

UDC 629.78

DOI: 10.15587/1729-4061.2018.123271

# DEVELOPMENT OF THE ALGORITHM FOR AIRCRAFT CONTROL AT INACCURATE MEASUREMENT OF THE STATE VECTOR AND VARIABLE ACCURACY PARAMETER

**N. Khatsko**

PhD, Senior Lecturer

Department of Computer Modeling of Processes and Systems  
National Technical University "Kharkiv Polytechnic Institute"

Kyrpychova str., 2, Kharkiv, Ukraine, 61002

E-mail: n.khatsko@gmail.com

**H. Makogon**

PhD, Senior Lecturer\*

E-mail: helmkg@ukr.net

**O. Isakov**

Lecturer\*

E-mail: alexalex999@ukr.net

**S. Krepchenko**

Lecturer\*

E-mail: s.krepchenko@gmail.com

**I. Cherepnov**

PhD, Associate Professor\*\*

E-mail: voenpred314@ukr.net

**N. Kiriyyenko**

PhD, Associate Professor\*\*

E-mail: hfinpomt@ukr.net

**V. Zadorozhnyia**

PhD, Associate Professor\*\*

E-mail: zadorvika@ukr.net

**A. Polyansky**

Doctor of Technical Sciences, Professor\*\*

E-mail: khadi.pas@gmail.com

\*Department of Armored vehicles and military equipment

Military institute of Tank Troops of National Technical University  
"Kharkiv Polytechnic Institute"

Poltavskiy Shliakh, str., 198, Kharkiv, Ukraine, 61098

\*\*Department of Life Safety and Law

Kharkiv Petro Vasylenko National

Technical University of Agriculture

Alchevskykh str., 44, Kharkiv, Ukraine, 61002

*Розглянуто розв'язання термінальної задачі управління та синтезований параметризований закон управління в аналітичному вигляді, який залежить від змінного параметра глибини прогнозу. Досліджено особливості впливу величини параметра управління на точність досягнення кінцевої точки, дані рекомендації з вибору параметра для нівелювання помилки інерційних вимірювань. Синтез управління здійснюється методом переслідування ведучої точки за інформацією, отриманою інтегруванням вимірювань фактичного прискорення і містить помилку, характерну для акселерометрів*

*Ключові слова: точність термінального управління, помилка інерціальних вимірювань, бесплатформена інерціальна навігаційна система*

*Рассмотрено решение терминальной задачи управления и синтезован параметризованный закон управления в аналитическом виде, обеспечивающий движение объекта в заданную точку и содержащий варьируемый параметр глубины прогноза. Исследованы особенности влияния величины параметра управления на точность достижения конечной точки, даны рекомендации по выбору параметра для нивелирования ошибки инерциальных измерений. Синтез управления осуществляется методом преследования ведущей точки по информации, полученной интегрированием измерений фактического ускорения и содержащей ошибку, характерную для акселерометров*

*Ключевые слова: точность терминального управления, ошибка инерциальных измерений, бесплатформенная инерциальная навигационная система*

## 1. Introduction

In the era of significant expansion of air traffic, which is characterized by a wide spread of unmanned aerial

vehicles (UAV), automatic methods of flight control are becoming increasingly important. Automatic control of an aerial vehicle (AV) allows solving practical problems in various areas.

One of the elements of the systems of automatic control of AV motion is an on-board navigation system which provides obtaining information about the position, speed and orientation of a vehicle in space. Integrated inertial-satellite navigation systems (IISNS), which have become widespread due to advances of satellite radio navigation [1], have proven themselves as an effective way to achieve necessary precision of air navigation [2]. Operation of the systems is based on aggregation of information, received from inertial sensors (gyroscopes and accelerometers), and satellite information on current coordinates and speed of an AV. Thus, at regular and sufficiently frequent information flow from both navigation systems, it is possible, as long as you want, to determine navigational parameters with small errors, the value of which are virtually in the vicinity of zero. However, in practice, the order of arrival of information from each system has its own specific features.

Thus, a signal from the satellite navigation system can be of inadequate quality. It may be associated with magnetic storms, low inclination of satellites' orbits, re-reflection of a radio signal. Another challenge may be a search for a satellite signal by a receiver after disconnection, because initially, a receiver does not know where a satellite is, whether it approaches or retreats and what the shift of the frequency of its signal is. In addition, the contact with the found satellite continues only when a complete set of information from it is received. Otherwise, the search for a suitable satellite continues.

