e-ISSN 1607-3274 Радіоелектроніка, інформатика, управління. 2020. № 4
p-ISSN 2313-688X Radio Electronics, Computer Science, Control. 2020. № 4

UDC 629.05:656.61:004.942

IMPROVING THE ACCURACY OF AUTOMATIC CONTROL WITH MATHEMATICAL METER MODEL IN ON-BOARD CONTROLLER

Zinchenko S. M. – PhD, Associate Professor of Ship Handling Department, Head of the Electronic Simulators Laboratory, Kherson State Maritime Academy, Ukraine.

Mateichuk V. M. – Senior Lecturer of Ship Handling Department, Head of the Electronic Simulators Laboratory, Kherson State Maritime Academy, Ukraine.

Nosov P. S. – PhD, Associate Professor of Navigation Systems Department, Kherson State Maritime Academy, Ukraine.

Popovych I. S. – Dr. Sc., Professor of General and Social Psychology Department, Kherson State University, Ukraine.

Appazov E. S. – PhD, Associate Professor of Innovation Technology and Technical Tools of Navigation Department, Kherson State Maritime Academy, Ukraine.

ABSTRACT

Context. The article discusses the issues of increasing the accuracy of automatic control of a moving object using a mathematical model of a meter and a device observing measurement errors in the on-board controller of the control system. The object of the research is the processes of automatic control of a moving object with a mathematical model of a meter and a device observing measurement errors in the on-board controller of the control system. The subject of the research is a method and algorithms for increasing the accuracy of automatic control of a moving object with a mathematical model of a meter and a device observing measurement errors in the on-board controller of the control system.

Objective. The aim of research is an improving the accuracy of automatic control of a moving object.

Method. This aim is achieved through the use in the on-board controller of the control system of the mathematical meter model and the observing device built on its basis, the estimation of the useful component and the systematic error, depending on the motion parameters of the controlled object, using only the useful component for control, without systematic error.

Results. A method and algorithms for increasing the control accuracy of a moving object through the use in the on-board controller of a mathematical meter model and an observer of systematic measurement errors, built on its basis, have been developed. The efficiency and effectiveness of the developed method and algorithms were confirmed by mathematical modeling in the MATLAB environment of the control processes of a moving object in a closed circuit with a control system.

Conclusions. The results of mathematical modeling confirmed the operability and efficiency of the proposed method and algorithms and allow them to be used for practical purposes in the development of mathematical support for high – precision automatic control systems.

KEYWORDS: automatic control, control accuracy, movement control systems, measurement errors, observing device, mathematical model.

ABBREVIATIONS

GCS $OX_2Y_2Z_2$ is a Gyroscopic Coordinate System;

GSE is a Gyrocompass Sensing Element.

NOMENCLATURE

$\mathbf{f}_n(\bullet)$ is a mathematical model of the control object;

$\mathbf{X}_n$ is a control object state vector;

$\mathbf{C}_n$ is a vector of control object constants;

$\mathbf{f}_{jm}(\bullet)$ is a j-th meter component of mathematical model;

$\mathbf{X}_m$ is a meter state vector;

$\mathbf{C}_m$ is a vector of meter constants;

$\mathbf{f}_u(\bullet)$ is a control law;

$\mathbf{U}$ is a control vector;

$\mathbf{X}_m^*$ is a vector of required movement parameters;

$\mathbf{C}_u$ is a vector of control law constants;

$\mathbf{F}$ is a quality control function;

$\hat{\mathbf{X}}_m$ is a measurement evaluation vector;

$\hat{\mathbf{X}}_{0m}$ is a vector of estimation of useful component of measurements;

$\hat{\mathbf{X}}_{jm}$ is an estimate vector j-th component of the systematic measurement error;

$\boldsymbol{\lambda}_j$ is a j-th observer coefficient vector;

$\mathbf{H}$ is a kinetic moment vector of the gyrocompass sensing element;

$\boldsymbol{\Omega}$ is an angular rate of kinetic moment vector;

$\mathbf{M}^j$ is a j-th vector of disturbance moment;

Θ_m is a measured deflection angle of gyrocompass sensetive element in vertical plane;

$\hat{\Theta}_m$ is an assessed deflection angle of gyrocompass sensetive element in vertical plane;

$\hat{\Theta}_{0m}$ is an assessed usefull components of deflection angle in vertical plane;

© Zinchenko S. M., Nosov P. S., Mateichuk V. M., Popovych I. S., Appazov E. S., 2020
DOI 10.15588/1607-3274-2020-4-19

$\hat{\Theta}_{jm}$ is an estimation of the j-th component of the systematic measurement error from $\mathbf{M}^j$ – disturbance moment;

Ψ_m is a measured deflection angle of gyrocompass sensetive element in horizontal plane;

$\hat{\Psi}_m$ is an assessed deflection angle of gyrocompass sensetive element in horizontal plane;

$\hat{\Psi}_{0m}$ is an assessed usefull components of deflection angle in horizontal plane;

$\hat{\Psi}_{jm}$ is an estimation of the j-th component of the systematic measurement error from $\mathbf{M}^j$-disturbance moment in the horizontal plane;

$\mathbf{f}_0^{\Theta}$ is a mathematical model of the useful component in vertical plane;

$\mathbf{f}_j^{\Theta}$ is a mathematical model of the j-th deviation component in the vertical plane;

$\mathbf{f}_0^{\Psi}$ is a mathematical model of the useful component in horizontal plane;

$\mathbf{f}_j^{\Psi}$ is a mathematical model of j-th deviation component in horizontal plane;

λ_j^{Θ} is a j-th observer coefficient in vertical plane;

λ_j^{Ψ} is a j-th observer coefficient in horizontal plane;

ω_3 is an Earth rate;

σ is a geographic latitude;

l is a gravity center displacement;

m is a displaced mass;

g is a free fall acceleration;

a is a vessel acceleration or deceleration;

V is a speed of the controlled object;

R is a radius of the Earth;

K is a course of the controlled object;

V_r is a speed of course change;

r is a radius of course change;

ω_z is a yaw rate;

ω_{zm} is a measured yaw rate;

ω_{zw} is an assessed yaw rate;

ψ is a yaw angle;

ψ_m is a measured yaw angle;

ψ_w is an assessed yaw angle;

δ is a rudder deflection angle.

INTRODUCTION

The quality of the control system as a whole is determined by the quality of the mathematical, algorithmic and software of the on-board controller designed to solve the set functional task, the quality of input information coming to the on-board controller from the measuring devices, as well as the quality of processing the output signals from the on-board controller by the executive devices.

Information from measuring devices, in addition to the useful component, also contains fluctuation and systematic measurement errors [1–4]. Fluctuating measurement errors cannot be completely eliminated, but can be reduced by hardware or software processing in the meter itself or on-board controller of the control system using bandpass filters. There are also more complex processing methods using a mathematical model of the control object for filtering and simultaneous observation of parameters of the state vector that are inaccessible to direct observation [5–7], including those that are optimal in noise [8]. Mathematical models of the controlled object are also used to predict the movement of the controlled object, determine failures [9], and other purposes [10–15].

Automation of control processes allows to exclude the human factor as much as possible [16–17], which is the cause of a large number of accidents and catastrophes, and to significantly reduce the human influence on the control processes of mobile objects [18–21].

This article discusses the issues of increasing the accuracy of automatic control of a moving object through the use of a mathematical meter model in the on-board controller. Existing solutions, as will be shown below in the review, do not use the capabilities of mathematical meter models in the on-board controller for improving the accuracy. Therefore, the development of such systems is actual scientific and technical task.

The object of the research is the processes of automatic control of a moving object with a mathematical model of a meter and a device observing measurement errors in the on-board controller of the control system.

The subject of the research is a method and algorithms for increasing the accuracy of automatic control of a moving object with a mathematical model of a meter and a device observing measurement errors in the on-board controller of the control system.

The purpose of research is an improving the accuracy of automatic control of a moving object.

