Розглянуто особливості процесу оцінки та нормування випадкової складової похибки вимірювання гоніометричної системи з елементами штучного інтелекту. Сформовано загальну методику нормування випадкової складової похибки вимірювання, яка дозволить обґрунтовано визначати необхідну та достатню кількість повторів вимірювань для досягнення заданої точності. Використання даної методики дозволяє зменшити трудомісткість і тривалість проведення експерименту та забезпечує досягнення заданої точності вимірювання. Запропоновано стратегію реалізації методики, яка складається з чотирьох основних етапів

Ключові слова: штучний інтелект, гоніометрична система, випадкова складова похибки вимірювання, математична статистика, математичний аналіз, теорія ймовірності

Рассмотрены особенности процесса оценки и нормировки случайной составляющей погрешности измерения гониометрической системы с элементами искусственного интеллекта. Сформулирована общая методика нормировки случайной составляющей погрешности измерения, которая позволит обоснованно рассчитывать необходимое и достаточное количество повторов измерений для достижения заданой точности. Использование данной методики позволяет уменьшить трудоемкость и длительность проведения эксперимента и обеспечивает достижение заданной точности измерения. Предложена стратегия реализации данной методики, которая состоит из четырех основных этапов

Ключевые слова: искусственный интеллект, гониометрическая система, случайная составляющая погрешности измерения, математическая статистика, математический анализ, теория вероятности

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THE PROCEDURE FOR DETERMINING THE NUMBER OF MEASUREMENTS IN THE NORMALIZATION OF RANDOM ERROR OF AN INFORMATION-MEASURING SYSTEM WITH ELEMENTS OF ARTIFICIAL INTELLIGENCE

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1. Introduction

Intensive progress in the automation of in-process measurements and the corresponding measuring means and systems determines stricter requirements to the efficiency of their operation. Accuracy is one of the efficiency-related indicators of functioning of the automated in-process measurement systems. Accuracy can be achieved, first, by improving proper technical means and, second, by improvement of measurement methods, computational algorithms and other procedures. The latter allows the desired accuracy to be ensured in less costly but not less effective ways. In particular, it concerns determination and normalization of measurement errors including those appearing in an automated goniometric system with elements of artificial intelligence proposed in [1].

Method-related, instrumental and human errors are the sources of measurement errors of all measurement means and systems including so-called intelligent measurement systems (IMS) and the proposed automated goniometric system with elements of artificial intelligence [2] among them. These errors manifest themselves in the measurement results as systematic and random components of the measurement errors [3]. Variation of these errors in time is a nonstationary random process. Normalization of such errors can be realized by using the probability theory and the mathematical statistics based on the results of multiple measurements. The procedure for processing results of multiple measurements is known as one possessing a long-standing practice of application, well-grounded and maximally formalized. However, the main problem of conducting multiple measurements is the number of measurements proper. In normalization of the measurement error, in particular its random component based on the results of multiple measurements, two errors appear: the first one is insufficient number of measurements that prevents achievement of high accuracy and the second one is excess of measurements which leads to a rise in the costs of measurement and lengthening of its conduction which is unacceptable for economic reasons (Fig. 1).

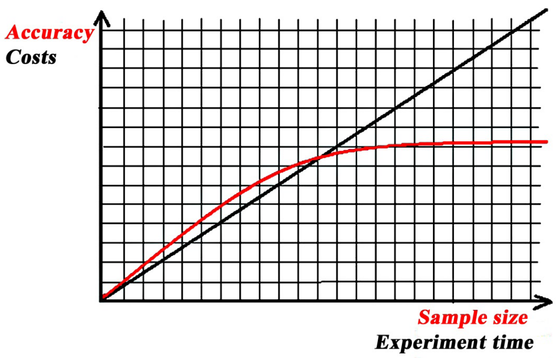

Fig. 1. Dependence of the number of measurements, accuracy and the experiment cost

Obviously, it is necessary to know clearly how to determine the required number of measurements which will ensure desired accuracy and consistency of the measurement results while the time that will be spent can be considered optimal from an economic point of view. Such necessary and sufficient number of measurements can be considered optimal from this point of view.

In view of the above, it is relevant to formulate a procedure for determining optimal number of measurements in normalization of random components of the measurement errors which will enable to:

– determine the necessary number of multiple measurements that will be sufficient to achieve the desired accuracy;

– follow the economic and management principles: rationality and economic expediency at which the expected effect of the improved accuracy will be greater than the cost of carrying out measurements;

– find some compromise between the accuracy grade-up, the measurement costs and the measurement time.

2. Literature review and problem statement

In well-known metrological works [4–10], the issue of determining quantity of measurements when evaluating the random error component is reduced to one corollary: the greater the number of measurements, the higher accuracy. For example, papers [4, 5] based on analysis of the methods for recording random and systematic errors in estimation of accuracy and metrological reliability of measuring devices using the results of multiple observations hold that higher accuracy and metrological reliability will be ensured by multiple measurements. However, they do not specify the number of measurements to be performed and how this number can be determined. Estimation of random components of the measurement errors occurring in goniometric systems was made in [6, 7] on the basis of multiple measurements. The issue of determining the number of measurements sufficient to achieve desired accuracy was not solved. Repeated measurements were performed with various numbers of observations in works [8, 9] studying goniometric systems used in the medical practice. As a result of the studies, it was claimed that the random error degree will decrease with the increase in the number of clinical studies and the rise of experimenter's skill level [10]. The issue of substantiation of the number of measurements remained unsolved.

