CREATION OF ORIENTATION SYSTEMS FOR MOBILE ROBOTS *

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Abstract

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The paper considers the requirements for orientation systems (OS) of robotic complexes of different weights: very lightweight (wearable), light (portable), average and heavy (mobile). A task of decreasing mass, size and cost of OS for mobile robots is solved providing the given accuracy. The proposed OS construction schemes compared to SINS (strapdown inertial navigation systems) schemes allow for an optimal use of sensing elements (SE) potential accuracy capabilities due to SE rotations. The OS construction schemes are implemented so that the azimuth gyroscope in the frame of the gimbal provides azimuth measurement in the horizontal position and direction storage in the vertical position, whereas a pair of low-precision gyroscopes and accelerometers in the analytic gyrovertical scheme provides pitches generation and mechanical implementation of the horizon plane. Operation principles and instrumental composition of different OS variants are described in the paper. A new aspect of the present research is application of the Allan variance for the purpose of gyrocompassing time and accuracy improvement and SE error autocompensation when applying discrete rotations in the proposed OS construction schemes.

Introduction

Nowadays much work is in progress on the creation of mobile robots and robotic complexes for different purposes, such as terrain mining and demining, rescue operations, evacuation of injured persons, terrain and room inspection, etc.

Robotic complexes control is implemented by means of on-board topographic connection and orientation equipment including orientation systems (OS) of different accuracy.

OS developers are mostly concentrated on creation of strapdown inertial navigation systems (SINS). SINS are better than platform navigation systems in terms of absence of a complex electromechanical system (a gyrostabilized platform), decreasing of overall dimensions, mass and power consumption, lower cost and simplified integration with navigation systems having different operation principles (namely, satellite navigation systems).

Yet, SINS make higher requirements for sensing elements (gyroscopes and accelerometers) regarding their accuracy and wider range of parameters measured, they also make higher requirements for computing machinery.

Depending on carrier type (man, towed buggies, trailers, etc., wheel and track-type (in perspective legged) ground mobile objects) wearable, portable, towed, mobile robotic complexes are divided into several weight classes. Robotic complex weight greatly determines weight/size characteristics of the equipment applied and, consequently, determines a certain limit of onboard OS accuracy. This is explained by the fact that modern OS projects show a rather strict dependence: the greater are size, mass and cost of the OS, the higher is its accuracy.

On the other hand, characteristics of OS for different robotic complexes are determined depending on the required accuracy of navigation tasks performance and self-sufficient operation duration when carrying out tasks depending on robots operation conditions (indoors, city, forest, mountains, open territory, etc.)

Thus, the task of ground mobile robots creation demands development of some OS with different accuracy, mass, dimensions and cost, these characteristics being optimized.

1. Specifications of OS's for mobile robots

The analysis of creation of different-purpose mobile robots allows specifying OS devices as robotic complexes of different classes:

1) very lightweight robotic complex;
2) light robotic complex;
3) light reconnaissance robotic complex;
4) average multifunctional robotic complex;
5) station of robotic complexes remote control.

As to functional requirements, OS's for the mentioned robotic complexes must provide the following:

[1] Sector head.
[2] Lead engineer.

- initial orientation of the robot longitudinal axis;
- storage of initial orientation angle while standing and moving;
- definition of longitudinal and transversal pitches.

The main requirements for OS's according to performance requirements for equipment and devices of various robotic complexes are given in the following Table 1.

Table 1

Basic specifications of OS variants for various mobile robots

Specification \ OS variants	Very lightweight robotic complex	Light robotic complex	Light reconnaissance robotic complex	Average multifunctional robotic complex	Station of robotic complexes remote control
	1	2	3	4	5
Error of initial orientation of the robot longitudinal axis (3σ), °	0.60	0.48	0.36	0.24	0.48
Time of initial orientation, min	1	5	5	5	6
Storage of azimuth angle of the robot longitudinal axis for the traveling time of up to 0.5 h (σ), °	1.2	0.60	0.36	0.15	0.18
Error of longitudinal and transversal pitches definition (σ), °	0.60	0.36	0.24	0.12	0.12
Mass[1], kg	0.4	1.5÷2.0	5.0	10.0	10.0

[1] For the whole topographic connection and orientation equipment

2. Proposals for construction of OS's for advanced robotic complexes

The analysis of the Table data allows determining a tentative instrumental composition of OS's for different weight robots, optimal in terms of the sensing elements used:

for OS of very lightweight robotic complex– a MEMS gyroscope (MMG) and MEMS accelerometer (MMA) (without self-alignment mode);

for OS of light robotic complex – a small fiber-optic gyroscope (FOG), MMG, a small hemispherical resonator gyroscope (HRG), MMA;

for OS of light reconnaissance robotic complex – FOG, HRG, a mechanical pendulous accelerometer (PA), MMA;

for average multifunctional robotic complex OS – RLG, FOG, mechanical PA;

for point of robotic complexes remote control OS – FOG, HRG, mechanical PA, MMA.

