UDC 004.852

METHOD OF IMPROVING THE ACCURACY OF NAVIGATION MEMS DATA PROCESSING OF UAV INERTIAL NAVIGATION SYSTEM

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ABSTRACT

Context. Modern theory and practice of preparation and conduct of hostilities on land, at sea, in the air, and recently in cyberspace dictates the relentless modernization of military equipment. The development of fundamentally new weapons is carried out considering one of the main requirements – maximum automation of operational processes, which allows combatants to distance themselves from each other as much as possible.

Among the newest models of armaments on the battlefield, due to the predominantly positional nature of the armed confrontation, unmanned aerial vehicles (UAVs) have become virtually indispensable due to their own multitasking. One of the ways to increase the efficiency of UAVs on the battlefield is to increase the level of technical perfection of flight control systems.

Creating new approaches to the design of unmanned aerial vehicle navigation systems, in particular, based on a platformless inertial navigation system is an urgent task that will provide automatic control of the UAV flight route in the absence of corrective signals from the global satellite navigation system.

Objective. The purpose of this work is to develop a method for improving the accuracy of MEMC navigation data processing of an inertial navigation system of an unmanned aerial vehicle based on an advanced Madgwik filter.

This method will increase the speed of data processing of navigation parameters and the accuracy of determining the positioning parameters in the space of the UAV through the use of an advanced Madgwik filter.

The paper shows the developed block diagram of MEMS PINS filtration on the basis of the improved Madgwik filter, the detailed mathematical description of filtration processes is carried out.

This method was tested experimentally in the MATLAB software environment using a real set of data collected during the flight of the UAV.

Method. To achieve this goal, the following methods were used: intelligent systems, theory of automatic control, pseudo-spectral method; methods based on genetic algorithm and fuzzy neural network apparatus.

Results. A method for improving the accuracy of MEMC navigation data processing of an inertial navigation system of an unmanned aerial vehicle based on an advanced Madgwik filter has been developed. The possibility of practical application of the obtained results and in comparison, with traditional methods is investigated. An experiment was performed in the MatLab software environment, and a comparison was made with the method of processing navigation data based on the Madgwik filter and the Kalman filter.

Conclusions. The developed method of increasing the accuracy of MEMC navigation data processing of an inertial navigation system of an unmanned aerial vehicle based on an advanced Madgwik filter shows an advantage over known methods in the absence of corrective signals from the global satellite navigation system for accuracy and speed of navigation data processing.

KEYWORDS: automatic control intellectual system, navigation system, unmanned aircraft vehicle.

ABBREVIATIONS

MEMS is a micro-electromechanical system;
PINS is a platformless inertial navigation system;
SLERP is a spherical linear interpolation algorithm;
LERP is a linear interpolation algorithm;
RKF is a recursive Kalman filter;
RMSE is a root mean square error.

NOMENCLATURE

ω – angular velocity;

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DOI 10.15588/1607-3274-2022-3-18

$q_{\omega,t}$ – quaternion of UAV orientation;

$\omega_{q,t}^{S}$ – the resulting angular velocity vector of the local frame of reference of the gyroscope sensor (rad / s);

${}_{S}^{E}q_{,t-1}$ – the quaternion of the preliminary estimation of orientation (at t–1 step of the local frame of reference S relative to the global frame of reference E);

$\otimes$ – Hamilton's product;

Δt – time interval of initial data processing;

$q_{g,t+1}$ – forecasting quaternion;

$q_{pos,t-1}$ – quaternion of orientation of the previous state;

$a^{S} + \Delta a^{S}$ – initial accelerometer data with an errors;

g^{E} – gravity vector data;

q_{E}^{*S} – inverse quaternion orientation;

$\bar{l}$ – the rotation vector of the magnetic relative field to the sensor reference system;

$m^{S} + \Delta m^{S}$ – magnetometer data with an errors;

G – quaternion of the optimal number of operations of rotation of the vector l in the vector projection lying on the positive half-plane Z relative to the global coordinate system;

$R^{T}\left(q_{mag}\right)$ – matrix of rotation of the magnetometer quaternion data;

$\hat{\Delta}q_{mag}$ – the result of calculating of the delta quaternion values of the magnetometer relative to the global frame of reference;

$\hat{\Delta}q_{acc}$ – the result of calculating of the delta quaternion the values of the accelerometer relative to the global frame of reference;

$\bar{g}_{p}^{E}$ – vector of predicted gravity relative to the global frame of reference (UAV positioning);

$\bar{u}_{m}$ – unit vector describing the axis of rotation;

$\left\|\tilde{a}^{S}\right\|$ – normalization of accelerometer data of the local frame considering of the gravitational constant $g = 9.81$ м/с^{2};

ε – the threshold value of the gain;

α – gain, which characterizes the cut-off frequency of high-frequency pulses of the accelerometer signal;

$q_{\nabla(f)}$ – the quaternion is obtained using the Nesterov gradient descent algorithm;

ξ – response time when tracking the drift of zero displacement of the gyroscope;

b_{pos}^{S} – quaternion of values of orientation deviation;

$\hat{q}_{pos,t}$ – the result of calculating the values of the quaternion of orientation prediction;

β – gain that is set adaptively, based on the characteristics of the sensors and the presence of errors in inertial sensors;

θ – pitch angle navigation parameter, (deg);

φ – yaw angle navigation parameter, (deg);

ψ – roll angle navigation parameter, (deg);

S – the index of the local calculation system;

E – the index of the global calculation system;

pos – the symbol of the local calculation system;

acc – the symbol of accelerometer;

mag – the symbol of magnetometer.

INTRODUCTION

Today, navigation systems are built using completely different technologies, and can perform a wide range of functions, depending on the requirements of the technical task.

The basis of navigation systems for unmanned aerial vehicles is GPS-receivers, which in combination with the block of inertial sensors form the input data for their processing and conversion into navigation.

Thus, the presence of signals from global satellite systems is a prerequisite for maintaining the flight control process of the aircraft. The absence or pre-planned pressure of navigation signals leads to the impossibility of accurately determining their own coordinates and, as a consequence, following a certain route.

