

NEW ALGORITHM FOR CALCULATING THE REQUIRED NUMBER OF UNMANNED AERIAL VEHICLES AND THE DURATION OF THEIR STAY IN DANGEROUS AREA

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This paper proposes a new approach to calculate the time spent by unmanned aerial vehicle (UAV) in dangerous area with the consideration of the maximum allowed probability of losing UAV and the increasing rate of this probability in a given area. Unlike the known approaches, which are based on flying around the dangerous areas, it is proposed to cross the boundaries of the dangerous area for a defined time, which is calculated to allow the obtaining of the required data set about the interested area. Based on the UAV loss probabilities estimates, an approach to planning the number of UAVs in a group flight is substantiated, taking into account losing them. The formula for calculating the required number of UAVs, obtained by this approach, consists of three terms, which consider the requirements for pre-flight task accomplishment, high-quality in-flight service of new requests, as well as the necessary reserve in case of the decrease of UAV performance. To evaluate the quality of the proposed algorithm, various case with different initial conditions in determining the time of stay in dangerous zone are considered. The specified time minimizes the given indicator. In addition, the paper presents practical example where the algorithm is used to observe a territory by a group of UAVs. It is shown that the algorithm can determine the required number of UAVs to study an area with a given dimension, and it also can calculate the time of stay of each UAV in the dangerous area in order to reduce the loss probability of UAVs.

Keywords: unmanned aerial vehicle, dangerous zone, survivability, observation

1 INTRODUCTION

Recently, there is an upgrowing tendance to solve a lot of tasks t with the help of UAV [1-3,17, 20]. Among these tasks, there is a great interest in tasks involved in obtaining information in extreme conditions (see Fig. 1), which prevent human presence in a given area. Moreover, these conditions prove to be unfriendly and cause a significant reduction in the allowed time to have UAV work there, due to the high probability of onboard radio-electronic equipment failure in such areas (high temperatures in area of fires, the effect of radiation on the contaminated area, the effect of chemicals etc.). These areas include: areas of fires, radiation contamination, chemical, etc.

Many papers have considered the flights around dangerous areas to reduce the risk of UAV loss [4, 5]. For example, in [4], the authors discuss that a short-term stay of an aircraft in dangerous area is not recommended, although the use of a group of UAVs [6, 7] significantly increases the valuable information received from UAVs even with a short-term stay of each of them in different parts of the dangerous area. Crossing of dangerous area is very important when there is a need to deliver medical supplies, food and communication devices into the disaster area.

In [8], a path-planning algorithm is proposed based on a threat probability map, which is built upon a priori observational data. This study analyzes the case when communication with the operator is lost, and the UAV has to map out a flight plan to perform the area survey by itself. Based on the results of this study, it is concluded that with the increase of the time spent in dangerous zone, the transition from manual control mode (by operator commands) to automatic mode is desired. However, the study doesn't provide the structure of the objective function, nor the specific factors affecting the survivability of UAV are indicated, and the conclusions provide only a recommendation about the choose of preferred control method in dangerous zone.

In [9], an algorithm for planning a safe UAV route in dangerous environment at low height with obstacles, static and dynamic threats is presented. The algorithm is formed on the basis of fuzzy sets. Nevertheless, implementing this approach requires an appropriate rule base, and does not always guarantee an exact solution, particularly for such tasks.

In [15], the authors propose an approach to reduce the length of UAV's path in order to reduce the task execution time. However, the algorithm does not take into account that in dangerous zones there is a risk of loss the efficiency of UAV devices. As dangerous factors for UAV, the authors consider only natural obstacles (terrain relief) and wind perturbation.



Fig. 1. Example of monitoring dangerous fire area using multi-rotor UAV.

Therefore, the task of calculating stay time of UAV in dangerous area, taking into account limitations of UAV's loss probability, is practically important and relevant.

2 PROBLEM STATEMENT

The algorithm of calculating the allowed time of an aircraft to stay in dangerous area is formulated as follow:

1. Given the total number of n UAVs and m dangerous areas;
2. The admissible probability of UAV losing is known: P_{ad} ;
3. The probability of UAV losing is a priori known: P_{0i} .

