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IMPROVEMENT OF THE METHOD OF PARAMETRIC CONTROL OF THE STATE OF THE CONTROL OBJECT BASED ON THE IMPROVED FIREFLY ALGORITHM

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The problem that is solved in the study is to increase the efficiency of decision-making regarding the state of the control object while ensuring a given reliability, regardless of the object's hierarchy. The object of the study is decision support systems. The subject of the study is the process of assessment and parametric control of the state of the control object using the firefly algorithm. The hypothesis of the study is an increase in the efficiency of assessing the state of the control object with a given reliability. In the course of the study, an improved method of parametric control of the control object based on the improved firefly algorithm was proposed. General provisions of artificial intelligence theory were used for solving the problem of object state analysis and subsequent parametric control in intelligent decision support systems.

The essence of improvement is to use the following procedures:

– taking into account the type of uncertainty about the state of the control object (complete uncertainty, partial uncertainty and complete awareness);

– taking into account the noise of data on the state of the control object. Data noise refers to the degree of information distortion created by the enemy's electronic and cyber warfare;

– using the improved firefly algorithm to find the path metric while assessing the state of the control object;

– deep learning of the synthesized ants using evolving artificial neural networks.

The application of the proposed method is presented on the example of assessing the state of the operational situation of a group of troops (forces). The specified example showed a 17–20 % increase in the efficiency of data processing using additional improved procedures

Keywords: control object, firefly algorithm, data noise, evaluation efficiency, reliability of decisions

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1. Introduction

The increase in the volumes of information circulating in various information collection, processing and transmission systems leads to significant use of hardware computing resources. The armed forces of technically developed countries have integrated decision-making architectures based on [1–8]:

– artificial intelligence and nanotechnology;

– effective processing of large amounts of information;

– multifunctional processors with real-time decision support;

– data compression technologies to increase processing speed.

The use of information systems with elements of artificial intelligence will increase the efficiency of operations (combat actions), affect the doctrine, organization and methods of application of groups of troops (forces).

At the same time, increasing the dynamics of operations, growing the number of various sensors and the need to integrate them into a single information space create a number of problems:

– implemented algorithms for determining correlations between events do not fully take into account the reliability of intelligence sources and information in the dynamics of hostilities;

– forms of information presentation complicate its transmission through communication channels;

– limited computing power of hardware;

– limited bandwidth of data transmission channels;

– radio-electronic suppression of SW and USW radio communication channels and cybernetic impact on information systems;

– transition to the principle of evaluating monitoring objects "everything affects everything at once", which covers the aggregate network and computing resources of all types of armed forces.

That is why it is necessary to develop algorithms (methods and techniques) that can assess the state of the control object from various sources of intelligence information in a limited time and with high reliability.

Given the above, an urgent scientific task is to improve the method of parametric control of the state of the control object based on the improved firefly algorithm, which would increase the efficiency of decisions regarding the control of the parameters of the control object with a given reliability.

2. Literature review and problem statement

The work [9] presents a cognitive modeling algorithm. The main advantages of cognitive tools are determined. The shortcomings of this approach include the lack of consideration of the type of uncertainty about the state of the analysis object.

The work [10] disclosed the essence of cognitive modeling and scenario planning. A system of complementary principles of building and implementing scenarios is proposed, different approaches to building scenarios are highlighted, the procedure for modeling scenarios based on fuzzy cognitive maps is described. The approach proposed by the authors does not take into account the type of uncertainty about the state of the analysis object and the noise of initial data.

The work [11] carried out an analysis of the main approaches to cognitive modeling. Cognitive analysis allows you to: investigate problems with fuzzy factors and relationships; take into account changes in the external environment and use objectively formed trends in the development of the situation to your advantage. At the same time, the issue of describing complex and dynamic processes remains unexplored in the paper.

The work [12] presents a method of analyzing large data sets. This method is focused on finding hidden information in large data sets. The method involves the operations of generating analytical baselines, reducing variables, detecting sparse features and specifying rules. The disadvantages of this method include the impossibility to take into account various decision evaluation strategies, the lack of consideration of the type of uncertainty of the input data.

