AN OBJECT-ORIENTED TECHNOLOGY FOR THE INTEGRATION OF NAVIGATION SENSORS AND ITS IMPLEMENTATION IN THE SINS-1000 STRAPDOWN INERTIAL SYSTEM BUILT AROUND FIBER-OPTIC GYROS

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Abstract

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Special features of implementing an object-oriented technology for the integration of navigation sensors in strapdown inertial satellite navigation systems (SISNS) are considered. A block diagram of the object-oriented hardware support and object-oriented mathematical-software support for the SINS-1000 system built around fiber-optic gyros is given. The results of testbed experiments and full-scale tests of the SINS-1000 system are presented, which corroborate the fact that it is possible and expedient to apply the proposed technology to the creation of different-purpose SISNSs which can be made to order.

Introduction

The development of airborne equipment is characterized by the designing and introduction of integrated navigation systems (INSs). The necessity and expediency of creating such systems are connected with more rigid requirements that are imposed upon the navigational flight safety of maneuverable aircraft (Acft). Integration of navigation systems (NSs) permits the following problems to be solved:

- maintenance of the continuity and global character of navigational determinations;
- maintenance of the required accuracy characteristics, reliability and integrity of the navigational determinations;
- combination, into a unified structure, of navigation sensors that vary in the operating principle and provision, on this basis, of NS mutual support;
- implementation of the integration capabilities of optimal estimation filters;
- provision of mutual testing and also of the counteraction of outliers and failures;
- maintenance of the required NS operational characteristics under varying noise conditions;
- reduction of the NS readiness time, etc.

The implementation of the INS potentialities requires that the computational process be adequately organized. Such an organization must exclude phase distortions and must provide the required frequency of determining the parameters of Acft motion.

In the present paper, an object-oriented technology intended for construction of the mathematical and hardware support of INSs is discussed. Such a technology involves tuning the hardware part to the problem being solved and also mapping the INS algorithms onto a measurement-computer environment (MCE), which is reconfigurable. The reconfigurable MCE permits the hardware and mathematical software of INSs to developed operationally when both testbed experiments and full-scale experiments are carried out.

The purpose of this paper is to improve INS operational characteristics on the basis of an object-oriented technology intended for the integration of navigation sensors.

Among the INS operational characteristics which significantly affect the navigational safety we may reckon the INS accuracy, INS reliability, INS integrity, and INS operational-readiness time.

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1. An Object-Oriented Technology for the Hardware Support of Integrated Strapdown Inertial Satellite Navigation Systems

At the "OPTOLINK" RPC (Zelenograd), the object-oriented technology is considered as a base one in the design of integrated strapdown inertial satellite navigation systems (SISNSs), which are built around fiber-optic gyros (FOGs), in particular around the SINS-500 and SINS-1000 systems. Figure 1 shows a SINS-1000 system prototype, and its block diagram is depicted in Fig.2.

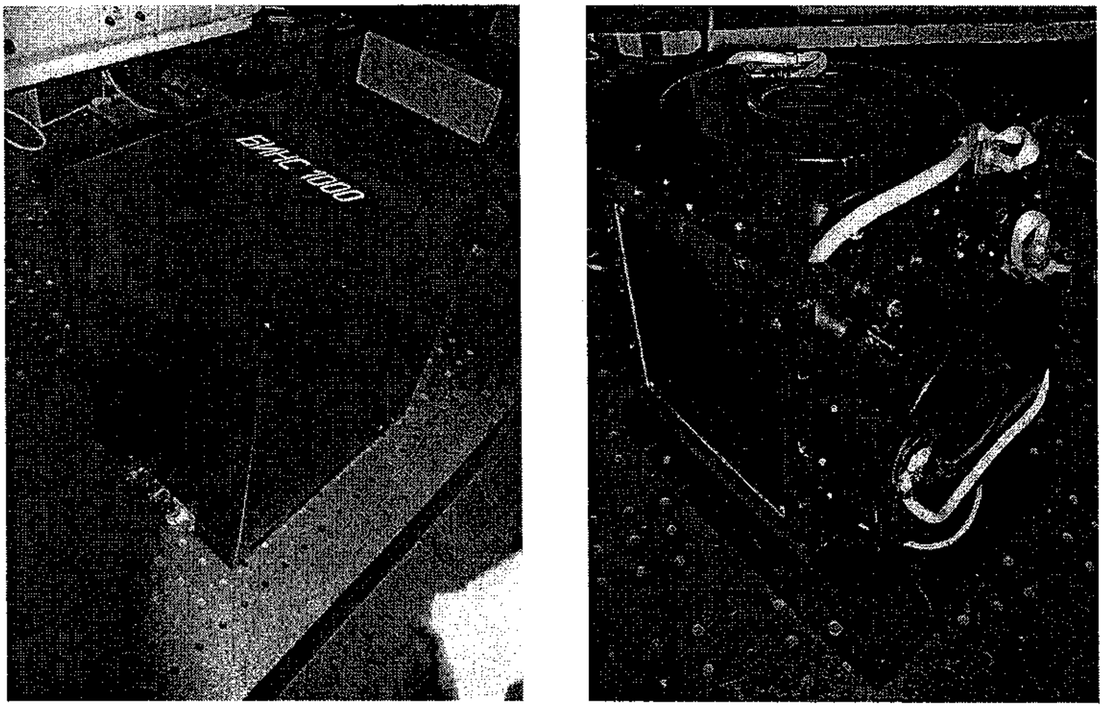


Fig.1. SINS-1000 strapdown inertial satellite navigation system

In these systems, the hardware tuning of a measurement-computer environment relies on the preliminary structuring of the algorithmic support and it is aimed at solving the following problems:

