COMPUTER-AIDED DESIGN SYSTEMS

UDC 625.735.(045)
DOI: 10.18372/1990-5548.55.12749

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INTEGRATED MICROMECHANICAL GYROVERTICAL

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Abstract*—The dubiousness of instantiation of the gyroverticales which based on micromechanical accelerometers and on micromechanical gyroscopic sensors is shown. Based on the analysis of the frequency characteristics of the errors of micromechanical gyroscopes and accelerometers, the expediency of their integration using the method of mutual compensation is shown. The algorithms and results of research of the integrated micromechanical gyroverticales which are based on compensation schemes with first-order and third-order dynamic filters with forcing are given. The approaches to the solution of the problem of the calibration integrated micromechanical gyroverticales in the flight are shown. The conducted researches of the proposed gyrovertical with the flight's calibration and with correction scheme showed good filtering properties and acceptable accuracy of measuring angular orientation parameters.*

Index Terms—Accelerometer; acceleration; angular velocity sensor; angular orientation; compensation scheme; estimation; correction; calibration.

I. INTRODUCTION

Analyzing the possibility of using high precision attitude gyroscope on miniature unmanned aerial vehicle (UAV), it can be noted that such gyroscopes are too expensive, heavy and overall size.

To measure the parameters of angular orientation (angles of a roll and a pitch) a number of alternative methods is proposed, including pyrometric and magnetometrical methods [1].

The disadvantage of the pyrometric method is the measurement error during UAV flight at low altitudes over sloping terrain, because the horizon of thermal radiation of ground surface is distorted.

Method of magnetometric measurement has areas of uncertainty, in particular with the magnetometer rotation around the axis close or coinciding with the direction of magnetic field vector and also with headings close to 90° ... 270° the uncertainty in measurements of roll and pitch angles appears.

Therefore now the use on UAVs of micromechanical gyroverticals (MMGV) and strapdown inertial navigation system (SINS), which are based on rather crude but microminiaturize sensors of source information – MEMS sensors, is becoming increasingly popular.

These standard specifications are mainly meet by micromechanical accelerometers (MMA) and angular velocity sensors (MMAVS), which are manufactured using solid state microelectronics technology, that are close to batch fabrication ultra-large integrated circuits. Such MEMS sensors are quantity-produced and cost as much as electronic chips – a few dollars.

However, the main shortcoming of micro-miniature information systems, to which the MMGV belongs, is low precision. Therefore, for the measurement of the angles of the roll and pitch, most designers of MMGV and SINS suggest the use of a method in the implementation of which data of MMA and MMAVS are subjected to special algorithmic processing.

Therefore, the development of algorithms for integrating the data of primary information sensors MMGV and BINS is a very urgent problem.

II. PROBLEM STATEMENT

The most commonly used for integrating of MMA and MMAVS data is the so-called complementary filter, or a Kalman filtration scheme. When solving the problem of integrated information processing in integrated information systems, Kalman's filtration, of course, is most attractive. However, the use of the Kalman filter concerned some difficulties of its practical implementation on airborn of the UAV.

In modern airborne complexes besides the optimal estimation algorithms, there are also other methods of data fusion that are well proved in practice. In particular, it is a method of mutual compensation [2]. The appropriateness of using the method of compensation in MMA and MMAVS integration is explained be the fact that errors of these systems are in different frequency ranges.

The main advantage of Kalman filtration is that when integrating the information systems at the Kalman filter output, the entire state vector is updated, including the systematic components of the errors of the sensors, which enables to carry out flight calibrations of these sensors. But in our view, and with the application of the compensation scheme in conjunction with the correction schemes, there is such an opportunity.

Thus, the problem statement can be formulated as following: to develop algorithms of an integrated MMGV for the UAV on the basis of the mutual compensation scheme and to conduct a thorough investigation of this MMGV.

III. Problem Solution

The accelerometer can be used both for measuring the projections of absolute linear acceleration and for indirect measurements of the gravitational acceleration projection. When positioning an accelerometer on the object which is a stationary and horizontal relative to the surface, it will measure the apparent acceleration $\bar{a} = -\bar{g}$, which created by the normal supporting force. The supporting force is equal in magnitude but opposite in the direction of the gravity at the point of finding the object.

