UDC 629.7.014-519(045)

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THE ANALYSIS OF THE DEPENDENCE OF UAV GUIDANCE QUALITY ON THE DYNAMICS FORECASTING ACCURACY OF MANEUVERING TARGET

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Abstract. *Investigated the quality of guidance depending on the accuracy of maneuvering aim dynamic forecasting on the example of several of the most common methods of guidance. The results clearly demonstrate the ability to improve the quality of guidance methods by improving forecasting accuracy.*

Keywords: quality of guidance; forecasting accuracy; methods of guidance; Unmanned Aerial Vehicle; hypothesis of target's movement.

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Introduction

The current stage of development of aviation technology is characterized by the gradual replacement of manned aircrafts by unmanned in the areas of application where it is possible and economically justified. Unmanned Aerial Vehicles (UAV) are the most rapidly growing segment of the aerospace industry. Currently UAVs are used primarily for military purposes (intelligence, surveillance, performing various combat missions), but their future civilian application potential is huge.

Fast-growing fleet of UAVs, along with the expansion of their application scope, poses new challenges for their developers. It is clear that a new generation of UAVs will increase demands on the accuracy of their guidance on the target. To meet these requirements is possible by optimizing the previously known guidance methods, as well as the synthesis and analysis of new methods of guidance. Solving these problems is inextricably linked with the development of the mathematical apparatus of the of optimal control theory. Algorithms of this theory allow synthesize the optimal control signal for the selected quality coefficient for a system described by differential equations.

Another option, to achieve higher navigating accuracy of UAV on the target is the option of increasing the forecasting accuracy of the dynamics of maneuvering target for existing guidance methods. Since the implementation of any existing guidance methods are based on the hypothesis of target's movement.

The analysis of researches and publications

The theory of optimal control of guidance systems has been developed for many years, built the best algorithms for information processing and control law formation. It presents a number of well-known basic methods of guidance (pursuit method, parallel and proportional guidance methods, etc.). [1; 2]. However, the solution of all these guidance methods is based on the assumption that the target is moving in straight lines and disturbances acting on the system of measurement as white noise.

Fundamental work on the principles of optimizing the control process were made by Soviet scientists – A. M. Letov, L. S. Pontryagin, V. A. Veytsel, Y. Z. Tsypkyn, R. V. Gamkrelidze, etc. and foreign - A. S. Locke, R. Isaacs, A. Brayson, Ho-Yushy, R. Bellman etc. In later works by Russian scientists V.I. Merkulov, V. N. Lyepina, V. Drohalinym, A. F. Samarin, V. P. Kharkov in addition to the already existing methods were presented modern methods of synthesis of control object optimal movement algorithms, based on the representation of processes and systems in a multidimensional state of space.

Objective – the analysis of the dependence of UAV guidance quality on the dynamics forecasting accuracy of the maneuvering target on the example of several existing guidance algorithms.

Main part

The dependence of the kinematic parameters and angles in the guidance process is presented in fig. 1.

Kinematic equations describing the changes of direction and magnitude of the range vector have the form:

$$r = V_T\cos(\theta_T - \varphi) - V_{UAV}\cos(\theta - \varphi);$$
$$r\dot{\varphi} = V_T\sin(\theta_T - \varphi) - V_{UAV}\sin(\theta - \varphi),$$

where r – a module of range vector; $\dot{r}$ – his derivatives, it makes sense of convergence speed.

The main indicator of the quality of guidance system is its accuracy, called UAV's miss on the target. For getting miss expression let's consider UAV's and target's motion in the same plane (fig. 2).

According to fig. 2 miss in a particular realization of the guidance process – is the smallest distance in relative motion “UAV – target”. The value of r is changed in the guidance process, and depends on the kinematic equations, and at the time $t = t_k$ becomes enough to be able to use payload $r_{\min} < \dot{r}(t_k) < r_{\max}$ Since miss $r(t_k)$ can be considered as a function of the kinematic parameters $(\varphi, \dot{\varphi}, r, \dot{r})$ at the final time t_k , then the appropriate control system should be formed as a control system of its end state. Final state control is based on its current forecast.

The forecasted miss vector is called a current miss $h(t)$

$$h(t) = r(t_k \mid t).$$

The vector $r(t_k \mid t)$ can be represented.

$$r(t_k \mid t) = r_{\text{UAV}}(t_k \mid t) - r_{\text{T}}(t_k \mid t),$$

where $r_{\text{T}}(t_k \mid t)$ and $r_{\text{UAV}}(t_k \mid t)$ is the corresponding forecasting of coordinate final state of goal and UAV.

