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Method for monitoring the functioning of information and measuring systems during operation

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Abstract

A generalized method of monitoring the functioning of information and measuring systems is considered, which takes into account the effect of random factor influences on the control result. It is noted that the accuracy and reliability of measurement results are influenced by external and internal factors that act both separately and mutually in terms of each other, which is why the task of assessing the levels of factor influence to ensure the required accuracy and reliability of measurements becomes an urgent task. To solve the problem, a generalized method of monitoring the functioning of information and measuring systems is proposed, which combines the advantages of existing structural-algorithmic methods, test control methods, statistical analysis, the theory of fuzzy sets, as well as an algorithm for calculating the measurement uncertainty. The method consists in forming additive and multiplicative independent test effects for information and measuring systems and, depending on the results obtained, using the metrological situation analysis block, which acts on the basis of fuzzy logic, choosing one of two ways of further analysis. The first way is chosen when it is necessary to take into account the effect of random factor influence on the operation of information and measuring systems, namely: a model of factor influence is developed based on variance analysis, a covariance analysis of factor influence levels and discriminant analysis with an assessment of the amount of information by control indicators are performed. The second way is chosen when it is necessary to test hypotheses about the absence of violations in metrological reliability of system elements. Two ways are based on the development of a situational system based on fuzzy logic to determine the degree of factor influence on the control indicator. The presence or absence of correlation between factors is established. The combined standard uncertainty is calculated for either for correlated, or uncorrelated data, and subsequently the expanded uncertainty is calculated. Thanks to the use of the proposed method, it becomes possible to increase the reliability of control of the functioning of information and measuring systems.

Keywords: information and measuring system; statistical analysis; test effect; fuzzy logic; measurement uncertainty; error.

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Introduction

Information and measuring systems (IMSs) are used for control and diagnostic objects with a priori uncertain parameters, which are dynamic multifunctional objects (process lines, conveyors, installations, internal combustion engines, etc.). When solving such complex tasks, difficulties arise in measuring control and metrological support of the equipment. There are also difficulties in increasing the probability of creating control and diagnostic systems for complex objects. In addition, difficulties arise when a stochastic parameter model is a priori uncertain. In turn, it is necessary to choose procedures to train these IMSs for a case when there is a parametric uncertainty in the models of primary information transformation. Analysis of domestic and foreign publications [1–4] showed the absence of a generalized method for controlling the functioning of IMSs, which makes it possible to simultaneously take into account the action of various factor influences, the results of test procedures and, based on fuzzy logic algorithms, to determine the levels of control parameters to ensure high quality of industrial products.

Analysis of recent research and publications

Random variables (factor influence parameters) that are expedient to control when analyzing the operation of IMSs exist objectively and reflect the real technical condition of control and diagnostic objects.

Analysis of the development of test control methods [5, 6] showed the interest of both manufacturers and the scientific community in the implementation of additive and multiplicative tests for controlling the technical and metrological condition of IMSs. The metrological condition of an IMS refers to its ability to provide accurate and reliable measurements in accordance with established metrological requirements. It includes: measurement accuracy – how accurately the system can measure physical quantities; reliability – stability and repeatability of measurement results; calibration – regular adjustment and verification of the system to maintain its accuracy [6].

The most interesting is the dynamic test control of IMSs, which requires continual improvement and adaptation to the growth of the number and nomenclature of quantities that need to be controlled. Today, a great contribution has been made to the development of the theory of test control methods by domestic and foreign scientists, but numerous problems still need to be solved, including the problem of implementing dynamic test control taking into account the action of factor influences. In this case, a study in the field of determining the factor influence comes to the aid of test control methods [7–11], which notes that the completeness of the expected information when controlling objects with random parameters depends on the number of factors, namely: the number of multiple measurements, the optimal combination of the number of controlled quantities, the number of levels of a control parameter, the volume of training samples.

A required condition for determining the action of the factor influence is the choice of an adequate mathematical model for transforming the vector of controlled quantities. The optimization criterion is the amount of expected information about the value of the level of a controlled quantity. The task of increasing the probability of control is a task of optimal synthesis of the system, and it becomes especially acute when the volume of training samples is significantly limited.

