Сучасний стан наукових досліджень та технологій в промисловості. 2021. № 4 (18) *ISSN 2522-9818 (print)* *ISSN 2524-2296 (online)*

UDC 68/32 DOI: https://doi.org/10.30837/ITSSI.2021.18.075

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METHOD OF IDENTIFICATION OF OBJECT STATES ACCORDING TO THE RESULTS OF FUZZY MEASUREMENTS OF CONTROLLED PARAMETERS

The **subject** of consideration is the task of identifying the states of an object based on the results of fuzzy measurements of a set of controlled parameters. The fuzziness of the initial data of the task further complicates it due to the resulting inequality of the controlled parameters. The **aim** of the study is to develop a method of identifying the states of a fuzzy object using a fuzzy mechanism of logical output taking into account possible differences in the level of information content of its controlled parameters. The **method** of obtaining the desired result is based on the modification of the known mathematical apparatus for building an expert system of artificial intelligence by solving two subtasks. The first is the development of a method for assessing the informativity of controlled parameters. The second is the development of a method for constructing a mechanism for logical inference of the relative state of an object based on the results of measuring controlled parameters, which provides identification. In the first problem, a method is proposed for estimating the informativity of parameters, free from the known disadvantages of the traditional Kulbak informativity measure. In implementing the method, it is assumed that the range of possible values for each parameter is divided into subbands in accordance with possible states of the object. For each of these states, the function of belonging to the fuzzy values of the corresponding parameter is defined. At the same time, the correct problem of estimating the informativity of a parameter is solved for cases when this parameter is measured accurately or determined fuzzily by its belonging function. The fundamental difference between the proposed logical output mechanism and the traditional one is the refusal to use the production rule base, which ensures the practical independence of the computational procedure from the dimension of the task. To solve the main problem of identifying states, a non-productive approach is proposed, the computational complexity of which practically does not depend on the dimension of the problem (the product of the number of possible states **Results.**per the number of controlled parameters). The logic output mechanism generates a probability distribution of the system states. In this case, a set of functions of belonging of each parameter to the range of its possible values for each of the states of the object is used, as well as a set of functions of belonging to fuzzy measurement results of each parameter. **Conclusions.** Thus, a method of identifying the state of fuzzy objects with a fuzzy non-productive output mechanism is proposed, the complexity of which does not depend on the dimension of the task.

Keywords: method of identifying object states; information value of controlled parameters; fuzzy mechanism of logical output.

Introduction

The problem of identifying the state of the object by measuring a set of controlled parameters is one of the most popular in many areas of human practice: technology, economics, medicine, sociology, military affairs, etc. The efficiency of solving the relevant problems depends, firstly, on the quantity and quality of the controlled parameters, but mainly on the adopted method of forming a solution based on the results of processing the measurements of these parameters. The simplest problems of this type belong to special sections of statistical analysis and are formulated as problems of linear (nonlinear) multifactor regression, or as clustering problems. The principal feature of the methods of solving these problems is that the decision is determined by the results of the calculation of a single identifying parameter. In regression problems, this is the value of the regression polynomial calculated from the values of the controlled factors. In clustering problems, this is the distance to the grouping centers calculated in the selected metric. Much more difficult to formulate and solve are the tasks of identifying the states of the object, the differences of which may not be parameterized, but set qualitatively or complexly ranked. Let's make a brief analysis of known publications on this issue.

Analysis of literature data

To solve the problems of identifying the states of objects, the so-called expert systems for assessing the state of these objects are effectively used based on the results of measurements of the controlled parameters. Such systems belong to the class of artificial intelligence systems, were first described in detail in [1] and are constructed as follows. It is assumed that the system can be in one of a set $(H_1, H_2, ..., H_m)$ of states. In order to identify the current state, *n* controlled parameters $(x_1, x_2, ..., x_n)$. are used. The range of possible values for each, for example, the j-th of these parameters is divided into m (according to the number of possible states) subranges that can intersect. Further, for each controlled parameter, a set of functions $\mu_i\left(x_j / H_i\right)$, is introduced which for a pair (i, j) determine the degree of the parameter x_j belonging to the *j*-th sub-range of possible values. The corresponding value $\mu\left(x_j / H_i\right)$ can be interpreted as the degree of confidence that the system, according to the results of the parameter x_j, control, is in the *i*-th state. The values $\left\{\mu_i\left(x_j / H_i\right)\right\}, i = 1,2,\ldots,m, j = 1,2,\ldots,n,$ are used to identify the state of the system. At the same time, a set of rules, called production rules, are introduced, which are formulated as follows: "IF the parameter x_1 has taken a value A_1, the parameter x_2 has taken the value A_2, , the parameter x_n has taken the value A_n, THEN the system is in a state $H(A_1, A_2, ..., A_n)$." Numerous systems of this type, differing in the inference mechanism, are successfully used to solve the problems of identifying the states of controlled objects. At the same time, in [2], the principle of construction and features of the application of

ISSN 2522-9818 (print)
ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2021. No. 4 (18)

the Mamdani algorithm are considered in detail, in [3], descriptions of the Takagi - Sugeno and Tsukamoto algorithms are given, in [4], the possibility of using ES for the analysis of multivariate systems is discussed, in [5], descriptions and comparison are given. algorithms Mamdani, Takagi - Sugzno, Tsukamoto and Larsen. The work [6], along with a detailed description of the work of the main inference mechanisms, contains a comparison of the effectiveness of the main methods of defuzzification. In [7] the possibility of using fuzzy ESs for solving problems of pattern recognition is considered, and in [8] the same idea is generalized to the vector case. The fundamental drawback of all the considered systems is the rapid growth in the number of rules with an increase in the dimension of the problem. If the number of possible states of the system is equal to *m*, and the number of controlled parameters is equal to *n*, then the total number of necessary rules is equal to $N = n^m$. This disadvantage is eliminated in non-production fuzzy export systems [9]. In these systems, based on the results of monitoring *n* parameters, a matrix $\left\{\mu_i\left(x_j/H_i\right)\right\}$, $i = 1,2,\ldots,m, j = 1,2,\ldots,n.$ is formed. Then, for each of the possible states, it is calculated

$$y_i = \prod_{j=1}^{n} \mu\left(x_j/H_i\right), \; i = 1,2,\ldots,m.$$

The obtained value y_i determines the degree of confidence that the system is in the state H_i. based on the results of control of n parameters. In order to use these values for a set of theoretical and probabilistic interpretations, they are normalized by calculating

$$\hat{y}_i = \frac{y_i}{\sum_{i=1}^{m} y_i}, \; i = 1,2,\ldots,m.$$

The resulting set $(\hat{y}_i), i = 1,2,\ldots,m,$ has the meaning of the distribution of the probabilities of the states of the system. The obvious design flaw of the introduced measure of information content is the way of combining the control results for different parameters: the criterion is multiplicative. This means that the final result obtained is majorized from above by the value of the minimum of the factors. However, the conceptual flaw is more significant. It is clear that the level of adequacy of the results obtained in the practical use of this system of diagnostics of the condition depends significantly on the accuracy of measuring the values of the controlled parameters. At the same time, in many works, for example, [7, 8], the understanding of the existence of a real inaccuracy in the measurement of these parameters is declared, but it is not used in solving the practical problem of assessing the state of objects under control. In this regard, we pose the problem of constructing a fuzzy expert system, analytically using the value of the membership functions of fuzzy values of the controlled parameters of the system. Let us formulate the purpose of the study.

