Assessment of Aviation Weapons Impact on the Effectiveness of the Guarantee Algorithm for Controlling an Unmanned Aerial Vehicle in the Operation of Intercepting an Air Target

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Assessment of the Air-launched Weapons Impact on the Effectiveness of the Unmanned Aerial Vehicle Control Guaranteeing Algorithm during the Air Target Interception

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Abstract — the unmanned interceptor trajectory guaranteeing control algorithm at the stage of its guiding into the zone of air-launched weapons use has been obtained. The results of the simulation reflecting the degree of impact of the unmanned aerial vehicle's maneuverable capabilities on it achieving positional advantage at various options of air-launched weapons location on the opposing aerial vehicles are shown.

Keywords — unmanned aerial vehicle, guaranteeing control, air-launched weapons, efficiency.

INTRODUCTION

Currently, the active use of systems with unmanned aerial vehicles (UAVs) to solve various tasks is the global trend [1]. However, the creation of UAVs for interception of aerial targets is considered by experts as one of the promising functional areas of unmanned aviation. Also, the absence of a pilot on board of an attacking UAV increases its dynamic capabilities (range of allowable overloads and speeds) because of the control of aerodynamic forces [2, 3].

Work on unmanned attack fighters is already underway in several world's major economies. For example, a spokesperson for the U.S. Defense Advanced Research Projects Agency (DARPA) said in 2010 that this agency had been already completing the creation of new UAV-fighters (the Peregrine-Killer UAV project) that would be capable "to solve the task of destroying of its kind — other miscellaneous UAVs." [4]. Another example is the unmanned fighter with artificial intelligence currently being created as part of a partnership between Boeing and the Australian Department of Defense. The result of this collaboration will be the creation of a demonstration model that will be used for the development of Boeing's new unmanned platform [5]. The Scat UAV project, which was developed by the Russian Aircraft Corporation "MiG", was one of the most promising projects for Russia. This vehicle was manufactured using the "flying wing" configuration without tail assembly, much of the design of the UAV is made of composites. The next step in the creation of an unmanned interceptor-fighter was the development by RAC "MiG" of cruise missiles long-range interception system to increase the effectiveness of countering a massive global strike of the enemy with subsonic cruise missiles and unmanned aerial vehicles.

Currently, it is necessary to create supermaneuverable aerial vehicles that can change the position of reference lines in space without changing the direction of flight to intercept air targets. Tactically, supermaneuverability is expected to significantly improve the combat efficiency and survivability of the aircraft. The results of system studies and tests conducted in Germany and the United States using a semi-scale simulation complex showed that a supermaneuverable aircraft is at least twice as effective in close air combat as the conventional one. These potential advantages of supermaneuverable aircraft can only be implemented with adequate dynamism of the information and control system and weapons, the dynamic properties of which are now real restrictions of super-maneuverable aerial vehicles combat capabilities. The desire to have an aircraft that implements greater angular speed values than an enemy fighter is explained by the ability to be the first to take a position to use weapons [7].

The main combat task of the fighter aviation guidance system — air target kill — is carried out in several stages, during which more specific tasks are solved:

- Flight to the target area;
- Guiding the fighter into the weapon use zone;
- Weapon use;
- Break.

The aerial targeting system should ensure that UAVs are guided into the region of space from which it is possible to detect and capture intercepted targets by certain onboard systems of UAVs or into the weapons use area.

Air-to-air missiles are used in the final stage of air combat, which consists of maneuver towards the target, aiming and launching missiles. All types of aerial vehicles can be considered as targets: aircraft, helicopters, cruise, and nonstrategic ballistic missiles, UAVs, and miscellaneous aeronautic vehicles. Attack with all-aspect missiles is most often carried out in the front hemisphere (FHS) and is characterized by fluidity due to the high speed of closing. Attack with short-range weapons is most often carried out on an intensely maneuvering target in the rear hemisphere (RHS). Analysis of the most important indicators of the main foreign and domestic missiles of the class in question shows that all of them, more often than not, have combined guidance systems, which provide greater self-sustainment and, in turn, increase the survivability of a fighter, as it allows it to make evasion maneuvers, get out of the danger zone or attack other targets.

All this points to the feasibility of developing an unmanned interceptor trajectory control algorithm based on a game approach that provides the creation of the UAV-interceptor trajectory guaranteeing control.

This article will deal with of UAV-interceptor trajectory control guaranteeing algorithm at the stage of the fighter's guidance into the weapon use zone, which ends with the preparation of missiles for launch, as well as an assessment of the impact of air-launched weapons (ALW) on the effectiveness of the developed algorithm [8-10].

THE MATHEMATICAL STATEMENT OF THE TASK OF UAV'S TRAJECTORY GUARANTEEING CONTROL DURING AIR TARGET INTERCEPTION

The paper will consider the most difficult stage of guidance — guidance of the fighter into the weapon use zone. The main challenge for this stage is to ensure that the UAV-interceptor is in position, for which the use of the ALW is as effective as possible. The aim of further discussion is to solve a task to create UAV trajectory control specifically for this stage.

An illustration of the statement of the task of UAV evading the enemy's attack is shown in Fig. 1. Let's enter the designations used in the further mathematical statement of the task: *a* — scout/attack UAV, the purpose of which is to evade the enemy's attack (UAV-interceptor); *b* — UAV-interceptor (presumptive enemy). UAVs are material points state vectors of which contain 6 components: three coordinates (*X*, *Y*, *Z*) setting their attitude in the starting coordinates system *OXYZ*, associated with the coordinates of departure airfield, and three components of the velocity vector (V_X, V_Y, V_Z).