If the only force acting on the object is the earth gravity, then the accelerometer, measuring the projection of the vector of gravity on its own axis of sensitivity $Ax = g\sin(\alpha)$, can be used as an inclinometer to determine the static angle of the accelerometer: $\alpha = \arcsin(Ax/g)$.

These properties of the accelerometer are used in the algorithms of the prelaunch BINS alignment for determining roll and pitch angles.

In the working condition of SINS parameters of the angular orientation of the object are determined using the information from the angular velocity sensors (AVS). In particular, these parameters can be determined through elements of the matrix of the directional cosines B, which can be obtained in various ways [2]. For example, the matrix B can be obtained by solving a generalized Poisson equation based on information about the angular velocity of the UAV relative to the inertial space $\boldsymbol{\omega}_{\text{UAV}}$ and the angular velocity of rotation of the navigational system of the coordinate relative to the inertial space $\boldsymbol{\omega}_{NHE}$. For one's turn, $\boldsymbol{\omega}_{NHE}$ takes into account the angular velocity of the Earth's rotation and the angular velocity arising when a UAV fly-around a spherical Earth.

$$\dot{\mathbf{B}} = \mathbf{B}\boldsymbol{\omega}_{\text{UAV}} - \boldsymbol{\omega}_{NHE}\mathbf{B},$$

where $\boldsymbol{\omega}_{\text{UAV}} = \begin{bmatrix} 0 & -\omega_{z_{\text{UAV}}} & \omega_{y_{\text{UAV}}} \\ \omega_{z_{\text{UAV}}} & 0 & -\omega_{x_{\text{UAV}}} \\ -\omega_{y_{\text{UAV}}} & \omega_{x_{\text{UAV}}} & 0 \end{bmatrix}$,

$$\boldsymbol{\omega}_{NHE} = \begin{bmatrix} 0 & -(\omega_{E_V} + \Omega_E) & (\omega_{H_V} + \Omega_H) \\ (\omega_{E_V} + \Omega_E) & 0 & -(\omega_{N_V} + \Omega_N) \\ -(\omega_{H_V} + \Omega_H) & (\omega_{N_V} + \Omega_N) & 0 \end{bmatrix},$$

$\omega_{x_{\text{UAV}}}$, $\omega_{y_{\text{UAV}}}$, $\omega_{z_{\text{UAV}}}$ are the angular velocities of the UAV relative to the body axes, measured by the AVS; $\Omega_E, \Omega_H, \Omega_N$ та $\omega_{E_V}, \omega_{H_V}, \omega_{N_V}$ are projections of the angular velocity of the Earth's rotation on the axes of the navigation system of coordinates and angular velocity that arising when a UAV fly-around a spherical Earth.

Rodriguez–Hamilton parameters in the form of quaternion may also be used to determine the angular orientation of an object, this information can be obtained and by solution of the kinematic equations:

$$\dot{\psi} = \left(\omega_{y_\Sigma}\cos\gamma - \omega_{z_\Sigma}\sin\gamma\right)\sec\vartheta;$$

$$\dot{\gamma} = \omega_{x_\Sigma} + \operatorname{tg}\vartheta\,\left(\omega_{z_\Sigma}\sin\gamma - \omega_{y_\Sigma}\cos\gamma\right);$$

$$\dot{\vartheta} = \omega_{y_\Sigma}\sin\gamma + \omega_{z\Sigma}\cos\gamma,$$

where ω_{x_Σ}, ω_{y_Σ}, ω_{z_Σ} are projections of the vector of absolute angular velocity on the axis of the body coordinate system, which again take into account the angular velocities of the UAV relative to the body axes, the projection of the angular velocity of the Earth's rotation on the axis of the navigating system of coordinates and angular velocities arising when a UAV fly-around a spherical Earth.

To demonstrate the problems that appear when attempting to obtain information about the angular orientation of the MEMS sensors Fig. 1 shows the output signals of a real block of inertial MEMS-sensors (chip MPU-6050). The MPU-6050 [3] combines a tri-axis accelerometer and a tri-axis gyroscope on one silicon crystal. In particular, in Fig. 1 shows the "raw" value of acceleration and integrated value of angular velocity, for one of the axes of the chip MPU-6050.