Existing methods [1–3] do not allow to ensure minimal deviation of the UAV trajectory in the autonomous mode of flight during the disappearance of signals of GPS, especially in the correlation period close to the disappearance of the GPS signal in the time interval (from 10 up to 300 s), which can be critical for the entire mission of the flight and the loss of the UAV in 38% of cases [4–6].

It is known that the determination of positioning data of UAV miniature type, as a rule, is based on an integrated MEMS free platform inertial navigation system (PINS) based on microcomputers such as Arduino Nano.

Thus, there is a need to reduce the computational load on such microcomputers during dynamic exposure to the environment, ie during nonlinear motion and in the presence of random perturbations.

The use of high-precision inertial navigation systems also does not completely solve the problem for the following reasons:

1) high cost of such systems;

2) restrictions on mass and dimensions;

3) the difficulty of minimizing errors in determining the coordinates with the time of autonomous operation.

The growing interest of scientists in intelligent control systems based on artificial neural networks, gives grounds to argue about the qualitative advantage of the latter on the performance of miniature drones. In addition, their use can significantly reduce the cost of such systems. Therefore, the intellectualization of management systems in modern conditions is one of the main scientific and practical areas of their improvement.

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1 PROBLEM STATEMENT

Suppose that at some small UAV moving at an arbitrary constant given speed, a platformless inertial navigation system built on the basis of MEMS–sensors is installed, with the input data data with an errors $\left\{\omega_{q,t}^{S}+b_{pos}^{S},a^{S}+\Delta a^{S},m^{S}+\Delta m^{S}\right\}$.

To compensate for the deviations in the installation of navigation parameters $\{\theta,\varphi,\psi\}$ in the process, it is proposed to apply filtration algorithms – RKF, Madgwick and developed advanced Madgwick, with a minimum RMSE criterion in the conditions of sudden disappearance of GPS signals, in order to minimize the deviation of the UAV flight path from the one $\Delta_{pos}(t)\Rightarrow \min$.

2 REVIEW OF THE LITERATURE

Analysis of recent publications has shown that the basic principle of filtering algorithms for navigation systems of inertial sensors MEMS is based on the evaluation of data comparison of two reference systems, relative to gravity and local magnetic field, compared with the reference vectors of the output signal. However, when the local magnetic field is disturbed by ferromagnetic objects (electrical devices), which leads to problems in determining the course of the UAV, as a consequence, the need for more sophisticated filtering algorithms is stated [5].

To date, the main methods of increasing the accuracy of position estimation in the autonomous mode of UAV based on MEMS sensors of inertial navigation systems are shown in [6], which proposes an optimal algorithm that calculates the estimate in quaternion form taking into account a set of reference vectors in a fixed system. computing data in a local frame of reference relative to a UAV in space that finds the optimal quaternion by parameterizing the orientation matrix, by minimizing quadratic gain, and by using Web loss functions [7]. However, such methods have high computational requirements for sampling rate, often exceeding the bandwidth of the object.

Eston and others [8] introduced a quaternion-based filter, the filter is supplemented by a first-order model of UAV dynamics to compensate for the effect of external acceleration. Mahoney and Hemel [9] investigated the problem of estimating zero drift of a gyroscope using a passive additional filter, and proposed a solution in the form of a nonlinear correcting device, but there is a difficulty in implementing this type of navigation algorithms for micro UAV class (minimum computational computer requirements micro UAV).

Marins and others [10] propose two different approaches to solve the problems of autonomous UAV navigation based on the use of Kalman filter to assess the orientation in the quaternion form of MEMS PINS. The first approach uses each MEMS data output with a magnetometer in a 9-component state vector, which leads to the use of a complex Kalman extended filter (RKF) algorithm, the second approach uses an external Gauss-Newton algorithm to directly estimate the measurement of angular velocity quaternion's. In this case, the relationship between the process and the measurement model is linear, which allows the use of an approximate Kalman filter, but for the process of calculating object kinematics (UAV) in three projections, requires a large number of state vectors and implementation of an extended Kalman filter to linearize the problem. does not meet the requirements for the use of navigation systems based on MEMS sensors.

Scientific work [11] presents a similar approach based on improved RKF, where the process of determining the position of the UAV is based on magnetometer vector data, and the MEMS PINS error model is built as a Gauss-Markov process to predict the reduction of zero drift of the gyroscope in magnetically inhomogeneous media. The advantages of the advanced Kalman filter in [12] include the process of predicting the navigation parameters of UAVs in space using a probabilistic model, which significantly reduces the distortion of the input signals of MEMS sensors, but increases the need for computationally complex iterative processes for linear regression algorithms.

In the work of the Madgwik filter [13], a filtration algorithm with a constant gain is used to assess the state (positioning) of the UAV in quaternion form based on the MEMS data of the inertial navigation system. First, the quaternion estimate is obtained by integrating the original gyroscope data, and then corrected by the quaternion based on the accelerometer and magnetometer data. The next step of the algorithm is the process of calculating data streams using the batch gradient descent algorithm. The Madgwik method can compensate for the effect of ferromagnetic errors on the orientation component, and provides a better estimate of positioning at low computational operations.

3 MATERIALS AND METHODS

The method of increasing the MEMS data processing speed of an inertial, UAV navigation system based on an advanced Madgwik filter is based on quaternion algebra.

Formalization of the proposed method occurs in three stages:

1. Stage of forecasting. At this stage, the process of calculating the angular velocity vector based on the measurement of gyroscope data, which determines the orientation of UAV in space, first calculates the quaternion derivative, which describes the rate of change of orientation, as a product of the previous position in space on the angular velocity vector.

2. Correction stage. In this step, the correction process of navigation parameters using the delta quaternions of the magnetometer and accelerometer.

3. Stage of adaptive adjustment based on gyroscope indicators.

At the time of dynamic motion of the UAV (series of turns) with highly dynamic acceleration, the accelerometer sensor data cannot be corrected [14], so an adaptive correction factor based on gyroscope data is used using the Nesterov gradient descent algorithm [15].