Answers to the question how to determine the sample size when processing results of multiple observations can be found in the problems of mathematical statistics and economic-mathematical planning. For example, methods of mathematical statistics in clinical laboratory studies were used in [11] to determine necessary number of patients for diagnostic researches, confirming therapeutic effects of drugs and epidemiological studies, etc., The same methods have also been used in [12] as the basis for determining necessary number of experts for expertise of investment projects. It is obvious that after its corresponding adaptation and refinement, the mentioned practice can be used as a basis for solving metrological problems related to evaluation and normalization of random components of the measurement errors in complex information-measuring systems (IMS) with elements of artificial intelligence [1].

Thus, the necessity of this study is brought about by the lack of clear instructions and methods for determining necessary and sufficient number of multiple measurements to achieve desired accuracy in normalization of random components of the errors occurring in intellectual IMS, compliance with the abovementioned principles of rationality and economic feasibility as well as establishing a compromise between the achieved accuracy and the measurement time and costs.

3. The aim and objectives of the study

The study objective was to define features of the procedure for estimation and normalization of the random components of the measurement errors occurring in a goniometric system and formulate a general procedure for determining optimal number of measurements (i. e. necessary and sufficient quantity of measurements to ensure desired accuracy and reliability of the measurement results).

To achieve this goal, the following tasks were solved:

– determine stages and sequence of calculation of the necessary and sufficient number of measurements for estimation and normalization of random components of the goniometric system measurement errors;

– determine and substantiate necessary and sufficient number of multiple measurements that can be considered optimal in the accepted concept to estimate and normalize random components of the goniometric system measurement errors with a specified accuracy and reliability of the measurement results using mathematical statistics, the probability theory and mathematical analysis.

4. The materials and procedure used in determining optimal number of measurements

The proposed information-measuring system (IMS) is a complex intellectual measuring system organized as a set of various technical means with heterogeneous properties (Fig. 2). The IMS was developed on the basis of the goniometrical system, the first commercial instrument developed by Arsenal PA (Kyiv, Ukraine) in cooperation with the Instrumentation Department at Sikorsky Kyiv Polytechnical Institute (KPI). A distinctive feature of the IMS proposed by the authors (Fig. 2) is the application of an artificial neural network (ANN) as the basic element [1].

The structure of IMS with ANN can be represented as a certain multilevel set of various technical means with heterogeneous properties. The lower level of the IMS (*level 0*) is the level of formation of the input measurement signal α_{in}. This level is organized in a form of a precision angle measurement (PAM) subsystem with a high-precision laser goniometer as the basic element. The next *level 1* is designed for pre-processing of the input analog signal α_{in}^{A} coming from the PAM and converting it into a digital signal α_{in}^{D}. This level is represented by a subsystem of signal preparing (SSP). Processing of the digital signal α_{in}^{D} from the SSP and its representation in a form convenient for visualization followed by on-line computer processing is carried out at the *level 2* with the help of a subsystem of signal processing and displaying (SSPD) with ANN.

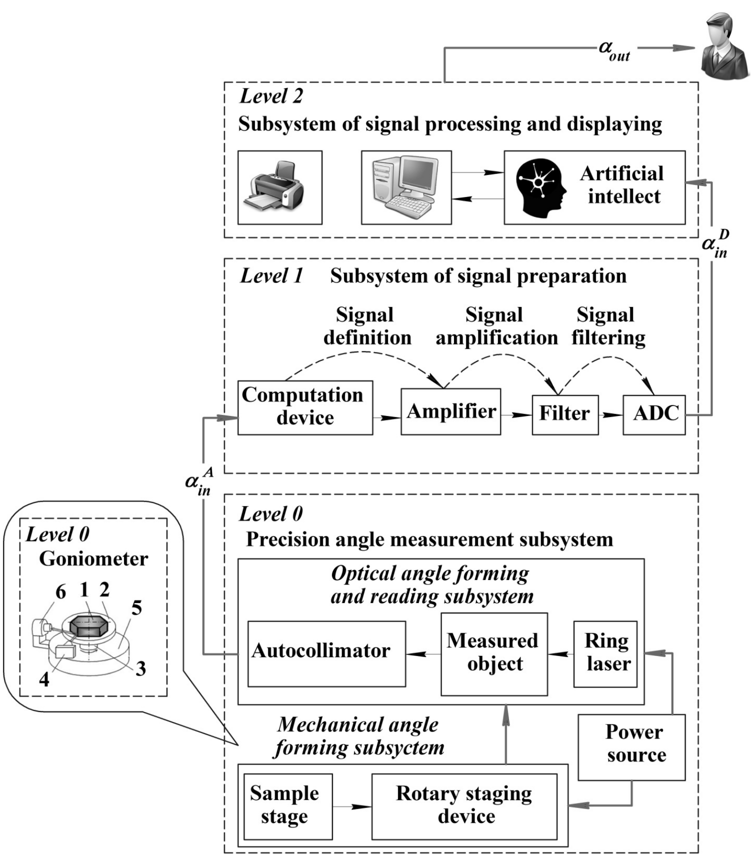

Fig. 2. Block diagram of IMS with ANN: object of measurement (1), sample stage (2), rotary staging device (3), ring laser (4), rotary activator (5), autocollimator (6)

In automated mode, the IMS with ANN enables contactless high-precision measurements of plane angles and pyramidality of prisms, refractive index of optical compositions with online processing of the measurement data. Besides that, the IMS with ANN can be used in flexible manufacturing systems when streamlining production environment for automated determination of angular positions of the manufactured objects in machine building and instrument engineering.

On the basis of the studies in [1], we can assert that all types of errors which are defined by the generally accepted classification are inherent to the IMS with ANN. In particular, the measurement error has systematic and random components. Their change in time is a non-stationary random process. Random errors feature impossibility of their exclusion from the measurement results by introducing appropriate corrections. However random errors can be significantly reduced by increasing number of observations.

