SEMINATURAL DEVELOPMENT OF MULTIPOSITION INERTIAL SATELLITE NAVIGATION SYSTEMS BUILT AROUND FIBER-OPTIC AND MICROMECHANICAL SENSORS *

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Abstract

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Basic features of the construction and use of multiposition strapdown inertial navigation systems (MSINSs), which are built around sensors having different operating principles are considered. New properties of the above MSINSs, which are connected with their unification into a single structure are justified. The possibility for the raising of both their accuracy characteristics and their reliability characteristics is shown. The proposed approaches to the realization of such a possibility for the MSINSs rely on majority schemes of stochastic monitoring and on the optimization of the structure of distributed sensors.

Monitoring and Optimization of the Structure of a Multiposition SINS

The current state of airborne measuring-and-computing complexes (MCCs) is characterized by the inclusion of multiposition strapdown inertial navigation systems (MSINSs) as components of these complexes. This is associated with the necessity of the provision of navigational support not only for aircraft (Acft), but also for airborne Earth surface surveillance systems in which the SINSs are included as components. Among such systems are radar systems, video monitors, laser scanners (lidars), and other surveillance devices.

At the same time, when the MSINSs are united into a single structure, new functional possibilities for such integrated navigation systems appear, namely: redundancy and mutual support of SINSs, and also an increase in MCC information reliability on this basis; mutual monitoring and mutual diagnosis of SINSs; optimization of MSINS structure for providing the required accuracy of navigation and attitude control under severe conditions of Acft operation.

Due to restrictions on overall dimensions and weight, SINSs of surveillance systems are built on the basis of microelectromechanical sensors (MEMSs). Such sensors have a wide insensitivity zone and low accuracy. Taking account of the above-mentioned features, SINS-MEMSs must rely on a base high-accuracy SINS which forms part of an Acft navigation complex. Moreover, the SINS-MEMSs cannot execute the initial alignment from attitude angles in the autonomous mode. Because of this, the initial alignment of such SINSs is realized from information obtained from the base system.

The features mentioned earlier were taken into account in a MSINS developed by the NaukaSoft Experimental Laboratory, Ltd., the Bauman Moscow State Technical University and "OPTOLINK" RPC in cooperation. A breadboard model of the MSINS is presented in Fig.1, where the following is shown:
SINS-500NS is a strapdown inertial satellite navigation system, which is based on fiber-optic gyros (FOGs), and the FOGs just mentioned were developed jointly by the "NaukaSoft EMNS" and by the "OPTOLINK" RPC; micromechanical SINS-MEMSs built on the basis of the ADIS16488 measuring modules developed by the Analog Devices Co. Technological decisions that are considered in the present paper have been executed on a basis of the Ethernet and Linux real-time operating system which provides the support of a modular architecture of the MSINS construction.

The purpose of this paper is to study the potentialities of MCCs when the MSINSs are united into a closely connected information-measuring structure.

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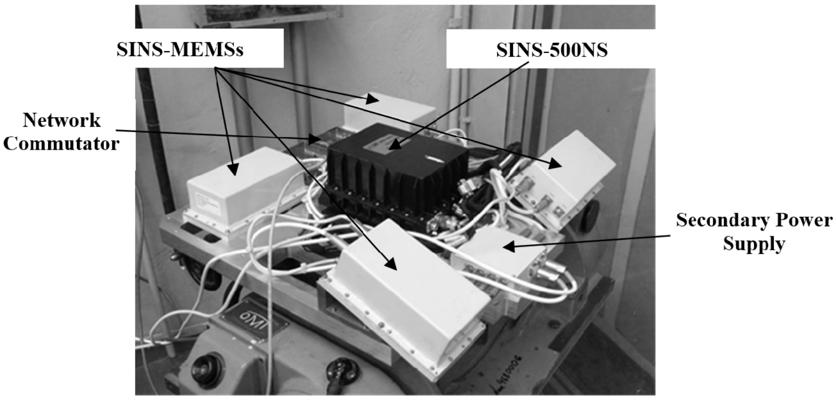

