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Dynamical Calibration and Testing of MEMS Unit Using a Reference Inertial Satellite Navigation System

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***Abstract* — A two-stage calibration of inertial micro-electro-mechanical (MEMS) sensors is considered. In this paper, such sensors are gyroscopes and accelerometers, oriented along three orthogonal axes and placed in a single inertial measurement unit. The first stage of calibration is carried out in the factory at the bench without linear overloads. The second stage is implemented in a dynamic mode in a mobile laboratory that provides linear overloads. At this stage, the drifts of the sensor signals are estimated, as well as the skews of their measuring axes, which remained after the factory calibration. In addition, parametric identification of dynamic models of sensor signal drifts is performed. Such models are used to compensate for the errors of MEMS sensors in autonomous inertial navigation modes, including the loss of satellite signals. The errors of MEMS sensors in motion are estimated using information from the reference inertial satellite navigation system and the extended Kalman filter. The results of full-scale experiments are analyzed.**

Keywords* — *inertial navigation system, global navigation satellite system, micro-electro-mechanical sensors, calibration, extended Kalman filter.

I. INTRODUCTION

The current state of onboard equipment of mobile objects is characterized by the use of integrated inertial satellite navigation systems (ISNS) [1,2]. In such ISNS global navigation satellite systems (GNSS) provide high-precision positioning, and inertial ones - the determination of the angular orientation and redundancy of the GNSS in case of failures. When limiting the size and mass of the ISNS, strapdown inertial navigation systems (SINS) should be built on the basis of micro-electro-mechanical (MEMS) measuring modules. A typical MEMS inertial measurement unit (IMU) includes [3]: a triad of orthogonally placed gyros and a triad of orthogonally placed accelerometers. SINS-MEMS [4] built on the basis of the ADIS16488 measuring module developed by the Analog Devices Co [5] is shown in Fig. 1. A digital signal processor (DSP, see Fig. 1) based on the OlinuXino A20 microcomputer board with an adapter is designed to match the SPI and UART interfaces. On Fig. 2 shows IMU based on GKV-10 [6] MEMS developed by the Laboratory of Microdevices (Zelenograd). Compared to the ADIS16488 module, MEMS GKV-10 has a standard RS-485 interface, which greatly facilitates the construction of ISNS based on it.

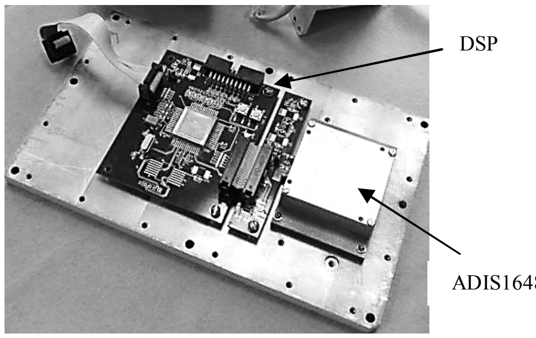

Fig. 1. INS-MEMS built on the basis of the ADIS16488 measuring module

Fig. 2. MEMS GKV-10

Taking into account the prospects of using small-sized ISNS, as well as the capabilities of modern embedded computers, it seems expedient to develop analytical approaches to improving the accuracy of MEMS sensors. At the same time, when operating ISNS, the task is not only to estimate the deterministic errors of MEMS sensors, but also to identify dynamic models of their change. Such models make it possible to maintain the required accuracy characteristics of the ISNS in an autonomous inertial mode when GNSS signals are lost. It can be noted that in the process of bench calibration, it is not possible to simulate the dynamic operating modes of the ISNS associated with linear and angular accelerations.

Traditionally [7] dynamic calibration of MEMS sensors in motion is performed using position and velocity data from GNSS. However, in this case, the drifts of the gyros and accelerometer signals have poor observability. Therefore, it is proposed to use for dynamic calibration of MEMS-IMU, in addition to velocity and position parameters, data on orientation, angular velocities and accelerations from a reference more accurate SINS.

The purpose of this paper is to improve the accuracy characteristics of MEMS-IMU based on combined calibration in stationary and dynamic modes.