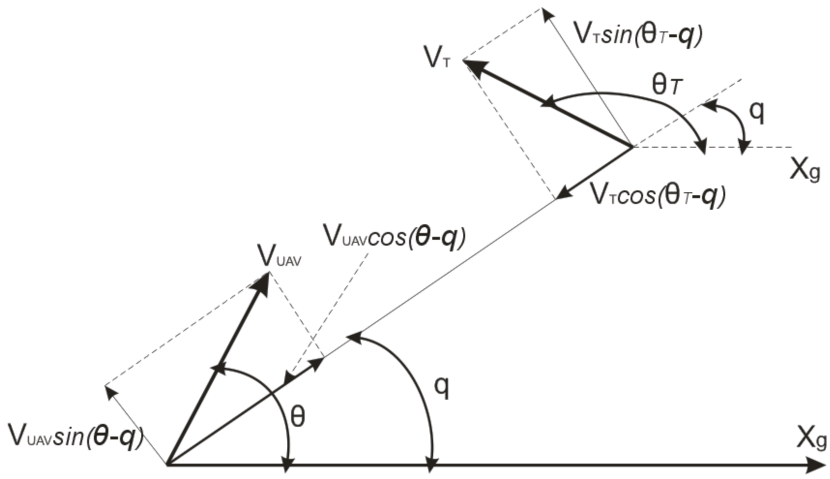

Fig. 1. A kinematics scheme of guidance

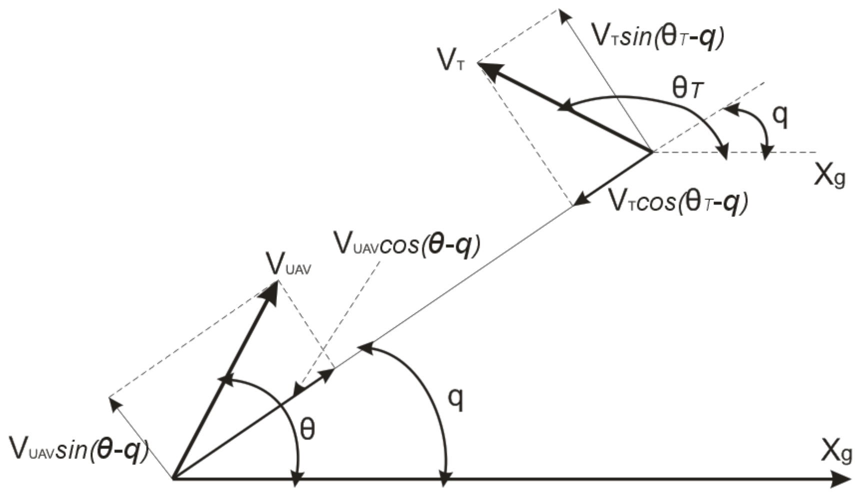

Fig. 2. A geometric definition of miss *h*

The controlling u_k should depends on these forecasts

$$u_k = u_k\{r(t_k \mid t)\} = u\{r_{\text{UAV}}(t_k \mid t) - r_{\text{T}}(t_k \mid t)\}.$$

The simplest hypothesis is obvious hypothesis that the UAV and the target moving rectilinearly and uniformly. Communication of the final state with the current determined by the expression:

$$r_{\text{UAV}}(t_k \mid t) = r_{\text{T}}(t) - V_{\text{T}}(t)(t_k - t);$$

$$r_{\text{UAV}}(t_k \mid t) = r_{\text{UAV}}(t) - V_{\text{UAV}}(t)(t_k - t),$$

where $t_k - t = \tau$ – the time left before the meeting, thus:

$$h(t) = \left[r_{\text{UAV}}(t) - r_{\text{T}}(t)\right] + \left[V_{\text{UAV}}(t) - V_{\text{T}}(t)\right]\tau = \\ = r(t) + V\tau.$$

The vector of current miss $h(t)$ is the value of $r(t)$, which has the minimum length at time $t_k = t$

$$h(t) = r(t)\sin\mu = r(t)\frac{V_q}{\sqrt{V_\varphi^2 + V_r^2}}. \qquad (1)$$

According to kinematic relations (1) $V_\varphi = \dot\varphi\, r$ and $V_r = \dot r$ can be obtained value of the miss vector

$$h(t) = \frac{\dot\varphi(t) r^2(t)}{\sqrt{(\dot\varphi r)^2 + \dot r^2(t)}}.$$

A geometric scheme of guidance is presented in a fig. 3. The initial position of the UAV shown in a point *O* and target's in a point *C*, a distance between them is r, and the angle of target's sight respectively equal to φ.