Fig.1. Redundant multiposition SINS

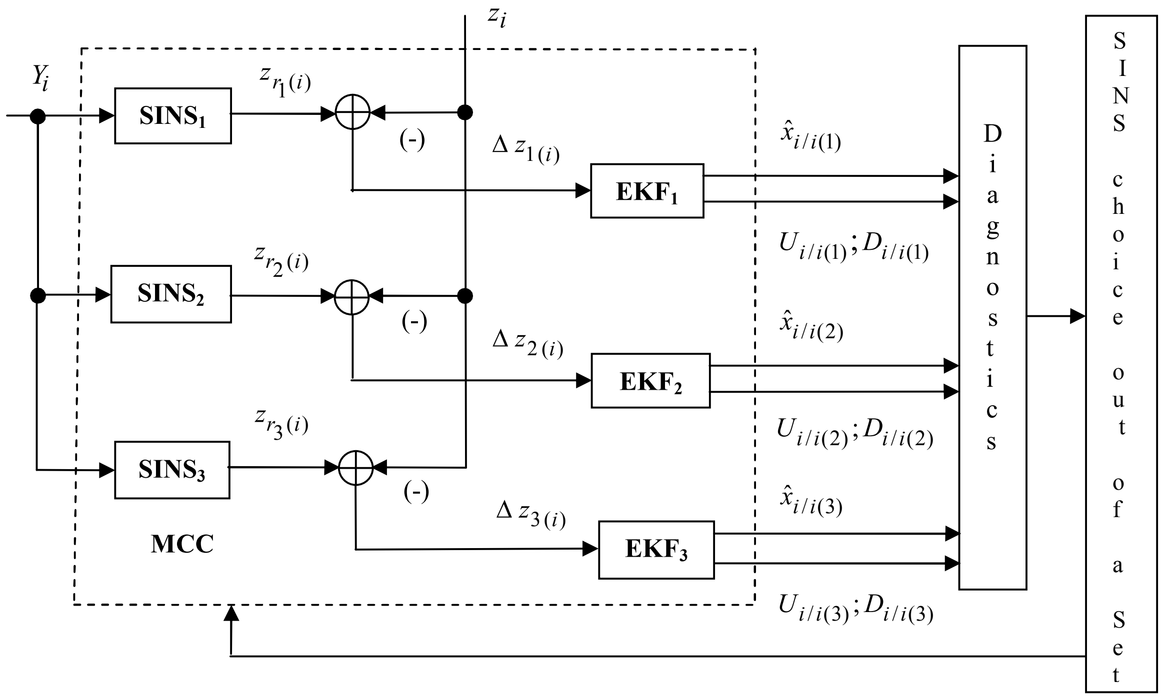

Fig. 2. Majority scheme for diagnosing a MSINS

In the MSINS data processing unit, the math-based software (MBS) has been implemented, which extends the capabilities of individual modules, namely: stochastic majority monitoring, and also the choice of the most preferable system out of a redundantized set. A majority scheme of diagnosis can be considered by the example of interaction among three identical SINSs, i.e, $SINS_1$, $SINS_2$, and $SINS_3$, which are shown in Fig. 2, where the following notation is introduced: Y_i is the vector of Acft motion parameters; $z_{r_1(i)}; z_{r_2(i)}; z_{r_3(i)}$ are the vectors of parameters that are formed by SINSs; z_i are the vectors of parameters measured by a system that is external with respect to the SINS-MEMS, for example, by an SNS or a SINS-FOG; $\Delta z_{1(i)}$; $\Delta z_{2(i)}$; $\Delta z_{3(i)}$; are the vectors of observations; $\hat{x}_{i/i(k)}$ is the vector of estimates of the errors $x_{i(k)}$ of a *k*-th SINS, which is formed after processing observations at the *i*-th instant of time, $k = \overline{1,3}$; $U_{i/i(j)}$ is the upper triangular matrix with identity diagonal and $D_{i/i(j)}$ is the diagonal matrix, which are components of the following covariance matrices of estimation errors: $P_{i/i(k)} = U_{i/i(k)} D_{i/i(k)} U^T_{i/i(k)} = M[\delta_{i/i(k)} \delta^T_{i/i(k)}]$; $\delta_{i/i(k)} = x_{i(k)} - \hat{x}_{i/i(k)}$; $x_{i(k)}$ is the vector of the actual errors of the *k*-th SINS at the *i*-th instant of time.