Therefore, estimation and reduction of the measurement errors, in particular their random components occurring in the IMS with ANN can only be accomplished by increasing number of measurement repetitions with verification of accuracy of the obtained experimental data. Obviously, along with improvement of accuracy, increase in the number of experimental studies leads to a growth of labor and time expenditures. In most cases, the latter is an essential component of the total cost of designing, manufacture and operation of automated measurement systems and means. Therefore, in estimation and normalization of the random errors occurring in the IMS with ANN it is necessary to substantiate determination of the necessary number of measurement repetitions. This task is of special importance for long-term and high-value studies.

An appropriate general procedure should be based on determination of the optimum (necessary and sufficient) number of measurements to achieve the specified high accuracy and reliability of the measurement results taking into account time and cost expenditures (Fig. 1). In this case, a multicriteria problem arises. The main property of multicriteria problems is the set of possible solutions characterized by a corresponding target function *F* which must express quantitative relationship between the desired result and the costs to achieve it [14]. In this case, the problem is to determine the optimal number of measurements *K* at which it is possible to achieve the highest accuracy ε→max and consistency of the results α→max. The economic costs *E* depending on the measurement tine *T* can be considered the smallest $E = f(T = f(K)) \to \min$ in the context of the problem being solved. The formal statement of the problem can be represented as follows:

$$F(K):\begin{cases} K = \left[(t^2 \sqrt{\sum_{i=1}^{n} (\bar{X} - X_i)^2 / (n-1)} / \varepsilon^2 \right] \to \text{opt}; \\ \varepsilon \to \max; \\ \alpha = (2\Phi(t)) \to \max; \\ E = f(T = f(K)) \to \min, \end{cases} \quad (1)$$

where *K* is the number of measurements optimal in the accepted sense; *n* is sample size; $\bar{X}$ is arithmetic mean of the measurement results; X_i is result of multiple measurements; ε is accuracy of the measurement results; α is consistency; *E* is measurement costs;

T is the measurement time at which the highest accuracy ε→max and consistency of the results α→max are achieved at time expenditures t→min:

$$E:\begin{cases}\varepsilon \to \max;\\ \alpha \to \max;\\ t \to \min.\end{cases} \qquad (2)$$

The above indicates multi-staging of the mentioned process and requires formulation of a common procedure the strategy of which can be implemented in the following sequence:

I. The experiment objective is formulated.

II. The studied IMS is analyzed and the error model is pre-formed.

III. An optimal number of experiment repetitions is determined with the use of approaches of mathematical statistics and the probability theory.

IV. An experiment is conducted and its results are processed, evaluated and interpreted.

The above enables formulation of a multi-stage optimization procedure of planning the experiment for estimating random component of the measurement error occurred in the IMS with ANN.

Stage I: formulation of the experiment objective. At this stage, the objective of conducting experiment is formulated as one consisting in conduction of multiple measurements for evaluation and normalization of the random component of the measurement error.

Stage II: analysis of the studied IMS and formation of a preliminary measurement error model. At this stage, analysis of the studied IMS is made with a preliminary formation of the model of the measurement error.

Stage III: definition of the optimal number of multiple measurements. At this stage, the necessary and sufficient number of repetitions of experiments (measurements) is calculated. Methods of mathematical statistics and the probability theory are used to ensure high accuracy and reliability of the obtained results with minimal resource costs.

Stage IV: carrying out repeated measurements and processing of experimental data. At this stage, the experiment is conducted, root-mean-square deviation is found, presence of gross errors in the measurement result is checked and interpretation of the results and correction of the error model are performed if necessary.

The generalized sequence of solving problems using the proposed procedure is presented in Fig. 3.

At each stage of the proposed procedure, a number of tasks are expected to be solved. In this case, the results obtained at each of the preceding stages are the source data for the next stage. Thus, at the *Stage 1* of the proposed methodology, the task is formulated and the objective of multiple measurements is set forth. The task consists in determining optimal (i. e. necessary and sufficient) number of measuring repetitions to achieve maximum precision at the specified reliability and as a consequence, minimization of costs by shortening the measurement time.

At *Stage II*, analysis of the operation principle of the studied IMS and the preliminary formation of the measurement error model are made.

Task II.1. Analysis of the operating principle of the measurement system. Simplified representation of the measurement principle of the IMS with ANN is as follows. The measured object *1* (Fig. 1), for example, a prism taken to measure its angles is mounted on a sample stage *2* rotating at a constant speed with the help of the rotary device *3.* During rotation of the sample stage *2* with prism *1,* electrical impulses from each of its faces are formed at the output of the autocollimator *6,* calculated by the counters in the SSP and transmitted to the computer of the SSPD of the IMS with ANN.

