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Software Seminatural Development for FOG Inertial Satellite Navigation System SINS-500

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Abstract—Special features of a technology for seminatural development of software of strapdown inertial satellite navigation systems (SISNS) are considered. The implementation of this technology relies on modern recording equipment and provides software optimization over the actual signals and on a set of the algorithms under study. The system SINS-500 based on fiber-optic gyros is described as the object of seminatural development. The results of seminatural tests of the SINS-500 system are presented which corroborate that applying the proposed technology to create different-purpose custom designed SISNS is possible and expedient.

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INTRODUCTION

Analytical approaches to the improvement of the operational characteristics of strapdown inertial navigation systems (SINS) involve optimization of their software under the given hardware constraints. The hardware constraints are determined by the available computational resources as well as by requirements on the SINS dimensions, mass, and cost.

The optimization of SINS software implies a study of the effectiveness of different algorithms for reckoning and updating of motion parameters of the objects of a given class. The following approaches to the solution of such a problem are possible:

—carrying out a great number of full-scale experiments with different versions of software architecture. In this case, SINS output parameters are recorded and analyzed. Such experiments entail a substantial expenditure of cash and time;

—carrying out only one full-scale experiment on a typical path of object motion when the GPS signals and the signals of inertial sensors, such as gyroscopes and accelerometers, are recorded. Such an approach enables one to perform, from the signals recorded, software optimization on set of the algorithms under study.

In accordance with the technology proposed for the software development, when carrying out a full-scale experiment, the signals of fiber-optic gyros (FOG) and accelerometers, and also the GPS signals are recorded. The data recorded are subsequently used for the tuning of operation modes of an inertial satellite navigation system with different algorithms for the reckoning and updating of motion parameters. Tuning quality is determined from the deviations of the reckoned inertial parameters from the GPS parameters. Thus, it is apparently possible to implement an iterative process for the software seminatural development.

The idea of seminatural implementation of algorithms for attitude control and navigation has been known for a long time. As far back as 1935, under the direction of academician N.A. Pilyugin, experiments [1] were carried out to determine aircraft motion parameters from the recorded signals of accelerometers and gyros. Therefore, the purpose of this paper was not the justification of a technology for seminatural development of SINS software, but the demonstration of its capabilities when creating integrated inertial satellite navigation systems. Such capabilities rely on computational resources of present-day equipment for acquisition, conversion, processing, and recording of the signals of navigational sensors. Today, the data recorded are used, as a rule, to analyze spectral characteristics of sensor errors [2, 3], e.g., by the Allan method [4, 5] and also to analyze SINS output errors [2, 6, 7].

1. TECHNOLOGY AND PROBLEMS OF SOFTWARE SEMINATURAL DEVELOPMENT FOR THE STRAPDOWN INERTIAL SATELLITE NAVIGATION SYSTEMS

A technology for seminatural development of the software for SISNS can be represented by a scheme shown in Fig. 1, where IMU is an inertial measurement unit that contains the triad of accelerometers and the triad of FOGs; $\overline{\omega}$ is the vector of FOG output signals; $\bar{a}$ is the vector of accelerometer output signals; φ, λ are the object geodetic latitude and longitude; $\bar{V}$ is the object relative velocity vector, given by

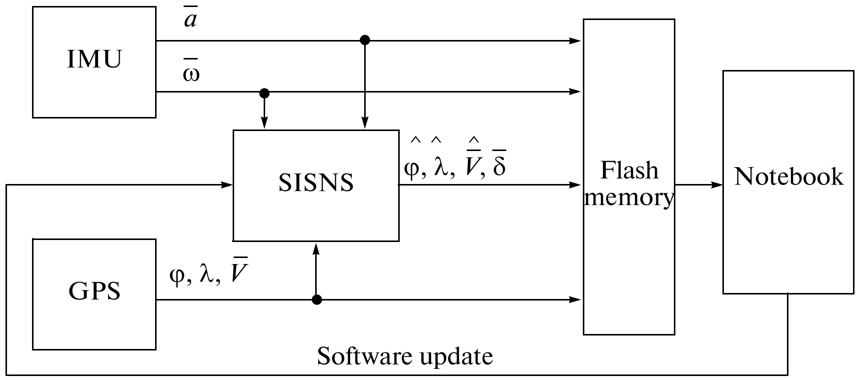

Fig. 1. Scheme for seminatural development of SISNS software.

its components along the axes of the navigation frame; $\bar{\delta}$ is the vector of attitude parameters.

In accordance with the scheme presented here during a seminatural experiment the motion parameters are reckoned and corrected in the notebook from the recorded signals of GPS, sensors and their temperatures. In order that the procedures for full-scale and seminatural software development be quite identical, recording is made at a frequency at which sensor signals are loaded into SISNS processor module. In the process of seminatural software development, the following problems can be solved:

—tuning the procedures of primary processing of sensor signals [1]. Such tuning includes determination of procedures for SINS protection from sensor malfunctions as well as determination of the structure, order, and parameters of a digital filter;

—choosing the methods of integrating the basic equations for the determination of attitude and position of a SINS;

—matching the frequency of picking off sensor signals agree the SINS available computational resources;

—carrying out sensor dynamic calibration that is found to be unfeasible under factory conditions;

—estimation of the misalignment of measurement axes both in accelerometers and in FOGs;

—estimation of and analytical compensation for sensor drifts remaining after factory calibration, which manifest themselves in each SINS start under service conditions;

—refinement of the structure and parameters of drift models of sensors [2];

—tuning the procedures of secondary processing of observed signals, which are based on the application of estimation filters of the Kalman type. Such tuning involves [3] making the parameters and tools used to protect the filter from divergence agree with the SISNS computational resources.

On the basis of solving the problems mentioned above in the process of seminatural development of SISNS software the loops for the sensor state control can be implemented.

As applied to aircraft SINS, such loops can be represented by scheme shown in Fig. 2.