Due to the need to acquire detailed information about the area to be observed, the UAV has to perform a low-height flight, which leads to an increase in the probability of UAV's loss [9].

Based on previous results [10], as well as works on the same topic, the objective function for optimization can be calculated as follow:

$$P_i = (P_{0i} + b \cdot t + k \cdot t^2) \cdot e^{-\alpha t}, \quad (1)$$

where t – duration of stay in the dangerous area, b – given coefficient of the UAV loss probability growth rate, k – given UAV loss probability growth acceleration coefficient, α – degree of uncertainty about the situation in the observed area, i – ordinal number of UAVs.

Then formula (1) can be written as:

$$P_i = P_{0i} \cdot e^{-\alpha t} + b \cdot t \cdot e^{-\alpha t} + k \cdot t^2 \cdot e^{-\alpha t}. \quad (2)$$

The optimization criterion takes the following form:

$$J = \min_t P_i(t). \quad (3)$$

2.1 Requirement

Determine for each UAV the amount of allowable time to stay in the dangerous area in order to minimize the probability of losing the UAV.

In order to do this, the following condition about the change rate of the losing UAV probability in dangerous area must be satisfied:

$$b + 2k \cdot t \leq dP_{ad}. \quad (4)$$

It is necessary to solve an optimization task and form an algorithm for calculating the required stay time for UAV in a dangerous area, depending on the conditions that caused by man-made catastrophe in a given observed area.

3 SOLUTION WITH METHOD OF LAGRANGE MULTIPLIERS

To solve this task, it is proposed to use the method of Lagrange multipliers [11, 12], which allows to reduce the task from finding the conditional extremum to finding the unconditional extremum of Lagrange function.

Considering (2), the equation (4) with Lagrange function takes following form:

$$L = P_{0i} \cdot e^{-\alpha t} + b \cdot t \cdot e^{-\alpha t} + k \cdot t^2 \cdot e^{-\alpha t} + \lambda [b + 2k \cdot t - dP_{ad}] \quad (5)$$

Then the extremum conditions can be calculated as:

$$\begin{cases} \frac{\partial L}{\partial t} = 0, \\ \frac{\partial L}{\partial k} = 0, \\ \lambda[b + 2k \cdot t - db] = 0. \end{cases} \quad (6)$$

Considering the calculated partial derivatives of the Lagrange function (5), the system (6) can be formulated as:

$$\begin{cases} -P_{0i} \cdot \alpha \cdot e^{-\alpha t} + b \cdot e^{-\alpha t} - \alpha \cdot t \cdot b \cdot e^{-\alpha t} + 2k \cdot t \cdot e^{-\alpha t} - k \cdot t^2 \cdot \alpha \cdot e^{-\alpha t} + 2\lambda \cdot k = 0, \\ t^2 \cdot e^{-\alpha t} + 2\lambda \cdot t = 0, \\ \lambda = 0, \\ \text{or} \\ b + 2k \cdot t - dP_{ad} = 0. \end{cases} \quad (7)$$

Equation (7) can be solved in two ways. The first way can be considered for $\lambda = 0$.

$$\begin{cases} -P_{0i} \cdot \alpha \cdot e^{-\alpha t} + b \cdot e^{-\alpha t} - \alpha \cdot t \cdot b \cdot e^{-\alpha t} + 2k \cdot t \cdot e^{-\alpha t} - k \cdot t^2 \cdot \alpha \cdot e^{-\alpha t} + 2\lambda \cdot k = 0, \\ t^2 \cdot e^{-\alpha t} + 2\lambda \cdot t = 0, \\ \lambda = 0, \end{cases} \quad (8)$$