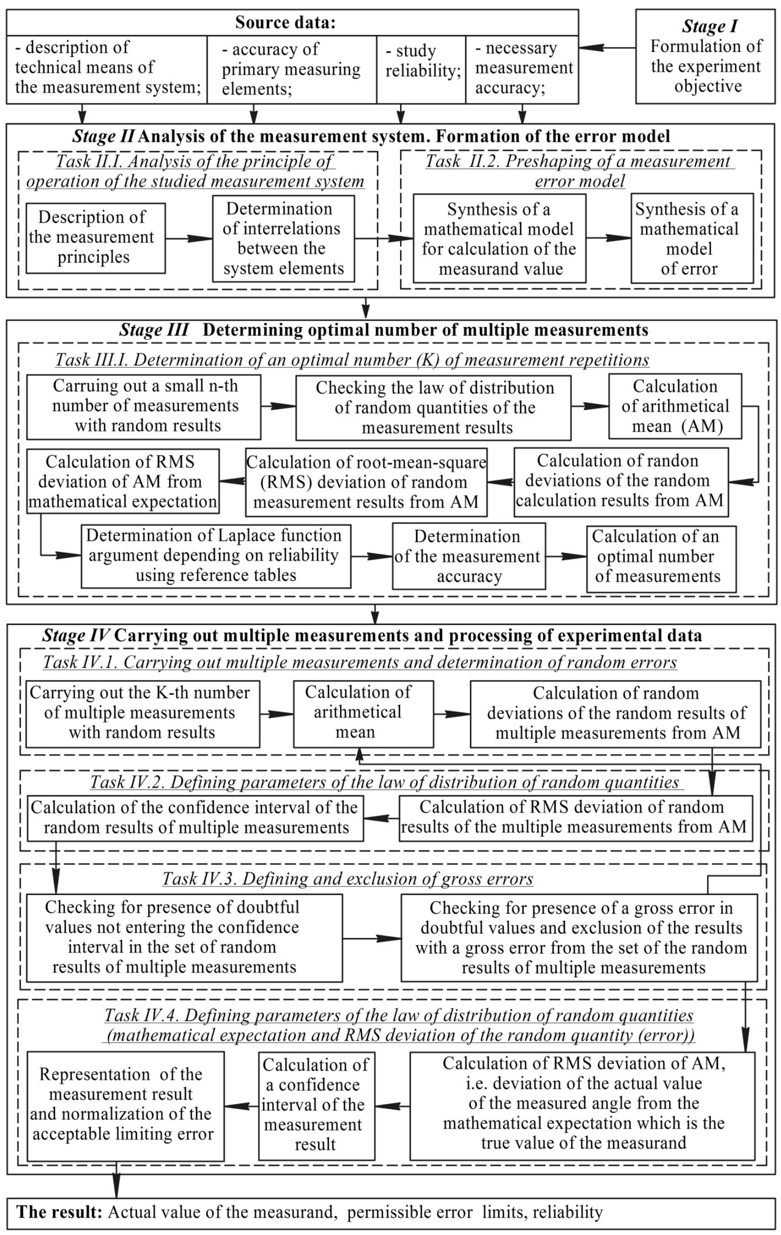

Fig. 3. Procedure for determining optimal number of measurements to estimate random component of the error

In one full revolution of the rotary device *3*, a set of numbers are obtained:

$$N=\{N_i, \ |i=\overline{1,n}\};$$

$$N_i = N_{i-2} + \int_{t_i}^{t_{i+1}} f_{Gout}(t)\mathrm{d}t, \quad (3)$$

where *i* is the ordinal number of the digit corresponding to the ordinal number of the prism face; *n* is the number of the prism faces; t_i is the time of arrival of the autocollimator impulses from the *i*-th prism face, $t_1, t_2, t_3, ..., t_{n+1}$ is the time of arrival of the autocollimator impulses from the 1st, 2nd, 3rd, *n*+1 prism face respectively; f_{Gout} is frequency of the signal α_{in}^{A} from the PAM, that is, the frequency of the signal from the goniometer.

Thus,

$$N_1 = \int_{t_1}^{t_2} f_{out}(t)\mathrm{d}t, \quad N_2 = \int_{t_2}^{t_3} f_{out}(t)\mathrm{d}t,$$

$$N_3 = N_1 + \int_{t_3}^{t_4} f_{out}(t)\mathrm{d}t, \quad N_4 = N_2 + \int_{t_4}^{t_5} f_{out}(t)\mathrm{d}t,$$

$$N_{n-1} = N_{n-3} + \int_{t_{n-1}}^{t_n} f_{out}(t)\mathrm{d}t, \quad N_n = N_{n-2} + \int_{t_n}^{t_{n+1}} f_{out}(t)\mathrm{d}t.$$

The value of the measured *i*-th angle ϕ_i is computed by the formula:

$$\phi_i = 2\pi \frac{N_{i-1}+N_i}{N_{n-1}+N_n} = 2\pi \frac{N_\phi}{N_{2\pi}},$$

$$N_{i-1} = 0 \ \text{ at } \ i = 1, \quad (4)$$

where *i* is ordinal number of the measured angle.

Task II.2. Preliminary formation of a measurement error model. Similar to [8], the model of the measurement error of the IMS with ANN can be anticipatorily represented by the expression:

$$\Delta\phi = 2\pi \frac{\int_{t_1}^{t_\phi}\left[K(t)\omega_{LG}(t)\cos\alpha(t) + \frac{K_{-1}(t)}{\omega_{LG}(t)\cos\alpha(t)} + f_0(t)\right]\mathrm{d}t + N_{q1}}{\int_{t_1}^{t_{2\pi}}\left[K(t)\omega_{LG}(t)\cos\alpha(t) + \frac{K_{-1}(t)}{\omega_{LG}(t)\cos\alpha(t)} + f_0(t)\right]\mathrm{d}t + N_{q2}} + \Delta\phi_{cal} - \phi, \quad (5)$$

where t_1, t_ϕ, $t_{2\pi}$ are the moments of the measurement start, rotation by the measured angle φ and angle 2π, respectively, fixed by the autocollimator; $K(t)$ is the scale factor of the laser goniometer; ω_{LG} is angular speed of rotation of the rotary device which influences the laser goniometer; $\alpha(t)$ is the angle between the axis of rotation of the rotary device and the goniometer sensitivity axis; $K_{-1}(t)$, $f_0(t)$ are nonlinearity and zero drift of the output characteristic of the goniometer, respectively; N_{q1}, N_{q2} are noise and discreteness of quantization of the laser goniometer signal; $\Delta\phi_{cal}$ is the error of calculations; ϕ is actual value of the measured angle.

