A Method for Formalizing Knowledge About Planning UAV Flight Routes in Conditions of Uncertainty

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Abstract

It is advisable to use heuristic methods for the task of planning the flight routes of unmanned aerial vehicles (UAVs) at the planning stage of monitoring and reconnaissance. With their help they look for solutions within some subspace of possible acceptable solutions. They are the best in terms of taking into account the practice, experience, intuition, knowledge of the decision maker. The values of individual predicted factors should be represented using the mathematical apparatus of fuzzy sets. A method of formalizing knowledge about UAV flight route planning has been developed. It is based on interval fuzzy sets. In conditions of uncertainty, they allow to formalize the factors that take into account the conditions of monitoring, search, detection and destruction of objects, the impact of the external environment on the range of UAVs. This effect is manifested in the form of linguistic and interval-estimated parameters for each option, which allow to take into account the uncertainty. The developed method allows to form the area of definition of linguistic variables. These variables are used to describe the conditions for monitoring, reconnaissance and the impact of the environment on the range of UAVs. Such variables are also used to form from the set of the most important objects of monitoring, exploration of the most significant ground objects on the basis of an assessment of the degree of non-dominance of elements. The proposed approach provides a formalization of UAV flight route options for each possible scenario of the location of objects, the impact of the external environment. The result of formalization is fuzzy production rules, where fuzzy linguistic utterances are used as the antecedent and consequent.

Keywords

Unmanned aerial vehicle, production rules, fuzzy linguistic statements

1. Introduction

The most important task of the Armed Forces (AF) of Ukraine in the defense nature of military doctrine is the constant monitoring of the enemy. Monitoring should ensure a timely and organized transition of troops from peacetime to martial law. The main role is played by monitoring and intelligence. Their tasks are to provide the leadership and headquarters in a timely manner with complete and reliable information about the enemy. Among the available technical means capable of quickly and efficiently collecting the necessary information, one can single out unmanned aerial vehicles (UAVs). When monitoring the area, UAVs fly over the area of interest and collect the necessary data.

Thus, UAVs can be used to monitor forests, fields, borders, for environmental and meteorological monitoring, search and rescue missions, for military purposes, etc. The presence of large potential capabilities of UAVs does not

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guarantee the achievement of the specified efficiency of reconnaissance and monitoring. Its increase can be achieved by intelligently predicting the behavior of UAVs. This takes into account the influence of environmental factors, the behavioral nature of the objects of monitoring, knowledge and experience of UAV operators.

The experience of practical application of UAVs [1-3] in performing field monitoring tasks in real combat conditions revealed the difficulty in making an informed decision on the selection and construction of rational flight routes. Managing UAVs for monitoring, searching, detecting, and destroying objects is a complex, poorly formalized task. It is resolved under the condition of opposition of the opposite party (conflict) and requires the use of methods in the field of artificial intelligence. First of all, it concerns decision support systems, methods of presentation and formalization of knowledge, models of fuzzy sets.

At present, the combination of stochastic and non-stochastic uncertainty factors influencing this process is insufficiently taken into account when selecting appropriate options for the UAV flight route. Factors of non-stochastic uncertainty have the nature of behavioral uncertainty. Therefore, it is necessary to adapt pre-designed decision-making models to change many possible situations.

Tasks of this class require increasing the level of automation of their solution. The reason for this is the dynamism, ephemerality and high degree of uncertainty of the air and ground conditions, time constraints. But the task of automating the planning of UAV flight routes is complicated by the need to take into account the experience of decision makers (DM). This requires formalizing one's own knowledge and experience in ATS. To work with knowledge, including its formalization, it is necessary to improve mathematical support and software (MSS). Trends in the development of MSS show the need for the introduction of modern information technology (IT), including intelligent IT. They are aimed at creating and using the knowledge bases (KB) of the UAV control system (CS) [13-16, 22].

