Methods of Planning the Flight Route for Class I Unmanned Aerial Vehicle of Special Purpose in a Given Area

Vadym Horbach [1], **Yurii Bondarenko** [1], **Anatolii Pelts** [1], **Vitalii Kolodnytskyi** [1], **Pavlo Pozdniakov** [2]

[1] *Serhiy Korolyov Zhytomyr Military Institute*
22 Prospect Myru, Zhytomyr, 10004, Ukraine

[2] *National University "Odessa Maritime Academy"*
8, Didrikhson Street, Odessa, 65029, Ukraine

Abstract. The article develops the methods of the flight route planning for Class I unmanned aerial vehicle (UAV) of special purpose in a given area. The basic indices of the flight route planning of Class I UAV within the monitoring of the objects area are defined. The article presents the order of indices normalizing. It proves the expediency and optimization scheme for the calculation of the generalized performance indicator of the flight route planning in a given area.

Keywords: an unmanned aerial vehicle, performance indicators, flight route plan, target area monitoring, a nonlinear scheme of compromises.

INTRODUCTION

The analysis of current military conflicts and combat operations in the East of Ukraine affirms the use of a large number of new weaponry, which in turn has enabled the belligerents to keep maximum distancing to prevent a shooting incident with each other. One of the newest weaponry on the battlefield is Class I unmanned aerial vehicles (UAVs), which have proven their ability to monitor aerial terrain and perform other special tasks without risk to personnel much more effectively than manned aircraft.

Though, there are many factors for the effectiveness of the monitoring results of Class I UAV in a given area to depend on. Those include high-quality flight route planning, proficient operator actions to control the UAV, the availability of software to automate flight route planning, the obstructive influence of the terrain on surveillance, the dependence of the effectiveness of target recognition in the area on the technical characteristics of the UAV payload. After analyzing the planning procedure of UAV when surveillance is in progress in a certain area [10], we can conclude that the software is poorly adapted to

the planning of the Class I UAV flight route in a given area.

Therefore, it is necessary to develop methods for planning the flight route of Class I UAVs of special purpose in a given area, which will enable us to increase the effectiveness of monitoring results in a given area.

On the principles of tasks peculiarities of Class, I UAVs of special-purpose [10], requirements for the flight route planning [16, 5, 3], aircraft application regulations [22, 19, 17, 18], technical capabilities of the unmanned aerial system (UAS), many factors have been to influence the flight route planning efficiency.

However, in the available planning software, only the criterion of the time of the monitoring task is preferred [14, 1]. In particular, software tools such as Mission Planner, eMotion AG-SenseFly, UgCS PC Mission Planning, DJI Ground Station Pro, mdCockpit are not adapted to take into account the impact of the enemy air defense facilities, and the ability to calculate the probability of enemy objects recognition.

In [14, 13, 20] the option to increase the efficiency of planning of UAS monitoring by calcu-

lation of the indicators which present the technical capabilities of the payload is investigated. The advantage of this approach is the accuracy of calculating the optimal flight altitude of the aircraft under the conditions of the task. Along with this, we can regard as a disadvantage the lack of consideration of the effect of the enemy firepower, which varies with altitude.

References [26, 2] introduce the methods for calculating the effectiveness of air monitoring of the area by UAS. Though, certain indicators allow us to assess the effectiveness of the application after the UAV flight by comparing them with the standard ones. This approach is effective only for the analysis of results and has low adaptability to be used under the conditions of uncertainty.

As a common drawback, we may note that none of the proposed approaches allows obtaining a generalized performance indicator of Class I UAV flight route plan in a given area, which reflects the main performance criteria of the flight route plan and performance characteristics of the UAS.

Thus, based on the analysis of publications, the problem of optimizing the flight route planning of Class I UAV in a given area is sufficient for science and practical application, and being relevant needs to be addressed.

The article aims to develop methods of planning the flight route for Class I UAV in a given area considering the defined performance indicators and tactical and technical characteristics of the UAV.

RESULTS

Under the conditions when many factors are influencing the UAV while performing the terrain monitoring special tasks, the operator, when planning the UAV flight route, selects the one that is optimal out of the possible routes. The list of requirements for special monitoring of the terrain, indicators, and parameters that reflect the performance characteristics of the UAS determine the system of performance criteria of the flight route plan.

It should be considered that depending on the UAV flight route different monitoring efficiency will be provided in a certain area, which in general will depend on a significant number of factors: time of the special monitoring task,

probability of UAV damage, the maximum probability of targets recognition and high resolution of images to be decoded effectively.