The most preferable system can be chosen out of a redundant set on the basis of an analysis of the following diagnostic parameters:

$$J_{1,2} = \Delta\nu_{1,2}^T \Delta P_{1,2}^{-1} \Delta\nu_{1,2}\,;\; J_{1,3} = \Delta\nu_{1,3}^T \Delta P_{1,3}^{-1} \Delta\nu_{1,3}\,;\; J_{2,3} = \Delta\nu_{2,3}^T \Delta P_{2,3}^{-1} \Delta\nu_{2,3}\,, \tag{1}$$

where

$$\Delta\nu_{1,2} = \hat{x}_{i/i(1)} - \hat{x}_{i/i(2)}\,;\; \Delta\nu_{1,3} = \hat{x}_{i/i(1)} - \hat{x}_{i/i(3)}\,;\; \Delta\nu_{2,3} = \hat{x}_{i/i(2)} - \hat{x}_{i/i(3)}\,; \tag{2}$$

$$\Delta P_{1,2} = P_{i/i(1)} + P_{i/i(2)}\,;\; \Delta P_{1,3} = P_{i/i(1)} + P_{i/i(3)}\,;\; \Delta P_{2,3} = P_{i/i(2)} + P_{i/i(3)}\,. \tag{3}$$

Relations (1) – (3) were formed taking account of $M[\delta_1\delta_2^T] = 0$; $M[\delta_1\delta_3^T] = 0$; $M[\delta_2\delta_3^T] = 0$;

$$\delta_1 = x_i - \hat{x}_{i/i(1)}\,;\; \delta_2 = x_i - \hat{x}_{i/i(2)}\,;\; \delta_3 = x_i - \hat{x}_{i/i(3)}\,.$$

In relations (1) – (3), the task of computing the inverse matrices $\Delta P_{1,2}^{-1};\Delta P_{1,3}^{-1};\Delta P_{2,3}^{-1}$ presents a problem. Such a problem can be solved in the execution of algorithms for observation processing on a basis of the *U-D* modification [1] of an extended Kalman filter (EKF)

$$\Delta P_{1,2}^{-1} = [U_{i/i(1)} D_{i/i(1)} U_{i/i(1)}^T + U_{i/i(2)} D_{i/i(2)} U_{i/i(2)}^T]^{-1} = [P_{i/i(1)} + \sum_{j=1}^{n} U_{j(2)} U_{j(2)}^T / D_{j(2)}]^{-1}, \tag{4}$$

where $P_{i/i(1)} = U_{i/i(1)} D_{i/i(1)} U_{i/i(1)}^T = M_0$; U_j is the upper triangular matrix with identity diagonal elements; D_j is the diagonal matrix; $U_{j(2)}$ is the *j*-th column of the matrix $U_{i/i(2)}$; $D_{j(2)}$ is the *j*-th element of $D_{i/i(2)}$.

Using the matrix inversion lemma [1] and relation (4), a recursive procedure both for the realization of formula (4) and for the computation of the matrix $\Delta P_{1,2}^{-1}$ can be formed in the following way:

$$M_i^{-1} = M_{i-1}^{-1} - M_{i-1}^{-1} U_{i(2)} / [U_{i(2)}^T M_{i-1}^{-1} U_{i(2)} + D_{i(2)}^{-1}]; \qquad \Delta P_{1,2}^{-1} = M_n^{-1}; \quad j = \overline{1,n}\,. \tag{5}$$