II. Factory Calibration of MEMS Sensors

At bench calibration of a MEMS sensors the vector of errors, as a rule, includes [8], [9] systematic drifts of signals of sensitive elements (SE): gyros and accelerometers, as well as angular deviations of the SE axes from an ideal orthogonal trihedron. For example, for a gyros module, such a vector will have the form

$$x_{\Delta\dot{\Theta}} = [x^{T}_{\delta\dot{\Theta}}\ x^{T}_{\delta}]^{T}, \quad (1)$$

where $x_{\delta\dot{\Theta}} = [\delta\dot{\Theta}_x\ \delta\dot{\Theta}_y\ \delta\dot{\Theta}_z]^{T}$ (2)

is the vector of systematic angular drifts of gyros;

$x_{\delta} = [\delta_{xy}\ \delta_{xz}\ \delta_{yx}\ \delta_{yz}\ \delta_{zx}\ \delta_{zy}]^{T}$ is the vector of gyros angular skews; *ox*, *oy*, *oz* are the axes of the IMU.

The calibration procedure is associated with the formation of observations, when the bench rotates sequentially around the axes *ox*, *oy*, *oz*. For example, when rotating around the *ox* axis of the IMU, the observation will have the form

$$Z_x = [\dot{\Theta}_x\ \dot{\Theta}_y\ \dot{\Theta}_z]^{T}_{\text{IMU -}} - [\dot{\tilde{\Theta}}_x\ 0\ 0]^{T}_{\text{Bench}}, \quad (3)$$

where $\dot{\bar{\Theta}} = [\dot{\Theta}_x\ \dot{\Theta}_y\ \dot{\Theta}_z]^{T}$ is a vector of signals of gyros angular velocity sensors; $\dot{\tilde{\Theta}}_x$ - is the reference signal.

Observation (3) can be associated with the following model,

$$Z_x = H_x x + \vartheta,$$

where $H_x = \begin{bmatrix} 1\ 0\ 0 & \omega_y & \omega_z & 0 & 0 & 0 & 0 \\ 0\ 1\ 0 & 0 & 0 & \omega_x & \omega_z & 0 & 0 \\ 0\ 0\ 1 & 0 & 0 & 0 & 0 & \omega_x & \omega_y \end{bmatrix}_{\text{IMU}}$;

ϑ is the vector of errors in the formation of the angular velocities of the bench rotation.

During factory calibration, as a rule, bench errors are not taken into account. Then the estimate of the error vector of the inertial sensors $\hat{x}$ can be found using the least squares method by solving the following equation

$$\hat{x} = H^{-1}_{xyz} Z_{xyz}, \quad (4)$$

where $H_{xyz} = [H^{T}_x\ H^{T}_y\ H^{T}_z]^{T}$; $Z_{xyz} = [Z^{T}_x\ Z^{T}_y\ Z^{T}_z]^{T}$

It is possible to increase the accuracy of estimating the errors of inertial sensors by means of sequential modification of the extended Kalman filter (EKF) [10]. In this case, the unreliable operation of inverting the H_{xyz} matrix in equation (4) is excluded, and random errors of the rotary bench are also taken into account.

During bench calibration, it is not possible to perform the following procedures:

- estimation of the dynamic errors of the IMU arising from the influence of linear overloads;
- estimation of the dynamic errors of the IMU arising from the complex effect of linear and angular jerks;
- identification of dynamic models of sensor errors;
- quality control of the performed calibrations.

Before testing in motion, the factory calibration coefficients are stored in the SINS-MEMS processor module.

III. In-Motion Calibration of MEMS Sensors

Dynamical calibration of SINS-MEMS sensors in motion can be performed by interacting with the reference ISNS. To do this, signals from inertial sensors of both systems, as well as GNSS signals, must be synchronously recorded. During the post-processing of the recorded data, the problem of inertial navigation is solved in SINS – MEMS, and the problem of inertial satellite navigation is solved in the reference ISNS. In the paper under consideration, the SINS-500NS system [11] was used as a reference ISNS.

When calibrating inertial sensors in motion, the basic SINS-MEMS state vector additionally includes systematic drifts, as well as skews of the measuring axes of gyros and accelerometers. Noise models of inertial sensors are formed so [8], [9] that their structure is mapped to the general error equation of SINS

$$dx/dt = \dot{x}(t) = A(t)x(t) + G(t)\xi(t), \quad (5)$$

where $A(t) = \partial F[Y(t)/\partial Y]\big|_{Y(t)=Y_{\text{SINS}(t)}}$ is the matrix of coefficients that characterize the dynamics of variation of SINS errors; $\zeta(t)$ is the vector of disturbances that affect the SINS; $G(t)$ is the matrix of disturbance intensities; $Y(t)$ is the motion parameter vector; $Y_{SINS}(t)$ is the vector of parameters formed by the SINS by solving the basic equations of inertial navigation.

