Vestnik of Don State Technical University. 2019. Vol. 19, no. 1, pp. 93-100. ISSN 1992-5980 eISSN 1992-6006
Вестник Донского государственного технического университета. 2019. Т. 19, № 1. С. 93-100. ISSN 1992-5980 eISSN 1992-6006

ИНФОРМАТИКА, ВЫЧИСЛИТЕЛЬНАЯ ТЕХНИКА И УПРАВЛЕНИЕ
INFORMATION TECHNOLOGY, COMPUTER SCIENCE, AND MANAGEMENT

UDC 62-50 https://doi.org/10.23947/1992-5980-2019-19-1-93-100

Method of terminal control in ascent segment of unmanned aerial vehicle with ballistic phase *

N. Y. Polovinchuk[1], S. V. Ivanov[2], M. Y. Zhukova[3], D. G. Belonozhko[4] **
[1] Moscow State Technical University of Civil Aviation, Rostov Branch, Rostov-on-Don, Russian Federation
[2,4] Krasnodar Higher Military School named after army general S. M. Shtemenko, Krasnodar, Russian Federation
[3] Don State Technical University, Rostov-on-Don, Russian Federation

Способ терминального управления на участке выведения беспилотного летательного аппарата с баллистической фазой полета***

Н. Я. Половинчук[1], С. В. Иванов[2], М. Ю. Жукова[3], Д. Г. Белоножко[4]**
[1] Ростовский филиал московского государственного технического университета гражданской авиации, г. Ростов-на-Дону, Российская Федерация
[2,4] Краснодарское высшее военное училище им. С. М. Штеменко, г. Краснодар, Российская Федерация
[3] Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация

Introduction. The solution to the problem on the centroidal motion control synthesis (guidance problem) of an unmanned aerial vehicle (UAV) with long-range capabilities in the boost phase is considered. Control condition requires optimum fuel consumption. The principle of dynamic programming considering the restrictions to the vector modulus of the thrust output is used to solve the problem. The implementation of terminal guidance requires the formation of control as a function of the object state at the end of the ascent phase. The attainment of these boundary conditions determines the further transition to the ballistic flight phase.

Materials and Methods. Bellman's principle of dynamic programming is the most reasonable from the point of view of the implementability of the computationally efficient on-board algorithms and the solution to the problems in the form of synthesis. With natural scarcity of thrust and energy resources on board, this principle enables to obtain solutions free from the switching functions. In this case, the optimal control is a smooth function (without derivative discontinuity) of the current and final parameters of the UAV.

Research Results. A new algorithmic method for the synthesis of terminal motion control is developed. Its difference is that the UAV movement control in the ascent phase is formed by the function of the motion actual and terminal parameters. This ensures movement along an energetically optimal trajectory into the given region of space. The problem solution results enable to build closed terminal guidance algorithms for

Введение. Статья посвящена решению задачи синтеза управления движением центра масс (задача наведения) беспилотного летательного аппарата (БЛА) с большой дальностью полета на разгонном участке. Условие управления: оптимальный расход топлива. Для решения задачи используется принцип динамического программирования с учетом ограничений на модуль вектора тяги двигателя. Реализация терминального наведения требует формирования управления как функции состояния объекта в конце участка выведения. Достижение этих граничных условий определяет дальнейший переход к баллистической фазе полета.

Материалы и методы. Принцип динамического программирования Беллмана является наиболее рациональным с точки зрения реализуемости эффективных в вычислительном отношении бортовых алгоритмов и решения задачи в форме синтеза. При естественной ограниченности величины тяги и энергетических ресурсов на борту данный принцип позволяет получить решения, не содержащие функции переключения. Оптимальное управление в этом случае является гладкой функцией (без разрыва производной) текущих и конечных параметров БЛА.

Результаты исследования. Разработан новый алгоритмический способ синтеза терминального управления движения. Его отличие в том, что управление движением БЛА на разгонном участке траектории формируется функцией текущих и конечных параметров движения. Таким образом обеспечивается движение по энергетически оптимальной траектории в заданную область пространства. Результаты решения задачи позволяют строить замкнутые алгоритмы терминального наведения для разгонного участка траектории БЛА с большой дальностью полета. Такие алгоритмы обладают

* The research is done within the frame of the independent R&D.
** E-mail: npolovinchuk@mail.ru, sta399@yandex.ru, marg88@list.ru, staeer@rambler.ru
*** Работа выполнена в рамках инициативной НИР.

the boost phase of the UAV trajectory with long-range capabilities. Such algorithms have good convergence and injection accuracy due to the prediction of parameters during the flight at a shorter time interval.
Discussion and Conclusions. The most preferred is the principle of dynamic programming. It should be used when solving the problem on the centroidal motion control synthesis (guidance problem) of the UAV with long-range capabilities in the boost phase.