To implement the loops for sensor state control, the level of detail for SINS error equations is to be brought to the level of FOG instrumental drifts and accelerometer biases. In this case the estimation of and analytical compensation for the above sensor errors can be implemented at the level of primary processing of sensor signals in real time [11].

The difference of this approach from the traditional ψ-technology [12] for constructing the model of SINS errors reduces to the following:

—the ψ-technology relies on the estimation of the reference frame simulation errors. Therefore, it is necessary to make angular errors and reference frame drifts agree with those of the of the inertial measurement unit;

—formation of sensor error equations in IMU-fixed frame is based [14] on the solution of quaternion equations separately for attitude parameters (1), for navigation parameters (2), and for their errors (3), i.e.,

$$2\dot{q}_0 = \Pi_0 q_0; \tag{1}$$

$$2\dot{q}_1 = \Pi_1 q_1; \tag{2}$$

$$\dot{x} = A(t)x(t) + G(t)\xi(t), \tag{3}$$

where

$$\Pi_0 = \begin{bmatrix} 0 & \dot{\Theta}_y & -\dot{\Theta}_x & -\dot{\Theta}_z \\ -\dot{\Theta}_y & 0 & \dot{\Theta}_z & -\dot{\Theta}_x \\ \dot{\Theta}_x & -\dot{\Theta}_z & 0 & -\dot{\Theta}_y \\ \dot{\Theta}_z & \dot{\Theta}_x & \dot{\Theta}_y & 0 \end{bmatrix};$$

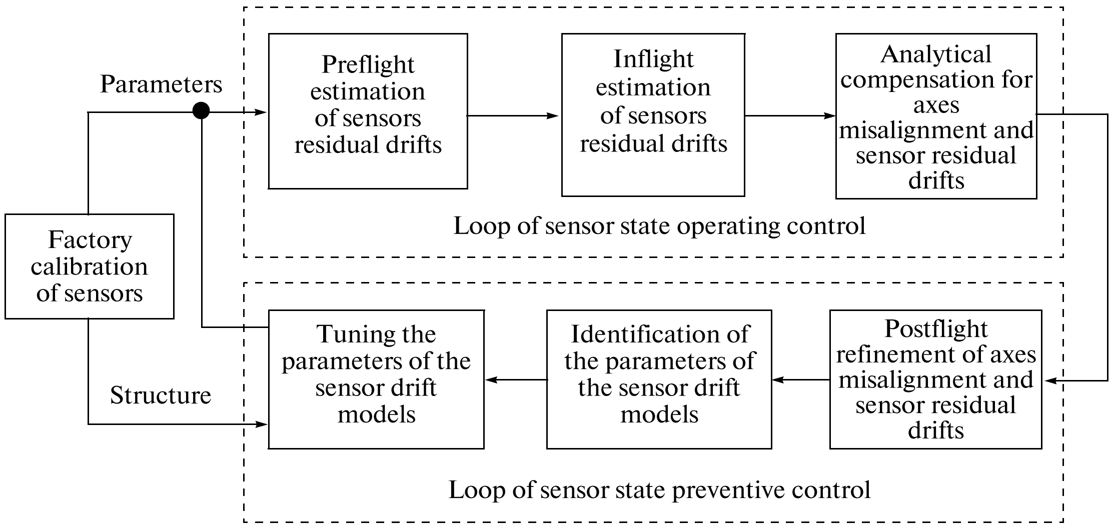

Fig. 2. Loops of SINS sensor state control.

$$\Pi_1 = \begin{bmatrix} 0 & -\omega_\xi & -\omega_\eta & -\omega_\zeta \\ \omega_\xi & 0 & \omega_\zeta & -\omega_\eta \\ \omega_\eta & -\omega_\zeta & 0 & \omega_\xi \\ \omega_\zeta & \omega_\eta & -\omega_\xi & 0 \end{bmatrix};$$

$\dot{\bar{\Theta}} = \left[\dot{\Theta}_x\ \dot{\Theta}_y\ \dot{\Theta}_z\right]^T$—is the vector of FOG output signals, given by its components along IMU axes; q_0 is a quaternion that characterizes the angular position of IMU-fixed frame *oxyz*, with respect to the inertial frame $OX_IY_IZ_I$ [13]; q_1 is a quaternion that characterizes the angular position of the free in azimuth reference navigation frame $o\xi\eta\zeta$ with respect to the Earth-fixed geodetic frame $OX_EY_EZ_E$ [13], $\bar{\omega} = \left[\omega_\xi\ \omega_\eta\ \omega_\zeta\right]^T$ is the vector of angular rates of the reference frame $o\xi\eta\zeta$ turn in the geodetic frame [13]. Moreover, for the frame free in azimuth $\omega_\zeta = 0$. Components of the vector $\bar{\omega}$ are determined from the orthogonal components V_ξ, V_η, V_ζ of the relative velocity vector $\bar{V}$, which are taken from the solution of the basic equation of inertial navigation [1, 12, 13]; Π_0, Π_1 are skew-symmetric matrices with the signs of elements corresponding to the IMU design. From the elements of quaternions q_0 and q_1 one can find the angles ψ, ϑ, γ of IMU angular position with respect to the local geodetic frame *oENH*, along with the geodetic latitude φ and geodetic longitude λ. The basic vector of SINS errors $x(t)$ was comprised of 17 parameters, namely: the errors ΔV_ξ, ΔV_η, ΔV_ζ in the reckoning of components of the relative velocity vector, the errors Δq_0 and Δq_1 in the reckoning of quaternion elements, the angular drifts $\Delta\dot{\Theta}_x$, $\Delta\dot{\Theta}_y$, $\Delta\dot{\Theta}_z$ of FOGs, and the biases Δa_x, Δa_y, Δa_z of accelerometers. Sensor error equations were formed in an IMU-fixed frame. This has enabled us to implement a tightly-coupled scheme for the damping of sensor errors, and the above scheme included a Kalman filter in the estimation loop; $A(t) = \left.\frac{\partial F(Y,t)}{\partial Y}\right|$ is the matrix of partial derivatives; $F(Y, t)$ is a function that represents, in the general form, the right-hand sides of SINS equations and sensor error equations; $Y = Y(t)$ is the vector of parameters that are determined by a SINS; $G(t)$ is the matrix for intensities of the disturbances $\xi(t)$.