This aim is achieved through the use in the on-board controller of the control system of the mathematical meter model and the observing device built on its basis, the estimation of the useful component and the systematic errors, depending on the motion parameters of the controlled object, using only the useful component for control, without systematic errors.

1 PROBLEM STATEMENT

A mathematical model of the control object is

$$\frac{d\mathbf{X}_n}{dt} = \mathbf{f}_n(\mathbf{X}_n, \mathbf{U}, \mathbf{C}_n), \qquad (1)$$

mathematical model of a meters is

$$\frac{d\mathbf{X}_m}{dt} = \mathbf{f}_0(\mathbf{X}_n, \mathbf{C}_m) + \mathbf{f}_1(\mathbf{X}_n, \mathbf{C}_m) + \ldots \mathbf{f}_k(\mathbf{X}_n, \mathbf{C}_m) \qquad (2)$$

© Zinchenko S. M., Nosov P. S., Mateichuk V. M., Popovych I. S., Appazov E. S., 2020
DOI 10.15588/1607-3274-2020-4-19

and the law of an object motion control is

$$\mathbf{U} = \mathbf{f}_u(\mathbf{X}_m, \mathbf{X}^*, \mathbf{C}_u) . \quad (3)$$

It is required to minimize the control error

$$F = \left\| \mathbf{X}_n - \mathbf{X}^* \right\| \to \min . \quad (4)$$

2 LITERATURE REVIEW

The article [22] discusses the issues of reducing an errors in measuring fluctuating concentrations for specific type of diffusion monitor. Observations have found that a significant error may be present in the estimates of the mean values of rapidly changing concentrations. Similar conclusions were also drawn from the numerical calculation of the error and its variance using the time-dependent field concentration data. The results indicate that when measuring substances with short-term exposure, excessive exposure estimates can be expected when sampling fluctuating concentrations. A simple modification of the sampler is proposed to reduce or eliminate this error.

In article [23] a method for eliminating the error in the results of measuring the surface shape of space structures with a high spatial resolution is proposed. When measuring the surface shape of a spherical mirror model, it turned out that measurement errors can be divided into systematic, depending on the projected gratings, and random, which are influenced by the optical properties of the object and the measuring system. A method for eliminating errors is proposed, including a band-pass filter to remove systematic errors and averaging procedures to reduce random errors. Using the example of measuring the surface shape of a spherical mirror model and a white plate model, it is shown that the proposed method can eliminate measurement errors by more than 50%. The effectiveness of the method is presented by the results.

In article [24] issues related to temperature drift and synchronous measurement error of the axial displacement sensor in an engine with a magnetic suspension are considered. There was proposed a configuration of the displacement sensor, consisting of three meters, a pair of meters is used to eliminate the synchronous measurement error, and the third sensor to take into account the temperature drift. A mechanism for generating a synchronous measurement error caused by incorrect assembly was presented, as well as an operational amplifier for obtaining the exact position of the axial center by adjusting the weighting coefficients of the readout signals of a pair of sensors. A temperature compensation circuit was also presented. An experiment was carried out on a test bench of an engine with a magnetic suspension, confirming the effectiveness of the proposed methods.

In article [25] the issues of eliminating the low-frequency vibrational disturbance in the constant component of the measurement of the Michelson interferometer, used to measure the communication signal with distributed polarization in fibers with high two-ray refraction, are considered. Compared to the space interferometer, the DC components in the interferograms of the all-fiber interferometer oscillate more intensely. These fluctuations are mainly caused by the disturbance of the motorized delay line in motion, which is confirmed by the corresponding models and experiments. A method for processing signals of group averages is proposed to eliminate low-frequency oscillatory disturbances, and the results of experimental confirmation are obtained.

The article [26] deals with the measurement of the flow rate of matter based on the phase method with homodyne frequency conversion. The principles of implementation of a contactless flow meter with compensation for fluctuations of electrophysical parameters in the flow are shown. The measuring device consists of a main channel, which extracts information about the flow rate of a substance, and a reference channel, to extract information about the electrophysical parameters of a substance in the flow. the minimum number of required adjustment elements, which has a positive effect on its reliability and stability in the presence of various external influences.

In article [27] the issues of motor speed control are considered. The quality of control largely depends on the accuracy of the speed feedback signal. The measuring method used in the incremental encoder is the most widely used due to its high theoretical accuracy. However, in practice, the internal error of the optical grating of the incremental encoder and the error of the analog-to-digital conversion make it difficult to achieve the theoretical accuracy of speed measurement. The article proposes a single-phase self-adaptive method for ideal suppression of the speed measurement error. The performed modeling and experiment confirm the efficiency of the proposed method.

In article [28] the issues of assessing the position of the rotor of synchronous machines with permanent magnets for medium and high speeds are considered. Describes an intelligent, non-touch speed control method for the entire speed range, which is especially suitable for pumps and fans. A simple method of observing the voltage of the reverse electromotive force was found, which is integrated into the control strategy. In addition, systematic errors and their effect on the accuracy of the calculated rotor position are systematically analyzed and documented. The theoretical results are confirmed by simulations and measurements.

In article [29] the issues of estimating deviations of the actual radar directional pattern from the ideal one for remote sensing of ocean surface currents are considered. A calibration method is proposed based on the time-averaged local spatial speed of coverage in order to reduce the influence of deviations of the actual radar radiation pattern on the measurements.

At the same time, as follows from the above review, the authors have not found solutions to improve control accuracy by using in the on-board controller of the motion

© Zinchenko S. M., Nosov P. S., Mateichuk V. M., Popovych I. S., Appazov E. S., 2020
DOI 10.15588/1607-3274-2020-4-19

control system a mathematical meter model and an observer, built on its basis, to determine of systematic measurement errors that depend on the parameters of the control object and taking them into account when control. Therefore, the solution of these issues is an urgent scientific and technical task.

3 MATERIALS AND METHODS

The right side of the mathematical model of the measurer (2) contains a vector – function $\mathbf{f}_0(\mathbf{X}_n,\mathbf{C}_m)$, determining the behavior of the useful component of the measured signal, and the vector of the function $\mathbf{f}_1(\mathbf{X}_n,\mathbf{C}_m)$, $\mathbf{f}_2(\mathbf{X}_n,\mathbf{C}_m)$, …, $\mathbf{f}_k(\mathbf{X}_n,\mathbf{C}_m)$, determining the behavior of the systematic components of measurement errors.

To estimate these components write the vector equation (2) in the form

$$\frac{d\hat{\mathbf{X}}_{0m}}{dt}=\mathbf{f}_0(\mathbf{X}_n,\mathbf{C}_m), \qquad (5)$$

$$\frac{d\hat{\mathbf{X}}_{1m}}{dt}=\mathbf{f}_1(\mathbf{X}_n,\mathbf{C}_m), \qquad (6)$$

$$\dots$$

$$\frac{d\hat{\mathbf{X}}_{km}}{dt}=\mathbf{f}_k(\mathbf{X}_n,\mathbf{C}_m), \qquad (7)$$

$$\hat{\mathbf{X}}_m=\hat{\mathbf{X}}_{0m}+\hat{\mathbf{X}}_{1m}+\ldots+\hat{\mathbf{X}}_{km}. \qquad (8)$$

After numerical integration of the system of differential equations (5)–(7) in the onboard controller, we obtain the vector of estimates of the measured parameters $\hat{\mathbf{X}}_m$ and the vector of estimates of its components $\hat{\mathbf{X}}_{0m}$, $\hat{\mathbf{X}}_{1m}$, …, $\hat{\mathbf{X}}_{km}$. Due to the inaccuracy of the mathematical model, integration errors, and other factors, the vector of estimates $\hat{\mathbf{X}}_m$ over time will more and more differ from the measurement vector $\mathbf{X}_m$ and estimates $\hat{\mathbf{X}}_{0m}$, $\hat{\mathbf{X}}_{1m}$, …, $\hat{\mathbf{X}}_{km}$ from their actual values.