хорошей сходимостью и точностью выведения за счет прогнозирования параметров в процессе полета на сокращающемся интервале времени.
Обсуждение и заключения. Наиболее предпочтительным представляется принцип динамического программирования. Именно его следует использовать при решении задачи синтеза оптимального по расходу топлива управления движением центра масс (задача наведения) БЛА с большой дальностью полета на разгонном участке.

Keywords: unmanned aerial vehicle (UAV), terminal guidance, direction cosines, pitching angle, angle of attack, boundary conditions, boost phase, ballistic flight phase.

Ключевые слова: беспилотный летательный аппарат (БЛА), терминальное наведение, направляющие косинусы, угол тангажа, угол атаки, граничные условия, разгонный участок, баллистическая фаза полета.

For citation: N.Y. Polovinchuk, et al. Method of terminal control in ascent segment of unmanned aerial vehicle with ballistic phase. Vestnik of DSTU, 2019, vol. 19, no. 1, pp. 93-100. https://doi.org/10.23947/1992-5980-2019-19-1-93-100

***Образец для цитирования*:** Способ терминального управления на участке выведения беспилотного летательного аппарата с баллистической фазой полета / Н. Я. Половинчук [и др.] // Вестник Донского гос. техн. ун-та. — 2019. — Т. 19, № 1. — С. 93-100. https://doi.org/10.23947/1992-5980-2019-19-1-93-100

Introduction. Currently, the capabilities and scope of applicability of the unmanned aerial vehicles (UAV) have increased significantly. This is primarily due to the UAV flying range extension. Vehicles with a ballistic phase of flight should be provided with the control in various areas, including the UAV positioning. For the control design, it is reasonable to apply the principle of terminal guidance. The control should be developed as a function of the terminal motion variables, and not as a temporal function.

A great many publications are devoted to this problem solution, but the task described above holds relevance. In particular, the development of highly computationally efficient algorithmic methods of terminal guidance is of interest. At the same time, the features universal for various types of launch vehicles should be considered. They have adaptive features and in a certain sense meet the optimality requirements.

Considering the guidance task, such a control, which uses the minimum amount of fuel, is valuable. The synthesis of optimal control is based on the use of the Bellman dynamic programming method [1].

Materials and Methods. The solution to the problem of the synthesis of optimal control of the UAV motion in the boost phase of power-on flight has been studied in many papers. However, the optimal control solution obtained in most cases is reduced to the implementation of a time or parametric program. We will solve the problem of finding the optimal control in the UAV ascent phase in the following formulation. The UAV motion parameters are known as X_0, Y_0, Z_0 coordinates of the current path point, obtained through solving the problem of navigation. $X_к$, $Y_к$, $Z_к$ parameters of the final point satisfy the boundary state that fixes the transition to the ballistic phase of flight determined by the hypersurface in the phase space. The condition of $S_k\,(X_к, Y_к, Z_к) = 0$ is satisfied by a whole set of finite parameters. It is required to synthesize optimal control in the task of UAV guidance, which ensures its transfer from the initial state to the hypersurface of the final conditions.

The optimality criterion is the amount of fuel consumed in the boost phase:

$$m(t) = \int_0^t \dot{m}(t)dt\,, \tag{1}$$

where $\dot{m}(t)$ is fuel mass flow rate.

The following system of differential equations is adopted as a mathematical model of the centroidal motion:

$$\dot{\bar{R}}(t) = \bar{V}(t)\,, \tag{2}$$

$$V(t) = \dot{W}(t)\bar{E}_w(t) + \bar{g}(\bar{r})\,,$$

where $\bar{R}(t)$ is radius-vector, $\bar{g}(\bar{r})$ is terrestrial attraction vector, $\dot{W}(t)$ is module of control acceleration vector.

