Improving the Productivity of UAV Operations Based on Granular Computing and Fuzzy Sets

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***Abstract*—The problem of assessing the quality of equipment of different unmanned aerial vehicles groups types based on fuzzy sets is considered. The growth in the number of unmanned aerial vehicles for various purposes and the expansion of their application in heterogeneous groups raises the question of developing new criteria for the effectiveness of their use. A new approach to increase the productivity of registration and information processing operations by determining the image quality based on the video camera's angle of inclination, altitude and flight speed of the unmanned aerial vehicle is proposed. Since the input information about the state of the scene and data from unmanned aerial vehicle sensors may be incomplete and poorly structured, the article proposes to apply the concept of granular calculations and fuzzy sets to build an air reconnaissance database. A new mathematical model (information granule) is proposed based on fuzzy data on the altitude and speed of flight and the angle of the camera, which allows obtaining a forecast of image quality that can be gotten by unmanned aerial vehicles while traveling along the route.**

Keywords—fuzzy sets, granular calculations, combinatorial optimization, UAV configuration

I. Introduction

The use of remote-controlled unmanned aerial vehicles (UAVs) has become widespread in various fields [1], including aerial reconnaissance. In Ukraine, military UAVs are also developing in the direction of group use [1] – [6], intellectualization and autonomy of operations, integration with NATO systems [7] – [9], raising the level of situational awareness (SA) about the operational situation [1], [4], [6]. It is possible to increase the efficiency of information collection for a heterogeneous group of UAVs based on optimizing the equipment of an aircraft and the choice of tactical and technical characteristics of group members.

The increase in the number of UAVs leads to an increase in the load on database systems that store the received information and which are designed to process Big Data methods. The problem of accelerating the processing of large amounts of data (Big Data) [6], [10] – [13] is solved by increasing the performance of distributed server systems and developing and improving methods of collecting and processing information. These speeds up decision-making with artificial intelligence (AI) systems or hybrid systems with human operators.

In many cases, to determine whether one or more UAVs can be used to perform a particular task, it is sufficient to evaluate these UAVs, according to a certain set of formalized characteristics (for example, based on their classifications), and determine whether the characteristics of certain UAVs meet the conditions of the problem [1] – [6]. However, in cases of complex tasks or in the presence of sufficient numbers of different types of UAVs, the information obtained by this method will not be enough to determine the optimal composition of the UAVs group to perform this task. There may be situations when several different types of UAVs can be used to perform the task. In this case, to formalize the choice optimization problem for the composition of the UAVs group to complete the task cannot be limited by the use of the UAVs developed classifications only. Therefore, it is expedient to form a unified UAV estimates system, using the mathematical apparatus of fuzzy set theory and statistical analysis, and to develop a mathematical apparatus that will solve these problems based on the use of these formal UAV estimates and automation [6]. The results can be used not only to select UAVs from available ones for a specific task, but also to select UAVs, which should be purchased to most effectively perform the whole set of tasks that may arise for them in the future [1], [2].

II. Development of a Unified UAV Selection System

Unmanned aerial vehicles are complex technical systems. The difficulty in forming a methodology for assessing their effectiveness in performing the tasks is caused by the following factors [4], [6]:

1) Many indicators (requirements) should be considered when evaluating and selecting a rational version of the UAV from the whole set available.

2) Qualitative nature of some indicators (requirements) that are considered when evaluating UAVs.

3) Significant relationship and interdependence of these indicators (requirements), which are contradictory (for example, a smaller UAV costs less but may carry less payload and has a shorter range).

These features make it virtually impossible to use traditional mathematical methods (methods of mathematical statistics and probability theory) in identifying the model that will most effectively meet the list of requirements.

Therefore, there is an urgent need to develop a unified system for assessing the characteristics of UAVs, in which the user will choose important criteria for the UAVs selection (indicating their priorities, for example, in numerical or percentage terms). For its implementation it is necessary:

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1) To formalize a set of their parameters and functions for all available UAVs, which should be consolidated into a single database.