2. THE STRAPDOWN INERTIAL SATELLITE NAVIGATION SYSTEM SINS-500 AS THE OBJECT OF SEMINATURAL DEVELOPMENT

The technology for seminatural software development has been approved in the process of testing the strapdown inertial satellite navigation system SINS-500 designed by RPC "OPTOLINK" (Zelenograd). Figure 3 shows a prototype of the system SINS-500 with the technological connecting cables.

The major modules of the system SINS-500 are as follows: the three-axis IMU TIUS-500 based on the triad of fiber-optic gyros and accelerometers; the satellite receiver K-161 developed by the Russian Institute of Radionavigation and Time, JSC (St. Petersburg); a computing module that conforms to the PC/104 standard; a power unit and input/output interface units. For the system SINS-500, the hardware and software are modular in architecture. Such an architecture is analogous to that of the system SINS-1000, which was discussed in [5]. However, the system SINS-500 is far less massive (no more then

4.5 kg) and it is much smaller in overall dimensions than the system SINS-1000.

For FOGs which form the part of the system SINS-500, random residual drifts are of the order of 0.1–0.3 deg/h, and for accelerometers the above drifts are of the order of 10^{-4} g. Hardware that was formed according to the "effectiveness-cost" criterion gives ground to classify the SINS version presented here among the systems of medium accuracy. Implementation of analytical compensation for sensor residual drifts is expedient in these systems.

The timing diagram of SINS operation includes the following stages: coarse initial alignment, fine initial alignment, and navigational mode that includes operation in autonomous inertial navigation submode and inertial satellite navigation submode.

At the stage of coarse initial alignment, IMU approximate angular position is determined using sensor output signals.

At the stage of fine initial alignment, errors in the IMU angular position and sensor residual drifts are estimated along with the parameters of their dynamic models. This problem is solved on a basis of the sequential processing of the observed signals z_i of the form given below by a robust Kalman-Brown filter [3]:

$$z_{\Theta(i)} = C_{0(i)}^{\mathrm{T}} \int_{t_{i-1}}^{t_i} \dot{\bar{\Theta}}(\tau) d\tau - [0 \vdots 0 \vdots \Omega \Delta t_i]^{\mathrm{T}}; \tag{4}$$

$$z_{k(i)} = [\varphi_i \lambda_i]_{\mathrm{SINS}}^{\mathrm{T}} - [\varphi_i \lambda_i]_{\mathrm{PIA}}^{\mathrm{T}}; \tag{5}$$

$$z_{v(i)} = [V_\xi V_\eta V_\zeta]_{(i)\mathrm{SINS}}^{\mathrm{T}} - [V_\xi V_\eta V_\zeta]_{(i-1)\mathrm{SINS}}^{\mathrm{T}}, \tag{6}$$

where PIA stands for the position of the initial alignment; φ_i, λ_i are SINS geodetic latitude and longitude; $\Delta t_i = t_i - t_{i-1}$ is the observation step; $\bar{\Omega} = \begin{bmatrix}\Omega_\xi & \Omega_\eta & \Omega_\zeta\end{bmatrix}^{\mathrm{T}}$ is the vector of the angular velocity of Earth rotation, given by its components along the axes of the reference frame $o\xi\eta\zeta$, semi free in azimuth; C_0 is the direction cosine matrix that characterizes the angular position of the IMU-fixed frame *oxyz* with respect to the inertial frame $OX_IY_IZ_I$; $\bar{V} = \begin{bmatrix}V_\xi & V_\eta & V_\zeta\end{bmatrix}^{\mathrm{T}}$ is IMU relative velocity vector, given by its components along the axes of the reference navigation frame $o\xi\eta\zeta$.

For the inertial satellite navigation, an integrated operation mode is implemented on the basis of sequential processing of the position and velocity observations by the robust Kalman filter [3]:

$$z_{k(i)} = [\varphi_i \lambda_i]_{\mathrm{SINS}}^{\mathrm{T}} - [\varphi_i \lambda_i]_{\mathrm{GPS}}^{\mathrm{T}}; \tag{7}$$

$$z_{v(i)} = C_{3(i)}^{\mathrm{T}} [V_\xi V_\eta V_\zeta]_{(i)\mathrm{SINS}}^{\mathrm{T}} - [V_E V_N V_H]_{(i)\mathrm{GPS}}^{\mathrm{T}}, \tag{8}$$

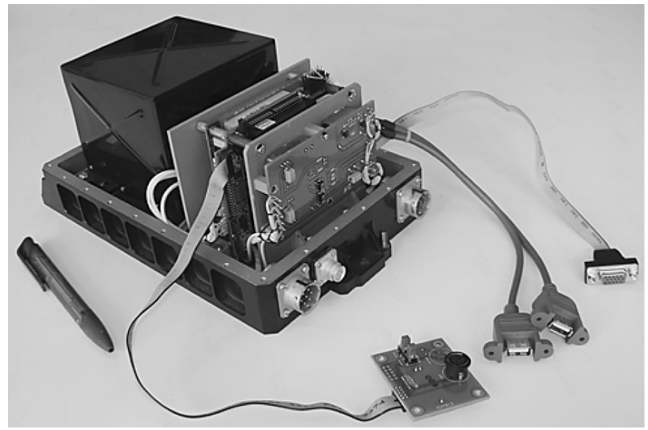

Fig. 3. Strapdown inertial satellite navigation system SINS-500.

where C_3 is the direction cosine matrix that characterizes the angular position of the reference frame $o\xi\eta\zeta$ with respect to the geodetic frame *oENH*.

Seminatural development of the SINS software was performed with account for compensation for the predicted estimations of FOG drifts and accelerometers biases.