Let's take into account that the air fight takes place in the conditions of full information contact between the enemies, i.e. each of the UAVs participating in the duel has information about the position and speed of the enemy at any given time.

Let's introduce the following designations in respect of the situation in question:

$$\boldsymbol{R(t)} = \left(\boldsymbol{X_a, Y_a, Z_a, V_{Xa}, V_{Ya}, V_{Za}}\right)^{\boldsymbol{m}};$$

$$\boldsymbol{S(t)} = \left(\boldsymbol{X_b, Y_b, Z_b, V_{Xb}, V_{Yb}, V_{Zb}}\right)^{\boldsymbol{m}} -$$

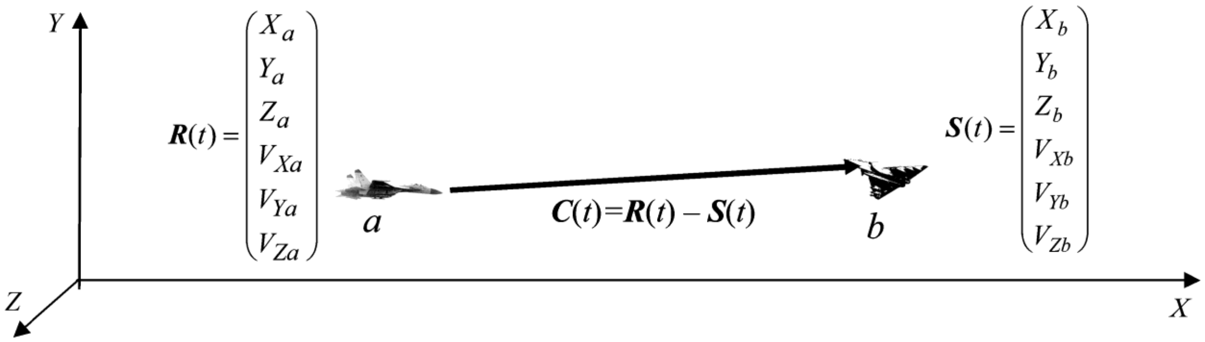


Fig. 1. An illustration of the statement of the task of UAV's trajectory control

vectors of the current state of the evading UAV and UAV-interceptor in the starting coordinate system *OXYZ*;

Then the point in the six-dimensional space of the relative state parameters of the opposing UAVs is set by a vector size (6X1). $\boldsymbol{C(t) = R(t) - S(t)}$ Let's assume that the closing process of evading UAV and UAV-interceptor takes place at the finite time interval $[\boldsymbol{0,\ T}]$.

It is assumed that the closing process of the UAV-interceptor and the target takes place at the finite time interval $[\boldsymbol{0,T}]$. At the same time, the vector $\mathbf{C}^1 = \mathbf{R}^1(T) - \mathbf{S}^1(T) = \left(C_1^1, C_2^1, C_3^1, C_4^1, C_5^1, C_6^1\right)^{\mathrm{T}}$ sets in relative parameters space a point that is "perfect" in terms of the interests of the UAV-interceptor, when it occupies a tactically advantageous position relative to the enemy aircraft that provides an advantage in the subsequent missile attack. As a result, the purpose of UAV-interceptor control can be presented with the following condition: $\mathbf{C}(T) = \mathbf{R}(T) - \mathbf{S}(T) \rightarrow \mathbf{C}^1$. Vector $\mathbf{C}^2 = \mathbf{R}^2(T) - \mathbf{S}^2(T) = \left(C_1^2, C_2^2, C_3^2, C_4^2, C_5^2, C_6^2\right)^{\mathrm{T}}$ sets in the relative parameters space a point that is "perfect" in terms of the interests of the enemy aircraft, i.e. moving to this point provides the enemy with an advantage in the subsequent missile attack of the UAV-interceptor. In this case, the aim of enemy aircraft control can be presented with a condition

$\mathbf{C}(T) = \mathbf{R}(T) - \mathbf{S}(T) \rightarrow \mathbf{C}^2$.

The specific selection of points $\mathbf{C}^1$, $\mathbf{C}^2$ is carried out at the pre-flight planning stage with allowances made for the type of own UAV and the enemy's UAV confronting it, the characteristics of their missile weapons, detecting equipment, dynamic capabilities, etc.

Let's consider a three-dimensional vector, the components of which are acceleration on the respective axes of the starting coordinate system, as a control vector of the attacked UAV $\boldsymbol{U} = (\boldsymbol{a}_{Xa}, \boldsymbol{a}_{Ya}, \boldsymbol{a}_{Za})^{\boldsymbol{m}}$. Next, each of the components of acceleration is converted to components of overload in the associated coordinates system, which provide the possibility of maneuvering.

The UAV-interceptor control vector has a similar structure $\boldsymbol{V} = (\boldsymbol{a}_{Xb}, \boldsymbol{a}_{Yb}, \boldsymbol{a}_{Zb})^{\boldsymbol{m}}$. Differentiation of the vector component $\boldsymbol{C}(t)$ will lead to a differential equation describing the dynamics of the change in the relative state of conflicting aircraft during their maneuvering:

$$\frac{d\boldsymbol{C}(t)}{dt} = \mathbf{A}\boldsymbol{C}(t) + \mathbf{B}\boldsymbol{U}(t) + \mathbf{D}\boldsymbol{V}(t), \qquad (1)$$

where **A**, **B**, **D** are constant matrices of appropriate sizes with components:

$$\mathbf{A} = \begin{pmatrix} 0&0&0&1&0&0 \\ 0&0&0&0&1&0 \\ 0&0&0&0&0&1 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&0 \end{pmatrix}; \mathbf{B} = \begin{pmatrix} 0&0&0 \\ 0&0&0 \\ 0&0&0 \\ 1&0&0 \\ 0&1&0 \\ 0&0&1 \end{pmatrix}; \mathbf{D} = \begin{pmatrix} 0&0&0 \\ 0&0&0 \\ 0&0&0 \\ -1&0&0 \\ 0&-1&0 \\ 0&0&-1 \end{pmatrix} \qquad (2)$$

