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ESTIMATION OF THE REQUIRED DIMENSION OF NET TO CAPTURE DRONE

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***Abstract**—A method for estimating of the required dimension net to capture drone is proposed. The results of calculations of the drone movement trajectories in horizontal and vertical planes depending on velocity and normal overload are presented. The calculation of the trajectories in the horizontal plane was carried out based on formula of the coordinated turn at constant values of a speed and normal overload. An analytical solution of the differential equation system for the isolated movement of the drone in the vertical plane is obtained. According to performed calculations, delivery of the net to the unwanted drone should be carried out with high-speed unmanned aerial vehicle in order to reduce the interception time and, accordingly, to reduce the required area of net for it capture.*

Index Terms—Net area; capture of drone; conus of trajectory**;** velocity and normal overload of drone; mean square deviation.

I. INTRODUCTION

One of the most important questions that have arisen in recent years among aviation specialists is the counteraction to armadas of drones with different flight characteristics [1], [2]. A number of systems provide only monitoring and detecting possible violations of the use of drones in the territory limited for their flights.

The task of other systems is to disrupt the channels of communication with the drone, data transmission and control channels of its flight, blackout of the GPS system signals, capture or destroy an enemy drone or group of drones.

One of the ways to physically destroy drones is to use special missiles or shells for this purpose. When they are detonated near the drone, a covering cloud of damaging elements (fractions) is formed and the unwanted drone is hit by these elements. The time delay for detonation is set according to the data from the launcher control system.

This is done automatically at the moment the missile or shell leaves the barrel, using an electronic device in the form of a winding on the muzzle [1].

It is important task to estimate of the size of such cloud, i.e. the calculation of the number of damaging elements in a shell to defeat a drone with a given probability.

Another, alternative, drone countermeasure involves the use of networks to capture drones. It is a simple but effective way to counter unwanted drone flights [3], [4], [6], [7]. Nets are shot in the direction of the drone or quickly rose along course of its motion can also be carried by so-called counter drones.

For example, English company OpenWorks Engineering presented the Sky Wall 100 system [7] – one of the latest developments in the field of countering drones.

The device is a “smart grenade launcher” that shoots a net towards the drone. The effective range of device is up to 100 meters. This device captures the target and helps operator to aim. Besides, it estimates the distance and the drone speed vector. Then the net is lowered by parachute with the captured drone. There are also longer range Sky Wall 200 and Sky Wall 300 systems.

Similar systems are being developed in the USA [4], Russia [3] and Japan [6].

From the above it follows that the task of estimating the zone size of possible positions of the drone during its interception is relevant.

II. PROBLEM STATEMENT

Suppose that at time t_0 position of the drone D1 at a certain point in the airspace and its velocity V_{D1} are fixed (Fig. 1). For the drone-interceptor D2, the time Δt is required in order to overcome the distance from the launcher (LA) to the intended meeting point of both drones. Estimation of the sizes of a zone of possible positions (ZPP) D1 at the moment of time $t_1 = t_0 + \Delta t$ is important for calculation of the necessary area of a net. Besides, analogical task it follows to solve for estimation of the required number of striking elements in the missile, which is detonated near D1.

Let drone D1 will try to move as far away as possible from the expected trajectory of its motion after moment of time t_0.

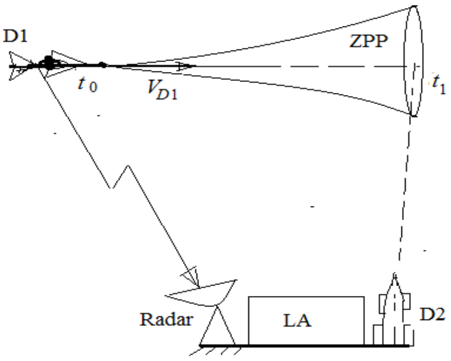

Fig. 1. Interception of a drone by means of a net

The radius of drone rotation D1 in the horizontal plane R_t, which moves with coordinated turn, is proportional to value V_{D1}^2

$$R_t = \frac{V_{D1}^2}{g\sqrt{n_y^2 - 1}}, \qquad (1)$$

where g is the acceleration of gravity, n_y is the normal overload of drone D1.

In this case, there is a relationship between the roll angle (γ) and the value of normal overload, and the centrifugal force F_c, the lifting force Y and the weight G form a triangle, as shown in Fig. 2.