Obviously, estimation of the error $\Delta\phi$ by expression (5) is more generally a rather complicated mathematical task. Therefore, when solving practical problems, one can use the expression:

$$\Delta\phi = \phi - \phi_0, \quad (6)$$

where ϕ is the measured angle value determined by expression (4), ϕ_0 is the true value of the angle.

It should be noted that it is practically impossible to determine the true value of the angle. Therefore, instead of the true the value actual value is used in practice. It is so close to the true value that it is used instead of it for particular purposes.

At the *Stage III*, determination of the necessary and sufficient number of repetitions of experiments (measurements) or the so-called sample size using the methods of mathematical statistics and the probability theory is made.

Task III.1. Determination of the necessary and sufficient quantity (K) of the experiment (measurement) repetitions

As it often takes place in practice when studying errors, an interval of possible values is taken with an assumption that any value within this interval is equally probable, that is, the random quantity is distributed evenly within the accepted interval. This statement does not meet current requirements as to the study of accuracy of the measurement made by the IMS with ANN since it was adopted to simplify and facilitate theoretical studies. Obviously, accuracy in estimating errors of the IMS with ANN depends primarily on the number of tests, i.e. the sample size (*K*) [15, 16]. However, the too large statistical sample size *K* leads to an unjustified increment in the measurement costs and increase in the time of its conduction which is unacceptable for economic reasons. In its turn, the sample size *K* depends on the interrelation between the volumes of the universal set of the studied quantity and the sample on the one hand and the accuracy ε and reliability α with which it is necessary to make probabilistic analysis of magnitude of the random measurement error component occurring in the IMS with ANN on the other hand. In machine building and instrument engineering practice, reliability α is usually taken at a level of 0.95 or 0.99 [15, 16].

The sample size *K* at various correlations of sizes of the universal set and the sample itself including the case of analysis of the measurement errors in the IMS with ANN by the simulation method can be determined with the help of the calculation formulas found in literature [15, 16]. In particular, the sample size can be obtained by the following formula [15, 16]:

$$K = \frac{t^2 \cdot \sigma^2}{\varepsilon^2}, \quad (7)$$

where *t* is argument of the Laplace function which is found in reference tables [10] depending on reliability $\alpha = 2\Phi(t)$; σ is RMS deviation of a small (not more than ten values) sample; ε is accuracy of the statistical sample.

According to the aforesaid, a necessary and sufficient number of measurements required to determine random component of the measurement error occurred in the IMS with ANN is determined by the following sequence of steps.

Step 1. A relatively small number (*n*) of measurements is carried out. The size of a small sample should not exceed 10 values.

Fig. 4 gives an example of graphical representation of distribution of random quantities of a comparatively small sample at *n*=10 when measuring plane angles of a 24-faceted prism with the help of the IMS with ANN.

Step 2. Check of the law of distribution of random quantities of a relatively small sample and parameters of the distribution law: mathematical expectation μ and root-mean-square deviation σ of the random quantity (error).

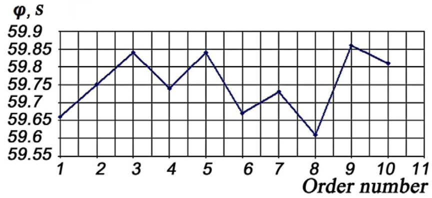

Fig. 4. Graphical representation of distribution of random quantities of a relatively small sample size n=10 in measuring flat angles of the 24-faceted prism with the help of the IMS with ANN

Since the components of the measurement errors occurring in the IMS with ANN are random quantities, it is impossible to predict the distribution law in advance. However, many scientists and researchers believe that the errors are subject to the normal distribution law [15, 16] for which a function of the probability distribution density takes the form:

$$f_x(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \tag{8}$$

where μ is mathematical expectation of a random quantity (error); σ is the root-mean-square deviation of the random quantity (error).

Step 3. According to the reference tables [15], the Laplace function argument t is found depending on reliability. Moreover, in accordance with the recommendations given in the literature [15], reliability α can be taken equal to 0.95.

Step 4. Accuracy of the statistical sample ε is set.

Step 5. The necessary and sufficient number of measurements is calculated by expression (7).

Multiple measurements and processing of experimental data are performed at *Stage IV*.

Task IV.1. Conduction of multiple measurements and defining random errors

Multiple measurements (in this case, K=37) are carried out. The quantity K was determined at *Stage III* of the proposed procedure which makes it possible to form a statistical sample as to the measurement error occurred in the IMS with ANN. It is obvious that the results obtained at each measurement repetition will differ from the true value by the error magnitude. For convenience of perceiving the results obtained and their subsequent use and analysis in estimation of the random component of the measurement error, a graphical representation of distribution of the random quantities of the resulting sample having size K=37 is presented in Fig. 5.