Purpose of the study – development of a method for identifying the state of an object using a fuzzy set of not equally informative controlled parameters and a fuzzy inference mechanism.

To achieve the goal, it is necessary to solve the following tasks.

1. Development of a method for assessing the information content of controlled parameters, taking into account the ambiguity of the description of their possible values.

2. Development of a method for assessing the informativeness of fuzzy controlled parameters, given by their membership functions, taking into account the vagueness of the description of possible states of the controlled object.

3. Development of a logical inference mechanism for an expert system with a fuzzy input and fuzzy descriptions of possible states of an object.

Main results

Development of a fuzzy system for identifying the state of the system.

1. Consider a method for assessing the informativeness of a controlled parameter. Let the controlled system in the process of functioning at each moment of time be in one of the set $(H_1, H_2, ..., H_m)$ of possible states. For each controlled parameter *x*, we introduce $\mu\left(x/H_i\right)$ – the membership function of a fuzzy value *x* when the system is in a specific state H_i, $i = 1,2,\ldots,m.$ The controlled parameters are informative in different ways. In this case, the level of information content of the parameter is the higher, the more significantly the numerical characteristics of the membership function of this parameter change when the state of the system changes. The traditional Kulbak probability measure [10] of the informativeness of the parameter *x* for a pair of states H_i, H_K is determined by the formula

$$J = \int_{-\infty}^{\infty} f_i\left(x/H_i\right) \ln \frac{f_i\left(x/H_i\right)}{f_K\left(x/H_K\right)} dx, \qquad (1)$$

where

$f_i\left(x/H_i\right)$ – distribution density of a random value *x*, provided that the system is in the state H_i,

$f_K\left(x/H_K\right)$ – distribution density of a random value *x*, provided that the system is in the state H_K.

A fuzzy analogue of the probability measure (1) can be easily constructed. Introduce

ISSN 2522-9818 (print)
Сучасний стан наукових досліджень та технологій в промисловості. 2021. № 4 (18) ISSN 2524-2296 (online)

$$\hat{\mu}_i\left(x/H_i\right)=\frac{\mu_i\left(x/H_i\right)}{\int\limits_{-\infty}^{\infty}\mu_i\left(x/H_i\right)dx},$$

$$\hat{\mu}_K\left(x/H_K\right)=\frac{\mu_K\left(x/H_K\right)}{\int\limits_{-\infty}^{\infty}\mu_K\left(x/H_K\right)dx}. \quad (2)$$

The functions $\hat{\mu}_i\left(x/H_i\right)$, $\hat{\mu}_K\left(x/H_K\right)$, introduced by relations (2), satisfy all the requirements for the distribution densities of random variables. They are non-negative on the whole axis and satisfy the normalization condition, that is,

$$\int\limits_{-\infty}^{\infty}\mu_i\left(x/H_i\right)dx=\int\limits_{-\infty}^{\infty}\mu_K\left(x/H_K\right)dx=1.$$

These circumstances determine the possibility of using relation (1) to assess the measure of the informativeness of a controlled parameter, taking into account transformations (2).

The Kulbak measure (1) has the following properties.

The value of the measure is equal to zero if the distribution densities (membership functions) coincide. The value of the measure is positive and can take on an arbitrarily large value if the densities do not match. The value of the measure is the greater, the more the distribution densities differ for different states.

Note the serious drawback of the Kulbak measure. Ratio (1) is asymmetric. In this case, the value of the measure depends on the order in which its components enter the calculation formula, which can lead to incorrect conclusions regarding the informativeness of the controlled parameter. In addition, the value of the measure is not normalized, that is, this value for a specific pair of states can be useful and reasonably used only in comparison procedures.

These disadvantages are eliminated if a different ratio is used to assess the informativeness of the parameter [11, 12]. Moreover, for the same pair $\hat{\mu}_i\left(x/H_i\right)$, $\hat{\mu}_K\left(x/H_K\right)$ the measure of the informativeness of the parameter x is determined by the formula

$$R=1-\int\limits_{-\infty}^{\infty}\left[\hat{\mu}_i\left(x/H_i\right)\hat{\mu}_K\left(x/H_K\right)\right]^{\frac{1}{2}}dx. \quad (3)$$

Measure R has the following important properties.

1. The value of R is equal to zero if the distribution densities for different states of the system coincide.
2. The R value is equal to one if the densities do not intersect.
3. The value of R does not change from the permutation of the places of the factors.

Difficulties in the practical use of the informativeness measure R are associated with the analytical complexity of the integrand in relation (3), which often leads to the need for numerical integration. In this regard, to calculate the measure of the informativeness of the parameter, we use a different approach.

For a pair $\hat{\mu}_i\left(x/H_i\right)$, $\hat{\mu}_K\left(x/H_K\right)$ let's calculate the areas of the figures that arise when these functions intersect and when combining them (fig. 1)

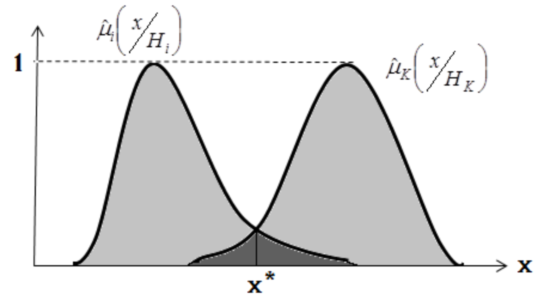

Fig. 1. Graphs of membership functions $\hat{\mu}_i\left(x/H_i\right)$, $\hat{\mu}_K\left(x/H_K\right)$

In this case, the area of the figure resulting from the intersection $\hat{\mu}_i\left(x/H_i\right)$, $\hat{\mu}_K\left(x/H_K\right)$, is defined by the formula

$$S^{\wedge}\hat{\mu}_i\left(x/H_i\right)\wedge\hat{\mu}_K\left(x/H_K\right)=\int\limits_{-\infty}^{x^*}\hat{\mu}_K\left(x/H_K\right)dx+\int\limits_{x^*}^{\infty}\hat{\mu}_i\left(x/H_i\right)dx,\ , \quad (4)$$

and the area of the figure arising from the union $\hat{\mu}_i\left(x/H_i\right)$ и $\hat{\mu}_K\left(x/H_K\right)$, is calculated by the formula

$$S^{\vee}\hat{\mu}_i\left(x/H_i\right)\vee\hat{\mu}_K\left(x/H_K\right)=\int\limits_{-\infty}^{x^*}\hat{\mu}_i\left(x/H_i\right)dx+\int\limits_{x^*}^{\infty}\hat{\mu}_K\left(x/H_K\right)dx. \quad (5)$$

Now the measure of the informativeness of the monitored parameter x when distinguishing between states H_i and H_K define by the value

$$\eta=\frac{S^{\wedge}}{S^{\vee}} \quad (6)$$

As

$$\int\limits_{-\infty}^{x^*}\hat{\mu}_i\left(x/H_i\right)dx+\int\limits_{x^*}^{\infty}\hat{\mu}_I\left(x/H_i\right)dx=1,$$

$$\int\limits_{-\infty}^{x^*}\hat{\mu}_K\left(x/H_K\right)dx+\int\limits_{x^*}^{\infty}\hat{\mu}_K\left(x/H_K\right)dx=1,$$

so

$$S^{\vee}=2-S^{\wedge}.$$

That's why

$$\eta=\frac{S^{\wedge}}{2-S^{\wedge}}\in[0;1]. \quad (7)$$

ISSN 2522-9818 (print)
ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2021. No. 4 (18)

The measure of information content (7) (a measure of the proximity of the membership functions of the controlled parameter for different states of the system) has the following properties.