Biases of signals of sensors: gyros (2) and accelerometers, as a rule, have an exponential correlation function and are described by equations of first-order shaping filters [12] of the form (5). Estimates of the drift $\hat{A}_{\mu}(t)$ and diffusion $\hat{G}_{\mu}(t)$ coefficients in such models have the form [13]

$$\hat{A}_{\mu} = -\sum_{j=0}^{N} \ln \hat{r}_j \Big/ \sum_{j=0}^{N} \tau_j \ ; \ \hat{G}_{\mu} = \hat{\sigma}_{\mu}\sqrt{2\hat{A}_{\mu}} \ ;$$

where $\mu = a$ is the index indicating the accelerometer; $\mu = g$ is the index indicating the gyros; $\hat{r}_j = \hat{K}_{\mu(j)} / \hat{\sigma}^2_{\mu}$ is the normalized correlation function; $\hat{K}_{\mu(j)}$ is the statistical correlation function, determined by the estimates $\hat{x}_j$ recorded during the operation of the SINS; $\hat{\sigma}^2_{\mu} = \hat{K}_{\mu}(0)$; $\tau_j = j\Delta t$; $\Delta t = t_i - t_{i-1}$; t_i are discrete moments in time.

After identification, the estimates of $\hat{\alpha}_\mu$, and $\hat{G}_\mu$ parameters are included in the SINS errors model (5).

Dynamic calibration of the MEMS-IMU is implemented in the navigation mode when interacting with the SINS-500NS reference system. The errors vector is estimated, extended with respect to the reference one in the SINS-500NS system and having the form

$$x = [\underbrace{x_q^T x_\omega^T x_p^T x_V^T x_a^T}_{\textit{basic elements}} \underbrace{x_{\Delta\dot{\Theta}}^T x_{\Delta a}^T}_{\textit{additional elements}}]^T ,$$

where x_q are the errors in the reckoning of elements of the attitude quaternion [14]; x_ω are autocorrelated gyros drifts with model parameters (6); x_p are the errors in the reckoning of elements of the navigation quaternion [14]; x_V are the errors in the reckoning of components of the relative velocity vector; x_a are autocorrelated biases of accelerometers signals; $x_{\Delta a}$ is the vector of systematic errors of accelerometers similar to (1).

The estimation of the SINS-MEMS error vector can be performed by processing the following observations using EKF

$$Z_{C(i)} = [\varphi_i \lambda_i]^T_{\text{SINS-MEMS}} - [\varphi_i \lambda_i]^T_{\text{ISNS}};$$

$$Z_{V(i)} = [V_\xi V_\eta V_\zeta]^T_{\text{SINS - MEMS}} - [V_\xi V_\eta V_\zeta]^T_{\text{ISNS}};$$

$$Z_{\bar{\Theta}(i)} = \bar{\Theta}_{\text{IMU-MEMS}(i)} - \bar{\Theta}_{\text{IMU-ISNS}(i)};$$

$$Z_{\bar{V}_a(i)} = \bar{V}_{a\,(\text{IMU-MEMS})_i} - \bar{V}_{a\,(\text{IMU-ISNS})_i},$$

where $\bar{\Theta}_i = \int_{t_{i-1}}^{t_i} \dot{\Theta}(\tau)\,d\tau$ is the vector of IMU angles of rotation; $\bar{V}_{a(i)} = \int_{t_{i-1}}^{t_i} \bar{a}(\tau)\,d\tau$ is the vector of increments of the apparent velocities of the IMU.

It is assumed that the mutual orientation of the inertial measurement modules MEMS-IMU and ISNS-IMU is known. After calibration, the estimates of systematic errors of the sensors and parameters (6) are stored in the SINS-MEMS processor module. In the navigation mode, as a rule, only the basic SINS-MEMS error vector is realized.

IV. ANALYSIS OF THE RESULTS OF STUDIES

Experiments have been carried out under terrestrial conditions when the necessary equipment was housed in a mobile laboratory. The timing diagram of operation of the SINS-500NS and SINS-MEMS systems included the following stages: initial alignment by the analytical gyrocompassing method [14] ($t = 0 \div 270$sec); fine initial alignment using geophysical invariants [14] and EKF ($t = 270 \div 740$sec), and a navigation mode based on all-latitude reckoning algorithm [14] ($t > 740$sec).

In the structure of the ISNS, the basic SINS-500NS system operates in the indicator mode. In this mode, error estimates are compensated in the output signals of the SINS. In addition, in the SINS-500NS system, monitoring and protection of the information integrity of inertial satellite observations is carried out [15].