The work [13] presents the mechanism of transformation of information models of construction objects to their equivalent structural models. This mechanism is intended to automate the necessary conversion, modification, and addition operations during such information exchange. The shortcomings of the mentioned approach include the impossibility of assessing the adequacy and reliability of the information transformation process and appropriate correction of the obtained models.

The work [14] developed an analytical web platform to study the geographical and temporal distribution of incidents. The web platform contains several information panels with statistically significant results by territory. The disadvantages of the specified analytical platform include the impossibility to assess the adequacy and reliability of the information transformation process and high computational complexity. Also, one of the shortcomings of the mentioned study is the fact that the search for a solution is not unidirectional.

The work [15] developed a method of fuzzy hierarchical assessment of library service quality. The specified method allows evaluating the quality of libraries based on a set of input parameters. The disadvantages of the specified method include the impossibility to assess the adequacy and reliability of the assessment and, accordingly, determine the assessment error.

The work [16] carried out an analysis of 30 algorithms for processing large data sets. Their advantages and disadvantages are shown. It was found that the analysis of large data sets should be carried out in layers, take place in real time and have the opportunity for self-learning. The disadvantages of these methods include high computational complexity and the inability to check the adequacy of the obtained estimates.

The work [17] presents an approach for evaluating input data for decision support systems. The essence of the proposed approach consists in clustering the basic set of input data, analyzing them, after which the system is trained based on the analysis. The disadvantage of this approach is the gradual accumulation of assessment and training errors due to the lack of an opportunity to assess the adequacy of decisions made.

The work [18] presents an approach to processing data from various sources of information. The disadvantages of this approach include the low accuracy of the obtained estimate and the inability to verify it.

The work [19] carried out a comparative analysis of existing decision support technologies, namely: analytic hierarchy process, neural networks, fuzzy set theory, genetic algorithms and neuro-fuzzy modeling. The advantages and disadvantages of these approaches are indicated. The scope of their application is defined. It is shown that the analytic hierarchy process works well if the initial information is complete, but due to the need for experts to compare alternatives and select evaluation criteria, it has a high share of subjectivity. The use of fuzzy set theory and neural networks is justified for problems of forecasting under risk and uncertainty conditions.

The work [20] developed a method of structural and objective analysis of the development of weakly structured systems. An approach to the study of conflict situations caused by contradictions in the interests of subjects that affect the development of the studied system and methods of solving poorly structured problems based on the formation of scenarios for the development of the situation is proposed. At the same time, the problem is defined as the non-compliance of the existing system state with the required one set by the control entity. The disadvantages of the proposed method include the problem of local optimum and the inability to conduct a parallel search.

The work [21] presents a cognitive approach to the simulation of complex systems. The advantages of the approach, which allows describing the hierarchical components of the system, are shown. The shortcomings of the proposed approach include the lack of consideration of system computing resources.

An analysis of the works [9–21] showed common shortcomings of the above studies:

– the lack of possibility to form a hierarchical system of indicators;

– the lack of consideration of computing resources of the system;

– the lack of mechanisms for adjusting the system of indicators during the assessment;

– the failure to take into account the type of uncertainty and noise of data on the state of the control object, which creates errors while assessing its real state;

– the lack of deep learning mechanisms for knowledge bases;

– the lack of consideration of computing (hardware) resources available in the system.

The problem that needs to be solved in the study is to increase the efficiency of parametric control of the state of the control object while ensuring the specified reliability, regardless of the hierarchy of the object.

For this purpose, it is proposed to improve the method of parametric control of the state of the control object based on the improved firefly algorithm.

3. The aim and objectives of the study

The aim of the study is to improve the method of parametric control of the state of the control object based on the improved firefly algorithm. This will allow increasing the efficiency of decisions regarding the state of the control object with a given reliability and developing subsequent management decisions. This will make it possible to develop software for intelligent decision support systems in the interests of combat management of the actions of troops (forces).

