An analysis of approach to the features of satellites classification determining based on modeling of linguistic variables and membership functions

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Abstract

The modern approaches to the classification of satellites was analyzed, the relevance of the use of the fuzzy logic apparatus and the main stages of solving the given problem using the theory of fuzzy sets was determined. The features of the classification of satellites, which can be obtained both from the analysis of a priori and a posteriori information about satellites, and can be numerical, categorical or linguistic, was determined. The need to define linguistic variables and their linguistic terms for those features of the classification of satellites that can be presented in a linguistic form was substantiated. The choice of the method of constructing the membership function of a fuzzy set of defined features of the satellites classification, which can be presented in a linguistic form, was justified. Further steps to solve the problem of satellites classification based on fuzzy logic was outlined: building a system of fuzzy rules for satellites identification and creating a fuzzy knowledge base for their classification.

Keywords

classification of satellites, features of classification, fuzzy set, linguistic variables, membership function,

1. Introduction

The composition of the space systems of the world's leading states that carry out space activities is actively changing today. The number of satellites is increasing, their functional capabilities are improving due to the development of the material, technical and scientific base.

Considering the martial law introduced in Ukraine from February 24, 2022, space support and, in particular, space situational awareness (space situation analysis) is an urgent need in the process of planning the activities of national security and defense entities, which requires a clear classification of satellites, which is determined by their purpose.

A clear understanding of the purpose of satellites allows you to take into account the peculiarities of their functioning and influence on various spheres of activity of state authorities, especially to ensure the national security and defense of Ukraine [1]. It is necessary to classify satellites, which is an important task for carrying out space activities (for example, planning observations, protection against possible observations from space, etc.).

The development of technologies and the appearance of new satellites may require the expansion of existing classification features, that is, such as the satellites classes defined for a certain period of time which are not static. Under such conditions, classification features obtained from both a priori and a posteriori information about satellites can be numerical, categorical or linguistic.

Taking into account heterogeneous features requires the use of appropriate mathematical apparatus, which will allow them to be formalized for the further classification of satellites, which is an current scientific task.

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2. Related works

Many scientific works are devoted to the issue of object classification. Different approaches have been proposed to solve the classification task, for example, using of the backpropagation algorithm of artificial neural networks for the classification of GPS satellites and the calculation of geometric accuracy coefficients of their positioning [2], deep and multi-core learning based on recurrent and convolutional neural networks [3, 4] for synchronous identification of the shape and position of satellites in geostationary orbit [5], etc.

But most of the attention is given to the classification of satellites from the point of view of their further application or the use of data that can be obtained from satellites.

Thus, the classification of GPS satellites using improved learning algorithms is considered to solve the problem of calculating the geometric accuracy coefficients of GPS satellites positioning [2]. The unified classification of satellites based on mass and size is one of the tools for determining the size of launch vehicles and the cost of launching satellites into orbit [6]. Classification of satellites in geostationary orbit with deep and multi-core learning is one of the approaches to ensure the safety of objects in geostationary orbit [5].

In Ukrainian works, options for the satellites classification are considered using the example of species observation satellites based on the analysis of their features and the systematization of information about space systems, a generalized classification of satellites is proposed [7, 8, 9]. In other publications, attention is paid to the problems of choosing satellites for the use of their target information [10, 11, 12].

Thus, in modern scientific works, the results of research on the classification of satellites by individual features are reflected, and the specified task by a set of features is almost not considered.

In the case when there is no clear boundary separating the classes (for example, heterogeneous features belong to several classes), the approach using fuzzy logic [13, 14, 15] will allow classifying satellites by a set of heterogeneous features with a certain probability of truth [16].

The *purpose* of the article is to determine the linguistic variables and the membership function of a set of features for the further satellites classification using the theory of fuzzy sets.

3. Method

In the modern conditions of using information about the state and changes of the space situation, there is an urgent need for reliable and complete information about the purpose of satellites, which is complicated by certain limitations in the use of measuring tools, etc. [1, 17].

In order to increase the accuracy of determining the purpose of satellites, the reliability of their classification, it is proposed to use the mathematical apparatus of the theory of fuzzy sets to classify satellites based on a priori and a posteriori information that can be obtained from open sources.