Figure 1 shows a block diagram of the filter of inertial measuring devices based on the advanced Madgwik filter.

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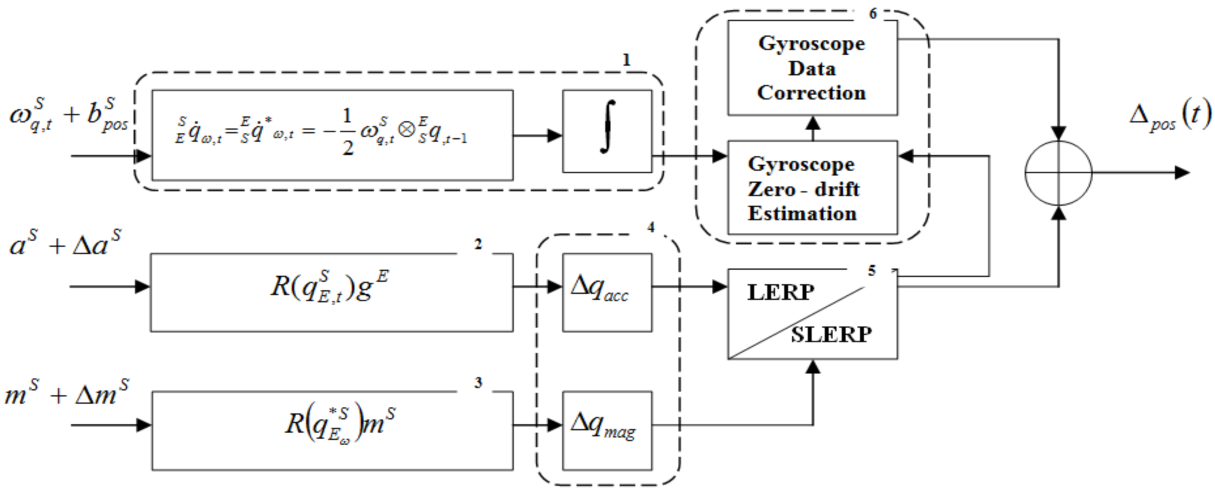

Figure 1 – Block diagram of MEMS PINS filtering based on the advanced Madgwik filter

Description of the blocks of the algorithm for increasing the data processing speed of the MEMS inertial, UAV navigation system based on the advanced Madgwik filter:

Block 1 – adjustment of the initial data of the gyroscope and integration;

Block 2 – accelerometer data processing;

Block 3 – block of magnetometer quaternion deltas;

Block 4 – accelerometer and magnetometer data filtering;

Block 5 – accelerometer and magnetometer data correction in quaternion form;

Block 6 – adaptive gyroscope data correction.

The work of the algorithm begins at the stage of forecasting and initialization of initial data.

In **block 1**, similarly to the algorithm proposed in the work of Madgwik, the initial estimation of UAV orientation in space is performed by calculating the orientation quaternion derivative using array velocity angular velocity MEMS arrays relative to the local frame of reference.

However, it should be noted that in contrast to the Madgwik algorithm, the proposed method uses the derivative of the inverse Valenti orientation function [16], which is calculated using the inverse unit of the conjugate quaternion, given in equation (1):

$$_E^S\dot{q}_{\omega,t} = _S^E\dot{q}^*_{\omega,t} = -\frac{1}{2}\omega_{q,t}^S \otimes _S^E q_{,t-1}\,, \quad (1)$$

where $\omega_{q,t}^S = [0\ \omega_x\ \omega_y \omega_z]$.

In addition, there is integration (Fig. 1) by processing the input data of the gyroscope in quaternion form

$$q_{g,t+1} = q_{pos,t-1} + q'_{\omega,t}\Delta t. \quad (2)$$

In **block 2,** the data of three axial accelerometers and errors are processed. Functionally, in the MEMS module of the accelerometer, the process of measuring linear acceleration takes place, calculating the vector of the magnitude and direction of the gravitational field relative to the local coordinate system in the form of a quaternion function $R(q_{E,t}^S)g^E = a^S + \Delta a^S$.

Calculation of gravity vector data allows you to find a quaternion that performs the conversion operation between two reference frames, based on accelerometer and magnetometer data:

$$R(q_{acc})R(q_{mag})\begin{bmatrix}0\\0\\1\end{bmatrix} = \begin{bmatrix}a_x\\a_y\\a_z\end{bmatrix}.$$

In **block 3,** at the output of the three-axis magnetometer is measuring the magnitude and direction of the Earth's magnetic field in the local frame of reference, taking into account local ferromagnetic distortions. The geomagnetic field is determined relative to the geographical position of the object in space, using the World Magnetic Model [17].

At the next stage of the algorithm, the delta quaternion of the magnetometer and the inverse quaternion of orientation are used, which describes the rotation vector of the magnetic field of the sensor reference system, which is shown in equation (3).

$$R\left(q_{E_\omega}^{*S}\right)m^S = l. \quad (3)$$

The next step is the process of calculating the quaternion $G = \sqrt{l_x^2 + l_y^2}$, to calculate (4)

$$R^T\left(q_{mag}\right) = \begin{bmatrix}l_x\\l_y\\l_z\end{bmatrix} = \begin{bmatrix}\sqrt{G}\\0\\l_z\end{bmatrix}. \quad (4)$$

Thus, there is a process of minimizing the influence of ferromagnetic errors on the magnetometer.

In **block 4**, there is an adaptive correction of the input data of the accelerometer and magnetometer.