It is possible to formalize the process of synthesizing new OS structures for robotic complexes using the method of basic gyroscopic elements [1].

Decomposition of existing gyroscopes and orientation systems structures allows defining the following devices as gyroscopic elements for classic platform gyrosystems, gyrocompasses, gyroverticals, etc. on classic gyromotors and for dynamically tuned gyroscopes (DTG): an azimuth gyroscope in a vertically-oriented suspension frame, an azimuth gyroscope in a horizontally-oriented suspension frame, a vertical gyroscope in a vertically-oriented suspension frame, a vertical gyroscope in a horizontal biaxial gimbal. Specific operation and control algorithms are developed for the basic gyroscopic elements. New gyroscopic devices structures on the basis of DTG having specified properties and characteristics are proposed in item [1] using the basic gyroscopic elements.

In regard of OS elements construction based on the SINS principle the mentioned basic gyroscopic elements are used in the same way. The only exception is that no continuous indicator stabilization of gimbal frames is applied during basic gyroscopic elements control, and a discrete change of SE arrangement is performed relative to the device casing. This fact causes simplification of actuator electromechanical elements, and at the same time (unlike using SINS) promotes optimal use of SE accuracy potential. To be more precise, it allows for SE error autocompensation, optimal SE orientation during operation in the specified mode (gyrocompassing, direction storage), reducing of high-precision SE (it is possible to apply one high-precision and two low-precision gyroscopes instead of three high-precision ones). At the same time the azimuth gyroscope in the frame of gimbal can perform azimuth measurement as well as direction storage, and a pair of low-precision gyroscopes and accelerometers in the analytic gyrovertical scheme provides pitches generation and instrument realization of the horizon plane.

The results of OS basic structures synthesizing by variants for different-weight robotic complexes are shown in Figs. 1 and 2.

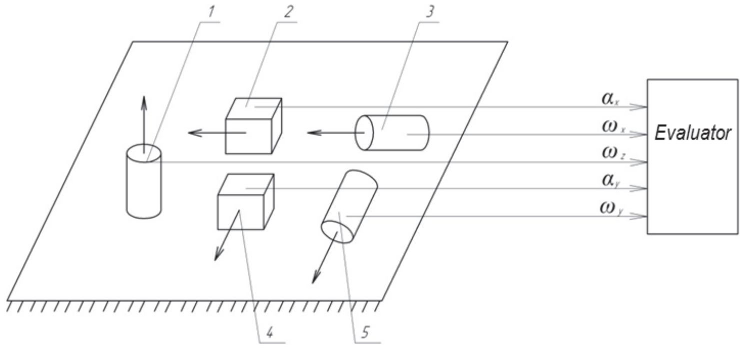

Fig.1. Elementary OS construction configuration without self-alignment mode for OS variants 1, 2 according to Table: 1 – MMG, small FOG, HRG; 2, 4 – MMA; 3, 5 – MMG, small HRG