The initial stage in the task of satellites classification using fuzzy set theory is the determination of the features of satellites that will be used for classification. These features can be numerical, categorical or linguistic.

It is possible to classify satellites according to the information that precedes their launch and the information that is available for analysis after the launch. Thus, it is possible to distinguish a priori (pre-launch) and a posteriori (post-launch) features of classification, which, in turn, can be direct and indirect [18].

The initial information before launch for classification is the satellite launch plan. Information from the satellite launch plan can be interpreted accordingly to table 1.

After launch, the satellite classification is refined based on the use of a posteriori information and its orbital parameters obtained from official sources or from measuring devices.

Taking into account that all features are different, it is possible to obtain a generalized conclusion and make a decision regarding the belonging of satellite to a certain class with a certain degree of truth using a mathematical apparatus of fuzzy derivation.

The problem of data classification can be solved by the fuzzy inference system, which is based on the

Table 1
Information from the satellite launch plan.

Category of information	Type of a priori feature
Declared purpose of the satellite	direct, categorical
The launch site (cosmodrome)	indirect, linguistic
The type of launch vehicle that will be used to launch the satellite	indirect, linguistic
Name of satellite	direct, linguistic
The customer of the satellite	indirect, linguistic
The developer of the satellite	indirect, linguistic
Configuration of the satellite	direct, linguistic
Launch mass of the satellite	indirect, numerical
Estimated (warranty) period of operation of the satellite	indirect, numerical
Type of orbit	indirect, linguistic
Inertial longitude of the ascending node of the orbit	indirect, numerical

algorithm of obtaining fuzzy conclusions based on fuzzy premises using concepts of fuzzy logic [16]. The process of fuzzy derivation combines the main concepts of fuzzy set theory: membership functions, linguistic variables, fuzzy logical operations, methods of fuzzy implication, and fuzzy composition [18].

The general scheme of the fuzzy inference system is presented in figure 1.

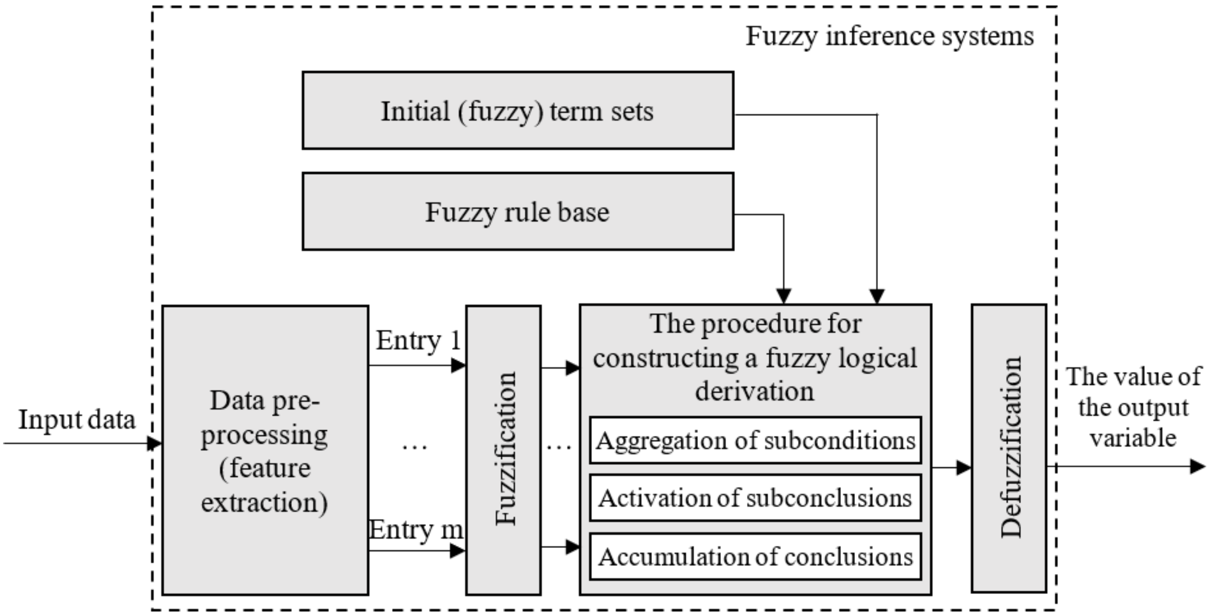

Figure 1: The general scheme of the fuzzy inference system.