Even at fully deployed satellite orbital groupings, over 24 hours in some areas of the globe, there can be time intervals of more than 15 minutes when satellite information is not suitable for high-precision navigation due to special reciprocal location of satellites in space (geometry factor). Under these conditions, control of AV is carried out only by information of the inertial navigation subsystem with its inherent errors of determining [3]. In most cases, the onboard strapdown inertial navigation system (SINS) is used. The enumerated circumstances determine the relevance of the considered problem in the context of modern flight control technology.

---

## 2. Literature review and problem statement

---

During implementation of flight tasks, there often arise the tasks of AV flight to a specified point in space with assigned parameters of motion within the allotted time. Such tasks are called terminal problems. Of course, the best solution to a terminal task in the algorithmic sense is to obtain explicit analytical dependences for control functions [4]. In this case, it is possible at any moment to synthesize the values of control actions for AV reaching the destination.

Modern control technology is based on the theory of feedback. Control of current parameters of the state of an AV and formation of motion correcting control increases efficiency of an automatic flight control system (AFCS). Typically, the control process includes the following stages [5]:

- development of a reference trajectory of AV motion to a specified destination, that is, obtaining the required state of AV after a specified period of time under ideal flight conditions;
- obtaining information about the current state of AV from navigation systems on the pitch of AFCS operation;

- analysis of obtained information and development of control actions for continuation of the AV motion.

Thus, so that AFCS can operate correctly, the data exchange between a navigation system and an automatic control system is required. In modern AFCS, the main tool for obtaining information about the current vector of the AV state is often IISNS, uniting gauges of various physical nature – satellite and inertial navigation systems. However, global satellite navigation systems are subjected to various threats (ionospheric disturbances, multi-path scattering, unfavorable location of satellites and so on), any of which may lead to partial or complete loss of a signal [6].

To improve the accuracy of determining navigation and angular orientation parameters, IISNS use different methods of information aggregation: separate, weakly connected, rigidly connected and deeply integrated. Possibilities of obtaining higher precision of estimation of navigation parameters are studied in [7].

However, regardless of the data integration degree, at a delay of obtaining of reliable information from the on-board satellite navigation equipment, SINS operate in the autonomous mode. At autonomous operation of SINS, the known shortcomings fully affects accuracy of measurements of navigation parameters and control, generated on their basis. That is why autonomous operation of SINS is often accompanied by data correction from the other, non-inertial measurement sources [8, 9].

The accuracy of obtaining navigation parameters of SINS is directly influenced by accuracy of its sensors of primary information. While aviation used to apply only expensive devices, lately, there has been a strong tendency to make inertial systems cheaper. Technology of micro-electro-mechanical systems (MEMS) has been developing rapidly for 20 last years.

Accuracy of MEMS-based sensors used to be low, and they could be used only in cars and household appliances. However, lately, the accuracy of MEMS-based accelerometers increased and reached the navigation accuracy, MEMS-gyroscopes also have a high precision level [10]. The world's leading companies organized production of navigation modules with MEMS sensors for small and medium aircraft aviation.

As already described, during its operation, SINS accumulates measurement errors of inertial sensors [11]. The nature of accumulation of SINS errors significantly depends on maneuvers, performed by AV in the process of SINS operation, so relationship of errors of SINS with errors of sensors is extremely complicated. Under these conditions, numerical modeling is most often applied for the study of peculiarities of AV control.

At the same time, to clarify some peculiarities of interaction of a control system and an inertial navigation system, it seems necessary to perform analytical studies of the impact of errors of SINS in general and of inertial sensors in particular on accuracy of control of three-dimensional AV motion.

---

## 3. The purposes and objectives of the research

---

The aim of present research is to obtain analytic expressions for the synthesis of control actions, taking into account the errors of inertial navigation system and to estimate accuracy of AFCS, receiving input data of the inertial module.

To accomplish the set goal, the following tasks were to be solved:

- to obtain the law of control in the analytical form, including the generalized error of PFINS, for synthesis for control actions of the closed AFCS;
- to study the influence of the generalized error of SINS on accuracy of solution of the terminal problem and to consider the ways of accuracy improvement by changing the values of the prediction depth parameter in the law of control;
- to verify analytical conclusions by the method of computer simulation.

**4. Obtaining the law of control for a closed AFCS**

General formulation of the problem is as follows. Let us assume that at the initial moment, the motion, position and speed of AV are known, they are contained in the state vector. It is required to transfer an AV to a desired point of space with the help of control actions within the specified time at a required ultimate speed. It is also known, that information about the current value of the state vector of an AV is available with an error, correspondent to the accepted model of the inertial system (in a general case) or of the inertial sensor (in a simplified one-dimensional case).

