Algorithm of Target Motion Prediction for Guidance Process based on Strapdown Inertial Navigation Data

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Abstract. The autonomous operation of the strap-down inertial navigation system has been considered and investigated for the process of capturing the target by the homing head on the inertial section of the trajectory. A technique for obtaining the model of predicted target motion using parametric identification methods has been developed, which can be used for a certain time interval during the autonomous guidance stage after the failure of the homing process. The researches have been conducted by mathematical modeling of the developed algorithms in mathematical software package MATLAB+Simulink. The results proved their efficiency and validity of their application for this class of developed strap-down inertial navigation system used in capturing and guidance of highly maneuverable unmanned aerial vehicles.

Keywords: Strapdown Inertial Navigation System, Guidance, Homing Head, Highly Maneuverable Targets, Motion Prediction, UAV.

1 Introduction

The motion of the unmanned aerial vehicle (UAV) usually has speed and acceleration constraints. They are modeled by high-order differential equations of motion, typically linearized for the task of control. To guide the vehicle towards the target it is necessary to solve the three-dimensional problem space, with incomplete information about the environment, erroneous on-board sensors, speed and acceleration constraints, and uncertainty in-vehicle state and sensor data [1].

The problem of developing algorithmic support for the strap-down inertial navigation system (SINS) is considered. Such systems are part of the combined system for the short-range object guidance to the maneuvering targets. It is assumed that in addition to SINS, the onboard target coordinator, so-called the homing head [3], is part of the combined guidance system. The guidance process includes the stages of inertial guidance (from the moment of the object moving away from the moving carrier to the moment the target is captured by the homing head) and homing (from the moment of the target capturing to the moment of object approach to the target).

The main tasks of the guidance system of the object on the inertial section are to bring the object to the estimated range of target capturing by the homing head, to issue and perform the target localization to ensure the guaranteed target capturing. At the end of the inertial section, it is necessary to ensure the fulfillment of the so-called geometric condition of target capturing, i.e. the target must come to the cone of the field of view of the homing head when reaching the estimated capture range. It is assumed that the half-angle aperture of the cone in the homing head field of view is 0.1 rad, and the target capture range is 3000 m. Information support of the process at the inertial section is carried out by the SINS of an object and the guidance system of the carrier.

2 Problem Statement

Here and further the following conditions will be assumed. The carrier is an unmanned aerial vehicle (UAV), and the main navigation system is SINS. The range of target speeds is 0..1000 m/s, the range of carrier speeds is 180..700 m/s, and the maximum overload of the target does not exceed 20. It is also supposed that the time of the inertial section of the guidance is no more than 10 s.

Information about the current values of linear and angular parameters of the UAV movement relative to the selected reference coordinate system (CS) is obtained from SINS. In turn, the target localization system of the carrier is designed to issue coordinates and components of the target's speed in the same reference CS. Possible options for pre-launch target designation and periodic target designation in the inertial area. When only pre-launch target localization is implemented to predict the target moves relative to the reference CS on the inertial guidance section, the hypothesis about the constancy of the target velocity vector is accepted. The need for periodic target localization from the carrier in the inertial guidance section arises in the case of highly maneuverable targets when the use of the hypothesis of the constancy of the target velocity vector in the inertial guidance section becomes unacceptable.

In this paper, we consider a variant of SINS based on three accelerometers and three angular velocity sensors. It is assumed that the sensitivity axes of the sensors are oriented along the axes of the $O_1X_1Y_1Z_1$ coordinate system associated with the vehicle and the output signals are quantized increments of the integrals from the components of the apparent acceleration of the point O_1 and the absolute angular velocity of the vehicle along the sensitivity axes of the instruments.

It is proposed to use the launch (inertial) rectangular CS OXYZ as the reference CS, the coordinate origin of which at the time of launch coincides with the point O_1, Y-axis is directed upward along the local vertical at the launch point, and X-axis is directed toward the object motion. To ensure the SINS operation at the launch, it is necessary to set the initial values of motion parameters of the point O_1 relative to the reference CS and the initial orientation of the body-fixed CS $O_1X_1Y_1Z_1$ relative to the reference CS, as well as the height h_0 of the point O above the ground. After capturing the target of the homing head, information support for the guidance process is carried out by SINS and the homing head. The last outputs the signals proportional to the components of the angular velocity of the target sightline, the angles of the target bearing, and the speed of approach to the target.

