taking into account that the tilt between the basis and a side equals 54.74°.

TABLE I. TABLE OF GUIDE COSINES FOR A MEASUREMENT DEVICE USING A TRIANGULAR POLYHEDRON AS A STRUCTURAL UNIT

Projection	φ_x	φ_y	φ_z
$c_1 = \varphi_{1x}$	1	0	0
$c_2 = \varphi_{1y}$	0	$\cos\gamma$	$-\sin\gamma$
$c_3 = \varphi_{1z}$	0	$\sin\gamma$	$\cos\gamma$
$c_4 = \varphi_{2x}$	$-\sin\delta_0\sin\delta_1 +$ $\cos\delta_0\cos\delta_1\cos\beta$	$-\sin\beta\cos\delta_1$	$\sin\delta_0\cos\delta_1\cos\beta +$ $\sin\delta_1\cos\delta_0$
$c_5 = \varphi_{2y}$	$\sin\beta\cos\delta_0$	$\cos\beta$	$\sin\delta_0\sin\beta$
$c_6 = \varphi_{2z}$	$-\sin\delta_0\cos\delta_1 -$ $\sin\delta_1\cos\delta_0\cos\beta$	$-\sin\alpha$	$-\sin\delta_0\sin\delta_1\cos\beta +$ $\cos\delta_0\cos\delta_1$
$c_7 = \varphi_{3x}$	$-\sin\delta_0\sin\delta_2 +$ $\cos\delta_0\cos\delta_2\cos\beta$	$\cos\alpha$	$\sin\delta_0\cos\delta_2\cos\beta +$ $\sin\delta_2\cos\delta_0$
$c_8 = \varphi_{3y}$	$\sin\beta\cos\delta_0$	$\cos\beta$	$\sin\delta_0\sin\beta$

$c_9 = \varphi_{3z}$	$-\sin\delta_0\cos\delta_2 -$ $\sin\delta_2\cos\delta_0\cos\beta$	$\sin\delta_2\sin\beta$	$-\sin\delta_0\sin\delta_2\cos\beta +$ $\cos\delta_0\cos\delta_2$
$c_{10} = \varphi_{4x}$	$-\sin\delta_0\sin\delta_3 +$ $\cos\delta_0\cos\delta_3\cos\beta$	$-\sin\beta\cos\delta_3$	$\sin\delta_0\cos\delta_3\cos\beta +$ $\sin\delta_3\cos\delta_0$
$c_{11} = \varphi_{4y}$	$\sin\beta\cos\,\delta_0$	$\cos\beta$	$\sin\delta_0\sin\beta$
$c_{12} = \varphi_{4z}$	$-\sin\delta_0\cos\delta_3 -$ $\sin\delta_3\cos\delta_0\cos\beta$	$\sin\delta_3\sin\beta$	$-\sin\delta_0\sin\delta_3\cos\beta +$ $\cos\delta_0\cos\delta_3$