A fundamental course of solving a problem will be considered in a one-dimensional case, so as not to clutter presentation of analytical results. Let us describe an undisturbed controlled motion of AV by equation

$$\ddot{r}(t) = u(t), \tag{1}$$

where  $r(t)$  is the coordinate of an object,  $u(t)$  is the sought-for controlling acceleration. At the initial ( $t=0$ ) and final ( $t=T$ ) moment, the state of a control object is characterized by a coordinate and speed of the motion:

$$r(0) = r_0, \quad \dot{r}(0) = \dot{r}_0, \tag{2}$$

$$r(T) = \bar{r}_T, \quad \dot{r}(T) = \dot{r}_T. \tag{3}$$

An object must reach the final state within time  $T$ .

Taking into account obtained information about the state vector, it is necessary to synthesize the law of control  $u(t, r, \dot{r})$ , providing satisfaction of conditions (3) due to (1) and (2).

The basic methodology of solving this problem is the methodology for solving inverse problems of dynamics, where it is necessary to determine the program control  $u^*(t)$  by the known trajectory of motion [4]. We will briefly describe obtaining of program control in the analytical form for control actions at non-disturbed motion.

Let us assign the program trajectory as the extreme of functional

$$\int_0^T \dot{r}^2(t) \cdot dt = \int_0^T u^2(t) \cdot dt.$$

In this case, the trajectory of motion takes the form

$$r^*(t) = b_3 \cdot t^3 + b_2 \cdot t^2 + b_1 \cdot t + b_0, \tag{4}$$

and coefficients  $b_i, i = \overline{0,3}$  are determined from conditions of agreement of solution (4) with boundary conditions (2), (3), and takes the following form:

$$b_0 = r_0, \quad b_1 = \dot{r}_0,$$

$$b_2 = \frac{3(r_T - r_0)}{T^2} - \frac{\dot{r}_T + 2\dot{r}_0}{T},$$

$$b_3 = \frac{2(r_0 - r_T)}{T^3} + \frac{\dot{r}_T + \dot{r}_0}{T^2}. \tag{5}$$

Knowing the equation of software trajectory (4), we easily find program control from (1) in the form of

$$u^*(t) = 6b_3t + 2b_2.$$

After substituting coefficients (5) into this expression, we will obtain

$$u^*(t) = \left( 12 \frac{r_0 - r_T}{T^3} + 6 \frac{\dot{r}_T + \dot{r}_0}{T^2} \right) \cdot t + 6 \frac{r_T - r_0}{T^2} - 2 \frac{\dot{r}_T + 2\dot{r}_0}{T}. \tag{6}$$

Motion of AV, caused by influence (6), taking into account the assumed ideal character of motion, will be subsequently called reference. Control (6) will be called program control and the trajectory (4) will be called a program or reference trajectory.

Program control (6) corresponds to control in the open control scheme and is not often used in practice, because usually control is adjusted taking feedback into consideration. To implement the motion along the program trajectory under conditions of possible, parametric and dynamic disturbances, it is proposed to use the algorithm of synthesis by the method of pursuing the leading point.

Let us carry out synthesis of control by the current value of the state vector of AV. Let us assume that measurements of coordinate  $\hat{r}(t)$  and speed  $\hat{\dot{r}}(t)$  are available at any moment. We will solve the problem of transferring the state vector of object  $(r, \dot{r})$  from point  $(\hat{r}, \hat{\dot{r}})$  to point  $(r^*(t + \tau), \dot{r}^*(t + \tau))$  within some time  $\tau$ . New variable  $\tau$  will be called the prediction depth.

It should be noted that according to the problem statement, the destination point is selected on the reference trajectory (4). It is ahead of the current point by time  $\tau$  and by point of time  $T$ , in accordance with the procedure of plotting of trajectory (4), it comes to the desired final position, providing a solution to the original problem of terminal control.

We will introduce additional disturbance in motion (1) and limit it by module  $|f| \leq f^*$ . Then the mathematical model of the problem of synthesis takes the form

$$\ddot{r}(t') = u(t') + f(t'),$$

under boundary conditions:

$$r(0) = \hat{r}(t), \quad \dot{r}(0) = \hat{\dot{r}}(t),$$

$$r(\tau) = r^*(t + \tau), \quad \dot{r}(\tau) = \dot{r}^*(t + \tau), \tag{7}$$

where  $t' \in [0, \tau]$  is the variable of local time.