The module of the control acceleration vector ($\dot{W}(t)$) is a specified temporal function, and it is determined by the UAV engine performance. Unknown is the unit vector of control acceleration – $\bar{E}_w(t)$. When solving the optimization problem, it will determine the required properties of the UAV guided motion in the boost phase. There is no need in the thrust vector control (in a sense, this is apparent acceleration amount – $\dot{W}(t)$). A more rational approach is to maximize this value for the engine booster. This ensures the application of the solutions obtained for the case of using solid fuel engines. The UAV engine performance is stable enough, and at $\dot{m}(t) = const$ constant fuel-flow rate, the optimal control is determined by the combustion duration. In this case, the functional (1) will be a function of the upper limit of integration. Hence, the problem of minimizing the fuel amount turns into an equivalent task of minimizing the flight time, and speed-of-response will be the optimality criterion. The task of the synthesis is to find the orientation of the thrust vector of the UAV engine, which is determined by the direction cosines of the thrust vector ($\bar{P}(t)$) as a function of the current parameters and the final state.

We admit two assumptions. The first is as follows. Since a large part of the boost phase lies outside the dense atmosphere, we will not consider the angle rate of evolution of the thrust vector in space (longitudinal axis of the UAV) as constraint. The second assumption is the following. Assume that the UAV motion is passing in a predetermined plane.

The UAV final state for the transition to the ballistic phase of flight is fixed by satisfying the following boundary condition [2]:

$$\begin{aligned} S_{1k} &= \left(V_{xk} y_k - x_k V_{yk}\right)\left[V_{xk}\left(y_k - y_ц\right) - V_{yk}\left(x_k - x_ц\right)\right] - \\ &- \pi_0 \left(x_ц^2 + y_ц^2\right)^{1/2} \left[1 - \frac{x_k x_ц + y_k y_ц}{\left(x_ц^2 + y_ц^2\right)^{1/2} \left(x_k^2 + y_k^2\right)^{1/2}}\right] = 0. \end{aligned} \tag{3}$$

Here, $x_k, y_k, x_ц, y_ц$ are, respectively, the coordinates of the initial point and the point of the starting of the UAV operation on the final path segment. The current value of the boundary condition ($S_{1k}(t_0)$) is a measure of non-compliance with the condition (3). A mathematical notation for this condition corresponds to the hypersurface, which is a smooth function of phase coordinates and describes the entire family of possible UAV ascent trajectories [2].

The boundary conditions are specified for the central field of attraction. For this case, the equations of the UAV motion will have the following form:

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= -\frac{\pi_0}{r^3} x_1 + \frac{1}{m} P\cos\alpha_1, \\ \dot{x}_3 &= x_4, \\ \dot{x}_4 &= -\frac{\pi_0}{r^3} x_3 + \frac{1}{m} P\cos\alpha_2. \end{aligned} \tag{4}$$

Here, $\pi_0 = f \cdot M_з$ is constant of the central field of the earth's attraction equal to the product of the gravitational constant (f) and the mass of the Earth ($M_з$); $r = (x_1^2 + x_3^2)^{1/2}$, $x_1 = x$, $x_2 = V_x$, $x_3 = y$, $x_4 = V_y$; P is thrust vector value; X_A is aerodynamic drag force; Y_A is aerodynamic lift.

Since the UAV is fitted up with a steerable thruster, its direction cosines will determine its pointing. In this case, the handling constraint will be determined by the ratio:

$$\left\|\bar{P}(t)\right\| = \left\{\left[P(t)\cos\alpha_1(t)\right]^2 + \left[P(t)\cos\alpha_2(t)\right]^2\right\}^{1/2} \le \left|\bar{P}^0(t)\right|. \tag{5}$$

The handling constraint (5) is "hypersphere restriction". This implies the solution in which optimal control is not piecewise constant, without switching. In this case, the time optimal ascent trajectory in the phase space has no "angles" and no discontinuities of the derivative. The time optimal control will be a nonlinear, continuous function of the boundary conditions (3) [3].

The synthesis task is formulated as follows. The control object from an arbitrary current state, taken as the initial one and determined by the current value (S_{1k}) at the time (t_0), is transferred to the hypersurface of the boundary condition $S_{1k} = 0$ at the time (t_k). This takes into account the control acceleration amount (engine thrust module). It is required to find the optimal control in the form of synthesis, which provides such a transfer in the shortest possible time.