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DOI 10.15588/1607-3274-2022-3-18

At the first stage there is a process of forecasting the quaternion in the components of the angles of roll and tango. The result of calculating the values of the delta quaternion of the accelerometer, we obtain by the formula

$$\Delta q_{acc} = \left[\sqrt{\frac{g_z + 1}{2}} - \frac{g_y}{\sqrt{2(g_z + 1)}} \frac{g_z}{\sqrt{2(g_z + 1)}} 0 \right]^T ,$$

then there is the process of calculating the delta quaternion of the magnetometer

$$\Delta q_{mag} = \left[\frac{\sqrt{l + g_x \sqrt{g}}}{\sqrt{2g}} \, 0 \, 0 \frac{l_y}{\sqrt{2\left(g + l_x \sqrt{g}\right)}} \right]^T .$$

The magnetometer delta quaternion describes the process of rotation around the global coordinate system of the Z axis, aligning the global X axis in the positive direction of the magnetic field. With this formulation, the process of calculating the turn does not affect the components of the yaw (course) and pitch, even in the presence of magnetic perturbations, limiting their impact only on the roll angle. Thus,

$$\Delta q_{mag} = \left[\Delta q_{0mag} \, 0 \, 0 \Delta q_{3mag} \right]^T .$$

Then, subject to the receipt of the magnetic field estimate, there is a correction of the vertical component of the quaternion of orientation

$$q_E^S = q_{E_\omega}^S \otimes \hat{\Delta} q_{acc} \otimes \hat{\Delta} q_{mag} . \quad (5)$$

However, predicting the magnitude of gravity has a deviation from the real vector of gravity, so there is a correction using the delta quaternion Δq_{acc}, which converts the gravitational data of the global frame of reference q_E^S in predicted gravity g_p^E :

$$R\left(q_{E_\omega}^{*S}\right) a^S = g_p^E . \quad (6)$$

Next is the transformation of the normalized UAV positioning data vector

$$R(\Delta q_{acc}) = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix} . \quad (7)$$

After solving the equation in closed form, the quaternion component is determined $\Delta q_{acc} = 0$.

The result of the accelerometer data processing provides the shortest rotation relative to the Z axis, so the vector $g_z \approx 1$.

In **block 5**, the process of scalar product Δq_{0acc} on the components of the quaternion Δq_{acc} .

Provided that $\Delta q_{0acc} > \varepsilon$, ($\varepsilon \geq 0.9$)

$$q_E^S = \Delta q_{0acc} \otimes \hat{\Delta} q_{acc} .$$

To predict the orientation quaternion in the conditions of influence of high-frequency accelerometer noise (dynamic influence on the determination of roll, UAV pitch), the interpolation algorithm of equation (8) [18] based on the identity quaternion is used $q_I = [1000]^T$, $\alpha \in [0,1]$:

$$Lerp(q_I + \Delta q_{acc}) = \left(\bar{\Delta} q_{acc} (1 - \alpha)\right) q_I + \alpha \Delta q_{acc} . \quad (8)$$

The LERP algorithm does not support single normalization of the delta quaternion, so the normalization operation occurs after the application of linear interpolation (9):

$$\hat{\Delta} q_{acc} = \frac{\bar{\Delta} q_{acc}}{\left\| \bar{\Delta} q_{acc} \right\|} . \quad (9)$$

The points of the UAV orientation quaternion lie on the surface of the hyper sphere (4D), provided that, $\Delta q_{0acc} \leq \varepsilon$, therefore, spherical linear interpolation was used [18]:

$$Slerp(q_I + \Delta q_{acc}) = \frac{\sin([1 - \alpha]\theta)}{\sin \theta} q_I + \frac{\sin(\alpha \theta)}{\sin \theta} \Delta q_{acc} .$$

Thus, ferromagnetic errors are compensated by the process of "merging" the data of the magnetometer and accelerometer, and switching between the respective algorithms SLERP or LERP, depending on the operating conditions of the algorithm.

In **block 6** adaptive adjustments of gyroscope data.

The process of adaptive adjustment is carried out when the UAV is moving at high acceleration and the magnitude and direction of the acceleration vector differ from gravity, so the orientation estimate can be based on erroneous navigation data, which increases the accumulation of position estimation error in space. However, it is known [8] that the indicators of the gyroscope are not affected by linear acceleration, so in this case the gyroscope data are used as the main source for evaluating the determination of UAV positioning parameters.

To solve the problem of adaptive adjustment of UAV positioning parameters, the error of setting a single vector is determined $\bar{u}_m$, which is given in the following equation:

$$\bar{u}_m = \frac{\left| \left\| \tilde{a}^S \right\| - g \right|}{g} . \quad (10)$$

The accelerometer and magnetometer data correction unit predicts a correction vector that initiates a prognosis to estimate the orientation of the local gyroscope date sensor reference system at the initial time point.

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The process of zero drift compensation of the gyroscope in a dynamic medium is based on the algorithm of the Nesterov gradient descent [19]. This reduces the time to find the extremes of the objective function (components of the quaternion error of the gyroscope at time t).

So, $b^S_{pos} = \xi\left(2q^*_{pos,t-1} \otimes q_{\nabla(f)}\right)$,

$$q_{\nabla(f)} = \gamma\Delta q_t + \eta q_{\nabla}\left(\overset{*}{q}\left(\hat{q}^S_E, \hat{a}^S, \hat{m}^S\right)_t - \gamma\Delta q_t\right), 0 \le \gamma \le 1,$$

$$\overset{*}{q}\left(\hat{q}^S_E, \hat{a}^S, \hat{m}^S\right)_{t+1} = q\left(\hat{q}^S_E, \hat{a}^S, \hat{m}^S\right)_t - \Delta q_{t+1}.$$

Next, the initial data of inertial sensors is normalized and, based on the obtained indicators; the UAV positioning parameters in space are predicted (11)

$$\hat{q}_{pos,t+1} = q_{g,t} - (\beta\Delta t) q_{\nabla,t}. \qquad (11)$$

4 EXPERIMENTS

The experiment was conducted in the MatLab software environment using a real set of UAV flight data at speed $v_{UAV} = 40 km/h$, at the time interval of the UAV flight t={1…300}c, sampling frequency of processing of MEMS sensors navigation parameters $\Delta F = 100 Hz$.

As initial data applied navigation parameters of MEMS MPU - 9255 inertial navigation system. It is necessary to achieve a minimum deviation of the UAV flight trajectory $f\left(\hat{q}^S_E, \hat{a}^S, \hat{m}^S, \hat{b}^S_t\right) \to \Delta_{pos}(t) \Rightarrow \min$, in conditions other MEMC sensors and INS elements do not increase the angular velocity setting error.