- based on the basic MCE architecture, provision of a possibility to implement different variants of SISNS organization, depending upon the object proper purpose, the required operational characteristics, and cost;
- sequential extension of the computational capability of an MCE kernel when various SISNS operating modes are implemented in a ripple-through fashion;
- provision of a possibility for multilevel hierarchical organization of the computational process;
- minimization of hardware expenditure on the basis of a modular integrated MCE architecture;
- provision of the possibilities for MCE reconfiguration and MCE adaptation to the ISNS and object operating modes on a basis of the unification of both hardware and software modules. The PC-104 standard has been taken as a base one in the design of a SINS series, which are built around FOGs;
- provision of a possibility for the preprocessing of digitized sensor information;
- provision of a possibility for the adaption of MCE interfaces to an object;
- provision of a possibility to implement all the computational procedures in the clock time that is established by the reference generator. Such a possibility can be realized on a basis of the following technological decisions:
  - data-flow RISC organization of the computational process;
  - buffering and paralleling of the input and output information;
  - synchronization of the procedures for data gathering, data processing, and data recording at all hierarchies;
  - use of the MCE system bus in order for data exchange among the SISNS modules to be accelerated.

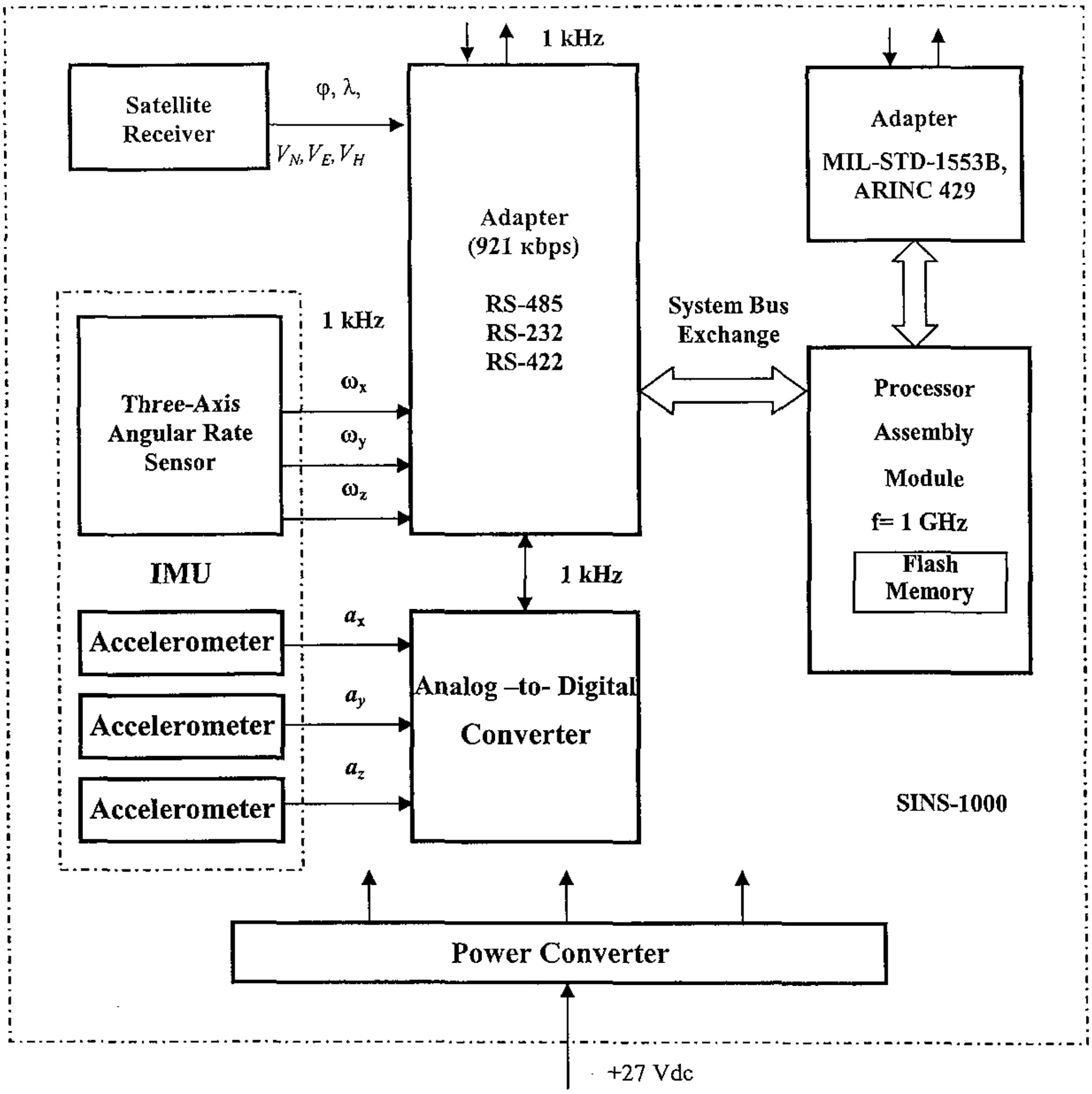


Fig. 2. Block diagram of the SINS-1000 strapdown inertial satellite navigation system