It is necessary to take into account the fact that many controlled quantities are mutually correlated. The circumstances that there are no conditions that ensure the reproducibility of the given values of controlled quantities limit the application of existing methods of increasing the probability. It is necessary to apply models of controlled quantities with previously known probabilistic properties.

The problem of building adequate models of the action of factor influences on the result of measurement control precisely arises when the volumes of training samples are significantly limited (at the stage of training the control system).

The use of experimental design methods [12] for the analysis of control objects is limited by the fact that they rely only on parametric testing models that use only the probabilities of errors of the first kind. These circumstances do not allow planning the procedure for optimal selection of the number of controlled signals with a given reliability, as well as determining the levels of the control parameter for further prediction of possible changes in the properties of IMSs. Based on the analysis, the task is to develop a method for controlling the functioning of IMSs, regardless of their purpose, which would make use of the advantages and minimizes the disadvantages of existing methods.

The essence and structure of a method for controlling the functioning of an IMS during its operation

Usually, to control the functioning of an IMS, the methods considered above are used separately, or in combination in two. For example, test effects are used with subsequent processing of measurement results. There are cases when it is necessary to take into account the factorial effect on the measurement result, and then the task becomes much more complicated. Difficulties almost always arise when building probabilistic models for complex objects, to which the IMS is attributed. These difficulties arise due to incomplete information about the state of the control object. It is for such cases that a method of controlling the functioning of the IMS is needed, which would make it possible to take into account the advantages of existing methods of increasing the accuracy of control and to solve the problem of increasing the reliability of controlling the functioning of IMSs. At the same time, the method should not be complicated and contain unnecessary algorithmic operations so as not to increase the time for controlling the functioning of IMSs in real operating conditions. To solve the problem, a method of controlling the functioning of IMSs is proposed, regardless of their purpose, taking into account the factorial effect. The proposed method combines the advantages of statistical analysis methods, test control methods, fuzzy set theory, and the theory of calculating the measurement uncertainty. The essence of the method of controlling the functioning of IMSs is that at the initial stage of control for any IMS, independent additive and multiplicative test effects are formed. Depending on the test results obtained, the metrological situation analysis unit, which works on the basis of fuzzy logic, chooses one of two possible paths for further analysis.

The first path is chosen in the case when, under operating conditions, it is necessary to take into account the effect of the factor influence on the operation of an IMS. In this case, a model of the effect of the factor influence is developed. The reliability of statistical conclusions for the developed model shall be assessed. Next, a covariance analysis of the levels of factor influence on the control indicator is performed. Using discriminant analysis models, the levels of information content of the control indicators are estimated with the determination of the maximum information parameter that has the greatest effect on the control indicator.

The second path of the study is chosen in the case when it is necessary to test the hypothesis that there are no violations in metrological reliability of the system elements. The hypothesis is tested using the sequential use of one-factor analysis of variance (equality of mean values), linear regression analysis (absence of the effect of time on the value of the indicator for each of the samples), and covariance analysis (absence of differences in the functional effect of time on the value of the control indicator). Both paths end with the development of a situational system based on fuzzy logic to determine the degree of factor influence on the IMS control indicator. The structural diagram of the generalized control method is presented in Fig. 1.

Let's consider the main stages of the proposed control method.