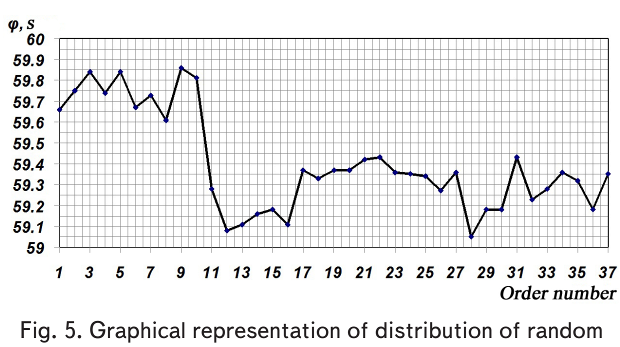

Fig. 5. Graphical representation of distribution of random quantities at multiple (K=37) measurement of flat angles of a 24-faceted prism with the help of the IMS with ANN

The total error is calculated by expression (6) as the difference between the measured and the true values. Taking into account that it is practically impossible to determine the true value, the actual value is used instead of it. It is calculated as arithmetical mean of the results obtained in multiple measurements. Let us take for an example the value obtained in measuring flat angles of a 24-faceted prism using the IMS with ANN:

$$\phi_{ca} = \overline{X} = \frac{\sum_{k=1}^{K} X_k}{K}, \tag{9}$$

where ϕ_{ca} is the actual value of the angle; $\overline{X}$ is arithmetical mean of the results of multiple measurements; X_k is the k-th result of multiple measurements; K is the sample size (number of measurements), K=37.

Further probabilistic analysis of the resulting sample is made when solving the next task.

Task IV.2. Defining parameters of the law of distribution of random quantities (mathematical expectation μ *and root-mean-square deviation σ of a random quantity (error))*

In order to determine error of the measurement made with the help of IMS with ANN, statistical studies were carried out and parameters of the law of probability distribution (mathematical expectation and root-mean-square deviation) determined using the obtained sample.

The task is solved in the following sequence of steps.

Step 1. Statistical studies consist in a statistical analysis of the sample by determining maximum and minimum values of the measured angle taking into account errors.

Step 2. Determination of parameters of the distribution laws:

– *the mathematical expectation μ* is the true value of the measured angle and can be determined for the number of measurements $K\to\infty$, therefore, an assumption is made that $\overline{X}\approx\mu$.

– *the root-mean-square deviation σ* of a random quantity from the actual value of the measured angle:

$$\tilde{\sigma} = \sqrt{\frac{\sum_{k=1}^{K} \Delta_k^{\ 2}}{K-1}}, \tag{10}$$

where Δ_k is the random deviation of the k-th result X_k of multiple measurements from the arithmetic mean $\overline{X}$,

$$\Delta_k = \overline{X} - X_k;$$

K is the number of measurements (sample size), K=37.

– *root-mean-square deviation* σ_{ca} of the actual value of the measured angle from the true value, that is, the arithmetical mean deviation from the mathematical expectation:

$$\tilde{\sigma}_{ca} = \frac{\tilde{\sigma}}{\sqrt{K}}, \tag{11}$$

where K is the number of measurements (sample size), K=37.

Task IV.2. Definition and elimination of gross errors. Gross errors or blunders significantly exceed the error expected in the given conditions and distort the measurement result and therefore must be excluded from the sample. Gross errors may arise from the experimenter's mistakes, sudden and unexpected changes in the measurement conditions and so on.

To determine and then exclude gross errors, mathematical methods are used in the following sequence of steps.

Step 1. Confidence interval Δ_{X_k} of the results obtained in multiple measurements X_k is calculated:

$$\Delta_{X_k} = \bar{X} \pm K_L \cdot \tilde{\sigma}, \quad (12)$$

where $\bar{X}$ is the arithmetical mean of the results obtaiued in multiple measurements calculated by expression (9); K_L is the value of Laplace function

$$P\{|t| < K_L\} = \frac{2}{\sqrt{2\pi}} \cdot \int_0^{K_L} e^{-\frac{y^2}{2}dy},$$

which is found from the reference tables depending on reliability α which according to the recommendations given in the literature [8] can be taken equal to 0.95.

Step 2. Cheching for the presence of questionable values X_k', that do not enter the confidence interval Δ_{X_k}, calculated by expression (12) in the set of the results X_k obtained in multiple measurements.

Step 3. Checking for presence of a gross error in questionable values X_k'. In absence of a gross error in the questionable value X_k', the following condition is fulfilled:

$$|\bar{X} - X_k'| < \Delta_G,$$

$$\Delta_G = K_G \cdot \tilde{\sigma}, \quad (13)$$

where K_G is the coefficient for defining limits of gross errors Δ_G. K_G is found from tables depending on reliability α and the sample size K; σ is the root-mean-square deviation of the random quantity from the actual value of the measured angle determined by expression (10).

The values X_k' for which condition (13) is not met contain a gross error and are deleted from the sample. Further, actual value of the measured angle as well as σ and σ_{ca} are refined by expressions (9)–(11), respectively.

Task IV.2. Presentation of the measurement result and normalization of the maximum permissible error

This task is solved in the following sequence of steps.

Step 1. Calculation of the confidence interval Δ_{ca} of the actual value of the measured angle:

$$\Delta_{ca} = \pm K_{ca} \cdot \tilde{\sigma}_{ca}, \quad (14)$$

where K_{ca} is the Student's coefficient

$$P\{|t| < t_S\} = 2\int_0^{t_S} f(t,n)\mathrm{d}t,$$

which is found in reference tables depending on reliability α and sample size K.

σ_{ca} is the root-mean-square deviation of the actual value of the measured angle from its true value determined by the expression (11).

Step 2. The result of measurement with the normalized value of the maximum permissible random error is represented as:

$$\phi = A = (\bar{X} \pm \Delta_{ca}); \ \alpha{=}0.95, \quad (15)$$

where $\bar{X}$ is the arithmetical mean of the results of multiple measurements or the actual value of the measured angle determined by expression (9); Δ_{ca} is the confidence interval determined by expression (14); α is the reliability at which probabilistic analysis of the magnitude of the random component of the measurement error was made. According to the recommendations of literary sources [10, 11] for machine building and instrument engineering, reliability is taken equal to 0.95.