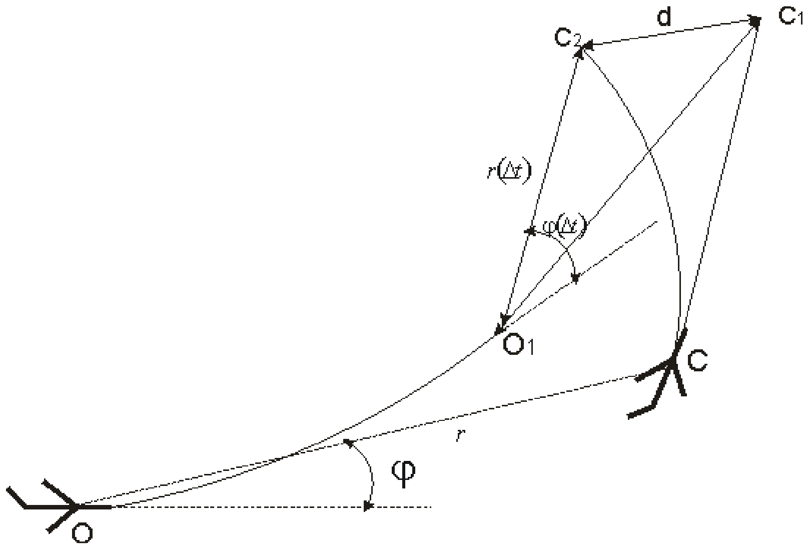

Fig. 3. A geometrical guidance scheme

In the process of applying of the guidance algorithm based on hypothesis of target's motion is done its location forecasting after time Δt. In fig. 3 forecasted target's location is in a point C_1. After applying of the guided algorithm after time Δt, the UAV moved to point O_1, while the actual location of the target is point C_2

Assume, the distance between two points C_1 and C_2 is the miss of forecasting. Respectively, at the point O_1, the distance to the target will have a value of $r(\Delta t)$ and the value of viewing angle is equal to $\varphi(\Delta t)$, and such position of the UAV and of a target is characterized by the appropriate value of the guidance miss $h(\Delta t)$, that is presented at every moment, throughout the whole guidance process, will have an appropriate value.

Fig. 4 shows the changing of a guidance miss with the time $h(\Delta t)$, throughout the whole guidance process. The dependence that designated by number 1 corresponds to the "ideal" guidance algorithm, in terms of a target's movement forecasting, i. e with the known moving of the target at the time interval Δt, when the forecasted point and the actual point are matched $C_1 = C_2$. According, the dependence, designated in (2) – is a dependence in the "real" guidance algorithm, that is shown in fig. 3.

The value that characterizes the guidance miss throughout the time interval for any guidance algorithms determined by the following formula:

$$S = \int |h(t)| dt.$$

Accordingly, we determine the prediction miss:

$$D_{progn} = \int d(t) dt.$$

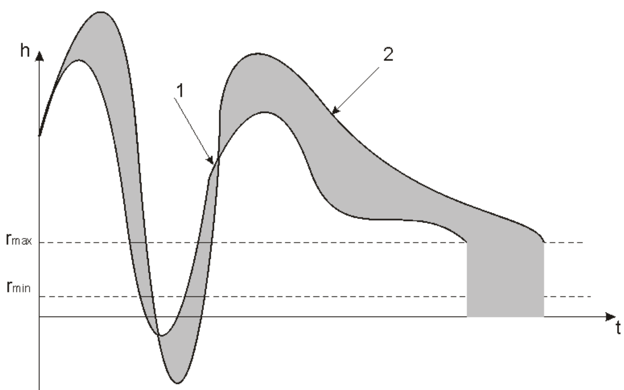

Fig. 4. The dependence of the guidance miss as a function of the time

Therefore, the efficiency criterion of forecasting methods for any guidance algorithm, we assume a value equal to the difference between the "ideal" guidance miss to the actual location point of a target

S_{fact} and a "real" guidance miss to the forecasted point S_{progn}. Graphically, this value can be represented as the difference between the area under graphs, that are shown on fig. 4 as number (1) and (2).

$$I = \Delta S = S_{fact} - S_{progn}.$$

To establish the dependence of the guidance quality of the UAV as a function of a forecasting accuracy of a maneuvering target, in case of several existing guidance algorithms, we will define the dependence of $\Delta S = f\left(D_{progn}\right)$ for different values of the forecasting interval Δt.