For a linear dynamic system (1), (2) there is a game task with two participants pursuing different interests:

- the first player (attacked UAV) by selecting the control $\boldsymbol{U}(t)$ seeks to convert the system (1) for a given time T from the initial state $\boldsymbol{C}(0)$ to the final state $\boldsymbol{C}(T)$ with a minimal deviation from the "perfect" state of $\boldsymbol{C}^{\boldsymbol{1}}$ with control restrictions;

- the second player (UAV-interceptor) by selecting the control $\boldsymbol{V}(t)$ seeks to convert the system (1) for a given time T from the initial state $\boldsymbol{C}(0)$ to the final state $\boldsymbol{C}(T)$ with minimal deviation from the "perfect" state $\boldsymbol{C}^{\boldsymbol{2}}$ with control restrictions.

Let's note that in the conditions of real air combat, the parameters of relative movement of opponents have natural restrictions set by the inequality system:

$$C_{i\min} \le C_i \le C_{i\max}, \quad i = \overline{1, 6}, \qquad (3)$$

where the values $\boldsymbol{C}_{\boldsymbol{i}\min}$, $\boldsymbol{C}_{\boldsymbol{i}\max}$ are determined by the dynamic capabilities of the opposing UAV and the visibility conditions of the on-board radar stations (RS) providing information on the enemy's position and speed.

Similar restrictions are imposed on control:

$$U_{i\,\min} \le U_i \le U_{i\,\max};\ V_{i\,\min} \le V_i \le V_{i\,\max},\ i = 1, 2, 3.$$

The presence of such objective restrictions allows to make the transition from the physical parameters of the relative motion of the attacked UAV and UAV-interceptor to their normalized analogs based on a linear transformation of the following form [14]:

$$\tilde{C}_i(t) = \frac{C_i(t) - 0.5(C_{i\,\min} + C_{i\,\max})}{0.5(C_{i\,\max} - C_{i\,\min})}, \quad i = \overline{1, 6}. \quad (4)$$

Given the normalizing transformation (4), model (1) preserves the linear structure and can be described by the differential equation

$$\frac{d\tilde{\boldsymbol{C}}(\boldsymbol{t})}{\boldsymbol{dt}} = \tilde{\boldsymbol{A}}\tilde{\boldsymbol{C}}(\boldsymbol{t}) + \tilde{\boldsymbol{B}}\tilde{\boldsymbol{U}}(\boldsymbol{t}) + \tilde{\boldsymbol{D}}\tilde{\boldsymbol{V}}(\boldsymbol{t}), \qquad (5)$$

all components of which are given in [9]. Moreover, the game task formulated with reference to the model (1) fully preserves its content.

Considering the interests of players, let's use the following criterion as a criterion in the considered game task of controlling a linear dynamic system (5):

$$\begin{aligned} \boldsymbol{J}(\tilde{\boldsymbol{U}}, \tilde{\boldsymbol{V}}) = \int_0^T \left(-\tilde{\boldsymbol{U}}^{\boldsymbol{m}}(\boldsymbol{t})\, \boldsymbol{Q}\, \tilde{\boldsymbol{U}}(\boldsymbol{t}) + \tilde{\boldsymbol{V}}^{\boldsymbol{m}}(\boldsymbol{t})\, \boldsymbol{W}\, \tilde{\boldsymbol{V}}(\boldsymbol{t}) \right) \boldsymbol{dt} + \\ + \left(\tilde{\boldsymbol{C}}(\boldsymbol{T}) - \tilde{\boldsymbol{C}}^{\boldsymbol{1}}\right)^{\boldsymbol{m}} \boldsymbol{G}^{\boldsymbol{1}} \left(\tilde{\boldsymbol{C}}(\boldsymbol{T}) - \tilde{\boldsymbol{C}}^{\boldsymbol{1}}\right) - \\ - (\tilde{\mathbf{C}}(T) - \tilde{\mathbf{C}}^2)^{\mathrm{T}} \mathbf{G}^2 (\tilde{\mathbf{C}}(T) - \tilde{\mathbf{C}}^2), \end{aligned} \qquad (6)$$

where **Q**, **W** are positive-definite matrices assumed to be preassigned; the elements of these matrices are defined more accurately at the stage of simulating the operation of the algorithm to ensure control restrictions;

$\mathbf{G}^1$ is a weight matrix that determines how strictly the requirements for certain parameters of the relative motion of the UAV-interceptor must be adhered to guide $\tilde{\mathbf{C}}^1$ to the "perfect" point. The weight matrix $\mathbf{G}^2$ has the same meaning for the enemy aircraft. The specific form of these matrices depends mainly on the type of air-launched weapons with which the conflicting aircraft are equipped. By choosing the matrix elements $\mathbf{G}^1$, $\mathbf{G}^2$, adaptation of trajectory control algorithms for aircraft participating in the air duel with an account of specifics of weapons located on them is achieved.