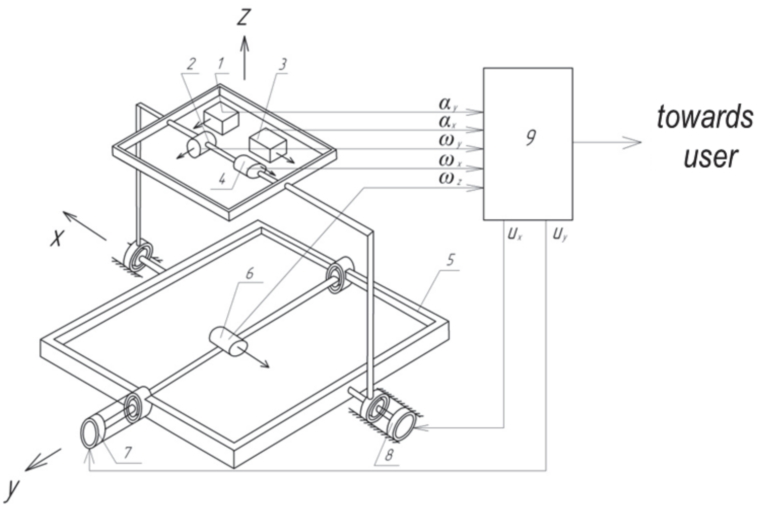

Fig.2. OS construction configuration with two rotating suspension frames with self-alignment mode with one orientable gyroscope for OS variants 3, 4, 5 according to Table

Functioning of the proposed OS structures is performed using reliable SINS algorithms [2, etc.]. They are not accented in this paper.

The scheme given in Fig.1 implies an elementary OS construction configuration without a self-alignment mode. This is explained by the fact that self-alignment mode implementation seems to be unpractical for very lightweight and light equipment (wearable, portable) in regard to existing SE parameters level (as in this case it causes substantial increasing of cost, dimensions and weight of this type OS). For these robotic complexes it seems reasonable to provide the only mode – the mode of direction storage and pitch angles determination. An initial orientation is rather to be performed by means of an azimuth transmission from a separate device.

The scheme given in Fig.2 implies OS construction configuration with two rotating suspension frames with a self-alignment mode with one orientable gyroscope. A high-precision angular sensor (AS) 6 is mounted on the inner frame axis. AS 6 is mounted in such a way that its sensitivity axis is perpendicular to the inner frame axis. Actuator 7 is mounted on the inner frame axis. The rotor of actuator 7 is connected to the inner frame, and the stator is mounted on outer frame 5. Outer frame 5 is mounted in the device casing with its axes. The second actuator 8 is mounted on the axis of suspension outer frame 5. The rotor of the second actuator 8 is connected to the axis of suspension outer frame 5, the stator being mounted in the OS casing. As a result, a high-precision AS 6 can rotate in the angular range of ±90º relative to longitudinal and transversal device axes relative to device base normal direction. Two accelerometers 1 and 3 as well as two low-precision AS 2 and 4 are mounted in the casing in such a way that their sensitivity axes are located in the base plane, sensitivity axes of one low-precision AS and one accelerometer being directed in the line of the suspension outer frame axis, and sensitivity axes of the second low-precision AS and the second accelerometer being directed perpendicularly. Angular velocity signals ω_x, ω_y, ω_z from AS and accelerations a_x, a_y from the accelerometers arrive to onboard evaluator 9. Control signals U_x, U_y arrive from onboard evaluator 9 to suspension actuators 7, 8. The proposed kinematic scheme and a set of sensing, microprocessor-based and load-bearing actuator elements (electromagnets) permit the following:

– gyrocompassing using the high-precision angular sensor and compensation of the systematic error component of the high-precision angular sensor (the sensor sensitivity axis is oriented in the device base plane in four various positions);

– compensation of a self-alignment error caused by object vibrations due to wind load, crew walking, etc. by vertical construction signals;

– mode of an azimuth angle storage using the high-precision angular sensor when the object is in motion (the sensor sensitivity axis is oriented by the elevation vertical (perpendicular to the object base));

– determination of object pitch angles when the object is standing or moving.

At the same time the OS structure according to Fig.2 allows reduction of weight, dimensions and cost against the SINS with the same accuracy characteristics.

3. Application of Allan variance for the purpose of gyrocompassing accuracy improvement when performing error autocompensation using SE discrete rotations

Nowadays various error compensation methods and methods for measurement optimization in the composition of OS's are applied in order to improve the gyrocompassing accuracy.

These methods have different efficiency characteristics. Accuracy improvement methods using computers and microcontrollers are more likely to be implemented for modern OS constructed as SINS (such methods as algorithmic error compensation and error autocompensation for analytic ways of orientation parameters acquisition).

The autocompensation method implies SE measuring axes rotation in space. For the OS construction with rotating frames SE rotations are discrete and fixed.

The following factors influence the gyrocompassing accuracy: a random noise, a random drift (a random drift walk), a drift rate trend, a change of drift angular rate trend and change of drift rate systematic component from start to start. The autocompensation method allows eliminating the influence of the change of the gyroscope drift rate systematic component from start to start and minimizing the influence of the drift rate trend and its change (trend acceleration).