We are consider that UAV is a material point which motion is described in the trajectory coordinate system by a system of equations:

$$\begin{cases} \dot{V} = g\left(n_x - \sin\theta\right); \\ \dot{\theta} = \dfrac{g}{V}\left(n_y \cos\gamma_c - \cos\theta\right); \\ \dot{\Psi} = -\dfrac{g n_y \sin\gamma_c}{V\cos\theta}. \end{cases}$$

where V – a speed of the UAV; θ – an inclination angle of the trajectory; Ψ – an angle of a path; n_x, n_y – a normal and tangential acceleration accordingly; γ_c – a speedy angle of a roll; g – an acceleration of a free fall.

A target location is presented in the normal coordinate system. The trajectory and the normal coordinate system linked via an inclination angle and a path angle respectively. Therefore, to find the position of the UAV in a normal coordinate system we use the following system of equations:

$$\begin{cases} \dot{X} = V\cos\theta\cos\Psi; \\ \dot{Z} = -V\cos\theta\sin\Psi. \end{cases}$$

Since the motion model of the UAV is flat we will consider maneuvers that he is able to make in the horizontal plane. Such maneuvers may be an acceleration or slow down by changing the parameter n_x and the correct turn left or right by changing the parameter n_y and a speedy angle of roll γ_c.

Finding a dependency of the UAV guidance quality as a function of the accuracy of target's movement forecasting, we will do using two most common classical guidance methods: pursuit method and a parallel rapprochement method. A brief description of these methods is shown below.

Let make assumption, at some moment of the time a target located at the point C, and an aircraft – at the point O (fig. 5). Velocity vectors of the aircraft $\overline{V}$ and $\overline{V}_T$ of a target determine in the space some plane, which we call a plane of rapprochement. Obviously, the distance vector $\overline{r} = \overline{OC}$ also lies in this plane and makes some angle η with the velocity vector of the aircraft. This angle commonly called a forestalling angle. The angle between the distance vector and the velocity vector $\overline{V}_T$ commonly called a course angle. Denote it through η_T.

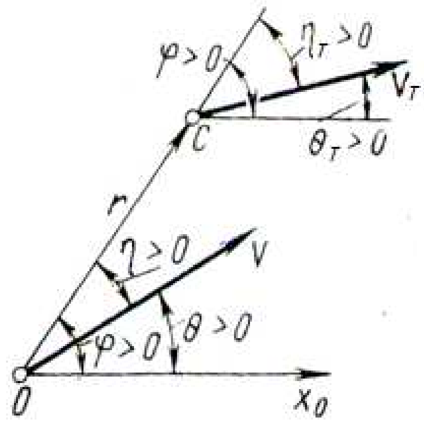

Fig. 5. A plane of rapprochement

Pursuit method lies in the fact that the velocity vector of the aircraft continuously directed at the target [3] (fig. 6). Obviously, when you guiding with this method the tangent to the trajectory coincides with the line of target's sight ($\theta = \varphi$) and forestalling angle always zero $\eta = 0$.

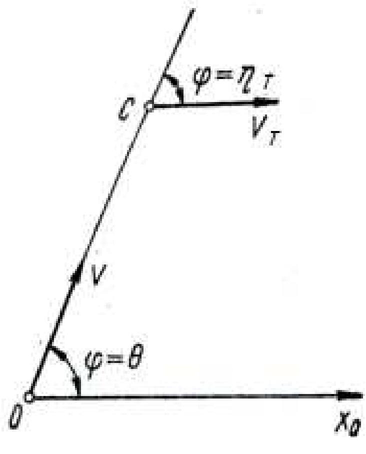

Fig. 6. A scheme of guidance by pursuit

Parallel rapprochement method lies in selection of such forestalling angle that the attacking aircraft, when guiding, moved to an instant point of a meeting with the target [3] (fig. 7). If the target maneuvers and the speed of the aircraft changes, to each timepoint t there corresponds the instant point of a meeting. Thus the angle continuously changes so that in each timepoint the condition was satisfied