The plant state at the final instance satisfies the boundary condition $S_{ik}[X(t_k)] = 0$ and determines the moment of transition to the ballistic phase of flight.

In accordance with R. Bellman's dynamic programming principle [4], the necessary and sufficient condition for optimality of the formulated problem will be the ratio:

$$\min_{u \in U} \left[\sum_{i=1}^{n} \frac{\partial T^0}{\partial x_i} f_i(\bar{x}, \bar{u})\right] = -1\,. \tag{6}$$

Considering the mathematical model of the object specified by the system (4), the dynamic programming equation [4] with the optimality criterion, is determined by the relation:

$$\min_{u\in U}\left[x_2\frac{\partial T^0}{\partial x_1}-\left(\frac{\pi_0}{r^3}x_1-\frac{1}{m}P_x\right)\frac{\partial T^0}{\partial x_2}+x_4\frac{\partial T^0}{\partial x_3}-\left(\frac{\pi_0}{r^3}x_3-\frac{1}{m}P_y\right)\frac{\partial T^0}{\partial x_4}\right]=-1\,, \tag{7}$$

where $P_x = P\cos\alpha_1, P_y = P\cos\alpha_2$.

Due to the methodology of Bellman's dynamic programming, the minimization can be carried out through the application of the Schwartz inequality [3] to the relation (5). This will significantly simplify the solution to the optimization problem. Then, the expression (7) with regard to inequality (5) will be determined by the relation:

$$\min_{u\in U}\left(\frac{1}{m}P_x\frac{\partial T^0}{\partial x_2}+\frac{1}{m}P_y\frac{\partial T^0}{\partial x_4}\right)=-P^0(t)\left[\left(\frac{1}{m}\frac{\partial T^0}{\partial x_2}\right)^2+\left(\frac{1}{m}\frac{\partial T^0}{\partial x_4}\right)^2\right]^{1/2}. \tag{8}$$

In this case, the Hamilton-Jacobi equation will be as follows:

$$\begin{aligned}&x_2\frac{\partial T^0}{\partial x_1}-\frac{\pi_0}{r^3}x_1+x_4\frac{\partial T^0}{\partial x_3}-\frac{\pi_0}{r^3}x_3-P^0(t)\times\\&\times\left[\left(\frac{1}{m}\frac{\partial T^0}{\partial x_2}\right)^2+\left(\frac{1}{m}\frac{\partial T^0}{\partial x_4}\right)^2\right]^{1/2}=-1.\end{aligned} \tag{9}$$

The equation (9) is solved considering the given boundary condition:

$$(x_1, x_2, x_3, x_4)\in S^*_{1k}. \tag{10}$$

The calculation of the partial derivatives of S for phase variables (x_1, x_2, x_3, x_4) gives the following dependences:

$$\begin{aligned}\frac{\partial S^0}{\partial x_1}&=\left(-2x_2x_3x_4+x_2x_4x_{3ц}+2x_4^2x_1-x_4^2x_{1ц}\right),\\\frac{\partial S^0}{\partial x_2}&=\left(2x_3^2x_2-2x_1x_4x_3-2x_2x_3x_{3ц}+x_1x_4x_{3ц}+x_4x_3x_{1ц}\right),\\\frac{\partial S^0}{\partial x_3}&=\left(2x_2^2x_3-2x_2x_4x_1-x_2^2x_{3ц}-x_2x_4x_{1ц}\right),\\\frac{\partial S^0}{\partial x_4}&=\left(2x_1^2x_4-2x_1x_2x_3+2x_4x_1x_{1ц}+x_2x_3x_{3ц}+x_2x_3x_{1ц}\right).\end{aligned} \tag{11}$$