In [6] the indicators that determine the effectiveness of the flight route of Class I UAV of special purpose are defined:

the probability of UAV damage – $P_{ураж}$;

probability of targets recognition – $P_{роз}$;

probability of targets detection – $P_{виявл}$;

total UAV monitoring time – $T_{заг}$.

Probability of UAV damage on the flight route. The probability of UAV damage on the flight route is an indicator that will characterize the process of performing a special task of the UAV in terms of the possibility of UAV loss and makes it possible to assess this risk. The probability of UAV damage in the area of enemy air defense actions, when there may be several, is determined by the following expression (1):

$$P^{БпЛА}_{ураж_i} = 1 - \prod_{i=1}^{q} P^{БпЛА}_{ураж_i}, \qquad (1)$$

where $P^{БпЛА}_{ураж_i}$ stands for probability of damage caused by *i*-facility of enemy air defense equipment;

q stands for the quantity of air defense equipment on the UAV flight route [24].

The peculiarity of this indicator is that it enables to assess the quality of flight route planning under known data on enemy air defense systems in the area of air monitoring.

Target's recognition probability reflects the probabilistic value of information quality, which depends on the specified or required resolution of photo and video information and the optimal altitude of aerial photography. It is advisable to perform its calculation using the improved formula of Zhyvychyn [15], which will regard the specified detail of image d_0, resolution of the target equipment of photo and video capture $d_{зн}$, and radiometric contrast of the target and the terrain Q. We will express this indicator as a functional dependence of the corresponding indicators (2):

$$P_{розп} = exp\left[\frac{\ln p}{\log\frac{1+Q}{1+Q}}\left(\frac{d_{зн}}{d_0}\right)^2\right], \qquad (2)$$

where ρ stands for the level of veracity, which usually is $\rho = 0,95$; Q stands for contrast [21].

The effectiveness of the operator's perception of information depends on the contrast between the reconnaissance target (RT) and the background. Contrast can be of two types: direct and reverse. This coefficient will be calculated by the formulae (3):

$$Q_{зв} = \frac{I_{OP} + I_{\Phi}}{I_{OP}}, Q_{np} = \frac{I_{\Phi} + I_{OP}}{I_{\Phi}}, (3)$$

where I_{Φ} stands for the background brightness; and $I_{OP}Q$ stands for the RT brightness [17, 18, 14].

The expression for determining the brightness of RT will be as follows (4):

$$I_{OP} = I_{вип} + I_{від}, \qquad (4)$$

where I_{Φ} stands for brightness of the RT emission; $I_{OP}Q$ stands for brightness of the exterior light reflected by RT.

The brightness of the reflected by RT light flux depends on the color and location of the target in relation to the observer (5):

$$I_{від} = \frac{\Xi\delta}{\pi}, (5)$$

where Ξ stands for surface illumination, lx;

δQ stands for coefficient of surface color reflection.

The optimal value of the contrast coefficient for normal perception by the photo interpreter will be in the range of 0.60–0.95. Usually the process in a direct contrast is more favorable than in a reverse one. However, to ensure the normal operation of the operator, it is necessary to know that he is accepted in specific conditions.

The expression to calculate RT while using an infrared camera will be presented as (6):

$$Q = \frac{M_O - M_\Phi}{M_O - M_\Phi}, \qquad (6)$$

where $M_0 - M_\Phi$ stands for spectral density of the energy brightness of the target's intrinsic thermal radiation and background, respectively.

When shooting at night, the radiometric contrast in infrared spectral and radiometric photo equipment is defined as spectral density of the energy brightness $M_{0\phi}(\lambda, T)$ of the intrinsic thermal radiation of RT and the background in accordance with Planck's law (7):

$$M_{0\phi}(\lambda, T) = \frac{2\pi\hbar c^2}{\lambda^5\left[exp\left(\frac{\hbar c}{к\hbar t_{OP}}\right) - 1\right]}, \qquad (7)$$

where λ stands for wavelength of electromagnetic radiation; t_{OP} stands for RT temperature; $\hbar$ stands for the Planck constant; c stands for the speed of light in vacuum; к stands for the Boltzmann Constant [1].

Payload resolution. The implementation of special tasks for monitoring the terrain by Class I UAV at different altitudes involves considering the changes in the payload resolution. The calculation of this indicator and regarding it when planning the UAV flight route will affect the result of the task. The expression for calculating the resolution is presented as (8):

$$d_{зн} = \frac{hc_O}{f_к}, \qquad (8)$$

where c_0 stands for pixel size; $f_к$ stands for the focal length of the optical system; h stands for altitude of UAV monitoring [1].