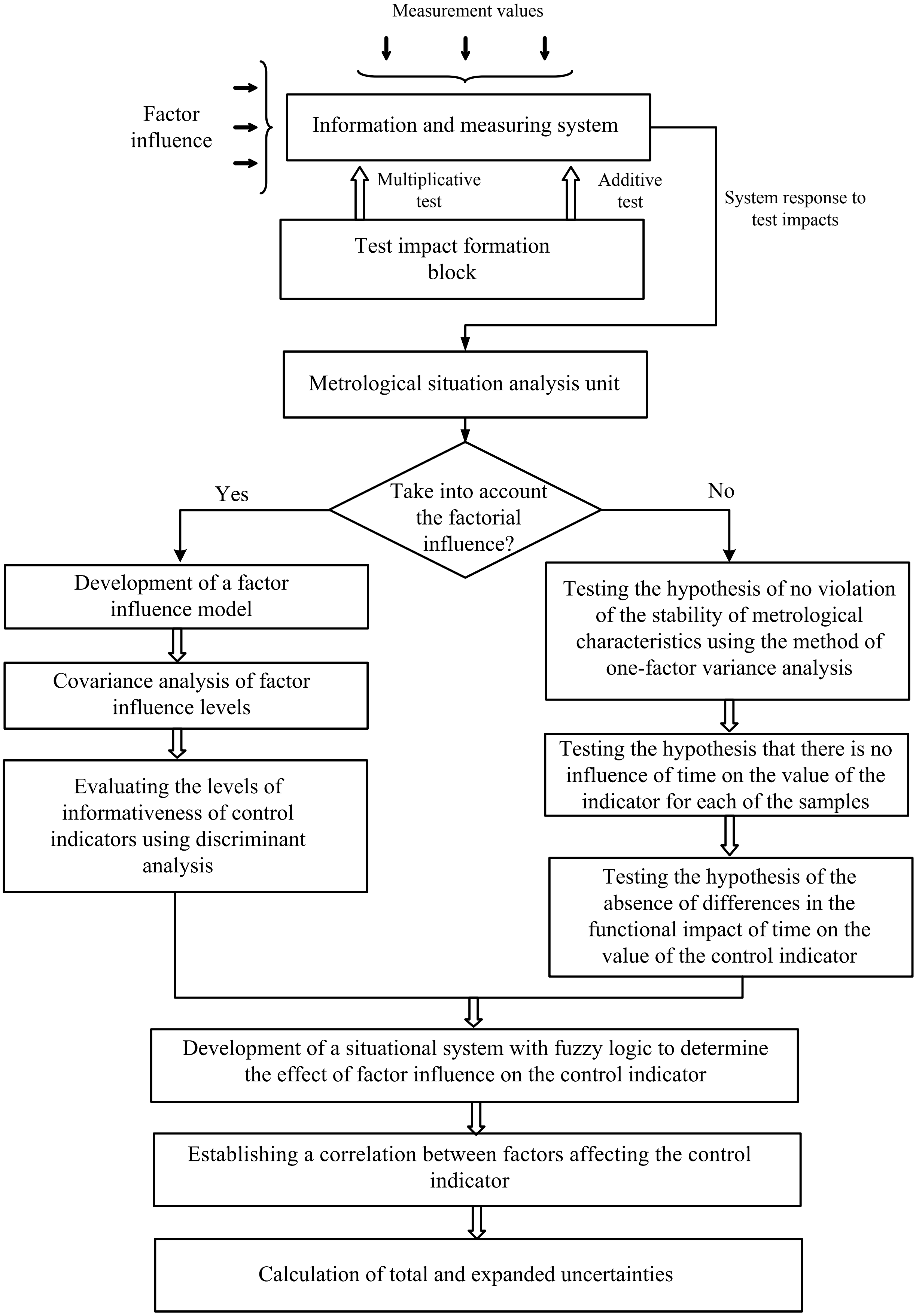

Fig. 1. Structural diagram of the method for controlling the functioning of IMSs

According to the classification, additive and multiplicative test effects are divided into independent and functional. The method involves independent tests. Additive tests are formed in the form of a sum

$$Y_i(x) = x + Q_i, \tag{1}$$

where $Y_i(x)$ is a function of the IMS output signal under the action of the additive test; Q_i is a quantity independent of x that is a constant component of an additive test.

The independent multiplicative test is formed in the form

$$\tilde{Y}_i(x) = k_i \cdot x, \tag{2}$$

where $\tilde{Y}_i(x)$ is a function of the output signal under the action of the i-th multiplicative test; k_i is an x-independent slope due to the action of the multiplicative test.

Functional additive and multiplicative tests are more often used in IMSs to measure electrical quantities, and in the x-dependent mode they have the following form:

$$Y_i(x) = x + Q_i(x); \tag{3}$$

$$\tilde{Y}_i(x) = k_i(x) \cdot x, \tag{4}$$

where $Q_i(x)$ and $k_i(x)$ are some known functions of x.

Independent additive and multiplicative tests are easily formed for both electrical and non-electrical quantities.