Analysis of output signals MPU-6050 shows that the MMA signal even in static mode has a considerable noise component. And given that on a moving object, in addition to the gravity, there are also act other forces caused by accelerations, rotations, shakes, etc., it becomes clear that measure the parameters of angular orientation in flight with the help of accelerometers is a very problematic task.

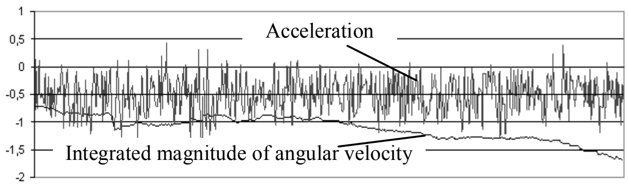

Fig. 1. Output signals of the chip MPU-6050

Unlike the accelerometer's method the method of obtaining information on the angles of a roll and pitch by integration the signal of AVS causes a rapidly increasing measurement error due to the presence of a standing error in the MMAVS.

On the other hand, the analysis of the output signals of the chip MPU-6050 shows that the errors of measuring the parameters of angular orientation using accelerometers and MMAVS are in different frequency ranges. Therefore, the method of compensation is ideally suited for the problem solving of integration of two gauges.

The block diagram that implements the compensation method for integrating the gyrovertical (GV) based on the MMAVS and the accelerometric vertical (AV) based on the MMA is presented in Fig. 2.

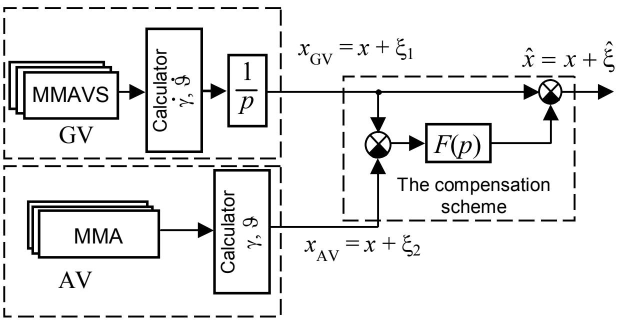

Fig. 2. The realization of the compensation method

The algorithm for integrated information processing which using the compensation method has a fairly simple kind, in comparison with optimal Kalman filtration:

$$\hat{x} = x_{\text{GV}} - F(p)(x_{\text{GV}} - x_{\text{AV}}),$$

where F(p) is the dynamic filter of the mutual compensation scheme; $x_{\text{GV}}, x_{\text{AV}}$ are angular orientation parameters are derived from GV i AV ; x is concrete parameter of angular orientation; $\hat{x}$ is the estimate of in question parameter of angular orientation.

If you select the filter $F(p)$ such that it misses the systems error ξ_1 with the minimum distortion and silences the noise ξ_2, then the error in the integrated system will be minimal, that is, the error will be reduced depending on the difference in the spectral characteristics of the errors ξ_1 and ξ_2. With a significant difference in the frequency characteristics of the errors at the output of the filter $F(p)$ (see Fig. 1), will be reproduced completely the error ξ_1, that is, the error of the GV, and at the output of the compensation scheme, the estimate of the parameter will coincide as exactly as possible with the measurable parameter x.

It remains to determine such a structure of the dynamic filter of the compensation scheme, which would ensure the co processing of homogeneous information from GV and AV with a suboptimal quality.

Converting the equation of the compensation scheme, we obtain:

$$\hat{x} = x + [1 - F(p)]\xi_{\text{GV}} + F(p)\xi_{\text{AV}} = x + \hat{\xi},$$

where $\hat{\xi} = [1 - F(p)]\xi_{\text{GV}} + F(p)\xi_{\text{AV}} = \xi_{\text{GV}} - F(p)\cdot(\xi_{\text{GV}} - \xi_{\text{AV}})$ is the error of integrated information processing.