In all SISNS operating modes, at the level of primary processing of sensor signals, their combined digital filtering was carried out including the following adjustable procedures:

—input predictive check of signals by the combined goodness-of-fit test χ^2/ϑ^2 [6];

—localization and counteraction of malfunctions [6];

—suppression of noise components of sensor errors through the signal recurrent smoothing [4];

—taking account of calibration coefficients that reflect sensor systematic errors, misalignment of their axes, and thermal drifts.

The first three procedures of primary processing of sensor signals can be combined into a unified structure of a robust digital filter [4, 6].

In the onboard implementation of the basic model of SINS errors, it is deemed possible to have an approximate [13] description of the gyro random drift $\Delta\omega$ and the accelerometer bias Δa as the Markov Gaussian first-order process

$$\Delta\dot{\omega} = -\alpha\Delta\omega + \xi\sigma\sqrt{2\alpha} \tag{9}$$

with the exponential correlation function

$$R(t) = \sigma^2 e^{-\alpha|t|}, \tag{10}$$

where $\alpha = 1/\tau$; τ is the correlation time; $R(0) = \sigma^2$ is the error variance; ξ is the white noise of unit intensity.

In relations (9) and (10), the quantities α and σ are the parameters to be identified during seminatural development of the SISNS software.

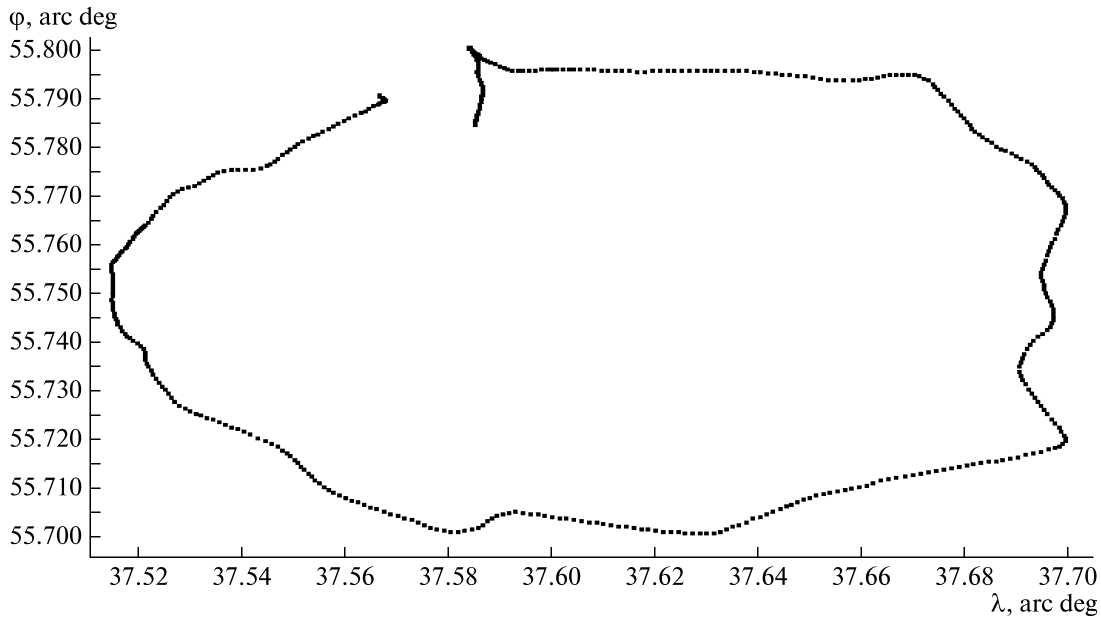

Fig. 4. Horizontal path of the test laboratory motion in urban conditions.

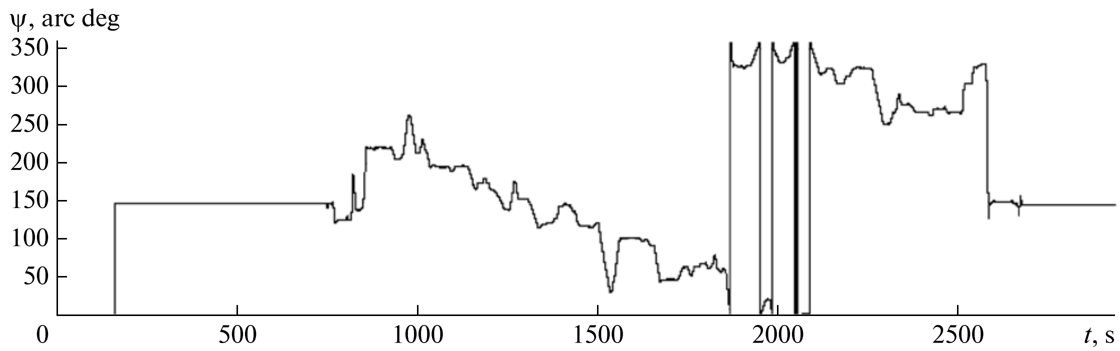

Fig. 5. True heading.

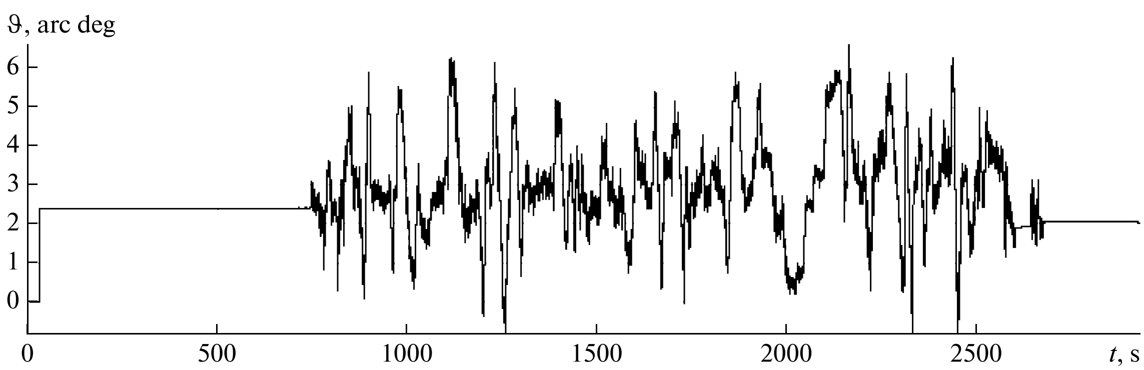

Fig. 6. Angle of pitch.