2. An Object-Oriented Technology for the Mathematical-Software Support of Integrated Strapdown Inertial Satellite Navigation Systems

The object-oriented technology for a mathematical-software support (MSS) involves mapping the ISNS algorithms onto a reconfigurable measurement-computer environment. Such a technology relies on the solution of the following problems:

- distribution of data gathering, data processing, and data recording problems among the MCE hierarchies;
- structuring of the ISNS algorithmic support with the aim of carrying out 1) the unification of mathematical–software modules and 2) data-flow RISC organization of computations;
- mapping of unified mathematical-software modules onto the MCE multilevel hierarchical structure;
- making the procedures of primary and second processing of navigation sensor signals agree with the MCE computational capability;
- increasing the degree of computational-process homogeneity on a basis of minimizing the number of tests and conditions.

In designing an MSS for the SINS-1000 system, the following object-oriented technological decisions have been used, which rely on tightly-coupled schemes for the damping of SINS errors [1]:

- homogeneity and data-flow implementation of algorithms for SINS autonomous functioning were achieved on the basis of solving quaternion equations separately for attitude parameters, for navigation parameters, and for their errors, 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 q_0 is a quaternion that characterizes the angular position of the frame *oxyz*, which is fixed to the inertial measurement unit (IMU), with respect to the inertial frame $OX_IY_IZ_I$ [2]; q_1 is a quaternion that characterizes the angular position of the wander azimuth reference navigation frame $o\xi\eta\zeta$ with respect to the ECEF frame $OX_EY_EZ_E$ [2,3].

$$\Pi_0 = \begin{bmatrix} 0 & \dot{\Theta}_y & -\dot{\Theta}_x & -\dot{\Theta}_z \\ -\dot{\Theta}_y & 0 & \dot{\Theta}_z & -\dot{\Theta}_x \\ \dot{\Theta}_x & -\dot{\Theta}_z & 0 & -\dot{\Theta}_y \\ \dot{\Theta}_z & \dot{\Theta}_x & \dot{\Theta}_y & 0 \end{bmatrix}; \qquad \Pi_1 = \begin{bmatrix} 0 & -\omega_\xi & -\omega_\eta & -\omega_\zeta \\ \omega_\xi & 0 & \omega_\zeta & -\omega_\eta \\ \omega_\eta & -\omega_\zeta & 0 & \omega_\xi \\ \omega_\zeta & \omega_\eta & -\omega_\xi & 0 \end{bmatrix};$$

$\dot{\bar{\Theta}} = \begin{bmatrix} \dot{\Theta}_x & \dot{\Theta}_y & \dot{\Theta}_z \end{bmatrix}^T$ is the vector of FOG output signals; $\bar{\omega} = \begin{bmatrix} \omega_\xi & \omega_\eta & \omega_\zeta \end{bmatrix}^T$ is the vector of turn rates of the reference frame $o\xi\eta\zeta$ in the geodetic frame [4]. Moreover, for the wander azimuth frame, $\omega_\zeta = 0$. Components of the vector $\bar{\omega}$ are determined from the orthogonal components V_ξ, V_η, V_ζ of the ground velocity vector $\bar{V}$, which are taken from the solution of the basic equation of inertial navigation, i.e.,

$$\dot{\bar{V}} = C_2{}^T \ \bar{a} + \bar{g} - 2\bar{\Omega} \times \bar{V} - \bar{\omega} \times \bar{V} - \bar{\Omega} \times \left(\bar{\Omega} \times \bar{R}\right), \tag{4}$$

where

$\bar{V} = [V_\xi \quad V_\eta \quad V_\zeta]^T$ is the ground velocity vector of IMU motion, given by its components along the axes of the reference navigation frame $o\xi\eta\zeta$;

$\bar{a} = [a_x \quad a_y \quad a_z]^T$ is the vector of output signals of accelerometers;

$\bar{g} = [g_\xi \quad g_\eta \quad g_\zeta]^T$ is the vector of gravitational acceleration;

$\bar{\Omega} = [\Omega_\xi \quad \Omega_\eta \quad \Omega_\zeta]^T$ is the vector of the angular velocity of Earth rotation;

$\bar{R} = [0 \quad 0 \quad R]^T$ is the IMU position vector;

$(\times)$ is the operator of vector product;

C_2 is the direction cosine matrix (DCM) which characterizes the angular position of the IMU-fixed frame *oxyz* with respect to the reference frame $o\xi\eta\zeta$, and the above matrix is determined from the elements of the quaternions q_0, q_1 and from the angle $\Omega\Delta t$, where Δt is the time of SINS functioning. Furthermore, from the elements of these quaternions 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; Π_0, Π_1 are skew-symmetric matrices the signs of elements of which correspond to the IMU design; $x(t)$ is the vector of SINS errors.