Through substituting the relations (11) into (9) and performing simple transformations, we obtain the dependence:

$$\begin{aligned}&\{\frac{\pi_0}{r^3}(x_1-x_3)-2x_2x_4^2x_{1ц}-\frac{P^0}{m}\times\\&\times[\left(2x_3^2x_2-2x_1x_4x_3-2x_2x_3x_{3ц}+x_1x_4x_{3ц}+x_4x_3x_{1ц}\right)^2+\\&+\left(2x_1^2x_4-2x_1x_2x_3+2x_4x_1x_{1ц}+x_2x_3x_{3ц}+x_2x_3x_{1ц}\right)^2]^{1/2}\}\frac{\partial T^0}{\partial S_1}=-1\end{aligned} \tag{12}$$

with the boundary conditions

$$T^0(S_1)=0,\ \text{at}\ (x_1, x_2, x_3, x_4)\in S^*_{1k}. \tag{13}$$

The expression in curly brackets in (12), denoted by $S'(x_i)$, can be written in a compact form:

$$S'(x_i)\cdot\frac{\partial T^0}{\partial S_1}=-1. \tag{14}$$

The equation (14) with boundary conditions (13) can be solved in various ways, for example, by the method of characteristics [5]. However, it is more rational to use the following method.

The expression (11) defines the optimal control structure [6]:

$$\begin{aligned}\overline{P}_{opt}(\overline{x})&=-PE^{опт}(\overline{x}),\\\dot{\overline{W}}^{опт}(\overline{x})&=-\dot{W}E^{опт}(\overline{x}),\end{aligned} \tag{15}$$

where $E(\overline{x})$ is unit thrust vector.

The ratio (15) in the scalar form:

$$\begin{aligned}P_x^{opt}&=P\cos\alpha_1,\\P_y^{opt}&=P\cos\alpha_2,\end{aligned} \tag{16}$$

$$\cos\alpha_1 = \frac{\dfrac{\partial T^0}{\partial x_2}}{\left[\left(\dfrac{\partial T^0}{\partial x_2}\right)^2 + \left(\dfrac{\partial T^0}{\partial x_4}\right)^2\right]^{1/2}},$$
$$\cos\alpha_2 = \frac{\dfrac{\partial T^0}{\partial x_4}}{\left[\left(\dfrac{\partial T^0}{\partial x_2}\right)^2 + \left(\dfrac{\partial T^0}{\partial x_4}\right)^2\right]^{1/2}}. \quad (17)$$

The equation (9) and relations (17) can be put in a more convenient form for the following reasons. According to the formation of a set of perturbed trajectories, through varying the control, it is possible to construct a hypersurface with equal ascent time, that is, an isochronous surface, in the phase space. Indeed, for each phase trajectory point, we will calculate the optimality criterion value: $J(t_1), J(t_2), \ldots, J(t_k)$.

Hence, we obtain a set of trajectories for each $t \in [t_н, t_k]$. Owing to the continuity of the dependence of $x(t)$ and J on the variable control, a set of trajectories forms a surface in the phase space (X). This boundary surface formed by the set of vectors $x[t_i, J(t_i)]$, is convex and smooth. For transition conditions to the ballistic flight phase, the isochronous surface has a tangency point with the hypersurface of the boundary conditions.

Under the qualitative implementation of the optimal control, the distance in the phase space between the hypersurface of the boundary conditions $S_k = 0$ and the isochronous surface $T(x, R_ц, t) = 0$ will decrease. During some time, the two surfaces will have a common point (Fig. 1).

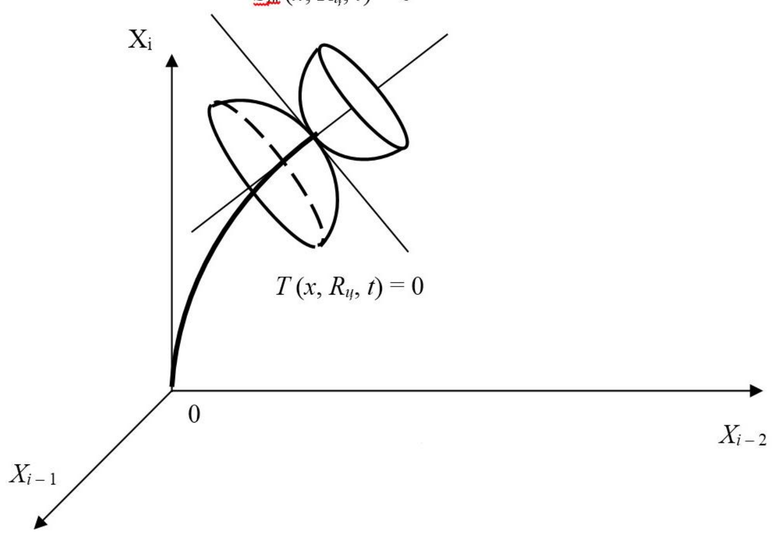


Fig. 1. Geometric interpretation of hypersurfaces in phase space under guidance in boost phase

At the point S_k and T^0, they have a common tangency, that is, their gradients coincide in the phase space. In this way:

- existence of the optimal trajectory $x_{opt}(t)$ and optimal control $u_{opt}(t)$ is noted;

- termination of the boost phase of the trajectory ($t = t_k$) and the transition to the ballistic flight phase are determined.