The value $\eta = 0$, if $S^{\wedge} = 0$, that is, the membership functions of the parameter for different states of the system do not intersect.

The value $\eta = 1$, if $S^{\wedge} = 1$ when the membership functions of the parameter coincide for different states.

The value η increases monotonically with increasing $S^{\wedge}$.

To calculate the value η it is enough to determine the value $S^{\wedge}$.

Integrals in (4), (5), as a rule, are easy to calculate.

Thus, the first task is solved.

2 Method for assessing the informativeness of a fuzzy controlled parameter in an expert system with a fuzzy description of possible states of the controlled object.

Let, as before, for each of the parameters a membership function $\hat{\mu}_i\left(x/H_i\right)$, defining H_i. Let us define the membership function $\mu(x_j)$ of the fuzzy measured value of the parameter x_j. Let us now calculate the degree of belonging of the measured value of the parameter x_j to the *i*-th sub-range of the values of this parameter:

$$\underline{Z}_{ji} = \int_{-\infty}^{\infty} \min\left\{\mu\left(x_j\right), \mu_i\left(x_j/H_i\right)\right\} dx_j. \quad (8)$$

The calculated value lies in the interval [0, 1]. Moreover, the closer this value is to 1, the more confidence we can assume that the object is in the i-th state. This relationship can be written differently, with a clearer account of the possible location of the membership functions $\mu\left(x_j\right)$, $\mu_i\left(x_j/H_i\right)$ and their intersection points. The possible variants arising in this case are shown in fig. 2-4.

Variant 1

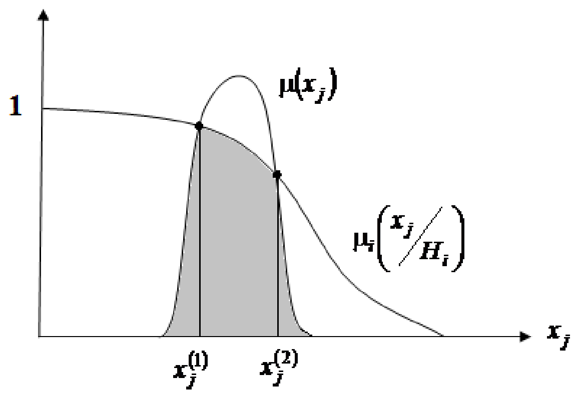

Fig. 2. Graphs $\mu\left(x_j\right)$ and $\mu_i\left(x_j/H_i\right)$ (variant 1)

$$\underline{Z}_{ji} = \int_{-\infty}^{x_j^{(1)}} \mu\left(x_j\right)dx_j + \int_{x_j^{(1)}}^{x_j^{(2)}} \mu_i\left(x_j/H_i\right)dx_j + \int_{x_j^{(2)}}^{\infty} \mu\left(x_j\right)dx_j. \quad (9)$$

Variant 2

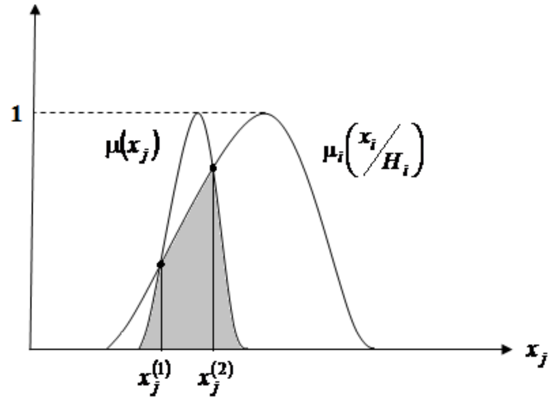

Fig. 3. Graphs $\mu\left(x_j\right)$ and $\mu_i\left(x_j/H_i\right)$ (variant 2)

$$\underline{Z}_{ji} = \int_{-\infty}^{x_j^{(1)}} \mu\left(x_j\right)dx_j + \int_{x_j^{(1)}}^{x_j^{(2)}} \mu_i\left(x^j/H_i\right)dx_j + \int_{x_j^{(2)}}^{\infty} \mu\left(x_j\right)dx_j. \quad (10)$$

Variant 3

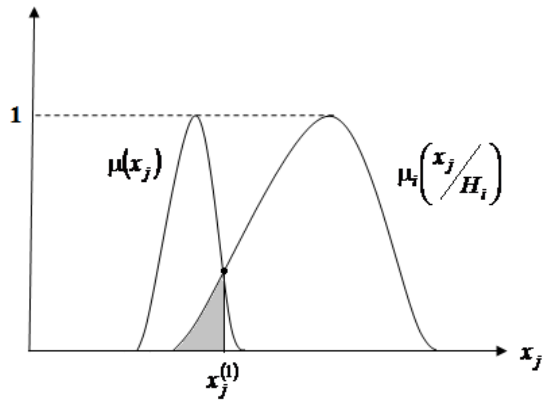

Fig. 4. Graphs $\mu\left(x_j\right)$ and $\mu_i\left(x_j/H_i\right)$ (variant 3)

$$\underline{Z}_{ji} = \int_{x_j^{(1)}}^{x_j^{(1)}} \mu_i\left(x^j/H_i\right)dx_j + \int_{x_j^{(1)}}^{\infty} \mu\left(x_j\right)dx_j. \quad (11)$$

It is clear that relation (8) is equivalent to relations (9) - (11).

An obvious drawback of measure (10) is that the value Z_{ji} is not standardized. Moreover, $Z_{ji} = 0$, if the membership functions $\mu\left(x_j\right)$ and $\mu\left(x_j/H_i\right)$ do not intersect, and Z_{ji} can take an arbitrarily large value otherwise. In order to eliminate this drawback, we use the technology implemented above in (7).