The knowledge base is a set of rules, facts, derivation mechanisms and software that describe a subject area and are designed to represent the accumulated knowledge in it [17]. The most difficult stage of creating a database is the formalization of knowledge in a given subject area.

Global trends in research in the field of control theory are concentrated in two areas – artificial intelligence and machine learning, robotics and decision theory. Artificial intelligence technologies are actively used in the military sphere. Work is being actively carried out to increase the autonomy of the functioning of combat systems.

The article [4] considers the principles of construction of the distributed external and onboard components of the control system of a group of reconnaissance and strike unmanned aerial vehicles.

In [5] the models of collective control of manned and unmanned aerial vehicles are presented. Methodical support of training of aircraft control operators and engineers of air navigation systems is offered.

In the article [6] the analysis of an estimation of efficiency and criteria of reliability of group flights of UAVs is carried out. The algorithm of search of the central repeater of group of UAV for ensuring transfer of a control signal in group is developed.

The article [7] discusses the advantages and disadvantages of centralized and decentralized architecture of UAV group management, presents tables of the dependence of the level of onboard automation and the number of UAVs in the group.

The article [8] developed a method of planning the flight path of UAVs to search for a dynamic object in the forest-steppe area, taking into account possible options for its movement.

The article [9] is devoted to the development of a meta-model of a multi-agent system for searching and influencing a ground object by a group of unmanned aerial vehicles under a centralized control variant. The base of rules of logical inference for agents according to the solved tasks and a role of the agent in group which is based on use of production model is developed.

The work [10] is devoted to the development of a method of UAV route planning when performing missions to search for a stationary object. The method allows to take into account the distribution of probabilities of importance of the area of the task.

In [11] a method of substantiation of the optimal route of air reconnaissance was developed. The paper proposes indicators and criteria for the effectiveness of the search for a dynamic object.

In [12] the issue of efficiency of decentralized control of UAV group and operator load when interacting with decentralized scheduler is considered.

In [13, 14] the factors of influence of the external environment are considered, which, in turn, make changes in the initial result of UAV flight planning. These factors are taken into account with a high degree of subjectivity of the person planning the flight route. In [14, 15] mathematical models are considered, which aim to increase the efficiency of monitoring. To determine the optimal flight route, it is necessary to calculate the probability of performing reconnaissance tasks. However, the experience of using UAVs in local conflicts shows the need to take into account the factors that affect the effectiveness of monitoring and reconnaissance operations with UAVs. It is necessary to take into account the threats and limitations of natural and technical nature [16, 17], which significantly affect the final result of the flight task.

The result of the literature analysis indicates the relevance and prospects of research in the direction of developing intelligent UAV control systems. search, detection and destruction of objects.

Thus, a change in approaches to planning UAV flight routes will make it possible to better solve the problems of observation, search, detection and destruction of objects.

The purpose of the study is to develop a method of formalizing knowledge about the planning of UAV flight routes on the basis of interval fuzzy sets in the monitoring, search, detection and destruction of objects in conditions of uncertainty.

2. Problem analysis (Main part)

To formalize the knowledge of UAV flight route planning, it is advisable to use interval fuzzy sets of type 2 (IFST2). For IFST2, the values of the membership functions of the second order are constant. That is, the membership function is unified (homogeneous) in contrast to the general fuzzy sets of type 2 (FST2).

Interval fuzzy sets of type 2 allow you to use all the tools of interval calculations and are expressed by the degree of truth of the uncertainty. It reflects the vagueness and inaccuracy of the element belonging to a given set. IFST2 ($\tilde{A}$) are characterized by the membership function of the second type (order) $\mu_{\tilde{A}}(x,u)$, where $x \in X$ and $u \in J_x^u \subseteq [0,1]$, $0 \leq \mu_{\tilde{A}}(x,u) \leq 1$,which is expressed

$$\tilde{A} = \{(x,u,\mu_{\tilde{A}}(x,u)) | \forall x \in X, \forall u \in J_x^u \subseteq [0,1]\}. \quad (1)$$

The discrete $\tilde{A}$ can be represented as

$$\tilde{A} = \left\{ \sum_{x \in X} \frac{\mu_{\tilde{A}}(x)}{x} \right\} = \left\{ \sum_{i=1}^{N} \left[\sum_{k=1}^{M} f_{x_i}(u_{ik})/u_{ik} \right] \Big/ x_i \right\}, \quad (2)$$

where $\sum\sum$ is the union of x and u.