CREATION OF UAV'S TRAJECTORY GUARANTEEING CONTROL DURING THE AIR TARGET INTERCEPTION

Taking into account the criterion (6), the control $\tilde{\mathbf{U}}^1$ that ensures the minimum of the above criterion in the worst-case scenario of the enemy aircraft actions $\tilde{\mathbf{V}}^1$ is the optimal one, from the point of view of UAV-interceptor's interests:

$$J(\tilde{\mathbf{U}}^1, \tilde{\mathbf{V}}^1) = \min_{\tilde{\mathbf{U}}} \max_{\tilde{\mathbf{V}}} J(\tilde{\mathbf{U}}, \tilde{\mathbf{V}}).$$

From the point of view of the enemy's interests, the optimal solution $\tilde{\mathbf{U}}^2$, $\tilde{\mathbf{V}}^2$ of the game task (5), (6) is such that the following condition is met:

$$J(\tilde{\mathbf{U}}^2, \tilde{\mathbf{V}}^2) = \max_{\tilde{\mathbf{V}}} \min_{\tilde{\mathbf{U}}} J(\tilde{\mathbf{U}}, \tilde{\mathbf{V}}).$$

Therefore, within the criterion (6), the interests of the players are strictly opposite: the first player seeks to minimize the criterion, and the second one to maximize it. Moreover, everyone presumes that the enemy will act most unfavorably.

In the theory of differential games, it was proved [11] that for linear systems with a quadratic criterion, which is a system (5) with criterion (6), a saddle point always exists, i.e. there is a solution that is optimal from the point of view of the interests of both conflicting parties:

$$J(\tilde{\mathbf{U}}^*, \tilde{\mathbf{V}}^*) = \min_{\tilde{\mathbf{U}}} \max_{\tilde{\mathbf{V}}} J(\tilde{\mathbf{U}}, \tilde{\mathbf{V}}) = \max_{\tilde{\mathbf{V}}} \min_{\tilde{\mathbf{U}}} J(\tilde{\mathbf{U}}, \tilde{\mathbf{V}})$$

In [17], a solution to this problem is given based on the Bellman dynamic programming method, provided that the duration of the closing process T of the conflicting aircraft is specified. Such a solution is described by the relations:

$$\begin{aligned} \tilde{\boldsymbol{U}}^*\left(\tilde{\boldsymbol{C}}, t\right) &= -\mathbf{Q}^{-1}\mathbf{B}^{\mathrm{T}}\left(\mathbf{P}(t)\tilde{\boldsymbol{C}}(t) + \boldsymbol{q}(t)\right); \\ \tilde{\boldsymbol{V}}^*\left(\tilde{\boldsymbol{C}}, t\right) &= -\mathbf{W}^{-1}\mathbf{D}^{\mathrm{T}}\left(\mathbf{P}(t)\tilde{\boldsymbol{C}}(t) + \boldsymbol{q}(t)\right). \end{aligned} \quad (8)$$

Relations (8) allow finding the control $\tilde{\boldsymbol{U}}^*$ of the trajectory of the attacked UAV depending on its current state relative to the UAV-interceptor specified by the vector $\tilde{\boldsymbol{C}}(t)$ for any time point t, provided that the enemy, pursuing its interests, will perform the maneuver best for it with allowances made for control $\tilde{\boldsymbol{V}}^*$. In this connection the matrix $\mathbf{P}=\mathbf{P}(t)$ with the size of (6×6) and the vector $\boldsymbol{q} = \boldsymbol{q}(t)$ with the size of (6×1) present in the formula (8) are determined by solving differential equations:

$$\begin{aligned} &\dot{\boldsymbol{P}} = -\boldsymbol{P}\tilde{\mathbf{A}}\text{-}\tilde{\boldsymbol{A}}^{\boldsymbol{T}}\boldsymbol{P} + \boldsymbol{P}(\tilde{\boldsymbol{B}}\boldsymbol{Q}^{-1}\tilde{\boldsymbol{B}}^{\boldsymbol{T}} + \tilde{\boldsymbol{D}}\boldsymbol{W}^{-1}\tilde{\boldsymbol{D}}^{\boldsymbol{T}})\boldsymbol{P}, \\ &\boldsymbol{P}(\boldsymbol{T}) = \boldsymbol{G}^1 - \boldsymbol{G}^2, \\ &\dot{\boldsymbol{q}} = ((\tilde{\boldsymbol{B}}\boldsymbol{Q}^{-1}\tilde{\boldsymbol{B}}^{\boldsymbol{T}} + \tilde{\boldsymbol{D}}\boldsymbol{W}^{-1}\tilde{\boldsymbol{D}}^{\boldsymbol{T}})\boldsymbol{P}\text{-}\tilde{\boldsymbol{A}})^{\boldsymbol{T}}\boldsymbol{q}, \\ &\boldsymbol{q}(\boldsymbol{T}) = \boldsymbol{G}^2\boldsymbol{C}^2 - \boldsymbol{G}^1\boldsymbol{C}^1. \end{aligned} \quad (9)$$

Let's note that the differential equations (9) include constant matrices $\tilde{\mathbf{A}}$, $\tilde{\mathbf{B}}$, $\tilde{\mathbf{D}}$, $\mathbf{Q}$, $\mathbf{W}$ present in the model (5) and in the expression for the criterion (6). Therefore, the dependences $\mathbf{P}(t)$, $\boldsymbol{q}(t)$ can be calculated in advance for any time point $t \in [0, T]$, including the time point $t = 0$, corresponding to the moment of the closing start, and can be included in the algorithm as known functions.

