Mathematical Model of Intelligent Decision Support System of UAV Operator

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***Abstract* — The article presents a conceptual and mathematical model of the intelligent decision support system of the unmanned aerial vehicle operator, what will allow one to make informed decisions in real time with a high degree of reliability.**

Keywords — unmanned aerial vehicle, intelligent decision support system, fuzzy logic.

I. INTRODUCTION

Currently, static and dynamic intelligent systems based on rules (expert knowledge) are widely used in the field of artificial intelligence. In general, in such systems, knowledge are presented in the form of rules that indicate what conclusions should be drawn in different situations. Systems, based on rules, consist of facts (system input), knowledge bases (rule set) and solver (interpreter, systems of logical inference) to control the output from the knowledge base [1]. A special case of rule-based systems is intelligent decision support systems (IDSS). Depending on the choice of the classification criterion, IDSS can be superficial and deep, autonomous and integrated, simple and complex, etc. [2]. From the analysis of the literature [1–8], we can conclude that a perspective way of creation of mathematical models of IDSS for operator of the unmanned aerial vehicle (UAV) is to develop a fuzzy logic-linguistic models based on fuzzy inference systems Mamdani-type [9].

II. A CONCEPTUAL MODEL OF IDSS

To develop a mathematical model of the intelligent decision support system for operator of UAV based on the hierarchical model development scheme given in [1], a preliminary development of a conceptual model is necessary. In general, the conceptual model of the IDSS is a "black box", the input of which is values of the system parameters describing the current situation – S*, and restrictions – E, and the output is solution, i.e. the set of values of dependent (endogenous) parameters of the complex with UAV – Z. Parameters describing the current situation should be divided into a number of disjoint subsets: set of current input data U*; set of current environmental impacts F*; set of current internal parameters of the complex with UAV Y*. In this case, the system sensors data X* can be divided into sensors data, which display the input data of the system; sensors data, showing the influence of the external environment; sensors data, showing the internal parameters of the complex with UAV.

Based on this, the overall conceptual model of the IDSS will take the form presented in Fig. 1.

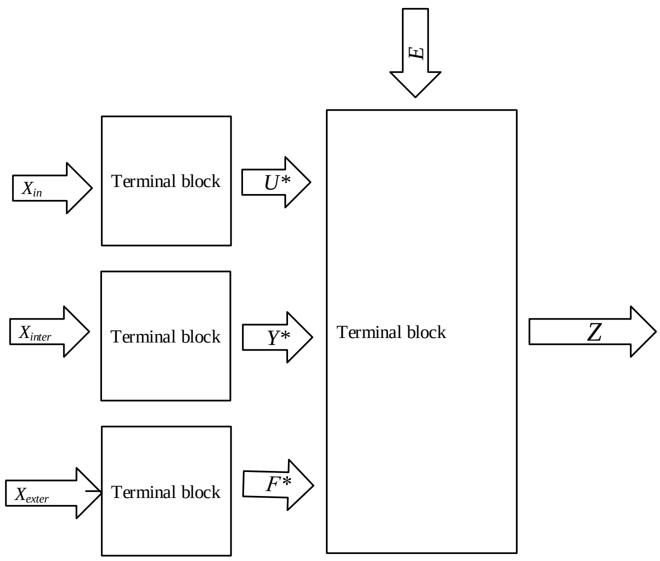

Fig. 1. Overall conceptual model of the IDSS.

Analysis of the flight task calculation of the complex with UAV allows the creation of a conceptual model IDSS for operator of UAV. This model, developed with the use of fuzzy inference machine Mamdani-type has the form shown in Fig. 2.

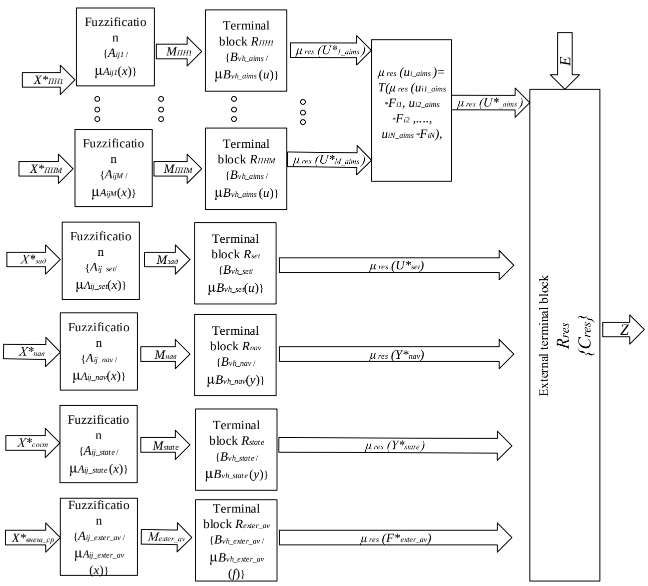

Fig. 2. Conceptual model IDSS for operator of UAV.