We will join the initial and the final points (7) by a cubic polynomial of the variable of local time, and obtain

$$r(t') = a_3 t'^3 + a_2 t'^2 + a_1 t' + a_0,$$

where

$$a_0 = \hat{r}(t), \quad a_1 = \dot{\hat{r}}(t),$$

$$a_2 = 3 \frac{r^*(t+\tau) - \hat{r}(t)}{\tau^2} - \frac{\dot{r}^*(t+\tau) + 2\dot{\hat{r}}(t)}{\tau},$$

$$a_3 = 2 \frac{\hat{r}(t) - r^*(t+\tau)}{\tau^3} + \frac{\dot{r}^*(t+\tau) + \dot{\hat{r}}(t)}{\tau^2}.$$

Then we will obtain dependence for control by the local trajectory

$$u(t') = 6a_3 t' + 2a_2. \quad (8)$$

We will limit the time interval of using control (8) only by one moment  $t' = 0$ , as it will be necessary to develop another local trajectory at the next moment.

As the law of control of synthesis of control, we will finally obtain

$$u(t, \hat{r}, \dot{\hat{r}}) = 6 \cdot \frac{r^*(t+\tau) - \hat{r}(t)}{\tau^2} - 2 \cdot \frac{\dot{r}^*(t+\tau) + 2\dot{\hat{r}}(t)}{\tau}, \quad (9)$$

in which both factual current values of assessment of the state vector and its predicted reference value, which is the known function of time, are used.

Fig. 1 shows that motion of the point deviated and point  $\hat{r}(t)$  actually does not lie on the reference trajectory. Deviation in position occurred due to disturbing influence. It is necessary to develop control, which will return the object to the reference trajectory. Local return trajectory is shown in the Figure by blue dots.

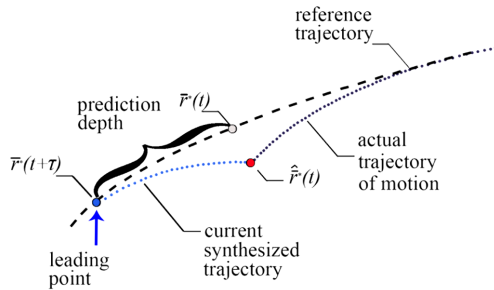


Fig. 1. Deviation of disturbed motion from the reference trajectory, where  $\hat{r}(t)$  is the measured state vector at time  $t$ ,  $\bar{r}^*(t)$  is the reference value of state vector at time  $t$ ,  $\bar{r}^*(t+\tau)$  is the reference value of state vector after time  $\tau$  (prediction depth)

We will analyze the accuracy of the obtained control of AV in a closed system. To analyze effectiveness of the selected scheme of synthesis, we will explore the closed control system in terms of possibility of implementation of the reference trajectory.

We will assume that the actual value of variable  $r(t)$ , corresponding to solution of the disturbed equation of motion is different from reference value  $r^*(t)$ , assigned by (4), by magnitude

$$\delta r(t) = r(t) - r^*(t).$$

Suppose that measurements of the state vector of SINS are ideal, in particular  $\hat{r}(t) = r(t)$ ,  $\dot{\hat{r}}(t) = \dot{r}(t)$ . Then control (9) can be represented as

$$u(t, r, \dot{r}) = u^*(t) + \delta u(\delta r, \delta \dot{r}),$$

where control error:

$$\delta u(t) = -\frac{6}{\tau^2} \delta r(t) - \frac{4}{\tau} \delta \dot{r}(t). \quad (10)$$

Let us write equation for error as

$$\delta \ddot{r}(t) = \delta u + f(t),$$

and, having substituted in it (10), we will obtain

$$\delta \ddot{r}(t) + \frac{4}{\tau} \delta \dot{r}(t) + \frac{6}{\tau} \delta r(t) = f(t) \quad (11)$$

Differential equation (10) has solution

$$\delta r(t) = e^{-\frac{2}{\tau}t} \left( C_1 \cos \frac{\sqrt{2}}{\tau} t + C_2 \sin \frac{\sqrt{2}}{\tau} t \right) + \delta r^f(t), \quad (12)$$

in which coefficients  $C_1, C_2$  are determined from original conditions  $\delta r(0), \delta \dot{r}(0)$ , but the forced component

$$\delta r^f(t) = \frac{\tau}{\sqrt{2}} \int_0^t e^{-\frac{2}{\tau}\theta} \sin \left( \frac{\sqrt{2}}{\tau} \cdot \theta \right) \cdot f(t-\theta) \cdot d\theta, \quad (13)$$

corresponds to the convolution of pulse transition function of the inertial section of the second order, which is (11), and function  $f(t)$ .