Separate solution of Eqs.(1) and (2) has made it possible to bring the depth of estimation of SINS errors to the level of sensors: gyroscopes and accelerometers. The basic vector $x(t)$ was comprised of 17 parameters, namely: the errors $\Delta V_\xi, \Delta V_\eta, \Delta V_\zeta$ in the reckoning of components of the ground 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 $\Delta a_x, \Delta a_y, \Delta a_z$

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 (1),(2), (4) 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 $\xi(t)$; homogeneity and data-flow implementation of algorithms for the integration of a SINS and the GPS were achieved on a basis of the W-D technology [5] for observation processing. Procedures for such processing rely on an $U - D$ modification of the Kalman-Joseph filter, which is characterized by computational stability, and they result from the following identity:

$$P_{i/j} = W_{i/j}\overline{D}_{i/j}W^T{}_{i/j} = U_{i/j}D_{i/j}U^T{}_{i/j}, \tag{5}$$

where

$P_{i/j}$ is the value of the "a posteriori" covariance matrix of estimation errors at the i –th step, which is obtained after processing the j-th component of the vector z_i of observations;

$W_{i/j}$ is an $n \times (n+j)$ rectangular matrix;

$\overline{D}_{i/j}$ is an $(n+j) \times (n+j)$ diagonal matrix;

$U_{i/j}$ is an $n \times n$ upper triangular matrix with identity diagonal elements;

$D_{i/j}$ is an $n \times n$ diagonal matrix.

On the basis of identity (5), a *W–D* modification of the algorithm for adaptive robust processing of observations was implemented, which has the following form:

Prediction

$$m_0 = \hat{x}_{i/i-1} = \Phi_i \hat{x}_{i-1/i-1}; \tag{6}$$

$$W_0 = \left[\Phi_i U_{i-1/i-1} \vdots \Gamma_i\right]; \tag{7}$$

$$\overline{D}_0 = diag(D_{i-1/i-1}, Q_{i-1}); \tag{8}$$

Tuning

$$\nu_j = z_j - H_j m_{j-1}; \qquad \beta_j = \nu_j / \alpha_j; \tag{9}$$

$$\psi_j = \psi(\beta_j); \qquad \psi'_j = \psi'(\beta_j); \tag{10}$$

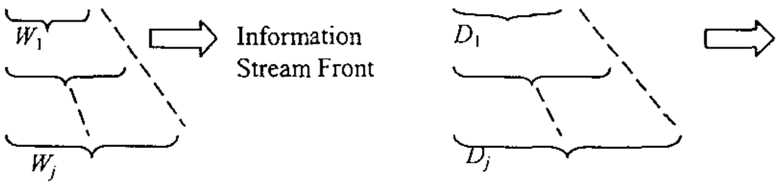
Updating

$$f_j = H_j W_{j-1}; \qquad V_j = \overline{D}_{j-1} f_j^T; \tag{11}$$

$$\tilde{\alpha}_j = f_j V_j \psi'_j + \alpha_j^2; \qquad K_j = W_{j-1} V_j / \tilde{\alpha}_j; \tag{12}$$

$$m_j = m_{j-1} + K_j \alpha_j \psi_j; \qquad \hat{x}_{i/i} = m_l; \; j = \overline{1,l}; \tag{13}$$

$$W_j = \left[W_0 \vdots K_1 \vdots \ldots \vdots K_j\right] \qquad \overline{D}_j = diag(\overline{D}_0, \alpha_1{}^2 \upsilon'_1, \ldots, \alpha_j{}^2 \psi'_j) \tag{14}$$



Orthogonal transformation

$$MWGS\left\{W_l; \overline{D}_l\right\} \to U_{i/i}; D_{i/i}, \tag{15}$$

where m_j, $\hat{x}_{i/i}$ are the estimates of the vector of SINS errors at the i-th step, which are obtained after processing the j-th component and the whole vector z_i of observations; α_j is a scaling parameter; Φ_i, Γ_i are transition matrices for the vector x_i of state and for the vector ξ_i of disturbances, respectively; Q_i is the covariance matrix for the vector of disturbances; ψ_j, ψ'_j are an influence function and its derivative [6], which set up the level of confidence in the incoming observations. These functions are formed with due regard for "a priori" assumptions made as to the distribution laws of the valid signal and noise, or the above functions are tuned in an adaptive way [7]; MWGS is the procedure [8], intended to transform the aggregate of matrices W_l and $\bar{D}_l$, which are an $n \times (n+l)$ matrix and an $(n+l) \times (n+l)$ matrix, respectively, into the aggregate of the $n \times n$ matrices $U_{i/i}$, $D_{i/i}$.

Data-flow organization of computations has enabled us to take the orthogonalization procedure (15) out of the basic loop of observation processing (9) – (14) and to execute it only once.

Algorithm (6) – (15) has been implemented at the level of primary and second processing of signals. Its place in the MSS structure for the SINS-1000 system is shown in Fig. 3, where Acc is the accelerometer triad; ARS is the triad of angular-rate sensors; DF is a digital filter; RKF is a robust W-D modification of the Kalman filter; CC is a coordinate converter; $\hat{x}_{\bar{a}}$ is the vector of estimates of the biases of accelerometer signals; $\hat{x}_{\bar{\omega}}$ is the vector of estimates of FOG drifts.

