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DATA-WARE OF PRECISION ATTITUDE AND HEADING REFERENCE SYSTEM

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Abstract
Purpose: *The paper focuses on features of data-ware of precision attitude and heading reference systems, which can be applied in the high-precision applications, for example, navigation of marine vehicles. The main goal is to create the data-ware adapted to functioning of the multi-mode navigation system.* ***Methods:*** *To solve the given problem the methods of the inertial navigation, automatic control theory including servo systems and methods of statistical processing of information are used.* ***Results:*** *The data-ware of the precision attitude and heading reference system is developed taking into consideration different modes of the system and interrelation between them. The basic expressions of data-ware for the high precision multimode attitude and heading reference system are obtained. The general block-scheme of operating algorithm of the system is given.* ***Conclusions:*** *The results of development of data-ware of the precision attitude and heading reference system taking into consideration presence of some operating modes are represented. Obtained results can be useful for design of precision navigation systems of the moving vehicles of the wide class.*

Keywords*:* attitude and heading reference system; data-ware, inertial navigation, multimode system.

1. Introduction

The modern trends of design of the precision attitude and heading reference systems are requirements to expansion of the functional possibilities and to decrease of period of design. Situation is complicated because these conflict requirements must be satisfied at the same time. To solve this problem is possible by means of careful development of the system data-ware at the early phases of design.

The precision attitude and heading reference system operates in many modes including calibration, coarse and fine levelling, gyrocompass azimuth alignment and finally modes of azimuth and course determination. Every mode is characterized by definite units and operation conditions. So, data-ware of the attitude and heading reference system must take into consideration features of every mode and interconnections between them.

2. Analysis of the latest researches and publications

This paper completes the series of papers dealt with development of the precision attitude and heading reference systems [1-4]. The papers [1, 2] describe basic features of creation of the mathematical models of such systems. The mathematical descriptions of the high-precision attitude and heading reference systems with biaxial and triaxial platforms are given in these papers. Features of design and simulation of the robust system perturbed by environmental disturbances are given in the paper [3, 4]. The general achievements of gimballed stabilization systems design and gimballed precision navigation systems are represented in papers [5, 6]. Features of inertial navigation are represented in [7]. Analysis of the possible ways to realize the high precision attitude and heading reference systems are given in [8].

3. Research tasks

The main goal of the research is to represent basic directions of data-ware development for application of precision attitude and heading reference system. These tasks include characteristic of all modes of the attitude and heading reference system and also interrelation between them.

4. General characteristic of data-ware

The high precision attitude and heading reference system can be based on the triaxial inertial platform. Basic features of such a system are described in the paper [1]. This system includes two dynamically tuned gyroscopes. The first device carries out functions of the course gyroscope. The second device is the gyro vertical. Gyroscopes are mounted at the rotation units. Such an approach provides execution of calibration and improves accuracy of the considered system as a whole. The considered system includes also three accelerometers. Presence of the third (vertical) accelerometer allows compensating an error caused by the vertical component of the vehicle speed.

It should be noted that compensation algorithms of the high precision attitude and heading reference systems are sufficiently complex. In this case it is necessary to compensate both instrumental and methodical errors. The methodical errors are caused by the Coriolis acceleration and also earth diurnal rotation. Errors caused by non-sphericity of the Earth must be also taken into consideration.

It should be noted that strapdown attitude and heading reference systems corrected by means of Global Positioning System (GPS) in some situations provide sufficiently high navigation accuracy. Topicality of the gimballed attitude and heading reference system is explained by vulnerability of GPS. From this point of view the advantages of the gimballed navigation systems for strategic applications makes no doubts [6]. Global Positioning System can be vulnerable due to five basic factors such as [9]:

1)dissipation of GPS signals in the space;
2)dissipation of signals of the ground receiver;
3)inaccessibility of the on-board GPS receiver;
4)inaccessibility of ground stations;
5) inaccessibility of GPS satellites.

In contrast to gimballed inertial navigation systems the modern gimballed inertial navigation systems are used in the case of need to satisfy some basic requirements. These requirements are the high accuracy in conditions of autonomous operation; high functional reliability and the ability to function in unfavourable environmental. An inertial platform is the important part of the strategic systems of guidance, navigation and control including attitude and heading reference systems.

One of the most important parts of design of the gimballed attitude and heading reference systems is development of data-ware. It should be noted that the system of the considered type is multi-mode [2]. So, every mode requires its own algorithm. Moreover, it is necessary to agree execution of these modes in time.