Fuzzy inference systems are defeaturesed to transform the values of input variables into output variables based on the use of fuzzy rules. For this, fuzzy inference systems should contain a base of fuzzy rules and initial term sets [18].

The main stages of fuzzy derivation (figure 1) are [18]:

- fuzzification of input variables;
- aggregation of preconditions in fuzzy rules;
- activation or composition of subconclusions in fuzzy rules;
- accumulation of conclusions of fuzzy rules.

In general, the classification of objects based on fuzzy logic is a complex process and requires a large amount of input data, but the main advantage of applying the proposed approach is the ability to use information that may be fuzzy, but still useful for decision-making.

Consider the first stage of the process of fuzzy derivation – fuzzification of input variables – establishing correspondence between the specific (usually numerical) value of a separate input variable of the system of fuzzy derivation and the value of the membership function of the corresponding term of the input linguistic variable. After that, specific values of membership functions for each of the linguistic terms used in the prerequisites of the fuzzy inference system rule base must be determined for all input variables [18].

Formally, the fuzzification procedure is performed as follows. At the beginning of fuzzification, the specific values of all input variables of the fuzzy inference system are determined, that is, the set of values $A = a^1, a^2, ..., a^m$.

In the general case, each $a_i \in E_i$, where E_i is the universe of the linguistic variable β_i.

Next, we consider each of the subconditions of the form $\beta_i \in T$ of the fuzzy derivation system rules, where T is some term with the corresponding membership function $\mu(x)$, which can be analytically specified, for example, in the following form:

$$\mu(x, a, b) = \left\{ \begin{matrix} 1, x \leqslant a \\ \frac{b-x}{b-a}, a < x < b \\ 0, b \leqslant x \end{matrix} \right\}, \tag{1}$$

or

$$\mu(x, a, b) = \left\{ \begin{matrix} 1, x \leqslant a \\ \frac{x-a}{b-a}, a < x < b \\ 0, b \leqslant x \end{matrix} \right\}. \tag{2}$$

At the same time, the value a_i is used as an argument of $\mu(x)$ and the quantitative value is found, which is the result of fuzzification of the subcondition.

The specified approach can be used to solve the task of satellites classification taking into account the majority of disparate features.

4. Experimental results

Suppose that the launch of the ViaSat 3.2 satellite (ViaSat 3 EMEA) is planned for 2024, which is about 6.4 tons, using an Atlas-5 launch vehicle in an orbit with an altitude of about 35,790 km [19].

For example, consider the features “Type of launch vehicle” and “Type of orbit”, which are indirect linguistic a priori features for further classification of the satellites.

Correspondence between the type of launch vehicle and its payload is shown in table 2 [19, 20, 21].

Table 2
Correspondence between the type of launch vehicle and its payload.

Type of launch vehicle	Payload, tons
Small	up 2
Medium	2-20
Heavy	20-50
Overweight	> 50

Correspondence between the type of orbit and its altitude is shown in table 3 [19, 20, 21].

Let’s define the linguistic variable “Type of launch vehicle” as β_1. Then “Small, Medium, Heavy, Overweight” will be the set of terms T_1 of this linguistic variable β_1:

$$T_1 = \{Small, Medium, Heavy, Overweight\}. \tag{3}$$

The set of all ranges of values of the variable β_1:

$$E_1 = [0, > 50]. \tag{4}$$

Table 3
Correspondence between the type of orbit and its altitude.