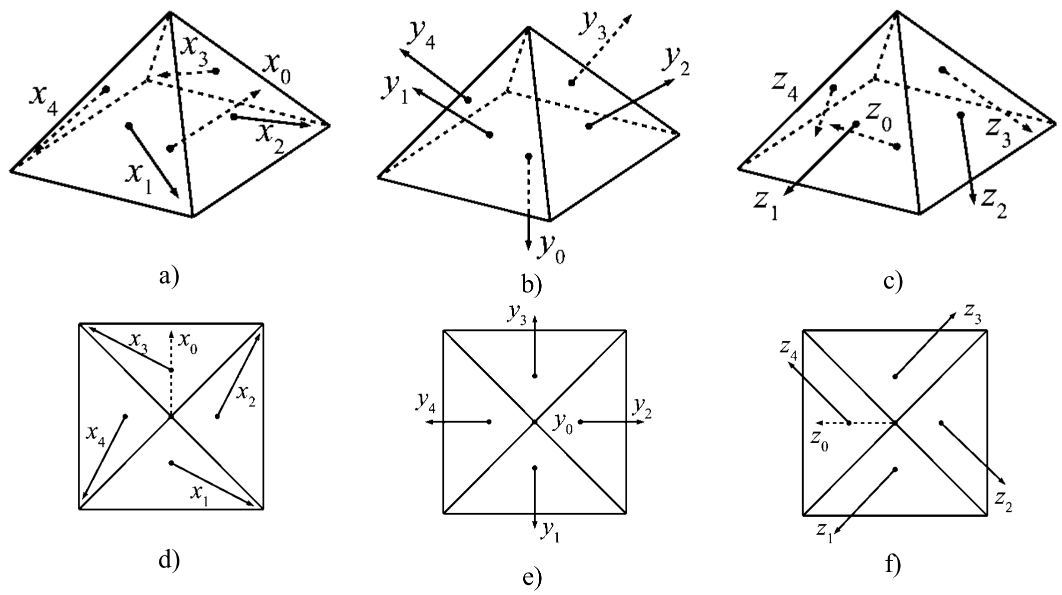

Fig. 3. Position of axes of measurement systems of coordinates on sides of the quadrangular polyhedron: (a) is the view of axes x_0, x_1, x_2, x_3, x_4 from front; (b) is the view of axes y_0, y_1, y_2, y_3, y_4 from front; (c) is the view of axes z_0, z_1, z_2, z_3, z_4 from front; (d) is the view of axes x_0, x_1, x_2, x_3, x_4 from above; (e) is the view of axes y_0, y_1, y_2, y_3, y_4 from above; (f) is the view of axes z_0, z_1, z_2, z_3, z_4 from above

Guide cosines of a non-collinear redundant measurement device based on such a structural element as a quadrangular polyhedron can be determined in the following way

$$\mathbf{B}_1 = \mathbf{M}_X,\quad \mathbf{B}_2 = \mathbf{M}_{Y1}\mathbf{M}_Z\mathbf{M}_Y,\quad \mathbf{B}_3 = \mathbf{M}_{Y2}\mathbf{M}_Z\mathbf{M}_Y,$$
$$\mathbf{B}_4 = \mathbf{M}_{Y3}\mathbf{M}_Z\mathbf{M}_Y,\qquad \mathbf{B}_5 = \mathbf{M}_{Y4}\mathbf{M}_Z\mathbf{M}_Y. \tag{3}$$

In formulas (3), matrix $\mathbf{M}_X$ determines the orientation of the inertial measurement units located on the basis of a quadrangular polyhedron. Slope ϑ is defined as 54.7 °. It allows us to determine the tilt of the side to the base of the quadrangular polyhedron. Angles ψ_i define the orientation of axes of measurement system of the coordinates located on the sides. They are equal to 0°, 90°, 180°, and 270°, respectively.

The information about guide cosines (numerical values) for non-collinear redundant measurement device using the quadrangular polyhedron as a structural element is given in Table II.

TABLE II. TABLE OF GUIDE COSINES (QUADRANGULAR POLYHEDRON)

Projection	ω_x	ω_y	ω_z
$c_1 = \varphi_{1x}$	1	0	0
$c_2 = \varphi_{1y}$	0	–1	0
$c_3 = \varphi_{1z}$	0	0	–1
$c_4 = \varphi_{2x}$	–0.289	–0.816	–0.500
$c_5 = \varphi_{2y}$	–0.409	0.577	–0.707
$c_6 = \varphi_{2z}$	0.866	0	0.5
$c_7 = \varphi_{3x}$	0.866	0	0.5

Projection	ω_x	ω_y	ω_z
$c_8 = \varphi_{3y}$	–0.408	0.577	–0.707
$c_9 = \varphi_{3z}$	0.289	0.816	0.5
$c_{10} = \varphi_{4x}$	0.866	0	0.5
$c_{11} = \varphi_{4y}$	–0.408	0.577	–0.707
$c_{12} = \varphi_{4z}$	0.2887	0.816	0.5
$c_{13} = \varphi_{5x}$	–0.86603	0	0.5
$c_{14} = \varphi_{5y}$	–0.410	0.577	-0.707
$c_{15} = \varphi_{5z}$	–0.289	–0.816	-0.5

It should be noted that in this case the expressions for determining the guide cosines are simpler in comparison with the measurement device with a structural block based on a triangular polyhedron.

