The probabilistic model of search and detection of ground objects using unmanned aerial vehicles in difficult weather conditions

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Abstract. The paper proposes the model of search and detection of ground objects in difficult weather conditions with the use of unmanned aerial vehicles. The model is based on the probabilistic approach and allows assessing the quality of reconnaissance missions taking into account the influence of the most significant meteorological values and weather phenomena.

1. Introduction
Effectiveness and safety of Unmanned Aerial Vehicles (UAV) operation during search and detection of different kind of objects mainly depends upon allowance for environments impact. One of the factors that mostly influence UAVs in launch and recovery area and in the terminal area is meteorological conditions [1,2]. Today there is a contradiction between the quality of meteorological conditions assessment that a person in charge requires and capabilities of scientific-methodological framework available. We suggest that the construction of ground objects search and detection model with UAVs application should decrease that contradiction. The model is based on the probabilistic-stochastic approach and allows assessing the quality of performance of reconnaissance tasks in terms of meteorological values and weather phenomena [3].

2. Ground objects search and detection model under adverse weather conditions with application of UAVs
The final result of the UAV operation is a complex event \( A \) that consists of a certain set of events \( \{ A_i \} \). These include: event of timely appearance of UAV over the reconnaissance target \( (A_1) \); event of establishing contact with the reconnaissance target under predicted weather conditions \( (A_2) \); event of getting the reconnaissance target caught in UAV payload coverage area \( (A_3) \); event of timely information delivery to a consumer \( (A_4) \).

Since these events are independent, the event \( A \) can be represented as a product [4]:

\[
A = A_1 \cdot A_2 \cdot A_3 \cdot A_4 .
\]

Let's denote the probability of occurrence of an event \( A_1 \) in \( P_{\text{准时}}^{\text{出现}}(A_1) \), an event \( A_2 \) in \( P_{\text{天气条件}}^{\text{预测}}(A_2) \), an event \( A_3 \) in \( P_{\text{覆盖}}^{\text{捕获}}(A_3) \), and an event \( A_4 \) in \( P_{\text{信息}}^{\text{及时}}(A_4) \), respectively.

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Then the probability of occurrence of the event $A - P^{\text{net mission}}_n (A)$ corresponding to the final result of the UAV operation will be equal to the product of probabilities:

$$P^{\text{net mission}}_n (A) = P^{\text{catch}}_n (A_1) \cdot P^{\text{cont}}_n (A_2) \cdot P^{\text{tmission}}_n (A_3) \cdot P^{\text{tmission}}_n (A_4) ,$$

where $P^{\text{net mission}}_n (A)$ – is the probability of successful mission completion under predicted meteorological conditions; $P^{\text{catch}}_n (A_1)$ – is the probability of timely appearance of UAV over the reconnaissance target, which allows to catch an object in the designated area under predicted meteorological conditions; $P^{\text{cont}}_n (A_2)$ – is the probability of establishing contact with the reconnaissance target under predicted weather conditions; $P^{\text{tmission}}_n (A_3)$ – is the probability of getting the reconnaissance target caught in UAV payload coverage area; $P^{\text{tmission}}_n (A_4)$ – is the probability of timely information delivery to a consumer.

If air reconnaissance is going to be carried out in several areas, then the expression like this should be used:

$$P^{\text{net mission}}_n (A) = 1 - \prod_{j=1}^K \left[ 1 - P^{\text{net mission}}_n (A) \right] ,$$

where $P^{\text{net mission}}_n (A)$ – is the probability of successful mission completion under predicted meteorological conditions in several areas; $K$ – is the number of reconnaissance areas; $P^{\text{net mission}}_n (A)$ – is the probability of successful mission completion under predicted meteorological conditions in a separate area.

The probability of timely UAV appearance over the reconnaissance object under adverse meteorological conditions should be derived from the expression:

$$P^{\text{net mission}}_n (A) = \frac{1}{1 + T^{\text{app}} + T^{\text{tmission}}}$

where $P^{\text{net mission}}_n (A)$ – is the probability of timely appearance of UAV over the reconnaissance target, which allows to catch an object in the designated area under predicted meteorological conditions; $T^{\text{app}}$ – is the time of UAV appearance in the mission area taking meteorological conditions into account; $T^{\text{tmission}}$ – meantime of reconnaissance object presence in the field; $T^{\text{tmission}}$ – mission statement; $T^{\text{tmission}}$ – the time of UAV preparation; $T^{\text{tmission}}$ – the estimated (planned) time of flight to the reconnaissance area; $T^{\text{tmission}}$ – duration of exposure to UAVs of dangerous weather factors associated with difficult weather conditions in the area under consideration; $T^{\text{tmission}}$ – the distance to the reconnaissance area; $V_{UAV}$ – UAV speed.

The probability of gaining the contact with the target under predicted weather conditions $P^{\text{net mission}}_n (A_2)$ depends on means of barrage patrol of UAV in the reconnaissance area.

