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DEVELOPMENT OF A METHOD FOR ASSESSING THE TECHNICAL CHARACTERISTICS OF SPECIALIZED HIERARCHICAL SYSTEMS USING ARTIFICIAL INTELLIGENCE

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The object of the study is specialized hierarchical systems. The problem addressed in the research is improving the efficiency of evaluating hierarchical systems while ensuring a specified level of reliability regardless of the volume of data entering the system. The originality of the method lies in the use of additional enhanced procedures that allow to:

– verify the topology and parameters of specialized hierarchical systems, considering the degree of uncertainty of the initial data known about them. The consideration of uncertainty is achieved through the application of corresponding correction coefficients;

– perform a primary selection of individuals for tuning the convolutional artificial neural network using an improved genetic algorithm, which reduces solution search time and increases the reliability of obtained results;

– explore the solution spaces of the problem of evaluating the state of specialized hierarchical systems described by atypical functions using an improved monkey swarm algorithm;

– tune the memory of the convolutional artificial neural network via a memory training procedure, thereby reducing the estimation error of parameters of specialized hierarchical systems;

– adjust the weights of the convolutional artificial neural network, which leads to increased accuracy in estimating parameters of specialized hierarchical systems;

– employ additional mechanisms to adjust convolutional artificial neural network parameters by changing the membership function.

An increase in decision-making efficiency of 15–18% was established due to the use of additional procedures, with the reliability of the decisions ensured at the level of 0.9

Keywords: convolutional artificial neural networks, genetic algorithm, destabilizing factors, metaheuristic algorithm

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1. Introduction

The problem of improving the efficiency of evaluating parameters of specialized hierarchical systems is highly relevant in modern information systems of various functional purposes [1, 2]. The experience of recent conflicts involving the use of contemporary information systems shows that existing methods for assessing parameters of specialized hierarchical systems do not allow obtaining reliable evaluations of their parameters with the required efficiency [3].

This is associated with the following reasons [4, 5]:

– the significant role of the human factor in the process of evaluating parameters of specialized hierarchical systems;

– a large number of heterogeneous information sources included in information systems;

– the evaluation of parameters of specialized hierarchical systems is carried out under conditions of uncertainty, which causes delays in data processing;

– the presence of a large amount of destabilizing data affecting the efficiency of parameter evaluation of specialized hierarchical systems;

– the presence of structured and unstructured data in information systems, which require processing, among others.

Considering the diversity, many destabilizing factors, and varying dimensionality of indicators describing them, the need to evaluate parameters of specialized hierarchical systems motivates the search for new approaches to their assessment. One such approach is the use of metaheuristic algorithms [6].

The use of metaheuristic algorithms in their canonical form allows for improving the efficiency of evaluating parameters of specialized hierarchical systems; however, further improvement of the evaluation efficiency is not possible by merely restricting them to their canonical form [7].

This motivates implementing strategies to improve the convergence speed and accuracy of basic metaheuristic algorithms when evaluating parameters of specialized hierarchical systems. One way to enhance the efficiency of parameter evaluation of specialized hierarchical systems is their further improvement through combining, comparing, and developing new procedures for their joint use [8].

Therefore, research dedicated to developing new approaches to assessing technical characteristics of specialized hierarchical systems using artificial intelligence theory is timely.

2. Literature review and problem statement

Work [9] presents a cognitive modeling algorithm and outlines the main advantages of mental tools. However, a significant drawback of this approach is its failure to consider the type of uncertainty regarding the state of the object being analyzed.

In [10], the essence of cognitive modeling and scenario planning is discussed. The authors propose a system of complementary principles for constructing and implementing scenarios, identify different approaches to scenario building, and describe a scenario modeling procedure based on fuzzy cognitive maps. Nevertheless, this approach does not account for the type of uncertainty concerning the state of the analyzed object and ignores noise in the input data.

Work [11] analyzes key approaches to cognitive modeling. Cognitive analysis allows researchers to explore problems involving fuzzy factors and relationships, account for changes in the external environment, and utilize objectively formed development trends to their advantage. However, the paper does not explore the issue of describing complex and dynamic processes.

[12] presents a method for analyzing large data sets. This method is aimed at uncovering hidden information in big data. It includes operations such as generating analytical baselines, reducing variables, identifying sparse features, and establishing rules. A significant drawback of this method is its inability to consider different decision evaluation strategies or account for the type of uncertainty in the input data.