To prevent this from happening, cover equations (5)–(7) with feedback on the deviation of the estimate vector $\hat{\mathbf{X}}_m$ from the measured vector $\mathbf{X}_m$.

$$\frac{d\hat{\mathbf{X}}_{0m}}{dt}=\mathbf{f}_0(\mathbf{X}_n,\mathbf{C}_m)+\boldsymbol{\lambda}_0(\mathbf{X}_m-\hat{\mathbf{X}}_m), \qquad (9)$$

$$\frac{d\hat{\mathbf{X}}_{1m}}{dt}=\mathbf{f}_1(\mathbf{X}_n,\mathbf{C}_m)+\boldsymbol{\lambda}_1(\mathbf{X}_m-\hat{\mathbf{X}}_m), \qquad (10)$$

$$\dots$$

$$\frac{d\hat{\mathbf{X}}_{km}}{dt}=\mathbf{f}_k(\mathbf{X}_n,\mathbf{C}_m)+\boldsymbol{\lambda}_k(\mathbf{X}_m-\hat{\mathbf{X}}_m), \qquad (11)$$

$$\hat{\mathbf{X}}_m=\hat{\mathbf{X}}_{0m}+\hat{\mathbf{X}}_{1m}+\ldots+\hat{\mathbf{X}}_{km}. \qquad (12)$$

The system of vector differential equations (9)–(11), together with the vector equation (12), ensure the retention of the vector of estimates $\hat{\mathbf{X}}_m$ near the measurement vector $\mathbf{X}_m$, and also an estimate of the vectors of the components $\hat{\mathbf{X}}_{0m}$, $\hat{\mathbf{X}}_{1m}$, …, $\hat{\mathbf{X}}_{km}$. Using in the control law (3) estimates of the vector $\hat{\mathbf{X}}_{0m}$ instead of a vector of dimensions $\mathbf{X}_m$

$$\mathbf{U}=\mathbf{f}_u(\hat{\mathbf{X}}_{0m},\mathbf{X}^*,\mathbf{C}_u)$$

allows to minimize control error (4)

$$F=\left\|\mathbf{X}_n-\mathbf{X}^*\right\|\to\min.$$

Consider a practical case of using this method on the example of a gyrocompass.The vector differential equation of the GSE motion has the form

$$\frac{d\mathbf{H}}{dt}=\frac{\partial\mathbf{H}}{\partial t}+\boldsymbol{\Omega}\times\mathbf{H}=\sum_{j=1}^{n}\mathbf{M}_j, \qquad (13)$$

GCS is located in the center of the gyrocompass sensor suspension, the axis OX_2 is directed along the kinetic momentum vector of the GSE, the axis OY_2 is perpendicular to the axis OX_2, the axis OZ_2 complements the GCS to the “right” one.

Vector differential equation (13) in GCS has the form

$$H\dot{\Theta}=\sum_{j=1}^{n}M_{yj}, \qquad (18)$$

$$-H\cos\Theta\dot{\Psi}=\sum_{j=1}^{n}M_{zj.}, \qquad (19)$$

or after defining the right-hand sides

$$\dot{\Theta}=-\omega_3\cos\sigma\sin\Psi-\frac{V}{R}(\sin K\sin\Psi-\cos K\cos\Psi),$$

$$\dot{\Psi}=\omega_3(\cos\sigma\cos\Psi tg\Theta-\sin\sigma)+lmgtg\Theta-$$
$$-\frac{V}{R}tg\Theta(\cos K\sin\Psi-\sin K\cos\Psi)-\frac{V_r}{r}-$$
$$-mal(\cos K\cos\Psi+\sin K\sin\Psi).$$

© Zinchenko S. M., Nosov P. S., Mateichuk V. M., Popovych I. S., Appazov E. S., 2020
DOI 10.15588/1607-3274-2020-4-19

To simplify the obtained equations of the course meter sensitive element motion, denote

$$f_0^{\Theta} = -\omega_3 \cos\sigma \sin\Psi ,$$

$$f_1^{\Theta} = -\frac{V}{R}(\sin K \sin\Psi - \cos K \cos\Psi) ,$$

$$f_0^{\Psi} = \omega_3(\cos\sigma \cos\Psi tg\Theta - \sin\sigma) ,$$

$$f_1^{\Psi} = lmg\mathrm{tg}\Theta ,$$

$$f_2^{\Psi} = -\frac{V}{R} tg\Theta(\cos K \sin\Psi - \sin K \cos\Psi) ,$$

$$f_3^{\Psi} = -\frac{V_r}{r} ,$$

$$f_4^{\Psi} = -mal(\cos K \cos\Psi + \sin K \sin\Psi).$$

Through the integration errors, inaccuracies of mathematical models, other factors, estimates $\hat{\Psi}_m, \hat{\Theta}_m$ will deviate more and more from the measured values Ψ_m, Θ_m.

To keep the estimates $\hat{\Psi}_m, \hat{\Theta}_m$ near the measured values Ψ_m, Θ_m, a observation device with component estimation was used.

$$\frac{d\hat{\Theta}_{0m}}{dt} = f_0^{\Theta} + \lambda_0^{\Theta}(\Theta_m - \hat{\Theta}_m) , \qquad (20)$$

$$\frac{d\hat{\Theta}_{1m}}{dt} = f_1^{\Theta} + \lambda_1^{\Theta}(\Theta_m - \hat{\Theta}_m) , \qquad (21)$$

$$\frac{d\hat{\Psi}_{0m}}{dt} = f_0^{\Psi} + \lambda_0^{\Psi}(\Psi_m - \hat{\Psi}_m) , \qquad (22)$$

$$\frac{d\hat{\Psi}_{1m}}{dt} = f_1^{\Psi} + \lambda_1^{\Psi}(\Psi_m - \hat{\Psi}_m) , \qquad (23)$$

$$\frac{d\hat{\Psi}_{2m}}{dt} = f_2^{\Psi} + \lambda_2^{\Psi}(\Psi_m - \hat{\Psi}_m) , \qquad (24)$$

$$\frac{d\hat{\Psi}_{3m}}{dt} = f_3^{\Psi} + \lambda_3^{\Psi}(\Psi_m - \hat{\Psi}_m) , \qquad (25)$$

$$\frac{d\hat{\Psi}_{4m}}{dt} = f_4^{\Psi} + \lambda_4^{\Psi}(\Psi_m - \hat{\Psi}_m) , \qquad (26)$$

$$\hat{\Theta}_m = \hat{\Theta}_{0m} + \hat{\Theta}_{1m} , \qquad (27)$$

$$\hat{\Psi}_m = \hat{\Psi}_{0m} + \hat{\Psi}_{1m} + \hat{\Psi}_{2m} + \hat{\Psi}_{3m} + \hat{\Psi}_{4m} . \qquad (28)$$

The mathematical model of the GSE motion, represented by the system of differential equations (20) – (26), is numerically integrated in the on-board controller of the automatic motion control system.

Component $\hat{\Psi}_{0m}$ of equations (28) is a useful component of the course meter reading without inertial deviation components $\hat{\Psi}_{jm}, j = 1..4$. Substituting this value into the control law (3), obtain an increase in the accuracy of the course movement of the control object (1)

$$\delta = \mathbf{f}_u(\hat{\Psi}_{0m}, \Psi^*, \mathbf{C}_u) .$$

4 EXPERIMENTS

Fig. 1 presents the results of mathematical modeling of the GSE motion when bringing into meridian.

Initial experimental conditions are: longitudinal speed of the vessel is $V(0) = 0\ m/s$, angular yaw rate is $\omega_z(0) = 0\ ^\circ/s$, course angle is $\psi(0) = 0^\circ$, initial deviation of the GSE frame from the meridian is $\Psi_m(0) = -40^\circ$.

As can be seen from the graphs $\Psi_m, \hat{\Psi}_m$, the reduction to the meridian occurred within 10000 s (about 2.8 hours).

Fig. 2 shows GSE motion during the acceleration of the vessel.

Initial experimental conditions are: longitudinal speed of the vessel is $V(0) = 0\ m/s$, angular yaw rate is $\omega_z(0) = 0\ ^\circ/s$, course angle is $\psi(0) = 0^\circ$, initial deviation of the GSE frame from the meridian is $\Psi_m(0) = 0^\circ$. From the moment of time $t = 2000\ s$ the vessel began to increase the speed to $V = 10\ m/s$.