The feature of data-ware of the high precision attitude and heading reference systems is the necessity to provide calibration process [6]. Performances of navigation inertial sensors such as scale factor, systematic error, alignment error, nonlinearity and sensitivity to acceleration, change in time due influence of environmental disturbances. To provide the high navigation accuracy it is necessary to specify values of basic errors of navigation instruments. The obtained values can be used for compensation of appropriate components of control laws. Obtaining information about changes in instrumental errors of navigation instruments is carried out by means of calibration.

The feature of data-ware of the high precision attitude and heading reference systems is also the necessity to provide the initial alignment of the platform with the inertial navigation instrument relative to the given navigation reference frame. This process includes levelling and gyrocompass azimuth alignment.

Levelling lies in setting of the inertial platform with the inertial measuring instruments to the horizontal plane. It should be noted that accelerometers during flight measure the specific force caused by the engine thrust. Accelerometers in pre-flight modes measure reaction on the local force of gravity. High-precision navigation (for example, navigation of marine vehicles) requires the coarse and fine levelling. Accuracy of the coarse depends on accelerometer drifts and stability of scale factors. The process of the coarse levelling is implemented by means of control by accelerometer signals. The process of the fine levelling is based on signals of accelerometers and gyroscopic devices.

Gyrocompass azimuth alignment is based on autonomous analytical determination of the true course of the controlled object. To provide this process is possible using projections of the horizontal components of the Earth rate, which depend on the true course. The gyrocompass azimuth alignment is a long process [6].

In fact the gyrocompass azimuth alignment is process of setting to the meridian. This process is implemented by means of rotation of the platform relative to the vertical axis. A position of the vertical axis is determined by the coarse levelling. It should be noted that the gyrocompass azimuth alignment is less precise in comparison with the levelling. As result the azimuth initial error significantly exceeds residual deviation of the platform from the horizontal plane.

Calibration and alignment are different navigation modes. They can be implemented in series or at the same time. Nevertheless the highest precision can be achieved in the case of their continuous and combined implementation.

The block-scheme of algorithm of the attitude and heading reference system functioning is represented in Fig. 1. Functioning of the system begins from the power on self test. After testing termination it is necessary to check signal from the thermostating system and provide information output failures in case of need.