To obtain a rough estimation of the magnitude of component  $\delta r^f(t)$  at  $t \rightarrow \infty$  without specifying functional dependence  $f(t)$ , we will use ratios  $|f(t)| \leq f^*$  and

$$\left| \sin \frac{\sqrt{2}}{\tau} \cdot \theta \right| \leq 1.$$

Thus, the inequality holds for any  $t \geq 0$ ,

$$|\delta r^f(t)| < \frac{\tau}{\sqrt{2}} \int_0^t e^{-\frac{2}{\tau}\theta} \cdot f^* \cdot d\theta =$$

$$= \frac{\tau^2}{2\sqrt{2}} f^* \left( 1 - e^{-\frac{2}{\tau}t} \right) \xrightarrow{t \rightarrow \infty} \frac{\tau^2}{2\sqrt{2}} f^*. \quad (14)$$

Expression (14) shows that the magnitude of error (12) is limited by module. The problem on roughness degree of the obtained estimation for the component of error  $|\delta r^f(t)|$ , caused by disturbance, is interesting. Consider a particular case, at  $f(t) = f^* = \text{const}$ . Then the forced component takes the form

$$\delta r^f(t) = \frac{\tau^2}{6} f^*$$

and differs from the estimation from (14) less than by two times. From this we can conclude that the used simplifications in obtaining estimation  $|\delta r^f(t)|$  do not lead to a significant distortion of the result.

It may be concluded from (12) that at ideal measurements of the state vector at  $f \equiv 0$  and non-zero initial conditions, control (9) provides asymptotic stability of motion relative to the reference trajectory. However, at non-zero, but limited disturbance  $|f(t)| \leq f^*$ , the point surely does not deviate from the reference trajectory more than by magnitude  $\frac{\tau^2}{2\sqrt{2}} f^*$ .

**5. Influence of measurement error on the accuracy of solution to a terminal problem**

Now that we have equation (11) for the error of the state vector, we will analyze the influence of the error of measurement of the state vector of SINS on accuracy of operation of the closed control system. In particular, we are interested in terminal accuracy of solution of the control problem, i.e. there is estimation of the error of reaching the reference state vector at the final moment.

Let the state vector  $(r, \dot{r})$  be estimated by SINS with an error. Because dependences of errors of SINS of all components of navigation parameters are quite complicated, it does not seem possible to introduce them into consideration. We will use some generalized error of determining of navigation parameters.

We will consider a one-dimensional case. We will assume that initial measurement is value  $a(t) = \ddot{r}(t) + \delta a$ , corresponding to the sum of true acceleration and constant of error  $\delta a$ . Estimation of the state vector  $(\hat{r}, \hat{\dot{r}})$  in this case is performed in accordance with the principle of inertial notation by double integration of measurements.

The considered case is characteristic of SINS operation, in which error  $\delta a$  consists of the error of accelerometer itself and the error of compensation of the vector of free fall acceleration, caused by the error of gyroscopes. In some modes of AV motion, such total error can be considered constant.

In view of the above, and considering that estimation of values  $\hat{r}, \hat{\dot{r}}$  comes from solutions to equation  $\ddot{\hat{r}}(t) = a(t)$ , we obtain

$$\begin{aligned} \hat{\dot{r}}(t) &= \dot{r}(t) + \delta a \cdot t, \\ \hat{r}(t) &= r(t) + \delta a \cdot \frac{t^2}{2}. \end{aligned}$$

Subsequently, after substitution of expressions (10), (11) in the law of control (9), for the closed system, equation of implementation of reference motion takes the form

$$\begin{aligned} \delta \ddot{r}(t) + \frac{4}{\tau} \delta \dot{r}(t) + \frac{6}{\tau^2} \delta r(t) &= \\ = -\frac{4\delta a}{\tau} \cdot t - \frac{3\delta a}{\tau^2} \cdot t^2 + f(t). \end{aligned} \tag{15}$$

Provided that  $\delta r(0) = 0, \delta \dot{r}(0) = 0$ , at the initial moment this equation (15) has the solution

$$\begin{aligned} \delta r(t) &= -\frac{\delta a}{2} t^2 + \frac{\delta a}{6} \tau^2 - \\ - e^{-\frac{2}{\tau} t} \frac{\delta a}{3} \tau^2 \left( \frac{1}{2} \cos \frac{\sqrt{2}}{\tau} t + \frac{1}{\sqrt{2}} \sin \frac{\sqrt{2}}{\tau} t \right) &+ \delta r^f(t). \end{aligned} \tag{16}$$

Thus, we obtained the expression for determining a control error in the closed circuit, which includes a constant measurement error and a random component.