As can be seen from the graphs $\Psi_m, \hat{\Psi}_m$, the GSE deviation and its estimate change up to 10° from the action of disturbing moments during the acceleration of the vessel. At the same time, the deviation of the useful component $\hat{\Psi}_{0m}$ does not exceed 0.5°.

Fig. 3 shows the GSE motion during the braking of the vessel. Initial experimental conditions are: the longitudinal speed of the vessel is $V(0) = 0\ m/s$, angular yaw rate is $\omega_z(0) = 0\ ^\circ/s$, course angle is $\psi(0) = 0^\circ$, initial deviation of the GSE frame from the meridian is $\Psi_m(0) = 0^\circ$. From the moment $t = 0\ s$ the vessel gradually increases a speed to $V = 10\ m/s$, further moves with constant speed $V = 10\ m/s$ to the moment $t = 2000\ s$, then carries out passive braking.

As can be seen from the graphs $\Psi_m, \hat{\Psi}_m$, the GSE deviates from the meridian by an angle of up to 5.0° from the action of disturbing moments during the braking of the vessel. At the same time, the deviation of the useful component $\hat{\Psi}_{0m}$ does not exceed 0.5°.

Fig. 4 shows the results of mathematical modeling of the GSE motion when changing the course of the vessel.

© Zinchenko S. M., Nosov P. S., Mateichuk V. M., Popovych I. S., Appazov E. S., 2020
DOI 10.15588/1607-3274-2020-4-19

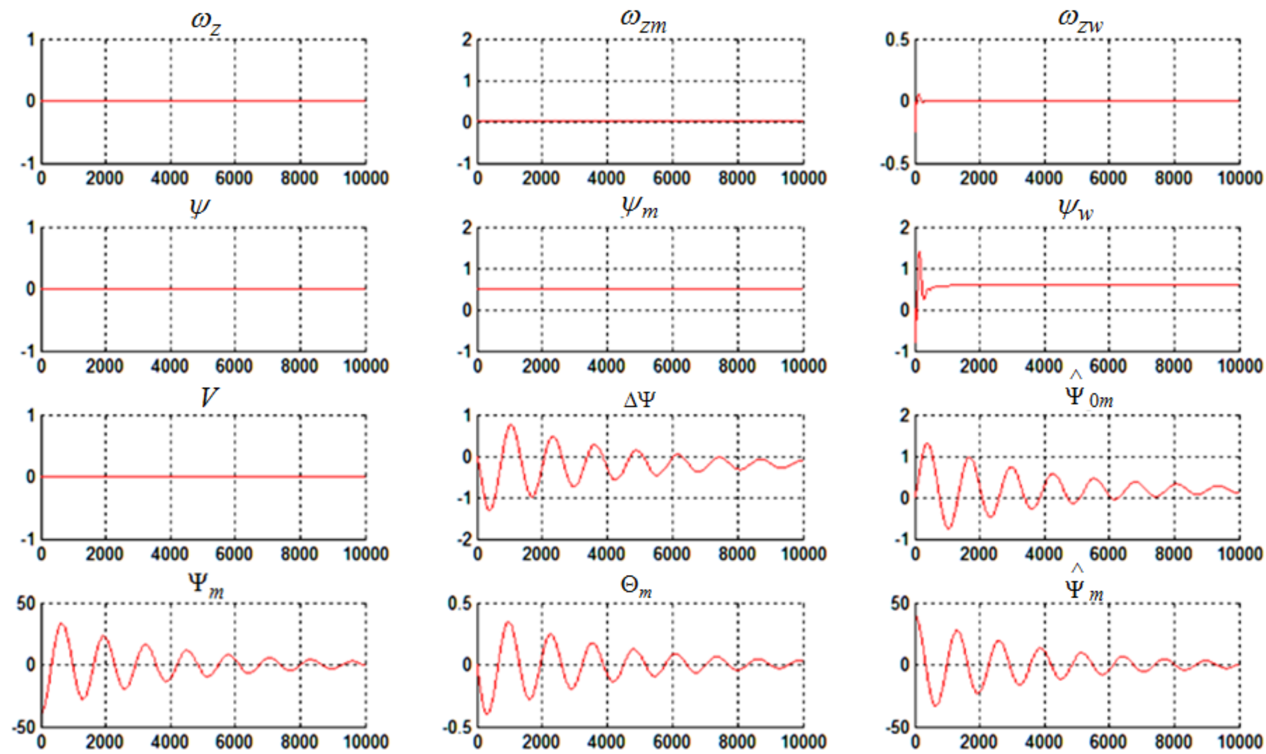

Figure 1 – The GSE motion when bringing into meridian

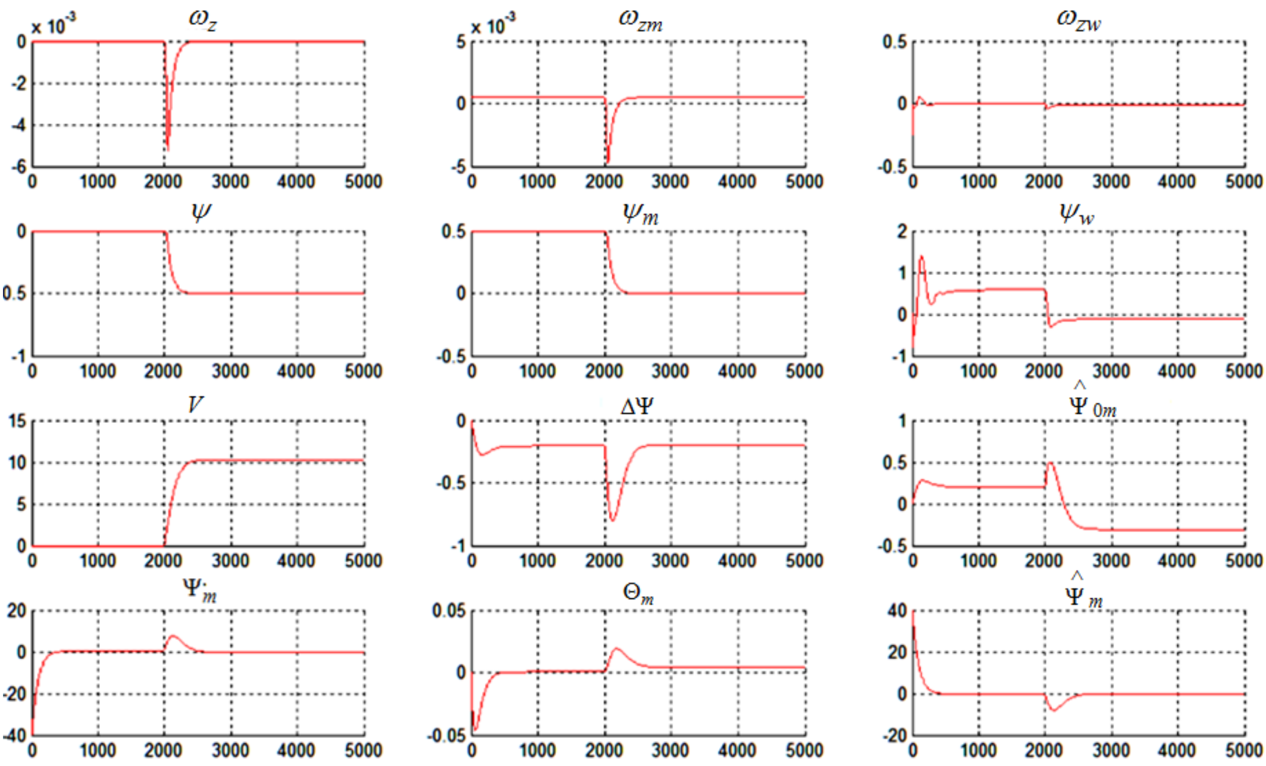

Figure 2 – The GSE motion during the acceleration of the vessel

© Zinchenko S. M., Nosov P. S., Mateichuk V. M., Popovych I. S., Appazov E. S., 2020
DOI 10.15588/1607-3274-2020-4-19