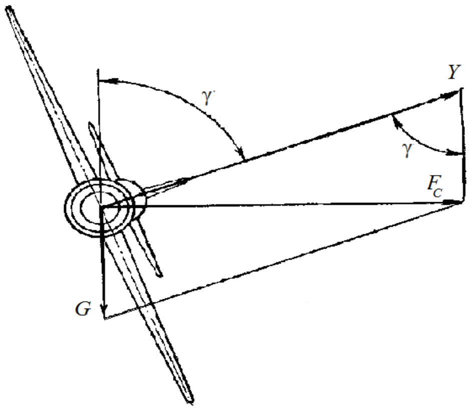

Fig. 2. The coordinated turn of an UAV

Calculating the turning radius of drone D1 in the vertical plane or rotation at spiral motion is a more complex task.

III. PROBLEM SOLUTION

To calculate of the ZPP size, it is convenient to enter a rectangular Cartesian coordinate system with the origin at the point of drone D1 position at time t_0, the OX axis directed along the vector V_{D1} and the OZ axis located in the horizontal plane perpendicular to the OX axis.

As shown in [5], there are relationships between the values L_1, L_2 and R_t (Fig. 3), namely

$$L_1 = R_t \cdot \sin\theta_C, \qquad R_t = L_2 = R_t(1 - \cos\theta_C),$$

where L_1, L_2 are distances that drone D1 travels in the direction of the OX, OZ axes; θ_C is an angle of the vector V_{D1} rotation.

The rotation angle value of the velocity vector D1 is equal

$$\theta_c = (V_{D1}\,\Delta t)\,/\,R_t. \qquad (2)$$

The distance that drone D1 can travel in time Δt without turning is L_3.

The results of the drone trajectories calculations in the horizontal plane for different values of velocity V and n_y at value of $\Delta t = 2$ s are given in Table I.

This method for estimating of the ZPP size can be used only at angles $\theta_C \le \pi/2 \approx 1.57(\text{rad})$, i. e. estimating of the values L1 and L2 for the rows underlined in Table I, namely for values of $V = 30$ m/s at $n_y \ge 3$ incorrect.

Zones of possible positions of the drone D1 for $\Delta t = 2$ s are shown in Fig. 4.

As follows from the calculations, with increasing flight speed of the drone D1 zone of its possible positions increases in equal proportions along the axes OX and OZ.

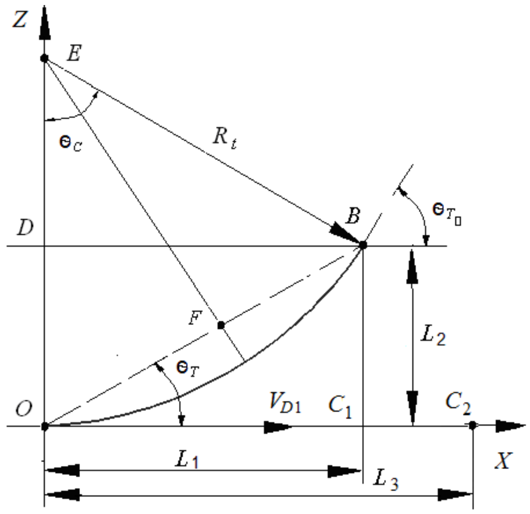

Fig. 3. The scheme of the drone D1 rotation

The expansion of the zone of possible positions along the axis OZ in absolute values is less noticeable and is determined primarily by the value of n_y (Table I).

The dependences of the value R_t from the value n_y for different speeds of the drone D1 are shown in Fig. 5.

At determining the size of the ZPP, it is necessary to take into account the possibility of reversal of the vector V_{D1} by an angle greater than $\pi/2$. The formula for calculating of the overload value n_y, at which such a reversal occurs, according to (1), (2) has the form

$$n_y = \sqrt{1 + \left(\frac{\pi V}{2g\Delta t}\right)^2}.$$

At low flight speeds of the drone, namely at V_{D1} = 30 m/s, the reversal of the velocity vector by an angle greater than π/2 is carried out in two seconds at $n_y \approx 2$.

When the interception time of D1 is doubled, the results do not change in principle (Table II).

However, the number of trajectories increased 3.5 times with the rotation angle of the velocity vector D1 more than by π/2 at the value of Δt = 4 s.