If $f_x(u) = 1$, $\forall u \in \left[\underline{J}_x^u, \bar{J}_x^u\right] \subseteq [0,1]$, then the membership function of the second type $\mu_{\tilde{A}}(x,u)$ is expressed by the lower membership function of the first type $\underline{J}_x^u \equiv \underline{\mu}_{\tilde{A}}(x)$ and, accordingly, the upper membership function of the first type $\bar{J}_x^u \equiv \bar{\mu}_{\tilde{A}}(x)$. Then IFST2 can be represented as

$$\tilde{A} = \left\{ (x,u,1) | \forall x \in X, \forall u \in [\underline{\mu}_{\tilde{A}}(x), \bar{\mu}_{\tilde{A}}(x)] \subseteq [0,1] \right\} \quad (3)$$

The article proposes the use of triangular fuzzy numbers (TFN) and trapezoidal fuzzy intervals (TFI). The expediency of their use is due to the simplicity of operations on them and visual graphical interpretation.

In the general case, the fuzzy interval is called IFST2 $\tilde{A}_{\Pi}$ with convex upper and lower membership functions, limiting the area of uncertainty of this IFST2. The fuzzy number of IFST2 is called IFST2 $\tilde{A}_{\Delta}$ with convex and unimodal upper and lower membership functions, which limit the area of uncertainty of this IFST2.

Features of the representation of TFN or TFI in terms of IFST2 are as follows:

– the left and right boundaries of fuzzy quantities in terms of IFST2 are not points but uncertainty intervals;

– the extreme values of the uncertainty intervals, in turn, are the boundaries of the two FST1. They are defined by the upper membership function $\bar{\mu}_{\tilde{A}}$ and the lower membership function $\underline{\mu}_{\tilde{A}}$. These functions limit the occupied area of uncertainty (FOU) TFNIFST2 or TFIIFST2 above and below, respectively;

– the upper $\bar{\mu}_{\tilde{A}}$ and lower $\underline{\mu}_{\tilde{A}}$ membership functions determine the normal convex FST1 on a non-empty carrier. Moreover, in the case of TFN IFST2 it will be unimodal normal convex FST1.

Thus, it is proposed to formally present the

FOU TFNIFST2 $\tilde{A}_{\Delta}$ in the form of a tuple with parameters [18-22]

$$FOU(\tilde{A}_{\Delta}) = \langle \alpha_{\overline{\mu}}, \alpha_{\underline{\mu}}, a_{\overline{\mu}}, a_{\underline{\mu}}, \beta_{\overline{\mu}}, \beta_{\underline{\mu}} \rangle, \quad (4)$$

where $\alpha_{\overline{\mu}}$ – left fuzzy coefficient $\overline{\mu}_{\tilde{A}_{\Delta}}$;

$\alpha_{\underline{\mu}}$ – left fuzzy coefficient $\underline{\mu}_{\tilde{A}_{\Delta}}$;

$a_{\overline{\mu}}$ – center (modal value) $\overline{\mu}_{\tilde{A}_{\Delta}}$;

$a_{\underline{\mu}}$ – center (modal value) $\underline{\mu}_{\tilde{A}_{\Delta}}$

$\beta_{\overline{\mu}}$ – right fuzzy coefficient $\overline{\mu}_{\tilde{A}_{\Delta}}$;

$\beta_{\underline{\mu}}$ – right fuzzy coefficient $\underline{\mu}_{\tilde{A}_{\Delta}}$.