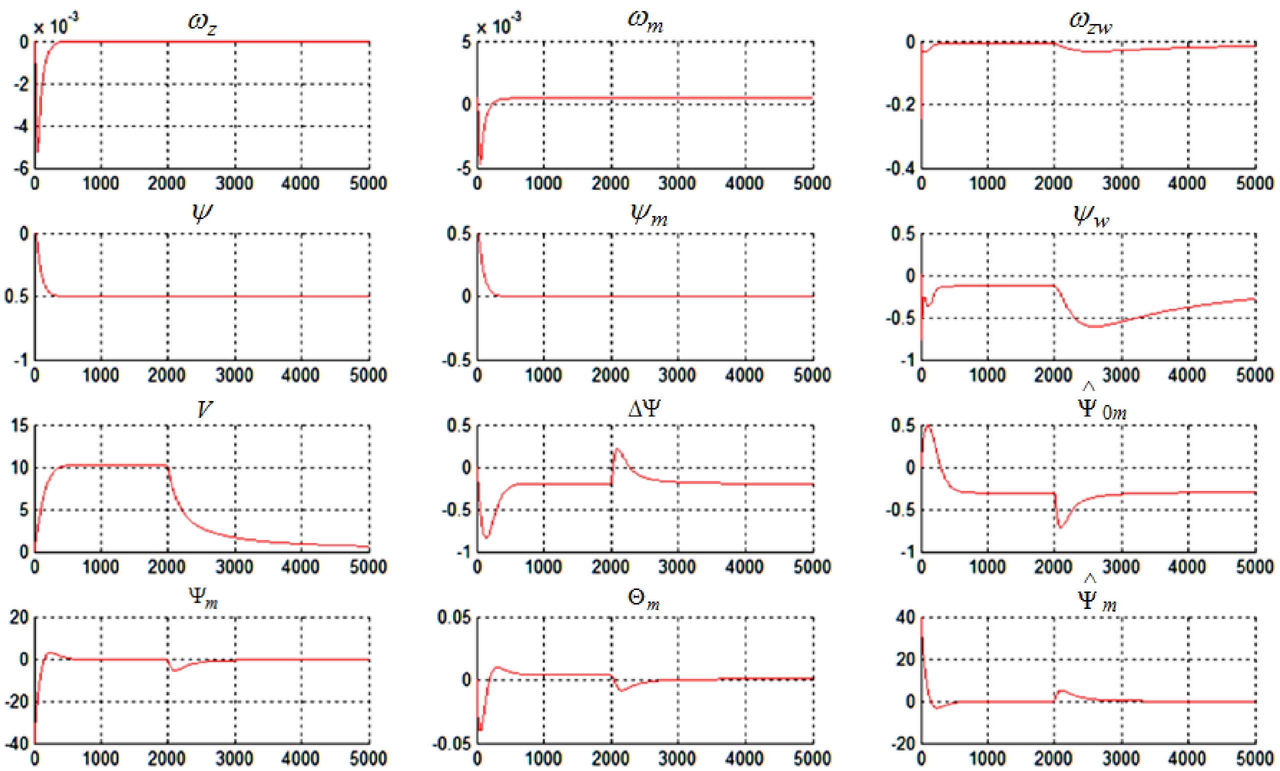

Figure 3 – The GSE motion during the braking of the vessel

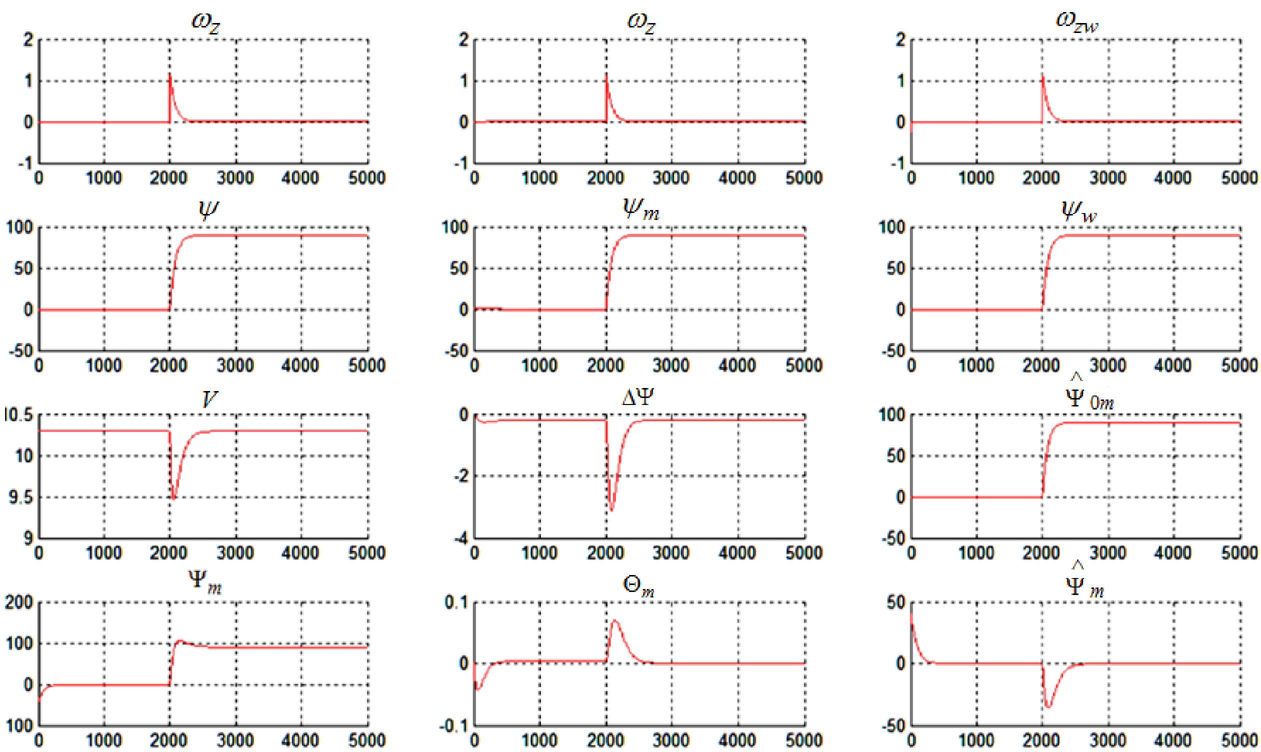

Figure 4 – The GSE motion during the course change

Initial experimental conditions are: longitudinal speed of the vessel is $V(0)=10{,}4\ m/s$, angular yaw rate is $\omega_z(0)=0\ {}^\circ/s$, course angle is $\psi(0)=0^\circ$, initial deviation of the GSE frame from the meridian is $\Psi_m(0)=0^\circ$.

© Zinchenko S. M., Nosov P. S., Mateichuk V. M., Popovych I. S., Appazov E. S., 2020
DOI 10.15588/1607-3274-2020-4-19

From the time $t = 2000\ s$ the vessel began to change course from $\psi = 0^\circ$ to $\psi = 90^\circ$. As can be seen from the graphs $\Psi_m, \hat{\Psi}_m$, the GSE deviates from the meridian at an angle of up to 20° from the action of disturbing moments during the course change. At the same time the useful component $\hat{\Psi}_{0m}$ changes almost perfectly.

5 RESULTS

The article discusses the issues of increasing the accuracy of automatic control of a moving object using a mathematical model of a meter and a device observing measurement errors in the on-board controller of the control system.

The existing methods for solving this problem are analyzed, their shortcomings are revealed, the urgency of the problem being solved is formulated.

A method and algorithms for increasing the control accuracy of a moving object through the use in the on-board controller of a mathematical meter model and an observer of systematic measurement errors, built on its basis, have been developed.

A particular case of application of the developed method and algorithms for a vessel's gyrocompass was considered.

6 DISCUSSION

There were considered the method and algorithms for improving the control accuracy using the mathematical meter model in the on-board controller of the control system.