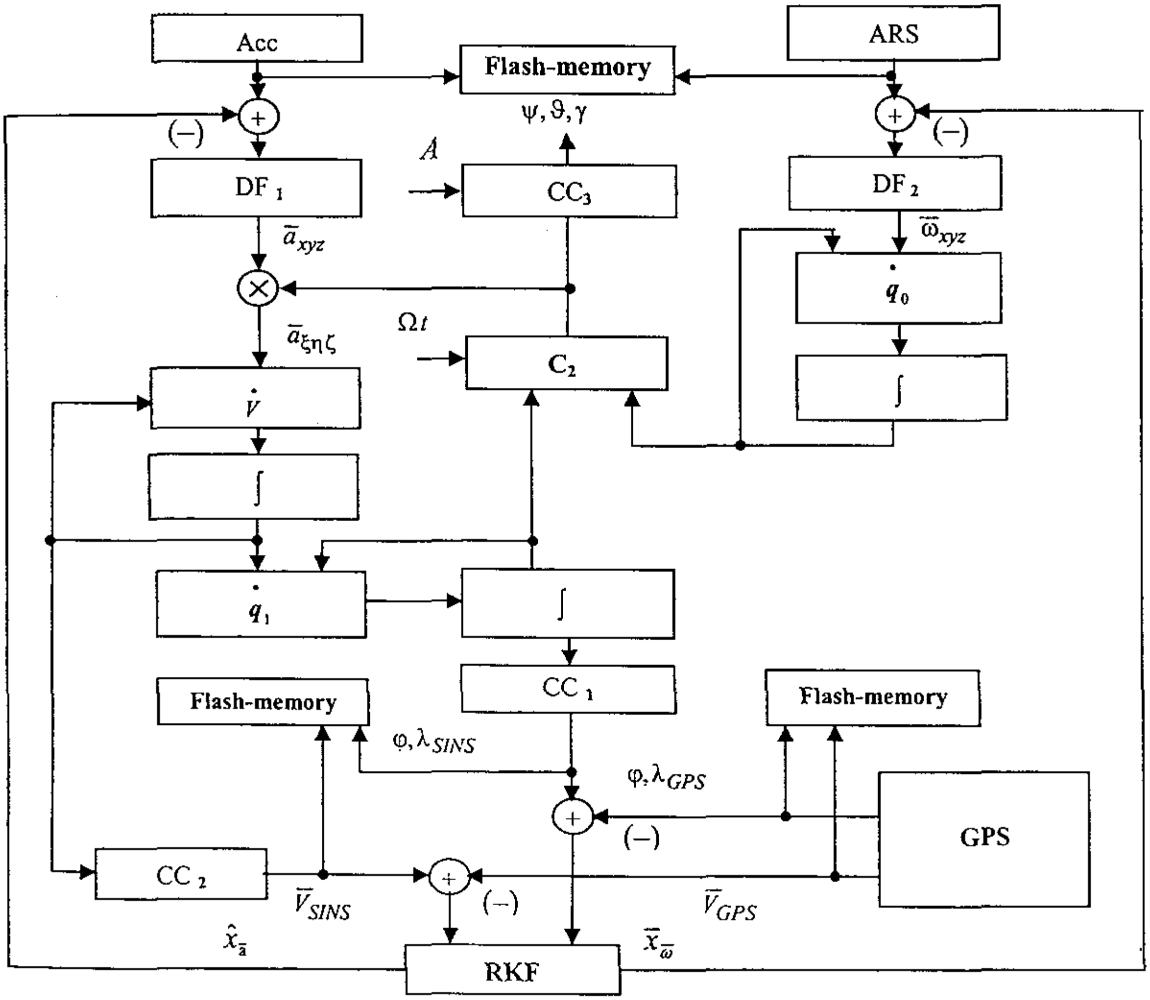


Fig.3. Block diagram of the mathematical-software support for the SINS-1000 system

3. Analysis of the Results of Studies

The SINS -1000 integrated strapdown inertial satellite navigation system that is built around the FOG -1000 fiber-optic gyros designed by the "OPTOLINK" RPC (Zelenograd) and also based on the K-161 satellite receiver developed by the "RIRT" JSC (Saint-Petersburg) has been the object of experimental studies [16].

Experiments have been carried out on the ground when the necessary equipment was placed on a test bed and then housed in a mobile laboratory. The timing diagram of SINS operation included the following stages: coarse initial alignment, fine initial alignment, and a navigational mode. At the stage of coarse initial alignment, IMU angular position was approximately determined using sensor output signals. At the stage of fine initial alignment, estimation of and compensation for both the errors of the angular position of IMU sensors and IMU sensor drifts were carried out by the sequentially processing of the observed signals z_i of the following form:

$$z_{\Theta(i)} = C_{0(i)}^{\mathrm{T}} \int_{t_{i-1}}^{t_i} \dot{\overline{\Theta}}(\tau)d\tau - [0\vdots 0\vdots \Omega\Delta t_i]^{\mathrm{T}} ; \tag{16}$$

$$z_{k(i)} = [\varphi_i\lambda_i]_{\mathrm{SINS}}^{\mathrm{T}} - [\varphi_i\lambda_i]_{\mathrm{FIA}}^{\mathrm{T}} ; \tag{17}$$

$$z_{\mathrm{v}(i)} = [V_\xi V_\eta V_\zeta]_{(i)\mathrm{SINS}}^{\mathrm{T}} , \tag{18}$$

where FIA stand for the position of fine initial alignment; φ_i, λ_i are the geodetic latitude and longitude of the SINS position; $\Delta t_i = t_i - t_{i-1}$ is an observation step.