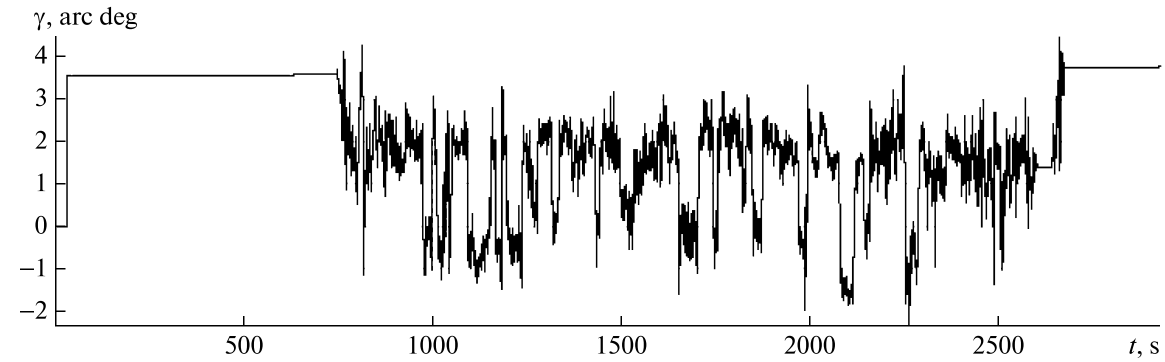

Fig. 7. Angle of roll.

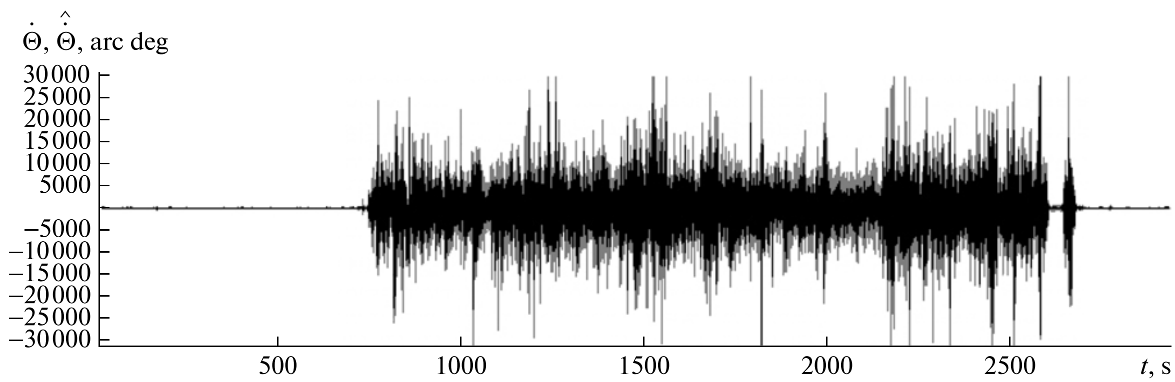

Fig. 8. Output signal of one of the gyros.

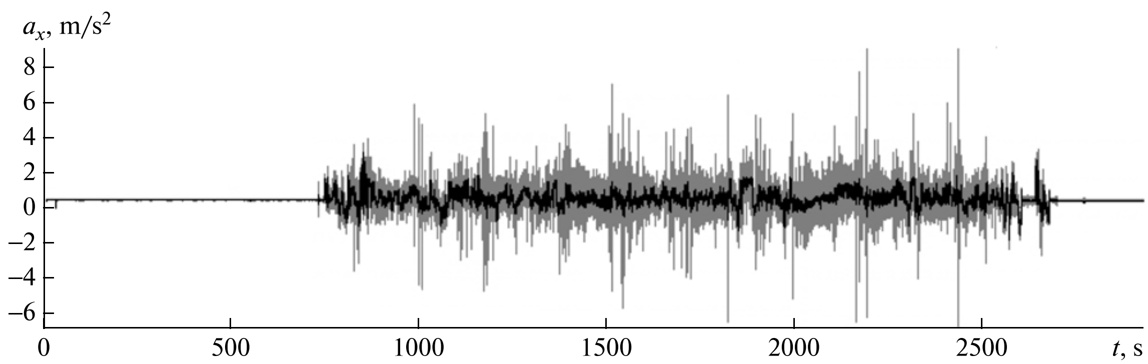

Fig. 9. Output signal of one of the horizontal accelerometers.

To implement the loop for preventive control of sensor state, in the course of seminatural software development, scale factors and coefficients characterizing the misalignment of sensor sensitivity axes are additionally included in the basis vector of SINS errors; these factors and coefficients have been determined under factory calibration conditions. Technological extension of the vector of SINS errors [2] enables one to carry out postflight refinement of the above-mentioned factors and coefficients from the recorded sensor signals in the dynamic mode of SINS operation.