5. The resulting stages of the procedure for determining optimal number of measurements

The results obtained in measuring one of the angles of a 24-faceted prism at the third tage of the proposed procedure are given in Table 1. For the given example, the necessary and sufficient number of measurements is 37. Such number of measurements makes it possible to assess the random component of the error occurring in measuring plane angle of a 24-faceted prism with the help of the IMS with ANN at an accuracy of 0.01″ and reliability of 0.95.

Table 1

Results of determination of the necessary and sufficient number of measurements for estimation of the random component of the error occurred in measurement of a plane angle of a 24-faceted prism using the IMS with ANN

Order number	Measured angle values, φ_i			$\Delta_i=\varphi_{ca}-\varphi_i$	Δ_i^2
	Degrees	Minutes	Seconds	Seconds	Seconds
1	164	59	59.66	0.091	0.0081
2	164	59	59.75	0.001	0
3	164	59	59.84	–0.089	0.0081
4	164	59	59.74	0.011	0.0001
5	164	59	59,84	–0.089	0.0081
6	164	59	59.67	0.081	0,0064
7	164	59	59.73	0.021	0.0004
8	164	59	59.61	0.141	0.0196
9	164	59	59.86	–0,109	0.0121
10	164	59	59.81	–0.059	0.0036
Arithmetical mean (actual angle value) φ_{ca}			59.751	Σ=0	Σ=0.086
RMS deviation of the measured values of the plane angle from arithmetical mean (actual angle value) $\tilde{\sigma}$			$\tilde{\sigma} = \sqrt{\frac{\sum_{i=1}^{n}\Delta_i^2}{n-1}} \Big\vert \ n = (\overline{1;10})$		0.098
RMS deviation of the actual angle value from the true value (of the mathematical expectation)			$\tilde{\sigma}_{ca} = \frac{\tilde{\sigma}}{\sqrt{n}} \Big\vert \ n = (\overline{1;10})$		0.031
Reliability α [15]		0.95	Argument of Laplace function t [15, p. 13, Table 3]		1.97
Accuracy of the statistical sample ε		0.01	Necessary number of experiments by expression (8)		37

The results of multiple measurement with the help of the IMS with ANN of one of the angles of a 24-faceted prism with the necessary and sufficient quantity of measurements K=37 determined according to the proposed procedure are presented in Table 2.

Table 2

Results of multiple measurements of the plane angle values of a 24-faceted prism with the help of the IMS with ANN for the specified number of experiments K=37

Order number	Measured angle values, φ_k			$\Delta_k=\varphi_{ca}-\varphi_k$	Δ_k^2
	Degrees	Minutes	Seconds	Seconds	Seconds
1	164	59	59.66	–0.2557	0.06538
2	164	59	59.75	–0.3457	0.11951
3	164	59	59.84	–0.4357	0.18983
4	164	59	59.74	–0.3357	0.11269
5	164	59	59.84	–0.4357	0.18983
6	164	59	59.67	–0.2657	0.0706
7	164	59	59.73	–0.3257	0.10608
8	164	59	59.61	–0.2057	0.04231
9	164	59	59.86	–0.4557	0.20766
10	164	59	59.81	–0.4057	0.16459
11	164	59	59.28	0.1243	0.01545
12	164	59	59.08	0.3243	0.10517
13	164	59	59.11	0.2943	0.08661
14	164	59	59.16	0.2443	0.05968
15	164	59	59.18	0.2243	0.05031
16	164	59	59.11	0.2943	0.08661
17	164	59	59.37	0.0343	0.00118
18	164	59	59.33	0.0743	0.00552
19	164	59	59.37	0.0343	0.00118
20	164	59	59.37	0.0343	0.00118
21	164	59	59.42	–0.0157	0.00025
22	164	59	59.43	–0.0257	0.00066
23	164	59	59.36	0.0443	0.00196
24	164	59	59.35	0.0543	0.00295
25	164	59	5934	0.0643	0.00413
26	164	59	59.27	0.1343	0.01804
27	164	59	59.36	0.0443	0.00196
28	164	59	59.05	0.3543	0.12553
29	164	59	59.18	0.2243	0.05031
30	164	59	59.18	0.2243	0.05031
31	164	59	59.43	–0.0257	0.00066
32	164	59	59.23	0.1743	0.03038
33	164	59	59.28	0.1243	0.01545
34	164	59	59.36	0.0443	0.00196
35	164	59	59.32	0.0843	0.00711
36	164	59	59.18	0.2243	0.05031
37	164	59	59.35	0.0543	0.00295
Arithmetical mean (actual angle value) φ_{ca}			59.404	Σ=0	Σ=2.046
RMS deviation of the measured values of the plane angle from arithmetical mean (actual angle value) $\tilde{\sigma}$			$\tilde{\sigma}=\sqrt{\frac{\sum_{i=1}^{K}\Delta_i^2}{K-1}}\,\Big\vert\,K=(\overline{1;37})$		0.238
Confidence interval Δ_{ϕ_k} of random results of multiple measurements of the angle values φ_k			$\Delta_{\phi_k}=\phi_{ca}\pm K_L\cdot\tilde{\sigma}$, where K_L – value of Laplace function, K_L=2.0		$\pm K_L\cdot\tilde{\sigma}=(\pm 0.476)$
					$\Delta_{\phi_r}=59.8803$
					$\Delta_{\phi_n}=58.9283$
RMS deviation of the actual angle from the true value (mathematical expectation)			$\tilde{\sigma}_{ca}=\frac{\tilde{\sigma}}{\sqrt{K}}\,\Big\vert\,K=(\overline{1;37})$		0.039
Confidence interval Δ_{ca} of the measurement result			$\Delta_{ca}=\pm K_{ca}\cdot\tilde{\sigma}_{ca}$, where K_{ca} – Students's coefficient, K_{ca}=2.02		$\pm K_{ca}\cdot\tilde{\sigma}_{ca}$=(±0.07878)
Reliability α [15]		0.95	Measurement result		164° 59′ 59.40″±0.08″
Accuracy of the statistical sample ε		0.01			