The matrices $\Delta P_{1,3}^{-1}$ and $\Delta P_{2,3}^{-1}$ are also computed by recursion formula (5). It can be shown [1] that with no faults in a MSINS, the quadratic forms J_{kj} must have the χ^2 distribution with *n* degrees of freedom, i.e., $J_{kj} \in \chi^2(n,2n)$. By analogy with the rule of 3σ [1], for the Gaussian distribution law, taking account of the quantile 0.02(*n*), we can state that with confidence probability 0.98, a necessary condition for the parameter J_{kj} to belong to the χ^2 distribution is as follows: $\quad J_{kj} \le \gamma_n^2 = n + 3\sqrt{2n}\,.$ (6)

Thus, the quantity γ_n^2 determines the region of acceptable values of the parameter J_{kj} when the MSINS is functional. In the diagnosis module shown in Fig. 2, the following monitoring procedures are executed:

$$\left\{\begin{matrix}\Delta J_{1,2} = J_{1,2} - \gamma_n^2 > 0 \\ \Delta J_{1,3} = J_{1,3} - \gamma_n^2 > 0\end{matrix}\right\} \to \begin{matrix}\text{Failure} \\ \text{SINS}_1\end{matrix};\; \left\{\begin{matrix}\Delta J_{1,2} = J_{1,2} - \gamma_n^2 > 0 \\ \Delta J_{2,3} = J_{2,3} - \gamma_n^2 > 0\end{matrix}\right\} \to \begin{matrix}\text{Failure} \\ \text{SINS}_2\end{matrix};\; \left\{\begin{matrix}\Delta J_{1,3} = J_{1,3} - \gamma_n^2 > 0 \\ \Delta J_{2,3} = J_{2,3} - \gamma_n^2 > 0\end{matrix}\right\} \to \begin{matrix}\text{Failure} \\ \text{SINS}_3\end{matrix}$$

In an operable MSINS, the most preferable SINS can be chosen out of a redundantized set on a basis of the realization of the following procedures:

$$(\Delta J_{1,2} + \Delta J_{1,3}) \to \left\{\begin{matrix}< (\Delta J_{1,2} + \Delta J_{2,3}) \\ < (\Delta J_{1,3} + \Delta J_{2,3})\end{matrix}\right\} \to \begin{matrix}\text{Choice} \\ \text{of SINS}_1\end{matrix}; \qquad (\Delta J_{1,2} + \Delta J_{2,3}) \to \left\{\begin{matrix}< (\Delta J_{1,2} + \Delta J_{1,3}) \\ < (\Delta J_{1,3} + \Delta J_{2,3})\end{matrix}\right\} \to \begin{matrix}\text{Choice} \\ \text{of SINS}_2\end{matrix}$$

$$(\Delta J_{1,3} + \Delta J_{2,3}) \to \left\{\begin{matrix}< (\Delta J_{1,2} + \Delta J_{1,3}) \\ < (\Delta J_{1,2} + \Delta J_{2,3})\end{matrix}\right\} \to \text{Choice of SINS}_3$$

If it is required, after the isolation of a failed SINS, to carry out its diagnosis, i.e., to determine with which component of the vector of the residuals $\Delta\nu_{j,k}$ the fault is most probably associated, it is necessary to perform a decomposition of the matrix $\Delta P_{j,k}^{-1}$ via its elements $\Delta U_{kj}^{-1}, \Delta D_{kj}^{-1}$. To do this, Eq. (5) can be represented in the following equivalent form:

$$M_j^{-1} = [K_j U_{j(2)}^T - I] M_{j-1}^{-1} [K_j U_{j(2)}^T - I]^T + K_j D_{j(2)}^{-1} K_j^T, \qquad (7)$$

where $K_j = M_{j-1}^{-1} U_{j(2)} / [U_{j(2)}^T M_{j-1}^{-1} U_{j(2)} + D_{j(2)}^{-1}]$; I is an identity $n \times n$ matrix.