V. Research of Precision of Non-collinear Measurement Instruments

Application of the non-collinear redundant measurement device including MEMS sensors needs the measured information to be converted. This is performed in the non-collinear reference frame. Measured information is converted into data in the orthogonal system of coordinates. This operation can be defined by the matrix transformation **H**.

In order to process the redundant information, the least square method can be applied [2], [3]. The minimal trace of the correlation error matrix is used as the objective function in this situation, thus it is assumed that the statistic performances of the measured parameter are independent and their mean is zero value. In case these presumptions are true, the error correlation matrix can be calculated by the formula [3]

$$\mathbf{D} = [\mathbf{H}^{\mathrm{T}}\mathbf{H}]^{-1}. \qquad (4)$$

The matrix trace **D** is defined by addition of diagonal elements. These elements represent dispersions of measurement errors [3]

$$tr(\mathbf{D}) = \sum_{i=1}^{n} d_{ii}, \qquad (5)$$

here d_{ii} are the diagonal elements of the matrix **D**; n is sensors' quantity.

Expressions (4), (5) in correspondence with [2], [3] can be the basis of theoretical research of the precision of non-collinear redundant measurement devices including inertial sensors. If the non-collinear measurement device consists of six sensors situated in accordance with the cone's forming, the correlation matrix of errors can be written as

$$\mathrm{trace}[\mathbf{H}^{\mathrm{T}}\mathbf{H}]^{-1} = \mathrm{trace}\begin{bmatrix} 0.50 & 0 & 0 \\ 0 & 0.50 & 0 \\ 0 & 0 & 0.50 \end{bmatrix} = 1.50.$$

The results of the theoretical research of precision for non-collinear measurement devices of one-axis sensors by formulae (4), (5) can be analyzed from Table III. It gives information on errors for various non-collinear redundant measurement device for differing cases of faults.

Theoretical research of precision of non-collinear measurement devices based on inertial MEMS units can be seen in Table IV.

TABLE III. RESULTS OF THEORETICAL RESEARCH OF NON-COLLINEAR MEASUREMENT DEVICES OF ONE-AXIS INERTIAL UNITS

Type of measurement device	**Characteristic of errors**		
	Without faults	***Faults of 2 sensors***	***Faults of 3 sensors***
5 sensors and the cone geometry unit	2.2	3.2	3.9
6 sensors and the cone geometry unit	1.8	2.1	4.5
4 sensors and the cone geometry unit including the axis of symmetry	1.9	3.1	5.0
5 sensors and the cone geometry unit including the axis of symmetry	1.7	2.2	3.3
6 sensors and the dodecahedron geometry unit	1.5	2.0	3.0

TABLE IV. RESULTS OF COMPARATIVE ANALYSIS OF NON-COLLINEAR MEASUREMENT DEVICES BASED ON INERTIAL MEASUREMENT UNITS

Non-collinear measurement device	Trace as error characteristic
Collinear measurement instrument	1.0
Measurement instrument based on the triangular polyhedron	0.55
Measurement instrument based on the quadrangular polyhedron	0.23

The results represented in Table IV prove advantages on the precision of the non-collinear redundant measurement device using the quadrangular polyhedron.

VI. CONCLUSIONS

The analysis of non-collinear inertial measurement instruments on the basis of uniaxial MEMS sensors has been performed and the corresponding matrices of guide cosines were obtained.

Matrixes of guide cosines, which provide transforming measurement information into navigation one for non-collinear measurement devices grounded on triangular and quadrangular polyhedra, have been also obtained.