The matrices $\mathbf{Q}, \mathbf{W}$ present in the expression for the criterion (6) are formed in such a way so that following inequalities hold for any moment $t \in [0, T]$ and any current vector $\tilde{\boldsymbol{C}}(t)$, components of which satisfy the conditions $-1 \le \tilde{\boldsymbol{C}}_i(\boldsymbol{t}) \le 1$, $\boldsymbol{i} = \overline{\boldsymbol{1}, \boldsymbol{6}}$:

$$\begin{aligned} -\boldsymbol{1} &\le -\mathbf{Q}^{-1}\mathbf{B}^m\left(\mathbf{P}(\boldsymbol{t})\tilde{\boldsymbol{C}}(\boldsymbol{t}) + \boldsymbol{q}(\boldsymbol{t})\right) \le \boldsymbol{1}; \\ -\boldsymbol{1} &\le -\mathbf{W}^{-1}\mathbf{D}^m\left(\mathbf{P}(\boldsymbol{t})\tilde{\boldsymbol{C}}(\boldsymbol{t}) + \boldsymbol{q}(\boldsymbol{t})\right) \le \boldsymbol{1}. \end{aligned}$$

The given optimal solution (8) is used in the future as a "reference" one with allowances made for relations (9), which allows forming an algorithm for UAV evasion on its base, provided that there are no restrictions on the duration of the closing process T. In paper [9], a method to determine the optimal duration of the closing process, which meets the requirements for the existence of a saddle point in the game task under consideration, was proposed. Here, the determined calculated duration of the closing process T^* is used to calculate the controls $\tilde{U}^*(\tilde{C})$, $\tilde{V}^*(\tilde{C})$ corresponding to the current normalized relative state $\tilde{C}(t)$ of the attacked UAV and UAV-interceptor.

Let's consider the results of the simulation of the duel between UAV-interceptor and an enemy UAV with various ALW options located on them.

EVALUATION OF POSITIONAL ADVANTAGE GAINED BY AN ATTACKING UAV-INTERCEPTOR FOR VARIOUS ALW CONFIGURATIONS

To assess the operability of the proposed algorithm, a simulation was carried out, the purpose of which is to assess the positional advantage that UAV-interceptor gains with allowances made for its maneuvering capabilities and the ALW located on it. An advanced vehicle was considered as a prototype of a UAV-interceptor [6]. The MQ-9 Reaper combat UAV with full-scale production in the USA was considered as a prototype of enemy UAV.

In the simulation process, the vector $\mathbf{C}(0)$, which sets the relative initial state of the UAV and the target at the moment of the closing start, was randomly selected within the given area $\mathbf{W}_C = \{\mathbf{C}(0) : |C_i(0)| \le C_{i\max}(0), i = \overline{1,6}\}$.

The maximum target capture range of the onboard radar was taken as the values $C_{i\max}(0), i = \overline{1,3}$ characterizing the relative position of the UAV-interceptor and the target according to the coordinates X,Y,Z of the starting coordinate system, taking into account the requirements of the information contact:

$$C_{1\max}(0) = 13.5 km;$$
$$C_{2\max}(0) = 7.5 km;$$
$$C_{3\max}(0) = 2.5 km$$

Components $C_{i\max}(0), i = \overline{4,6}$ determine the maximum allowable closing speeds of the UAV-interceptor and the target, which were assumed equal.

$$C_{4\max}(0) = 900 km/h$$
$$C_{5\max}(0) = 300 km/h$$
$$C_{6\max}(0) = 100 km/h$$

The area $\mathbf{W}_C$ was used in the further procedure for normalizing the parameters of the relative motion of the UAV-interceptor and the target.

The paper assesses the impact of the AWL on the efficiency of the obtained onboard UAV control algorithm for three cases (UAV interceptor AWL — enemy UAV AWL):

1. Air-to-air air-launched missile — aviation artillery weapon

$$\mathbf{C}^1 = \begin{pmatrix} 4{,}900\,\text{m} \\ 1{,}500\,\text{m} \\ 250\,\text{m} \\ 69.44\,\text{m/s} \\ 11.11\,\text{m/s} \\ 1.39\,\text{m/s} \end{pmatrix}, \mathbf{C}^2 = \begin{pmatrix} 200\,\text{m} \\ 150\,\text{m} \\ 25\,\text{m} \\ 20.83\,\text{m/s} \\ 5.55\,\text{m/s} \\ 0.69\,\text{m/s} \end{pmatrix};$$

2. Aircraft artillery weapon — air-to-air air-launched missile

$$\mathbf{C}^1 = \begin{pmatrix} 200\,\text{m} \\ 175\,\text{m} \\ 25\,\text{m} \\ 27.77\,\text{m/s} \\ 5.55\,\text{m/s} \\ 0.69\,\text{m/s} \end{pmatrix}, \mathbf{C}^2 = \begin{pmatrix} 5{,}250\,\text{m} \\ 1{,}750\,\text{m} \\ 250\,\text{m} \\ 41.67\,\text{m/s} \\ 12.5\,\text{m/s} \\ 3.47\,\text{m/s} \end{pmatrix};$$

3. The air-to-air air-launched missile with the heat-seeking head (target seeker device) —air-to-air air-launched missile with a semi-active radar target seeker device.

$$\mathbf{C}^1 = \begin{pmatrix} 4{,}900\,\text{m} \\ 1{,}500\,\text{m} \\ 250\,\text{m} \\ 69.44\,\text{m/s} \\ 11.11\,\text{m/s} \\ 1.39\,\text{m/s} \end{pmatrix}, \mathbf{C}^2 = \begin{pmatrix} 5{,}250\,\text{m} \\ 1{,}750\,\text{m} \\ 250\,\text{m} \\ 41.67\,\text{m/s} \\ 12.5\,\text{m/s} \\ 3.47\,\text{m/s} \end{pmatrix};$$