If UAV trajectory is selected by chance (random searching) [5], the probability of establishing contact with the target $P^{\text{net mission}}_n (A_2)$ may be found with the following expression:

$$P^{\text{net mission}}_n (A_2) = 1 - \exp \left( - \frac{S_{\text{inv}}}{S_{\text{area}}} \right) ,$$

where $S_{\text{inv}}$ – area investigated by a UAV; $S_{\text{area}}$ – size of the reconnaissance area with adverse meteorological conditions zones; $t_{\text{max mission}}$ – UAV reconnaissance meantime in one area; $B$ – swath...
width of UAV payload; $V_{UAV}$ – UAV speed; $N_{cloud}$ – cloud amount, influencing UAV operation; $S_{area}$ – size of the reconnaissance area.

If the reconnaissance is ordered, the probability with gaining contact with the target $P_{\text{est. cont. ord.}}$ under complex weather conditions should be derived from the expression:

$$
P_{\text{est. cont. ord.}}(A) = \min \left\{ \frac{S_{area} - S_{DMF}}{S_{area}}, 1 \right\},
$$

(9)

If the target is known to be mobile, it is suggested to use the following expression to determine the probability of gaining the contact with the target $P_{\text{est. cont. mob.}}$:

$$
P_{\text{est. cont. mob.}}(A) = \frac{t_{area}}{t_{UAV}},
$$

(10)

where $t_{area}$ – time of the object presence in the area; $t_{UAV}$ – meantime of UAV reconnaissance in the given area.

To determine the probability of a single object appearance in UAV payload scope of view the following expression $P_{\text{get.3}}(A)$ should be used:

$$
P_{\text{get.3}}(A) = \frac{S_{width}}{S_{area}},
$$

(11)

where $S_{width}$ – swath width of UAV payload in one flight.

Research conducted in [6] suggests that the Probability of timely delivery of information to the consumer with the required accuracy $P_{\text{inf.4}}(A)$ will be determined by the formula:

$$
P_{\text{inf.4}}(A) = e^{-\frac{t_{UAV}}{T_{proc.}}},
$$

(12)

where $v$ – characteristics of the object mobility; $T_{proc.}$ – meantime of information processing and delivering it to the consumer; $T_{proc.}$ – meantime of reconnaissance object presence in the field.

If the search of an object is carried out by a group of UAVs ($N$), the probability of carrying out mission assigned is determined by the expression:

$$
P_{\text{mission}}(A) = 1 - \left(1 - P_{\text{mission}}(A)\right)^N,
$$

(13)

where $P_{\text{mission}}(A)$ – the probability of carrying out the mission assigned with a single UAV.

Thus the developed model allows to calculate the probability of completing the ground object search mission with UAVs in different situations under adverse meteorological conditions.

3. Effectiveness assessment
To assess the effectiveness of the offered model a numerical experiment has been carried out during the search. Aerosinoptical surveillance data as initial data was used from 2008 to 2018 on the territory of the Krasnodar region. The choice of the territory is determined by its physical and geographical characteristics and climatic variety in dealing with weather – climatic factors [7]. Besides, there has been a significant growth of dangerous weather conditions strongly influencing the efficiency of UAV operations [8].

According to the conditions of the experiment, a UAV has to carry out a reconnaissance mission in the area $S_{area}$ with the size of $10 \times 10$ km. A short range UAV was considered in the experiment. The developed model has been used for one of the most difficult cases of search situations – a regular search in the given area, when the search area is divided into successively surveyed sectors, while a UAV travels along a given trajectory.

A stand – alone building was used as a fixed reconnaissance object. Motion direction of moving objects was set at the right angle to the boundary of the search, which provided the shortest residence
time in the search area. To determine meantime of the object presence at the given area $T_{\text{pre}}$, we analyzed a man moving at a rate of 5 km/h and a car moving at a rate of 80 km/h. Besides, during the numerical experiment it was adopted that: UAV operators training level is excellent; time of mission assignment $t_{\text{mis.\,a}} = 10\text{ min}$; time of UAV preparation before launch $t_{\text{prep}} = 40\text{ min}$; time of information processing and delivery of information to the consumer $T_{\text{cons}} = 15\text{ min}$; comprehensiveness and assurance of the acquired information (number of correctly found and defined objects) not less than 90%.

![Figure 1](image1.png)

**Figure 1.** Dependence of the probability of mission performance on the base of cloud level.

![Figure 2](image2.png)

**Figure 2.** Dependence of the probability of mission performance on meteorological range of visibility.

![Figure 3](image3.png)

**Figure 3.** Dependence of the probability of mission performance on the number of adverse meteorological conditions areas.
Results of the numerical experiment are illustrated in figures 1–3.

Thus as a part of the study a mathematical model has been developed allowing to quantify of the probability of performing a ground object search and acquisition mission under adverse weather conditions using UAV, based on factual and predicted data.

4. Conclusion
The formalized modelling process description given here allows us to assess numerically the effectiveness of using UAV under adverse weather conditions for carrying out the reconnaissance [9]. The probability of assigned mission performance is a numerical magnitude, which reflects the purpose of UAV operation during air reconnaissance and the degree of performance of the tasks assigned to the UAV.

As the results of the numerical experiment demonstrate, if we apply the developed probabilistic model for assigned mission performance assessment, we increase the effectiveness of UAV application by 32-34% over the Krasnodar region, accounting predicted meteorological conditions, while traditional approaches increase the effectiveness by 26-28%. That proves the usefulness of the model for operational application of UAVs under adverse meteorological conditions.

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