III. A MATHEMATICAL MODEL OF IDSS

Development of the mathematical model of IDSS is reduced to:

a) Assessment of the current situation

$$S^* = \{U^*, F^*, Y^*\}. \tag{1}$$

b) Finding the reference situation with the maximum degree of belonging to the current situation

$$S_{res} = \arg\max \mu(S_i, S^*),\ i = 1, N, \tag{2}$$

where N is the number of reference situations (rules from knowledge base (KB) R_{res}).

c) The Formation of a decision Z, based on the rules KB $Rres$ corresponding to this reference situation, the degree of its compliance with the current situation $\mu(S_{res}, S^*)$ and the current limitations E.

$$(R_{res}, \mu(S_{res}, S^*), E) \to Z. \tag{3}$$

To assess the current situation it is necessary to determine the current set of input data U^*, the effects of the external environment F^* and internal parameters Y^*, from the current set of various sensors data X^*. U^*, F^* and Y^* are represented as:

$$U^* = \{U^*_{aims} = (u^*_{1\_aims}, u^*_{2\_aims}, \ldots, u^*_{n\_aims}),\ U^*_{set} = (u^*_{1\_set}, u^*_{2\_set}, \ldots, u^*_{m\_set})\}, \tag{4}$$

that is, the set of input parameters consists of sets of target parameters and parameters of the current task;

$$Y^* = \{Y^*_{nav} = (y^*_{1\_nav}, y^*_{2\_nav}, \ldots, y^*_{k\_nav}),\ Y^*_{state} = (y^*_{1\_state}, y^*_{2\_state}, \ldots, y^*_{l\_state})\}, \tag{5}$$

the set of internal parameters consists of a set of navigation parameters of the UAV and the parameters of the state of the complex with UAV.

$$F^* = \{F^*_{exter\_av} = (f^*_{1\_exter\_av}, f^*_{2\_exter\_av}, \ldots, f^*_{p\_exter\_av})\}. \tag{6}$$

Based on the adopted conceptual model presented in Fig. 2, initial data for the development of a mathematical model of the IDSS for operator of UAV are:

$X_{ПНi} = \{x_{11i}, x_{12i}, \ldots, x_{kni}\}$ - the set of input parameters of i-type UAV payloads, (i=1,M), where M-the number of types of payloads, used by UAV;

$A_{ПНi} = \{A_{1i} = \{A_{11i}, A_{21i}, \ldots, A_{a1i}\},$
$A_{2i} = \{A_{12i}, A_{22i}, \ldots, A_{b2i}\}, \ldots, A_{ni} = \{A_{1ni}, A_{2ni}, \ldots, A_{cni}\}\}$
-the set of linguistic variables (A_{ij}) and terms of these linguistic variables (A_{kij}), describing the possible values of input parameters of payloads $x_{kni} \in X_{ПНi}$ (i=1,M); { $\mu_{A_{jki}}(x_{kmi})$ } – the set of belonging functions of parameters $x_{kmi} \in X_{ПНi}$ to terms of linguistic variables $A_{jki} \in A_{ПНi}$ (i=1,M);

$B_{aims} = \{B_{1\_aims} = \{B_{11\_aims}, B_{21\_aims}, \ldots, B_{a1\_aims}\},$
$B_{2\_aims} = \{B_{12\_aims}, B_{22\_aims}, \ldots, B_{b2\_aims}\},$
$\ldots, B_{n\_aims} = \{B_{1n\_aims}, B_{2n\_aims}, \ldots, B_{cn\_aims}\}\}$
- the set of linguistic variables (B_{i_aims}) and terms of these linguistic variables (B_{ji_aims}), possible values of the target parameters as an object of the flight task U_{aims}; { $\mu_{B_{ji\_aims}}(u_{ik\_aims})$ } – the set of belonging functions of target parameters $u_{ik\_aims} \in U_{aims}$ to terms of linguistic variables $B_{ji\_aims} \in B_{aims}$;