Type of launch vehicle	Payload, tons
Low	160-2000
Medium	2000-35786
High	> 35786

Let's define the linguistic variable "Type of orbit" as β_2. Then "Low, Medium, High" will be the set of terms T_2 of this linguistic variable β_2:

$$T_2 = \{Low, Medium, High\}\,. \tag{5}$$

The set of all ranges of values of the variable β_2:

$$E_2 = [160, > 35786]\,. \tag{6}$$

Consider the process of fuzzification of four fuzzy statements for the input linguistic variable β_1 – "Type of launch vehicle": "Type of launch vehicle small", "Type of launch vehicle medium", "Type of launch vehicle heavy", "Type of launch vehicle overweight". The fuzzification of the first fuzzy statement gives the value "0", which is obtained by substituting the value $x_1 = 6.4$ into of the argument of the membership function. The fuzzification of the second fuzzy statement gives the value "0.24", which is obtained by substituting the value $x_1 = 6.4$ into the argument of the function accessories. The fuzzification of the third and fourth fuzzy statement gives the value "0", which is obtained by substituting the value $x_1 = 6.4$ into the argument of the function accessories. The result of fuzzification for the input linguistic variable β_1 on figure 2.

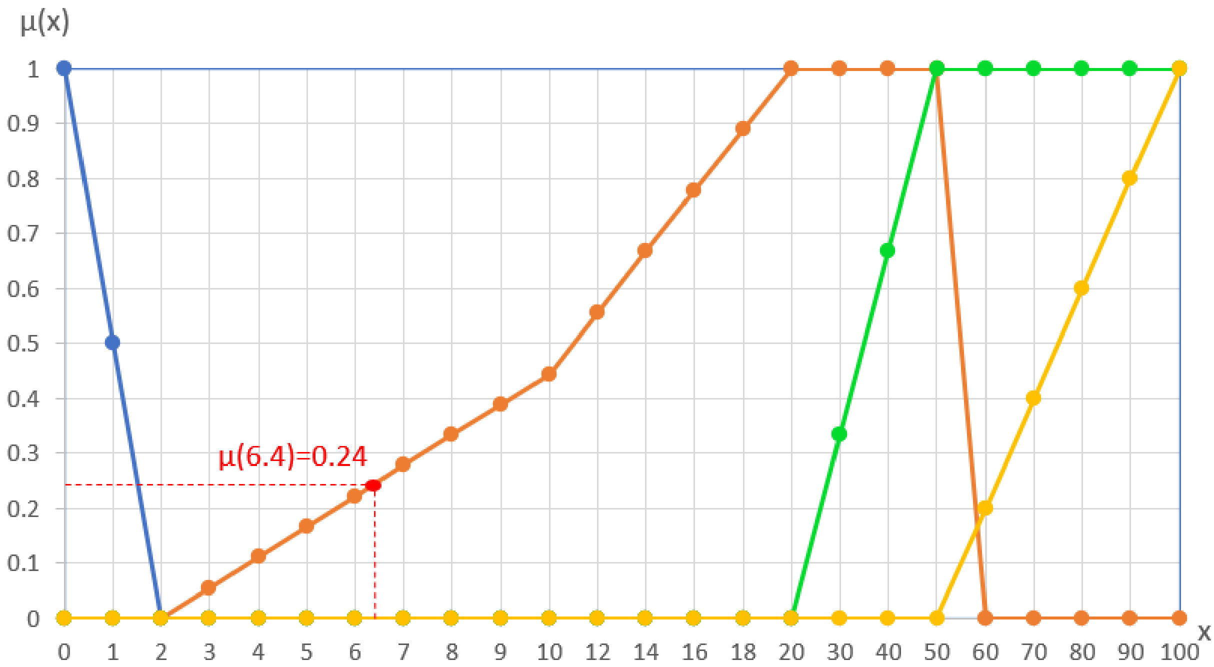

Figure 2: The result of fuzzification for the input linguistic variable β_1.

Consider the fuzzification process of three fuzzy statements for the input linguistic variable β_2 – "Type of orbit": "Orbit type is low", "Orbit type is medium", "Orbit type is high". The fuzzification of the first and second fuzzy statements gives the value "0", which is obtained by substituting the value $x_2 = 35790$ to the argument of the membership function for linguistic variable "Orbit type is low" and "Orbit type is medium". The fuzzification of the third fuzzy statement gives the value "0.84", which is obtained by substituting the value $x_2 = 35790$ to the argument of the membership function for linguistic variable “Orbit type is high”. The result of fuzzification for the input linguistic variable β_1 on figure 3.