Work [13] describes a mechanism for transforming construction object information models into equivalent structural models. The mechanism is designed to automate necessary operations for converting, modifying, and supplementing information during such data exchanges. However, the approach cannot evaluate the adequacy and reliability of the transformation process and perform corresponding corrections of the resulting models.

In [14], the authors develop an analytical web platform for studying incidents' geographic and temporal distribution. The platform includes several dashboards with statistically significant results by region. However, it cannot assess the adequacy and reliability of the information transformation process and suffers from high computational complexity. The research also lacks a unified direction in its solution approach.

Work [15] presents a fuzzy hierarchical method for evaluating library service quality. The process enables the evaluation of libraries based on multiple input parameters. However, it does not allow for the assessment of the adequacy and reliability of the assessment or estimation errors to be determined.

In [16], the authors analyze 30 big data processing algorithms, highlighting their advantages and drawbacks. They conclude that big data analysis should be layered, operate in real-time, and support self-learning. However, the high computational complexity and inability to verify the adequacy of the obtained evaluations are significant drawbacks.

Work [17] proposes a method for evaluating input data for decision support systems. This method involves clustering the base set of input data, analyzing it, and then using the analysis results for system training. However, this approach suffers from a gradual accumulation of evaluation and training errors due to the inability to assess the decisions' adequacy.

Work [18] presents an approach to processing data from various information sources. This approach enables the processing of heterogeneous data; however, its main drawbacks include low accuracy of the obtained evaluation and the inability to verify the reliability of the results.

In work [19], a comparative analysis of existing decision support technologies is conducted: the Analytic Hierarchy Process, neural networks, fuzzy set theory, genetic algorithms, and neuro-fuzzy modeling. The advantages and disadvantages of each approach are indicated. For example, the Analytic Hierarchy Process works well with complete initial information. Still, it involves a high degree of subjectivity due to the need for expert comparison of alternatives and selection of evaluation criteria. For forecasting tasks under risk and uncertainty, fuzzy set theory and neural networks are justified.

In work [20], the use of combined strategies of metaheuristic algorithms and their integration with other components of artificial intelligence theory is discussed. However, the drawbacks of this approach include the insufficient processing speed of heterogeneous data when multiple metaheuristic algorithms are used together.

The analysis of works [9–20] reveals common shortcomings in the above studies:

– lack of the ability to form a hierarchical system of indicators for a comprehensive assessment of the state of specialized hierarchical systems;

– lack of consideration of the computational resources of the system that manages the assessment process of specialized hierarchical systems;

– an absence of mechanisms for adjusting the system of indicators for managing the assessment process of specialized hierarchical systems;

– lack of mechanisms for selective involvement of convolutional artificial neural network training methods;

– high computational complexity;

– an absence of consideration for available computing (hardware) resources in the system;

– lack of prioritization in search direction.

The above indicates the need to develop new (or improve existing) approaches for evaluating the technical characteristics of specialized hierarchical systems.

3. The aim and objectives of research

This research aims to develop a method for evaluating the technical characteristics of specialized hierarchical systems using artificial intelligence. This will improve the efficiency of assessing the technical attributes of specialized organizational and technical systems with a given level of reliability and facilitate subsequent managerial decisions based on the assessment results. It will also enable software development (or enhancement) to evaluate the technical characteristics of specialized hierarchical systems.

To achieve this aim, the following objectives were set:

– to define the algorithm for implementing the method;

– to provide an example of applying the method to assess the technical characteristics of means used by operational military groupings (forces).

4. Materials and methods of research

The object of research is specialized hierarchical systems. The research hypothesis is that it is possible to increase the speed of evaluation of hierarchical systems while ensuring a given level of reliability, regardless of the volume of input data. The subject of the research is the process of evaluating the state of specialized hierarchical systems.

The indicators in the evaluation system of specialized hierarchical systems usually include data with different origins, units of measurement, and varying degrees of influence on the overall assessment result. For this purpose, artificial intelligence theory is applied, namely:

– an improved genetic algorithm allows automation of the assessment process and performing random, structured information modification and entity rearrangement within the search space of specialized organizational and technical systems. In this research, the improved genetic algorithm is also used at the preliminary selection stage to improve the reliability of the system's condition evaluation. Additionally, it is employed to tune the parameters of a convolutional artificial neural network [18];

– an improved monkey swarm algorithm – for verifying the topology and parameters of specialized hierarchical systems and the topology and parameters of destabilizing influence factors. This contributes to increasing the reliability of the obtained assessment of the condition and parameters of specialized hierarchical systems [19].