In the navigational mode, SINS errors were estimated and compensated for from position and velocity observations, i.e.,

$$z_{k(i)} = [\varphi_i\lambda_i]_{SINS}^{\mathrm{T}} - [\varphi_i\lambda_i]_{GPS}^{\mathrm{T}} ; \tag{19}$$

$$z_{\mathrm{v}(i)} = C_{3(i)}^{\mathrm{T}}[V_\xi V_\eta V_\zeta]_{(i)SINS}^{\mathrm{T}} - [V_E V_N V_H]_{(i)GPS}^{\mathrm{T}} , \tag{20}$$

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

The results of a comparison analysis of SINS operation when using different schemes for the damping of sensor errors were obtained on a basis of the reckoning of motion parameters from the recorded signals of sensors such as the IMU and the GPS.

Certain of the results of a testbed experiment on the estimation of accuracy characteristics of the SINS 1000 system are shown in Figs.4-7. Figure 4 depicts the following signals: the output signal (a light-colored graph, arc secs/sec) of the "vertical" gyro; the output signal (a dark-colored graph) of the same gyro, which was smoothed by means of a robust digital filter [10]. In Fig.5, the following signals are shown: the output signal (a light-colored graph, m/sq.sec) of one of horizontal accelerometers; the output signal (a dark-colored graph) of the same accelerometer, which was smoothed with the aid of a robust digital filter. The above smoothing has been performed when sensor signals were picked off with a frequency of 1 kHz. Figure 6 depicts the FOG actual instrumental drift (deg/h), which is determined as the mean value of "zero" bias on the time intervals of 10 sec, and its estimate which was obtained both in the processing of observations (16)-(18) with a frequency of 1 Hz during the fine initial alignment (100-600 sec) and when predicting such an estimate in the navigational mode with the aid of algorithm (6). In Fig.7, an estimate of the accelerometer bias is shown. Beginning with the moment t=600 sec, the SINS-1000 system was functioning in the autonomous inertial mode. Figures 8-11 show errors in the reckoning of the ground velocity ΔV and circular error in the object position ΔS. Figure 8 reflects the dynamic behavior of the ground velocity error when sensor drifts are damped, and Figure 9 reflects the above behavior when the sensor drifts are not damped. Figure 10 reflects the dynamic behavior of the circular error in the object position when sensor drifts are damped, and Figure 11 reflects the dynamic behavior of the circular error in the object position when sensor drifts are not damped.

Figures 12-17 reflect certain of the results of experiments conducted in the mobile laboratory. In Figs. 12-14 the true heading, pitch, and roll of the IMU are shown, respectively. In Fig. 15, the ground velocity is depicted when the testing laboratory is moving under urban conditions. The timing diagram of SINS operation under dynamic conditions is as follows: coarse initial alignment (0-10 sec); fine initial alignment (10-15 sec); algorithm (16)-(18); navigation (15-220sec); algorithm (19),(20). Figure 16 shows the error ΔV of estimating the ground velocity, and Fig. 17 depicts the circular error ΔS of estimating the object position, where

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

$$R = a(1-0{,}5e^2\sin^2\varphi);\ a=6378245\ \text{м};\ e^2 = 0{,}0066934;$$

$$\Delta V_E = V_{E(SINS)} - V_{E(GPS)} ; \Delta V_N = V_{N(SINS)} - V_{N(GPS)} ; V_{E(SINS)} = V_\xi \cos A - V_\eta \sin A ; \quad V_{N(SINS)} = V_\xi \sin A - V_\eta \cos A .$$

A is the azimuth angle of the reference frame $o\xi\eta\zeta$ with respect to the local geodetic frame $oENH$.