The analysis of the literature has shown that the known methods of increasing the control accuracy imply the improvement of the experimental conditions [22], the use of bandpass filters and averaging procedures [23, 25, 29], design solutions [24], the use of reference models [26], self-adjusting algorithms [27], mathematical models of the control object and observers [28]. However, in open sources, the authors failed to find methods and algorithms that increase the accuracy of controlling by using a mathematical meter model in the on-board controller of the control system.

The efficiency and effectiveness of the developed method and algorithms were confirmed by mathematical modeling in the MATLAB environment of the control processes of a moving object in a closed circuit with a control system.

As shown in Fig. 1–Fig. 4 simulation results, the proposed method and algorithms, in comparison with the known solutions, make it possible to increase several times the accuracy of automatic control of a moving object due to the use of a mathematical meter model and an observer built on its basis in the on-board controller of the control system, assessing systematic measurement errors and eliminating them when controlling a moving object.

This allows to assume that the considered method and algorithms can be recommended for use in the development of software for high – precision automatic control systems.

Further studies can be related to improving the accuracy of control movement with the Kalman filter.

CONCLUSIONS

A method and algorithms for improving the accuracy of automatic control with mathematical meter model in on-board controller were proposed.

The scientific novelty of the obtained results consists in the fact that for the first time a method and algorithms for improving the control accuracy using the mathematical meter model in the on-board controller of the control system, have been proposed.

This is achieved through the use in the on-board controller of the control system of the mathematical meter model and the observing device built on its basis, the estimation of the useful component and the systematic errors, depending on the motion parameters of the controlled object, using for control only the useful component, without systematic errors.

The practical value of the obtained results lies in the fact that the developed method and algorithms were tested by mathematical modeling in the MATLAB environment of the control object movement in a closed circuit with a control system.

The results of mathematical modeling confirmed the operability and efficiency of the proposed method and algorithms and allow them to be used for practical purposes in the development of mathematical support for high-precision automatic control systems.

ACKNOWLEDGEMENTS

The work was carried out in the framework of the research “Development of software solutions for dynamic functions of dynamically positioning systems of marine vessels”, (state registration number 0119U100948), Department of Navigation and Electronic Navigation Systems of Kherson State Maritime Academy.

REFERENCES

1. Iozan L. I., Kirkko-Jaakkola M., Collin J. et al. Using a MEMS gyroscope to measure the Earth’s rotation for gyrocompassing applications, *Measurement Science and Technology*, 2012, Vol. 23, No. 2. DOI: 10.1088/0957-0233/23/2/025005.
2. Xu B., Liu Y., Shan W. et al. Error analysis and compensation of gyrocompass alignment for SINS on moving base, *Mathematical Problems in Engineering,* 2014. DOI: 10.1155/2014/373575.
3. Wang B., Liu J., Deng Z. et al. A Model-free Calibration Method of Inertial Navigation System and Doppler Sensors, *IEEE Sensors Journal*, 2020, pp. 1558–1748. DOI: 10.1109/JSEN.2020.3015845.
4. Hu J., Zhu Y., Shi X. Estimation of azimuth gyro drifts with single-axis rotational SINS, *Systems Engineering and Electronics*, 2018, Vol. 40, pp. 2334–2339. DOI: 10.3969/j.issn.1001-506X.2018.10.26

© Zinchenko S. M., Nosov P. S., Mateichuk V. M., Popovych I. S., Appazov E. S., 2020
DOI 10.15588/1607-3274-2020-4-19

5. Luenberger D. G. An Introduction to Observer, *IEEE Transactions on Automatic Control*, 1971, pp. 596–602.
6. Luders G., Narendra K. S. New Canonical Form for an Adaptive Observers, *IEEE Transactions on Automatic Control*, 1974, pp. 117–119.
7. Hostetter G. H., Meditch J. S. Observing Systems with Unmeasurable Inputs, *IEEE Transactions on Automatic Control,* 1973, pp. 307–308.
8. Kalman R. E., Busi R. S. New results in linear filtering and prediction theory, *Journal of Basic Engineering*, 1961, pp. 95–108.
9. Zinchenko S. M., Ben A. P., Nosov P. S. et al. Improving Accuracy and Reliability in Automatic Ship Motion Control Systems, *Radio Electronics, Computer Science, Control,* 2020, Vol. 2, pp. 183–195. DOI:10.15588/1607-3274-2020-2-19
10. Lee D., Lee Y. Application of neural-network for improving accuracy of roll-force model in hot-rolling mill, *Control Engineering Practice*, 2002, Vol. 10, Issue 4, pp. 473–478. DOI: 10.1016/S0967-0661(01)00143-5.
11. Martin J., Milliken D., Cobb J. et al. Validation of a Mathematical Model for Road Cycling Power, *Journal of Applied Biomechanics*, Vol. 14, Issue 3, pp. 276–291. DOI: https://doi.org/10.1123/jab.14.3.276
12. Sutulo S., Moreira L., Guedes C. SoaresMathematical models for ship path prediction in manoeuvring simulation systems, *Ocean Engineering*, 2002, Vol. 29, Issue 1, pp. 1–19. DOI: 10.1016/S0029-8018(01)00023-3
13. Jikuang Y., Wei X., Dietmar O. Brain injury biomechanics in real world vehicle accident using mathematical models, *Chinese journal of mechanical engineering*, 2008, Vol. 21, No. 4. DOI: 10.3901/CJME.2008.04.081
14. Xue Y., Liu Y., Ji C. et al. Hydrodynamic parameter identification for ship manoeuvring mathematical models using a Bayesian approach, *Ocean Engineering*, 2020, Vol. 195, Issue 1. DOI: 10.1016/j.oceaneng.2019.106612
15. Wada T., Fujisawa S., Doi S. Analysis of driver's head tilt using a mathematical model of motion sickness, *International Journal of Industrial Ergonomics*, 2018, Vol. 63, P. 89–97. DOI: 10.1016/j.ergon.2016.11.003
16. Shevchenko R., Popovych I., Spytska L. et al.Comparative analysis of emotional personality traits of the students of maritime science majors caused by long-term staying at sea, *Revista Inclusiones*, 2020, Vol. 7. num Especial, pp. 538–554.
17. Shevchenko R., Cherniavskyi V., Zinchenko S. et al. Research of psychophysiological characteristics of response to stress situations by future sailors, *Revista Inclusiones*, 2020, Vol. 7, num Especial, pp. 566–579.
18. Nosov P. S., Zinchenko S. M., Popovych I. S. at al. Diagnostic system of perception of navigation danger when implementation complicated maneuvers, *Radio Electronics, Computer Science, Control,* 2020, Vol. 1, pp. 146–161. DOI: 10.15588/1607-3274-2020-1-15.
19. Nosov P., Palamarchuk I., Zinchenko S. et al. Development of means for experimental identification of navigator attention in ergatic systems of maritime transport, *Bulletin of University of Karaganda. Technical Physics,* 2020, Vol. 1, Issue 97, pp. 58–69. DOI: 10.31489/2020Ph1/58-69.
20. Zinchenko S. M., Nosov P. S., Mateychuk V. M. et al. Automatic collision avoidance with multiple targets, including maneuvering ones, *Radio Electronics, Computer Science, Control*, 2019, Vol. 4, pp. 211–221. DOI: 10.15588/1607-3274-2019-4-20.
21. Zinchenko S., Ben A., Nosov P. et al. The vessel movement optimisation with excessive control, *Bulletin of University of Karaganda. Technical Physics,* 2020, Vol. 3. No. 99, pp. 86–96, DOI: 10.31489/2020Ph3/86-96.
22. Bartley D., Doemeny L., Taylor D. Diffusive Monitoring of Fluctuating Concentrations, *American Industrial Hygiene Association Journal,* 1983, Vol. 44, Issue 4, pp. 241–247. DOI: 10.1080/15298668391404734
23. Iwasa T., Hiramatsu M., Kishimoto N. et al. An Error Elimination Method for Surface Shape Measurement using the Grating Projection Method, *Transactions of the Japan society for aeronautical and space sciences, aerospace technology Japan,* 2014, Vol. 12, pp. 81–88. DOI: 10.2322/tastj.12.81
24. Zheng S., Wang Y., Ren H. Simultaneous Temperature Compensation and Synchronous Error Elimination for Axial Displacement Sensors Using an Auxiliary Probe, *IEEE Transactions on Industrial Electronics*, 2016, Vol. 63, Issue 5. DOI: 10.1109/TIE.2015.2511165
25. Wen G., Zhang H., Wang Y. et al. Analysis and elimination the vibration disturbance in all-fiber distributed polarization coupling measurement, *Measurement,* 2019,Vol. 144, pp. 118–125. DOI: 10.1016/j.measurement.2019.05.033
26. Shirokov I. V., Polivkin S. N., Gimpilevich Y. B. et al. The elimination of error of measurement of substance flow speed by the accounting of variation of its electrophysical parameters, *IEEE Xplore*, 2009. DOI: 10.1109/EEEI.2008.4736573
27. Chen Y. Yang M., Long J. et al. M/T method based incremental encoder velocity measurement error analysis and self-adaptive error elimination algorithm, *Engineering, Computer Science*, 2017. DOI: 10.1109/IECON.2017.8216350
28. Hutter P., Grabner H., Silber S. et al. A study on systematic errors concerning rotor position estimation of PMSM based on back EMF voltage observation, *IEEE Xplore*, 2009. DOI: 10.1109/IEMDC.2009.5075385
29. Lai Y., Zhou H., Zeng Y. et al. Quantifying and Reducing the DOA Estimation Error Resulting from Antenna Pattern Deviation for Direction-Finding HF Radar, *Remote Sensing*, Vol. 9, Issue 12. DOI: 10.3390/rs9121285