In this case, the first equation can be rewritten as follow:

$$\begin{aligned} -P_{0i} \cdot \alpha + b - \alpha \cdot t \cdot b + 2k \cdot t - k \cdot t^2 \cdot \alpha &= 0, \\ k \cdot \alpha \cdot t^2 - (2k - \alpha \cdot b)t + (P_{0i} \cdot \alpha - b) &= 0, \end{aligned} \quad (9)$$

$$\text{So, we have } t_{1,2} = \frac{(2k - \alpha \cdot b) \pm \sqrt{(2k - \alpha \cdot b)^2 - 4k \cdot \alpha (P_{0i} \cdot \alpha - b)}}{2k\alpha}.$$

With given k, α, b, P_{0i} , the time of stay in dangerous area can be calculated if the following inequality is fulfilled:

$$\begin{aligned} (2k - \alpha \cdot b)^2 - 4k \cdot \alpha (P_{0i} \cdot \alpha - b) &\geq 0, \\ (2k - \alpha \cdot b)^2 &\geq 4k \cdot \alpha (P_{0i} \cdot \alpha - b). \end{aligned}$$

Then, by squaring the left-hand side and subtracting the similar terms, we obtain the following inequality

$$\alpha \leq \frac{2k}{\sqrt{4k \cdot P_{0i} - b^2}}. \quad (10)$$

After that, considering the second case when $\lambda \neq 0$, we will get:

$$\begin{cases} -P_{0i} \cdot \alpha \cdot e^{-\alpha t} + b \cdot e^{-\alpha t} - \alpha \cdot t \cdot b \cdot e^{-\alpha t} + 2k \cdot t \cdot e^{-\alpha t} - k \cdot t^2 \cdot \alpha \cdot e^{-\alpha t} + 2\lambda \cdot k = 0, \\ t^2 \cdot e^{-\alpha t} + 2\lambda \cdot t = 0, \\ b + 2k \cdot t - dP_{ad} = 0. \end{cases} \quad (11)$$

From the third equation we have:

$$t_3 = \frac{dP_{ad} - b}{2k}. \quad (12)$$

Thus, the solutions of the system of equations (7) for $\lambda = 0$ and ($\lambda \neq 0$) are obtained.

3.1 The calculation part

In order to test the performance of the developed algorithm, the calculation according to two cases will be considered.

3.1.1 First case

There is a priori information about the dangerous area as follows:

1. A priori probability of UAV loss: $P_{0i} = 0.1$;
2. The increasing rate of the probability of losing UAV: $b = 0.01$ 1 pcs/sec;
3. The acceleration of the increasing rate of the probability of losing UAV: $k = 0.001$ 1 pcs/sec².

According to (10), we have:

$$\alpha \leq \frac{2k}{\sqrt{4k \cdot P_{0i} - b^2}}$$

or

$$\alpha \leq \frac{2 \cdot 0,001}{\sqrt{4 \cdot 0,001 \cdot 0,1 - 0,01^2}} \leq 0,12.$$

Taking $\alpha = 0,1$.

Then, for the first case ($\lambda = 0$), we have:

$$t_{1,2} = \frac{(2k - \alpha \cdot b) \pm \sqrt{(2k - \alpha \cdot b)^2 - 4k \cdot \alpha(P_{0i} \cdot \alpha - b)}}{2k\alpha}$$

$$t_{1,2} = \frac{(2 \cdot 0,001 - 0,1 \cdot 0,01) \pm \sqrt{(2 \cdot 0,001 - 0,1 \cdot 0,01)^2 - 4 \cdot 0,001 \cdot 0,1(0,1 \cdot 0,1 - 0,01)}}{2 \cdot 0,001 \cdot 0,1}$$

$$t_{1,2} = \frac{0,001 \pm 0,001}{0,0002},$$

$$t_1 = 0 \text{ sec},$$

$$t_2 = 10 \text{ sec}.$$

Next, t_1 and t_2 – the duration of UAVs in the danger zone, are substituted into the right side of the objective function (1).

