Control of unmanned aerial vehicles during fire situation monitoring

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Abstract: *The issues of increasing the efficiency of fire situation monitoring are discussed, during which the search for objects of interest is being conducted to organize rescue operations and plan activities to fight the fire and reduce the consequences. Modern unmanned aerial vehicles equipped with vision systems, allow us to automatically explore the search area and detect various objects of interest. Monitoring is realized by controlling the trajectories and altitude of the aircraft, as well as receiving and analyzing images of the underlying surface, taken by onboard visual systems. The article offers a method for determining the altitude of flight of unmanned aerial vehicles during monitoring of the fire situation, taking into account the safety of aircraft and the conditions of observability of objects of interest. We consider some options for assessing the effectiveness of monitoring based on the search criteria of objects and the safety of unmanned aerial vehicles.*

Key Words: *unmanned aerial vehicle, fire monitoring, search for objects of interest, observability, flight safety*

1. INTRODUCTION

Aviation monitoring by unmanned aerial vehicles (UAV), in particular the search for objects [1], [2], [3], [4], is one of the important stages of the survey of areas of interest, including the events of various emergencies. In the process of monitoring of fire situation, people, cars and other equipment are searched for organizing rescue operations, the danger of fire spreading, the possibility of damage to important objects, etc. is estimated, firefighting and mitigation measures are planned.

Modern unmanned aerial vehicles (UAVs) are equipped with technical vision systems (TVS) [5], [6], [7] that allow automatic detection of various objects of interest. The monitoring process of the surveyed area is done by managing search tools, for example, the UAV trajectory, flight altitude, as well as receiving and analyzing TVS images of the underlying surface and depends on specific search situations.

The construction of navigation systems (NS) and control systems (CS) of UAVs are considered in [8], [9], [10], [11]. It was shown that in modern NS the information obtained from various on-board sensors and integrated using Kalman filtering [12] is used to ensure the required accuracy of navigation. In the works [13], the existing methods of planning and control of the effective flight of UAVs as a group are discussed. In [14], [15], the results of studies on the formation of the management of UAV groups are shown. In [16], a demonstration of the flight of a group of UAVs is described.

To search for objects in difficult conditions it was suggested to use the methods of analysis and assessment of situations (situation assessment) [17], [18], [19]. These methods permit to create reference descriptions of objects of search, in particular, using heuristic methods. The basic issues of the formation of descriptions, which are the basis of the analysis of situations, are discussed in [20]. There are some known works on solving the problems of situational management, but in the analysis of observed emergencies in area of research is not well developed.

Fire monitoring should be performed, taking into account the special conditions of operation of aircraft. The presence of flame and smoke increases the possible errors of object detection and compromises the safety of a UAV flight. The arising contradiction between the required observability of objects and the safety of UAVs must be solved by finding the altitude at which the extremum of the monitoring criteria used will be ensured. Nonetheless, control of flight altitude with regard to observability and safety criteria can be implemented only with the use of fire situation models [21].

When the fire situation is affecting the specified criteria, it depends on many factors. For example, in case of forest fires, the factors include height and species of trees, density of forests, humidity and precipitation, strength and direction of wind, etc. All of these factors influence the observability of the ground target objects of interest, as well as safety of a UAV flight.

In this work, a method for calculating the optimal UAV flight altitude is proposed. The novelty of the technique is the using of a monitoring efficiency criterion that takes into account losses associated with errors in detecting objects of interest and losses of UAV associated with exposure to fire hazards. The calculation of losses is based on the heuristic models of object observability and the safety of a UAV flight suggested by the authors. The practical significance of the technique lays in the possibility of increasing productivity and reducing the required search means of aviation monitoring in difficult conditions of UAV operation.

2. METHODOLOGY

2.1 Selection of monitoring performance criteria

Let us assume that the evaluation of the effectiveness of monitoring is determined by the losses associated with errors in detecting objects of interest and possible losses of UAV when exposed to destructive factors of fire. Let us MENTION the total monitoring loss when searching for objects by a group of UAVs:

$$R_{\Sigma}(h) = a_a R_a(h) + a_s R_s(h) \tag{1}$$

where $R_a(h)$- losses associated with errors in the search for objects; $R_a(h)$- UAV losses due to flight altitude h; $R_a(h)$- loss ranking coeficients.