$R_{ПНi}$ – production knowledge base – the set of conjunctive-type rules that correspond the input parameters of payloads ($X_{ПНi}$) to characteristics of the target (U_{aims}) (i=1,M);

$F_{ij} = [0,1]$ – coefficients of certainty in the correct determination of the i-type target characteristics from j-type payload (j=1,M);

X_{set} – the set of input data, characterizing the General task of the complex with UAV;
A_{set} – the set of linguistic variables (A_{i_set}) and terms of these linguistic variables (A_{ji_set}), which determines the possible values $x_{i\_set} \in X_{set}$;
$\{ \mu_{Aji\_set}(x_{i\_set}) \}$ – the set of belonging functions of the input data $x_{i\_set} \in X_{set}$ to terms of linguistic variables $A_{ji\_set} \in A_{set}$;
B_{set} – the set of linguistic variables (B_{i_set}) and terms of these linguistic variables (B_{ji_set}), which determines the possible values of the parameters of the UAV flight task U_{set};
$\{ \mu_{B_{ji\_set}}(u_{i\_set}) \}$ – the set of belonging functions of flight task parameters $u_{i\_set} \in U_{set}$ to the terms of linguistic variables $B_{ji\_set} \in B_{set}$;
R_{set} – production knowledge base – the set of conjunctive-type rules, which put in accordance with the input parameters of the General task (X_{set}) and parameters of the current task (U_{set}) $R_{set} : X_{set} \to U_{set}$;
X_{nav} – the set of navigation sensors data;
A_{nav} – the set of linguistic variables (A_{i_nav}) and terms of these linguistic variables (A_{ji_nav}), describing the possible values $x_{i\_nav} \in X_{nav}$;
$\{ \mu_{Aji\_nav}(x_{i\_nav}) \}$ – the set of belonging functions of input data from navigation sensors $x_{i\_nav} \in X_{nav}$ to terms of linguistic variables $A_{ji\_nav} \in A_{nav}$;
B_{nav} – the set of linguistic variables (B_{i_nav}) and terms of these linguistic variables (B_{ji_nav}), determining the possible values of the UAV navigation parameters Y_{nav};
$\{ \mu_{B_{ji\_nav}}(y_{i\_nav}) \}$ – the set of belonging functions of UAV navigation parameters $y_{i\_nav} \in Y_{nav}$ to the terms of linguistic variables $B_{ji\_nav} \in B_{nav}$;
R_{nav} – production knowledge base – the set of conjunctive-type rules, putting in accordance with the input navigation sensors data (X_{nav}) and UAV navigation parameters (Y_{nav}) $R_{nav} : X_{nav} \to Y_{nav}$;
X_{state} – the set of the complex with UAV state sensors data;
A_{state} – the set of linguistic variables (A_{i_state}) and terms of these linguistic variables (A_{ji_state}) that determines the possible values $x_{i\_state} \in X_{state}$;
$\{ \mu_{Aji\_state}(x_{i\_state}) \}$ – the set of belonging functions of the input state sensors data $x_{i\_state} \in X_{state}$ to the terms of linguistic variables $A_{ji\_state} \in A_{state}$;
B_{state} – the set of linguistic variables (B_{i_nav}) and terms of these linguistic variables (B_{ji_nav}) that determines the possible values of the complex with UAV status parameters Y_{state};
$\{ \mu_{B_{ji\_state}}(y_{i\_state}) \}$ – the set of belonging functions of the complex with UAV status parameters $y_{i\_state} \in Y_{state}$ to terms of linguistic variables $B_{ji\_state} \in B_{state}$;
R_{state} – production knowledge base – the set of conjunctive-type rules, putting in accordance with input state sensors data (X_{state}) and complex with UAV status parameters (Y_{cocm}) $R_{state} : X_{state} \to Y_{state}$;
X_{exter_av} – the set of environmental parameters sensors data ;
A_{exter_av} – the set of linguistic variables ($A_{i\_exter\_av}$) and terms of these linguistic variables ($A_{ji\_exter\_av}$) that determines the possible values $x_{i\_exter\_av} \in X_{exter\_av}$;
$\{ \mu_{Aji\_exter\_av}(x_{i\_exter\_av}) \}$ – the set of belonging functions of the input environmental parameters sensors data $x_{i\_exter\_av} \in X_{exter\_av}$ to terms of linguistic variables $A_{ji\_exter\_av} \in A_{exter\_av}$;
B_{exter_av} – the set of linguistic variables ($B_{i\_exter\_av}$) and terms of these linguistic variables ($B_{ji\_exter\_av}$), which determines the possible values of the generalized state of the environment parameters F_{exter_av};
$\{ \mu_{B_{ji\_exter\_av}}(f_{i\_exter\_av}) \}$ – the set of belonging functions of the generalized state of the environment parameters $f_{i\_exter\_av} \in F_{exter\_av}$ to the terms of linguistic variables $B_{ji\_exter\_av} \in B_{exter\_av}$;
R_{exter_av} – production knowledge base – the set of conjunctive-type rules, which put in accordance with the input environmental parameters sensors data (X_{exter_av}) and generalized state of the environment parameters (F_{exter_av}) $R_{exter\_av} : X_{exter\_av} \to F_{exter\_av}$;