The metrological situation analysis block, operating on the basis of fuzzy logic according to the *IF…TO* principle, determines whether the controlled quantity is within the established tolerance limits or not by reaction to test effects. Depending on the nature of deviations from the tolerance (by quantity – additive test, by the nature of the parameter change – multiplicative test), a possible cause of the deviations is determined, and one of the paths of further analysis is selected.

When choosing the first path, a mathematical model of variance analysis is developed. Such a model should take into account factors influencing the control parameter, deviations that are due to pairwise interactions of all factors, and random variables describing residual effects. For example, the model of the influence on the result of determining the control indicator Q with six factors (change in operating temperature, influence of electromagnetic field, influence of vibration, instability of power source, change in air humidity, change in radiation background), which influence the control indicator, taking into account their cross-pair interactions, has the form

$$\begin{aligned} Q_{ABCDEF_i} &= \bar{Q} + A + B + C + D + E + F + (AB) + (AC) + \\ &+ (AD) + (AE) + (AF) + (BC) + (BD) + (BE) + \\ &+ (BF) + (CD) + (CE) + (CF) + (EF) + \varepsilon_{ABCDEF_i}, \end{aligned} \tag{5}$$

where A, B, C, D, E, F are the letters indicating factor levels;

$\bar{Q}$ is the average value of the control indicator;

A is the deviation of the measurement result of the control indicator Q from its average value $\bar{Q}$, which is due to the influence of the control parameter;

(AB), (AC), (AD), (AE), (AF), (BC), (BD), (BE), (BF), (CD), (CE), (CF), (EF) are deviations caused by pairwise interactions of influence factors;

ε_{ABCDEF_i} is a random remainder;

i is the number of multiple measurements at fixed levels A, B, C, D, E, F.

Next, covariance analysis is used, since it allows for simultaneous consideration of factors that are impossible or difficult to control during measurements. A cross-classification table is constructed, i.e. when all levels of each factor occur in all possible combinations with all factors. For example, as noted in [13], for a model with one influence factor B, an information indicator Q_1, and a parameter Z, represented by the equation

$$Q_1 = \bar{Q} + A + B + (AB) + \lambda_{AB}, \tag{6}$$

where λ_{AB} is a random residual, the cross-classification table of the original data looks like Table 1.

Table 1

Output data of two-dimensional observations

Control parameter Z	Factor levels Q_1					
	1	2	…	j	…	k
Z_{1jg}	Q_{11g}	Q_{12g}	…	Q_{1jg}	…	Q_{1kg}
Z_{2jg}	Q_{21g}	Q_{22g}	…	Q_{2jg}	…	Q_{2kg}
Z_{ajg}	…	…	…	Q_{ajg}	…	…
Z_{mjg}	Q_{m1g}	Q_{m2g}	…	Q_{mjg}	…	Q_{mkg}

In Table 1 $g = \overline{1,n}$ is the numbering index in the middle of the cells (groups).

The indices j and k specify the levels of the control parameter Z and the influence factor Q_1, respectively.

Discriminant analysis models correspond to parametric control with known probabilities of the first and second kind. The test statistic is the maximum likelihood ratio, which minimizes the total probability of control error.

The total probability of the estimate includes the probabilities of errors of the first and second kind, Λ_1 and Λ_2 respectively:

$$P_\Sigma = P_1\Lambda_1 + P_2\Lambda_2,$$

where P_1 and P_2 are a priori probabilities characterizing the membership of the control parameter in the region of permissible values of z and in the region of critical values ω, respectively.

For the adopted model of alternative testing of the parameter V by the measured values of the control indicator D, the test statistic will be the maximum likelihood ratio.

$$S = \frac{f(\overline{v}_0)}{f(\overline{v}_1)}, \tag{7}$$

where $\overline{v}_0$ – the control parameter – is normal, and $\overline{v}_1$ – the control parameter – exceeds the established norm.

The numerator and denominator of (7) include one-dimensional likelihood functions, which are identical to the conditional densities of the probability distribution of the values of the indicator D.