Introduce $\underline{Z}_{ji} \int_{-\infty}^{\infty} \max\left\{\mu\left(x_j\right), \mu_i\left(x_j/H_i\right)\right\} dx_j$ (12)

ISSN 2522-9818 (print)
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Then, using formulas (2), we normalize the membership functions $\mu(x_j)$ and $\mu_i\left({x_j}/{H_i}\right)$, $i=1,2,...m,\ j=1,2,...n.$. With this in mind, we rewrite (10) and (14):

$$Z_{ji}^{(\wedge)}\int_{-\infty}^{\infty}\min\left\{\hat{\mu}(x_j),\hat{\mu}_i\left({x_j}/{H_i}\right)\right\}dx_j, \qquad (13)$$

$$Z_{ji}^{(\vee)}\int_{-\infty}^{\infty}\max\left\{\hat{\mu}(x_j),\hat{\mu}_i\left({x_j}/{H_i}\right)\right\}dx_j. \qquad (14)$$

Now, as a measure of the belonging of the parameter value x_j to the *i*-th sub-range of this parameter, we define

$$\eta_{ji}=\frac{Z_{ji}^{(\wedge)}}{Z_{ji}^{(\vee)}}$$

As

$$\int_{-\infty}^{\infty}\mu(x_j)dx_j=\int_{-\infty}^{\infty}\mu_i\left({x_j}/{H_K}\right)dx_j=1,$$

then as before, $\underline{Z}_j+\overline{Z}_j=2$. That's why $Z_j^{(\vee)}=2-Z_j^{(\wedge)}$, from where

$$\eta_{ji}=\frac{Z_{ji}^{(\wedge)}}{2-Z_{ji}^{(\wedge)}}.$$

The technology of calculations by formulas (13), (14) will be illustrated by an example, when the membership functions $\mu(x_j)$ and $\mu\left({x_j}/{H_i}\right)$ are described by triangular functions of the (L-R) -type.

Let us describe the membership function of the values of the controlled parameter x_j by a tuple $<a_0,b_0,c_0>$, and the membership function of this parameter to the range of its possible values corresponding to the state of the object H_i, as a tuple $<a_i,b_i,c_i>$. Possible variants of the relative position of these membership functions are shown in fig. 5.

Variants 1-3

1) $a_0<a_i,\ b_0<a_i,\ c_0\in[a_i,b_i]$;

2) $a_0<a_i,\ b_i<a_i,\ c_0\in[b_i,c_i]$;

3) $a_0<a_i,\ b_0<a_i,\ c_0>c_i$.

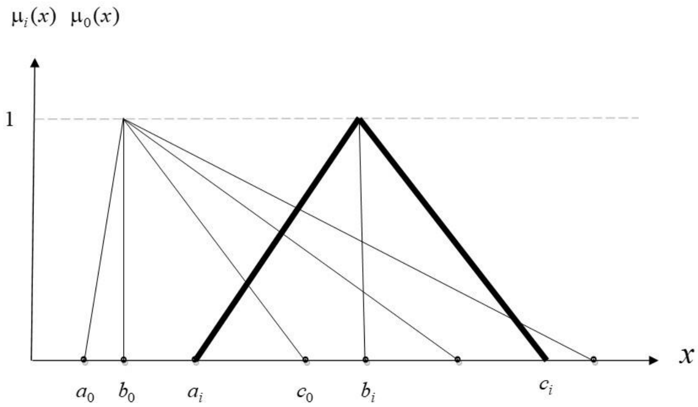

Fig. 5. Membership functions $\mu_0(x)$, $\mu_i(x)$ graphs for variants 1-3

4) $a_0<a_i,\ b_0\in[a_i,b_i],\ c_0\in[a_i,b_i]$;

5) $a_0<a_i,\ b_0\in[a_i,b_i],\ c_0\in[b_i,c_i]$;

6) $a_0<a_i,\ b_0\in[a_i,b_i],\ c_0>c_i$.

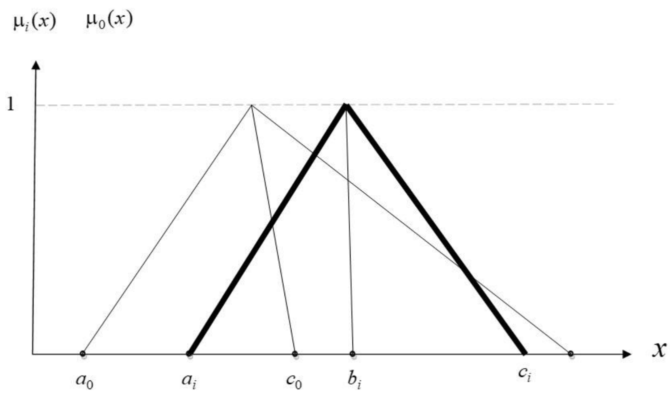

Fig. 6. Membership functions $\mu_0(x)$, $\mu_i(x)$ graphs for variants 4-6

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Variants 7-8

7) $a_0 < a_i$, $b_0 \in [b_i, c_i]$, $c_0 \in [b_i, c_i]$;

8) $a_0 < a_i$, $b_0 \in [b_i, c_i]$, $c_0 > c_i$.

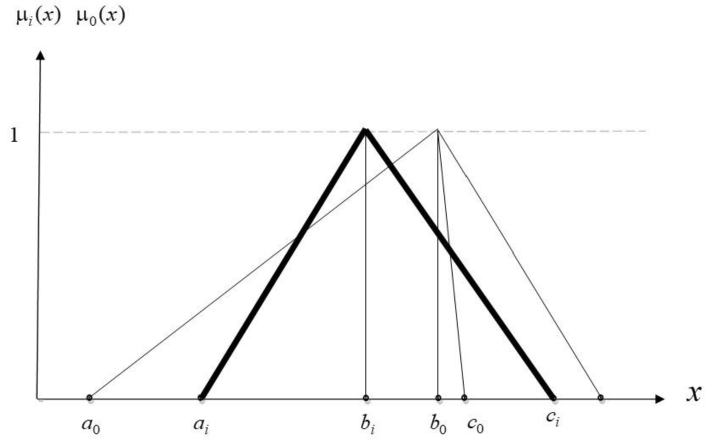

Fig. 7. Membership functions $\mu_0(x)$, $\mu_i(x)$ graphs for variants 7-8

Variant 9

9) $a_0 < a_i$, $b_0 > c_i$, $c_0 > c_i$.

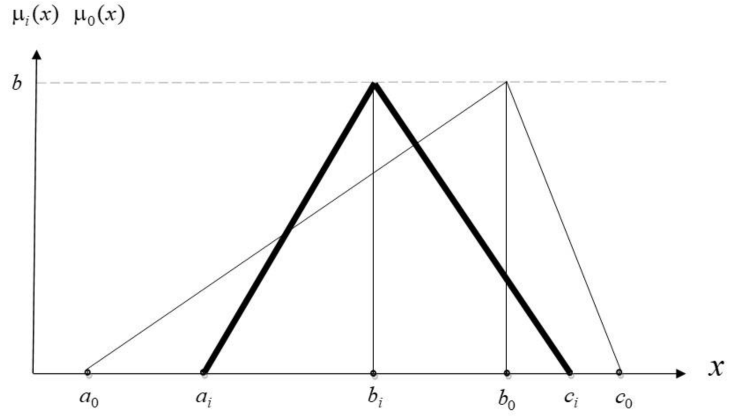

Fig. 8. Membership functions $\mu_0(x)$, $\mu_i(x)$ graph for variant 9

Variants 10-12

10) $a_0 \in [a_i, b_i]$, $b_0 \in [a_i, b_i]$, $c_0 \in [a_i, b_i]$;

11) $a_0 \in [a_i, b_i]$, $b_0 \in [a_i, b_i]$, $c_0 \in [b_i, c_i]$;

12) $a_0 \in [a_i, b_i]$, $b_0 \in [a_i, b_i]$, $c_0 > c_i$.