The ideal filter $F(p)$ should have such an amplitude-frequency response (AFR) $A = f(\omega)$ (Fig. 3) so that it in the frequency domain ω_{GV} would miss the low-frequency errors of ξ_{GV}, without distortion, and in the frequency domain ω_{AV} muffled the error ξ_{AV}. Now, at the output of the filter $F(p)$ (see Fig. 2), there is observed exact value of low frequency error of the GV, and at the output of the second subtraction device is reproduced the exact value of the measured angular parameter x

$$\hat{x} = x + \xi_{\text{GV}} - \xi_{\text{GV}} = x.$$

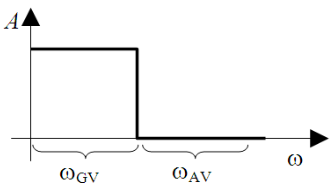

Fig. 3. Amplitude-frequency response of the ideal $F(p)$

In existing compensation schemes (for example, in the Inertial-Doppler system), the high-frequency filter has the form of the aperiodic link with the transfer function

$$F(p) = \frac{1}{(Tp + 1)},$$

where T is the time constant of the filter, and the transfer function of the low-frequency filter

$$[1 - F(p)] = \frac{Tp}{Tp + 1}$$

is a so-called isodromic (real differentiating) link.

Such a low-frequency filter is effective only for constant, non-time-varying errors. However, even an approximate analysis of GV errors (see Fig. 1) shows that errors in the calculation of the parameters of angular orientation increase over time. Therefore, for this kind of error in [4] a more complicated third-order filter was proposed. The transfer function of such third-order filter has the form:

$$F(p)=\frac{3Tp+1}{(Tp+1)(Tp+1)(Tp+1)}.$$

For such a dynamic filter, the transfer function of the low-frequency filter has the form:

$$[1-F(p)]=\frac{T^2p^2(Tp+3)}{T^3p^3+3T^2p^2+3Tp+1}.$$

For sufficiently large constants T, a number 3 in the numerator can be not to take into account and then the low-frequency filter acquires the form:

$$[1-F(p)]=\frac{T^3p^3}{T^3p^3+3T^2p^2+3Tp+1}.$$

Such a filter, providing an absence of offset of third order, no longer passes not only the constant component of the GV error, but also the errors that vary according to the laws of the first and second order.

The high-frequency filter

$$F(p)=\frac{3Tp+1}{(Tp+1)(Tp+1)(Tp+1)}$$

due to the presence of forcing link ($3Tp$ + 1) slightly amplifies the high-frequency component of the AV error, but this is successfully compensated by a triple increase in its filtering properties.

Investigations of the integrated information processing algorithms implementing the compensation method with various dynamic filter configurations were carried out by means of mathematical modeling in the Delphi environment.

To investigate the proposed algorithms, it is necessary to formulate mathematical models of errors of the MMA and MMAVS, which are, for example, given in [1]. These models take into account many components that form the final sensor errors. In particular, this is the errors of scale factors, the error of alignment, quadratic errors due to the nonlinearity of the characteristics of the sensors, systematic drift and random (noise) components, etc. However, when considering the motion of a UAV with a constant speed on straight-line trajectory, the models of errors can be substantially simplified to the form:

$$\Delta a_i=K_{a_i}+Q_{a_i}\varepsilon_{a_i},\quad \Delta\omega_i=K_{\omega_i}+Q_{\omega_i}\varepsilon_{\omega_i},$$

where K_{a_i}, K_{ω_i} are systematic errors of gauges (zero drift); Q_{a_i}, Q_{ω_i} are the intensity of random errors of gauges; ε_{a_i}, ε_{ω_i} are noise measurements. This model of error sensors is the sufficiently simple, but in many practical cases, it is quite effective, and allows you to solve the problems of integration of such gauges.

The results of studies of compensation schemes with a first-order dynamic filter in the form of an aperiodic link $F(p)=\frac{1}{(Tp+1)}$ show (Fig. 4) that the error of estimating the angular orientation parameters is incomparably smaller than the error of the GV. However, in comparison with the root-mean-square error of AV, there is a change in the error of the compensation scheme in time. But through the third-order filter no passes not only the constant component of the GV error, but also the errors that vary according to the laws of the first and second order, and this filter also provides good filtering properties of the compensation scheme. The filter also provides sufficiently high accuracy characteristics of the estimation of the angular orientation parameters, not even worse than the scheme of optimal Kalman filtration.