At the tangency point, the isochronous surface and the hypersurface of the boundary conditions have a common tangency and a normal. Mathematically, the condition for the existence of a common normal is determined by the expression [2]:

$$\left\{\frac{\partial T^0}{\partial x_i}\right\} = A\left\{\frac{\partial S_{ik}}{\partial x_i}\right\}, \quad (18)$$

where A is constant determined from the analysis of the convexity of both hypersurfaces.

From the relations (11) and (18), we transform (17). We obtain the expression for the direction cosines of the thrust vector as a function of the current and final motion parameters:

$$A = \frac{\left(-2x_2x_3x_4 + x_2x_4x_{3ц} + 2x_4^2x_1 - x_4^2x_{1ц}\right)}{\left[\left(-2x_2x_3x_4 + x_2x_4x_{3ц} + 2x_4^2x_1 - x_4^2x_{1ц}\right)^2 + \left(2x_4x_1^2 - 2x_1x_2x_3 + 2x_1x_4x_{1ц} + x_2x_3x_{3ц} + x_2x_3x_{1ц}\right)^2\right]^{1/2}}, \qquad (19)$$

$$B = \frac{\left(2x_1^2x_4 - 2x_2x_1x_3 + 2x_4x_1x_{1ц} + x_2x_3x_{3ц} + x_2x_3x_{1ц}\right)}{\left[\left(-2x_2x_3x_4 + x_2x_4x_{3ц} + 2x_4^2x_1 - x_4^2x_{1ц}\right)^2 + \left(2x_4x_1^2 - 2x_1x_2x_3 + 2x_1x_4x_{1ц} + x_2x_3x_{3ц} + x_2x_3x_{1ц}\right)^2\right]^{1/2}}, \qquad (20)$$

where $A = \cos\alpha_1$, $B = \cos\alpha_2$.

From the relations (19), (20), it is easy to obtain a parameter natural for this UAV type to determine the orientation vector of the control acceleration (in a certain sense, of the thrust vector), the pitching angle:

$$\vartheta(S) = arctg\frac{\cos\alpha_2}{\cos\alpha_1} = \frac{\left(2x_1^2x_4 - 2x_2x_1x_3 + 2x_4x_1x_{1ц} + x_2x_3x_{3ц} + x_2x_3x_{1ц}\right)}{\left(-2x_2x_3x_4 + x_2x_4x_{3ц} + 2x_4^2x_1 - x_4^2x_{1ц}\right)}. \qquad (21)$$

In our case, the UAV motion takes place in the given plane, and the yaw angle is $\varphi(S) = 0$. Using the proposed methodology for the synthesis of terminal optimal control, an algorithm for calculating the pitching angle was developed [2], and the computational simulation of the UAV flight was carried out [7].

Research Results. The numerical studies have been conducted using the software that implements the proposed method. We are talking about the algorithmic software for terminal guidance of ballistic aircraft based on the solution to boundary problems of ballistics. The corresponding computer program was registered in 2013.

When modeling, a hypothetical accelerating tool was used with the characteristics and initial conditions for the UAV launch ascent, given in [8].

The initial conditions of the simulation and the calculation results of the early ascent are given in Table 1.