The value $t_1 = 0$ sec corresponds to the recommendation not to enter the dangerous area. In this case, there will be no information about the given area, and the probability of losing the UAV will correspond to the a priori value:

$$P_{i1} = (0,1 + 0,01 \cdot 0 + 0,001 \cdot 0) \cdot e^{-0,1 \cdot 0} = 0,1.$$

With $t_2 = 10$ sec the probability of losing the UAV is:

$$P_{i2} = (0,1 + 0,01 \cdot 10 + 0,001 \cdot 100) \cdot e^{-0,1 \cdot 10} = 0,3 \cdot 0,37 = 0,11 > 0,1.$$

In the second case ($\lambda \neq 0$) we have:

$$t_3 = \frac{dP_{ad} - b}{2k}.$$

So, let's consider the situation 2 when $\lambda \neq 0$ with the corresponding t_3 and P_{i3} :

Suppose $dP_{ad} = 0,02$, then:

$$t_3 = \frac{0,02 - 0,01}{2 \cdot 0,001} = 5 \text{ sec}.$$

$$P_{i3} = (0,1 + 0,01 \cdot 5 + 0,001 \cdot 25) \cdot e^{-0,1 \cdot 5} = 0,175 \cdot 0,6 = 0,105 > 0,1.$$

The first case shows that being in a dangerous area for a period of 5-10 seconds provides a probability of losing UAV comparable with flights around this area without crossing its borders. At the same time, it is possible to reduce the level of entropy about the specified area.

3.1.2 Second case

In this case, the following a priori information about the dangerous area are known:

1. $P_{0i} = 0,1$;
2. $b = 0,02$ pcs/sec;
3. $k = 0,003$ pcs/sec².

As formula (10) stated above, having

$$\alpha \leq \frac{2k}{\sqrt{4k \cdot P_{0i} - b^2}}$$

or

$$\alpha \leq \frac{2 \cdot 0,003}{\sqrt{4 \cdot 0,003 \cdot 0,1 - 0,02^2}} \leq 0,214.$$

Taking $\alpha = 0,21$.

Then, for the first case ($\lambda = 0$), having

$$t_{1,2} = \frac{(2k - \alpha \cdot b) \pm \sqrt{(2k - \alpha \cdot b)^2 - 4k \cdot \alpha (P_{0i} \cdot \alpha - b)}}{2k\alpha}$$

$$t_{1,2} = \frac{(2 \cdot 0.003 - 0.21 \cdot 0.02) \pm \sqrt{(2 \cdot 0.003 - 0.21 \cdot 0.02)^2 - 4 \cdot 0.003 \cdot 0.21(0.1 \cdot 0.21 - 0.02)}}{2 \cdot 0.003 \cdot 0.21}$$

$$t_{1,2} = \frac{0.0018 \pm 0.00084}{0.00126},$$

$$t_1 = 0.76 \text{ sec},$$

$$t_2 = 2 \text{ sec}.$$

Next, t_1 and t_2 are substituted into the right side of the objective function (1).

$$P_{i1} = (0.1 + 0.02 \cdot 0.76 + 0.003 \cdot 0.76^2) \cdot e^{-0.21 \cdot 0.76} = 0.1169 \cdot 0.85 = 0.099 < 0.1,$$

$$P_{i2} = (0.1 + 0.02 \cdot 2 + 0.003 \cdot 2^2) \cdot e^{-0.21 \cdot 2} = 0.152 \cdot 0.657 = 0.099 < 0.1.$$

For the second case ($\lambda \neq 0$), having:

$$t_3 = \frac{dP_{ad} - b}{2k}$$

Take $dP_{ad} = 0.04$, then:

$$t_3 = \frac{0.04 - 0.02}{2 \cdot 0.003} = 3.3 \text{ sec}.$$

$$P_{i3} = (0.1 + 0.02 \cdot 3.3 + 0.003 \cdot 3.3^2) \cdot e^{-0.21 \cdot 3.3} = 0.199 \cdot 0.5 = 0.0995 < 0.1.$$

In this situation, there are 3 options for the stay time in the dangerous area. The option with $t_3 = 3,3$ sec is considered preferable, since it provides more time in the dangerous zone for data collection and at the «cost of observation» comparable to the other two cases (P_3).