6. Discussion of the results obtained in measuring values of a plane angle of a 24-faceted prism with the help of the IMS with ANN using the proposed procedure

Estimation of the random component of the error occurring in measurement of a flat angle of a 24-faceted prism with the help of the IMS with ANN was made on the basis of multiple measurements. The number of measurements K was pre-determined according to the proposed procedure and amounted to 37 measurements. The result was as follows: φ=164° 59′ (59.40±0.08)″ at a specified accuracy of the statistical sample of 0,01″ and reliability of 0,95. The measurement time for K=37 was approximately 6 hours.

To estimate effectiveness of the proposed procedure, the results of a similar study in [7] can be used. As indicated in [7], measurement of the plane angle of the 24-faceted prism was carried out in 50 repetitions for 8 hours. For the number of measurement repetitions N=50, accuracy was around 0.014″.

Obviously, the number K 37 of measurements of a plane angle of the 24-faceted prism determined by the proposed procedure was approximately 1.4 times less compared with the number of measurements N=50 carried out in a similar work [7] while accuracy remained approximately the same (0.01″ for K=37 and 0.014″ for N=50).

Reduction of the measurement repetition number can give approximately 1.3 times shorter total measurement time with no loss of accuracy and, accordingly, reduce the measurement costs, say at the expense of energy savings, etc.

However, the main assumption when applying the proposed procedure should be that random errors are subject to the normal law of distribution of random quantities. Indeed, the results of multiple measurements are mostly reduced to the normal distribution law although there are other laws, such as gamma distribution, Weibull distribution, etc. which may occur in practice but are not considered in the proposed procedure. The study of the effect of these laws on accuracy in estimation of the random component of the measurement error can be used in searching for lines and prospects of further studies.

7. Conclusions

1. A procedure for determining number of measurements in normalization of random components of the measurement errors has been developed. It enables calculation of the necessary number of measurements that will be sufficient to ensure desired accuracy and reliability of the measurement results.

2. Operationability of the proposed procedure was experimentally confirmed. In particular, when the results, that is the calculated number of measurements according to the proposed procedure, were compared with those obtained in the known work [7], it has been found out that the same accuracy of the measurement results can be ensured by a smaller number of measurements. This reduces the measurement costs. For example, the measurement time was reduced by approximately 1.3 times without loss of accuracy.

It was established that the effect of improving accuracy through application of the proposed procedure will be greater than the measurement expenses. For example, comparison of the results of experimental studies with a similar work [7] indicates the possibility of reaching high accuracy of 0.01″ and reliability of 0.95 in a relatively shorter time (the measurement time was reduced by about 2 hours which is 1.3 times less than in the similar work).

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DEVELOPMENT OF STRATIFIED APPROACH TO SOFTWARE DEFINED NETWORKS SIMULATION

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Запропоновано стратифікований підхід до імітаційного моделювання програмно-конфігурованих мереж. Запропоновано імітаційні моделі мережі, активних і пасивних компонентів – контролера, комутатора, хоста та комунікаційних каналів. Придатність підходу до цільового використання підтверджено шляхом співставлення одержаних результатів імітаційного моделювання із результатами емуляції мережі у середовищі Mininet

Ключові слова: програмно-конфігурована мережа, імітаційне моделювання, дискретно-подійна специфікація системи, великі дані

Предложен стратифицированный подход к имитационному моделированию программно-конфигурируемых сетей. Предложены имитационные модели сети, активных и пассивных компонентов – контроллера, коммутатора, хоста и коммуникационных каналов. Пригодность подхода к целевому использованию подтверждена путем сопоставления полученных результатов имитационного моделирования с результатами эмулирования сети в среде Mininet

Ключевые слова: программно-конфигурируемая сеть, имитационное моделирование, дискретно-событийная спецификация системы, большие данные

1. Introduction

Nowadays the current state of global networking is on a verge of its drastic refinement. The questions of networks management convenience, control, monitoring, reconfiguring and scaling are topical here. The answer can be in modern approaches and concepts usage. Possible solution can be found in Software Defined Networking (SDN) principles following. There are some of them: differentiation between control and data planes, lightweight switches utilization, "controller" concept adoption – to coordinate switches in a centralized manner [1].

The SDN abbreviation will also be associated with Software Defined Network itself.

One of the main goals of SDN technology adoption is to foster the existing opportunities to effectively utilize available network resources in order to operatively meet the ad-hoc requirements of certain business-process (processes). To do that properly, the significant work yet has to be done. A plethora of different approaches and techniques have already been proposed to date though, e. g., to divert important traffic on a backup path to prevent packets loss and reduce jitter [2]. Appropriate solutions can be generalized as follows: it can be painful to get on with, the majority of solutions are aimed at emulation. This is not always acceptable in terms of corresponding time costs.

The development and deployment of systems on a basis of SDN principles is a non-trivial task, because of technology novelty and complexity. The validation of resulting solutions can be conducted by way of simulation or by way of testing. The simulation herein is a significantly less resource-intensive process, especially in the context of iterative development [3]. That's why the creation of an approach to such systems simulation is a topical task.