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FAULT-TOLERANCE RESEARCH OF NAVIGATIONAL NONORTHOGONAL MEASURING INSTRUMENTS

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Problems of fault-tolerance and possibilities of reliability growth of the nonorthogonal redundant navigational measuring instruments are studied.

Розглянуто питання відмовостійкості та можливості підвищення надійності неортогональних надмірних навігаційних вимірювачів.

Introduction

One of the modern navigational instrument-making trends typical for industrial countries of the whole world is creation of the complex navigation devices with functionalities being close to those of the inertial navigation systems but characterising significantly smaller dimensions and cost for their designing. Successful development of such trend is conditioned by appearance of the high-precision small-size navigation sensors, progress of computer engineering namely processing speedup and high-capacity memory, progress of the electronic devices [1].

Due to the first condition it is possible to include the attitude sensors and accelerometers in the navigational device for creation of a small-size system able to carry out functions of the inertial navigation system and to use redundancy for reliability growth. Presence of accelerometers in such systems provides correction and correspondingly higher accuracy of the attitude sensors as well as the possibility of the moving object's speed and path determination after appropriate integration [2].

Due to the second condition it is possible to realize sufficiently complex algorithms of navigation information processing as well as to increase accuracy of obtained information by the algorithmic means.

And finally due to the third condition it is possible to realize a complex process of high-precision sensors, electronics devices and computers integration. At the same time, increase of accuracy of the sensors being a part of the navigation system with simultaneous growth of their reliability stays one of the actual problems to be solved. In many cases, growth of reliability is connected with the equipment redundancy. At the same time, it is necessary to take into account the mass and dimension restrictions existing in spite of significant progress in miniaturization of the modern navigation sensors.

There are some approaches to application of redundancy in the navigation systems.

The most widespread approach is reservation of the sensors. In case of determination of the navigation parameter projections onto the axes of a basic navigation reference frame it is possible to use the redundant reference frames for reliability growth. Solution of such problem is of current importance for the modern navigational instrument-making, since information about the angular speed or the acceleration projections onto the axes of the navigational system is widely used in control laws of the modern moving objects.

Analysis of the latest publications

Basic approaches to use of the redundant measuring reference frames in the navigational systems are presented in [3; 4].

But now that significant progress has been achieved in the miniaturization of sensors and computing facilities, the development and analysis of the considered approach requires a special research. Increase of information processing speed in the modern navigation systems ensures the following advantages:

– the possibility to use the complex algorithms providing higher accuracy of information processing;
– the possibility to identify the failures of the separate navigation sensors;
– the possibility to change the reconfiguration of a measuring system taking into account these failures.

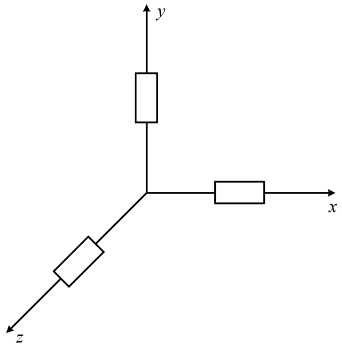
The goal of the study

The goal of this paper is to investigate the fault-tolerance of the navigational nonorthogonal redundant measuring instruments.

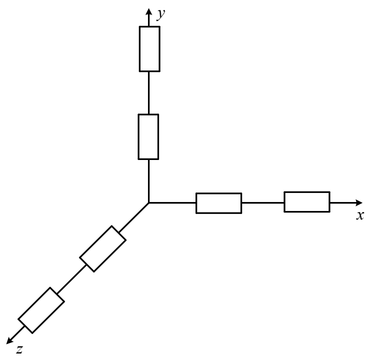
Research of the fault-tolerance of the nonorthogonal redundant systems

The standard problem statement of measurement of the navigational parameter projections is illustrated by fig. 1, *a*.

The possibility of growth of the system's reliability due to reduplication of the measuring instruments installed at every measuring axis is shown in fig. 1, *b*.



a



b

Fig. 1. The orthogonal (*a*) and the redundant (*b*) measuring systems

It worth to notice that, in spite of significant progress in the miniaturization of the navigation sensors, use of more than two measuring instruments installed along every measuring axis is not expedient due to restrictions of a mass and dimensions.