The factor of compensation of the influence of the drift rate trend and its change is determined by the values of the trend itself and its change on the one hand, and by time intervals between adjacent measurements on the other hand. Fig. 3 shows a graphical representation of a discrete autocompensation during gyrocompassing in 2 positions and in 4 positions for the linear model of the drift rate trend. The further are measuring span centers (corresponding to mean measuring results) from each other (t_{aut} time) and the heavier is sloped the trend line, the more is autocompensation error $\Delta\omega$.

The influence of a random noise and drift is connected with an averaging time when performing measurements. The more is the averaging time, the less is the influence of the mentioned factors. Thus, it is possible to optimize the measurement time in each SE position t_{chg} in the mentioned OS construction with SE rotations (or to optimize measurement number n given the preset gyrocompassing time) in order to minimize azimuth definition error when applying autocompensation.

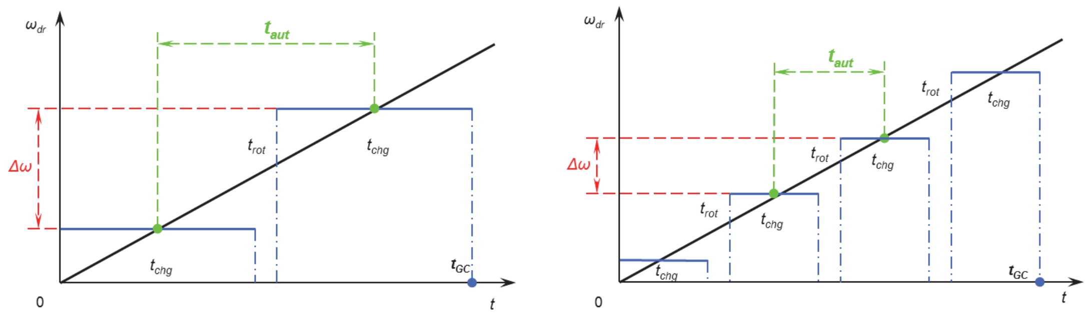

Fig.3. Gyrocompassing autocompensation error $\Delta\omega$ in 2 positions and in 4 positions

Initial parameters for the given task solution are the parameters of gyroscopic SE drift structure, these parameters being determined by the parameters of Allan variance approximating curve [3, 4]. The following factors are considered when analyzing the Allan variance: Q – quantizing noise coefficient (a random noise), N – random angular drift coefficient (a random drift walk), B – bias stability error coefficient, K – coefficient of angular velocity random drift (a change of zero signal trend), R – angular speed linear change coefficient (zero signal trend). The initial data for the gyrocompassing process are the following: t_{GC} – preset time of gyrocompassing, t_{rot} – time of SE rotation into the position for measurement.

When performing the analysis the following allowances are made: 1 the influence of averaging is considered for the total measurement time in all positions, the gyrocompassing process becomes one-positional by way of bringing all the measurements to the initial position and matching the results corrected by the value of the constant measurement component in each position into a single sequence; 2 component B is not taken into account because its influence does not change when performing the autocompensation; 3 it is considered that the influence of the change of the gyroscope drift rate systematic component from start to start is completely eliminated due to the autocompensation.

The influence of noise structure parameters on the measurement error during the gyrocompassing process is expressed as follows with regard for the Allan variance approximating expression:

$$\Delta\omega(n) = \sqrt{R^2 \frac{(t_{GC} + t_{rot})^2}{2n^2} + K^2 \frac{t_{GC} + t_{rot}}{3n} + N^2 \frac{1}{t_{GC} - (\mathrm{n}-1)t_{rot}} + Q^2 \frac{3}{(t_{GC} - (\mathrm{n}-1)t_{rot})^2}}$$

$$\text{or } \Delta\omega(t_{chg}) = \sqrt{R^2 \frac{(t_{chg} + t_{rot})^2}{2} + K^2 \frac{t_{chg} + t_{rot}}{3} + N^2 \frac{1}{n \cdot t_{chg}} + Q^2 \frac{3}{(n \cdot t_{chg})^2}} \;. \quad (1)$$

Using expressions (1) optimization can be performed in order to reduce the gyroscope error when performing autocompensation $\Delta\omega$, and thus to improve the azimuth definition accuracy depending on the time of one measurement t_{chg} (or number of measurements n) given gyrocompassing time t_{GC} and time t_{rot} of rotation to the set angle and on the measurement time with the preset error. As a result, the azimuth definition process optimal in terms of time and accuracy can be obtained with regard for a concrete gyroscope noise structure.