Convolutional artificial neural networks derive a generalized evaluation of specialized hierarchical systems based on indicators that differ in origin and measurement units [20].

The research hypothesis assumes the possibility of increasing the speed of evaluating the condition of specialized hierarchical systems with a set level of reliability using an improved combined algorithm.

The proposed method was simulated in the Microsoft Visual Studio 2022 (USA) software environment. The task addressed during the simulation of the evaluation process of specialized hierarchical systems was determining the composition of a military (forces) grouping.

The hardware used in the research process was an AMD Ryzen 5.

Parameters of the improved algorithm operation:

– number of iterations – 25;

– number of individuals in the algorithm swarm – 25;

– feature space range — [–150, 150].

The structure of the convolutional artificial neural network is provided in the work [20].

5. Development of the method for evaluating the technical characteristics of specialized hierarchical systems using artificial intelligence

5. 1. Algorithm of the method for evaluating the technical characteristics of specialized hierarchical systems using artificial intelligence

The method for evaluating the technical characteristics of specialized hierarchical systems using artificial intelligence consists of the following sequence of actions:

Action 1. Input of initial data.

At this stage, the available input data regarding specialized hierarchical systems and destabilizing influence factors are entered, namely:

– the number and types of technical means included in the specialized hierarchical systems;

– the number and types of destabilizing means that affect the objectivity of the assessment of the state of specialized hierarchical systems;

– the technical characteristics of the means that are part of the specialized hierarchical systems;

– the technical characteristics of the destabilizing means that influence the objectivity of the assessment of the state of specialized hierarchical systems;

– the topology of connections within the specialized hierarchical systems;

– the topology of connections of the destabilizing influence means;

– the types of data circulating within the specialized hierarchical systems;

– the available computational resources of the specialized hierarchical system;

– information about the environment in which the specialized hierarchical systems are applied, etc.

Action 2. Verification of parameters required for calculations.

At this stage, the input data on the specialized hierarchical system and the means of destabilizing influence are clarified. This is carried out considering the type of uncertainty about the state of the specialized hierarchical systems using the improved monkey swarm algorithm proposed by the authors in [20].

Action 3. Formation of the topology of the convolutional artificial neural network.

At this stage, the improved monkey swarm algorithm is used to form the topology of the convolutional artificial neural network, as proposed by the authors in [20], based on the verified data.

Action 4. Preliminary selection of genetic algorithm individuals.

A preliminary selection of individuals is performed using the improved genetic algorithm proposed by the authors in [19] to improve the reliability of the obtained decisions.

Action 5. Training the memory of the convolutional artificial neural network.

In training the memory of the convolutional artificial neural network, forward and backward error propagation are alternated. The specialized convolutional neural network iteratively repeats the steps until the difference between the output and expected values becomes acceptable for this evaluation class. After that, the system halts until a new value is input into the network and a new output value for the hidden layer is calculated [18]:

$$y_i = f\left(net_j\right),\ j = 1,2,...,m, \tag{1}$$

$$net_j = \sum_{i=0}^{n} v_{ij} x_i,\ j = 1,2,...,m. \tag{2}$$

Action 6. Refinement of the evaluation error of the specialized hierarchical system.

When the evaluation result at the input layer from the output of the convolutional artificial neural network does not match the expected output, there is an output error E, which is defined as follows

$$E = \frac{1}{2}\left(d - 0\right)^2 = \frac{1}{2}\sum_{k=1}^{1}\left(d_k - 0_k\right)^2. \tag{3}$$

Applying the above definition of the error to the hidden layer

$$E = \frac{1}{2}\sum_{k=1}^{l}\left[d_k - f\left(net_k\right)\right]^2 = \\ = \frac{1}{2}\sum_{k=1}^{l}\left[d_k - f\left(\sum_{j=0}^{m} w_{jk} y_j\right)\right]^2. \tag{4}$$

Applying the above definition of the error to the hidden layer, let's get w_{jk} and y_j of each layer, so adjusting the weights can change the evaluation error E.

Action 7. Adjustment of the weights of the convolutional artificial neural network.