3. ANALYSIS OF THE TEST RESULTS

Experiments were carried out on the ground with the required equipment mounted in a mobile laboratory on an automobile. The timing diagram of operation of the system SINS-500 included the following stages: coarse initial alignment ($t = 0$–100 s), fine ini-

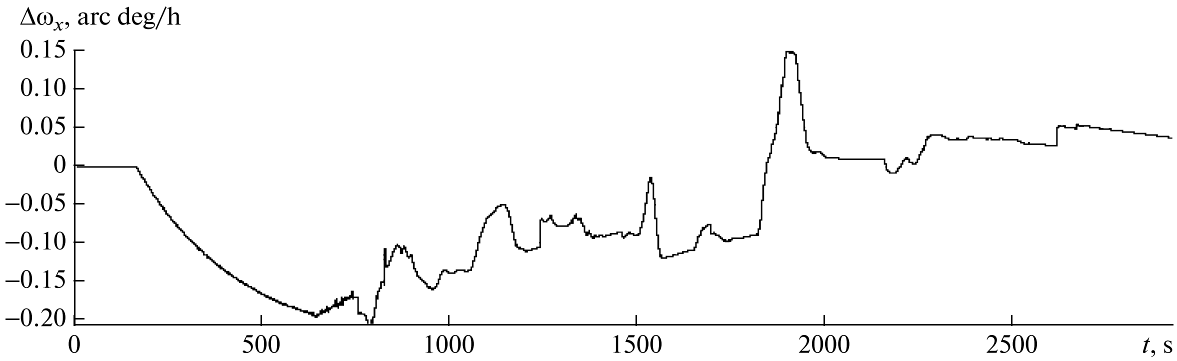

Fig. 10. Estimation of the residual drift for the *ox* FOG.

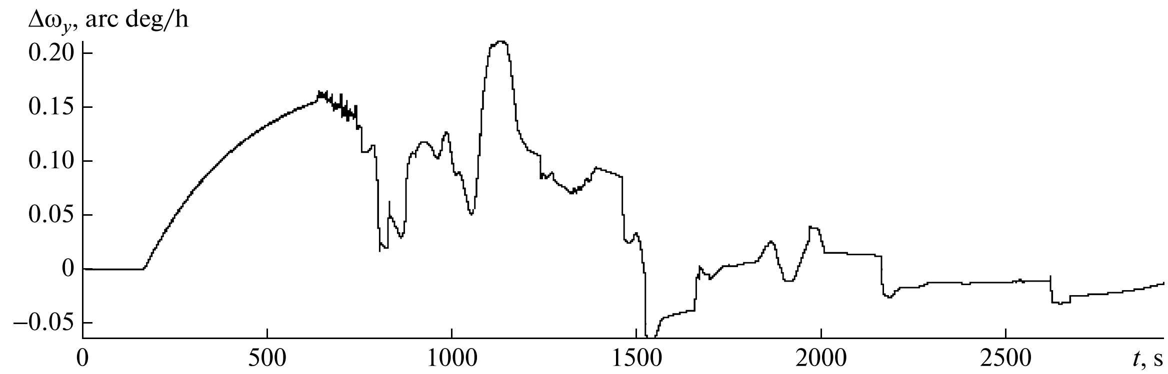

Fig. 11. Estimation of the residual drift for the *oy* FOG.

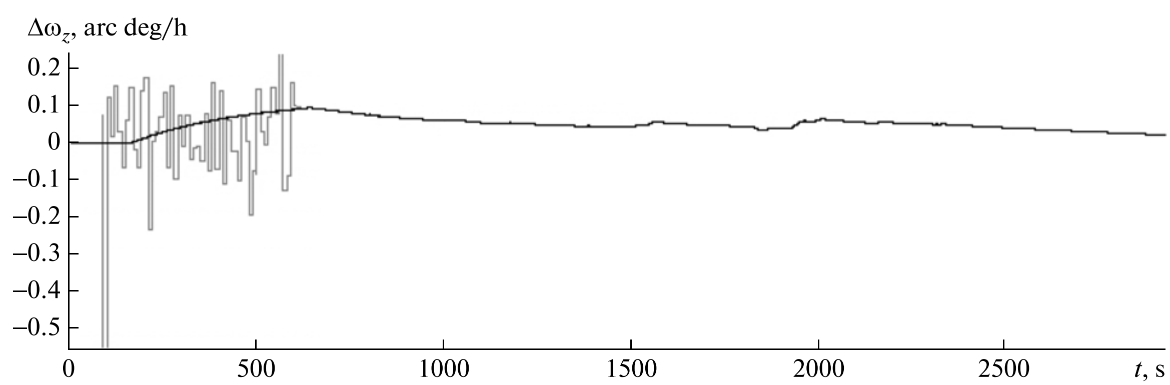

Fig. 12. Actual residual drift of vertical *oz* FOG and its estimation.

tial alignment ($t = 100–600$ s), and navigational mode ($t > 600$ s).

Some results of the SINS-500 accuracy test are shown in Figs. 4–19. The results of comparative analysis of SINS operation when using different schemes for the damping of sensor errors were obtained using reckoning of motion parameters from the recorded signals of IMU and GPS sensors.

Figure 4 shows the horizontal path when the testing laboratory is moving in urban conditions.

In Figs. 5–7, IMU true heading, pitch, and roll angles are shown, respectively.

Figure 8 depicts the following signals: the output signal (a light-colored graph, arc s/s) of one of the gyros; the output signal (a dark-colored graph) of the

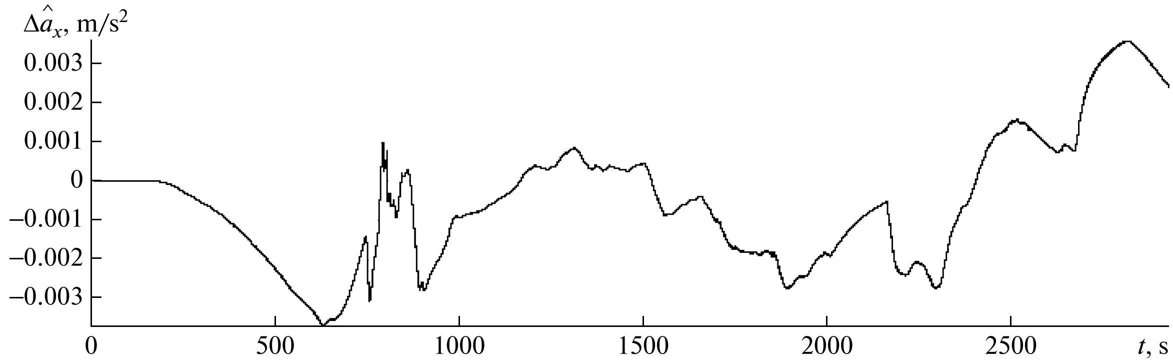

Fig. 13. Bias estimation for the considered accelerometer.