TABLE I. CHARACTERISTICS OF ZPP DRONE D1 AT $\Delta t = 2$ S

V_{D1}, m/s	n_y	R_t, m	θ_C, rad	L_1, m	L_2, m	L_3, m
30	1.5	82.05	0.731	54.79	20.97	60
30	2	52.96	1.133	47.96	30.5	60
30	2.5	40.04	1.499	39.93	37.14	60
30	3	32.43	1.849	31.18	41.36	60
30	4.5	20.91	2.869	5.6213	41.05	60
60	1.5	328.23	0.365	117.34	21.69	120
60	2	211.87	0.566	113.68	33.08	120
60	2.5	160.16	0.749	109.08	42.89	120
60	3	129.74	0.924	103.6	51.64	120
60	4.5	83.64	1.434	82.86	72.29	120
90	1.5	738.51	0.243	178.22	21.82	180
90	2	476.71	0.378	175.75	33.58	180
90	2.5	360.36	0.5	172.60	44.02	180
90	3	291.92	0.616	168.80	53.75	180
90	4.5	188.19	0.956	153.78	79.71	180

TABLE II. CHARACTERISTICS OF ZPP DRONE D1 AT $\Delta t = 4$ S

V_{D1}, m/s	n_y	R_t, m	θ_C, rad	L_1, m	L_2, m	L_3, m
30	1.5	82.05	1.46	81.57	73.17	120
60	1.5	328.23	0.731	219.17	83.9	240
60	2	211.87	1.13	191.86	122	240
60	2.5	160.16	1.49	159.74	148.59	240
90	1.5	738.51	0.48	345.91	86.01	360
90	2	476.71	0.75	326.74	129.59	360
90	2.5	360.36	0.99	303.03	165.35	360
90	3	291.92	1.23	275.44	195.23	360

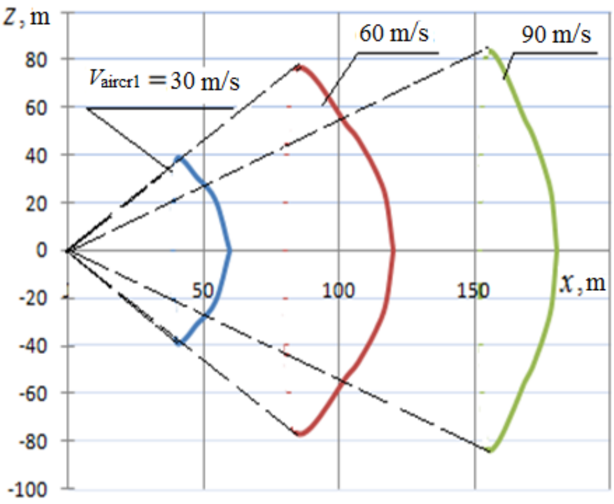

Fig. 4. The ZPP of drone after two seconds

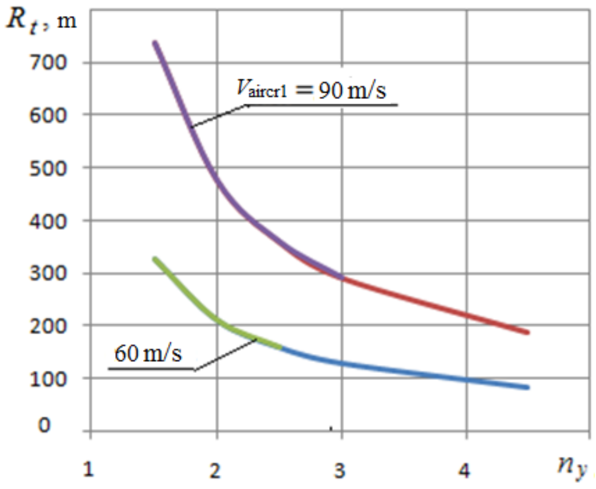

Fig. 5. The dependencies of the value R_t from n_y

To clarify the dimensions of the ZPP, it is necessary to consider typical drone maneuvers in the vertical plane. In this case, the system of equations that describes the drone D1 motion at angles $\gamma = \beta = 0$ and $\Psi = \text{const}$ can be written in the form [8]

$$\dot{V} = g(n_x - \sin\theta), \tag{3}$$

$$\dot{\theta} = \frac{g}{V}(n_y - \cos\theta), \tag{4}$$

$$\dot{L} = V\cos\theta, \tag{5}$$

$$\dot{H} = V\sin\theta, \tag{6}$$

where n_x is longitudinal overload; θ is the angle of the velocity vector inclination to horizontal plane, L (L is analog L_1), H (H is analog L_2) range and flight altitude of the drone.