Analysis of expression (16) makes it possible to argue that unlike (12), where  $\delta r(t)$  is a magnitude, limited by module, in (16) absolute value of error  $\delta r(t)$  infinitely increases at an increase in time  $t$ , which is explained by accumulation of the error of identification of the state vector. It can be seen from (16) that the higher  $\tau$ , the less the influence  $\delta a$  on  $\delta r$  ceteris paribus. It is possible to show that  $\lim_{\tau \rightarrow \infty} (\delta r_T(\tau)) = 0$  holds for any final  $T$ .

A similar conclusion is also true for the error of terminal speed.

$$\delta \dot{r}_T^{\delta a}(\tau) = \frac{\delta a}{\sqrt{2}} \tau \cdot e^{-\frac{2T}{\tau}} \cdot \sin \frac{\sqrt{2}}{\tau} T - \delta a \cdot T.$$

The limit value of the error of terminal speed at  $\tau \rightarrow \infty$  is equal to zero. Thus, at negligibly small dynamic disturbances  $f^*$ , it is advisable to choose large parameter  $\tau$ , included in the law of control (9). This choice makes it possible to decrease the influence of the error of acceleration measurement on the accuracy of terminal control.

**6. Discussion of results: experimental research into the influence of magnitude of parameter  $\tau$  on improvement of control accuracy**

To verify the assumptions about a possibility for improvement of accuracy of AV control by SINS data, a computation experiment with the use of the developed software package, simulating operation of AFCS [12, 13], was conducted on some time interval. Here, we will present the results of modeling of steady rectilinear motion, at which only one coordinate changes.

Simulation of motion was conducted on a small time interval equal to 100 seconds, assuming that within this period, connection with a satellite is sure to be resumed. In the course of the experiment, accelerometer measurement errors  $\delta a$  remained at the assigned level, for example, during plotting the curves, value  $\delta a = 0.02 \text{ m/s}^2$  in Fig. 2. The magnitude of prediction depth  $\tau$  changes, to demonstrate this, values of  $\tau$  were selected: 1 sec., 200 sec. and 500 sec.

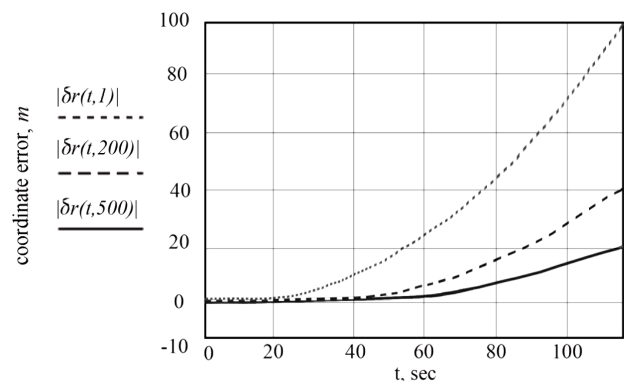


Fig. 2. Coordinate error when using the law of control with different values of  $\tau$

The curves in Fig. 2 show the change in control error  $\delta r(t)$  during the modeled motion of an object. The figure shows a monotonous rise of the curves, i. e., error  $\delta r(t)$  in-

creases, but with different dynamics. The rate of an increase depends on the magnitude of prediction depth  $\tau$  – an increase in  $\tau$  slows down the increase rate  $\delta r(t)$ . Indeed, at the final point of section of motion at  $\tau=1$  sec at the 100th second of the flight,  $\delta r(t)=100$  m, at  $\tau=200$  sec at the 100th second of the flight, the error decreased to 47.5 m, while at  $\tau=500$  sec, it decreased to 23 m.

The form of the curves in Fig. 2 proves the theoretical findings that at an increase in the value of interval  $\tau$ , the rate of an increase in the coordinate error of AV to the final point decreases.

In the second experiment, the possibility of weakening of the influence of errors of inertial measurement on control influence due to a change in the parameter of synthesis of  $\tau$  was explored. But, unlike the previous experiment, in which the value of  $\tau$  was fixed in each particular session of flight simulation, this parameter changed.