Received 13.10.2020.
Accepted 04.11.2020.

УДК 629.05:656.61:004.942

ПІДВИЩЕННЯ ТОЧНОСТІ АВТОМАТИЧНОГО КЕРУВАННЯ З МАТЕМАТИЧНОЮ МОДЕЛЛЮ ВИМІРЮВАЧА У БОРТОВОМУ КОНТРОЛЕРІ

Зінченко С. М. – кандидат технічних наук, доцент кафедри управління судном, завідувач лабораторії електронних тренажерів, Херсонська державна морська академія, Херсон, Україна.

Матейчук В. М. – старший викладач кафедри управління судном, завідувач лабораторії електронних тренажерів, Херсонська державна морська академія, Херсон, Україна.

Носов П. С. – кандидат технічних наук, доцент кафедри судноводіння та електронних навігаційних систем, Херсонська державна морська академія, Херсон, Україна.

© Zinchenko S. M., Nosov P. S., Mateichuk V. M., Popovych I. S., Appazov E. S., 2020
DOI 10.15588/1607-3274-2020-4-19

Попович І. С. – доктор психологічних наук, професор кафедри загальної та соціальної психології, Херсонський державний університет, Херсон, Україна.

Аппазов Е. С. – кандидат технічних наук, доцент кафедри інноваційних технологій і технічних засобів судноводіння, Херсонська державна морська академія, Херсон, Україна.

АНОТАЦІЯ

Актуальність. У статті розглянуті питання підвищення точності автоматичного керування рухомим об'єктом з використанням математичної моделі вимірювача та спостерігаючого за похибками вимірювання пристрою у бортовому контролері системи керування. Об'єктом дослідження є процеси автоматичного керування рухомим об'єктом з математичною моделлю вимірювача та спостерігаючого за похибками вимірювання пристрою у бортовому контролері системи керування. Предметом дослідження є метод і алгоритми підвищення точності автоматичного керування рухомим об'єктом з математичною моделлю вимірювача та спостерігаючого за похибками вимірювання пристрою у бортовому контролері системи керування.

Мета. Метою дослідження є підвищення точності автоматичного керування рухомим об'єктом.

Метод. Дана мета досягається за рахунок використання у бортовому контролері системи керування математичної моделі вимірювача і спостерігаю чого пристрою, побудованого на її основі, оцінки корисної складової і систематичної похибки вимірювання, що залежить від параметрів руху об'єкта керування, використання для керування тільки корисної складової без систематичної помилки вимірювання.

Результати. Розроблено метод і алгоритми підвищення точності автоматичного керування рухомим об'єктом за рахунок використання у бортовому контролері системи керування математичної моделі вимірювача і спостерігаючого пристрою, побудованого на її основі. Працездатність та ефективність розробленого методу і алгоритмів перевірені математичним моделюванням у середовищі MATLAB процесів керування рухомим об'єктом у замкнутій схемі із системою керування.

Висновки. Результати математичного моделювання підтверджують працездатність і ефективність запропонованого методу та алгоритмів і дозволяють рекомендувати їх для практичного застосування при розробці математичного забезпечення високоточних систем автоматичного керування рухом.

КЛЮЧОВІ СЛОВА: автоматичне керування, точність керування, система керування рухом, помилки вимірювання, спостерігаючий пристрій, математична модель.

УДК 629.05:656.61:004.942

ПОВЫШЕНИЕ ТОЧНОСТИ АВТОМАТИЧЕСКОГО УПРАВЛЕНИЯ С МАТЕМАТИЧЕСКОЙ МОДЕЛЬЮ ИЗМЕРИТЕЛЯ В БОРТОВОМ КОНТРОЛЛЕРЕ

Зинченко С. Н. – кандидат технических наук, доцент кафедры управления судном, заведующий лабораторией электронных тренажеров, Херсонская государственная морская академия, Херсон, Украина.

Матейчук В. Н. – старший преподаватель кафедры управления судном, заведующий лабораторией электронных тренажеров, Херсонская государственная морская академия, Херсон, Украина.

Носов П. С. – кандидат технических наук, доцент кафедры судовождения и электронных навигационных систем, Херсонская государственная морская академия, Херсон, Украина.

Попович И. С. – доктор психологических наук, профессор кафедры общей и социальной психологи, Херсонский государственный университет, Херсон, Украина.

Аппазов Э. С. – кандидат технических наук, доцент кафедры инновационных технологий и технических средств судовождения, Херсонская государственная морская академия, Херсон, Украина.

АННОТАЦИЯ

Актуальность. В статье рассмотрены вопросы повышения точности автоматического управления подвижным объектом с использованием математической модели измерителя и наблюдающего за ошибками измерения устройства в бортовом контроллере системы управления. Объектом исследования являются процессы автоматического управления подвижным объектом с математической моделью измерителя и наблюдающего за ошибками измерения устройства в бортовом контроллере системы управления. Предметом исследования являются метод и алгоритмы повышения точности автоматического управления подвижным объектом с математической моделью измерителя и наблюдающего за ошибками измерения устройства в бортовом контроллере системы управления.

Цель. Целью исследования является повышение точности автоматического управления подвижным объектом.

Метод. Данная цель достигается за счет использования в бортовом контроллере системы управления математической модели измерителя и наблюдающего устройства, построенного на ее основе, оценки полезной составляющей и систематической ошибки измерения, зависящей от параметров движения объекта управления, использования для управления только полезной составляющей без систематической ошибки измерения.

Результати. Разработан метод и алгоритмы повышения точности автоматического управления подвижным объектом за счет использования в бортовом контроллере системы управления математической модели измерителя и наблюдающего устройства, построенного на ее основе. Работоспособность и эффективность разработанного метода и алгоритмов проверены математическим моделированием в среде MATLAB процессов управления подвижным объектом в замкнутой схеме с системой управления.

Выводы. Результаты математического моделирования подтверждают работоспособность и эффективность предложенного метода и алгоритмов и позволяет рекомендовать их для практического применения при разработке математического обеспечения высокоточных систем автоматического управления движением.

КЛЮЧЕВЫЕ СЛОВА: автоматическое управление, точность управления, система управления движением, ошибки измерения, наблюдающее устройство, математическая модель.