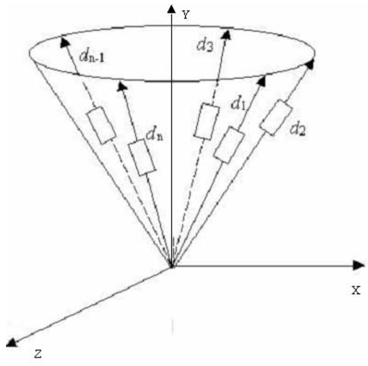
The scheme represented in fig. 1, *b* provides the navigation system's capacity for operation even in case of failures of three measuring instruments under condition, that these instruments lie at the different measuring axes. In other words, failure of two measuring instruments mounted at the same measuring axis, that is quite possible, leads to failure of the orthogonal redundant system of the navigation sensors.

To solve this problem is possible due to use of the nonorthogonal redundant measuring frames. It is known that there are three ways of building of such reference frames [3; 4]:

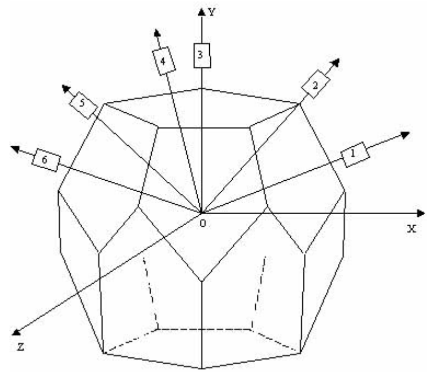
– use of a cone as a figure of symmetry and arrangement of the navigational sensors along the cone's generators as it is shown in fig. 2, *a*;

– use of a cone as a figure of symmetry and arrangement of the navigational sensors along the cone's generators and the axis of symmetry;

– arrangement of sensor sensitivity axes relative to the faces of regular polyhedrons in accordance with fig. 2, *b*.



a



b

Fig. 2. The nonorthogonal measuring system with arrangement of the sensors along the cone's generators (*a*) and relative to the faces of regular polyhedrons (*b*)

Use of the redundant measuring frames based on arrangement of the measuring sensors along the cone's generators and relative to the faces of regular polyhedrons allows to increase a number of redundant projections onto every axis of the basic reference frame. In the first place, such approach leads to growth of the system's reliability with lesser mass and dimensions. In the second place, it gives definite possibilities for increase of measuring information accuracy by means of redundant data processing algorithms. Besides, application of such reference frames allows to use algorithms of failed sensors detection to exclude them from the further process of information forming and processing.

Using the nonorthogonal reference frames, it is necessary to transform measuring information determined in the nonorthogonal reference frame into information in the orthogonal reference frame which coincides with the moving body-axis system. Such transformation provides control of the moving object. It may be described by the matrix of the directional cosines **L**.

This matrix error may be determined in accordance with the formula $\mathbf{D}=[\mathbf{L}_T\mathbf{L}]^{-1}$ [3]. The error of the transformation is characterized by the trace of the matrix $\mathbf{D}$.

To prove effectiveness of using of the nonorthogonal redundant systems is possible comparing the matrices of the directional cosines of the orthogonal system represented in fig. 1, *a* and the system consisting of sensors arranged along the cone's generators (fig. 2, *a*).

The matrix of the directional cosines of the orthogonal system is represented in the tab. 1.

Table 1

The matrix of the directional cosines of the orthogonal system

	x	y	z
d_1	cos 0	0	0
d_2	0	cos 0	0
d_3	0	0	cos 0

The matrix of the directional cosines of the nonorthogonal system consisting of the six sensors arranged along the cone's generators $\mathbf{L}_2$ may be determined in the following way (tab. 2).