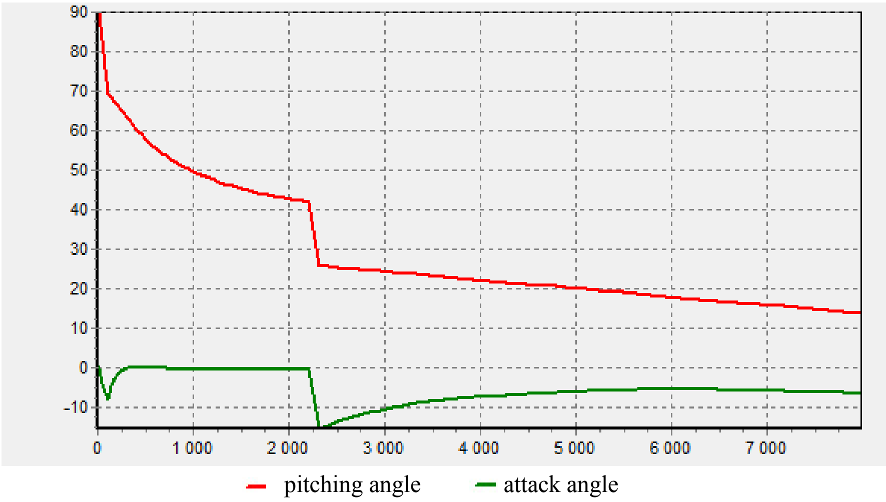
Table 1

Initial conditions for UAV launch ascent

t	x/vx	y/vy	z/vz	wx/tang	wy/tet	w1/alf
0.0000	0.0 5.6323	0.0 –0.0000	0.0 322.6757	0.0000 90.00	0.0000 0.00	0.0000 0.000
0.5537	3.1 5.6323	3.1 11.1626	178.7 322.6756	–0.0000 90.00	16.6000 1.98	16.6000 –0.048
3.4580	34.7 21.4565	120.9 69.4705	1115.8 322.6727	15.8242 69.34	103.4286 12.13	105.3386 –7.881
13.0193	832.4 155.6274	1683.4 259.0827	4200.8 322.6335	150.0000 60.00	386.9131 35.91	419.3209 0.011
23.0193	3384.5 368.3725	5300.4 464.9493	7426.8 322.5441	362.7748 50.02	690.8797 43.59	790.8281 –2.076
33.0193	8469.9 662.2567	11009.1 679.2317	10651.6 322.4053	656.7462 43.44	1003.1187 42.79	1219.9140 –2.582
43.0193	16923.8 1044.7345	18956.0 915.1428	13874.7 322.2176	1039.4134 38.74	1336.7768 40.11	1727.7590 –2.677
50.9898	26729.1 1429.1498	27089.4 1131.2610	16442.2 322.0334	1424.0909 36.01	1630.6058 37.94	2211.8627 –2.501

Fig. 2 shows the pitching-angle profile in the boost flight phase.

Dependence of pitching and attack angles on apparent speed rate



Dependence of UAV entrance angle on apparent speed rate

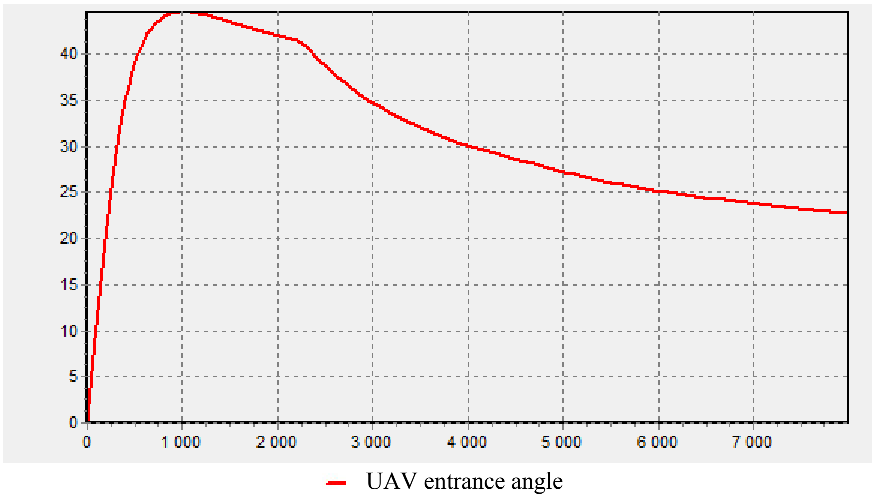


Fig. 2. Variation of UAV pitching and entrance angles

Fuller information on the simulation results given in [8] is as follows.

1. The resulting control is suboptimal due to the use of boundary conditions in an analytical form. To improve the accuracy of the boundary conditions in the navigation algorithm, it is necessary to introduce an up-date algorithm, which is based on attracting more accurate models of the Earth's gravitational field. Hence, the launch ascent accuracy will be improved.