Z – the set of values of dependent (endogenous) parameters of complex with UAV;

C – the set of linguistic variables (C_i) and terms of these linguistic variables (C_{ji}) that determines the possible values of the dependent (endogenous) parameters of complex with UAV (*Z*);

R_{res} – the result knowledge base – the set of conjunctive-type rules, that put in accordance with input (external) parameters ($U = \{U_{aims}, U_{set}\}$), parameters of the external environment (F_{exter_av}), internal parameters ($Y = \{Y_{nav}, Y_{state}\}$) and a set of values of the dependent (endogenous) parameters of complex with UAV (*Z*) $R_{res} : \{U, F, Y\} \to Z$. The left parts (antecedents) of the rules of KB R_{res} are the reference situations $S = \{U, F, Y\}$, and the right parts (consequents) are the values of dependent parameters of these reference situation $R_{res} : S \to Z$.

The assumptions in the development of this mathematical model of IDSS are:

– The belonging functions of terms of linguistic variables are triangular and have a single modal value [3]

$$\mu_A(x) = w\left(\frac{a-(x-m)}{a}\right), \qquad (7)$$

where *m* – the modal value $\mu_A(m) = 1$;
a – the width of the triangular function;

$$w = \begin{cases} 1\,for & (m-a) \le x < (m+a) \\ 0 \quad in & other \quad cases \end{cases};$$

– For each term of possible parameter values, there is at least one value that is typical of it:

$$\forall i\_(1 \le i \le n)\_\exists x \in X : \mu_{A_i}(x) = 1; \qquad (8)$$

– For each value of any parameter there is a term describing it with a non-zero degree.

$$\forall x \in X\_\exists A_i\_(1 \le i \le n) : \mu_{A_i}(x) \ne 0; \qquad (9)$$

– In the set of values of terms of linguistic variables there are no synonyms and semantically similar terms

$$\forall x \in X : \sum_{i=1}^{n} \mu_{A_i}(x) = 1. \qquad (10)$$

Determination of the set of target parameters $U*_{aims}$, based on the known indications of payloads $X*_{ПН}$, using the fuzzy inference apparatus, is reduced to finding the resulting belonging functions of the target parameters.

$$\mu_{res}(U*_{aims}) = (\mu_{res}(u*_{1\_aims}), \mu_{res}(u*_{2\_aims}),.. \\ .., \mu_{res}(u*_{n\_aims})) \qquad (11)$$

To do this, the first step is to carry out the fuzzification [3] – calculation the degree of belonging of the numerical values of the input payloads parameters $X*_{ПН}$ to the terms of linguistic variables $\{A_{ijk}\}$, where *i* is the characteristic term of the input parameter (for example, "high"), *j* is the input parameter (for example, “brightness”) *k* is the type of payload supplying the input parameter (for example, “optical”). So for the payloads of the first type, the fuzzification unit will look like:

$$X*_{ПН1} = \{x*_{111}, x*_{121},..., x*_{ij1}\} \to \\ M_{ПН1} = \{\mu_{A_{111}}(x*_{111}), \mu_{A_{111}}(x*_{121}),... \\ .., \mu_{A_{ji1}}(x*_{ik1})\} \qquad (12)$$