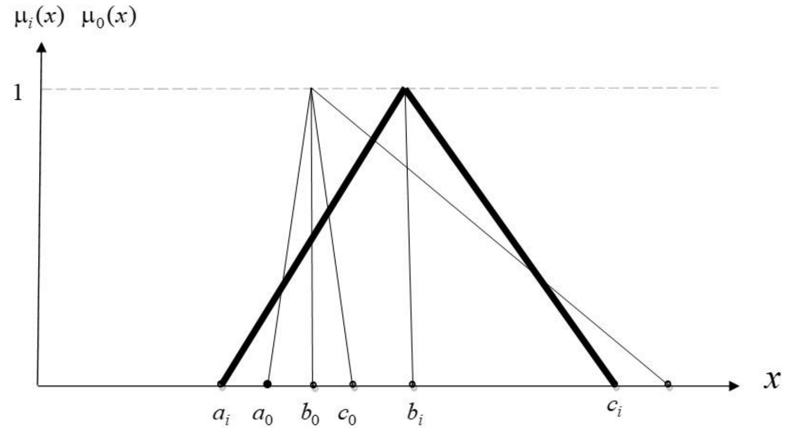

Fig. 9. Membership functions $\mu_0(x)$, $\mu_i(x)$ graphs for variants 10-12

ISSN 2522-9818 (print)
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Variants 13-14

13) $a_0 \in [a_i, b_i]$, $b_0 \in [b_i, c_i]$, $c_0 \in [b_i, c_i]$;

14) $a_0 \in [a_i, b_i]$, $b_0 \in [b_i, c_i]$, $c_0 > c_i$.

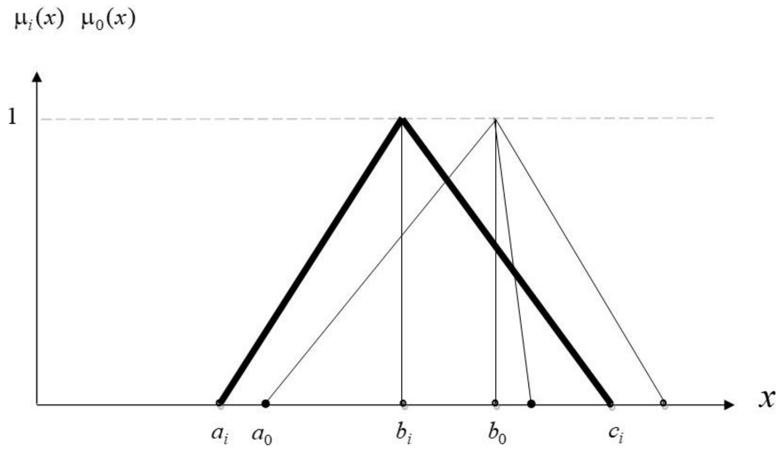

Fig. 10. Membership functions $\mu_0(x)$, $\mu_i(x)$ graphs for variants 13-14

Variants 15

15) $a_0 \in [a_i, b_i]$, $b_0 > c_i$, $c_0 > c_i$.

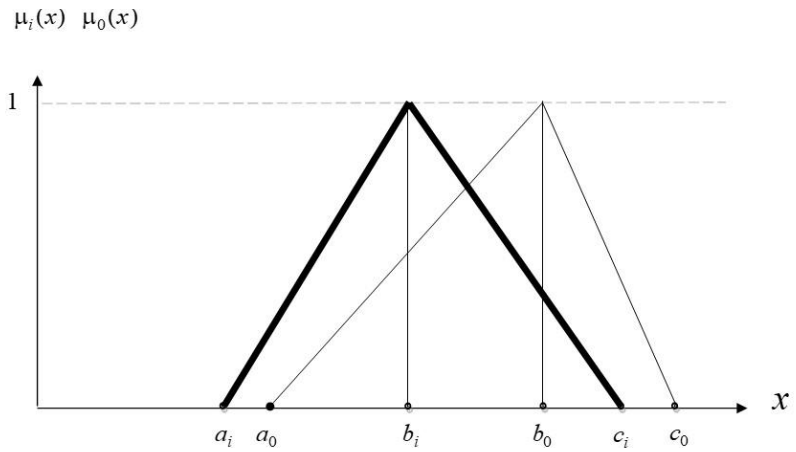

Fig. 11. Membership functions $\mu_0(x)$, $\mu_i(x)$ graph for variant 15

Variants 16-17

16) $a_0 \in [b_i, c_i]$, $b_0 \in [b_i, c_i]$, $c_0 \in [b_i, c_i]$;

17) $a_0 \in [b_i, c_i]$, $b_0 \in [b_i, c_i]$, $c_0 > c_i$.

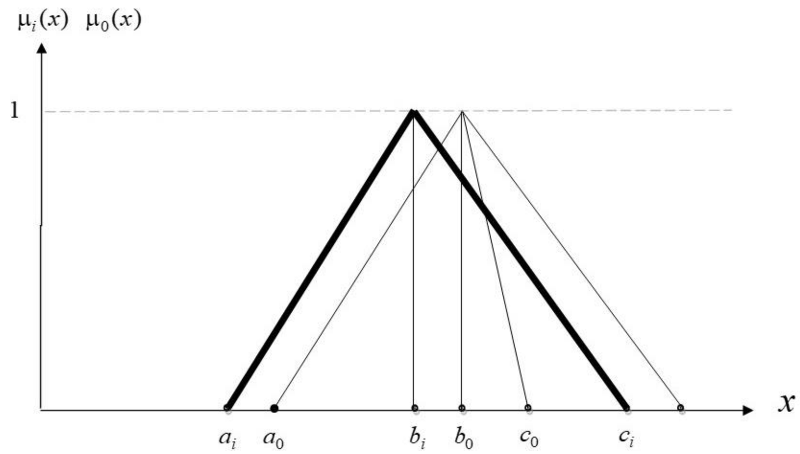

Fig. 12. Membership functions $\mu_0(x)$, $\mu_i(x)$ graphs for variants 16-17

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Variant 18

18) $a_0 \in [b_i, c_i]$, $b_0 > c_i$, $c_0 > c_i$.