For the values V = const and n_y = const, the system of equations (3) – (6) breaks down, and from (3) follows the condition for the fulfillment of this flight mode $n_x = \sin\theta$, and (4) can be solved independently of (5) and (6).

After transformation the equation (4) has form

$$\frac{d\theta}{(1-\bar{b}\cos\theta)} = \frac{gn_y}{V}dt, \tag{7}$$

where $\bar{b} = \dfrac{1}{n_y} < 1$.

To solve analytically (7), it is advisable to expand the function $\cos\theta$ in the Maclaurin series

$$\cos\theta = 1 - \frac{\theta^2}{2} + o(\theta^4). \tag{8}$$

Representation (8) gives an error not exceeding 8% at $\theta \le 1$.

Substituting instead of function $\cos\theta$ two terms of the power series from (8) into (7) and integrating both sides of (8) from time $t = 0$ to $t = T$, provided that at $\theta(t=0) = 0$, it is easy to obtain the dependence of the angle θ from time

$$\theta(T) = \sqrt{2(n_y-1)} \cdot \mathrm{tg}\left[\frac{gT\sqrt{2(n_y-1)}}{2V}\right]. \tag{9}$$

After substituting the function $\theta(t)$ from (9) into (5) and (6) and expanding the trigonometric functions into power series, it is can obtain analytical dependences of the range and altitude of the drone flight from time for given initial conditions

$$L = Vt - \frac{g^2k^2t^3}{6V} - \frac{g^4k^3t^5}{30V^3}, \tag{10}$$

$$H = \left[\frac{gkt^2}{2} + \frac{g^3(k^2-k^3)t^4}{24V^2} - \frac{g^5k^4t^6}{72V^4}\right]. \tag{11}$$

where $k = n_y - 1$.

Dependencies of the magnitudes L (10) and H (11) from value n_y in the vertical plane (*VP*) for the drone velocity V = 60 m/s are shown in Fig. 6, and for V = 90 m/s – in Fig. 7.

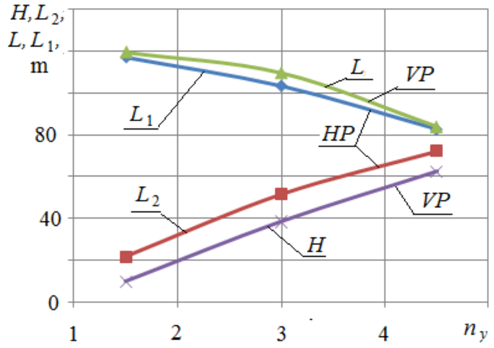

Fig. 6. The range of the drone in direction of *OX* axis and its deviation in direction of axes *OY* and *OZ* at V = 60 m/s

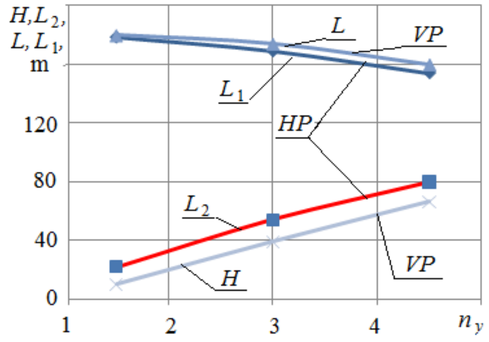

Fig. 7. The range of the drone in direction of *OX* axis and its deviation in direction of axes *OY* and *OZ* at V = 90 m/s

In Figures 6 and 7, for comparison, the values of the distance traveled along the *OX* axis in the horizontal plane (*HP*) and deviations from the trajectory of its movement along the *OZ* axis are shown also. It is follows from calculation at increasing of value n_y absolute magnitudes H are ascended and L descended (Table III). The discrepancy between the distances traveled along the *OX* axis in the vertical and horizontal planes is insignificant. More significant discrepancy is between the deviations of the trajectories in direction of axes *OY* and *OZ*.

So, shape of the ZPP is an ellipse, in which the semi-major axis $a = L_2$ and the semi-minor axis $b = H$.