The effectiveness of guaranteeing control was assessed on the tactical advantage that UAV-interceptor gains after it is guided into the ALW use zone. To do this, at the time of completion of the closing process T, the distances $d_1(T), d_2(T)$ that characterize in the space of normalized relative coordinates the proximity of each of the conflicting aircraft to the corresponding "perfect" point, moving to which provides it with a tactical advantage in terms of subsequent use of weapons, were calculated. These distances are the terminal components of criterion (6):

$$d_1(T) = (\tilde{\mathbf{C}}(T) - \tilde{\mathbf{C}}^1)^{\mathrm{T}} \mathbf{G}^1 (\tilde{\mathbf{C}}(T) - \tilde{\mathbf{C}}^1)$$
$$d_2(T) = (\tilde{\mathbf{C}}(T) - \tilde{\mathbf{C}}^2)^{\mathrm{T}} \mathbf{G}^2 (\tilde{\mathbf{C}}(T) - \tilde{\mathbf{C}}^2) \qquad (10)$$

Per (10), the inequality $d_1(T) < d_2(T)$ indicates that the UAV-interceptor at the time of completion of the closing process had acquired a tactical advantage in terms of the subsequent attack on the target since its terminal state is consistent with the conditions for the effective use of weapons in a greater degree.

The maneuverability of the UAV-interceptor was evaluated on the following tactically significant indicators [12] calculated in the starting coordinate system:

- acceleration response characterizing the speed of UAV acceleration to the required speed; the effect is manifested through the value of axial acceleration a_X;
- ascensional rate determining the maneuverability of a UAV in a vertical plane; the effect is manifested through the value of the normal acceleration a_Y;
- agility reflecting the ability of UAV to perform horizontal maneuvers; the effect is manifested through the lateral acceleration value a_Z.

To study the effect of ALW on achieving a positional advantage in air combat conditions, three series of computational experiments were conducted for various types of ALW located on opposing UAV for each of the three cases presented above, each of which included simulation of 150 enemy movement trajectories corresponding to different randomly selected initial states $\boldsymbol{C}(0) \in W_C$. In all cases, restrictions on the control of the UAV-interceptor, by analogy with [14], were set in the form of $|\boldsymbol{U}_i| \le \boldsymbol{U}_{i\,\max}$, $\boldsymbol{i} = \overline{\boldsymbol{1, 3}}$, where $\boldsymbol{U}_{1\,max} = 2\boldsymbol{g}$, $\boldsymbol{U}_{2\,max} = 4\boldsymbol{g}$, $\boldsymbol{U}_{3\,max} = \boldsymbol{g}$, g is the acceleration of gravity.

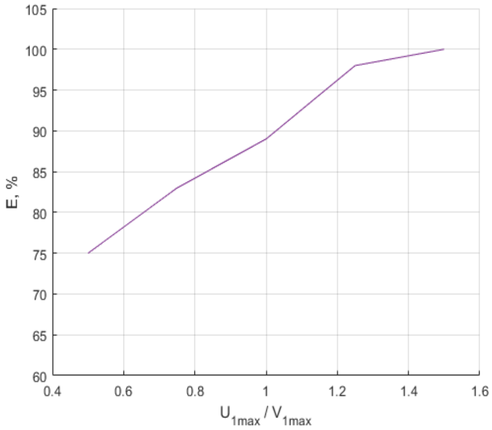
In the process of maneuvering, the opposing UAV used the optimal control laws $\tilde{\boldsymbol{U}}^*(\tilde{\boldsymbol{C}})$, $\tilde{\boldsymbol{V}}^*(\tilde{\boldsymbol{C}})$, calculated using formulas (8), (9), based on the optimal duration of the closing process T^* determined by the conditions for the existence of a saddle point [9]. First, the influence of the acceleration response of an attacked UAV on the positional advantage gained by it was investigated. For this, the ratio $U_{1\max} / V_{1\max} = \boldsymbol{k}$, k = 0.5, 0.75, 1.0, 1.25, 1.5 was varied during the simulation process.

The value $\boldsymbol{k} < \boldsymbol{1}$ indicates that the UAV-interceptor has a maneuverable advantage in terms of acceleration response indicator. The value $\boldsymbol{k} = \boldsymbol{1}$ is a sign that conflicting UAVs have comparable maneuverable capabilities on this indicator; $\boldsymbol{k} > \boldsymbol{1}$ indicates on the maneuverable advantage of the attacked UAV. It was assumed that the attacked UAV and UAV-interceptor possess comparable maneuverable capabilities on ascensional rate and agility, i.e. $\boldsymbol{U}_{2max} = \boldsymbol{V}_{2max}$, $\boldsymbol{U}_{3max} = \boldsymbol{V}_{3max}$.

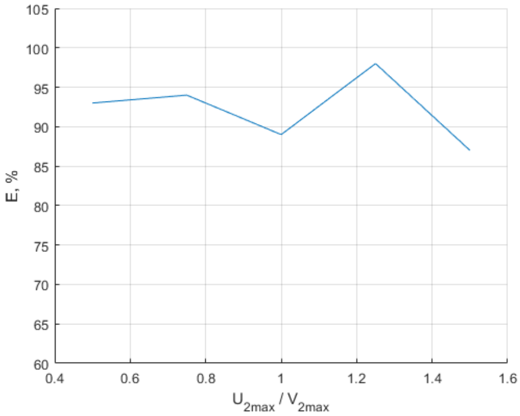
For each fixed value of $\boldsymbol{U}_{1max} / \boldsymbol{V}_{1max}$, random implementations $\boldsymbol{C}^j(0) \in W_C$, $\boldsymbol{j} = \boldsymbol{1}, ..., \boldsymbol{150}$ were generated per the uniform distribution, which set the relative initial values of the attacked UAV and the UAV-interceptor, and the trajectories were calculated $\tilde{\boldsymbol{C}}^j(t)$, $t \in [\boldsymbol{0}, \boldsymbol{T}^*]$, $\boldsymbol{j} = \boldsymbol{1}, ..., \boldsymbol{150}$ reflecting their relative position during the maneuvering. For this, equations (5) were integrated with control laws (8), (9). As a result, the implementations were obtained