3 Mathematical Models Used in Research

The equations of object motion relative to the reference CS can be represented in the form:

$$\dot{\bar{R}} = \bar{V}(t); \quad \dot{\bar{V}} = \bar{a}(t) - \bar{g}(\bar{R}), \tag{1}$$

where $\bar{R} = (X, Y, Z)^T$ is the coordinate vector of point O_1 of the object in the reference CS; $\bar{a} = (a_X, a_Y, a_Z)^T$ is the projection vector of the apparent acceleration of point O_1 in the reference CS; $\bar{g} = (g_X, g_Y, g_Z)^T$ is the projection vector of gravitational acceleration on the axis of the reference CS.

Given the short guidance time and the short range of the object, we can assume that $g_X = g_Z = 0$, and

$$g_Y = g_0\left(\frac{R_0}{R_0 + h_0 + Y}\right)^2, \tag{2}$$

where R_0 is the radius of the Earth; g_0 is the value of the gravity acceleration on the surface of the Earth.

The motion equation of the target center of mass in the reference CS has a form similar to (1):

$$\dot{\bar{R}}_t = \bar{V}_t(t); \quad \dot{\bar{V}}_t = \bar{a}_t(t) - \bar{g}(\bar{R}_t), \tag{3}$$

where $\bar{R}_t = (X_t, Y_t, Z_t)^T$; $\bar{a}_t = (a_{Xt}, a_{Yt}, a_{Zt})^T$.

The model of the target relative motion in the reference CS has the form:

$$\dot{\bar{D}} = \bar{V}_t(t) - \bar{V}(t), \tag{4}$$

where $\bar{D}(t) = \bar{R}_t(t) - \bar{R}(t),$.

The angles of the bearing (sighting) of the target satisfy the ratios:

$$\beta = -\text{arctg}\frac{D_{Z_1}}{D_{X_1}}; \quad \varepsilon = \arcsin\frac{D_{Y_1}}{D}, \tag{5}$$

where D_X, D_Y, D_Z are projections of the relative range of the target on the axes of body-fixed CS $O_1X_1Y_1Z_1$, X_1 axis is oriented along the longitudinal axis of the vehicle, and Y_1 axis is directed upward in the plane of vertical symmetry of the vehicle.

The following relationship is true

$$\begin{pmatrix} D_{X_1} \\ D_{Y_1} \\ D_{Z_1} \end{pmatrix} = \left[\mathbf{C}_{\text{reference}}^{\text{body-fixed}}\right]^T \bar{D}, \tag{6}$$

where $\mathbf{C}_{\text{reference}}^{\text{body-fixed}}$ is the matrix of conversion from the body-fixed CS to the reference CS, calculated in SINS.

The conversion from the body-fixed CS to the sight CS $O_1X_sY_sZ_s$ (X_s axis is directed along the sightline to the target) is characterized by the transition matrix of the following form

$$\mathbf{C}_{\text{sight}}^{\text{body-fixed}} = \begin{pmatrix} \cos\beta\cos\varepsilon & \sin\varepsilon & -\sin\beta\cos\varepsilon \\ -\cos\beta\sin\varepsilon & \cos\varepsilon & \sin\beta\sin\varepsilon \\ \sin\beta & 0 & \cos\beta \end{pmatrix} \tag{7}$$

$\mathbf{C}_{\text{sight}}^{\text{reference}}$ is the transition matrix from the reference CS to the sight CS, then the following relation is true

$$\begin{pmatrix} \dot{D} \\ D\omega_{DZ} \\ -D\omega_{DY} \end{pmatrix} = \mathbf{C}_{\text{sight}}^{\text{reference}} \, \dot{\bar{D}}, \tag{8}$$

where ω_{DZ}, ω_{DY} are components of the absolute angular velocity of the sightline of the target

$$\mathbf{C}_{\text{sight}}^{\text{reference}} = \mathbf{C}_{\text{sight}}^{\text{body-fixed}} \left[\mathbf{C}_{\text{reference}}^{\text{body-fixed}} \right]^T .$$