3.2 Planning the number of aircrafts in group flight considering the loss of their survivability

When planning a group flight in a dangerous area, the number of UAVs N in the group should be increased due to possible losses of some of them [13, 14].

In this situation, by using the value P_d , which is calculated by the already described approach, the average number K of UAV that could be lost might be approximately estimated with a given number of observation objects n as follow:

$$K = 1 - (1 - P_d)^n \cong nP_d. \quad (13)$$

Analysis shows that the specified value of K determines the required number of additional UAVs ΔN_2 . Moreover, estimating this value allows to calculate the required number of backup plans before departure. Thus, in various cases, the number of UAVs lose could be: one, two, etc. Consequently, this allows switching to a new group flight mode during the current flight in the seek of optimizing the time. The number L of possible backup plans for pre-flight planning is calculated as:

$$L = 0.5[N(N + 1) - K(K + 1)]. \quad (14)$$

The scheme for switching the operation of UAVs group from the main plan to a backup plan due to the loss of one UAV is shown in fig. 2. This figure shows as an example the transition of the 4th UAV to the backup plan for carrying out the observation of the lost 3rd UAV.

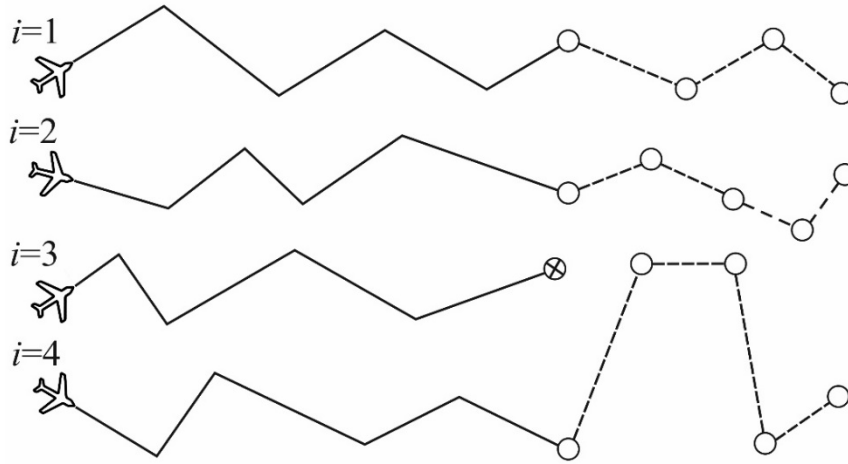


Fig. 2. Four UAVs group flight scheme in the case of one UAV failure.

The results of computer simulation show that the required number of UAVs to service requests that appeared before the flight on average equals to:

$$\Delta N_0 = \frac{n(r_{av} + V\Delta t)}{V \cdot T} \tag{15}$$

where $V \cdot T / (r_{av} + V\Delta t)$ – the average number of requests before the flight, served by one UAV during flight.

Then the general formula for estimating the number of UAVs N required for successful service takes the following form:

$$N = \Delta N_0 + \Delta N_1 + \Delta N_2 = \frac{n(r_{av} + V\Delta t)}{V \cdot T} + \frac{\lambda \cdot r_{av}}{V} + n \cdot P_d \tag{16}$$

where Δt – idle time for service-free UAVs, V – medium speed of UAV, r_{av} – medium length of UAV's path, T – UAV flight duration.

The first term allows to calculate the number ΔN_0 to complete the pre-flight task. The second term involves the calculation of the required number of UAVs to serve the new requests received during flight, where λ is the frequency of requests. The third term determines the number of UAVs, taking into account the necessary reserve for replenishment of the aviation group in the event of a partial failure of UAV. In general, the value of N depends on the seven parameters specified in the initial data for the example above.