$$d_{1j} = \left(\tilde{\boldsymbol{C}}^j(T^*) - \tilde{\boldsymbol{C}}^1\right)^m \mathbf{G}^1 \left(\tilde{\boldsymbol{C}}^j(T^*) - \tilde{\boldsymbol{C}}^1\right),$$
$$d_{2j} = \left(\tilde{\boldsymbol{C}}^j(T^*) - \tilde{\boldsymbol{C}}^2\right)^m \mathbf{G}^2 \left(\tilde{\boldsymbol{C}}^j(T^*) - \tilde{\boldsymbol{C}}^2\right),$$

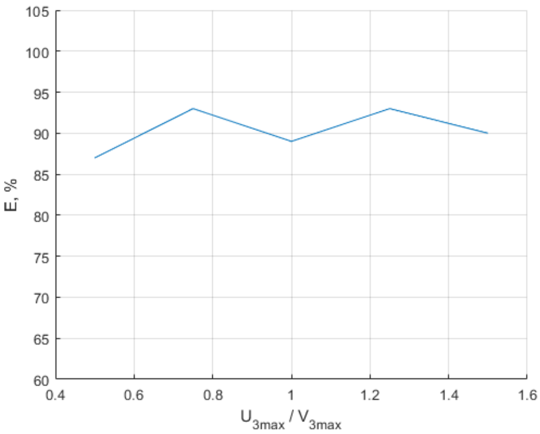
quantitatively expressing the degree of proximity of conflicting UAVs to their own "perfect" points $\tilde{\boldsymbol{C}}^1, \tilde{\boldsymbol{C}}^2$ at the time of completion of the maneuvering process. Similarly, the effect of other indicators of the maneuverability of its UAV on its positional advantage was investigated.



a)



b)

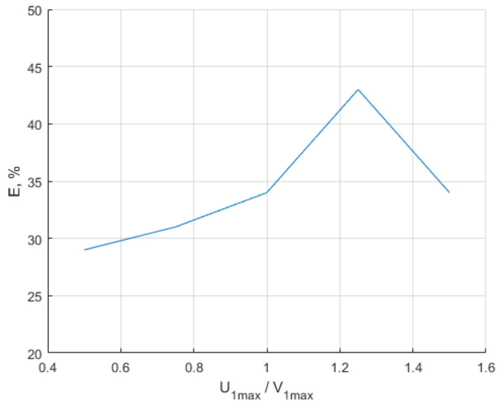


c)

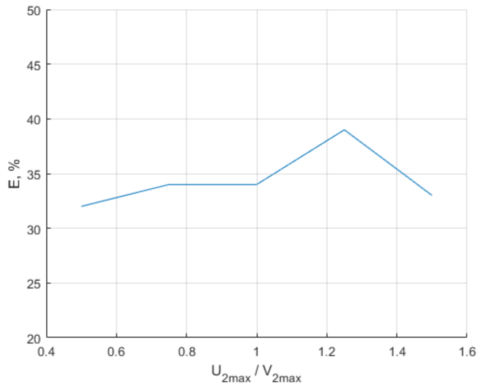
Fig. 2. Graphs of the influence of acceleration response (a), ascensional rate (b) and agility (c) of an own UAV compared to an enemy's UAV on the positional advantage it achieves for 1 case of ALW location on conflicting UAVs

Figure 2 shows the graphs of the influence of acceleration response (2, a), ascensional rate (2, b) and agility (2, c) of own UAV compared to the enemy's aircraft on positional advantage gained by it for the first case (air-to-air air-launched missile — aviation artillery weapon), where E is the efficiency of the developed algorithm, which shows the percentage of trajectories that ensure guiding of own UAV into the area of possible ALW launches. The graphs show that on average own UAV gains an advantage in a subsequent attack in 89% of cases.

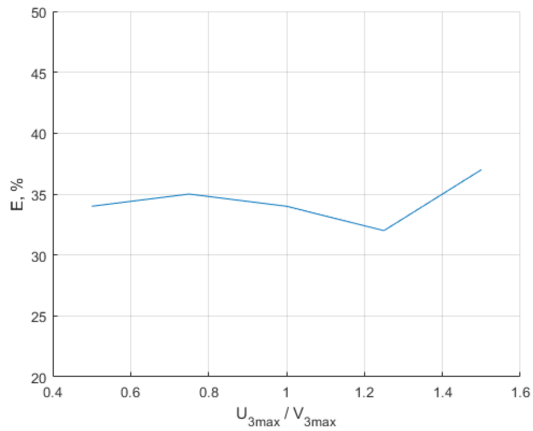
Figure 3 shows the graphs of the influence of acceleration response (3, a), ascensional rate (3, b), and agility (3, c) of own UAV compared to an enemy's aircraft on the positional advantage it achieves for the second case (aircraft artillery weapon — air-to-air air-launched missile). Analyzing the graphs, we can conclude that in 34% of cases, the UAV-interceptor gets an advantage for the attack.



a)