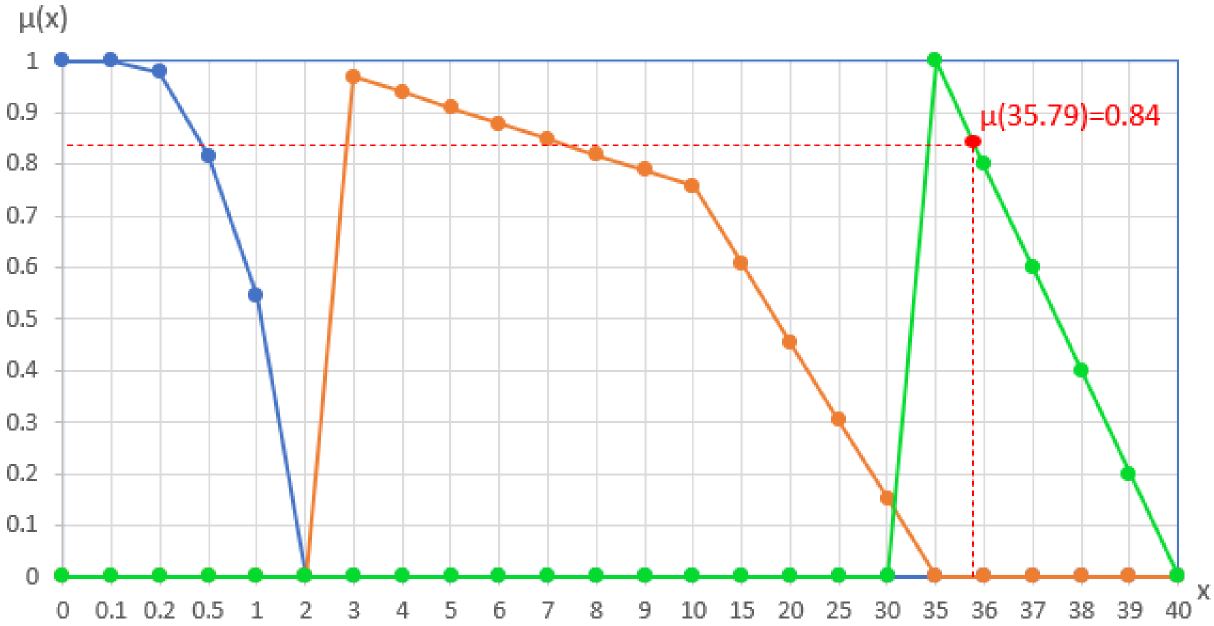

Figure 3: The result of fuzzification for the input linguistic variable β_2.

With the known values of the variables “Payload weight” = 6.4 tons and “Orbital height” = 35790 km, a preliminary conclusion can be made about the type of launch vehicle that can be used during the launch of the satellites and the likely type of orbit to which it will be possible the satellites will be launched.

5. Conclusions and further research

Thus, using the theory of fuzzy sets, the linguistic variables of some features of the satellites classification were formalized and an example of the calculation of their membership functions was given. The following steps in the classification process are:

1) finding the degrees of truth of the simplest statements based on the given values of the input parameters;
2) calculation of the truth of the prerequisites of the rules;
3) determination of membership functions of each of the conclusions for the general linguistic variable;
4) unification of membership functions through the construction of their maximum;
5) obtaining a specific value of the output variable.

The proposed approach can be used to solve the problem of complex classification of satellites, taking into account the majority of heterogeneous features.

6. Contributions by authors

The author’s contribution to the article is distributed as follows:

- Conceptualisation of reseach, formulation of the research idea, Dmytro V. Pekariev and Iryna A. Bespalko;
- Formal analysis, preparing data for analysis, Leonid M. Naumchak;

- Research of satellites classification, Leonid M. Naumchak;
- Methodology for defining linguistic variables and terms, Iryna A. Bespalko and Leonid M. Naumchak;
- Project administration, Ihor A. Pilkevych;
- Software of modeling membership function, Iryna A. Bespalko;
- Supervision throughout the research process, Ihor A. Pilkevych and Dmytro V. Pekariev;
- Writing – original draft, Iryna A. Bespalko and Leonid M. Naumchak;
- Writing – review and editing, Iryna A. Bespalko.

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