If $P_1 = P_2 = 0.5$ then the formula for estimating the amount of expected information about the value of the control parameter from the measured values of the indicator has the form

$$I = 1 + 0.5\begin{bmatrix}\Lambda_1 \log_2 \Lambda_1 + \Lambda_2 \log_2 \Lambda_2 + (1-\Lambda_1)\times \\ \times\log_2(1-\Lambda_1) + (1-\Lambda_2)\log_2(1-\Lambda_2)\end{bmatrix},$$

where $\Lambda_1 = \int\limits_{V\in z} f(S/V)\,\partial S;\;\; \Lambda_2 = \int\limits_{V\in \omega} f(S/V)\,\partial S,$

V is a control parameter; S are test statistics.

When choosing the second path, a one-way analysis of variance model is built.

$$X_{ji} = \overline{X} + \gamma_j + e_{ji}, \tag{8}$$

where X is a control indicator, during the measurement of which the value of j samples with the results X_{ji}, $i = 1,\ldots,n_j$ are obtained; $\overline{X}$ is the average value of all observation results over all results of j samples; γ_j is the deviation caused by the influence of the factor; e_{ji} is the random deviation in the j-th group for the i-th observation.

The hypothesis of the absence of violations of the stability of metrological characteristics of the IMS elements is checked by the equality of the average values. Finally, according to the known formulas of linear regression analysis, the absence of the influence of time on the value of the indicator for each of the samples is checked. Also, a covariance analysis is performed for the absence of differences in the functional influence of time on the value of the control indicator.

After performing the above procedures, a situational system based on fuzzy logic is developed. For example, when making caramel syrup, it is necessary to determine what the levels of the technological process parameters should be to ensure the highest quality of the final product. It has been established that the quality of caramel is influenced by three factors: compliance with the temperature regime of production, the level of vapor pressure, and the value of the humidity of the substance.

Three inputs are given in the fuzzy logic model: temperature (temperature), pressure (pressure), and humidity of the substance (%RH). The quality of caramel syrup is chosen as the output parameter – (quality). The window for setting the input and output parameters according to the Mamdani fuzzy logical conclusion is presented in Fig. 2.