© Zinchenko S. M., Nosov P. S., Mateichuk V. M., Popovych I. S., Appazov E. S., 2020
DOI 10.15588/1607-3274-2020-4-19

ЛІТЕРАТУРА / ЛИТЕРАТУРА

1. Using a MEMS gyroscope to measure the Earth's rotation for gyrocompassing applications / L. I. Iozan, M. Kirkko-Jaakkola, J. Collin et al. // Measurement Science and Technology. – 2012. – Vol. 23, № 2. DOI: 10.1088/0957-0233/23/2/025005.
2. Error analysis and compensation of gyrocompass alignment for SINS on moving base / B. Xu, Y. Liu, W. Shan et al. // Mathematical Problems in Engineering. – 2014. DOI: 10.1155/2014/373575.
3. A Model-free Calibration Method of Inertial Navigation System and Doppler Sensors / B. Wang, J. Liu, Z. Deng et al. // IEEE Sensors Journal. – 2020. – P. 1558–1748. DOI: 10.1109/JSEN.2020.3015845.
4. Hu J. Estimation of azimuth gyro drifts with single-axis rotational SINS / J. Hu, Y. Zhu, X. Shi // Systems Engineering and Electronics. – 2018. – Vol. 40. – P. 2334–2339. DOI: 10.3969/j.issn.1001-506X.2018.10.26
5. Luenberger D. G. An Introduction to Observer / D. G. Luenberger // IEEE Transactions on Automatic Control. – 1971. – P. 596–602.
6. Luders G. New Canonical Form for an Adaptive Observers / G. Luders, K. S. Narendra // IEEE Transactions on Automatic Control. – 1974. – P. 117–119.
7. Hostetter G. H. Observing Systems with Unmeasurable Inputs / G. H. Hostetter, J. S. Meditch // IEEE Transactions on Automatic Control. – 1973. – P. 307–308.
8. Kalman R. E. New results in linear filtering and prediction theory / R. E. Kalman, R. S. Busi // Journal of Basic Engineering. – 1961. – P. 95–108.
9. Improving Accuracy and Reliability in Automatic Ship Motion Control Systems / S. M. Zinchenko, A. P. Ben, P. S. Nosov et al. // Radio Electronics, Computer Science, Control. – 2020. – Vol. 2. – P. 183–195. DOI:10.15588/1607-3274-2020-2-19
10. Lee D. Application of neural-network for improving accuracy of roll-force model in hot-rolling mill / D. Lee, Y. Lee // Control Engineering Practice. – 2002. – Vol. 10, Issue 4. – P. 473–478. DOI: 10.1016/S0967-0661(01)00143-5.
11. Validation of a Mathematical Model for Road Cycling Power / J. Martin, D. Milliken, J. Cobb et al. // Journal of Applied Biomechanics. – Vol. 14, Issue 3. – P. 276–291. DOI: https://doi.org/10.1123/jab.14.3.276
12. Sutulo S. Mathematical models for ship path prediction in manoeuvring simulation systems / S. Sutulo, L. Moreira, C. Guedes Soares // Ocean Engineering. – 2002. – Vol. 29, Issue 1. – P. 1–19. DOI: 10.1016/S0029-8018(01)00023-3
13. Jikuang Y. Brain injury biomechanics in real world vehicle accident using mathematical models / Y. Jikuang, X. Wei, O. Dietmar // Chinese journal of mechanical engineering. – 2008. – Vol. 21, № 4. DOI: 10.3901/CJME.2008.04.081
14. Hydrodynamic parameter identification for ship manoeuvring mathematical models using a Bayesian approach / Y. Xue, Y. Liu, C. Ji et al. // Ocean Engineering. – 2020. – Vol. 195, Issue 1. DOI: 10.1016/j.oceaneng.2019.106612
15. Wada T. Analysis of driver's head tilt using a mathematical model of motion sickness / T. Wada, S. Fujisawa, S. Doi // International Journal of Industrial Ergonomics. – 2018. – Vol. 63. – P. 89–97. DOI: 10.1016/j.ergon.2016.11.003
16. Comparative analysis of emotional personality traits of the students of maritime science majors caused by long-term staying at sea / R. Shevchenko, I. Popovych, L. Spytska et al. // Revista Inclusiones. – 2020. – Vol. 7. num Especial – P. 538–554.
17. Research of psychophysiological characteristics of response to stress situations by future sailors / R. Shevchenko, V. Cherniavskyi, S. Zinchenko et al. // Revista Inclusiones. – 2020. – Vol. 7. num Especial – P. 566–579.
18. Diagnostic system of perception of navigation danger when implementation complicated maneuvers / P. S. Nosov, S. M. Zinchenko, I. S. Popovych et al. // Radio Electronics, Computer Science, Control. – 2020. – Vol. 1. – P. 146–161. DOI: 10.15588/1607-3274-2020-1-15.
19. Development of means for experimental identification of navigator attention in ergatic systems of maritime transport / P. Nosov, I. Palamarchuk, S. Zinchenko et al. // Bulletin of University of Karaganda. Technical Physics. – 2020. – Vol. 1, Issue 97. – P. 58–69. DOI: 10.31489/2020Ph1/58-69.
20. Automatic collision avoidance with multiple targets, including maneuvering ones / S. M. Zinchenko, P. S. Nosov, V. M. Mateychuk et al. // Radio Electronics, Computer Science, Control. – 2019. – Vol. 4. – P. 211–221. DOI:10.15588/1607-3274-2019-4-20.
21. The vessel movement optimisation with excessive control / S. Zinchenko, A. Ben, P. Nosov et al. // Bulletin of University of Karaganda. Technical Physics. – 2020. – Vol. 3, No. 99. – P. 86–96, DOI: 10.31489/2020Ph3/86-96.
22. Bartley D. Diffusive Monitoring of Fluctuating Concentrations / D. Bartley, L. Doemeny, D. Taylor // American Industrial Hygiene Association Journal. – 1983. – Vol. 44, Issue 4. – P. 241–247. DOI: 10.1080/15298668391404734
23. Iwasa T. An Error Elimination Method for Surface Shape Measurement using the Grating Projection Method / T. Iwasa, M. Hiramatsu, N. Kishimoto et al. // Transactions of the Japan society for aeronautical and space sciences, aerospace technology Japan. – 2014. – Vol. 12. – P. 81–88. DOI: 10.2322/tastj.12.81
24. Zheng S. Simultaneous Temperature Compensation and Synchronous Error Elimination for Axial Displacement Sensors Using an Auxiliary Probe / S. Zheng, Y. Wang, H. Ren // IEEE Transactions on Industrial Electronics. – 2016. – Vol. 63, Issue 5. DOI: 10.1109/TIE.2015.2511165
25. Analysis and elimination the vibration disturbance in all-fiber distributed polarization coupling measurement / G. Wen, H. Zhang, Y. Wang et al. // Measurement. – 2019. – Vol. 144. – P. 118–125. DOI: 10.1016/j.measurement.2019.05.033
26. The elimination of error of measurement of substance flow speed by the accounting of variation of its electrophysical parameters / I. V. Shirokov, S. N. Polivkin, Y. B. Gimpilevich et al. // IEEE Xplore. – 2009. DOI: 10.1109/EEEI.2008.4736573
27. M/T method based incremental encoder velocity measurement error analysis and self-adaptive error elimination algorithm / Y. Chen, M. Yang, J. Long et al. // Engineering, Computer Science. – 2017. DOI: 10.1109/IECON.2017.8216350
28. A study on systematic errors concerning rotor position estimation of PMSM based on back EMF voltage observation / P. Hutterer, H. Grabner, S. Silber et al. // IEEE Xplore. – 2009. DOI: 10.1109/IEMDC.2009.5075385
29. Quantifying and Reducing the DOA Estimation Error Resulting from Antenna Pattern Deviation for Direction-Finding HF Radar / Y. Lai, H. Zhou, Y. Zeng et al. // Remote Sensing. – Vol. 9, Issue 12. DOI: 10.3390/rs9121285

© Zinchenko S. M., Nosov P. S., Mateichuk V. M., Popovych I. S., Appazov E. S., 2020
DOI 10.15588/1607-3274-2020-4-19