Research of precision of non-collinear measurement devices based on one-axis and three-axis MEMS sensors using correlation matrices of errors has been carried out.

The comparative analysis for non-collinear redundant inertial instruments based on triangular and quadrangular polyhedrons has been implemented.

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Sushchenko Olha. orcid.org/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

Bezkorovainyi Yurii. Candidate of Engineering. Associate Professor.
Faculty of Air Navigation, Electronics and Telecommunications, National Aviation University, Kyiv, Ukraine.
Education: National Aviation University, Kyiv, (2002).
Research area: control systems information-measurement devices.
Publications: 40.
E-mail:yurii.bezkor@gmail.com

Golitsyn Volodymir. Post-graduate student.
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

О. А. Сущенко, В. М. Безкоровайний, В. О. Голіцин. Досліження точності неколінарних інерціальних вимірювачів

Представлені неколінеарні конфігурації на основі інерціальних триосних приладів та конструктивних елементів у вигляді трикутних та чотирикутних пірамід. Отримані відповідні матриці напрямних косинусів. На відміну від відомих неколінеарних вимірювачів, враховуються вимірювання всіх датчиків, що входять до складу тривісних пристроїв. Дано опис взаємного розташування вимірювальних осей окремих датчиків у пропонованих конфігураціях. Отримано теоретичну оцінку точності неколінеарних вимірювальних приладів на основі одновісних та тривісних датчиків кутової швидкості з використанням кореляційних матриць похибок вимірювань. Отримані результати корисні, оскільки спрямовані на забезпечення високоточних та надійних вимірювань, що важливо для безпілотних літальних апаратів, які в даний час широко використовуються в Україні.

Ключові слова: напрямні косинуси; інерціальний датчик; неколінеарнй вимірювач; похибка вимірювання; точність.

Сущенко Ольга Андріївна. orcid.org/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

Безкоровайний Юрій Миколайович. Кандидат технічних наук. Доцент.
Факультет аеронавігації, електроніки та телекомунікацій, Національного авіаційного університету, Київ, Україна.
Освіта: Національний авіаційний університет, Київ, (2002).
Область досліджень: системи управління інформаційно-вимірювальні прилади.
Публікації: 40.
E-mail:yurii.bezkor@gmail.com

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

О. А. Сущенко, Ю. Н. Безкоровайный, В. О. Голицин. Исследование точности неколлинеарных инерциальных измерителей

Представлены неколлинеарные конфигурации на базе инерциальных трехосных измерителей и конструктивных элементов в виде треугольных и четырехугольных пирамид. Получены матрицы направляющих косинусов. В

отличие от известных неколлинеарных измерительных приборов учитываются измерения всех датчиков, входящих в состав трехосных устройств. Дано описание взаимной ориентации измерительных осей отдельных датчиков в предлагаемых конфигурациях. Получена теоретическая оценка точности неколлинеарных измерительных приборов на основе одноосных и трехосных датчиков угловой скорости с использованием корреляционных матриц ошибок измерений. Полученные результаты полезны тем, что они направлены на обеспечение высокоточных и достоверных измерений, что имеет значение для беспилотных летательных аппаратов, широко используемых в Украине в настоящее время.
Ключевые слова: направляющие косинусы; инерциальный датчик; неколлинеарный измерительный прибор; погрешность измерения; точность.

Сущенко Ольга Андреевна. orcid.org/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: системы стабилизации информационно-измерительных устройств.
Количество публикаций: 250.
E-mail: sushoa@ukr.net

Безкоровайный Юрий Николаевич. Кандидат технических наук. Доцент.
Факультет аэронавигации, электроники и телекоммуникаций, Национального авиационного университета, Киев, Украина.
Образование: Национальный авиационный университет, Киев, (2002).
Область исследований: информационно-измерительные приборы.
Публикации: 40.
E-mail: yurii.bezkor@gmail.com

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