The analysis [2] shows that the evolution of the parameters of the relative motion of the target in time can be described by the following system of equations:

$$\begin{aligned}
&\dot{V}_a = -\left(\omega_{DZ}^2 + \omega_{DY}^2\right) D(t) - [a_{tX}(t) - a_X(t)]; \\
&\dot{D} = -V_a(t); \\
&\dot{\omega}_{DY} = \frac{1}{D(t)}\left[2V_a(t)\omega_{DY}(t) + \omega_{DX}(t)\omega_{DZ}(t)D(t) - \left(a_{tZ}(t) - a_Z(t)\right)\right]; \\
&\dot{\omega}_{DZ} = \frac{1}{D(t)}\left[2V_a(t)\omega_{DZ}(t) - \omega_{DX}(t)\omega_{DY}(t)D(t) + \left(a_{tY}(t) - a_Y(t)\right)\right]; \\
&\dot{\varepsilon} = \omega_{DZ}(t) - \omega_Z(t); \\
&\dot{\beta} = \frac{1}{\cos\varepsilon(t)}\left[\omega_{DY}(t) - \omega_Y(t)\right],
\end{aligned} \tag{9}$$

where $V_a(t)$ is the speed of target approach; $\omega_{DX} = \omega_X + \left(\omega_{DY} - \omega_Y\right)\text{tg}\varepsilon$; $\omega_X, \omega_Y, \omega_Z$ are projections of the angular velocity of the vehicle on the axes of the sighting CS; a_X, a_Y, a_Z are projections of the apparent acceleration of the vehicle on the axes of the sighting CS; a_{tX}, a_{tY}, a_{tZ} are projections of the apparent acceleration of the target on the axes of the sighting CS.

4 Choice of the Guidance Law on the Inertial Section

The feature of the problem under consideration is the high maneuverability of the targets (the overload is up to 20). The analysis of various variants of the guidance laws [4], taking into account the mentioned feature, gives the possibility to recommend the law of proportional guidance for the inertial section, described by the following relationships:

$$n_{YT}(t) = 2\frac{N_a}{g}\hat{V}_a(t)\hat{\omega}_{DZ}(t); \quad n_{ZT}(t) = -2\frac{N_a}{g}\hat{V}_a(t)\hat{\omega}_{DY}(t), \tag{10}$$

where $\hat{V}_a(t)$, $\hat{\omega}_{DZ}(t)$, $\hat{\omega}_{DY}(t)$ are the estimates of the speed of approach to the target calculated based on information from SINS and the target localization system of the carrier using the relationship (8) $V_a(t) = -\dot{D}(t)$ and components of the angular velocity of the sightline of the target; N_a is the given constant of approach; $n_{YT}(t)$, $n_{ZT}(t)$ are the required values of the normal components of overload (in the sighting CS) [5].

5 Simulation Results

The developed algorithms were investigated by mathematical modeling. The studies were carried out using the Simulink visual modeling program, which is a part of the MATLAB software package. The block diagram of the model is shown in Fig. 1.

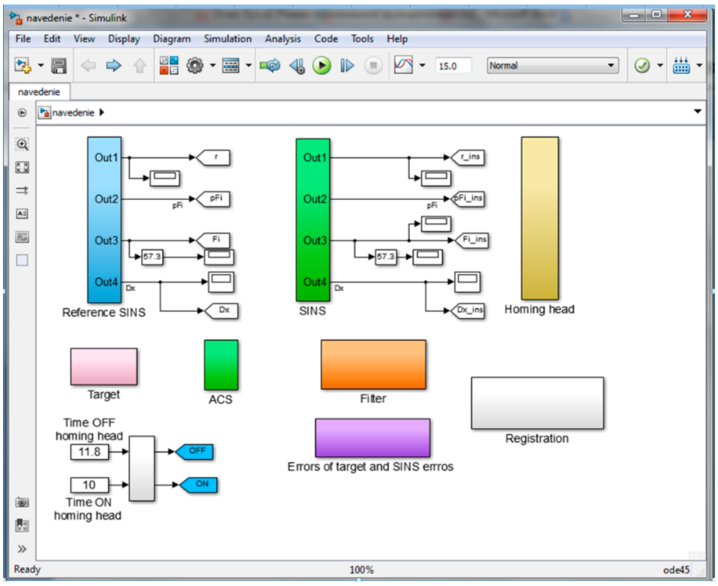

Fig. 1. Block diagram of simulation scheme.