Table 2

The matrix of the directional cosines of the nonorthogonal system, $\theta = 54^{\circ}44'$

	x	y	z
d_1	0	$\cos\vartheta$	$\sin\vartheta$
d_2	$\sin\pi/3\sin\vartheta$	$\cos\vartheta$	$\cos\pi/3\sin\vartheta$
d_3	$\sin\pi/3\sin\vartheta$	$\cos\vartheta$	$-\cos\pi/3\sin\vartheta$
d_4	0	$\cos\vartheta$	$-\sin\vartheta$
d_5	$-\sin\pi/3\sin\vartheta$	$\cos\vartheta$	$-\cos\pi/3\sin\vartheta$
d_6	$-\sin\pi/3\sin\vartheta$	$\cos\vartheta$	$\cos\pi/3\sin\vartheta$

Correspondingly, the traces of these matrices representing the criteria of information processing effectiveness look like:

$$\mathrm{tr}[\mathbf{L}_{1T}\mathbf{L}_1]^{-1} = \mathrm{tr}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = 3;$$

$$\mathrm{tr}[\mathbf{L}_{2T}\mathbf{L}_2]^{-1} = \mathrm{tr}\begin{bmatrix} 0{,}5 & 0 & 0 \\ 0 & 0{,}5 & 0 \\ 0 & 0 & 0{,}5 \end{bmatrix} = 1{,}5.$$

The comparative analysis of these criteria shows that the nonorthogonal redundant system provides higher accuracy of information processing.

We will consider the variant of failure of two navigation sensors in the nonorthogonal redundant system. The matrix of the directional cosines $\mathbf{L}_3$ for this variant is represented in the tab. 3.

Table 3

The matrix of the directional cosines

	x	y	z
d_1	0	$\cos\vartheta$	$\sin\vartheta$
d_3	$\sin\pi/3\sin\vartheta$	$\cos\vartheta$	$-\cos\pi/3\sin\vartheta$
d_5	$-\sin\pi/3\sin\vartheta$	$\cos\vartheta$	$-\cos\pi/3\sin\vartheta$
d_6	$-\sin\pi/3\sin\vartheta$	$\cos\vartheta$	$\cos\pi/3\sin\vartheta$

The trace of the matrix $\mathbf{D}$ looks like:

$$\mathrm{tr}[\mathbf{L}_{3T}\mathbf{L}_3]^{-1} = \mathrm{tr}\begin{bmatrix} 0{,}75 & 0 & 0 \\ 0 & 0{,}83 & 0 \\ 0 & 0 & 0{,}92 \end{bmatrix} = 2{,}5.$$

So, even taking into account the possibility of two sensors failure, the nonorthogonal redundant system is characterized by the better criterion of information processing.

Analysis of the possible variants of sensor orientation in the nonorthogonal redundant systems has been carried out in [5]. To research the fault-tolerance of the above stated systems we will consider the possibility of failure of one and two sensors correspondingly and estimate effectiveness of information processing for every variant. Results of this analysis are represented in the tab. 4.

Table 4

The fault-tolerance of redundant systems

Sensors	1	2	3
5 sensors along the cone's generators	2,21	3,20	3,92
4 sensors along the cone's generators, 1 along the axis of symmetry	1,93	3,15	5,00
6 sensors along the cone's generators	1,79	2,13	4,50
5 sensors along the cone's generators, 1 along the axis of symmetry	1,70	2,18	3,35
6 sensors along the dodecahedron	1,50	2,00	3,00

In the tab. 4 the first, second and third columns correspond to the following situations: all sensors are able to operation, one sensor is failed, two sensors are failed.

Now we will analyse possibilities of the system's reliability growth due to using of the nonorthogonal redundant systems (fig. 3).

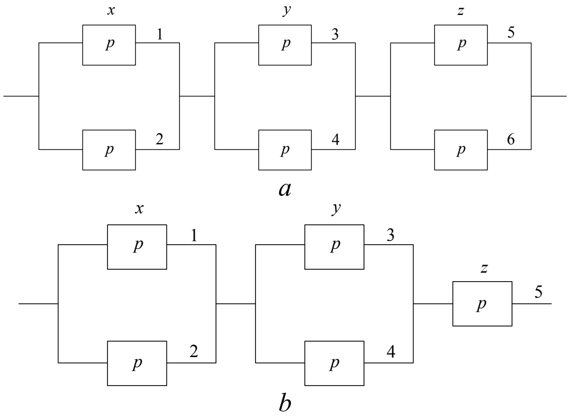


Fig. 3. The functional scheme for calculation of the orthogonal redundant system's reliability:
a is all the sensors are able for operation;
b is one sensor is failed;
1, 2, 3, 4, 5, 6 are numbers of the sensors;
x, y, z are notations of the projections onto the body-axis reference frame;
p is the reliability probability of every sensor