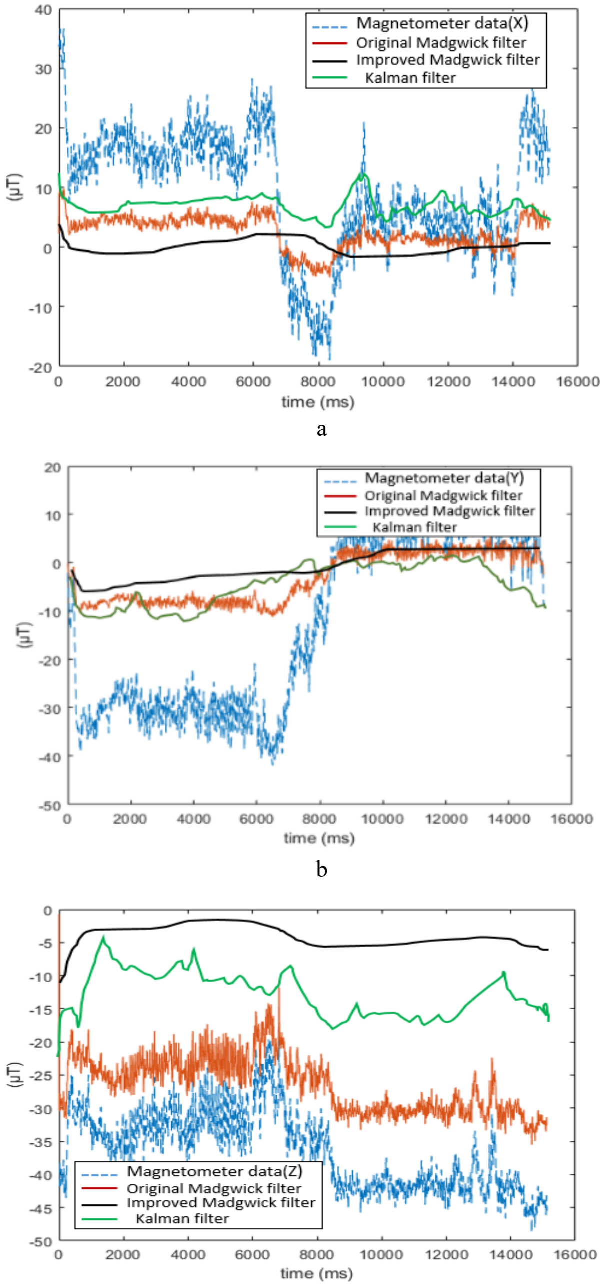
During the experiment, attention was focused on the response of the system during the dynamic movement (series of turns) of the UAV. The phenomenon of displacement of the sensors is a signal that changes slowly over time. In order to avoid filtering of useful information, the low-pass filter is used only when the sensor is stationary. If the sensor is stationary, the offset is updated; otherwise it is assumed that the correctness of the indicators corresponds to the previous state.

The experiment compares the evaluation of the characteristics of the proposed improved Madgwik filter in different conditions with other MEMS PINS filtration methods based on the original Madgwik filter and.

At the beginning, the general characteristics are evaluated, and then the efficiency of different methods under conditions of magnetic perturbation and high non-gravitational acceleration is compared [20].

In the process of the experiment to ensure the correctness of the measurements (acceleration, angular velocity and value of the magnetic field strength) was used sensor inertial navigation system MEMS "MPU-9250".

The process of determining the orientation of the UAV during the disappearance of GPS signals, was due to the processing of acceleration data and magnetic field data.



c

Figure 2 – The process of compensating for MEMS magnetometer errors in the process of changing the ferro-magnetic environment in the axis: a – X, b – Y, c – Z

The first two tests were to apply the effect of magnetic perturbation for 2–3 seconds, while in the third – the perturbation was static until the end of the experiment.

At the beginning of the experiment, the norm of the measured magnetic field is constant; its value differs from the norm of the reference vector of the magnetic field (0.54 Gauss). The graph (Fig. 3, 4) compares the results of three MEMS PINS filtering algorithms:

– the Madgwick filter is marked on the graph with a red line;

– Kalman filter with green line;

– advanced Madgwick filter with black line.

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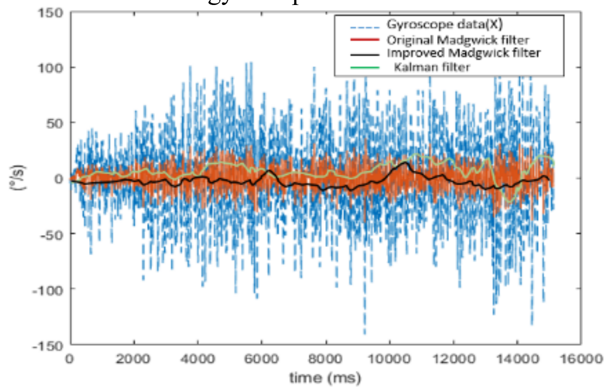
DOI 10.15588/1607-3274-2022-3-18

A popular RMSE error metric is used (Table 2), which shows an estimate of the accuracy of determining the navigation parameters of the PINS during the disappearance of the GPS.

Figure 3 shows the result of the operation of filtering algorithms for the process of compensating for the shift of the drift zero of the gyroscope.