Equation (7) is written on the assumption that the $SINS_1$ is a failed system, and, for the purpose of diagnosis, the $SINS_2$ has been chosen as a reference system. Expression (7) can be implemented using *U-D* procedures [1], then $\Delta P_{1,2}^{-1} = \Delta U_{1,2}^{-T} \Delta D_{1,2}^{-1} \Delta U_{1,2}^{-1}$, where $U_j^{-T} = (U_j^{-1})^T$.

On formation of the matrices $\Delta U_{1,2}^{-1}; \Delta D_{1,2}^{-1}$, the $SINS_1$ diagnosis is performed using the following recurrent algorithm that results from test condition (6), i.e.,

$$\Delta J_{1,2(j)} = \Delta J_{1,2(j-1)} + \Delta \tilde{\nu}_{1,2(j)}^2 \Delta D_j^{-1} \overset{?}{\underset{<}{>}} j + 3\sqrt{2j} \quad j = \overline{1,n}; \text{ for } \Delta J_{1,2(0)} = 0,$$

where $\Delta \tilde{\nu}_{1,2} = \Delta U_i^{-1} \Delta \nu_{1,2}$; ΔD_j^{-1} is the *j*-th element of the diagonal matrix $\Delta D_{1,2}^{-1}$; $\Delta \tilde{\nu}_{1,2(j)}^2$ is the *j*-th component of the vector of the residuals $\Delta \tilde{\nu}_{i,2}$.

In a distributed MSINS, counteraction against faults is performed through the reconfiguration and redistribution of the functions of a failed SINS in the data processing unit.

Analysis of the Results of Studies

The considered technology has been approved in a bench and flight experiments. Estimation of and periodic compensation for SINS-MEMS errors, including the errors of angular attitude and sensor drifts were carried out on a basis of the method of vector matching and sequential processing, with the use of an *U-D* filter, of the signals of observations, which are of the form:

$$\Delta z_V = [V_\xi V_\eta V_\zeta]_{\text{SINS-MEMS}}^T - [V_\xi V_\eta V_\zeta]_{\text{SINS-VOG}}^T; \ \Delta z_c = [\varphi\, \lambda\, H]_{\text{SINS-MEMS}}^T - [\varphi\, \lambda\, H]_{\text{SINS-VOG}}^T,$$

where φ_i, λ_i, H are the geodetic latitude, longitude and elevation above the Earth ellipsoid, which are reckoned by a SINS; $\bar{V} = [V_\xi V_\eta V_\zeta]^T$ is the vector of the reckoned relative velocity, given by its components along the axes of the semi-wander azimuth reference navigation frame $o\xi\eta\zeta$ [1].

The results that are characteristic of a combined action of the base SINS and micromechanical SINSs are presented in Fig. 3,4, where the circular position errors ΔS are shown, which correspond to the reckoning of SINS-MEMSs motion parameters both in the autonomous mode and in the interaction with the SINS-VOG.

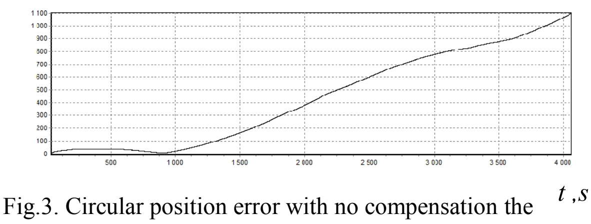

Fig.3. Circular position error with no compensation the estimates of SINS-MEMS state parameters

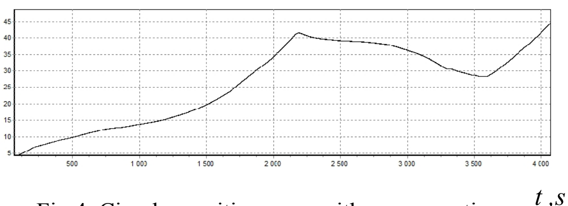

Fig.4. Circular position error with compensation the estimates of SINS-MEMS state parameters

It is seen that the accuracy characteristics of the SINS-MEMS cannot be provided without the support of the base system.

References

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