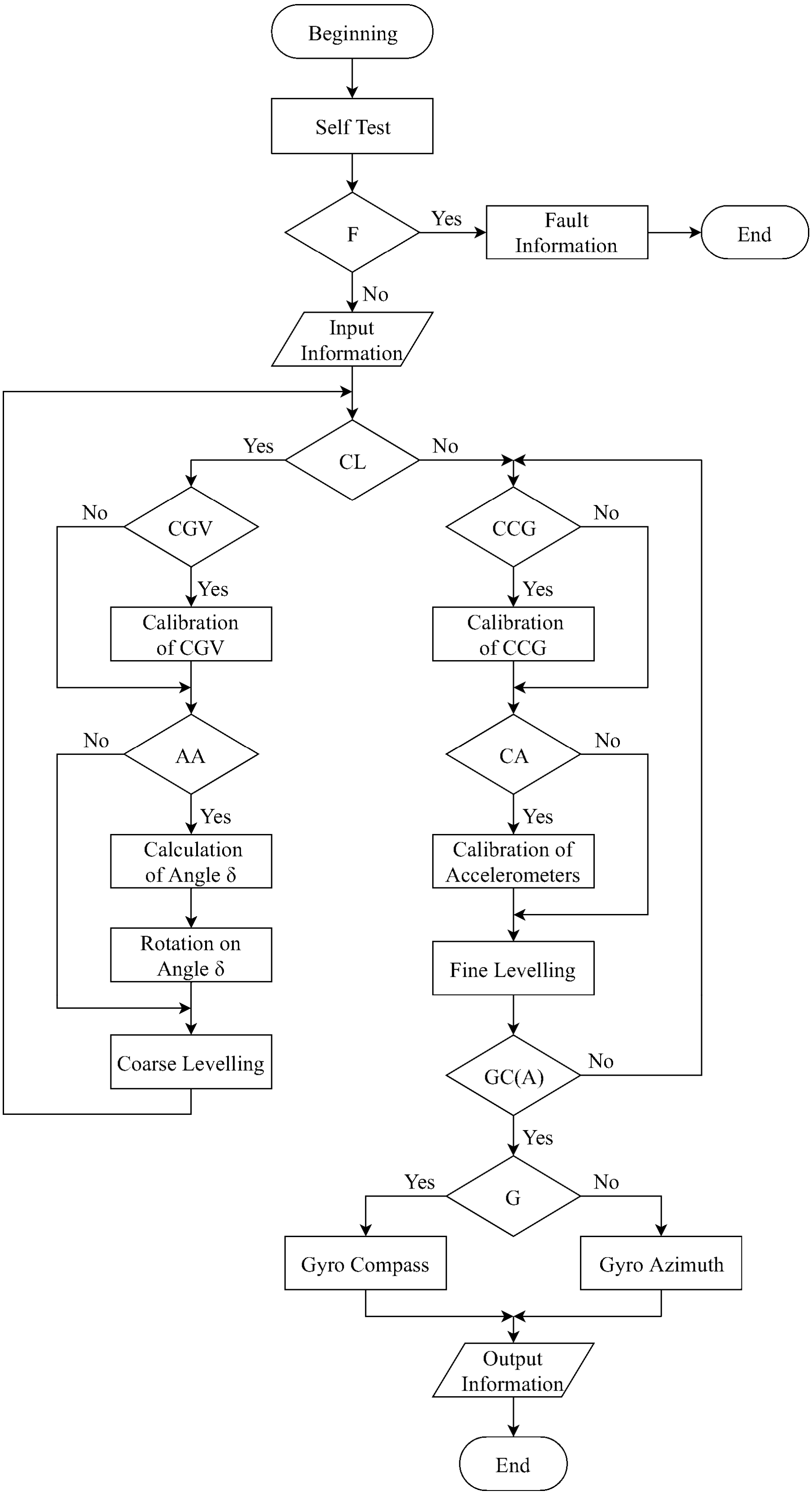

Fig. 1. The block-scheme of functioning of the high-precision attitude and heading reference system

The mode of the fine levelling can be implemented after calibration of the dynamically tuned gyro, which carries out functions of the course gyroscope. Further calibration of accelerometers is carried out against the background of the fine levelling. After setting of the system in the state of precision measurement of the course, functioning in the mode of the gyroscopic compass can be implanted.

5. Description of data-ware of separate modes

Coarse levelling. The mode of the coarse levelling includes the following steps.

1. It is necessary to provide pickup of accelerometers signals and calculate following values

$$A_x^c = A_x + a_{xs} + a_{xt};\quad A_y^c = A_y + a_{ys} + a_{yt}. \qquad (1)$$

where A_x, A_y are accelerometers readings; a_{xs}, a_{ys} are systematic errors given in the technical documentation; a_{xt}, a_{yt} are accelerometer drifts due to temperature.

2. Determining angles of roll and pitch (γ and θ) using angle-data transmitters mounted at axes of the platform gimbals is implemented.

3. Control moments can be calculated by the formulas

$$M_x = k_x A_y^c + k_\theta \dot{\theta};\quad M_y = k_y A_x^c + k_\gamma \dot{\gamma}, \qquad (2)$$

where $k_x, k_y, k_\gamma, k_\theta$ are appropriate transfer constants; $\dot{\gamma} = \gamma / \Delta t$; $\dot{\theta} = \theta / \Delta t$. Here Δt is duration of control cycle in real time.

4. Forming currents entering to the torque motors are obtained in the following way. In accordance with the expression (2) these signals can be represented in the following form

$$I_x = M_x / k_{tm};\quad I_y = M_y / k_{tm}, \qquad (3)$$

where k_{tm} is the transfer constant of the torque motor.

Formulas (1) – (3) represent data-ware of the mode of the coarse levelling.

Calibration of the course gyroscope. Calibration of the dynamically tuned gyroscope, which carries out functions of the course gyroscope, is implemented based on functioning of the dynamically tuned gyroscope in the mode of the angular rate measurement. Calibration of the course gyroscope is carried out mutually with the coarse levelling. The basic goal of this mode is to calculate drifts of the course gyroscope. To solve this task it is necessary to form a control moment, which provides rotation of the course gyroscope with the angular rate $\dot{\psi}_g$ equal to 2 deg/s. During this rotation the projections of the Earth angular rate onto measuring axes of the course gyroscope ω_x, ω_y are measured at the instants of time, which correspond to turns on the angles 0°, 10°, …, 360° respectively. Gyroscope drifts $\dot{\alpha}_d, \dot{\beta}_d$ can be determined based on measured values ω_x, ω_y.