Then calculate the degree of fulfillment of the conditions $h_{R_{ПН1}i}$ of the individual rules of the KB $R_{ПН1}$:

$$h_{R_{ПН1}i} = T(\mu_{A_{1R_{ПН1}i}}(x*_{1R_{ПН1}i}), \\ \mu_{A_{2R_{ПН1}i}}(x*_{2R_{ПН1}i}), \mu_{A_{3R_{ПН1}i}}(x*_{3R_{ПН1}i})... , \\ ..\mu_{A_{nR_{ПН1}i}}(x*_{nR_{ПН1}i})) \qquad (13)$$

where $x*_{1R_{ПН1}i}$ – the current value of the 1st variable of the left part of the *i*-th rule from KB $R_{ПН1}$;
$A_{1R_{ПН1}i}$ – term (value) of the variable $x_{1R_{ПН1}i}$ in the *i*-th rule of the knowledge base $R_{ПН1}$;
T – any *t*-norm operator (for example, MIN).
In the next step we define the modified belonging functions of the conclusions of the individual rules from $R_{ПН1}$:

$$\mu_{B^*_{vh\_aims}}(u_{h1\_aims}) = \\ T(\max(h_{R_{ПН1}i}, h_{R_{ПН1}j}, h_{R_{ПН1}k}), , \\ \mu_{B_{vh\_aims}}(u_{h1\_aims})) \qquad (14)$$

where $h_{R_{ПН1}i}, h_{R_{ПН1}j}, h_{R_{ПН1}k}$ - rules from $R_{ПН1}$ the right part (consequent) of which contains B_{vh_aims}.

The resulting belonging functions of the current target parameters determined from the data of the first type of payloads are calculated by the formula:

$$\mu_{res}(u*_{i1\_aims}) = S(\mu_{B^*_{1i\_aims}}(u_{i1\_aims}), \mu_{Baims}(u_{i1\_aims}),..., \mu_{B^*_{ji\_aims}}(u_{i1\_aims})) \quad (15)$$

where S is any s-norm operator (for example, MAX).

Similarly, we calculate the resulting belonging functions of the target parameters determined from the data of payloads of all types.

Having the resulting belonging functions parameters of the target identified according to all payloads we can determine the total resulting belonging function parameters of the target by the formulas:

$$\mu_{res}(u*_{1\_aims}) = S(\mu_{res}(u*_{11\_aims})F_{11}, \mu_{res}(u*_{12\_aims})F_{12}),..., \mu_{res}(u*_{1n\_aims})F_{1n}) \quad (16)$$

$$\cdots\cdots\cdots\cdots\cdots\cdots$$

$$\mu_{res}(u*_{m\_aims}) = S(\mu_{res}(u*_{m1\_aims})F_{m1}, \mu_{res}(u*_{m2\_aims})F_{m2}),..., \mu_{res}(u*_{mn\_aims})F_{mn}), \quad (17)$$

where $F_{ij} = [0,1]$ is the coefficient of certainty in the correct determination of the value of the i-th characteristic of the target by the j-th type of payload.

As a result, for all payloads, the resulting belonging functions of the target parameter set will take the form:

$$\mu_{res}(U*_{aims}) = \{\mu_{res}(u*_{1\_aims}), \mu_{res}(u*_{2\_aims}),.. ., \mu_{res}(u*_{m\_aims})\} \quad (18)$$

Determination of the set of flight task parameters $U*_{set}$, based on the analysis of the complex with the UAV current task (for example, combat orders) $X*_{set}$, with the use of fuzzy inference is reduced to finding the resulting belonging function parameters of the flight task $\mu_{res}(U*_{set})$:

Fuzzification:

$$X*_{set} = \{x*_{1\_set}, x*_{2\_set},..., x*_{i\_set}\} \rightarrow M_{set} = \{\mu_{A_{11\_set}}(x*_{1\_set}), \mu_{Aset}(x*_{2\_set}),.. .., \mu_{A_{ji\_set}}(x*_{i\_set})\} \quad (19)$$

Calculation of the degree of fulfillment of the conditions $h_{R_{set}i}$ of individual rules from KB R_{set}:

$$h_{R_{set}i} = T(\mu_{A_{1Rseti}}(x*_{1Rseti}), \mu_{A_{2R_{set}i}}(x*_{2R_{set}i}), \mu_{A_{3Rseti}}(x*_{3R_{set}i}).....\mu_{A_{nR_{set}i}}(x*_{nR_{set}i})). \quad (20)$$

Definition of modified belonging functions of the conclusions of individual rules from R_{set}:

$$\mu_{B^*_{mq\_set}}(u_{q\_set}) = T(\max(h_{R_{set}i}, h_{Rsetj},..., h_{R_{set}k}), \mu_{B_{mq\_set}}(u_{q\_set})), \quad (21)$$

Defining the resulting belonging functions of the flight task parameters:

$$\mu_{res}(u*_{i\_set}) = S(\mu_{B^*_{1i\_set}}(u_{i\_set}), \mu_{B^*_{2i\_set}}(u_{i\_set}),.. .., \mu_{B^*_{ji\_set}}(u_{i\_set})) \quad (22)$$

$$\mu_{res}(U*_{set}) = \{\mu_{res}(u*_{1\_set}), \mu_{res}(u*_{2\_set}),.. .., \mu_{res}(u*_{m\_set})\} \quad (23)$$

For, $Y*_{nav}$, $Y*_{state}$, $F*_{exter\_av}$ the resulting belonging functions are found similarly.