To achieve the aim, the following objectives were set:

– to develop a mathematical model of parametric optimization based on the improved firefly algorithm in special-purpose information systems;

– to determine the algorithm for implementing the method;

– to give an example of the application of the proposed method in the analysis of the operational situation of a group of troops (forces).

4. Materials and methods

The object of the study is decision support systems. The subject of the study is the process of assessment and parametric control of the state of the control object using the firefly algorithm. The hypothesis of the study is an increase in the efficiency of assessing the state of the control object with a given reliability.

In the course of the study, the general provisions of artificial intelligence theory were used to solve the problem of analyzing the state of objects in intelligent decision support systems. Thus, artificial intelligence theory is the basis of this study. The study uses an improved firefly algorithm and evolving artificial neural networks. The simulation was carried out using MathCad 2014 software (USA) and an Intel Core i3 PC (USA).

5. Results of the study on improving the method of parametric assessment of the control object based on the improved firefly algorithm

5. 1. Mathematical model of parametric optimization based on the improved firefly algorithm

The mathematical model of any object is a formalized description of a quality criterion that ensures the fulfillment of specified functions, requirements, etc. [6, 7, 22–27].

In order to develop a method of parametric assessment of the control object, it is proposed to develop a mathematical model of simulating a colony of fireflies.

During the development of the algorithm model, the life of a swarm of fireflies was not simulated, which uniquely copied the existing natural ecosystem, but a colony simulation was used as an optimization tool, in which the system is slightly different from the natural one.

Therefore, for the formal description of the model, we use the concept of "agent" instead of "firefly". While initializing the search, all agents are randomly distributed in the search space of the objective function.

Each agent releases a certain amount of luciferin and has its own decision-making area. Agent i considers another agent j as a neighbor if it is within the radius of agent i search neighborhood and agent j luciferin level is higher than that of agent i, i.e. $l_j>l_i$. The local decision-making area is determined by the radius of the search neighborhood for each i-th agent.

Using a probabilistic mechanism, each agent selects a neighboring agent with a higher luciferin level than its own and moves in its direction. In other words, each agent moves in the direction of the agent with a higher glow level.

The glow intensity of each agent is determined by the value of the objective function in the current position. The higher the glow intensity, the greater the value of the objective function [13]. In addition, the radius of each agent's search neighborhood depends on the number of agents in that search area. If there is a small number of agents in the search neighborhood, its radius increases. Otherwise, the search radius is reduced. This algorithm has the following global steps: initial distribution of agents in the search space, updating the luciferin level, moving of agents to a more promising search area, updating the search radius of each agent [14–16].

The task of parametric optimization of the state of the control object is to find such internal parameters of construction, at which the initial parameters would have the given characteristics, the construction elements and the method of their connection would remain unchanged.

Let the control object have n controlled parameters forming the vector $X=(x_1, x_2,..., x_n)$. Let's define the objective function by $F(X)$ and the domain of its definition by XO. Vector X

determines the coordinates of a point in the *XO* definition area. If the elements of the vector *X* take only discrete values, then *XO* is a discrete set of points and the optimization problem belongs to the field of discrete programming.

The purpose of algorithms for solving the parametric optimization problem is to determine such a vector of control parameters (influences) in which a given objective function acquires a minimum value.

In the process of developing the mathematical model, it is necessary to determine the object parameters that affect the criterion of optimality. Then, the parametric, discretization and functional constraints imposed on the parameters of the control object are defined [5, 6].

Parametric are the constraints of the following form:

$$x_i' \le x_i \le x_i'', \qquad (1)$$

where x_i is the *i*-th object parameter; x_i' and x_i'' are the min and max values of the *i*-th parameter, respectively.

Discretization constraints are as follows:

$$x_j = \{x_{j1}, x_{j2}, ..., x_{jm}\}, \qquad (2)$$

where x_j is the *j*-th control object parameter; x_{jk} are the allowed values of the *j*-th parameter (k=1, 2, ... m). Such restrictions are imposed on the values of the parameters or in connection with their physical nature [28–32].