The total time of the accomplishment of special task is an indicator of the UAV flight route

planning efficiency, which characterizes the capabilities of the aircraft in relation to the total length of the flight route under the given conditions [24]. In this case, to calculate the distance, it is necessary to keep to consider the average optimal flight speed (9).

$$T_{заг} = T_{пл} + T_{пол} + T_{роз},\qquad(9)$$

where $T_{пл}$ stands for time of UAV flight route planning measures accomplishment; $T_{пол}$ stands for flight time from the moment of take-off to the first RT and from the last RT to the landing of the aircraft; $T_{розв}$ stands for flight time from the first to the last target without arrival and return.

For further research we will apply the following formulae:

– the area of the elementary survey area of the UAV (10):

$$S_{розв}^{ел} = H_{СМ}^2,\qquad(10)$$

– the scan swath (11):

$$H_{СМ} = 2h\tan(\frac{\varphi}{2}),\qquad(11)$$

where φ stands for scanning angle of UAV payload in the nadir.

In accordance with the payload equipment characteristics, taking into account (10)–(11), the time of monitoring tasks of a given area can be represented as a rectangle (Figure 1).
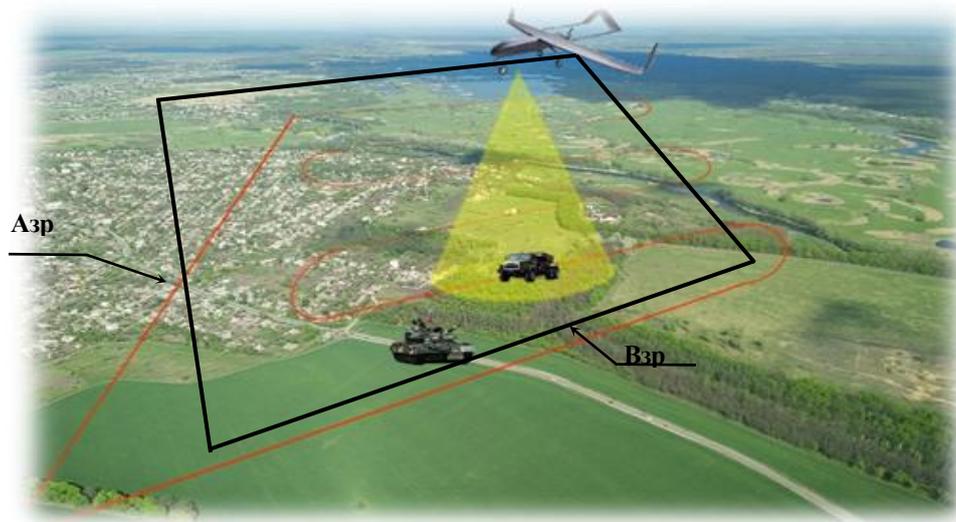

Figure 1 − A variation to perform the monitoring tasks of a given area in the form of a rectangle

The number of UAS scanning overflights in the area of air monitoring is determined regarding the fact that the adjacent scanning swaths should overlap by 20 %, in this case the number of UAV overflights in the survey area (number of aircraft pivoting) equals (12):

$$\eta_p = \frac{А_{зр}}{0,8.2h\tan(\frac{\varphi}{2})},\qquad(12)$$

where η_p stands for the number of aircraft pivoting for the area of monitoring.

The length of the UAV flight route in the survey area (including aircraft pivoting) in the process of air monitoring (along the route according to Figure 2).

$$L_{пол} = B_{зр}\frac{А_{зр}}{0,8.2h\tan(\frac{\phi}{2})} +$$

$$+\frac{А_{зр}}{0,8.2h\tan(\frac{\phi}{2})}l_p + l_{вх} + l_{вих}\qquad(13)$$

where $B_{зр}$ stands for width of the air monitoring zone; l_p stands for additional way to perform one

pivot; l_{ex}, l_{eux} stand for lengths of the sections of the inward and outward flights to and out the monitoring area (see Figure 1).

The duration of the UAV flight for air monitoring of a given area will be determined by the formula (14):

$$T_{роз} = \frac{L_{пол}}{V_{сер}},\qquad(14)$$

where $V_{сер}$ stands for the UAV flight velocity.

In this case the expression will be as follows (15):

$$T_{заг} = T_{пл} + \frac{B_{зр}\dfrac{A_{зр}}{0{,}8.2h\tan(\frac{\varphi}{2})} + \pi A_{зр} + l_{ex} + l_{eux}}{V_{сер}}.\quad(15)$$

Also, to perform the tasks of UAVs for monitoring the area of special attention (ASA), which has a rounded shape, a variant of the flight route in a spiral from or to the center with certain coordinates is possible (Figure 2).