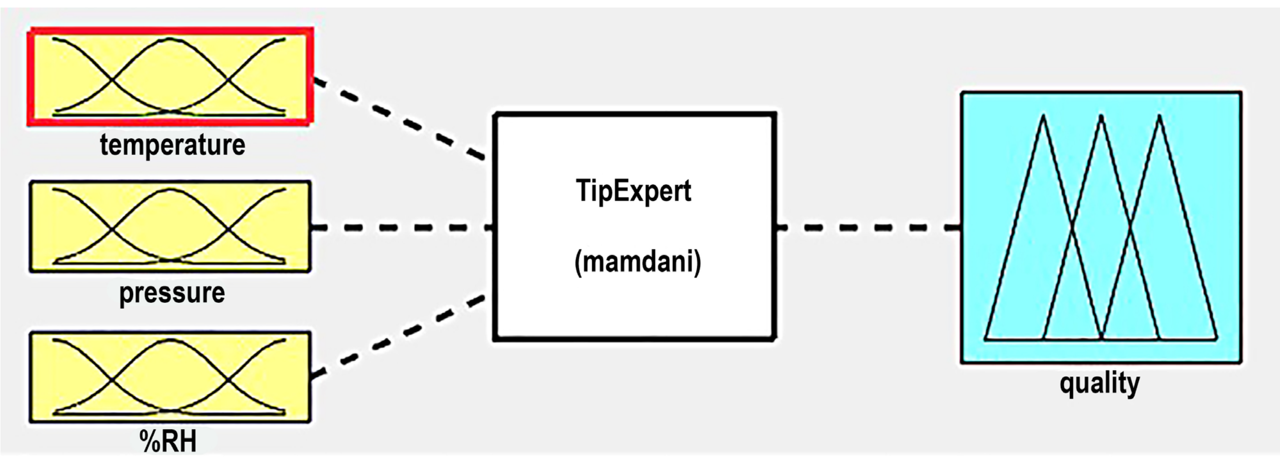

Fig. 2. Input and output parameters task window

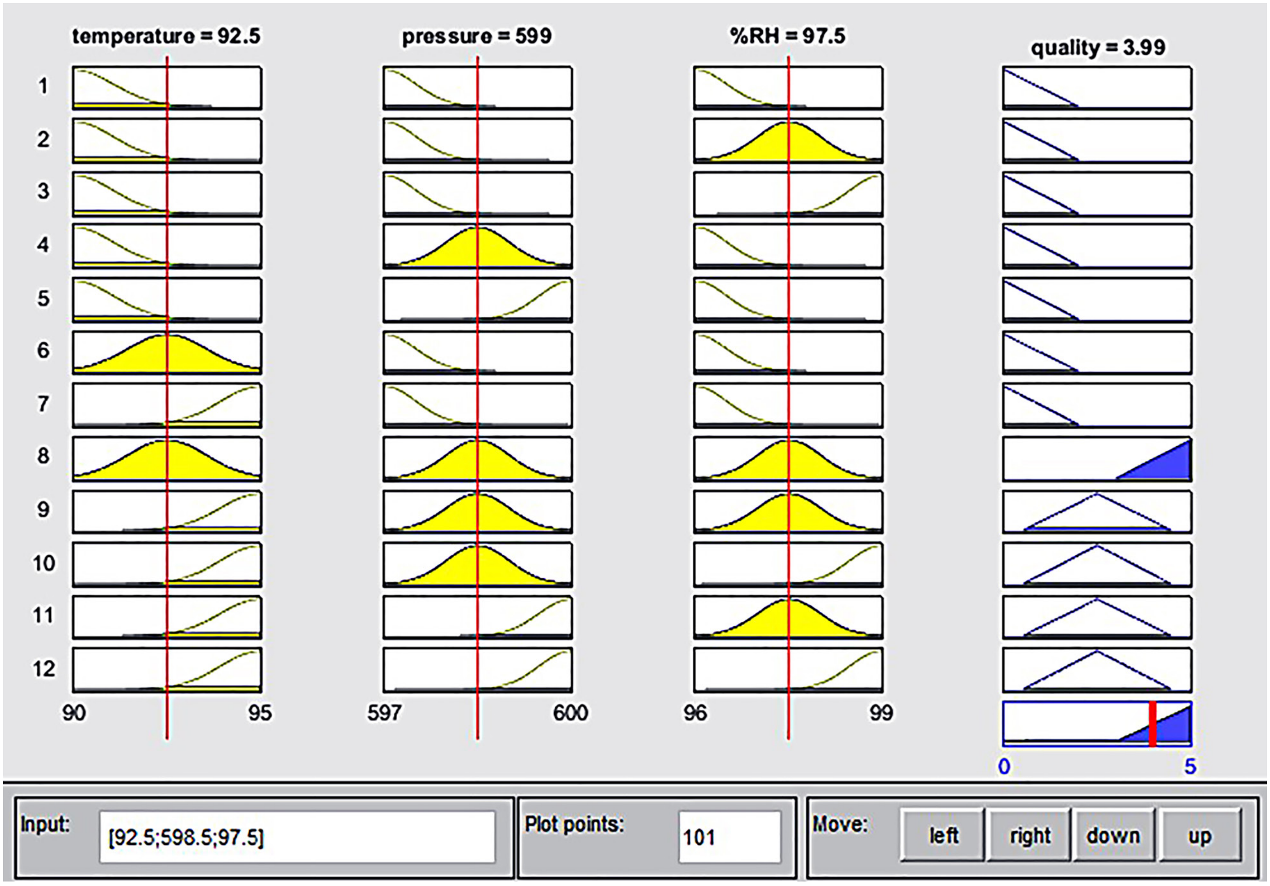

Fig. 3. Graphical representation of the action of the principles

When specifying input parameters, the range in which the temperature changes is set in the range from 90 °C to 95 °C, the pressure – in the range from 597 to 600 kPa, the humidity of the substance – in the range from 96 to 99% RH.

The output parameter – quality is assessed on a point scale, the length of which is set by the product quality expert. In this example, the quality is set in the range from 0 to 5 points.

The distribution law is set for each of the functions of the input and output variables. The distribution law of the measurement results is determined using the Pearson criterion.

The principles are established by which the model will work according to the principle:

$$IF\ \left[x \in A_1\right]\ AND\ \left[y \in B_1\right]\ TO\ \left[z \in C_1\right], \qquad (9)$$

where x, y, z... are input (output) linguistic variables, A_1, B_1, C_1... are fuzzy sets that are described by their membership functions.