Functional restrictions imposed on the parameters of control objects are the conditions for linking their values. These restrictions are:

$$g_i(x) \le 0; \quad g_j(x) = 0; \quad g_k(x) < 0. \qquad (3)$$

Functional limitations in the optimal object control can be the conditions of control system immunity, survivability and mobility. These conditions provide the desired values of certain technical characteristics [7–9].

From (1)–(3), it can be concluded that the expressions describe processes in the control object, determine the controlled parameters of the object and also describe the cause-and-effect relationships between them. The specified description is universal and describes the control object taking into account the hierarchy and individual specifics of each control object.

5. 2. Algorithm for implementing the method of parametric control of the object state

5. 2. 1. Algorithm for implementing the method of parametric control of the control object

The method of parametric control of the state of the control object consists of the following sequence of actions:

Step 1. Initialization of input parameters. At this stage, initial parameters are introduced for calculating the state of the control object and justifying subsequent management decisions.

Step 2. Allocation of the initial (current) population. The initial allocation of agents takes into account the type of uncertainty about the state of the control object. Unlike the classic firefly algorithm, the initial allocation takes into account the type of uncertainty about the state of the control object and the degree of data noise. The corresponding correction factors are given in [2]. Allocation of the initial (current) population of solutions in the search space in the parametric control problem consisting of *n* agents.

Initially, all agents have the same amount of luciferin. At each iteration, the level of luciferin is updated, and then the agent's position in space changes based on the given rules. The state of agent $s_i \epsilon i[l{:}|S|]$ is determined by the following variables: X_i – the current state of the agent in the search space; l_i – the agent glow level; r_i – the neighborhood radius.

Agent s_i is considered a neighbor of agent $s_j \epsilon i$, $j[l{:}|S|]$, $i \ne j$ if the following conditions are met: the Euclidean distance between the agents does not exceed the current radius r_i; the current glow level of agent s_j exceeds the same level of agent s_i, $l_j > l_i$. If the agent has several neighbors, then the agent randomly chooses one of them with a probability proportional to their glow levels (roulette rule).

Suppose that agent s_i chose agent s_j.

Then the new position of agent s_i is determined by the formula:

$$X_i^{'} = X_i + \lambda \frac{X_j - X_i}{\|X_j - X_i\|}, i, j\left[l : |S|\right], i \ne j, \qquad (4)$$

where λ is the constant step value (free parameter of the algorithm).

The new neighborhood radius of agent s_i is determined by the expression:

$$r_i^{'} = \min\left(r_{\min}, \max\left(\left(0, r_i + \varepsilon\left(n - |N_i|\right)\right)\right)\right), i \in \left[1 : |S|\right], \qquad (5)$$

where N_i is the current set of neighbors of agent s_i; $r_{\min}$ is the minimum permissible neighborhood radius; *n* is the desired number of neighbors.

Step 3. Updating the luciferin level depends on the agent's position in space (the value of its objective function). All agents at the initial iteration have the same luciferin level, so the value of each agent's objective function depends on its position in the search space.

The luciferin level of each agent increases in proportion to the measured characteristics of the agent (temperature, radiation level). In terms of optimization, this is the objective function. To simulate the process of decay of a fluorescent substance, part of luciferin is subtracted.

Calculation of the luciferin level $l_i(t)$ (glow level) of the *i*-th agent at time *t* is shown below:

$$l_j(t+1) = (1-\rho) l_j(t) + \gamma J_j(t+1), \qquad (6)$$

where ρ is the attenuation factor of the luciferin level for modeling the decay process of a fluorescent substance (0<ρ<1), γ is the attractiveness factor of the agent, J_j is the value of the objective function of the *j*-th agent at time *t*.

Step 4. Each agent selects the agent within the search neighborhood radius r_i, whose luciferin level is higher than its own. The problem $N_i(t)$ is the set of neighbors of the *i*-th agent at time *t*, r_i is the radius of the search neighborhood of the *i*-th agent at time *t*.