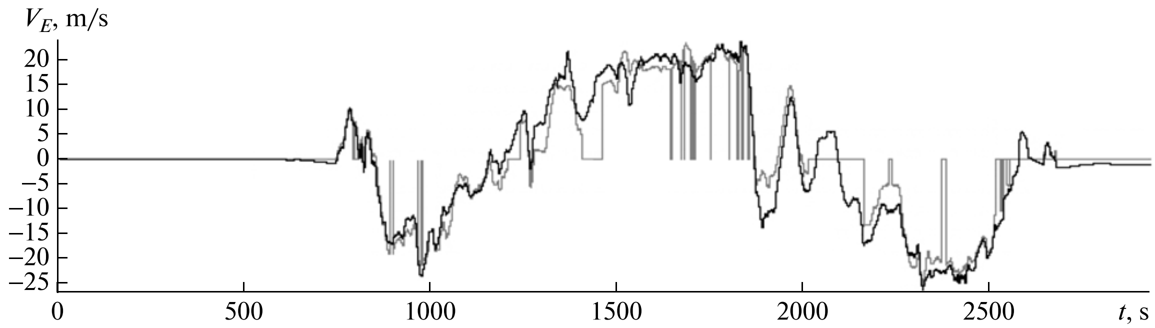

Fig. 14. Dynamics of velocity V_E variation with the coefficients of FOG drift model tuned properly.

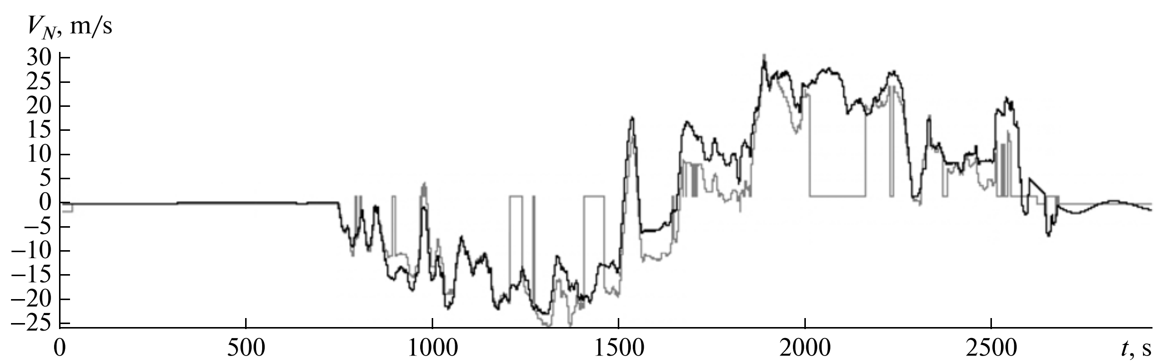

Fig. 15. Dynamics of velocity V_N variation with the coefficients of FOG drift model tuned properly.

same gyro, which was smoothed using a robust digital filter [4].

In Fig. 9, the following signals are shown: the output signal (a light-colored graph, m/s^2) of one of the horizontal accelerometers; the output signal (a dark-colored graph) of the same accelerometer, which was smoothed using a robust digital filter [4]. The above smoothing has been performed when sensor signals were picked off with a frequency of 1 kHz.

Figures 10–12 show estimations of FOG residual drifts. These estimations were obtained in the processing of observations (1)–(5) with a frequency of 1 Hz during the fine initial alignment and in the navigational mode.

Also, Fig. 12 depicts the FOG actual instrumental drift (deg/h), which was determined as the mean value of zero bias on 10 s time intervals during the fine initial alignment.

In Fig. 13, estimation of the bias of the considered accelerometer is shown.

Starting from the moment $t = 600$ s, the system SINS-500 was functioning in the autonomous inertial

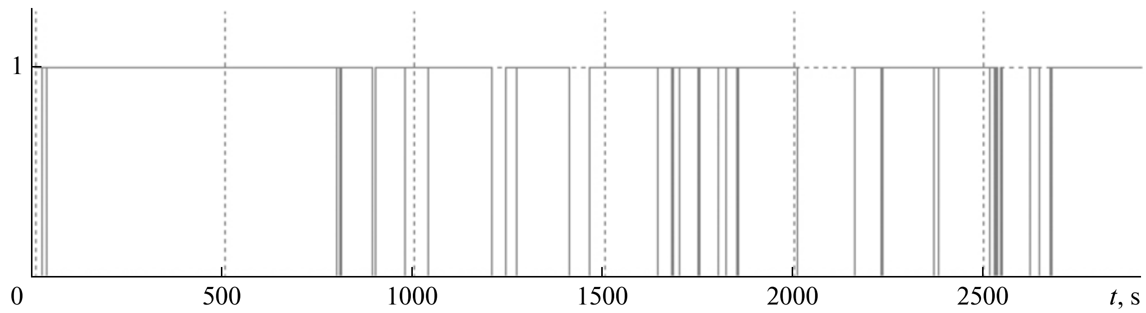

Fig. 16. Indicators of the GPS signal availability when moving in urban conditions.

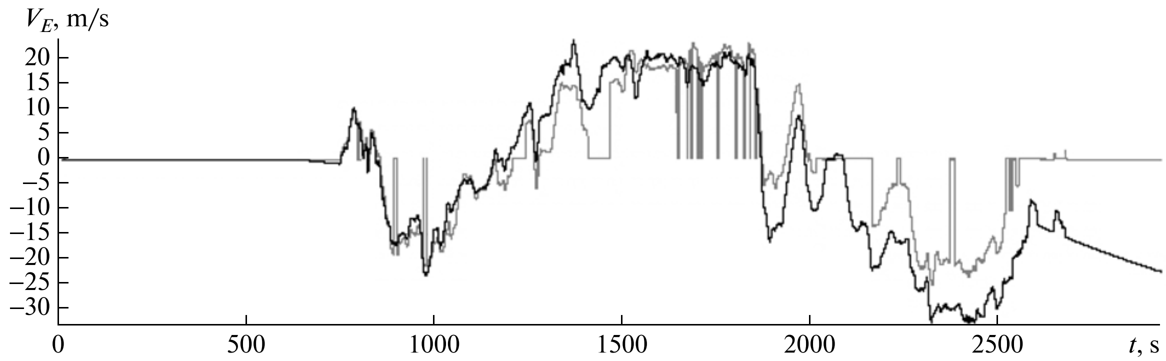

Fig. 17. Dynamics of velocity V_E variation with the coefficients of FOG drift model tuned improperly.