Supposing that the reliability probability of every sensor is the same, we will obtain the following expressions for determination of the system's reliability probability:

$P_c(t) = \left[1-(1-p)^2\right]^3$ — all the sensors are able for operation;

$P_c(t) = p\left[1-(1-p)^2\right]^2$ — failure of one sensor;

$P_c(t) = p^2\left[1-(1-p)^2\right]$ — failure of two sensors;

$P_c(t) = p^3$ — failure of three sensors.

The functional scheme for reliability calculation of the nonorthogonal redundant system consisting of six sensors oriented along the cone's generators is represented in fig. 4.

In this case, the system's reliability probability may be described by the following formulae:

$P_c(t) = \left[1-(1-p)^4\right]\left[1-(1-p)^6\right]^2$ — all the sensors are able for operation;

$P_c(t) = \left[1-(1-p)^3\right]\left[1-(1-p)^5\right]^2$ — failure of one sensor at every measuring axis;

$P_c(t) = \left[1-(1-p)^2\right]\left[1-(1-p)^4\right]^2$ – failure of two sensors at every measuring axis;

$P_c(t) = p\left[1-(1-p)^3\right]^2$ – failure of three sensors at every measuring axis.

Analysis of the obtained formulae shows advantages of using of the nonorthogonal redundant systems for reliability growth. Redundancy of information provides the possibility of using of sufficiently complex algorithms of information processing. One of the most widespread algorithms provides detection of the navigation sensor with the maximal error to exclude it from the measuring system.

But analysis of the requirements to the modern navigation systems shows, that using of combination of the weighted mean algorithm and the median algorithm is the most preferable. In this case, the maximal and minimal errors of the navigational errors are determined. These values are excluded from the further process of information processing. The rest of values may be used for navigation parameter projections determination.

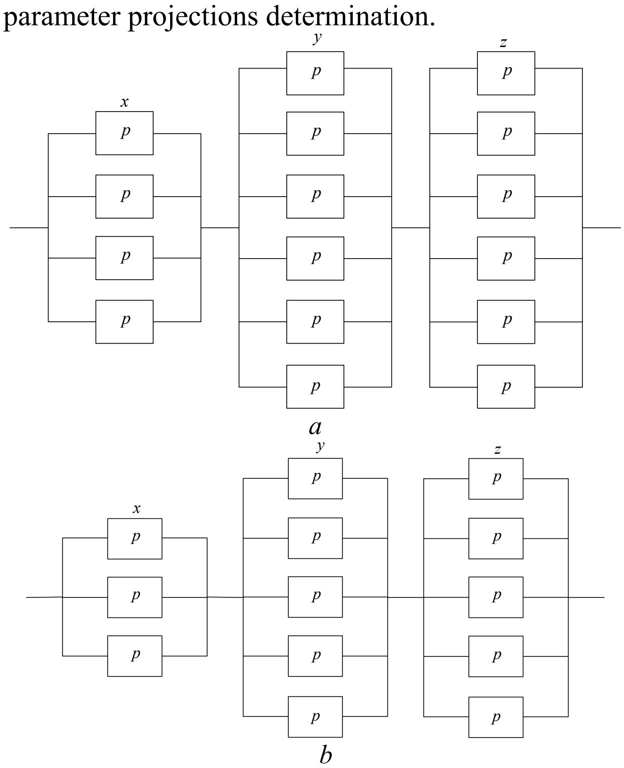


Fig. 4. The functional scheme for reliability calculation of the nonorthogonal redundant system:
a is all the sensors are able for operation;
b is one sensor is failed

Conclusions

Research of the failure-tolerance of the nonorthogonal redundant systems proves the possibility of their using for organization of high-accurate and reliable measurements.

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