As a result, using fuzzy logic, it was established that the highest quality caramel will be in the case when the temperature is 92.5 °C, % RH is 97.5%, and pressure is 599 kPa (Fig. 3).

A graphical representation of the principles for finding a solution that corresponds to the highest quality of caramel syrup is presented in Fig. 3.

An important stage of the proposed method is the analysis of the presence of correlation between factors that affect the control indicator. Pairwise correlation coefficients between factors are calculated and, depending on whether a correlation is established or not, the combined standard uncertainty is also calculated [14] either for correlated data, or for uncorrelated data. For example, in the production of butter, at the stage of pasteurization of cream, the IMS controls the level of vapour pressure, temperature during pasteurization and pH. To detect the presence of a correlation dependence in the interaction of these three quantities (temperature (t), pH level (h), and vapour pressure (p)), the correlation coefficients and the combined correlation coefficient are calculated. The correlation coefficients between pairs of quantities t and h, t and p, h and p are calculated as follows:

$$b_{p|t} = \frac{r_{tp} - r_{th} \cdot r_{hp}}{1 - r_{th}^2} \cdot \frac{q_p}{q_t}; \quad b_{p|h} = \frac{r_{hp} - r_{th} \cdot r_{tp}}{1 - r_{th}^2} \cdot \frac{q_p}{q_h}, \qquad (10)$$

where r_{tp}, r_{th}, r_{hp} are the correlation coefficients between pairs of quantities that are determined by the formulas:

$$r_{th} = \frac{\sum_{i=1}^{N} \left(t_i - \bar{t}\right) \cdot \left(h_i - \bar{h}\right)}{\left(N-1\right) q_t q_h};$$

$$r_{tp} = \frac{\sum_{i=1}^{N}\left(t_i - \overline{t}\right)\cdot\left(p_i - \overline{p}\right)}{\left(N-1\right)q_t q_p};$$

$$r_{hp} = \frac{\sum_{i=1}^{N}\left(h_i - \overline{h}\right)\cdot\left(p_i - \overline{p}\right)}{\left(N-1\right)q_h q_p};$$

N is the total number of experimental results, i.e. the total number of points (t_i, h_i, p_i);

$$q_t^2 = \frac{\sum_{i=1}^{N}\left(t_i - \overline{t}\right)^2}{\left(N-1\right)},$$

$$q_h^2 = \frac{\sum_{i=1}^{N}\left(h_i - \overline{h}\right)^2}{\left(N-1\right)},$$

$$q_p^2 = \frac{\sum_{i=1}^{N}\left(p_i - \overline{p}\right)^2}{\left(N-1\right)}.$$

The measure of the dependence between the value t and the values h and p is the combined correlation coefficient

$$R = \sqrt{\frac{r_{tp}^2 + r_{hp}^2 - 2\cdot r_{th}\cdot r_{tp}\cdot r_{hp}}{1 - r_{th}^2}}. \tag{11}$$

The values of combined standard uncertainties in the absence of an established correlation between the input values t, h, p are determined by the formulas:

$$u_c(t) = \sqrt{u_A^2\left(t\right) + u_B^2\left(t\right)},$$

$$u_c(h) = \sqrt{u_A^2\left(h\right) + u_B^2\left(h\right)}, \tag{12}$$

$$u_c(t) = \sqrt{u_A^2\left(p\right) + u_B^2\left(p\right)},$$

where $u_A(t)$, $u_A(h)$, $u_A(p)$ are type A uncertainties;

$u_B(t)$, $u_B(h)$, $u_B(p)$ are type B uncertainties.