2) To form a unified system of UAV estimates based on the mathematical apparatus of fuzzy set theory and statistical analysis theory.

3) To develop a mathematical apparatus that will allow these formal assessments of the UAV and using automation to solve the problem.

The complexity of the decision-making process [14], the lack of the necessary mathematical apparatus led to the fact that the evaluation must process and use high-quality expert information generated based on fuzzy set theory. Mathematical statistics and probability theory use experimental data that have strictly defined accuracy and reliability. The fuzzy set theory works with qualitative characteristics, which are also called expert information [15].

Under the UAV effectiveness, we understand the degree of its suitability to meet the requirements set for the specific operating conditions. The UAV effectiveness is a generalized characteristic and can be expressed as a function of many different individual characteristics (range, time, cost, etc.) and is represented as a multidimensional vector. Various requirements are set for the efficiency vector components, some of which may contradict each other [14], [15].

III. Mathematical Apparatus of Fuzzy Logic, Suitable for Choosing the Composition of the UAV Team

Let X be a universal set, i.e. a complete set that covers the entire problem area of the UAV selection to perform the task. A fuzzy set $A \subset X$ is a set of ordered pairs $\{(x, \mu^A(x))\}$, where $x \in X$ and $\mu^A : X \to [0,1]$ is a membership function, which is some subjective measure of the element's correspondence to a fuzzy set $\mu^A(x)$ and can take values from zero, which means absolute non-belonging, to one, which, on the contrary, means absolute belonging. element x to the fuzzy set A. If the fuzzy set A is defined on a finite universal set $X=\{x_1, ..., x_n\}$, then it can be represented as follows:

$$A = \mu^A(x_1)/x_1 + \mu^A(x_2)/x_2 + ... + \mu^A(x_n)/x_n = \sum_{i=1}^{n} \mu^A(x_i)/x_i, \quad (1)$$

where $\mu^A(x_i)/x_i$ is the pair "membership function/element", called a singleton, and "+" – defines a set of pairs. Fuzzy sets define fuzzy numbers – this is a fuzzy set A defined on the set of real numbers, if its membership function is normal and convex, i.e.:

$$\sup_{x \in \mathbb{R}} \mu^A(x) = 1,$$
$$x \le y \le z \Rightarrow \mu^A(y) \ge \min(\mu^A(x), \mu^A(z)).$$

But arithmetic operations on fuzzy numbers in the general case are quite complex and inefficient, so they are mainly presented in *LR*-form, which corresponds to the description of the left and right parts of the function. Then the fuzzy number A has the form:

$$\mu^A(x) = \begin{cases} L\left(\frac{m-x}{\alpha}\right), \alpha > 0, \forall x \le m, \\ R\left(\frac{m-x}{\beta}\right), \beta > 0, \forall x \le m, \end{cases}$$

where L and R are functions having the following properties: $L(-x) = R(x)$; $L(0) = 1$; R decreases monotonically on the interval $[0, +\infty]$. Here m is the average value of the fuzzy number A, α is the deviation to the left, β is the deviation to the right. The use of fuzzy numbers and sets makes it possible to apply fuzzy logic.

A fuzzy logical expression is a formula that includes fuzzy predicates - mappings P^F: $X^n \to [0,1]$, where n is any natural number belonging to the segment [0,1]. The number that the predicate matches the specific set of x_i is called the level of truth of the expression. Complex fuzzy logical expressions are subject to valid actions – conjunction, disjunction, and inversion. Fuzzy is logic, where the level of truth of an expression is calculated using operations on fuzzy sets and numbers. This is done by setting the threshold of the desired level of truth $\gamma_0 \in [0,1]$, and in the general case, the level of truth will also be not a number from the segment [0,1], but a fuzzy number.