Choice of coefficients $R_a(h)$ made on the basis of expert evaluation in accordance with the conditions of the specific problem being solved. Optimum flight height UAV $R_a(h)$ is determined at minimal losses:

$$h_{opt} = arg[min\, R_{\Sigma}(h)]. \tag{2}$$

The height value that determines the minimum of the total loss of function (1) depends on the type and parameters of the functions $R_a(h)$ and $R_s(h)$, as well as the choice of ranking coefficients a_s, a_a. The complexity of solving the issue is determined by the lack of analytical dependencies $R_a(h)$ and $R_s(h)$. The derivation of these functions based on well-known physical laws seems extremely difficult, therefore, the authors suggest using a heuristic approach based on the methods of analyzing cases. The loss model is associated with object search mistakes. Losses connected with observations will be limited by the conditional probability of the error of detecting some object of interest ("goal skipping" error).

In the present study, cars are taken as the searched objects of interest. The invariant moments [5] of the chosen objects were chosen as the working features. Object detection errors increase as the image contrast becomes worse, which in turn is determined by the smoke over the observed scene. Let's suppose in the surveyed area there F are sites differing in conditions of supervision. At the same time on each $f \in F$ observation conditions remain the same at the site (constant smoke parameters). For an empirical description of the change in contrast from the height h in the region *f*, a sigmoid was selected with parameters k_f and K_{fmax} where k_f – is empirical ratio of fire conditions, atmospheric conditions, etc.; h_f – the height at which the contrast of the image of the *f*- th region is 0.5, $f \in F$ – is fire area index, F – number of sites.

Parameter evaluation k_f, h_f is suggested to make on the basis of methods for analyzing situations using previously prepared rules. The following are examples of rules for estimating visibility parameters:

- If the surface is in forest and the fire is strong and the humidity is at high level, then $0.7 < k_a < 0.9$;
- If the surface is in forest and the fire is weak and the forest is rare and the humidity level is low, then $h_a > 0.7\ h_t$, $0.4 < k_a < 0.6$;
- If the surface is a field and the fire is strong and the humidity level is low, then $h_a >$ 3m;
- If the surface is a field and the fire is strong and the humidity level is high, then $h_a >$ 5m;

In addition to changes in contrast, the received images are influenced by random factors, which are taken into account in the model by the value $\beta = \frac{\sigma_s^2}{\sigma_n^2}$ where σ_s – is the standard deviation of the signal, σ_n – means the standard deviation of the additive white Gaussian noise with zero expectation.

Based on studies in statistical modeling, the following empirical dependence for losses was obtained, based on an estimate of the probability of detection errors.

$$R_a(h) = \left[1 - \frac{1}{1 + e^{-k_f(h-h_f)}}\right]\left[\frac{1}{1 + e^{-\beta}}\right] \tag{3}$$

2.2 The model of UAV loss

Let's assume that at low altitudes (for example, several meters) flight safety is significantly influenced by the thermal effects of fire and objects located on the flight path of a UAV (buildings and structures, trees, bushes, etc.). Let's assume that the relative safety of the UAV is estimated by the probability of the loss (accident) of the UAV and varies depending on the flight altitude in the range: 0 ÷ 1:

$$R_s(h) = \frac{1}{1 + e^{-k_s(h-h_s)}}, \tag{4}$$

where k_s – is empirical ratio determined by taking into account the intensity of the fire, the location of ground objects, flight conditions; h_s – flight altitude of the UAV, at which the relative safety of the flight is 0.5, respectively; s is the index of flight safety criteria.

At $R_s(h) = 1$ UAV suffers an accident leading to its destruction, while $R_s(h) = 0$ flight conditions are absolutely safe. Therefore, the total losses in monitoring, in accordance with (1) and taking into account (3), (4), are defined as:

$$\boldsymbol{R_\Sigma(h) = a_a R_a(h) + a_s R_s(h)} \tag{5}$$

therefore,

$$\boldsymbol{R_\Sigma(h) = a_a \left[1 - \frac{1}{1 + e^{-k_f(h-h_f)}}\right]\left[\frac{1}{1 + e^{-\beta}}\right] + a_s \frac{1}{1 + e^{-k_s(h-h_s)}}} \tag{6}$$

3. RESULTS AND DISCUSSIONS

On the basis of mathematical modeling, in accordance with (5), losses can be calculated for various monitoring conditions. Fig. 1 shows graphs of total losses with the same parameters of the fire and with different loss ranking factors: a_s = 0.2, a_a = 0.8 – dashed line, a_s = 0.8, a_a = 0.2 – solid line.