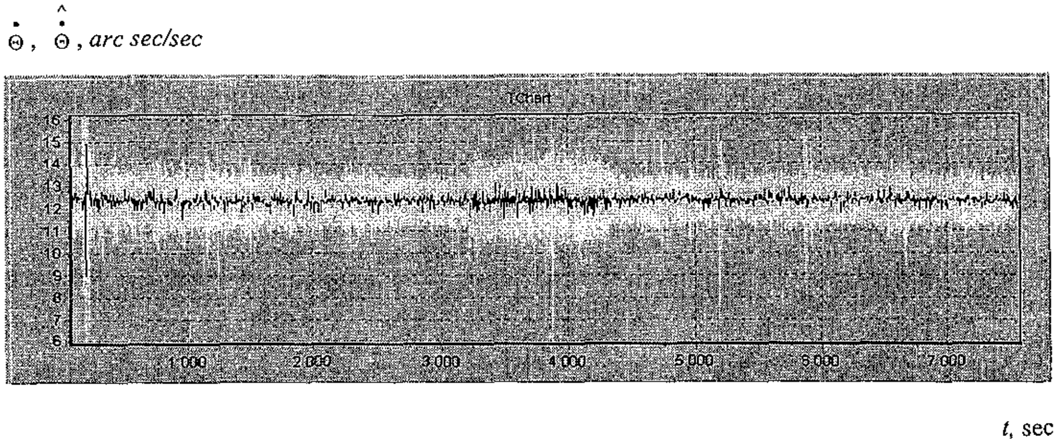


Fig. 4. Output signal of the "vertical" gyro

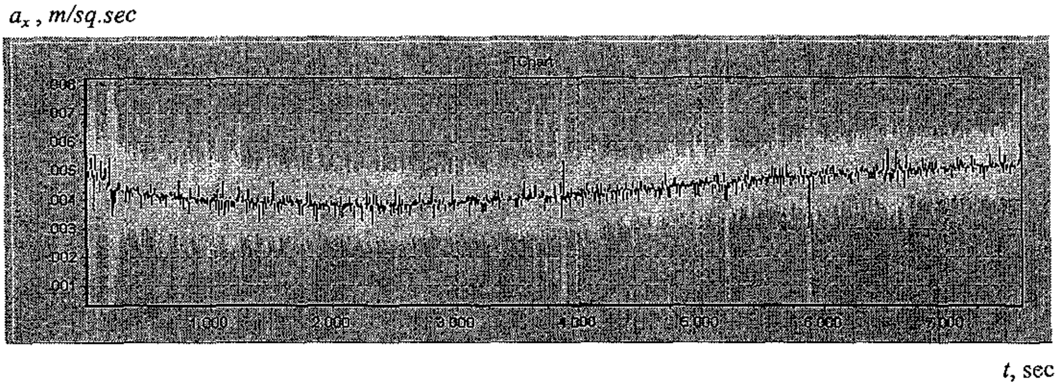


Fig. 5: Output signal of one of horizontal accelerometers

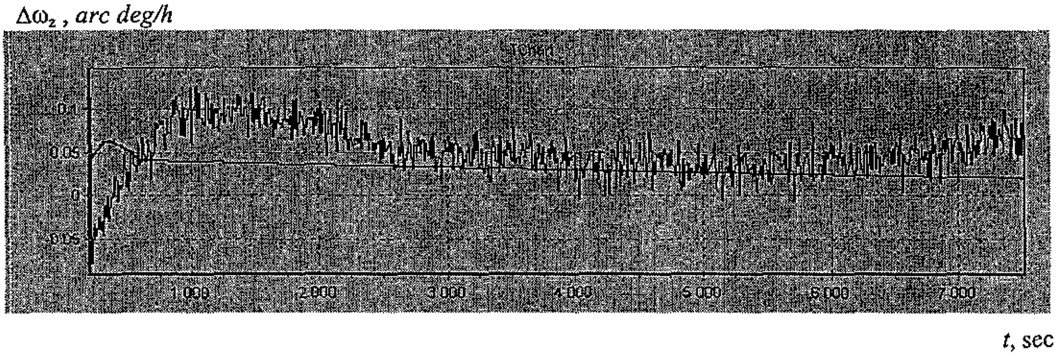


Fig. 6. FOG instrumental drift and its estimate

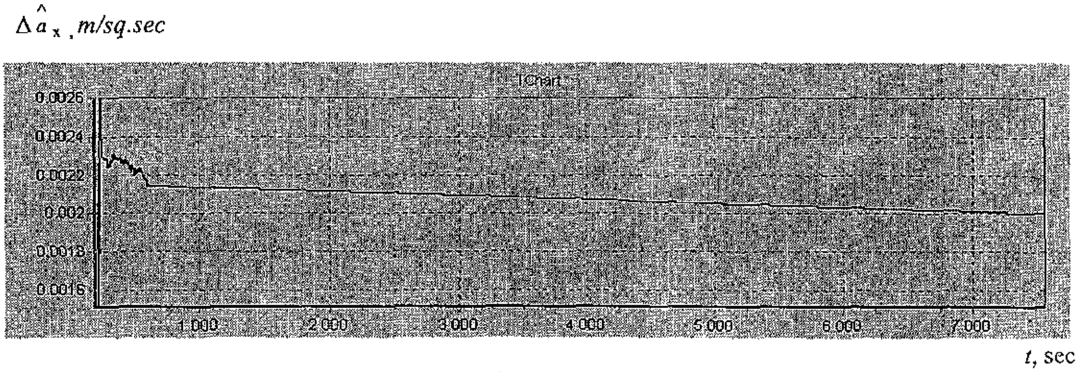


Fig. 7. Accelerometer bias estimate

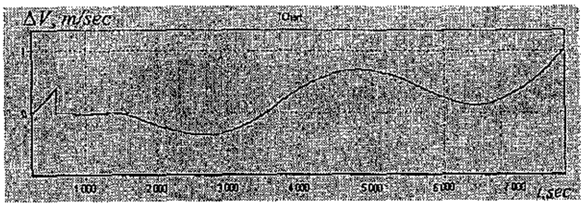


Fig. 8. Dynamic behavior of the errors of the ground velocity when sensor drifts are damped