In this case, the triangular upper membership function $\overline{\mu}_{\tilde{A}_{\Delta}}$; $FOU(\tilde{A}_{\Delta})$ generates a normal unimodal convex FST1 on a nonempty carrier – an open interval $[a_{\overline{\mu}} - \alpha_{\overline{\mu}}, a_{\overline{\mu}} + \beta_{\overline{\mu}}]$, and the triangular function $\underline{\mu}_{\tilde{A}_{\Delta}}$ $FOU(\tilde{A}_{\Delta})$ generates a normal unimodal convex FST1 on a nonempty carrier – open interval $\left[a_{\underline{\mu}} - \alpha_{\underline{\mu}}, a_{\underline{\mu}} + \beta_{\underline{\mu}}\right]$.

It is also proposed to formally represent *FOU* TFI IFST2 in the form of a tuple with the following parameters:

$$FOU(\tilde{A}_{\Pi}) = \\ = \langle \alpha_{\overline{\mu}}, \alpha_{\underline{\mu}}, a_{\overline{\mu}}, a_{\underline{\mu}}, b_{\overline{\mu}}, b_{\underline{\mu}}, \beta_{\overline{\mu}}, \beta_{\underline{\mu}} \rangle, \quad (5)$$

where $\alpha_{\overline{\mu}}$ – left fuzzy coefficient $\overline{\mu}_{\tilde{A}\Pi}$;

$\alpha_{\underline{\mu}}$– left fuzzy coefficient $\underline{\mu}_{\tilde{A}\Pi}$;

$a_{\overline{\mu}}$ – lower modal value $\overline{\mu}_{\tilde{A}\Pi}$;

$a_{\underline{\mu}}$– lower modal value $\underline{\mu}_{\tilde{A}\Pi}$;

$b_{\overline{\mu}}$ – upper modal value $\overline{\mu}_{\tilde{A}\Pi}$;

$b_{\underline{\mu}}$– upper modal value $\underline{\mu}_{\tilde{A}\Pi}$;

$\beta_{\overline{\mu}}$– right fuzzy coefficient $\overline{\mu}_{\tilde{A}\Pi}$;

$\beta_{\underline{\mu}}$– right fuzzy coefficient $\underline{\mu}_{\tilde{A}\Pi}$.

In this case, the trapezoidal upper membership function $\overline{\mu}_{\tilde{A}\Pi}$ $FOU(\tilde{A}_{\Pi})$ generates a normal convex FST1 on a nonempty carrier – an open interval $[a_{\overline{\mu}} - \alpha_{\overline{\mu}}, b_{\overline{\mu}} + \beta_{\overline{\mu}}]$, and the trapezoidal lower function $\underline{\mu}_{\tilde{A}\Pi} FOU(\tilde{A}_{\Pi})$ generates a normal unimodal convex FST1 on a non-empty carrier – open interval.

In this case, the set of fuzzy production rules will be called the base of rules (BR). It is intended for the formal presentation of empirical knowledge or expert knowledge (DM) on a subject area based on IFST2 [22]. In the general case, there are the following BP:

• by type of fuzzy production rules [17] (depending on the formal representation of the derivation of the rule): fuzzy statements; clear statements; functions;

• by the structure of fuzzy production rules: SISO – a structure that implements one input and one output; MISO – a structure that implements many inputs and one output; MIMO is a structure that implements many inputs and many outputs.

When formalizing knowledge about the process of planning the route of the UAV flight in the form of a fuzzy production rule that describes a predetermined version of the UAV routes, we will use the rules with MISO-structure.

These conditions are factors that take into account the conditions of monitoring, the impact of the external environment, and the conclusions – recommendations on the appropriate route of the UAV flight in specific conditions.