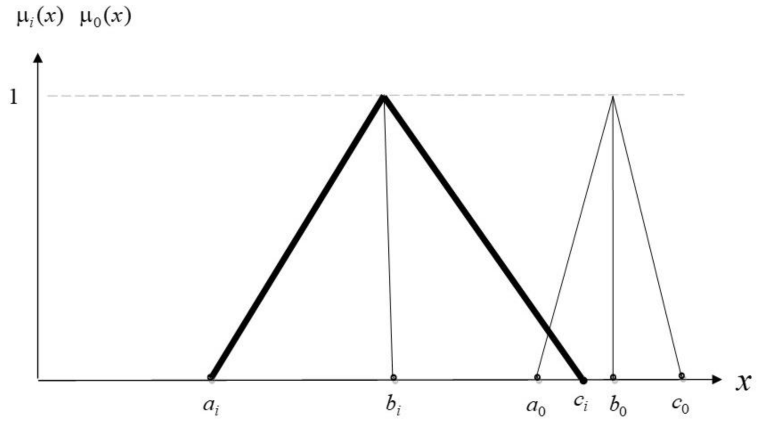

Fig. 13. Membership functions $\mu_0(x)$, $\mu_i(x)$ graph for variant 18

For each of the variants of the relative position of the membership function of the measured value of the controlled parameter $\mu_0(x)$ and the membership function of this parameter to the i-th range of possible values of the parameter $\mu_0(x)$, a natural estimate of the degree of membership of this controlled parameter to the selected range of possible values is calculated.

Let, for example, a specific arrangement of membership functions $\mu_0(x)$ and $\mu_i(x)$ corresponds variant 7, that is $(a_0 > a_i)$, $b_0 \in [b_i, c_i]$, $c_0 \in [b_i, c_i]$. To calculate the desired degree of membership, we calculate at the beginning the area of the figure resulting from the intersection of the areas under the membership functions , $\mu_i(x)$, and then when combining these areas (fig. 14, fig. 15). Let's number the points of intersection of these membership functions, fixing their coordinates: (x_1, y_1), (x_2, y_2), (x_3, y_3), (x_4, y_4), (x_5, y_5). The required areas are now easily computed using their triangles and unequal trapezoids. In this case, the area of the figure formed at the intersection of membership functions is calculated by the following formulas.

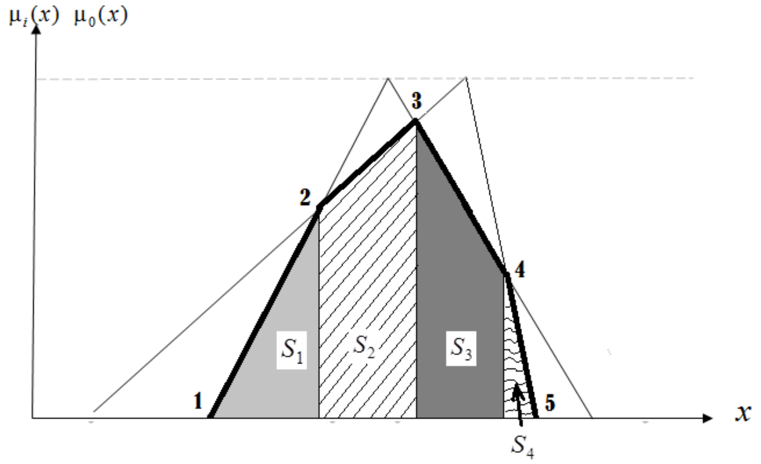

Fig. 14. The area of the figure at the intersection of the MF $\mu_0(x)$, $\mu_i(x)$ (variant 7)

$$S_1 = \frac{1}{2}(x_2 - x_1)y_2 = \frac{1}{2}x_2y_2 - \frac{1}{2}x_1y_2,$$

$$S_2 = \frac{1}{2}[y_2 + y_3](x_3 - x_2) = \frac{1}{2}x_3y_2 + \frac{1}{2}x_3y_3 - \frac{1}{2}y_2x_2 - \frac{1}{2}y_3x_2,$$

$$S_3 = \frac{1}{2}[y_3 + y_4](x_4 - x_3) = \frac{1}{2}x_4y_3 + \frac{1}{2}x_4y_4 - \frac{1}{2}x_3y_3 - \frac{1}{2}x_3y_4,$$

$$S_4 = \frac{1}{2}y_4(x_5 - x_4) = \frac{1}{2}x_5y_4 - \frac{1}{2}x_4y_4,$$

ISSN 2522-9818 (print)
Сучасний стан наукових досліджень та технологій в промисловості. 2021. № 4 (18) ISSN 2524-2296 (online)

$$S_{\Sigma}^{(\wedge)} = \frac{1}{2}x_2y_2 - \frac{1}{2}x_1y_2 + \frac{1}{2}x_3y_2 + \frac{1}{2}x_3y_3 - \frac{1}{2}x_2y_2 - \frac{1}{2}x_2y_3 + \frac{1}{2}x_4y_3 + \frac{1}{2}x_4y_4 -$$

$$-\frac{1}{2}x_3y_3 - \frac{1}{2}x_3y_4 + \frac{1}{2}x_5y_4 - \frac{1}{2}x_4y_4 = \frac{1}{2}\left[x_3y_2 + x_4y_3 + x_5y_4 - x_1y_2 - x_2y_3 - x_3y_4\right].$$

Let us now calculate the area of the figure obtained by combining the membership functions. Taking into account the renumbering of the intersection points (x_1, y_1), (x_2, y_2), (x_3, y_3), (x_4, y_4), (x_5, y_5), (x_6, y_6), (x_7, y_7) the corresponding formulas have the following form

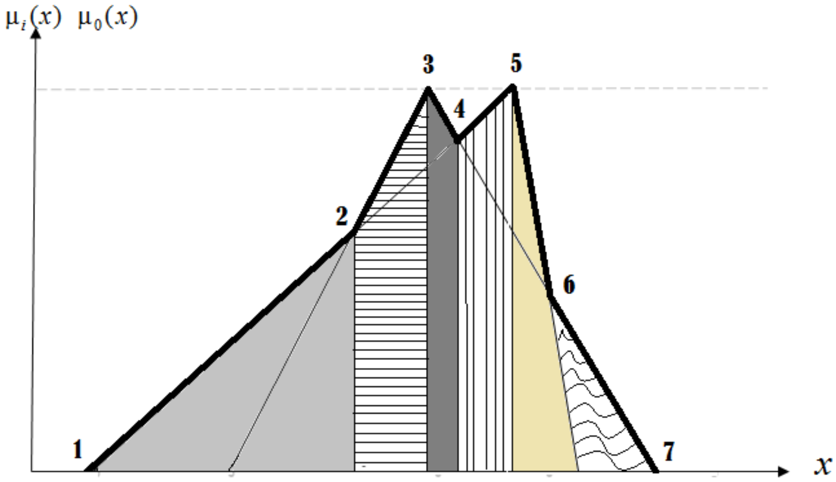

Fig.15. The area of the figure at the intersection of the MF $\mu_0(x)$, $\mu_i(x)$ (variant 7)

$$S_1 = \frac{1}{2}y_2(x_2 - x_1) = \frac{1}{2}x_2y_2 - \frac{1}{2}x_1y_2$$

$$S_2 = \frac{1}{2}(y_2 + y_3)(x_3 - x_2) = \frac{1}{2}x_3y_2 + \frac{1}{2}x_3y_3 - \frac{1}{2}x_2y_2 - \frac{1}{2}x_2y_3$$