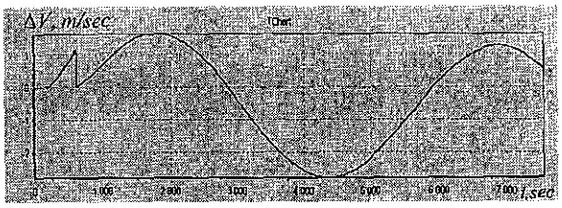


Fig. 9. Dynamic behavior of the errors of the ground velocity when sensor drifts are not damped

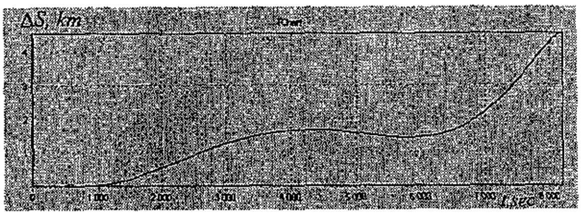


Fig. 10. Circular error of the object position estimate when sensor drifts are damped

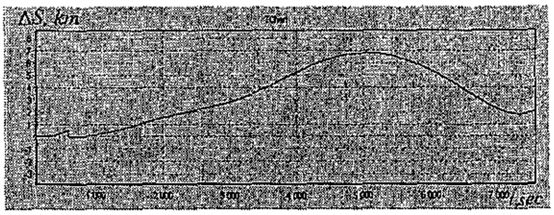


Fig. 11. Circular error of the object position estimate when sensor drifts are not damped

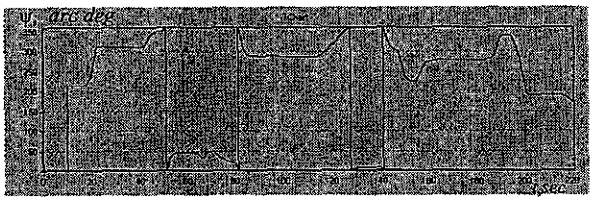


Fig. 12. True heading

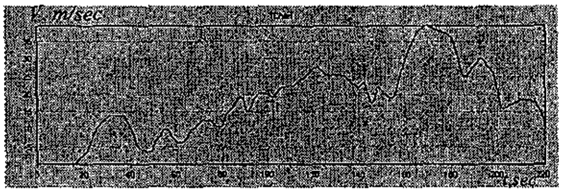


Fig. 15. Ground velocity

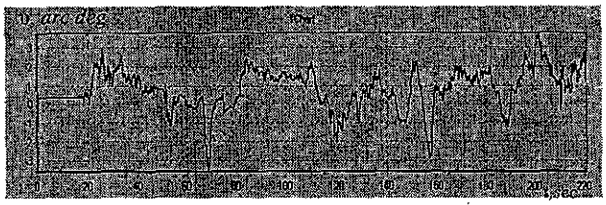


Fig. 13. Angle of pitch

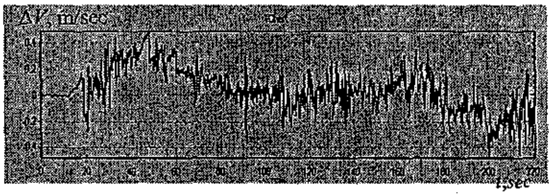


Fig. 16. Error of the ground speed estimate

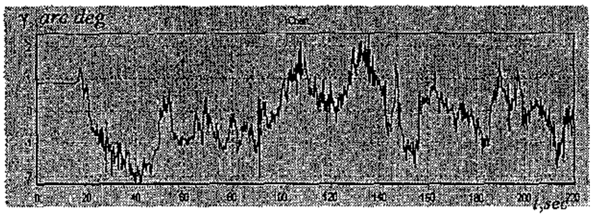


Fig. 14. Angle of roll

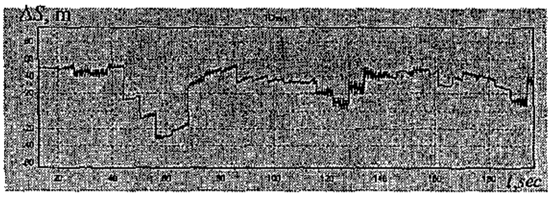


Fig. 17. Circular error of the object position estimate

The studies conducted have corroborated the fact that it is effective to apply the object-oriented technology to the creation of SINSs which can be made to order.

Conclusions

In the paper presented here, an object-oriented technology for the integration of navigation sensors is considered. Such a technology is closely connected with systems approaches to the design of different-purpose airborne equipment according to the cost-effectiveness criterion. The employment of the above technology in creating the

SINS-1000 strapdown inertial satellite navigation system built around fiber-optic gyros is demonstrated. Systems design of the mathematical-software support and hardware support (MSS&HS) for the SINS-1000 system has been performed beginning with the problem that is the most consuming one in the sense of computational resources, i.e., the problem of the integration of navigation sensors at all hierarchies. In this case, it is apparently possible to keep the MSS&HS organization unchanged when different attitude parameters and different navigation parameters are used and also when mathematical models of sensor errors are updated.

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