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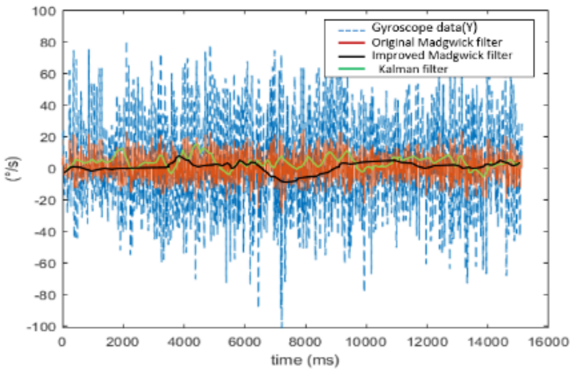

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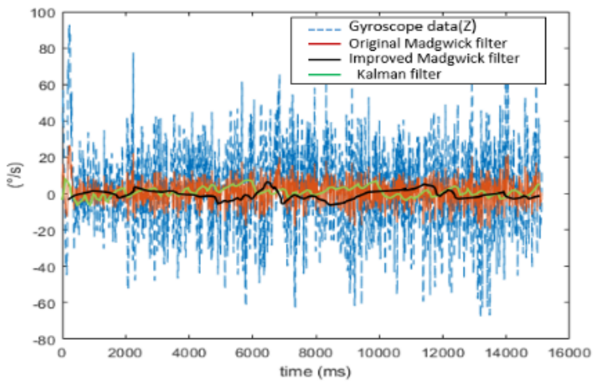

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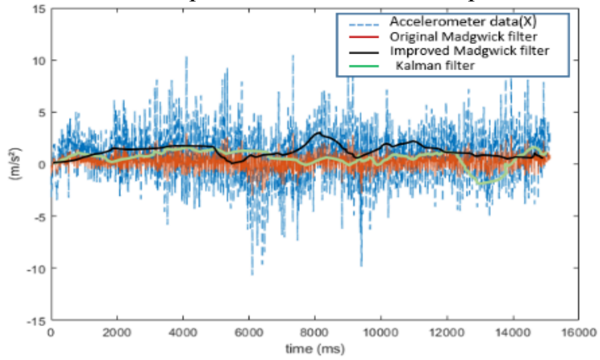
Figure 3 – The result of the MEMS gyroscope filtration algorithms in the axis: a – X, b – Y, c – Z

During the operation of the proposed improved Madgwik filter, the effect of ferromagnetic interference on course determination was reduced due to the two-step filtering process of the correcting delta quaternion (accelerometer and magnetometer), while in the algorithm ferromagnetic perturbations, and the restoration of the correctness of the sensor occurs when eliminating the source of ferromagnetic perturbation.

As a rule, the compensation of the drift of zero deviation of the gyroscope occurs in stationary positions in the process of finding the average value of the gyroscope or the incompatibility matrix (Jacobi) is used to linearize complex dynamic processes [10]. However, such methods are not able to eliminate the trend of drift, being in dynamic motion and also increasing the increasing computational complexity. For this purpose, it is proposed in the advanced Madgwik filtering algorithm to alternatively use **the block of the corrector of the gyroscope-quaternion**, at the time to predict the drift of zero displacement (Fig. 1).

Figure 4 shows the result of the MEMS PINS filtering algorithms in the process of error compensation affecting the accelerometer performance of different speeds.



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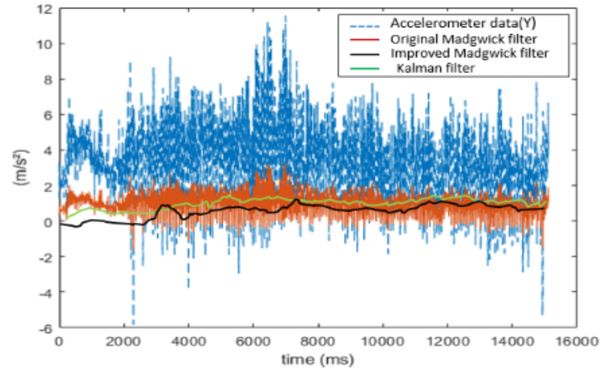
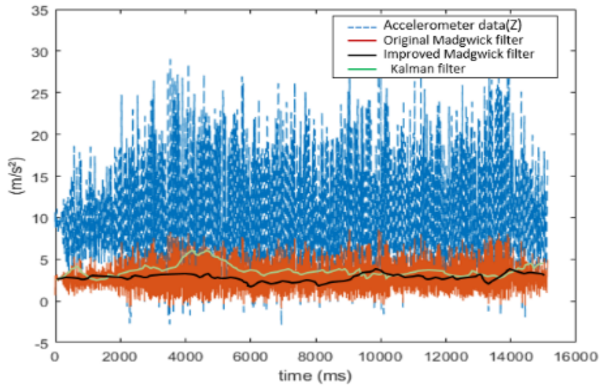


b



c

Figure 4 – The result of the MEMS accelerometer filtering algorithms in the axis: a – X, b – Y, c – Z

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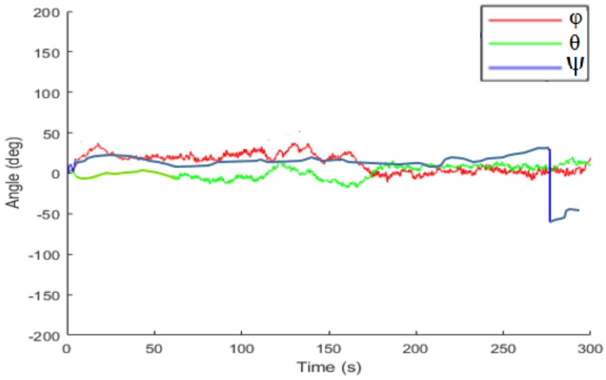
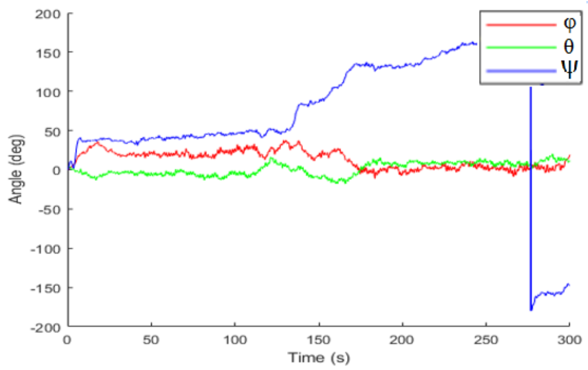
DOI 10.15588/1607-3274-2022-3-18