Figure 2 − A variation to perform the monitoring tasks of a given area in a spiral from or to the center with certain coordinates

The solution of this problem is possible with the use of a flat curve (Archimedean spiral) [4, 12]. The Archimedean spiral is a curve described by a point as it moves uniformly at a velocity along a straight line that rotates uniformly in a plane around one of its points at an angular velocity. The equation of the Archimedean spiral in polar coordinate system is expressed as $\rho = a\phi$. For practical application of this type of spiral, when performing air monitoring tasks with UAVs, it is necessary to find the following values: arc length (of air monitoring), number of turns (ASA radius) and displacement step (observation swath of the UAV payload).

Let us consider the option of monitoring a given ASA with known coordinates of the center and radius. In this case, the length of the UAV flight route in a given area will be as follows (16):

$$L_{пол} = \frac{a}{2}(\phi\sqrt{1+\phi^2} + \ln(\phi + \sqrt{1+\phi^2})),\quad(16)$$

where a stands for the winding pitch of a spiral; and ϕ stands for the number of pivots around a given point (ASA centre).

The value of pitch we will present as (17):

$$a = H_{СМ} = 1.6h\tan(\frac{\varphi}{2}),\qquad(17)$$

In this case, according to the situation, we have (18):

$$\phi = \frac{\pi R_{poy}}{0.8h\tan(\frac{\varphi}{2})},$$ (18)

where R_{POY} stands for ASA radius.

The expression to find the total task execution time in accordance with the selected flight route scheme will be as follows (19):

$$T_{заг} = T_{пл} +$$
$$+ \frac{0.8h\tan(\frac{\phi}{2})\left[\varphi\sqrt{1+\varphi^2} + \ln(\varphi+\sqrt{1+\varphi^2})\right] + l_{вх} + l_{вих}}{V_{сер}}.$$ (19)

Another option is possible if one of the requirements of the task may be to search for ASA area. In this case, we will use the following expression (20):

$$S_{POY} = \frac{1}{2}\int_0^{\varphi} p^2(\varphi)d\varphi =$$
$$= \frac{1}{2}\int_0^{\varphi}\left(1.6h\tan\left(\frac{\phi}{2}\right)\right)^2\varphi^2 d\varphi =$$ (20)
$$= 1.25\left(h\tan\left(\frac{\phi}{2}\right)\right)^2\frac{\varphi^3}{3}\bigg|_0^{\varphi}$$

Criteria for the effectiveness of flight route planning of Class I UAVs of special purpose are determined [19, 17, 18, 16, 5, 3, 10] by the specified task; the capabilities of the enemy to disrupt it; time parameters of planning and (or) task execution; parameters that determine the technical capabilities of UAS.

Based on the determined indicators of the effectiveness of the flight route planning, the system of criteria for evaluating the effectiveness of the flight route plan of Class I UAVs of special purpose will be as follows (21):

$$P_{opt} = F\left(P_{ураж}, P_{роз}, d_{зн}, T_{заг}\right)\begin{vmatrix} P_{ураж} \to \min, & P_{ураж} \leq P_{ураж}^{\max}, \\ P_{роз} \to \max, & h \leq h_{\max}, \\ d_{зн} \to \max, & d_{зн} \geq d_{зн}^{зад}, \\ T_{заг} \to \min, & L_{пол} < L_{\max}. \end{vmatrix}$$ (21)

where $P_{ураж}^{\max}$ stands for the preassigned maximum allowable probability of UAV damage on the flight route; $d_{зн}^{зад}$ stands for the preassigned payload resolution.

When developing a method aimed to calculate the optimal flight plan of Class I UAV of special purpose in a given area, it is necessary to consider the solution of this problem as a multi-stage process, which assumes considering tactical indicators, which are presented in the form of special tasks; indicators to show the technical capabilities of UAS for performing special tasks; conditions of monitoring.