When developing a method of formalizing knowledge about the planning of UAV flight routes on the basis of interval fuzzy sets, the following limitations and assumptions are taken into account:

- issues related to the assessment of the adequacy and informativeness of the parameters used to describe the projected situation are considered resolved and are not considered in this study;
- construction of membership functions for conditions and conclusions of fuzzy production rules begins with the use of the simplest forms of membership functions – piecewise linear functions. Subsequently, their nature can be clarified and taken into account during the adjustment of the rules (for example, at the stage of learning a fuzzy logical system);
- issues of ensuring the completeness and consistency of a set of fuzzy production rules in this study are not considered.

The method of formalizing knowledge about the process of planning a reconnaissance flight of a UAV based on IFST2 includes the following main stages:

- presentation of factors that take into account the conditions of monitoring, exploration, environmental impact in the form of linguistic variables for each projected option;
- formation of the area of definition of linguistic variables used to describe the conditions of monitoring, exploration and environmental impact;
- formation for each linguistic variable of the term set, as elements of which use the names of fuzzy variables that describe the linguistic meanings of the conditions of monitoring, the impact of the external environment;
- description of UAV flight route options;
- formation of many of the most important objects of monitoring, intelligence based on the

assessment of the degree of non-dominance of the elements;

- presentation of options for the location of ground objects, the impact of the external environment, the appropriate variant of the UAV flight route in the form of fuzzy production rules, where as an antecedent, a follower use fuzzy linguistic statements.

Thus, it is investigated that for the task of UAV flight route planning at the planning and reconnaissance planning stage it is expedient to use heuristic methods. They are looking for solutions within some subspace of possible acceptable solutions. They are the best in terms of taking into account the practice, experience, intuition, knowledge of ATS. The values of individual predicted factors should be represented using the mathematical apparatus of fuzzy sets. A method for formalizing knowledge about UAV flight route planning based on interval fuzzy sets in conditions of uncertainty has been developed. With its help it is possible to formalize the factors that take into account the conditions of monitoring, search, detection and destruction of objects, the impact of the external environment on the range of UAVs.

They are presented in the form of linguistic and interval-estimated parameters for each option. This approach allows:

- take into account uncertainty;
- to form the area of definition of linguistic variables that are used to describe the conditions of monitoring, reconnaissance and the impact of the external environment on the range of UAVs;
- to form from a set of the most important objects of monitoring, reconnaissance of the most significant ground objects on the basis of an estimation of a degree of non-dominance of elements;
- to formalize the flight options of the UAV for each possible variant of the location of objects, the influence of the external environment in the form of fuzzy production rules, where fuzzy linguistic statements are used as an antecedent, a consequent.

3. Conclusions

The calculation of the mathematical expectation of the time to perform individual operations in the construction of UAV flight routes at the planning stage is carried out.

In the traditional approach, the time for information preparation and direct planning of UAV routes is up to 66% of the total time for making a decision [10, 19, 22].

The mathematical expectation of the total time for making a decision is $M^*[\overline{T}_t]$=211,59 s; the time spent on entering the initial data – $M^*[\overline{T}_e]$=67 s (up to 31% from $M^*[\overline{T}_t]$) the waiting time for the result of solving the problem – $M^*[\overline{T}_r]$=73,63 s (up to 35% from $M^*[\overline{T}_t]$). Efficiency of decision-making by a decision-maker at the stage of planning UAV flight routes may turn out to be unacceptably low (P=0.47 ... 0.9). To increase the efficiency of decision-making, it is necessary to reduce the time for preparation and the direct solution of the problem.

In the proposed approach to planning the routes of the UAV reconnaissance flight, the mathematical expectation of the total time for making a decision was $M^*[\overline{T}_t]$=103,59 s, the time spent by the decision-maker for entering the initial data was – $M^*[\overline{T}_e]$=13,74 s (up to 13% from $M^*[\overline{T}_t]$), the waiting time for the decision result was – $M^*[\overline{T}_r]$=33,71 s (up to 32% from $M^*[\overline{T}_t]$).

The proposed approach to planning UAV flight routes under conditions of uncertainty makes it possible to reduce the total decision-making time by up to 2 times.

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