2. The effect of random disturbances is compensated by the adaptive properties of terminal guidance, as well as by predicting the motion parameters and the formation of control at a decreasing time interval each time until the end of the launch ascent process.

3. The obtained estimates under modeling allowed us to rationally select the discreteness of the navigation and guidance algorithms and thereby limit the range of requirements for the FMC during its implementation.

4. The implementability of guidance algorithms based on the developed methodology on modern onboard computers creates no difficulties. The required response rate is $(1–1.5)\times10^6$ k.o./s.

Discussion and Conclusions. Thus, the principle of dynamic programming seems to be most preferable. It should be used when solving the problem on the centroidal motion control synthesis (guidance problem) of the UAV with long-range capabilities in the boost phase. The well-known remark on the applicability of dynamic programming, the so-called "curse of dimensionality", is inappropriate in the task of developing control as a function of the final state [5]. In addition, the use of boundary conditions in an analytical form simplifies essentially the formation of suboptimal control and enables to change strategically the flight missions. This scales up the applicability of this algorithm for UAV of various purposes.

References

1. Polovinchuk, N.Y., Ardashov, A.A. Proektirovanie sistem upravleniya raket-nositeley i mezhkontinental'nykh ballisticheskikh raket. [Design of control systems for launch vehicles and intercontinental ballistic missiles.] Rostov-on-Don: RVIRV, 2010, 242 p. (in Russian).
2. Mogilevskiy, V.D. Navedenie ballisticheskikh letatel'nykh apparatov. [Ballistic targeting.] Moscow: Mashinostroenie, 197, 208 p. (in Russian).
3. Athans, M., Falb, P. Optimal'noe upravlenie. [Optimal control.] Moscow: Mashinostroenie, 1968, 764 p. (in Russian).
4. Bellman, R. Dinamicheskoe programmirovanie. [Dynamic programming.] Moscow: Mir, 1965, 286 p. (in Russian).
5. Bryson, A., Yu-Chi Ho. Prikladnaya teoriya optimal'nogo upravleniya. [Applied Optimal Control.] Moscow: Mir, 1972, 544 p. (in Russian).
6. Petrov, B.N., et al. Bortovye terminal'nye sistemy upravleniya. [Onboard terminal control systems.]. Moscow: Mashinostroenie, 1983, 200 p. (in Russian).
7. Polovinchuk, N.Y., Shcherban, I.V. Metody i algoritmy terminal'nogo upravleniya dvizheniem letatel'nykh apparatov. [Methods and algorithms for terminal motion control of aircraft.] Moscow: RF MD Print.-Publ., 2004, 290 p. (in Russian).
8. Polovinchuk, N.Y., Ivanov, S.V., Kotelnitskaya, L.I. Sintez upravleniya manevrom ukloneniya bespilotnym letatel'nym apparatom s uchetom terminal'nykh ogranicheniy. [Synthesis of evasive maneuver control of unmanned aerial vehicle for terminal restrictions.] Vestnik of DSTU, 2018, vol. 18, no. 2, pp. 190–200 (in Russian).

Received 22.09.2018
Submitted 24.09.2018
Scheduled in the issue 15.01.2019

Authors:

Polovinchuk, Nikolay Y.,
professor of the Airborne Electrical Systems and Navigation Instrumentation Department, Moscow State Technical University of Civil Aviation, Rostov Branch (262c, Sholokhov pr., Rostov-on-Don, RF), Cand.Sci. (Eng.), professor ,
ORCID: http://orcid.org/0000-0003-0002-5120
npolovinchuk@mail.ru

Ivanov, Stanislav V.,
associate professor of the Production Automation Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344000, RF), Cand.Sci. (Eng.),
ORCID: https://orcid.org/0000-0002-3237-0415
sta399@yandex.ru

Zhukova, Maria Y.,
postgraduate of the Computer and Automated Systems Software Department, Don State Technical University (1, Gagarin sq., Rostov-on-Don, 344000, RF), Cand.Sci. (Eng.),
ORCID: http://orcid.org/0000-0001-9555-3756
marg88@list.ru

Belonozhko, Dmitry G.,
adjunct, Krasnodar Higher Military School named after army general S. M. Shtemenko (4, ul. Krasina, Krasnodar, 350035, RF),
ORCID: http://orcid.org/0000-0002-7185-9475
staeer@rambler.ru