The dashed line depicts that when flying at a height of less than 9 m, the relative losses do not exceed a value of 0.2. A low level of losses is determined by a small value of the ratio a_s = 0.2. Although many UAVs may be lost at these heights, for this monitoring case as a whole, these losses are insignificant. For example, if the search objects are of high value, the correct detection of one object may compensate for the loss of several UAVs. When flying above 9 m, the observability of objects decreases, which leads to an increase in detection errors. Due to the deterioration of visibility, the total monitoring loss increases due to an increase in non-detection errors ("goal skipping" errors).

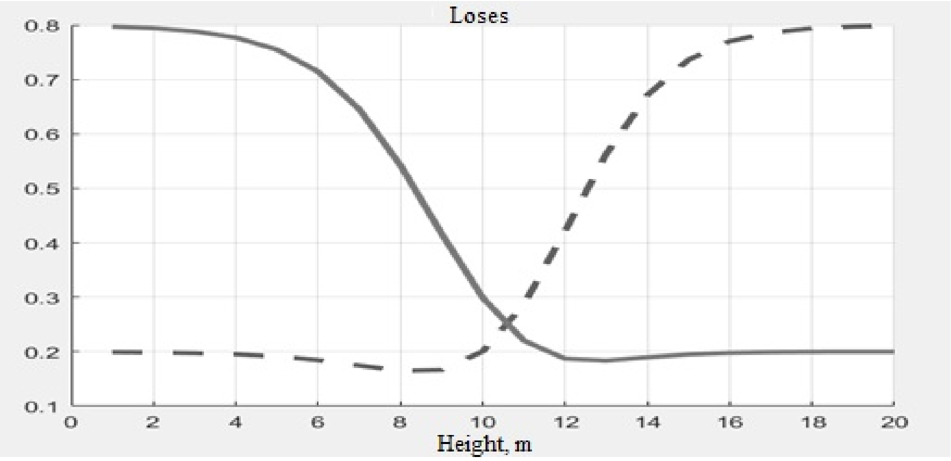

Fig. 1 – Losses at various ranking coefficients

In case when the relative cost of the OAV is high ($a_s = 0.8$, $a_a = 0.2$), losses during flight at low altitudes sharply increase (solid line). In this case, high detection efficiency of objects does not compensate for possible loss of UAV. Changes in the ranking ratio (Fig. 1) allow us to select search parameters depending on the tasks that needs to be solved. With a high importance (value) of search objects (dashed line in Fig. 1), the optimal flight altitude decreases to 8.47 m, which increases the probability of correct detection to 0.95, but reduces the probability of safety of the UAV to 0.41 (loss – 6 UAV from 10).

If the value of the search objects is less than the value of the UAV (the solid line in Figure 1), then the optimum flight altitude can be increased to 12.65 m, which ensures the safety level for the UAV, 0.93, and the probability of detection decreases to 0.38. Fig. 2 shows the diagrams of losses with equal ranking factors ($a_s = 0.5$, $a_a = 0.5$) and various parameters of the fire situation (Table 1).