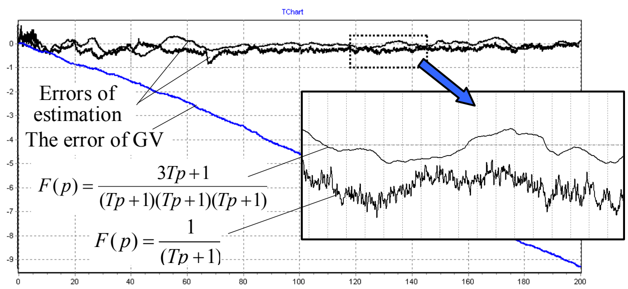

Fig. 4. Results of research of compensation schemes

The proposed filtration scheme was also investigated in the case of effect on UAV of random turbulence perturbations and showed itself efficiency. However, accelerations, which a long period of time acting on the UAV, for example, when accelerating or braking, and most importantly when performing turns and circles, significantly distort estimates of the angular orientation parameters. To prevent this in the integration algorithms, it is advisable to foresee circuits of shutting down, such as the circuit breakers of the correction of existing gyroscopic devices. Such switches snap into action at certain values of longitudinal acceleration, as well as at certain fixed values of angular speed of turning.

The analysis of MMGV errors (see Fig. 4) shows that they are continuously increasing, so it is expedient to carry out periodic or continuous flight's calibration of MMAVS and correction of MMGV on the information about the estimated values of the parameters of angular orientation.

Estimated values of angular velocity $\hat{\omega}_x, \hat{\omega}_z$ can be obtained from the following equations:

$$\hat{\omega}_x = \hat{\dot{\gamma}} + \dot{\psi} \sin\hat{\vartheta}, \quad \hat{\omega}_z = \hat{\dot{\vartheta}} \cos\hat{\gamma} - \dot{\psi} \cos\hat{\vartheta} \sin\hat{\gamma},$$

where $\hat{\gamma}, \hat{\vartheta}$ are estimated values of the roll and pitch; $\hat{\dot{\gamma}}, \hat{\dot{\vartheta}}$ are the rate of change of the angular orientation parameters, which is formed by the ordinary differentiation. Information about $\dot{\psi}$ can be obtained from the MEMS-magnetometer, which is commonly used on UAV as a sensor of the magnetic course.

Estimated values of angular velocity can also be obtained from simplified equations:

$$\hat{\omega}_x \approx \hat{\dot{\gamma}}, \quad \hat{\omega}_z \approx \hat{\dot{\vartheta}} \cos\hat{\gamma}.$$

Here it is taken into account that under certain fixed values of the angular velocity of the turn $\dot{\psi}$ the compensation scheme is disconnect.

Using estimated values of angular velocity and the angular velocity values arriving from MMAVS, the current values of zero drift values of the sensor on the corresponding axises are calculated, which are used for the calibration in the flight of the MMAVS.

In order to implement the GV correction, the difference between the current values of the angular orientation parameters and their estimate is used.

In the paper, calibration and correction schemes and algorithms are not given.

Results of research of the work of the compensation schemes with a third-order filter with the simultaneous work of calibration and correction schemes are show in Fig. 5.

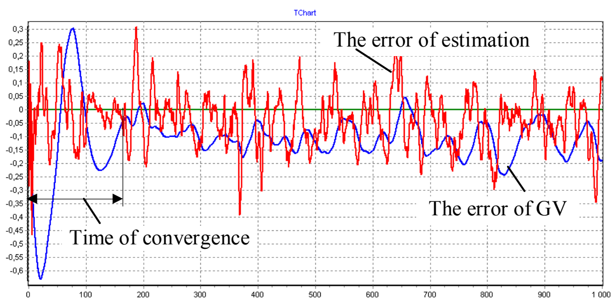

Fig. 5. Results of research of algorithms flight's calibration and correction

After the end of the transient processes in the schemes of integration and calibration (this time is mainly determined by the time of convergence of filtration algorithms), the GV enters the working mode demonstrating good filtering properties and acceptable accuracy of measuring the parameters of the angular orientation. In particular, the accuracy of the calibrated GV is not inferior to the accuracy of the estimation of the angular orientation parameters.

For the research of the dynamic characteristics of MMGV during the simulation, an ideal angular velocity and the corresponding ideal angular orientation parameters, which was compared with the measurable and estimated parameters, was formed.

The simulation results, shown in Fig. 6, indicate quite acceptable dynamic characteristics of the proposed MMGV.