The principle of weight adjustment is based on the continuous reduction of the error; therefore, the weight adjustment should be proportional to the negative gradient of the error, that is:

$$\Delta\omega_{jk} = -\eta\frac{\partial E}{\partial \omega_{jk}}, \tag{5}$$

$$\Delta v_{ij} = -\eta\frac{\partial E}{\partial v_{ij}}. \tag{6}$$

The minus sign in the equation represents gradient descent and the constant $\eta \in (0,1)$ proportional coefficient that reflects the learning rate.

Below are the equations for calculating the training error of the convolutional artificial neural network and the fitness function:

$$E = \frac{\sum_{k=1}^{p}\sum_{j=1}^{I}\left(y_j^k - o_j^k\right)}{2}, \tag{7}$$

$$fitness = \frac{1}{E}, \tag{8}$$

where E – the training error; p – the number of training samples in the evaluation data sets; I – the number of output nodes of the convolutional artificial neural network; and y_j^k, o_j^k – the error of the k-th sample concerning the j-th output node of the convolutional artificial neural network.

Action 8. Verification of the sufficiency of weight adjustments of the convolutional artificial neural network.

At this stage, the permissible level of the evaluation error E of the specialized hierarchical system is verified for each type of measurement.

If the evaluation error E exceeds the permissible level and cannot be corrected by adjusting the weights, then the membership function of the convolutional artificial neural network is changed.

The change of the membership function of the convolutional artificial neural network is carried out using the learning method proposed in the work [2].

Action 9. Calculation of the probability of adaptive mutation.

The probability of adaptive mutation P is calculated as follows

$$p = \frac{\left(p_1 + p_2\right)}{2} = \\ = \frac{\left(\left(p_0\left(p_0 - p_{\min}\right)\cdot m/M\right) + \left(p_0 \cdot \max F\left(x_k\right)/\bar{F}\right)\right)}{2}, \tag{9}$$

where M – maximum evolutionary algebra; m – current evolutionary algebra; p_1 – inversely proportional to the evolutionary algebra; p_2 – inversely proportional to the average fitness value of individuals; p_0 – predicted initial mutation probability; $p_{\min}$ – minimum mutation value in the probability range; F – average fitness value of the current group, which is the maximum fitness value.

Action 10. Checking the stopping criterion for agents of the hybrid algorithm swarm.

The algorithm terminates if the maximum number of iterations is reached. Otherwise, the generation of new locations and the condition check is repeated.

Action 11. Determination of the required computational resources of the system for evaluation.

System load is additionally determined to prevent looping of computations in Actions 1–10 of this method and increase computational efficiency. If the defined threshold of computational complexity is exceeded, the number of software and hardware resources that need to be additionally involved is determined using the method proposed in the work [20].

5. 2. Example of applying the proposed method for evaluating the parameters of specialized hierarchical systems

A simulation was conducted to evaluate the technical characteristics of a specialized hierarchical system under the initial conditions specified in Section 4 to determine the effectiveness of the proposed method. The purpose of the simulation was to compare the accuracy, processing speed, and adaptability of the proposed approach with standard evaluation methods. The proposed method uses a convolutional artificial neural network with mechanisms for adaptive learning, error refinement, and dynamic management of computational resources.

The simulation results are presented in Table 1, which compares the effectiveness of different methods for evaluating technical characteristics.

As can be seen from Table 1, the efficiency of assessing the parameters of specialized hierarchical systems is achieved at the level of 15–18% due to the use of additional procedures and ensuring the reliability of the decisions made at the level of 0.9.

Table 1

Evaluation of the effectiveness of the proposed method for assessing the technical characteristics of specialized hierarchical systems

Approach name	Completeness of assessment	Accuracy	Sensitivity	Average value
Densenet 201	0.6763	0.4943	0.4985	0.4935
Densenet 121	0.9623	0.8689	0.8690	0.8688
MobileNetV2	0.9289	0.9295	0.9289	0.9287
DenseNet-SEGR	0.9588	0.9514	0.9511	0.9512
Gradient Boosting Classifier	0.92021	0.91128	0.9003	0.91449
KNN	0.8736	0.8839	0.88529	0.9003
LSTM	0.7981	0.8005	0.8271	0.8322
RNN	0.8012	0.8162	0.8129	0.8127
CNN	0.9437	0.9405	0.9431	0.9462
Proposed method	0.9611	0.9609	0.9681	0.9652

6. Discussion of the method results in the evaluation of specialized hierarchical systems parameters

A solution to the research problem has been proposed, which consists of improving the efficiency of evaluating specialized hierarchical systems by developing a method for assessing their technical characteristics using artificial intelligence.