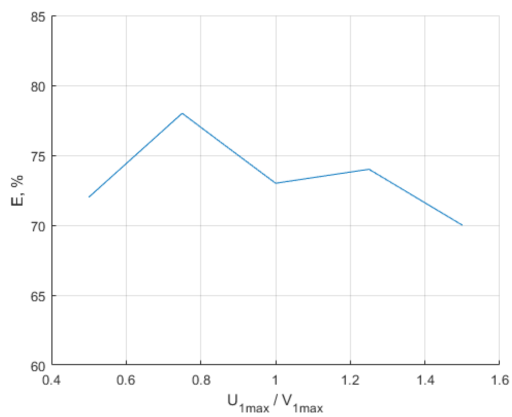
b)



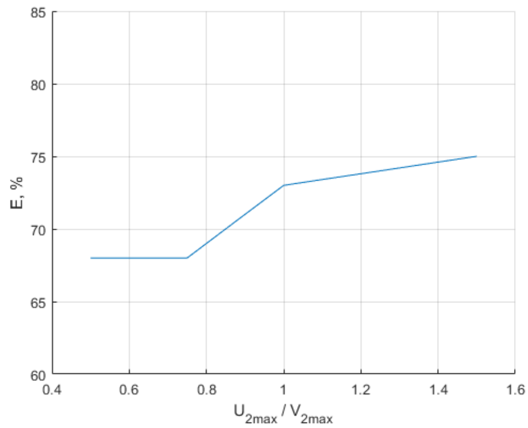
c)

Fig. 3. Graphs of the influence of acceleration response (a), ascensional rate (b) and agility (c) of an own UAV compared to an enemy's UAV on the positional advantage it achieves for 2 case of ALW location on conflicting UAVs

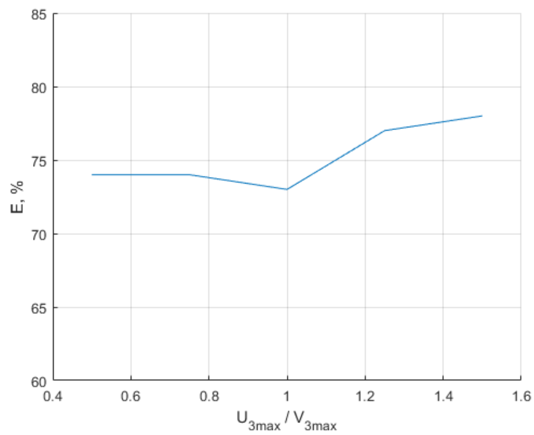
Figure 4 shows the graphs of the influence of acceleration response (4, a), ascensional rate (4, b), and agility (4, c) of own UAV compared to the enemy's aircraft on the positional advantage it achieves for the third case (air-to-air air-launched missile with the heat-seeking head (target seeker device) — air-to-air air-launched missile with a semi-active radar target seeker device). As follows from Fig. 4, on average, in 73% of implementations, own UAV receives a tactical advantage.



a)



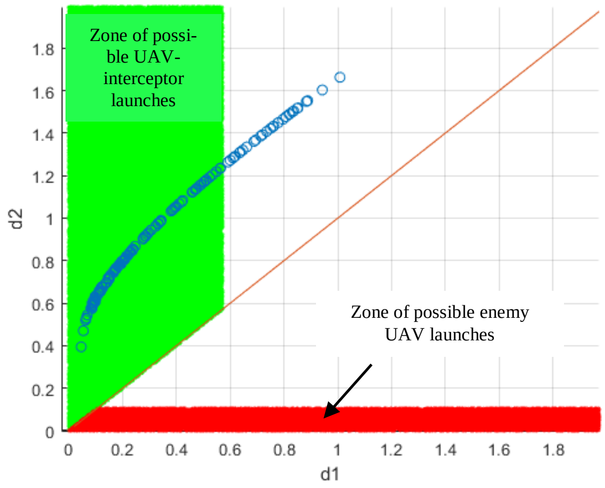
b)



c)

Fig. 4. Graphs of the influence of acceleration response (a), ascensional rate (b) and agility (c) of an own UAV compared to an enemy's UAV on the positional advantage it achieves for 3 case of ALW location on conflicting UAVs

For this case, a complete factorial experiment was conducted, the results of which gave the values of the acceleration components ($U_{1\,max} = 2.59g$, $U_{2\,max} = 5.67g$, $U_{3\,max} = 1.03g$), at which the maximum efficiency (Fig. 5) of the developed algorithm (78%) is achieved.



An analysis of the dependencies (see Figs. 2, 3, 4) allows us to state that the use of the guarantee control algorithm, regardless of the relative initial state of the attacked UAV and the UAV-interceptor, while their maneuverability is comparable, provides the positional advantage of the attacking UAV in the first and third cases. At the same time, the tactical indicator of agility, i.e. the ability of an attacking UAV to perform horizontal maneuvers, has the greatest impact on the positional advantage gained by the attacked UAV.

Conclusion

The article describes the original algorithm for UAV interceptor trajectory guaranteeing control at the stage of its guiding into the area of ALW use, suitable for onboard implementation. The guaranteeing approach that is based on the game formulation of the control creation task is the basis of the proposed algorithm. To obtain a constructive solution, the movement of players at the stage of their guiding into the ALW use zone is described in the space of normalized relative coordinates. It is shown that, within such description, the task to create the guaranteeing control for a linear dynamical system with a quadratic criterion, for which the presence of a saddle point is proved, arises.

A series of computational experiments have been carried out, the results of which allow us to state that the use of the developed UAV interceptor trajectory control algorithm provides a tactical advantage for it for a subsequent missile attack in the case of using ALW such as an air-to-air missile.

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