Fig. 4 shows a typical Allan variance for device OIUS-1000 manufactured by Scientific Production Concern "Optolink" for Joint Stock Company "Signal". This device is tested in a climate sell in the temperature range from -30 to +60°C under the maximal temperature gradient of 20°C/h.

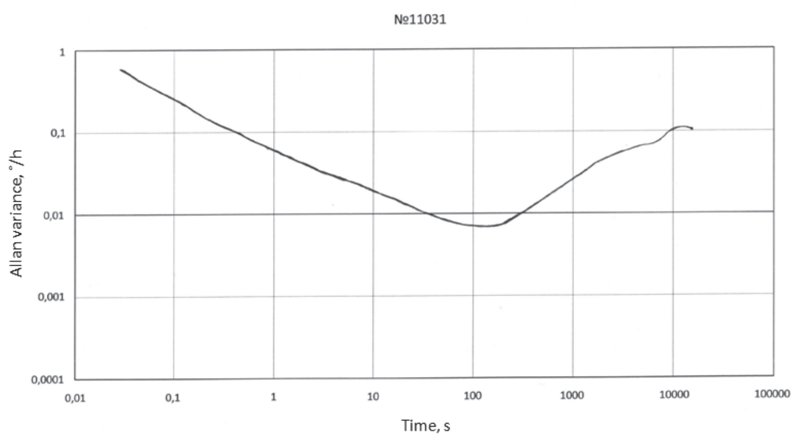

Fig.4. Allan variance OIUS-1000 under the temperature gradient of 20°C/h

Time, s

The following Allan variance parameter estimations are received for three devices OIUS-1000, the temperature gradient being 20°C/h (Tab. 2)

Table 2

Allan variance parameter	OIUS-1000 №11030	OIUS-1000 №11031	OIUS-1000 №12003
N, °/√h	0.00105	0.00091	0.00091
B, °/h	0.0070	0.0070	0.0070
R, °/h^2	0.127	0.127	0.153

The optimization process is illustrated by an example of the simplest autocompensation algorithm during the gyrocompassing process when gyroscopes measurements are performed in positions 180° away from each other.

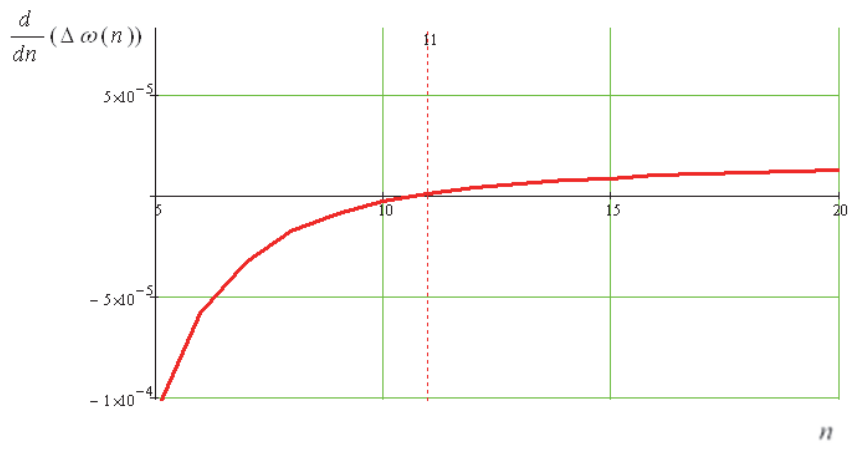

Fig.5. Diagram of autocompensation error optimization by measurement number n for device OIUS-1000

Fig. 5 shows the diagram of dependence $\frac{d}{dn}(\Delta\omega(n))$ for device OIUS-1000 for the received Allan variance parameters N=0.001°/√h and R=0.127°/h^2 with autocompensation parameter t_{rot}=2s and gyrocompassing parameter t_{GC}=5min according to Table for a light reconnaissance robotic complex.