This mode includes the following steps.

1. Angles of pitch, roll and yaw (θ, γ, ψ) are measured.

2. Control of torque motors is implemented in accordance with the expression (2) except for determination of moment M_z, which can be determined in the following way

$$M_z = M_{\max}(\dot{\psi}_g - \dot{\psi}_m);\quad I_z = M_z / k_{tq}, \qquad (4)$$

where ψ_g, ψ_m are given and measured angles of the yaw respectively; here $\dot{\psi}_m = \psi_m / \Delta t$.

3. The arrays of values $\Delta\omega_x, \Delta\omega_y$ are calculated by the formulas

$$\Delta\omega_{x_i} = \frac{\omega_{x_i} + \omega_{x_{i+18}}}{2},\quad i = \overline{1,18};\qquad \Delta\omega_{y_i} = \frac{\omega_{y_i} + \omega_{y_{i+18}}}{2},\quad i = 1,18. \qquad (5)$$

4. Drifts of the course gyroscope $\dot{\alpha}_d, \dot{\beta}_d$ can be determined in the following way

$$\dot{\alpha}_d = \frac{\sum_{i=1}^{18} \Delta\omega_{x_i}}{18};\quad \dot{\beta}_d = \frac{\sum_{i=1}^{18} \Delta\omega_{y_i}}{18}. \qquad (6)$$

Formulas (4) – (6) describe data-ware of the mode of coarse levelling.

Alignment in azimuth. The mode of the alignment in azimuth is carried out at the same time with the mode of the coarse levelling. An angle δ_a between the axis of sensitivity of the course gyroscope and the meridian plane is defined by components, which can be measured by the dynamically tuned gyroscope operated in the mode of the measuring instrument of the angular rate. The above mentioned gyroscope in the attitude and heading reference system of the considered type carries out functions of the gyro vertical.

In this situation a position of the platform with the navigation measuring instruments can be determined based on projections of the Earth angular rate onto the platform axes [10]. This mode includes the following steps.

1. Angles of pitch, roll and yaw (θ, γ, ψ) are measured.

2. Control of torque motors M_x, M_y is implemented in accordance with the expression (2) taking into consideration above obtained drifts of the course gyroscope

$$M_x = k_x A_y^c + k_\psi \dot{\psi} + \dot{\alpha}_d;$$
$$M_y = k_y A_x^c + k_\theta \dot{\theta} + \dot{\beta}_d. \quad (7)$$

3. Forming of currents at the input of the torque motors is carried out in accordance with the formulas (3).

4. Calculation of the angle of setting to the meridian based on measurements of the Earth angular rate is carried out as a mean value

$$\omega_{xm} = \sum_{i=1}^{10} \omega_{xi};$$
$$\omega_{ym} = \sum_{i=1}^{10} \omega_{yi}; \quad (8)$$
$$\delta_s = \text{artcg}(\omega_{xm} / \omega_{ym}).$$

5. For navigation tasks it is important to know both a value and direction of the calculated angle [11]. Therefore the expression (8) must be divided into some expressions

$$\delta = \delta_s - 180^\text{o} \text{ if } \omega_{xm} \le 0; \ \omega_{ym} \le 0;$$
$$\delta = -\delta_s \text{ if } \omega_m \le 0; \ \omega_{ym} > 0;$$
$$\delta = 180^\text{o} - \delta_s \text{ if } \omega_{xm} \le 0; \ \omega_{ym} \le 0;$$
$$\delta = \delta_s \text{ if } \omega_{xm} > 0; \ \omega_{ym} > 0. \quad (9)$$

Rotation of the gyroscope on the calculated angle is implemented by means of the rotation unit of the course gyroscope. The control current of the torque motor provides rotation with the speed 10 deg/s. The calculated value is checked by the signal of the angle-data transmitter of the rotation unit. The control current can be determined by the following expression

$$I_A = M_A / k_{tm};$$
$$M_A = M_{\max}(\dot{\psi}_g - \dot{\psi}_m), \quad (10)$$

where ψ_g, ψ_m are given and measured angular rates; $\dot{\psi}_m = \psi / \Delta t$;

Termination of the rotation and nulling of the control current is implemented by the relation

$$\psi \le \delta \text{ if } \omega_y \ge 0 \text{ and } \psi \le 180^\text{o} - \delta \text{ if } \omega_y < 0. \quad (11)$$

Formulas (7) – (11) describe data-ware of the mode of the alignment in azimuth.