IV. Choosing a UAV to Solve the Composition of the UAV Team Problem

The most effective way to use this method is to implement it as a software product to automate the above calculations to select the most applicable UAV for a certain task, based on pre-formed unified sets of indicators of all available UAVs, and the system user will choose which indicators (functions), and weight coefficients of each indicator from the chosen vector of functions. As an additional indicator, you can also add the convenience of UAV control. After that, the search is performed taking into account the established requirements for the entire list of UAVs of this class (several classes) by the formula that uses the above mathematical apparatus of fuzzy logic [6], [14], [15]:

$$z = \sum_{i=1}^{n} \sum_{j=1}^{k} \Delta q_i \alpha_{ij} x_j + \sum_{i=1}^{n} \sum_{j=k+1}^{m} \Delta q_i \alpha_{ij} \mu(x_j) \quad (2)$$

where x_j is the current value of the jth requirement, α_{ij} is the influence of the requirement on the overall result (it is coefficient set by the user), Δq_i is the area of tolerances of the result's compliance with the requirements. In the general case, the evaluation is performed both on quantitative parameters (the first k requirements of the general set m) and on qualitative ones (last $m - k$), for the evaluation of which fuzzy logic is used.

This search allows you to determine the UAV that meets the personal requirements of the current task. Also, in accordance with the number of obtained results, Δ is selected – the zone of acceptable solutions, which will establish the permissible level of deviation of the obtained results from the specified requirements. The size of this zone (deviation level) can also be selected by the system user. It is also possible to use several gradations of the sample – sampling from the already formed sample on secondary parameters to reduce the number of results and select the best of them.

V. Dependence of Quality of UAV Airphoto on Flight Parameters

For a horizontal flight of a UAV at a fixed altitude with one type of camera, the dependence of the aerial photography quality on the angle of the camera can be described by a deterministically Gaussian function (Fig. 1).

Modern UAVs are equipped with several cameras and the image quality is affected by: altitude, maneuvering of the UAV, acceleration and speed during registration of information, and rotation of the camera during registration. The image quality can \\ roughly described by the function shown in Fig. 1. Otherwise, we can describe it as the vagueness of the image quality from the angle of the camera. That is, the image quality is described by a fuzzy set of the first type (Fuzzy set, type-1) [13] – [15].

The blurring of the image quality relationship describes the effect of height and other factors, which can be called measurement noise and motion distortion, that affect the resolution of the camera. The higher the height, the lower the resolution of the system, and, consequently, the poorer the quality of photo detail. The dependence of image quality on the flight altitude of the UAV has a similar appearance. Fig. 1.

We developed a fuzzy model for predicting the quality of aerial photography data [6] to control flight parameters based on telemetry data to set the optimization problem of UAV group acquisition.

The data obtained from the developed model are an example of an information granule that can be used to predict the achievable image quality when the UAV is moving along the route and the selection of appropriate equipment and equipment of the UAV or its choice.

Thus, a model for predicting the quality of aerial photography data based on fuzzy logic has been developed, which allows adjusting the height and speed of an individual UAV and the angle of the video camera to obtain the best image quality, as well as determining technical and economic requirements for optimal UAV equipment.

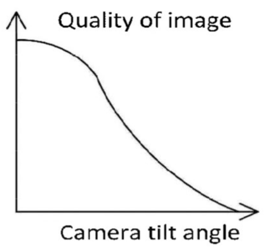

Fig. 1. The dependence of the quality of aerial photography on the angle of the UAV camera relative to the vertical at a fixed altitude.

VI. Substantive Statement of the Problem

When taking aerial photography, the UAV moves along the planned route and visits the points according to the flight task. The best conditions for aerial photography are determined based on the customer's requirements (e.g. cartography service, construction company, agricultural holding, military intelligence unit) to the detail of a series of photos or video stream, which is easiest to achieve at a certain (set or defined camera) altitude. For this consideration, we neglect the parameters of speed, time of day, time of year, weather conditions, optical and digital magnification of the camera and other factors, that affect the quality of shooting. Failure to take these factors into account adds uncertainty to the dependence of image quality on the parameters displayed in the model.