$$\sin\eta(t) = \frac{V_T(t)}{V(t)}\sin\eta_T(t).$$

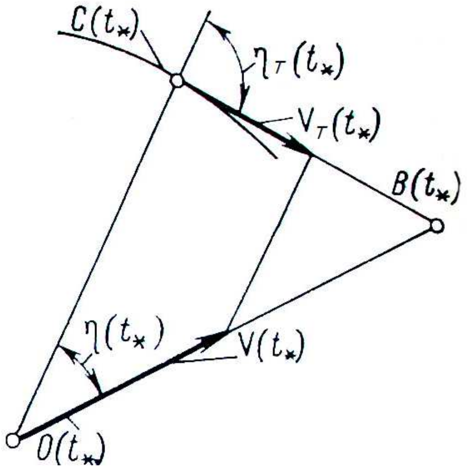

Fig. 7. Definition of an Instant point of a meeting at a method of parallel rapprochement

So, we will simulate guidance algorithms of the UAV on the target. For descriptive reasons received results we will consider a case when the target carries out a turn with an overload which changes during the whole time of guidance and which value comes nearer to maximum (near $6 \ldots 7g$). Other parameters of modeling have the following values:

Height: $H = 3000$ m.

Initial coordinates of the UAV: $X = 0$ m; $Z = 0$ m.

Initial coordinates of the purpose: $X = 1250$ m; $Z = 3500$ m.

Distance and corner of use of payload: $200\text{ m} < r < 1500\text{ m}$ and $\varphi = 8°$.

As a result of modeling for a method of a pursuit the data presented in table 1 were obtained.

Their graphical representation and the approximated line of dependence is shown in fig. 8.

Table 1

Results of modeling for a pursuit method

$\Delta t, s$	1	2	3	4	5
$D_{progn}, 10^3$ m	0,5941	1,1879	1,9569	2,8766	4,1897
$\Delta S, 10^3$ m	0,138	1,6311	2.2441	2,1692	5,9523

Similarly for a method of parallel rapprochement the data presented in table 2 were obtained.

Their graphical representation and the approximated line of dependence is shown in fig. 9.

Table 2

Results of modeling for a method of parallel rapprochement

$\Delta t, s$	1	2	3	4	5
$D_{progn}, 10^4$ m	7,6852	7,8537	8,0164	7,9029	8,3265
$\Delta S, 10^4$ m	0,7043	1,5586	2,2813	1,8365	2,8686