Fig. 3 shows the results of three series of experiments under the following conditions:  $\tau$  ranges from 0.1 to 10,000 sec; the time of AFCS control only by data of the inertial unit is fixed:  $T=\{100, 200, 300\}$  sec; there is no dynamic disturbance ( $f(t)\equiv 0$ ); the error of the inertial unit measurement is non-zero and corresponds to error of MEMS-based accelerometers.

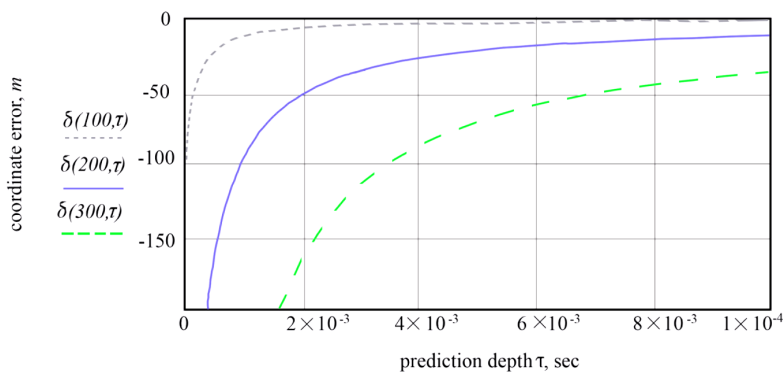


Fig. 3. Dependence of coordinate error at the terminal point on prediction depth

Fig. 3 shows that at an increase in parameter  $\tau$ , there is a decrease in terminal error. Such an effect of an increase in terminal accuracy and, consequently, an increase in AFCS accuracy are caused by slowing down of an increase in terminal error with an increase in parameter  $\tau$ . We will note that in the motion interval of 100 seconds (the upper curve), which is permissible at a temporary loss of connection with satellites, the error decreases very fast and tends to zero. The results of the second experiment indicate a monotonous decrease in terminal error at an increase in  $\tau$ .

A method of synthesis of control functions, which unlike traditional methods contains the parameter, which makes it possible to regulate AFCS accuracy *ceteris paribus*, was proposed. This enables us to argue that data, coming from the MEMS sensors with high accuracy, can be used for control and control accuracy will be quite high.

To improve the accuracy of operation of inertial units, algorithmic compensation the primary measurements is widely used. For this, one conducts experiments on calibration of particular sensors and the inertial unit in the assembly, during which components of measurement errors are assessed. If each sensor of the unit is assessed and characterized in this way, results are sure to improve, but such

experiments take time, might be difficult to carry out, and are expensive.

However, each sensor or, in the case of MEMS-based sensors, a particular model, have a technical passport with accuracy characteristics, given by manufacturer. It would be possible to use the data from the passport for the algorithmic compensation of measurement errors, but actual values of measurement errors do not comply with the passport data for a variety of reasons. In this case, algorithmic compensation will not improve accuracy of control. In comparison with the above, the proposed method makes it possible to improve control accuracy without conducting complicated experiments on calibration, but rather by appropriate choice of the parameter. It is enough to consider the generalized error of inertial measurements, which can be estimated based on the data of the technical passport. Roughness of this assessment will be compensated by selection of parameter  $\tau$  in the law of control, because the influence of the parameter was proved analytically and experimentally. Subsequently, it is possible to make a table of correspondence of accuracy of the inertial unit to the value of the parameter of synthesis of control actions.

Another method of application of the established dependence is to change parameter  $\tau$  during the control session only by SINS data. This will be done in the subsequent modeling experiments.

Analysis of the results of experimental studies makes it possible to argue that the data, coming from the MEMS sensors of medium accuracy, can be used for control and control accuracy will be high enough.

## 7. Conclusions

1. We present the procedure of deriving an analytical expression for calculation of values of the control function, which takes into account the value of the generalized error of measurements of the inertial module and the level of external dynamic disturbance. This approach made it possible to extend and modify the traditional method for solving the inverse problem of dynamics in the case of the terminal control problem. Thus, we received a modified law of control that can be applied in AFCS, which has a new component, such as the parameter, leveling the factors of decrease in accuracy control. The value of the so-called prediction was selected as the parameter.

2. Some aspects of the problem of using output information of the inertial navigation system as input data for synthesis of control influence on AV were explored. Analytical expressions for estimation of accuracy of object control at the point of destination of the motion were obtained. It was shown that, despite distorted navigation parameters, it is possible to maintain the accuracy of solution of the terminal problems within some time due to increasing errors of the inertial module. This possibility was obtained due to parameterization of the law of control.