As an example, the number of UAVs was calculated with the following data:

$n = 100$; $T = 220$ minutes; $V = 2$ km/min; $\Delta t = 1$ min; $r_{av} = 20$ km; $\lambda = 0.1$ pcs/min; $P_d = 0.02$. As a result of the calculation, $N = 5 + 2 + 1 = 8$. Therefore, the number N , which ensures successful observation process, is calculated.

The functional system architecture of the algorithm proposed in this paper is represented in fig. 3. On the basis of a priori data on the given area, the number of UAVs (N) and their time stay in the zone of in the field of man-made disaster (t), which minimizes the probability of UAV loss, are calculated. It is assumed that the developed algorithm is implemented as a prototype of a program module in the ground UAV control station.

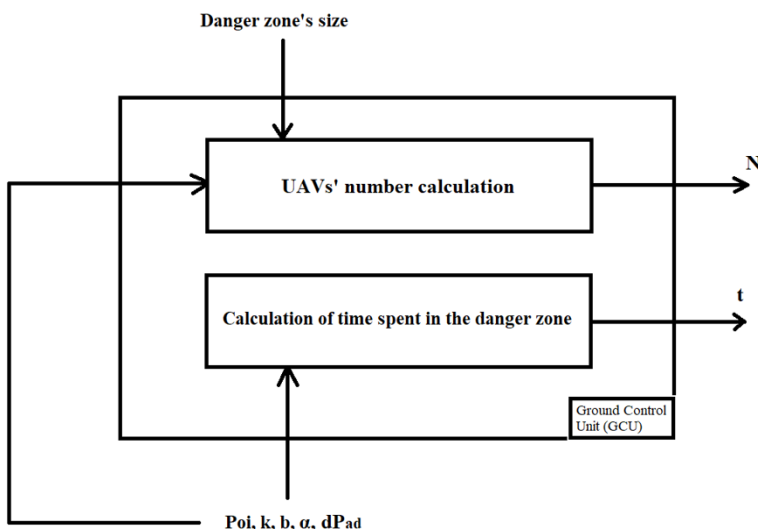


Fig. 3. Functional scheme of the proposed algorithm.

4 EXPERIMENTAL SETUP

Table 1. Initial data for experiment

| | | |
|----|--|-------------|
| 1. | A dangerous zone to observe, $d \times d$ [m ²] | 1000 x 1000 |
| 2. | The view area of UAV camera is a circle with radius R , [m] (Note: The height of the flight is 15 m, the view angle – 80°). | 12 |
| 3. | UAV average velocity, V_{av} , [km/h] | 30 |
| 4. | Probability of UAV loss, P_{0i} | 0.1 – 0.2 |
| 5. | The limitation of probability of UAV loss changing rate in dangerous zone, dP_{ad} , [1/sec] | 0.04–0.05 |
| 6. | For the group of UAVs there is a requirement to prevent the decrease of successful performance possibility at a given threshold, P_{pri} | 0.9 |

4.1 Requirements

1. Calculate the required number of UAVs.
2. Estimate the total time needed to observe entire area of the given zone under different initial conditions (k , α , b , P_{0i} , dP_{ad}).
3. Calculate how many times UAV needs to get in and out of the zone, taking into account the rate of the increase of the probability of UAV's loss in a given area.

By applying the proposed algorithm, the results were obtained considering the following initial conditions:

$P_{0i} = 0.1$; $b = 0.02$; $k = 0.003$; $dP_{ad} = 0,04$ and $\alpha = 0.21$.

Table 2. Simulation results

| Variable indicator of formula (2) | Time spent in the zone (t_1 , t_2), [s] | The indicator value (2) | Required number of UAVs (N_r) | Full time of observation, [min] | Number of times that one UAV can be in the zone |
|---|---|-------------------------|-----------------------------------|---------------------------------|---|
| $P_{0i} = 0.2$ ($\alpha < 0,134$) $\alpha = 0.13$ | 6.26 | 0.196 | 24 | 13-13.5 | 93 |
| | 2.46 | 0.194 | 32 | 10 | 69 |
| $b = 0.015$ | 4.17 | 0.066 | 28 | 11-11.5 | 79 |
| $k = 0.001$ | 10 | 0.026 | 19 | 17-18 | 117 |
| $dP_{ad} = 0.05$ | 5 | 0.064 | 26 | 12-13 | 86 |
| $k = 0.0008$ | 12.5 | 0.018 | 17 | 18.5-19 | 131 |
| $dP_{ad} = 0.125$ | 17.5 | 0.0265 | 14 | 23 (> 20) | 159 |