During the simulation, the following subsystems have been created: the reference guidance system, SINS, and automatic control system (ACS), the target, and the homing head. Also, two additional subsystems have been created: the subsystem for registering simulation results "Registration" and the subsystem for filtering and identifying the parameters of the target models and SINS errors. The capture of the target and homing failure have been simulated by a timer.

With the study of algorithms for identifying SINS error models, the hypothesis has been adopted that for a short initial time interval ($t \approx 10$ sec) the dead reckoning errors of speed are changed linearly. Thus, the model of dead reckoning errors of speed components can be calculated by linear models of the first order:

$$\frac{dV_y}{dt} = C_1; \quad \frac{dV_x}{dt} = C_2,$$

where C_1, C_2 are parameters of identification.

The behavior of changes in the dead reckoning errors of speed components on the autonomous stage of guidance proves this hypothesis.

At the time of transition to the homing stage, using the latest target localization from the carrier and information from the homing head, the relative components of the speed of the rocket and the targets are calculated by which the components of the rocket speed are determined. Given the time of the autonomous operation of SINS, it is possible to determine the parameters C_1, C_2, which can be further refined using parametric identification algorithms [6].

In identifying and predicting the target motion parameters, the linear first-order models can also be used:

$$\frac{dV_{y_t}}{dt} = K$$

or models of the second-order

$$\frac{dV_{y_t}}{dt} = a_{y_t}; \quad \frac{da_{y_t}}{dt} = K,$$

where K is the identifying parameter.

At the same time, the process of identifying the target motion parameters, as noted earlier, begins already at the stage of autonomous guidance according to target localization information from the carrier. The results of the current parametric identification algorithm using the example of the target velocity component estimation V_{y_t} are shown in Fig. 2.

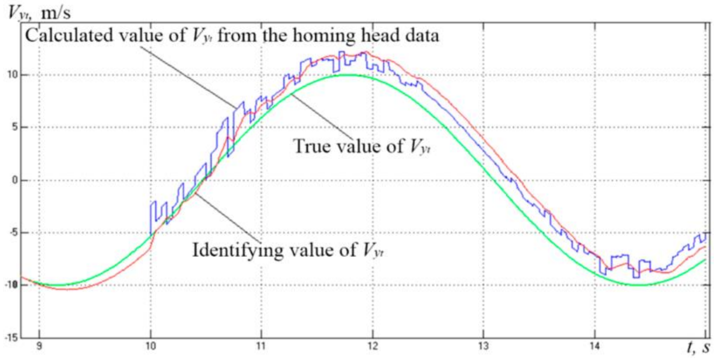

Fig. 1. Simulation results with parametric identification.

After the failure of the homing process, this information can be used to continue guidance from the adjusted SINS. The results of predicting the movement of the target after losing information from the homing head (failure of the homing process) are shown in Fig. 3 and Fig. 4, using the linear first-order model, as well as remembering the last value of the target velocity component $V_{y\,t}$.

The worst prediction result using the 1st-order model occurs when the failure of homing occurs at the peak of the anti-ballistic maneuver. There are three types of estimates of the dynamic object state: smoothing, filtering, and prediction. When solving the smoothing problem, it is necessary to construct an estimate of the object state vector at time t by observations of the object output to time t', if $t' > t$. Thus, the state is determined with some delay $(t' - t)$. In filtering tasks $t' = t$, and in prediction problems $t' < t$. In this case, it is necessary to solve the prediction problem, which in the simplest case comes down to identifying the 2nd-order model of the target movement. The results of such a prediction are shown in Fig. 5 in comparison with the linear 1st-order model, as well as when remembering the last value of the target velocity component $V_{y\,t}$.