Step 5. While updating its position in the search space, each agent, based on a probabilistic mechanism, moves in the direction of the agent whose luciferin level is higher than its own.

For each *i*-th agent, the possibility to move in the direction of agent *j* is determined by the formula:

$$p_{ij}(t) = \frac{l_j(t) - l_i(t)}{\sum_{k \in N_i(t)} l_k(t) - l_i(t)}, \qquad (7)$$

where $j\epsilon N_i(t)$, $N_i(t)=\{j:d_{ij}(t)\langle r_d^i(t)\}$; $l_i(t)\langle l_j(t), d_{ij}(t)$ is the Euclidean distance between agents i and j at time t; $l_j(t)$ is the luciferin level of agent j at time t; $r_d^i(t)$ is the local decision domain of agent i that changes at time t.

Step 6. Agent i, using the roulette wheel method, chooses agent j and moves in its direction. Then, the updated position of agent i is determined by the formula:

$$x_i(t+1)=x_i(t)+st*\left\{\frac{x_j(t)-x_i(t)}{\left\|x_j(t)-x_i(t)\right\|}\right\}, \quad (8)$$

where st is the step size.

Step 7. Updating the search neighborhood radius r_d^i using the formula:

$$r_d^i(t+1)=\min\left\{r_s,\max\left\{0,r_d^i(t)+\beta\left(n_t-\left|N_i(t)\right|\right)\right\}\right\}, \quad (9)$$

where β is the constant parameter and n_t is the parameter to control the number of neighboring agents.

The values ρ, γ, st, β, n_t are the algorithm parameters determined experimentally.

Step 8. Training of agents. At this stage, agents are trained using the method of training evolving artificial neural networks proposed in [2].

Step 9. Identifying the need for additional computing resources. At this stage, using the approach proposed in [33], the necessary amount of computing resources, which must be involved in the assessment and parametric control of the state of the control object, is calculated.

End of the algorithm.

5. 3. Example of applying the proposed method in the state analysis and parametric control of an operational group of troops (forces)

Modeling of the evaluation method based on the firefly algorithm was carried out in accordance with the algorithm and expressions (1)–(8). Simulation of the proposed method was made in the MathCad 14 software environment (USA). The task of the simulation was to assess the elements of the operational situation of the group of troops (forces).

Modeling was carried out for the assessment of the state of the control object and subsequent parametric control. The operational grouping of troops (forces) was considered as an object of assessment and control. The operational grouping of troops (forces) is formed on the basis of an operational command with a typical composition of forces and means according to the wartime staff and with a range of responsibility in accordance with current regulations.

Input data for the parametric control of the operational group of troops (forces) using the proposed method:

– the number of sources of information about the operational grouping of troops (forces) – 3 (radio monitoring means, earth remote sensing facilities and unmanned aerial vehicles). To simplify the modeling, the same number of each tool was taken – 4 tools each;

– the number of information features to determine the state of the operational grouping of troops (forces) and parametric control – 200. Such parameters include: affiliation, type of organizational and staff formation, priority, minimum width along the front, maximum width along the front. The number of personnel, the minimum depth along the flank, the maximum depth along the flank, the total number of personnel, the number of weapons and military equipment samples, the number of types of weapons and military equipment samples and the number of communication devices), etc. are also taken into account;

– options of organizational and staff formations – company, battalion, brigade.

The simulation results made it possible to determine the dependence of the algorithm operating time on the input parameters. The graph of the algorithm operating time versus the amount of input data is presented in Fig. 1.