The advantages of the proposed method are due to a combination of interconnected procedures, structurally and logically linked, which allow for:

– verification of the topology and parameters of specialized hierarchical systems considering the degree of uncertainty of the initial data about the known information (action 2) through an improved monkey swarm algorithm, compared to the work [9]. This reduces the time required for the initial setup of specialized hierarchical systems during their primary configuration;

– verification of the topology and parameters of specialized hierarchical systems considering the degree of uncertainty of the initial data about the known information (action 2) using the improved monkey swarm algorithm, compared to works [10, 11];

– initial selection of individuals for tuning the convolutional artificial neural network using an improved genetic algorithm (action 3), which reduces solution search time and increases the reliability of the obtained results, compared to works [12, 13];

– an exploration of solution spaces for the problem of assessing the state of specialized hierarchical systems described by atypical functions through the use of an improved monkey swarm algorithm (actions 2, 3), compared to works [14, 15];

– memory tuning of the convolutional artificial neural network by the memory training procedure (action 5), which reduces the error in estimating parameters of specialized hierarchical systems, compared to works [14, 16];

– weight tuning of the convolutional artificial neural network, which increases the accuracy of parameter estimation of specialized hierarchical systems (action 7), compared to work [17];

– engagement of additional parameter adjustment mechanisms of the convolutional artificial neural network using the membership function modification procedure (action 8), compared to work [15];

– calculation of the necessary amount of computational resources to be engaged if calculations cannot be performed with available resources (action 12), compared to works [10, 12].

This method allows for:

– determining the optimal evaluation indicator of specialized hierarchical systems parameters according to a defined optimization criterion;

– identifying practical measures to improve the efficiency of parameter evaluation of specialized hierarchical systems;

– increasing the speed of parameter evaluation of specialized hierarchical systems.

The proposed approach is advisable to use in special-purpose information systems such as "Dzvin-AS", "Logistics-IT", and "Delta" for tasks including refining the characteristics of objects of interest and adjusting delivery routes for goods and services in the interests of the Defense Forces of Ukraine.

Limitations of the study include the necessity of having information about the degree of uncertainty regarding the parameters of specialized hierarchical systems evaluation and the need to consider the delay time for collecting and transmitting information from the components of specialized hierarchical systems.

The drawbacks of the proposed method include:

– loss of informativeness when evaluating specialized hierarchical systems parameters due to the construction of the membership function;

– lower accuracy in evaluating individual parameters of specialized hierarchical systems;

– loss of reliability of obtained decisions when evaluating parameters of specialized hierarchical systems due to searching for solutions in multiple directions simultaneously;

– higher computational complexity than other methods when evaluating parameters of specialized hierarchical systems due to advanced procedures for adjusting convolutional artificial neural network parameters.

Directions for further scientific research should include the development (improvement) of methods for increasing the efficiency and reliability of decision-making using artificial neural networks.

7. Conclusions

1. An implementation algorithm of the method has been defined, which, thanks to additional and improved procedures, allows to:

– verify the topology and parameters of specialized hierarchical systems, considering the degree of uncertainty in the initial data about the available information. Topology verification is achieved using the monkey swarm algorithm, while adjustment for data uncertainty is done through appropriate correction coefficients. This significantly reduces the time required for the initial setup of specialized hierarchical systems during their primary configuration;

– carry out the initial selection of individuals for tuning the convolutional artificial neural network using an improved genetic algorithm, which decreases solution search time and increases the reliability of the results;

– explore the solution spaces of the problem of assessing the state of specialized hierarchical systems, described by atypical functions, by employing the improved monkey swarm algorithm;

– configure the memory of the convolutional artificial neural network through a memory training procedure, which reduces the estimation error of the parameters of specialized hierarchical systems;

– adjust the weights of the convolutional artificial neural network to improve the accuracy of parameter estimation;

– modifying the membership function by adding additional parameter adjustment mechanisms for the convolutional artificial neural network.

2. An example application of the proposed method for assessing parameters of specialized hierarchical systems demonstrated an increase in decision-making efficiency by 15–18% due to the use of additional procedures while ensuring the reliability of decisions at a level of 0.9.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship, or any other nature that could have influenced the research and its results presented in this article.

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The manuscript has associated data available in a data repository.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in the creation of this work.

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