The essence of the problem is to automatically adjust the flight altitude, which provides the customer with the required quality of photos. The experience of using UAVs, which is reflected in NATO statutes [8], [9], allows us to formulate several heuristic rules that are used by the UAV pilot to select the flight altitude [6], [16]:

1) If the height is too low, you should increase the thrust of the engine.

2) If the height is not very high, you should slightly increase the thrust of the engine.

3) If the flight altitude is satisfactory, do not change the thrust of the engine.

4) If the flight altitude is slightly higher than required, you should slightly reduce the thrust of the engine.

5) If the flight altitude is too high, the thrust of the engine should be reduced.

These heuristic rules are proposed to be used in the construction of the rules base of the fuzzy inference system, which technically allows the implementation of this model of fuzzy program control.

A. Construction of fuzzy linguistic rules

To formulate the base of the rules of fuzzy inference systems [18], it is necessary to determine the input and output linguistic variables. As an input linguistic variable, it is proposed to use the flight altitude of the UAV or formally – "flight altitude". As the output linguistic variable, we will use the angle of rotation of the rudders on the wings of the UAV or formally – the "angle of rotation".

Thus, in our example, the fuzzy inference system will consist of the following fuzzy rules:

RULE_1: IF "height is small", THEN "increase engine thrust"

RULE_2: IF "height is not very small", THEN "increase engine thrust by not very big value"

RULE_3: IF "height is satisfactory", THEN "do not change the thrust of the engine"

RULE_4: IF "height is not very big", THEN "reduce engine thrust to not very big value"

RULE_5: IF "height is high", THEN "reduce engine thrust to a large value".

B. Fuzzification of input variables

As a set of values of the first linguistic variable we will use the set {"Small"; "Not very small"; "Satisfactory"; "Not very big"; "Large"} with linear membership functions. As the second linguistic variable, we will use the set {"large angle of the camera"; "Small-angle of the camera"; "Zero"} with piecewise linear membership functions. The angle of rotation is measured in degrees and the height in meters.

VII. Results

Based on the analysis of several works on UAV classification and the proposed model of image quality, the method of equipment for the UAV group and the choice of UAV types are built, as well as the content of the combinatorial optimization problem based on the classic backpack problem.

For this purpose, a model for forecasting the quality of the obtained aerial photographs based on data on the speed, height of the UAV and the angle of the video camera is proposed. The model is based on the development of the theory of fuzzy sets of the first and second types. An example of the implementation of the model in the system of computer mathematics MATLAB 2020b is given [6], [15].

VIII. Conclusions

1) The growth in the number of UAVs for various purposes and the expansion of their application in heterogeneous groups raises the question of developing new criteria for the effectiveness of their use, optimizing the acquisition of UAVs, minimizing the time of flight preparation, etc. Based on the development of fuzzy approaches, the considered problems of UAV groups functioning are formulated as combinatorial optimization problems.

2) One of the main applications of UAVs or their groups is aerial photography. Granular computing is one of the new concepts of combining poorly structured information obtained from different types of UAVs into intelligent databases and its further processing using AI and Big Data technologies - is used to solve problems that arise when using individual UAVs or their groups during aerial photography.

3) A new mathematical model (information granule) is proposed based on fuzzy data on the altitude and speed of flight and the angle of the camera, which allows obtaining a forecast of image quality that can be gotten by UAVs while traveling along the route.

4) A new method of automated equipment selection for UAV groups has been developed based on fuzzy logic, which allows finding in the future the optimal version of its equipment, several equivalents in a wide range of parameters of equipment options and compares them according to a set of objective criteria.

5) Thus, the AI or the pilot will be able to choose the UAV or set of UAVs that are needed to perform the current task, without spending time each time to search and check the parameters and characteristics of the UAV. Developed algorithmic tools can be used to address the issues that UAVs are the best choice for a set of tasks that may arise in the future, when selecting these UAVs for purchase.

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