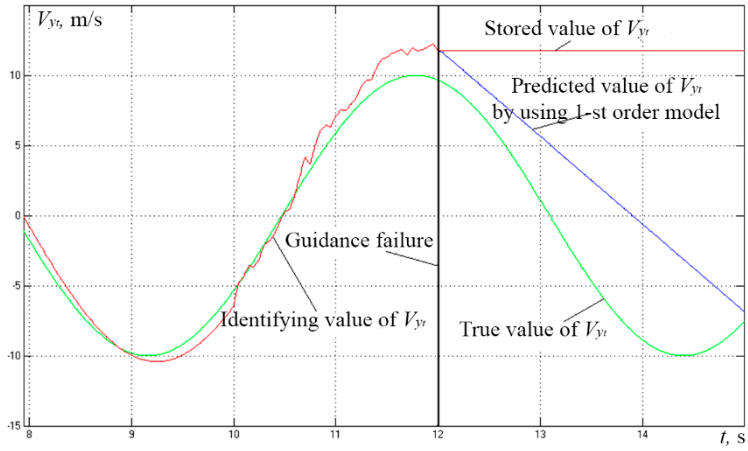

Fig. 3. Simulation results with parametric identification using the 1st-order model of target motion and the stored value of speed.

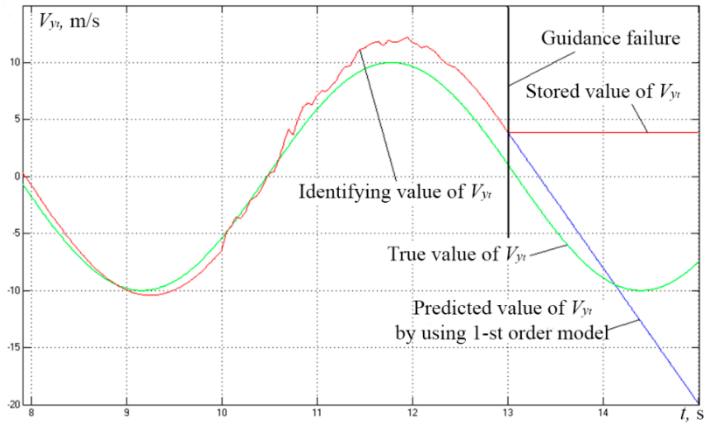

Fig. 4. Simulation results with parametric identification using the 1st-order model of target motion and the stored value of speed.

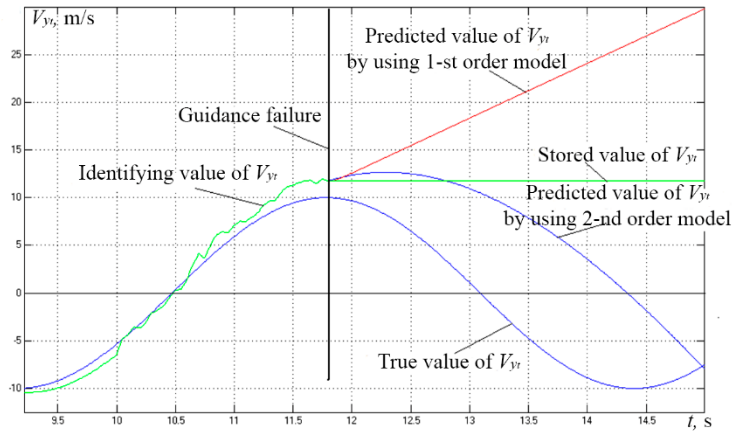

Fig. 5. Simulation results with parametric identification using 1st- and 2nd-order models of target motion and the stored value of speed.