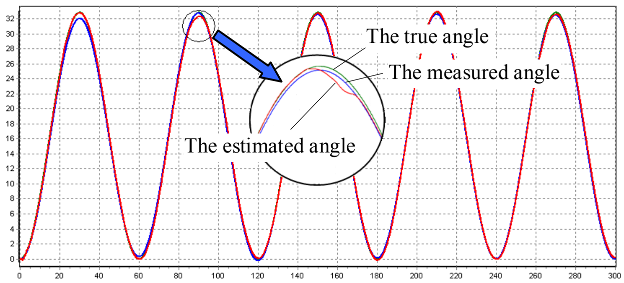

Fig. 6. The simulation results of the dynamic characteristics MMGV

And, finally, the work of MMGV with the switch of correction was investigated. In Figure 7 shows the results of modeling of MMGV before and after switching off the compensation, correction and flight's calibration schemes. After operation of the switch of the correction, the UAV flight continues with the stored and averaged calibration parameters. The analysis of simulation results shows the principal possibility for a not long time to continue to fly from an autonomous MMGV.

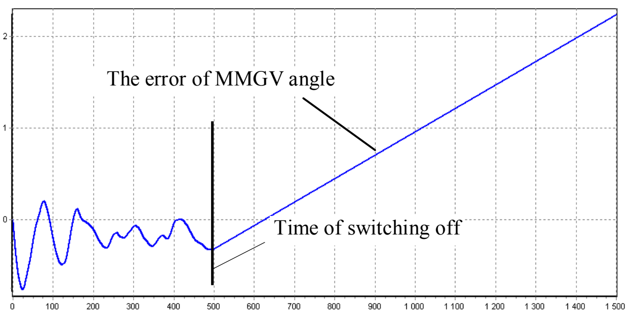

Fig. 7. Results of research of autonomous operation of calibrated MMGV after switching off correction

IV. Conclusions

The analysis of the output signals of MMA and integrated signal of MMAVS shows that the errors of their measurements are in different frequency ranges. Therefore, the mutual compensation method is ideally suited for solving the problem of integrating these sensors.

The results of the investigation of the integrated gyroverticals constructed on the basis of compensation schemes with a third-order filter with simultaneous operation of calibration and correction schemes show good filtering properties and acceptable accuracy of measuring angular orientation parameters.

The analysis of simulation results shows the principal possibility for a not long time to continue to fly from an autonomous MMGV after operation of the switch of the correction

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Received October 16, 2017

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М. К. Філяшкін. Комплексирована мікромеханічна гіровертикаль

Показано проблемність побудови вимірників вертикалі на основі мікромеханічних акселерометрів і гіроскопічних датчиків. На основі аналізу частотних характеристик похибок мікромеханічних гіро- і акселерометричних вертикалей обґрунтовується доцільність їх комплексування з використанням методу компенсації. Наведено алгоритми та результати досліджень інтегрованих мікромеханічних гіровертикалей, що базуються на схемах компенсації з динамічними фільтрами першого порядку та третього порядку з форсуванням. Показані підходи до розв'язання задач польотного калібрування мікромеханічної гіровертикалі. Проведені дослідження запропонованої гіровертикалі з польотним калібруванням і схемою корекції показали хороші фільтруючі властивості і прийнятну точність вимірювання параметрів кутової орієнтації.

Ключові слова: акселерометр; прискорення; датчик кутової швидкості; кутова орієнтація; схема компенсації; оцінка; корекція; калібрування.

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Н. К. Филяшкин. Комплексированная микромеханическая гировертикаль

Показана проблематичность построения измерителей вертикали на основе микромеханических акселерометрических и гироскопических датчиков. На основе анализа частотных характеристик погрешностей микромеханических гиро- и акселерометрических вертикалей обосновывается целесообразность их комплексирования с использованием метода взаимной компенсации. Приведены алгоритмы и результаты исследований комплексированной микромеханической гировертикали, основанные на схемах компенсации с динамическими фильтрами первого порядка и третьего порядка с форсированием. Показаны подходы к решению задачи полетной калибровки комплексированной микромеханической гировертикали. Исследования предлагаемой гировертикали с полетной калибровкой и схемой коррекции показали хорошие фильтрующие свойства и приемлемую точность измерения параметров угловой ориентации.

Ключевые слова: акселерометр; ускорение; датчик угловой скорости; угловая ориентация; схема компенсации; оценка; коррекция; калибровка.

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