Fine levelling. The mode of the fine levelling is implemented after calibration of the gyroscope, which carries out functions of the gyroscopic vertical. This mode includes following steps.

1. Control moments M_x, M_y are determined in the following way

$$M_x = k_{1f}\gamma_{vg} + k_{2f}\dot{\gamma}_{vg};$$
$$M_y = k_{3f}\theta_{vg} + k_{4f}\dot{\theta}_{vg}, \quad (12)$$

where $k_{1f}, k_{2f}, k_{3f}, k_{4f}$ are transfer constants; γ_{vg}, θ_{vg} are signals of the gyroscope, which carries functions of the gyro vertical. Here

$$\dot{\gamma} = \frac{\gamma_{vg_i} - \gamma_{vg_{i-1}}}{\Delta t}; \ \dot{\theta} = \frac{\theta_{vg_i} - \theta_{vg_{i-1}}}{\Delta t}.$$

2. The currents at the input of torque motors can be determined based on relations

$$I_x = \sum_{i=1}^{4} M_{x_i} / k_{tm};$$
$$I_y = \sum_{i=1}^{4} M_{y_i} / k_{tm}, \quad (13)$$

where M_{x_1}, M_{y_1} are moments of integral correction; M_{x_2}, M_{y_2} are moment, which correct influence of the Earth rotation; M_{x_3}, M_{y_3} are correction moments based on the external information; M_{x_4}, M_{y_4} are moments, which correct influence of the gyroscope, which carries out functions of the gyro vertical.

The above stated correction moments are described in details in the paper [2].

3. In the mode of the fine levelling the calculation of the course gyroscope drifts using information of GPS can be used if it is possible. Correction is carried out every 30 min by means of the formula

$$\Delta\dot{\psi} = \frac{(\psi_{gps1} - \psi_1) + (\psi_{gps2} - \psi_2)}{2\Delta t}, \quad (14)$$

where ψ_{gps1}, ψ_{gps2} are values obtained from GPS at instants of time, differing on 30 min; ψ_1, ψ_2 are values measured by the course gyroscope.

If information of GPS is absent, the data-ware uses previous values of $\psi, \Delta\psi$.

Formulas (12) – (13) describe data-ware of the mode of the fine levelling.

Calibration of course gyroscope. The mode of calibration of the course gyroscope is carried out mutually with the mode of the fine levelling. Using experience of the considered systems design and operation this algorithm it is convenient to represent in the following form.

1. Output values of the course gyroscope $\psi_i, i = \overline{1,...,6}$ are measured through 90 s.

2. The drift of the course gyroscope is determined based on measured information by means of relations

$$\Delta\psi_i = \frac{\psi_{2i} - \psi_{2i-1}}{90}; \ \Delta\dot{\psi} = \sum_{i=1}^{3} \Delta\psi_i . \quad (15)$$

The expression (15) allows obtaining of the course gyroscope drift.

Calibration of accelerometers. Calibration of accelerometers is carried out mutually with the mode of the fine levelling. Accelerometer drifts are determined in the following succession.

1. Using accelerometer readings A_x, A_y, A_z the speeds and traversed paths along the platform axes are determined

$$\Delta V_i = V_0 + \int_0^{\Delta t} A_i \ ; \ i = x, y, z , \quad (16)$$

$$\Delta S_i = S_0 + \int_0^{\Delta t} V_i, \ \ i = x, y, z . \quad (17)$$

2. Based on expressions (16), (17) the following components can be calculated

$$a_i^1 = 2\Delta S_i / t^2 \ ; \ a_i^2 = \Delta V_i / t \ , \ i = x, y, z . \quad (18)$$

3. Accelerometer drifts can be determined in the following way

$$a_i = (a_i^1 + a_i^2)/2; \ \ i = x, y, z . \quad (19)$$

The expression (19) allows obtaining of the course gyroscope drift.

Mode of gyroscopic compass. To provide the high accuracy of course determination it is necessary to carry out the mode of the gyroscopic compass at the same time with the mode of the fine levelling. The system in this mode can function in the mode of the gyroscopic compass or gyroscopic azimuth depending on the control command signal. The main goal of the system in this mode is to provide correspondence of the platform angular rate and angular rates of the geographical navigation reference frame taking into consideration the diurnal rotation of the Earth and motion of the vehicle [10, 11].