The study was also conducted for a strap-down guidance system with various options of parametric identification of SINS error models and using the results of identification of SINS error models and prediction models for target maneuvers at the stage of autonomous guidance after the failure of the homing process. The nature of the change of the linear miss Δy for various conditions of the homing process were studied. The results of modeling the guidance process for the case of absence of homing failure are shown in Fig. 6, 7, and 8 there are the modeling results of the guidance process when switching to homing for 10 seconds with data fusion from SINS and homing head and again to autonomous guidance after the homing failure with 13 sec of the process. Here at the stage of repeated autonomous guidance, information on the target movement was idealized. The last stages of the guidance process are shown in Fig. 7 and 8 with the enlarged scale [7].

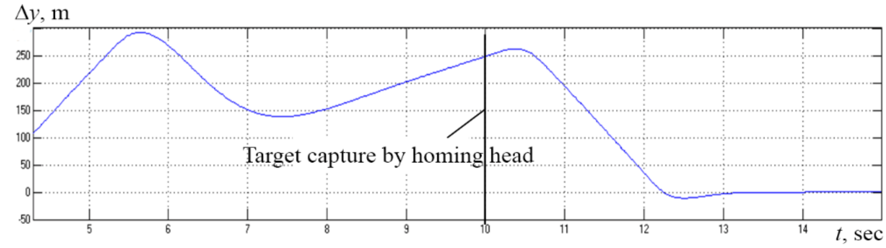

Fig. 6. Results of modeling the guidance process for the case of absence of homing failure.

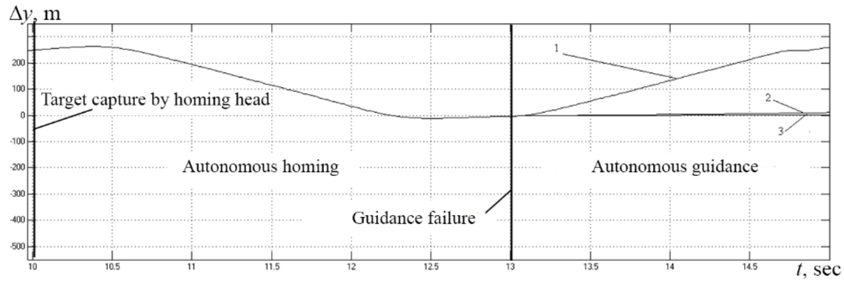

Fig. 7. Modeling results of the guidance process by switching to homing for 10 seconds.

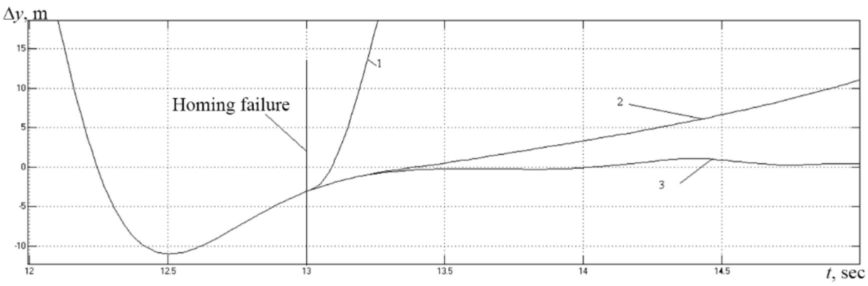

Fig. 8. Modeling results of the guidance process when switching to homing for 13 seconds.

The last stages of the guidance process are shown with the enlarged scale in Fig. 7 and Fig. 8. Curve 1 illustrates the process of changing the linear miss after the homing failure when receiving information from the unadjusted SINS at the homing stage. Curve 2 shows how much the accuracy of the autonomous guidance process improves only by compensation of SINS errors accumulated at the guidance stage of the target localization on the carrier and the homing stage. Curve 3 is given as a reference and illustrates the nature of the elimination of a linear miss in the absence of homing failure, i.e. duplicates the transient curve shown in Fig. 6.

In Fig. 9, in comparison with the previously given curves 2, 3, the linear miss elimination is shown taking into account the SINS error model identified at the homing stage by the dead reckoning of the rocket velocity components (curve 4). Fig. 10 illustrates the nature of the change in the dead reckoning error for the viewing angle after the homing failure.