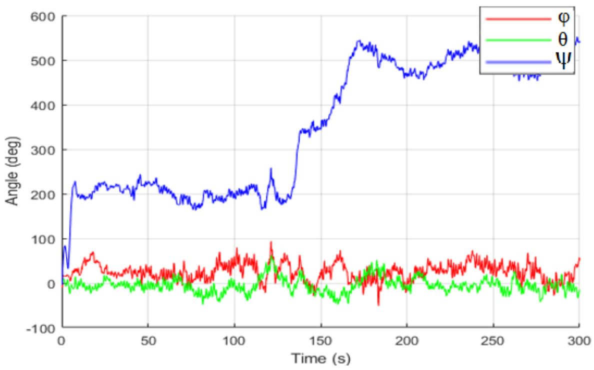
Figure 5 shows graphically the results of determining the navigation parameters (θ,φ,ψ) using the classic and advanced Madgwik filter, and the Kalman filter.



a



b



c

Figure 5 – The result of filtering to determine the navigation parameters of the orientation using
a – Advanced Madgwick filter, b – the Madgwik filter, c – Kalman filter

5 RESULTS

Evaluation of the effectiveness of the method of improving the accuracy of data processing MEMS – inertial navigation system sensors in the autonomous mode of UAV flight is performed using the software environment MatLab 2020b and Python 3.7.

Table 1–2 presents an assessment of the effectiveness of the results of filtering algorithms on the criterion of standard deviation.

The navigation estimation algorithm uses accelerometer, magnetometer, and gyroscope measurements combined into a linked coordinate system using the Earth's magnetic field and gravity vector to compensate for the zero-angle MEMS error of the gyroscope when GPS signals are lost.

Table 1 – Comparison of data processing speed MEMS signals of PINS

Algorithm	Processing time (μs)	Standard deviation
Madgwik filtration	1.2839	0.7101
Advanced Madgwick	0.9846	0.4032
RKF	7.0408	0.2342

Table 2 – The standard deviation of navigation parameters

Navigation parameters	Madgwik filtration	Advanced Madgwik	RKF
θ	1,6	**1,932**	1,9
φ	1,3	**0,292**	6,5
ψ	12,3	**1,163**	32,1

The results of applying the Kalman filter to determine the navigation parameters of the orientation showed the following: angle φ <6,5º, θ<1,9º, course angle ψ <32º, at a time interval t={1…300}s.

Low levels of accuracy of the Kalman filter are caused by the following factors: process of linearization of the dynamic UAV model reduces the accuracy of forecasting taking into account nonlinear errors of the dynamic state of the system.

The results of the application of the Madgwik filter on the value of navigation parameters of orientation showed the following: angle φ<1,3º, angle θ<1,6º, course angle ψ <32º.

Low levels of accuracy of application of the Madgwik filter are caused by the following factors: there is a difficulty of exact definition of positioning in the course of transformation of a quaternion of orientation from local system of reference of the magnetometer sensor and gyroscope, into the global frame of reference. This phenomenon occurs due to the limitation of the degree of freedom in the system of orientation equations proposed by Madgwik [13], which has two free-levels when the UAV moves in a dynamic environment, the magnitude and direction of the total measured acceleration vector different from gravity, in this case the vector state is estimated using noisy data, which leads to a significant deterioration in the determination of UAV orientation in space, the Madgwik algorithm uses a packet gradient descent to find the optimum error function of the orientation quaternion, which in turn limits the signal processing speed of MEMS PINS.

The application of the advanced Majvik filter to determine the navigation parameters of the orientation showed the following results: angle φ<0,292º, angle θ<1,93º, course angle ψ <0,16º at a time interval t={1…300}c.

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6 DISCUSSIONS

In the framework of the work the main theoretical aspects of the method of improving the accuracy of MEMS navigation data processing of the inertial navigation system of UAVs are revealed. Implementation became possible as a result of in-depth study of existing methods of processing UAV navigation systems. With the help of experimental research of the proposed solutions it was possible to obtain the adequacy of the proposed method by comparing the results obtained with the results of their application in the MathLab software environment. Structural and functional schemes of the PINS control system, which is the basis of the methodology of the algorithm for implementing an intelligent automatic control system of the UAV control system, are given, especially in the case of short-term signals from global positioning systems.

The proposed method gives positive results in terms of a significant reduction in the standard deviation of navigation parameters, and as a result of a significant reduction in the course deviation of the UAV.

CONCLUSIONS

The proposed method based on the advanced Madgwik filter shows better speed of data processing of navigation parameters and accuracy of positioning parameters in UAV space based on PINS micro electromechanical system compared to extended filtering methods based on extended filtering. 32%, and Madgwik 20%.

The difference between the proposed method and the existing ones is as follows:

– firstly, it reduces the effect of ferromagnetic noise on the course and pitch components when the magnetometer sensor is perturbed by local ferromagnetic noise;

– secondly, the proposed method does not use complex calculations of matrix inversions while maintaining low computational costs through the use of linear interpolation algorithm;

– thirdly, the fast convergence of the UAV orientation quaternion due to the algebraic solution;

– fourth, two different gain for the process of separate filtration of different speeds and ferromagnetic noise of the magnetic field;

– fifth, during the flight of the UAV in a dynamic environment, the Nesterov gradient descent algorithm is used to calculate the component of the quaternary orientation error, while reducing computational costs and time to find the minimum error function PINS MEMS navigation parameters.

The obtained scientific result is expedient to use in control systems of unmanned aerial vehicles in a complex signal-interfering environment.

ACKNOWLEDGMENTS

The work is the result of research carried out by the employees of educational and scientific structural studies of Military Institute of Telecommunications and Informatization named after Heroes of Kruty according to Research Department of the Research Institute of the Ministry of Defense of Ukraine during the implementation of the project as part of research tasks to improve UAV control systems.

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Received 14.02.2022.
Accepted 28.07.2022.

УДК 004.852

МЕТОД ПІДВИЩЕННЯ ТОЧНОСТІ ОБРОБКИ НАВІГАЦІЙНИХ ДАНИХ МЕМС ІНЕРЦІАЛЬНОЇ НАВІГАЦІЙНОЇ СИСТЕМИ БПЛА

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АНОТАЦІЯ

Актуальність. Сучасна теорія і практика підготовки та ведення воєнних дій на суші, на морі, повітрі, а віднедавна і у кіберпросторі диктує невпинну модернізацію військової техніки. Розробка принципово нового озброєння здійснюється з урахуванням однієї із основних вимог – максимальної автоматизації процесів експлуатації, що дозволяє комбатантам максимально дистанціюватися один від одного.