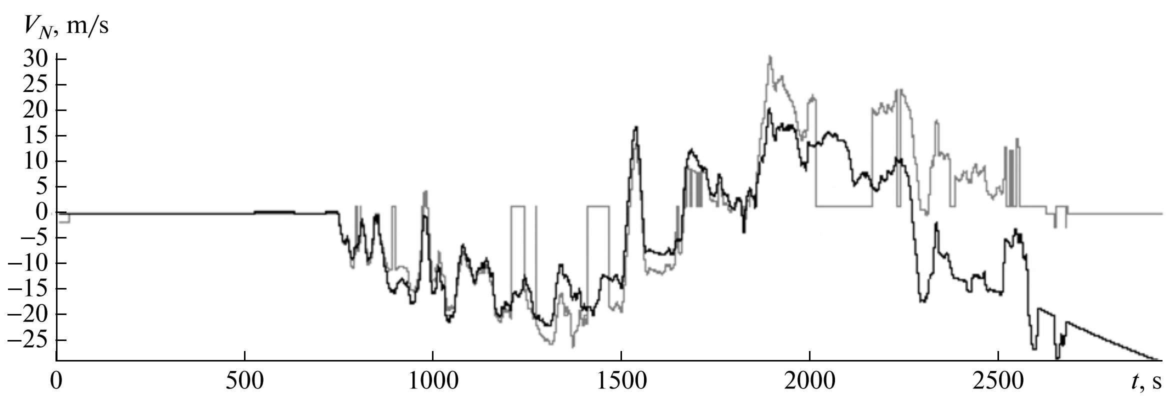

Fig. 18. Dynamics of velocity V_N variation with the coefficients of FOG drift model tuned improperly.

mode and compensation of estimated residual drifts and estimated biases in sensor signals.

Figures 14–18 show the components V_E, V_N of the object relative velocity reckoned by SINS (dark-colored graphs) and determined using GPS (light-colored graphs). Figures 14, 15 depict the dynamics of variation of the above velocities when the drift coefficients α in the model (9) of the gyro random drift and the accelerometer bias are tuned properly ($\tau_a = 960$ s and $\tau_\omega = 720$ s), and Figs. 17, 18 depict the above dynamics when the coefficients mentioned earlier differ ($\tau_a = 120$ s and $\tau_\omega = 3000$ s) from the required ones.

Figure 16 reflects the availability of GPS signals when moving in urban conditions: "1" shows that the signals are available; "0" shows that the signals are unavailable.

The comparison of the results shows that with the parameters of models of sensor errors tuned inaccurately, SINS accuracy characteristics substantially decline.

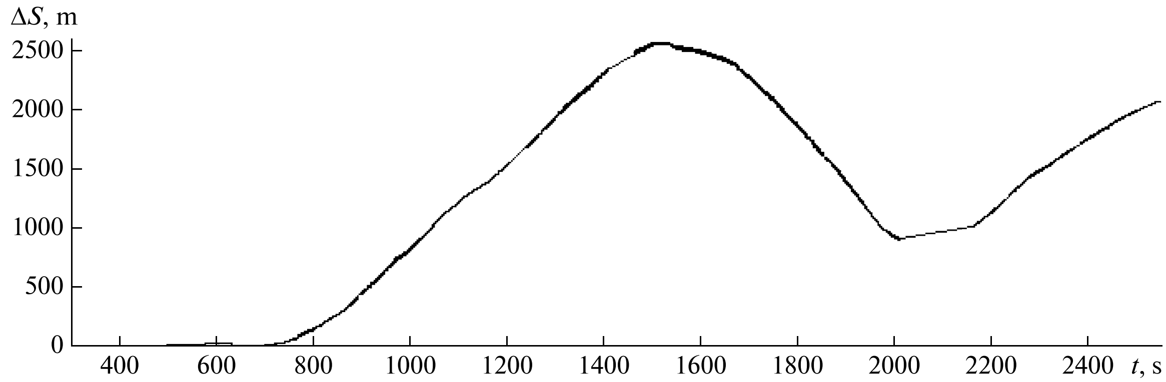

Fig. 19. Dynamics of variation of the object position circular error with the damped sensor drifts.

Figure 19 shows the circular error ΔS of the estimated object position, which corresponds to the reckoning of SINS velocities depicted in Figs. 14 and 15, where

$$\Delta S = \sqrt{\delta_\varphi^2 + \delta_\lambda^2}; \quad \delta_\varphi = (\varphi_{SINS} - \varphi_{GPS})R;$$

$$\delta_\lambda = (\lambda_{SINS} - \lambda_{GPS})R;$$

$$R = a(1 - 0.5e^2\sin^2\varphi); \quad a = 6378245 \text{ m};$$

$$e^2 = 0.0066934.$$

The studies conducted and the graphs presented here corroborate the fact that it is expediency of including the seminatural simulation stage in the structure of the technological process for developing the hardware and software of strapdown inertial satellite navigation systems.

CONCLUSIONS

Seminatural software development for strapdown inertial satellite navigation systems can be carried out from the recorded sensor signals. This approach provides the simulation of actual operating conditions and software optimization on a set of the considered algorithms. The capabilities of modern avionics and of signal acquisition and processing equipment permit making use of seminatural development technology to control SISNS technical state and to update software at all stages of the life cycle.

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