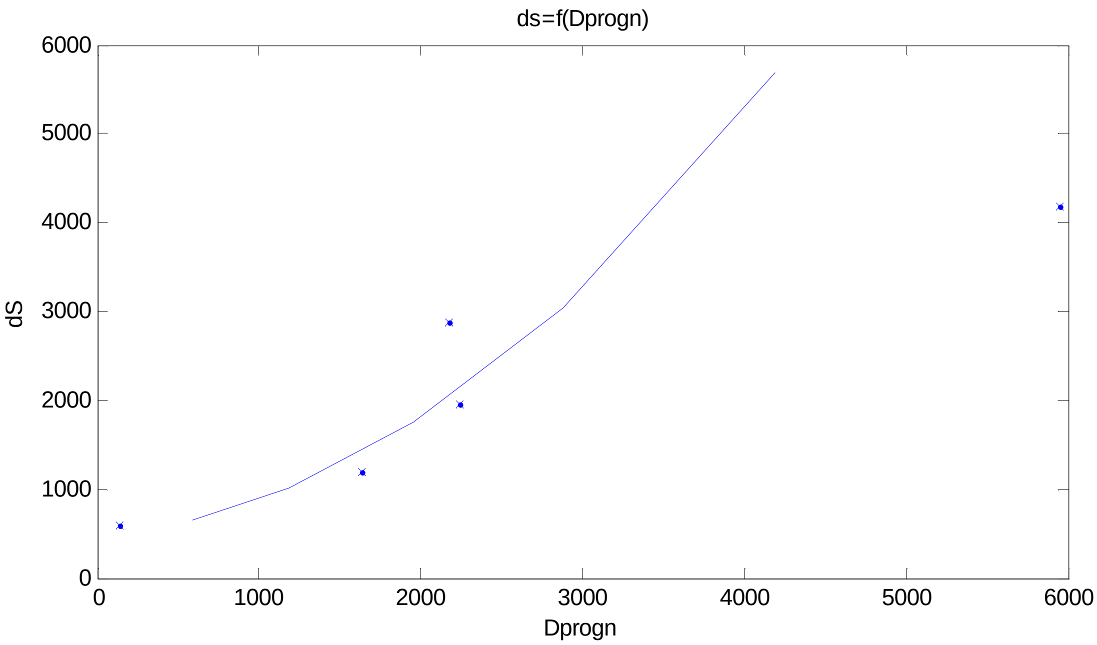

Fig. 8. $\Delta S = f(D_{progn})$ for a pursuit method

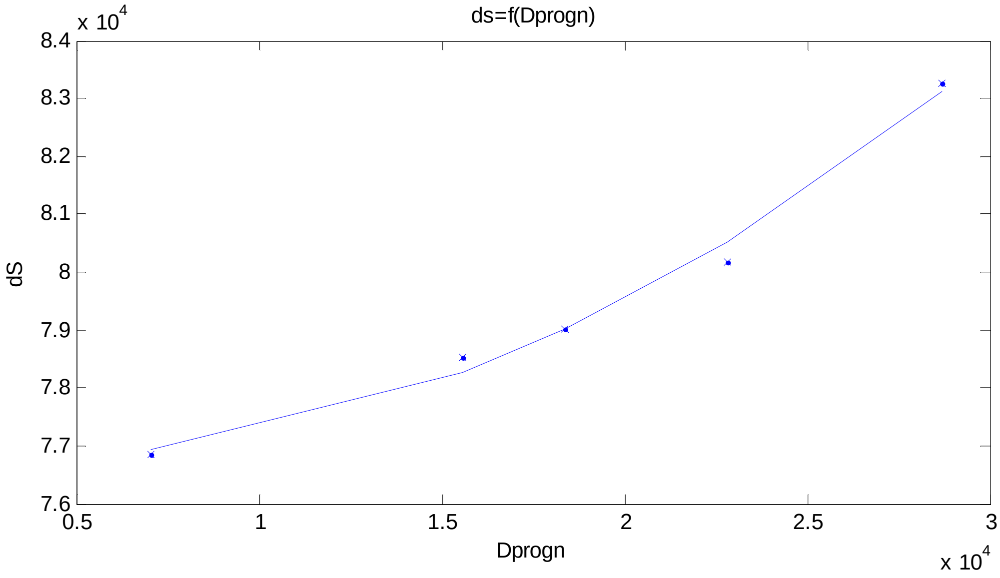

Fig. 9. $\Delta S = f\left(D_{progn}\right)$ for a method of parallel rapprochement

Conclusion

Research of dependence of guidance quality on the forecasting accuracy of movement of the maneuvering target is conducted on the example of several most widespread methods of guidance. The received results clearly demonstrate considerable influence of an error of forecasting on quality of guidance. In practice this means the possibility of quality improvement of guidance methods by increasing of forecasting accuracy.

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Received 25 November 2013

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В. П. Бочарніков, Я. В. Беженар. Аналіз залежності якості наведення БПЛА від точності прогнозування динаміки руху маневруючої цілі

Проведено дослідження залежності якості наведення від точності прогнозування руху маневруючої цілі на прикладі декількох найбільш поширених методів наведення. Отримані результати наглядно демонструють можливість в покращенні якості методів наведення шляхом підвищення точності прогнозування.

Ключові слова: якість наведення; точність прогнозування; методи наведення; безпілотний літальний апарат; гіпотези руху цілі.

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Кількість публікацій: 2.
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В. П. Бочарников, Я. В. Беженарь. Анализ зависимости качества наведения БПЛА от точности прогнозирования динамики движения маневрирующей цели

Проведено исследование зависимости качества наведения от точности прогнозирования движения, маневрирующей цели на примере нескольких наиболее распространенных методов наведения. Полученные результаты наглядно демонстрируют возможность в улучшении качества методов наведения путём повышения точности прогнозирования.

Ключевые слова: качество наведения, точность прогнозирования, методы наведения, беспилотный летательный аппарат, гипотезы движения цели.

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Направление научной деятельности: область математического моделирования и вычислительных методов.
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