Серед новітніх зразків озброєння на полі бою, через переважно позиційний характер ведення збройного протистояння, стали фактично незамінними, через власну мультизадачність, безпілотні літальні апарати (БПЛА). Одним з шляхів підвищення ефективності БПЛА на полі бою є підвищення рівня технічної досконалості систем керування польоту.

Створення нових підходів для проектування навігаційних систем безпілотних літальних апаратів, зокрема, на основі безплатформенної інерціальної навігаційної системи є актуальним завданням, що дозволить забезпечити автоматичне керування маршрутом польоту БПЛА за відсутності коригувальних сигналів від глобальної системи супутникової навігації.

Мета. Метою роботи є розробка методу підвищення точності обробки навігаційних даних МЕМС інерціальної навігаційної системи безпілотного літального апарату на основі вдосконаленого фільтру Маджвіка.

Зазначений метод дозволить підвищити швидкість обробки даних навігаційних параметрів та точність визначення параметрів позиціювання в просторі БПЛА за рахунок застосування вдосконаленого фільтру Маджвіка.

В роботі показано розроблену блок-схему фільтрації МЕМС БІНС на основі вдосконаленого фільтра Маджвіка, проведено деталізований математичний опис процесів фільтрації.

Зазначений метод був апробований експериментально в програмному середовищі MatLab використовуючи реальний набір даних зібраний в процесі польоту БПЛА.

Метод. Для досягнення поставленої мети використано такі методи: інтелектуальні системи, теорія автоматичного управління, псевдоспектральний метод; методи на базі генетичного алгоритму та апарат нечіткої нейронної мережі.

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DOI 10.15588/1607-3274-2022-3-18

Результати. Розроблено метод підвищення точності обробки навігаційних даних МЕМС інерціальної навігаційної системи безпілотного літального апарату на основі вдосконаленого фільтру Маджвіка. Досліджено можливість практичного застосування отриманих результатів та порівняно з традиційними методами. Проведено експеримент в програмному середовищі MatLab, та проведено порівняння із методом обробки навігаційних даних на основі фільтру Маджвіка і фільтру Калмана.

Висновки. Розроблений метод підвищення точності обробки навігаційних даних МЕМС інерціальної навігаційної системи безпілотного літального апарату на основі вдосконаленого фільтру Маджвіка показує перевагу порівняно із відомими методами за відсутності коригувальних сигналів від глобальної системи супутникової навігації із точності та швидкості обробки навігаційних даних.

КЛЮЧОВІ СЛОВА: інтелектуальна система автоматичного управління, навігаційна система, безпілотний літальний апарат.

УДК 004.852

МЕТОД ПОВЫШЕНИЯ ТОЧНОСТИ ОБРАБОТКИ НАВИГАЦИОННЫХ ДАННЫХ МЭМС ИНЕРЦИАЛЬНОЙ НАВИГАЦИОННОЙ СИСТЕМЫ БПЛА

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АННОТАЦИЯ

Актуальность. Современная теория и практика подготовки и ведения военных действий на суше, на море, воздухе, а с недавних пор и в киберпространстве диктует неустанную модернизацию военной техники. Разработка принципиально нового вооружения осуществляется с учетом одного из основных требований – максимальной автоматизации процессов эксплуатации, позволяет комбатантам максимально дистанцироваться друг от друга.

Среди новейших образцов вооружения на поле боя, через преимущественно позиционный характер ведения вооруженного противостояния, стали фактически незаменимыми, через собственную мультизадачность, беспилотные летательные аппараты (БПЛА). Одним из путей повышения эффективности БПЛА на поле боя является повышение уровня технического совершенства систем управления полетом.

Создание новых подходов для проектирования навигационных систем беспилотных летательных аппаратов, в частности, на основе бесплатформенной инерциальной навигационной системы является актуальной задачей, что позволит обеспечить автоматическое управление маршруту полета БПЛА при отсутствии корректирующих сигналов от глобальной системы спутниковой навигации.

Цель. Целью работы является разработка метода повышения точности обработки навигационных данных МЕМС инерциальной навигационной системы беспилотного летательного аппарата на основе усовершенствованного фильтра Маджвика.

Указанный метод позволит повысить скорость обработки данных навигационных параметров и точность определения параметров позиционирования в пространстве БПЛА за счет применения усовершенствованного фильтра Маджвика.

В работе показано разработанную блок-схему фильтрации МЭМС БИНС на основе усовершенствованного фильтра Маджвика, проведено детализированное математическое описание процессов фильтрации.

Указанный метод был апробирован экспериментально в программной среде MatLab используя реальный набор данных, собранных в процессе полета БПЛА.

Метод. Для достижения поставленной цели использованы следующие методы: интеллектуальные системы, теория автоматического управления, псевдоспектральний метод, методы на базе генетического алгоритма и аппарат нечеткой нейронной сети.

Результаты. Разработан метод повышения точности обработки навигационных данных МЕМС инерциальной навигационной системы беспилотного летательного аппарата на основе усовершенствованного фильтра Маджвика. Исследована возможность практического применения полученных результатов и по сравнению с традиционными методами. Проведен эксперимент в программной среде MatLab, и проведено сравнение с методом обработки навигационных данных на основе фильтра Маджвика и фильтра Калмана.

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DOI 10.15588/1607-3274-2022-3-18

Выводы. Разработанный метод повышения точности обработки навигационных данных МЕМС инерциальной навигационной системы беспилотного летательного аппарата на основе усовершенствованного фильтра Маджвика, показывает преимущество по сравнению с известными методами, при отсутствии корректирующих сигналов от глобальной системы спутниковой навигации с точности и скорости обработки навигационных данных.

КЛЮЧЕВЫЕ СЛОВА: интеллектуальная система автоматического управления, навигационная система, беспилотный летательный аппарат.

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DOI 10.15588/1607-3274-2022-3-18