From Table 2 it can be concluded that when using fewer UAVs for observing the zone of man-made catastrophes, the number of the necessary times to get into the dangerous area will increase, and the observation time of the entire area also increases. Therefore, it is necessary to choose a compromise solution here: to use smaller number of UAVs to reduce the costs, or to use more of them for faster observation of the dangerous zone. The results of calculating the time for full coverage of the territory make it possible, during preliminary and operational planning, to estimate the number of UAVs involved, taking into account the need for UAV rotation for refueling or recharging.

In addition, with the increasing probability of UAV's loss while planning a group flight in a dangerous zone, the following steps should be taken:

- the number of UAVs planned to service in one flight must be reduced, and the total number of them and backup routes of the flight L should be increased
- the use of backup plans before flights will expectedly significantly increase the probability of successful task and reduce the time of acquiring information about the situation in the man-made disaster zone.

5 DISCUSSION AND COMPARISON

The task of ensuring the flight of UAVs in dangerous area has recently received considerable attention. In addition, various ways of operation in such difficult conditions are suggested. For example, in [4, 5, 18], the authors propose to bypass dangerous areas in order to minimize the probability of loss of UAVs. Part of the work [8] is devoted to compare UAV control methods in dangerous area in order to increase the probability of successful flight. There is a

known approach which use intelligent algorithms based on fuzzy logic to build a safe route in a dangerous area. However, if it is about a man-made catastrophe, then the affected area can be quite large, and the task of route creation must still take into account the limitations of the time stay in this area, which is not considered in these works. In [21], the authors used only the weighted sum of risk and flight time as indicator of the effectiveness of UAV trajectory planning. In this regard, the functionality (2) presented in this paper takes into account the rate and acceleration of risk growth, and also the change in the uncertainty of information about the situation in the disastrous zone. This, in our opinion, is extremely important to consider when solving such problems. Moreover, the papers do not consider the flight of a group of UAVs in a distributed area of a man-made catastrophe, which should significantly increase the efficiency of UAVs in such conditions. As a result, it is necessary to determine the required number of UAVs and backup plans in the case of performance loss of one or more UAV.

6 FUTURE WORK

The algorithm given in this work will be further improved, that's because to perfectly optimize the observation of a given dangerous area by a group of UAVs, it is necessary to use modern clustering methods [16]. In this regard, the whole area will be divided into clusters, and each UAV will be assigned its cluster to execute the observation over it. This will increase the speed of the algorithm, reduce the time for obtaining complete information about the given observed area, and also reduce the probability of UAV's loss during group flight.

7 CONCLUSIONS

This paper proposed and evaluated a new algorithm that allows the calculation of the time stays of UAV in a dangerous area, considering the minimization of the probability of losing UAV. Unlike the known methods of flights into dangerous areas, this approach increases situational awareness, including crossing the borders of these areas. The calculation results are presented, which demonstrate that by increasing the time stay in dangerous area in 2.5 times, the required number of UAVs for observing this area will decrease in 1.5 times, and in this case the probability of UAV lose is commensurate. This proposed algorithm can be implemented as a software module for UAV ground control stations.

Furthermore, a general formula has been obtained for determining the number of UAVs in one flight, and it consists of three terms – to complete the pre-flight mission, to service the requests received during flight, and to replenish the reserve taking into account the loss of survivability of UAVs, which generally ensures successful fulfilling of the observation process.

8 ACKNOWLEDGEMENT

The reported study was funded by RFBR, project number 20-08-00652 a.

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Paper submitted: 02.03.2022.

Paper accepted: 11.05.2022.

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