X-axis intersection is achieved when n_{opt} = 11. Thus, a minimal angular speed measurement error selected from the errors that depend on OIUS-1000 signal averaging time makes up 3.651·10^{-3} °/h (1σ) (Fig. 6) on the condition that SE perform 10 successive turnovers for the time of 5 min, measurements being performed in 11 positions. Accounting for the received maximal bias stability error $\Delta\omega_B = B\sqrt{\frac{2}{\pi}\ln 2}$ =4.650 ·10^{-3} °/h (1σ) it turns possible to reach the gyrocompassing accuracy of about 0.07°·sec(latitude) (3σ) on the basis of device OIUS-1000 in the temperature range from -30 to +60°C applying the scheme of Fig.2. In accordance with OIUS-1000 devices test data, without autocompensation (for SINS) the azimuth measurement error may reach 1.03°·sec(latitude) (3σ) for an hour of measurements in the temperature range from -30 to +60°C.

Allan variance-based optimization may be applied for any of the known autocompensation methods using the following gyroscope sensitivity axis positions: 2 positions different by 180º, 3, 4 positions different by 90º, and more positions. In so doing time and accuracy optimal gyrocompassing mode is implemented in OS with the use of the proposed method of estimation of Allan variance parameters influence.

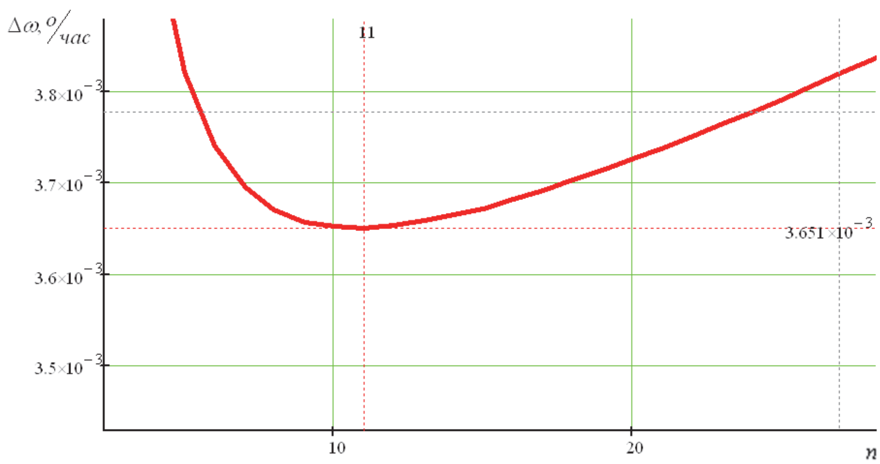

Fig.6. Angular speed measurement error during autocompensation for device OIUS-1000 depending on measurement number n

Conclusions

This work presents the analysis of performance characteristics of SE for OS's of mobile robots. Prospective trends and tendencies of self-contained OS's construction and development in Russia and abroad have been analyzed.

The research on determination of the composition, schemes and construction principles (construction variants) of orientation systems has been performed for the following robotic complexes:

1) very lightweight robotic complex;
2) light robotic complex;
3) light reconnaissance robotic complex;
4) average multifunctional robotic complex;
5) station of robotic complexes remote control.

The results obtained confirm the feasibility of the technical specifications and engineering solutions applied. Cost, weight and size characteristics of the proposed orientation systems have been estimated.

It is proposed that the Allan variance should be applied for optimization of gyrocompassing time and accuracy with error autocompensation in the construction schemes of OS's with SE rotations.

References

1. **Kokoshkin, N. N., Verzunov, E. I., Burov, D.A., and Feofanov, V. N.,** Application of Base Gyro Structural Elements When Developing the Variety of Gyroscopes for Ground Vehicles, 15th St. Petersburg International Conference on Integrated Navigation Systems, St. Petersburg, Concern CSRI Electropribor, JSC, 2008, pp. 160–162.
2. **Matveev, V.V., Raspopov, V.Ya.,** Osnovy postroeniya besplatformennykh inertsialnykh navigatsionnykh sistem (Constructive Theory of Strapdown Inertial Navigation Systems), Ed. Raspopov, V.Ya., Dr. Sci., St. Petersburg, Concern CSRI Electropribor, JSC, 2009.
3. **IEEE Std 952-1997.** IEEE Standard Specification Format Guide and Test Procedure for Single-Axis Interferometric Fiber Optic Gyros.
4. **Siraya, T.N.,** Allan Variance as Measurement Error Estimate, Giroscopiya i Navigatsiya, 2010, no. 2, pp. 29–35.