$$S_3 = \frac{1}{2}(y_3 + y_4)(x_4 - x_3) = \frac{1}{2}x_4y_3 + \frac{1}{2}x_4y_4 - \frac{1}{2}x_3y_3 - \frac{1}{2}x_3y_4$$

$$S_4 = \frac{1}{2}(y_4 + y_5)(x_5 - x_4) = \frac{1}{2}x_5y_4 + \frac{1}{2}x_5y_5 - \frac{1}{2}x_4y_4 - \frac{1}{2}x_4y_5$$

$$S_5 = \frac{1}{2}(y_5 + y_6)(x_6 - x_5) = \frac{1}{2}x_6y_5 + \frac{1}{2}x_6y_6 - \frac{1}{2}x_5y_5 - \frac{1}{2}x_5y_6$$

$$S_6 = \frac{1}{2}y_6(x_7 - x_6) = \frac{1}{2}x_7y_6 - \frac{1}{2}x_6y_6$$

$$S_{\Sigma}^{(\vee)} = \frac{1}{2}x_2y_2 - \frac{1}{2}x_1y_2 + \frac{1}{2}x_3y_2 + \frac{1}{2}x_3y_3 - \frac{1}{2}x_2y_2 - \frac{1}{2}x_2y_3 + \frac{1}{2}x_4y_3 + \frac{1}{2}x_4y_4 -$$

$$-\frac{1}{2}x_3y_3 - \frac{1}{2}x_3y_4 + \frac{1}{2}x_5y_4 + \frac{1}{2}x_5y_5 - \frac{1}{2}x_4y_4 - \frac{1}{2}x_4y_5 + \frac{1}{2}x_6y_5 + \frac{1}{2}x_6y_6 - \frac{1}{2}x_5y_5 -$$

$$-\frac{1}{2}x_5y_6 + \frac{1}{2}x_7y_6 - \frac{1}{2}x_6y_6;$$

$$S_{\Sigma}^{(\vee)} = \frac{1}{2}\left[x_3y_2 - x_1y_2 - x_2y_3 + x_5y_4 - x_3y_4 + x_6y_5 - x_4y_5 + x_7y_6 - x_5y_6\right].$$

The degree of belonging of the controlled parameter x_0 to the i-th range of possible values (corresponding to the i-th state of the object) is determined by the formula

$$\eta_i = \frac{S_{\Sigma}^{(\wedge)}}{S_{\Sigma}^{(\vee)}}. \qquad (19)$$

ISSN 2522-9818 (print)
ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2021. No. 4 (18)

The measure of proximity η_i introduced in accordance with (19) has the important properties:

- numerical value $\eta_i \in [0;1]$;

- value $\eta_i = 0$, if membership functions $\mu_0(x)$ and $\mu_i(x)$ do not intersect;

- value $\eta_i = 1$, if $\mu_0(x) = \mu_i(x)$.

Thus, the problem is solved.

3 Methods for identifying the states of an indistinctly defined object. The above relations make it possible to implement the procedure for assessing the state of an object based on the results of measurements of a set of monitored parameters. In doing so, two different approaches can be used. Let's consider them.

First approach. For each of the monitored parameters, using the formulas obtained above, the values of the degree of membership of this parameter to each of the ranges of possible values corresponding to various states of the system are calculated. In this case, for the *j*-th controlled parameter, we obtain the set $(\eta_{ij}),\ i = 1,\ 2,\ldots,\ m,,\ \ j = 1, 2,\ldots, n.$ Here η_{ij} is the measure of the j-th parameter belonging to the i-th state of the system.

Now let's enter

$$P_{ij} = \frac{\eta_{ij}}{\sum_{i=1}^{m} \eta_{ij}},\ i = 1,\ 2,\ldots,\ m. \tag{20}$$

Since the value calculated in accordance with (20)

$$P_{ij} \in [0;1],\ \sum_{i=1}^{m} P_{ij} = 1,$$

the resulting number P_{ij} can be interpreted as the probability that the *j*-th controlled parameter has a value corresponding to the *i*-th state of the object.

As a result of performing these procedures for all controlled parameters, we obtain the matrix

$$P = (P_{ij}) = \begin{pmatrix} P_{11} & P_{12} & \ldots & P_{1n} \\ P_{21} & P_{22} & \ldots & P_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ P_{m1} & P_{m2} & \ldots & P_{nn} \end{pmatrix}.$$

The values can now be calculated

$$P_k = \prod_{j=1}^{n} P_{kj},\ k = 1,\ 2,\ldots,\ m.\,, \tag{21}$$

In this case, it is natural to interpret the value P_k as the probability that, according to the results of controlling n parameters, the system is in a state k. The resulting set of values $P_k,\ k = 1,\ 2,\ldots,\ m,$ specifies the probability distribution of the system states.

Second approach. For each pair (*i*, *j*), using formulas (15), (16), we determine the areas of the figures resulting from the intersection and combination of the corresponding membership functions, which are equal $Z_{ji}^{(\wedge)},\ Z_{ji}^{(\vee)}$. Now, for the selected state of the system H_i, we calculate

$$Z_i^{(\wedge)} = \sum_{j=1}^{n} Z_{ji}^{(\wedge)},\ Z_i^{(\vee)} = \sum_{j=1}^{n} Z_{ji}^{(\vee)}. \tag{22}$$

The values $Z_i^{(\wedge)}$ and $Z_i^{(\vee)}$ obtained in this case determine the total areas of the figures obtained by the intersection of the membership functions of each controlled parameter $\mu(x_j)$ with the membership $\mu_i\left(x_j / H_i\right)$.

Now we calculate

$$\zeta_i = \frac{Z_i^{(\wedge)}}{Z_i^{(\vee)}},\ i = 1,\ 2,\ldots,\ m. \tag{23}$$

The measure ζ_i defined by relation (23) has the following properties.

1. The value $\zeta_i = 0$, if all $Z_{ji}^{(\wedge)} = 0$, that is, the membership functions of the controlled parameters do not intersect with any of the membership functions $\mu_i\left(x_j / H_i\right)$.

2. The value $\zeta_i = 1$, if these membership functions coincide.

3. The value ζ_i is the more, the higher the closeness of the compared membership functions.

Note that the second approach has an important advantage over the first, since its final result is additive due to (22) (in contrast to the multiplicative (23)).

Discussion of the results of the development of a method for identifying the states of an object with a fuzzy input and a fuzzy inference mechanism. The paper proposes a method for assessing the states of an object based on the results of fuzzy measurements of a set of monitored parameters with a fuzzy mechanism for their processing. The principal merit of the method is the replacement of the production mechanism of logical inference with an analytical one. The practical use of a production system for identifying states is possible only for problems of a very small dimension (for example, if the number of controlled parameters is only five, and the number of possible states of an object is four, then the required number of production rules is equal). Another significant drawback of production systems is the difficulty of their implementation in conditions of fuzzy measurement results of controlled parameters. The fact is that under conditions of a fuzzy input, any resulting set of such measurements can correspond with varying degrees of confidence not to one but to several production rules, which leads to the need to enumerate their entire set. A well-known variant of constructing a non-production diagnostic system was developed on the assumption of accurate results of measurements of parameters. When

Сучасний стан наукових досліджень та технологій в промисловості. 2021. № 4 (18) ISSN 2522-9818 (print)
ISSN 2524-2296 (online)

implementing the proposed method for identifying states, these difficulties do not arise.