We provided a set of recommendations on selection of a changing parameter of control synthesis depending on the precision level of the measuring sensor, used in the inertial module. While selecting a variable value of prediction depth in the law of synthesis by the method of pursuing of leading point, it is recommended to consider the following:

– if the information-measuring inertial system provides obtaining of coordinates and speed of an object with a high degree of accuracy, i. e. inertial sensors have a small measurement errors, a selected prediction parameter should be minimal;

– when using low-precision sensors, the prediction parameter should be increased.

For determining a value of the parameter and final solution to the problems of adjustment of the algorithm of synthesis while working with certain inertial module, it is

necessary to conduct AFCS modeling using data on sensors' accuracy.

3. By using computer simulation, and analytically previously, it was shown that it is possible to decrease the influence of SINS measurement errors on the synthesis of values of control functions by selecting the value of prediction depth.

Subsequently, it is planned to use the presented algorithm for conducting of a full-scale experiment using a small unmanned aerial vehicle.

---

## References

1. Revniviyh S. G. Tendencii razvitiya global'noy sputnikovoy navigacii // Mezhdunarodnaya konferenciya po integrirovannym navigacionnym sistemam: XIX mezhdunarodnaya konferenciya. Sankt-Peterburg: GNC RF CNII "Elektropribor", 2012. P. 266–276.
2. INS/CNS/GNSS Integrated Navigation Technology / Quan W., Li J., Gong X., Fang J. Springer, 2015. 372 p. doi: 10.1007/978-3-662-45159-5
3. Chiang K.-W., Duong T., Liao J.-K. The Performance Analysis of a Real-Time Integrated INS/GPS Vehicle Navigation System with Abnormal GPS Measurement Elimination // *Sensors*. 2013. Vol. 13, Issue 12. P. 10599–10622. doi: 10.3390/s130810599
4. Krut'ko P. D. Obratnye zadachi dinamiki upravlyaemyh sistem. Lineynye modeli. Moscow: Nauka, 1987. 304 p.
5. Nebylov A., Tikhomirov M., Benzerrouk H. Development Stages and Prospects of Flight Control and Navigation Complexes for Aircraft // *IFAC-PapersOnLine*. 2017. Vol. 50, Issue 1. P. 6434–6439. doi: 10.1016/j.ifacol.2017.08.1032
6. Sabatini R., Moore T., Ramasamy S. Global navigation satellite systems performance analysis and augmentation strategies in aviation // *Progress in Aerospace Sciences*. 2017. Vol. 95. P. 45–98. doi: 10.1016/j.paerosci.2017.10.002
7. Miao L., Shi J. Model-based robust estimation and fault detection for MEMS-INS/GPS integrated navigation systems // *Chinese Journal of Aeronautics*. 2014. Vol. 27, Issue 4. P. 947–954. doi: 10.1016/j.cja.2014.06.012
8. Integrirovannaya s magnitnym kompasom BINS s vrashchayushchimsya izmeritel'nym modulem na MEMS / Ci U., Czichzhou L., Ya C., Czyan'e L. // *Giroskopiya i navigaciya*. 2016. Issue 3 (94). P. 3–13.
9. Vas'kov A. G., Klychnikov V. V. Sposoby kompleksirovaniya navigacionnyh sistem letatel'nyh apparatov // *Nauchno-prakticheskie issledovaniya*. 2017. Issue 2. P. 49–52.
10. Barbour N. M. Inertial Navigation Sensors // NATO RTO Lecture Series, RTO-EN-SET-116. 2010. URL: <http://www.dtic.mil/get-tr-doc/pdf?AD=ADA581016>
11. Golovan A. A., Parusnikov N. A. Matematicheskie osnovy navigacionnyh sistem. Chast' I. Matematicheskie modeli inercial'noy navigacii. Moscow: Izd-vo MGU, 2011. 132 p.
12. Khatsko N. Ye. Prohramne zabezpechennia dlia modeliuвання roboty systemy avtomatichnoho keruvannya polotom po vymiram inertsiyalnykh datchyviv // *Materialy mizhnarodnoi naukovo-praktychnoi konferentsiyi «Suchasni metodyky, innovatsiyi ta dosvid praktychnoho zastosuvannya u sferi tekhnichnykh nauk»*. Liublin, 2017. P. 30–33.
13. Hac'ko N. E. Issledovanie vozmozhnosti upravleniya polotom po dannym inercial'nyh datchikov nizkogo klassa tochnosti // *Problemy mashynobuduvannya*. 2013. Vol. 16, Issue 5. P. 32–35.