With an established correlation between the values t, h, p, the combined standard uncertainty is determined by the formulas:

$$u_c(y)_{th} = \sqrt{\begin{matrix} u_A^2(t) + u_B^2(t) + u_A^2(h) + u_B^2(h) + \\ +2\cdot r_{th}\cdot u_A(t)\cdot u_A(h) \end{matrix}}, \tag{13}$$

$$u_c(y)_{tp} = \sqrt{\begin{matrix} u_A^2(t) + u_B^2(t) + u_A^2(p) + u_B^2(p) + \\ +2\cdot r_{tp}\cdot u_A(t)\cdot u_A(p) \end{matrix}}, \tag{14}$$

$$u_c(y)_{hp} = \sqrt{\begin{matrix} u_A^2(h) + u_B^2(h) + u_A^2(p) + u_B^2(p) + \\ +2\cdot r_{hp}\cdot u_A(h)\cdot u_A(p) \end{matrix}}. \tag{15}$$

Calculations of expanded uncertainties are performed in case of pairwise correlation in the form:

$$U(y)_{th} = k_{th}\cdot u_c(y)_{th}, \tag{16}$$

$$U(y)_{tp} = k_{tp}\cdot u_c(y)_{tp}, \tag{17}$$

$$U(y)_{hp} = k_{hp}\cdot u_c(y)_{hp}, \tag{18}$$

where k_{th}, k_{tp}, k_{hp} are coverage ratios, which are found based on the Student distribution for a probability of 0.95 and the effective number of degrees of freedom.

Thus, the full cycle of monitoring the functioning of the IMS is completed, regardless of its purpose.

Summaries

The analysis proved the absence of a generalized control method that would be appropriate to use for any IMS regardless of its purpose. For the first time, a generalized method for controlling the functioning of IMSs was developed, which solved the scientific and practical problem of increasing the reliability of methods for controlling the functioning of IMSs by determining and taking into account the factor influence on the measurement result through the combined use of test control methods, statistical analysis methods, and fuzzy logic apparatus, which ensured high reliability of the results obtained and, as a result, compliance with the established standards for the initial parameters of the final product.

The possibility of using the proposed control method on examples of IMSs during the technological process of manufacturing butter and caramel syrup has been established, which can be applied to IMSs for other technological processes. The advantage of the proposed method compared to others is that it is generalized and integrally takes into account the positive effects of most existing methods for controlling the quality of IMS functioning, which allows it to be used to control IMSs regardless of their purpose.

Метод контролю функціонування інформаційно-вимірювальних систем у процесі експлуатації

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Анотація

Розглянуто узагальнений метод контролю функціонування інформаційно-вимірювальних систем, який враховує дію випадкових факторних впливів на результат контролю. Зазначено, що на точність і достовірність результатів вимірювань впливають зовнішні та внутрішні фактори, які діють як окремо один від одного, так і взаємно. Саме тому постає завдання оцінки рівнів факторного впливу для забезпечення необхідної точності та достовірності вимірювань. Для вирішення поставленого завдання запропоновано узагальнений метод контролю функціонування інформаційно-вимірювальних систем, який об'єднав переваги наявних структурно-алгоритмічних методів, методів тестового контролю, статистичного аналізу, теорії нечітких множин, а також алгоритму розрахунку невизначеності вимірювань.

Метод полягає у формуванні адитивних і мультиплікативних незалежних тестових впливів для інформаційно-вимірювальних систем та, залежно від отриманих результатів, за допомогою блока аналізу метрологічної ситуації, що діє на підставі нечіткої логіки, обрання одного із двох шляхів подальшого аналізу. Перший шлях обирається за необхідності врахування дії випадкового факторного впливу на роботу інформаційно-вимірювальних систем, а саме: розробляється модель факторного впливу на підставі дисперсійного аналізу, виконується коваріаційний аналіз рівнів факторного впливу та дискримінантний аналіз із оцінюванням кількості інформації за показниками контролю. Другий шлях обирається за необхідністю перевірки гіпотез про відсутність порушень метрологічної надійності елементів системи. Два шляхи ґрунтуються на розробці ситуаційної системи із нечіткою логікою для визначення ступеня факторного впливу на показник контролю. Встановлюється наявність чи відсутність кореляції між факторами. Проводиться розрахунок сумарної стандартної невизначеності для корельованих або некорельованих даних і подальший розрахунок розширеної невизначеності. Завдяки використанню запропонованого методу стає можливим підвищення достовірності контролю функціонування інформаційно-вимірювальних систем.

Ключові слова: інформаційно-вимірювальна система; статистичний аналіз; тестовий вплив; нечітка логіка; невизначеність вимірювань; похибка.

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