In addition to a radical restructuring of the inference mechanism, an important issue related to the assessment of the information content of controlled parameters is considered. The traditionally used measure of the information content of the Kulbak parameters, which has a number of serious drawbacks, has been developed for the case when the corresponding distribution densities of the random values of the parameters are given for a pair of possible states of the object. The paper proposes an alternative approach to assessing the informativeness of fuzzy parameters described by their membership functions.

Thus, the paper considers a method for identifying the states of an object based on the results of monitoring fuzzy parameters using the membership functions of these parameters to the ranges of their values for each possible state of the object. Note that if the system of controlled parameters is multicollinear, then in the case of a large number of states, the identification procedure can be simplified by enlarging these states [13].

Conclusions

1. A method for assessing the informativeness of the controlled indicators of an object has been developed for the case when for each state of the object the possible values of the parameters are given indistinctly.

2. A method has been developed for assessing the informativeness of fuzzy controlled indicators of an object, taking into account the vagueness of descriptions of possible states of the object.

3. A non-production mechanism of logical inference of the expert system has been developed, which provides identification of the object states in conditions of fuzzy measurements of the values of the controlled parameters and fuzzy descriptions of the possible states of the object.

4. The direction of further research is the strengthening of the method, which can be achieved if, when assessing the quality of the controlled parameter, the value of its informativeness is combined with the values of its other characteristics with the importance determined by the method of pairwise comparisons [14, 15].

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Received 01.12.2021

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ISSN 2522-9818 (print)
ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2021. No. 4 (18)

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МЕТОД ІДЕНТИФІКАЦІЇ СТАНІВ ОБ'ЄКТУ ЗА РЕЗУЛЬТАТАМИ НЕЧІТКИХ ВИМІРЮВАНЬ КОНТРОЛЮВАНИХ ПАРАМЕТРІВ

Предмет розгляду – задача ідентифікації станів об'єкта за результатами нечітких вимірювань набору контрольованих параметрів. Нечіткість вихідних даних задачі додатково її ускладнює за рахунок нерівнозначності контрольованих параметрів. **Метою** дослідження є розробка методу ідентифікації стану нечітко заданого об'єкта з нечітким механізмом логічного висновку і з урахуванням можливих відмінностей у рівні інформативності контрольованих його параметрів. **Метод** отримання необхідного результату заснований на модифікації відомого математичного апарату побудови експертної системи штучного інтелекту шляхом вирішення двох наступних підзадач. Перша – розробка методу оцінки інформативності контрольованих параметрів. Друга – розробка методу побудови механізму логічного виведення відносного стану об'єкта за результатами вимірювання контрольованих параметрів, що забезпечує ідентифікацію. У першому завданні з метою оцінки інформативності параметрів запропоновано метод, вільний від відомих недоліків традиційної міри інформативності Кульбака. При реалізації методу передбачається, що діапазон можливих значень кожного параметра розділений на піддіапазони відповідно до можливими станами об'єкта. Для кожного з цих станів визначено функцію належності нечітких значень відповідного параметра. При цьому коректне завдання оцінки інформативності параметра вирішується для випадків, коли цей параметр вимірюється точно або нечітко визначений своєю функцією приналежності. Принципова відмінність запропонованого механізму логічного висновку від традиційного полягає у відмові від використання бази продукційних правил, що забезпечує практичну незалежність обчислювальної процедури від розмірності завдання. **Результати.** Для вирішення основного завдання ідентифікації станів запропоновано непродукційний підхід, обчислювальна складність якого практично не залежить від розмірності задачі (добуток кількості можливих станів на число контрольованих параметрів). Механізм логічного висновку виробляє розподіл ймовірностей станів системи. При цьому використовується набір функцій належності кожного параметра діапазону можливих значень для кожного зі станів об'єкта, а також набір функцій належності нечітких результатів вимірювань кожного параметра. **Висновки.** Отже, запропоновано непродукційний метод ідентифікації стану нечітко заданих об'єктів з нечітким непродукційним механізмом логічного висновку, складність якого не залежить від розмірності завдання.

Ключові слова: метод ідентифікації станів об'єкта; інформаційна цінність контрольованих параметрів; нечіткий механізм логічного висновку.

МЕТОД ИДЕНТИФИКАЦИИ СОСТОЯНИЙ ОБЪЕКТА ПО РЕЗУЛЬТАТАМ НЕЧЕТКИХ ИЗМЕРЕНИЙ КОНТРОЛИРУЕМЫХ ПАРАМЕТРОВ

Предмет рассмотрения – задача идентификации состояний объекта по результатам нечетких измерений набора контролируемых параметров. Нечеткость исходных данных задачи дополнительно ее усложняет за счет возникающей при этом неравнозначности контролируемых параметров. **Целью** исследования является разработка метода идентификации состояний нечетко заданного объекта с использованием нечеткого механизма логического вывода с учетом возможных различий в уровне информативности контролируемых его параметров. **Метод** получения требуемого результата основан на модификации известного математического аппарата построения экспертной системы искусственного интеллекта путем решения двух подзадач. Первая – разработка метода оценки информативности контролируемых параметров. Вторая – разработка метода построения механизма логического вывода относительного состояния объекта по результатам измерения контролируемых параметров, обеспечивающего идентификацию. В первой задаче для оценки информативности параметров предложен метод, свободный от известных недостатков традиционной меры информативности Кульбака. При реализации метода предполагается, что диапазон возможных значений для каждого параметра разделен на поддиапазоны в соответствии с возможными состояниями объекта. Для каждого из этих состояний определена функция принадлежности нечетких значений соответствующего параметра. При этом корректная задача оценки информативности параметра решается для случаев, когда этот параметр измеряется точно или определен нечетко своей функцией принадлежности. Принципиальное отличие предложенного механизма логического вывода от традиционного состоит в отказе от использования базы продукционных правил, что обеспечивает практическую независимость вычислительной процедуры от размерности задачи. **Результаты.** Для решения основной задачи идентификации состояний предложен непродукционный подход, вычислительная сложность которого практически не зависит от размерности задачи (произведение числа возможных состояний на число контролируемых параметров). Механизм логического вывода вырабатывает распределение вероятностей состояний системы. При этом используется набор функций принадлежности каждого параметра диапазону возможных его значений для каждого из состояний объекта, а также набор функций принадлежности нечетких результатов измерений каждого параметра. **Выводы.** Таким образом, предложен метод идентификации состояния нечетко заданных объектов с нечетким непродукционным механизмом логического вывода, сложность которого не зависит от размерности задачи.

Ключевые слова: метод идентификации состояний объекта; информационная ценность контролируемых параметров; нечеткий механизм логического вывода.

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