For convenient it can be used the ZPP to capture drone the rectangular form with common square $S = L_2H$.

TABLE III. THE REQUIRED AREA OF NET AT $\Delta t = 2$ s

V_{D1}, m/s	n_y	L_2, m	H, m	S, m^2
60	1.5	21.69	9.8314	213.27
60	2.5	42.89	29.2	1252.49
60	3.5	59.46	47.17	2805.03
90	1.5	21.83	9.82	214.34
90	2.5	44.03	29.34	1291.62
90	3.5	62.93	48.27	3037.71

As it follows from calculations, the required area of net significantly increases at growing n_y.

The required network dimensions are calculated based on the ensure that the D1 drone reliably hits the net.

Assuming the law of dispersion of drone trajectories in the ZPP to be Gaussian and circular, we can write down the probability its hitting the network of radius R in the form [9]

$$P = 1 - \exp(R^2 / 2\sigma^2), \tag{12}$$

where σ is mean square deviation.

At condition that the form of the ZPP is circular and its sizes for vertical and horizontal planes are identical, we obtain, for example, at V_{D1} = 60 m/s and n_y = 2.5 the area

$$S = 1252.49\ (\text{m}^2) = 3.14 \times 19.97^2\ (\text{m}^2), \text{ i.e.}$$

$$\sigma = 19.97/3 = 6.67\ (\text{m}).$$

Now we can estimate the required sizes of ZPP for given probability of drone hitting the net, for example, setting the probability P = 0.96 (according to the two sigma rule), in accordance with (10)

$$R = \sigma\sqrt{-2\ln(1-P)} = 6.67 \times 2.54 \simeq 16.91\ (\text{m}).$$

Consequently, for a practically reliable hit of D1 in a vertical net with a circular shape, its diameter should be 33.82 m, and its area should be 897.84 m^2. When using a square net, the square side should be approximately the diameter of the circle.

IV. CONCLUSION

According to performed calculations, following conclusions to be made:

- delivery of the net should be carried out with high-speed UAV D2 in order to reduce the time Δt and, accordingly, to reduce the required area of net to capture UAV D1;
- even with a small value of speed V_{D1} = 30 m/s and the overload value n_y = 4.5, the velocity vector of drone for four seconds makes a turn of 329 degrees and when increasing the D1 speed to V_{D1} = 90 m/s and the same value of n_y, the turn of the drone in four seconds is only 110 degrees;
- at increasing overload n_y of D1 the required area of net significantly increases.

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М. Ф. Тупіцин. Оцінювання необхідного розміру мережі для захоплення дрона

Запропоновано методику розрахунку необхідного розміру мережі для захвату дрона. Наведено результати розрахунків траєкторій руху дрона у горизонтальній і вертикальній площинах в залежності від швидкості і нормального перевантаження. Розрахунок траєкторій в горизонтальній площині проводився за формулою координованого розвороту при постійних значеннях швидкості і нормального перевантаження. Отримано аналітичний розв'язок системи диференціальних рівнянь ізольованого руху дрона у вертикальній площині. Згідно з проведеними розрахунками, доставка мережі до небажаного дрону повинна здійснюватися за допомогою високошвидкісного безпілотного літального апарата, щоб скоротити час перехоплення і, відповідно, зменшити необхідну площу мережі для його захоплення.

Ключові слова: чиста площа; захоплення безпілотника; конус траєкторії; швидкість і нормальне перевантаження безпілотника; середнє квадратичне відхилення.

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Н. Ф. Тупицин. Оценка необходимого размера сети для захвата дрона

Предложена методика расчета необходимого размера сети для захвата дрона. Приведены результаты расчетов траекторий движения дрона в горизонтальной и вертикальной плоскостях в зависимости от скорости и нормальной перегрузки. Расчет траекторий в горизонтальной плоскости производился по формуле координированного разворота при постоянных значениях скорости и нормальной перегрузки. Получено аналитическое решение системы дифференциальных уравнений изолированного движения дрона в вертикальной плоскости. Согласно проведенным расчетам, доставка сети к нежелательному дрону должна осуществляться с помощью высокоскоростного беспилотного летательного аппарата, чтобы сократить время перехвата и, соответственно, уменьшить требуемую площадь сети для его захвата.

Ключевые слова: площадь нетто; захват дрона; конус траектории; скорость и нормальная перегрузка дрона; среднеквадратическое отклонение.

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