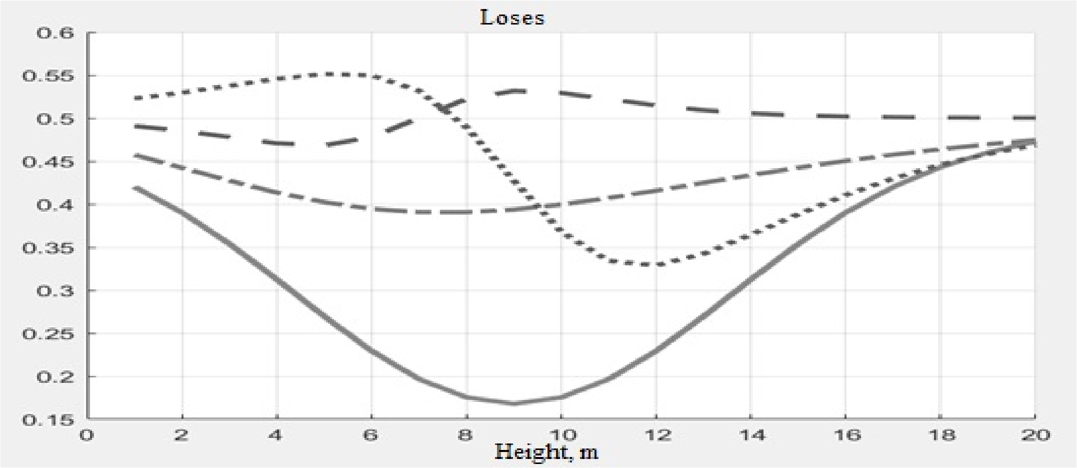

Fig. 2 – Losses at various fire situations

Table 1. – Fire Situation Parameters

Source number $a_s = 0.5$, $a_a = 0.5$		1 (continuous)	2 (dashed)	3 (dash-dotted)	4 (double dotted line)
Parameters of situation	K_a	0.4	0.8	0.2	0.3
	H_a, m	13	7	6	11
	K_s	0.4	0.6	0.3	0.8
	H_s, m	5	7	3	9
W_s (safety)		0.84	0.21	0.80	0.90
W_a (detection)		0.84	0.86	0.43	0.45
R (minimum loss)		0.16	0.47	0.39	0.33
Height h m		9.00	4.78	7.52	11.7

Source No. 1 (continuous line) is characterized by relatively high smoke level $H_a = 13$ m and low flame height (danger of heat effects on UAV) $H_s = 5$ then, the smoke density decreases significantly as the flight height of the UAV decreases ($K_a = 0.4$). Such a combination of fire parameters allows us to organize a search in the area from a height of 6–12 m with a relatively low total monitoring loss.

Source No. 2 (dashed line) is characterized by similar parameters of smoke and influence of fire $H_a = 7$ m and $H_s = 7$ m. The density of smoke and flame does not much change depending on the height ($K_a = 0.8$, $K_s = 0.6$). This combination of fire parameters is one of the most difficult, since does not allow the UAV to reduce flight altitude to improve detection level. Thus, the survey of source No. 2 will be accompanied by high monitoring losses.

Source No. 3 (continuous line) is characterized by remote centers of exposure to smoke and flame: $H_a = 6$ m and $H_s = 3$ m. Nevertheless, the observation process is complicated by the fact that smoke and the effects of fire occupy a wide range of heights ($K_a = 0.2$, $K_s = 0.3$). These areas are intersecting, not allowing the flight altitude to be lowered to improve detection level without compromising the safety of UAV.

Source No. 4 (double dotted line). The parameters of the source are determined by the relatively close parameters of smoke and exposure to fire ($H_a = 11$ m and $H_s = 9$ m). Smoke is spread through a wide range of heights ($K_a = 0.3$). The density of the flame, does not change significantly in dependence on height ($K_s = 0.8$). These parameters of the fire situation allow us to select the UAV flight altitude in region (10-14 m) with relatively low monitoring losses.

The calculation of losses (5) for various UAV flight altitudes and various fire situations shows the presence of minima (Fig. 2), which allow to determine the optimum UAV flight altitude. As it can be seen from the diagrams, the optimal flight altitude can vary widely. At the same time, a transition to altitudes other than the optimal ones leads to a sharp increase in losses. For example, when flying over source 2 at an altitude of 9 m, losses increase (compared to optimal flight) by 20%, when flying over source 3 – by 2%, and when flying over source 5 – by more than 30%. When flying at a height of 12 m, the loss will be: for the source No. 1 – 50%, for the source No. 2 – 24%, for the source No. 3 – 10%.

4. CONCLUSIONS

A method of choosing the optimal (in terms of minimizing losses) flight altitude of the UAV when searching for objects in diverse fire conditions is proposed. The technique is based on using heuristic models of fire conditions. The received results show an increase in the monitoring efficiency with a variable UAV flight altitude compared with flying at a constant altitude over all fire sources.

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