The formation of the performance function $F(K_i)$ for alternatives to some domain Ω occurs due to the convolution of the vector criterion F into a scalar one by different types of convolutions [24, 11], in particular the adapted one (22):

$$F(K_i) = \prod_{j=1}^{w} K_{ij}^{\lambda_j} \quad \sum_{j=1}^{w} \lambda_j = 1,$$ (22)

where λ_i stands for weighting coefficient of efficiency indicator of

multiplicative (23)

$$F(K_i) = \prod_{j=1}^{w} K_{ij}^{\lambda_j} \quad \sum_{j=1}^{w} \lambda_j = 1,$$ (23)

additive-multiplicative (24)

$$F(K_i) = \sum_{j=1}^{w} \lambda_j K_{ij} + \prod_{j=1}^{w} K_{ij}^{\lambda_j} \quad \sum_{j=1}^{w} \lambda_j = 1,$$ (24)

and derivatives of these convolutions, based on the specifics of the tasks.

A common disadvantage of such convolution methods is that the insufficient value of one utility criterion about another one can be compensated by increasing the value of another criterion. Also, there are restrictions on their unidirectionality. The use of these convolutions is not advisable to find the best options for the UAV flight route plan, as it is not advisable to use the additive convolution to find the optimums of the interrelated criteria. The multiplicative convolution is highly sensitive to the changes in the values of indicators, so a slight change in the parameters leads to an inadequate change in the result of the generalized indicator.

Approach [24] is based on combining many quality criteria of the system into one, uses a nonlinear scheme of compromises, and allows to formally obtain the optimal (about the proposed criteria) solution. Compared to many other optimization schemes, along with common disadvantages, it has the following advantages:

– the optimization problem is solved under the restrictions, which guarantees a solution in any case;

– the method guarantees unimodality of the resulting functional;

– the slight computational complexity of the solution search algorithm.

Therefore, for this set of criteria it is advisable to apply a convolution according to a nonlinear scheme of compromises (25):

$$E(P_M) = \sum_{i=1}^{w} \lambda_i \left[1 - K_{0i}^{H}\right]^{-1}, \ \sum_{j=1}^{w} \lambda_j = 1, \ (25)$$

where $P_M = \{k_w\}_{i=1}^{w}$ stands for Ω-dimentional vector of performance indicators; and K_{0i}^{H} stands for normalized performance indicator [24, 25, 8, 9, 15, 21].

We will normalize the general indicators of the UAV flight route plan in accordance with [23, 24, 11, 7]:

$$\overline{P}_{ураж}^{H} = P_{ураж}, \overline{P}_{ураж}^{H} \in [0...1], \quad (26)$$

where $P_{ураж}$ stands for calculated indicator value i.e. UAV damage probability;

$$\overline{T}_{заг}^{H} = \frac{T_{заг}}{T_{заг}^{\max}}, \overline{T}_{заг}^{H} \in [0...1], \quad (27)$$

where $T_{заг}, T_{заг}^{\max}$ stands for calculated and maximum value of the indicator i.e. the total time of monitoring, respectively;

$$\overline{P}_{розп}^{H} = 1 - P_{розп}, \overline{P}_{розп}^{H} \in [0...1], \quad (28)$$

where $P_{розп}^{OP}$ stands for calculated indicator value i.e. probability of target recognition;

$$\overline{d}_{зн}^{H} = \frac{d_{зн}}{d_{зн}^{\max}}, \overline{d}_{зн}^{H} \in [0...1], \quad (27)$$

where $d_{зн}, d_{зн}^{\max}$ stand for calculated and maximum value of the indicator i.e. the detail of the image, respectively.

Reasoning from the defined performance indicators of the flight route planning of Class I UAVs, the selected optimization scheme and the indicators normalizing procedure, the expression for calculating the value of the generalized indicator of planning performance will be as follows (28):

$$\begin{aligned} E(P_M) = &\lambda_1 \frac{1}{1 - \overline{P}_{ураж}^{H}} + \lambda_2 \frac{1}{1 - \overline{P}_{розп}^{H}} + \\ &+ \lambda_3 \frac{1}{1 - \overline{T}_{заг}^{H}} + \lambda_4 \frac{1}{1 - \overline{d}_{зн}^{H}}, \end{aligned} \quad (28)$$

where $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ stand for weighting coefficients of advantage of respective general performance indicators.

The calculated value of the optimal flight plan of Class I UAV of special purpose in a given area will correspond to the minimum value of the generalized performance indicator.

CONCLUSIONS

The developed method (1–8, 10–28) of planning the flight route of Class I UAV of special purpose in a given area provides an opportunity to calculate the optimal flight route plan by the determined idicators. It also considers the weighting coefficients of each of the defined performance

indicators, which affects the flexibility of the method in relation to each of the selected performance indicators of the plan. For futher research we plan to study other indicators of planning the flight route of Class I UAV in a given area as for their effect on the optimality of the flight route and automation of decision-making process for monitoring enemy objects in the UAVs effective area.

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