Figure 3 shows the circular positional error ΔS of the basic SINS-500 system in inertial satellite mode, where

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

$$\delta_\lambda = (\lambda_{\text{SINS}} - \lambda_{\text{GNSS}})R\cos\varphi_{\text{GNSS}};$$

R is the value of the radius vector of ISNS position.

It can be seen that the error of the SINS-500 system in this mode does not exceed 11 meters per hour.

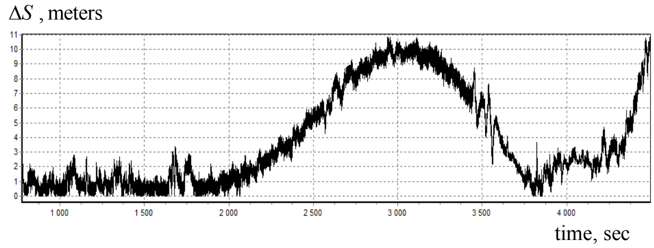

Fig. 3. Circular position error of the basic SINS-500 system in inertial satellite mode

The value of parameter ΔS is taken as a quality criterion for the calibration, which is performed iteratively using the recorded data.

Figure 4 shows the circular position error of SINS based on MEMS GKV-10 in inertial mode without calibration. It can be seen that in this case the error reaches 1000 km per hour, which corresponds to gyros drifts at the level of 10 arc. deg. per hour.

When testing the SINS-MEMS, the estimates of gyros drifts and accelerometer signal biases obtained during calibration were compensated.

Figure 5 shows the circular positional error of the SINS-MEMS system in the inertial mode after pre-calibration under stationary conditions. It can be seen that the error of the SINS-MEMS system in this case reaches 40 km per hour, which corresponds to gyros drifts at the level of 0.4 arc. deg. per hour.

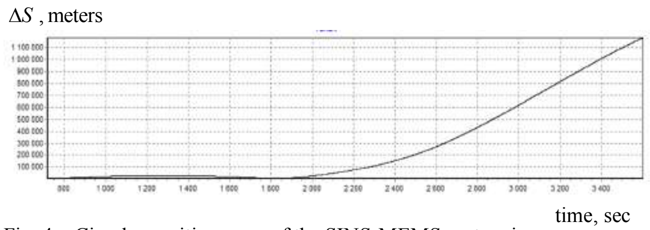

Fig. 4. Circular position error of the SINS-MEMS system in inertial mode

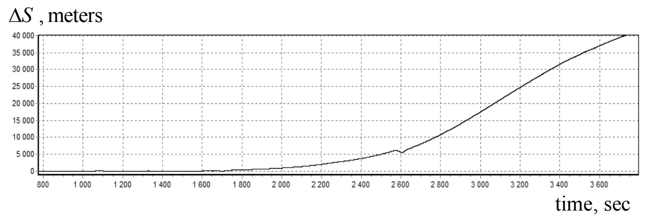

Fig. 5. Circular position error of the SINS-MEMS system in inertial mode after pre-calibration under stationary conditions

Figure 6 shows the circular position error of the SINS-MEMS system in inertial mode after pre-calibration in stationary conditions and in motion, and also taking into account the parametric identification of the noise models of the sensors.

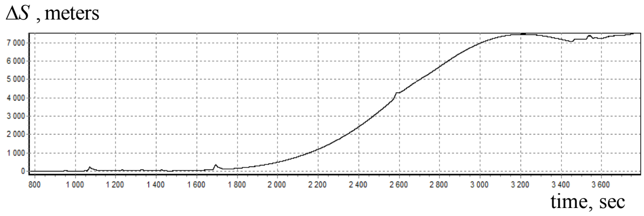

Fig. 6. Circular position error of the SINS-MEMS system in inertial mode after pre-calibration under stationary conditions

It can be seen that after integrated calibration in stationary conditions and in dynamic mode, the circular positional error of the SINS-MEMS additionally decreased by 6 times.

It should be noted that the presented results were obtained without compensating for the temperature drifts of the SINS-MEMS sensors.

V. CONCLUSIONS

The conducted studies have shown the feasibility of performing a combined ground-onboard calibration of inertial measuring units based on MEMS sensors. The proposed technology for such a calibration is based on the use of a reference inertial-satellite navigation system and the mathematical apparatus of the EKF. In addition, in the process of dynamic calibration, the parametric identification of the error models of MEMS sensors, which are necessary for integration with the GNSS, can also be performed. In practice, the information from the reference ISNS can be used to calibrate several measurement modules based on MEMS sensors.

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