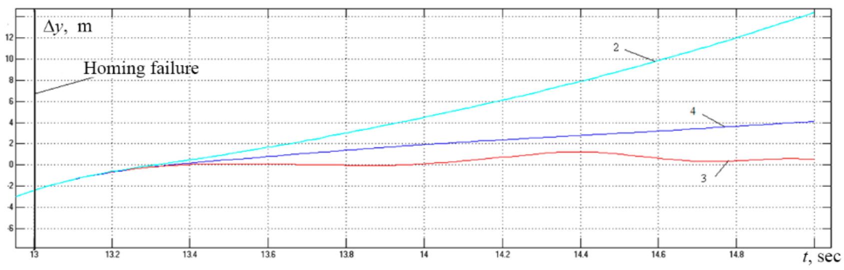

Fig. 9. Simulation results of linear miss elimination.

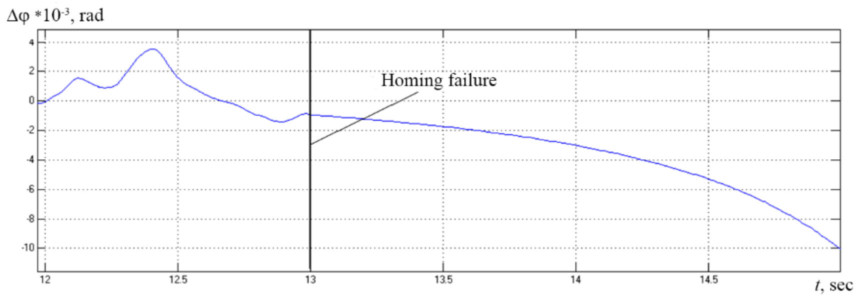

Fig. 10. Simulation results of dead reckoning error for the viewing angle after the homing failure.

The simulation shows that the use of the SINS error model, identified at the homing stage by the dead reckoning of the rocket velocity components, reduces the total linear miss three times, and the error in the viewing angle dead reckoning allows the target to be recaptured.

Similar studies were carried out using the stage of repeated autonomous guidance predicted by various algorithms of target maneuver identification. The nature of elimination of the linear miss using information both on the last value of the target speed components and with its predicted value is shown in Fig. 11. The fact that the final value of the linear miss in both cases practically coincides is explained by the nature of the target maneuver in the last guidance phase—the target itself returns to the line of sight. When using information about the predicted value of the target maneuver, the rocket tracks this maneuver [8].

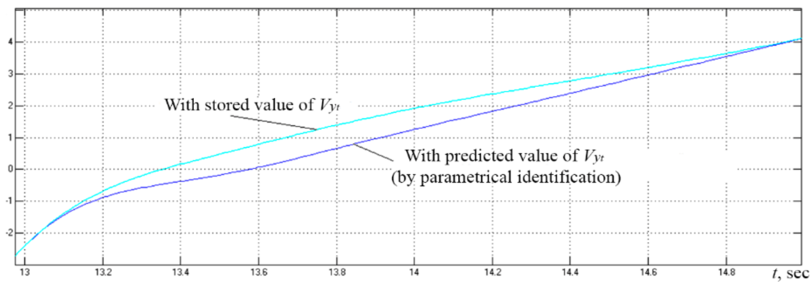

Fig. 11. Results of elimination of the linear miss using additional information.

The conducted studies confirm the efficiency of the developed algorithms and prove the effectiveness of their application for this class of developed missiles. To conduct full-scale studies, information is needed on the dynamic characteristics of the targets and the rocket, as well as the development research on complete SINS models taking into account the characteristics of primary information sensors, the characteristics of the command radio line of carrier-rocket, characteristics of the missile control system, etc.

6 Conclusions

Under theoretical studies, it was concluded that it is advisable to use the proportional guidance law as a method of guidance on the inertial section.

A technique is proposed for obtaining a model of target predicted motion using parametric identification methods, which can be used for some time during the homing step.

The conducted researches by mathematical modeling of the developed algorithms proved their efficiency. The second-order model is recommended for use since it allows capturing the target after homing failure even after 10 s of turning on. The value of linear miss in both cases practically coincides. Future studies can be related to data protection techniques [8–10] in navigation processes.

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