At this stage, we have all belonging functions necessary to assess the current situation

$$S* = \{U*, F*, Y*\} = \{U*_{aims}, U*_{set}, F*_{exter\_av}, Y*_{nav}, Y*_{state}\}. \quad (24)$$

To determine the reference situation with the maximum degree of belonging to the current one, it is necessary to calculate the degree of fulfillment of the conditions of individual rules $h_{R_{res}i}$ from the KB of reference situations R_{res}, provided that the input of the fuzzy inference system is fed previously calculated belonging functions that characterize the current situation and meet the established restrictions E (for example $h_{R_{res}i} \geq 0.3$).

$$\begin{aligned} h_{R_{res}i} = T(&S(\mu_{B_{1\_aims\_R_{res}i}}(u*_{1\_aims\_R_{res}i})),.. \\ &.., S(\mu_{B_{a\_aims\_R_{res}i}}(u*_{a\_aims\_R_{res}i})), \\ &S(\mu_{B_{1\_set\_R_{res}i}}(u*_{1\_set\_R_{res}i})),.. \\ &.., S(\mu_{B_{b\_set\_R_{res}i}}(u*_{b\_set\_R_{res}i})), \\ &S(\mu_{B_{1\_nav\_R_{res}i}}(y*_{1\_nav\_R_{res}i})),.. \\ &.., S(\mu_{B_{c\_nav\_R_{res}i}}(y*_{c\_nav\_R_{res}i})), \\ &S(\mu_{B_{1\_state\_Rresi}}(y*_{1\_set\_R_{res}i})),.. \\ &.., S(\mu_{B_{d\_state\_R_{res}i}}(y*_{d\_state\_R_{res}i})), \\ &S(\mu_{B_{1\_exter\_av\_R_{res}i}}(f*_{1\_exter\_av\_R_{res}i})),.. \\ &.., S(\mu_{B_{e\_exter\_av\_R_{res}i}}(f*_{e\_exter\_av\_R_{res}i}))) \end{aligned} \quad (25)$$

The solution is a set of values of dependent (endogenous) parameters of the complex with UAV, proposed to the operator $Z = (z_1, z_2,..., z_g)$, which is the conclusion of the reference rule from the KB $R_{рез}$ with the maximum degree of fulfillment

$$h^{\max}_{R_{res}} = \max(h_{R_{res}1}, h_{R_{res}2},..., h_{R_{res}n}) \quad (26)$$

and satisfying the constraints E with the use of the modifier Δ, depending on the degree of fulfillment of the reference rule. If several rules with the maximum degree of fulfillment are activated the solution proposed by the UAV operator will be the conclusion of either all or (preferably) the conclusion of several (for example, three $\bigcup_{j=1}^{3}$) first rules:

$$\bigcup_{j=1}^{3} \forall i = 1, n\_(h_{R_{res}i} \equiv h_{R_{res}^{\max}}) \cap (h_{R_{res}i} \geq 0.3) \Rightarrow \quad , \quad (27)$$
$$Z_j = \Delta(z_{1\_R_{res}i}, z_{2\_R_{res}i}, ..., z_{g\_R_{res}i})$$

where

$$\begin{cases} \Delta = "possible", \_with\_0.3 \leq h_{R_{res}i} \leq 0.5 \\ \Delta = "more\_likely", \_with\_0.5 < h_{R_{res}i} \leq 0.7 \\ \Delta = "definitely", \_with\_0.7 < h_{R_{res}i} \leq 1 \end{cases} \quad (28)$$

IV. Conclusion

Currently, mathematical models IDSS based on logical inference systems Mamdani-type in the known complexes with unmanned aerial vehicles do not apply [10]. However, IDSS, developed on the basis of the proposed mathematical model, will allow the UAV operator to make informed decisions in real time with a high degree of reliability when using different payloads on it. The software implementation of this model will create an IDSS that can be integrated into the software of the complex with an unmanned aerial vehicle and work in parallel with other components.

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