This mode includes following steps.

1. Control moments M_x, M_y are determined in the following way

$$\begin{aligned} M_z &= k_{1f}\psi_{vg} + k_{2f}\dot{\psi}_{vg}; \\ M_y &= k_{3f}\theta_{vg} + k_{4f}\dot{\theta}_{vg}, \end{aligned} \quad (20)$$

where $k_{1f}, k_{2f}, k_{3f}, k_{4f}$ are transfer constants; ψ_{vg}, θ_{vg} are signals of the gyroscope, which carries functions of the course gyroscope. Here

$$\dot{\psi} = \frac{\psi_{vg_i} - \psi_{vg_{i-1}}}{\Delta t}; \ \dot{\theta} = \frac{\theta_{vg_i} - \theta_{vg_{i-1}}}{\Delta t} .$$

2. The currents at the input of torque motors can be determined based on relations (20)

$$\begin{aligned} I_z &= \sum_{i=1}^{4} M_{z_i} / k_{tm}; \\ I_x &= \sum_{i=1}^{3} M_{x_i} / k_{tm}, \end{aligned} \quad (21)$$

where M_{z_1}, M_{z_1} are moments of horizontal correction by signals of course; M_{z_2}, M_{x_2} are moments of horizontal correction by signals of accelerometers; M_{z_3}, M_{x_3} are moments of azimuth correction; M_{z_4} is a moment based on the course gyroscope drift.

The above listed correction moments of the expression (22) are described in the paper [2].

7. Conclusions

Data-ware for the high precision attitude and heading reference system was developed. The generalized block-scheme of functioning of the above mentioned system is represented.

Basic expressions of data-ware for every mode of the high precision attitude and reference system are obtained.

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Алгоритмічне забезпечення високоточної системи визначення просторової орієнтації

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Мета: У статті розглянуто особливості алгоритмічного забезпечення високоточної систем визначення просторової орієнтації, що можуть бути застосовані у високоточних застосуваннях, наприклад, навігації морських рухомих об'єктів. Головною метою є створення алгоритмічного забезпечення, спрямованого на забезпечення функціонування багаторежимної навігаційної системи. **Методи дослідження:** Для розв'язання зазначеної проблеми використовуються методи інерціальної навігації, теорії автоматичного управління, включаючи слідкувальні системи та статистичної обробки інформації. **Результати:** Розроблене алгоритмічне забезпечення високоточної системи визначення просторової орієнтації з урахуванням наявності різних режимів системи та взаємозв'язків між ними. Отримано основні вирази для алгоритмічного забезпечення високоточної багаторежимної системи визначення просторової орієнтації. Представлено узагальнену блок-схему алгоритму функціонування системи. **Висновки:** Представлено результати розробки алгоритмічного забезпечення високоточної системи визначення просторової орієнтації з урахуванням наявності декількох експлуатаційних режимів. Отримані результати можуть бути корисними для проектування високоточних навігаційних систем рухомих об'єктів широкого класу.

Ключові слова: алгоритмічне забезпечення; багаторежимна система; інерціальна навігація; система визначення просторової орієнтації

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Алгоритмическое обеспечение высокоточной системы определения пространственной ориентации

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Цель: В статье рассмотрены особенности алгоритмического обеспечения высокоточных систем определения пространственной ориентации, которые могут быть использованы в высокоточных применениях, например, в навигации морских подвижных объектов. Главной целью создания алгоритмического обеспечения, направленного на обеспечения функционирования многорежимной навигационной системы. **Методы исследования:** Для решения данной проблемы используются методы инерциальной навигации, теории автоматического управления, включая следящие системы, и методы статистической обработки информации. **Результаты:** Разработано алгоритмическое обеспечение высокоточной системы определения пространственной ориентации с учетом наличия разных режимов системы и взаимосвязей между ними. Получены основные выражения для алгоритмического обеспечения высокоточной многорежимной системы определения пространственной ориентации. Представлена обобщенная блок-схема алгоритма функционирования системы. **Выводы:** Представлены результаты разработки алгоритмического обеспечения высокоточной системы определения пространственной ориентации с учетом наличии нескольких эксплуатационных режимов. Полученные результаты могут быть полезными для проектирования высокоточных навигационных систем подвижных объектов широкого класса.

Ключевые слова: алгоритмическое обеспечение; инерциальная навигация; многорежимная система; система определения пространственной ориентации

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