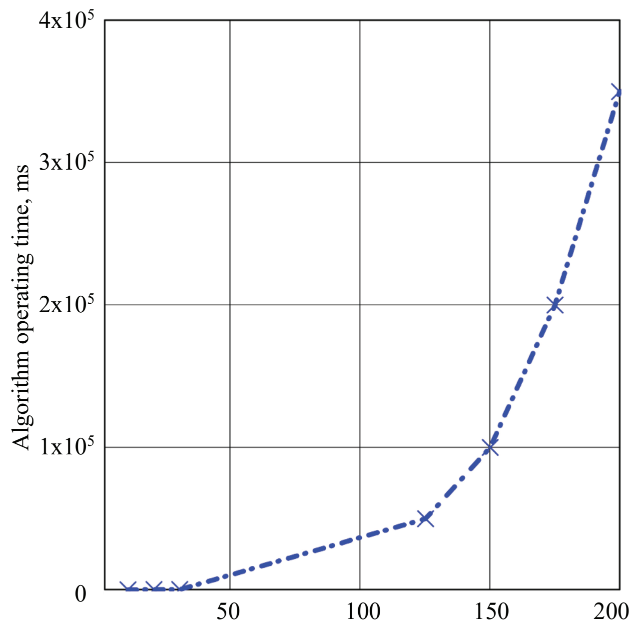

Fig. 1. Time complexity of the algorithm depending on the number of input parameters

The time complexity of the algorithm was $O(n^2)$, where n is the number of input parameters. The dependence of the algorithm's operating time on the number of iterations was also considered. The simulation results are shown in Fig. 2.

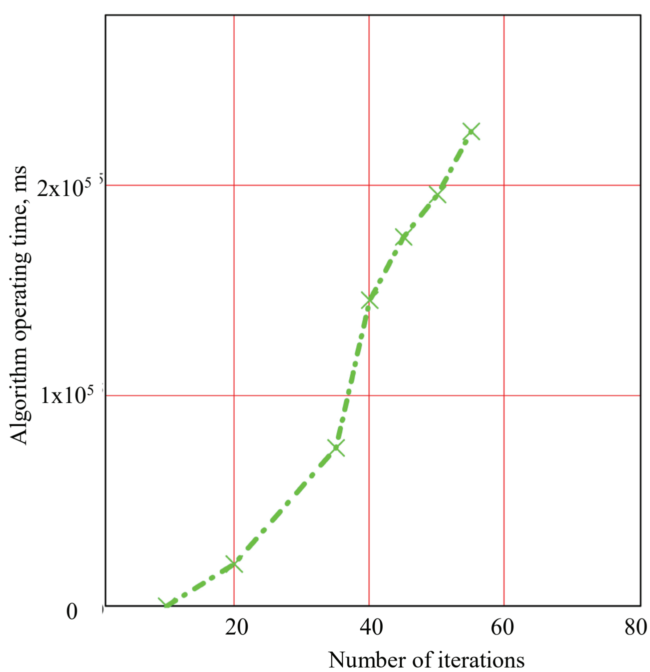

Fig. 2. Dependence of the problem solving time on the number of iterations

This dependence is equal to $O(n^4)$, where n is the number of iterations.

To determine the effectiveness of the proposed method, studies were conducted in comparison with other swarm methods, namely the ant colony optimization algorithm (ACO) and particle swarm optimization (PSO) method. The results of the experiments are given in Table 1.

Fig. 1, 2 show that the developed method outperforms the ACO and PSO algorithms in terms of the quality of the obtained solutions. In addition, the method operates with fewer parameters and, accordingly, does not require large computing resources.

The main advantage of the method based on firefly swarm behavior is that it sharply decreases the probability of falling into the local optimum and reduces the time due to parallelization. At each iteration, it is equal to the search time in the most promising block.

According to the analysis of the data given in Table 1, the proposed method has an acceptable computational complexity.

In the range from 50 to 100, the proposed method becomes more efficient in terms of operating time compared to other algorithms (faster than the particle swarm optimization method by 72.9–81.6 % and the ant colony optimization method by 7–9.1 %. The proposed method provides adequate solutions with a complex hierarchical structure of the monitoring object. The effectiveness of the proposed method is on average from 17 to 20 % with different hierarchies of the control object.

Table 1

Comparative analysis of swarm algorithms

Number of intermediate solution points	Particle swarm optimization method	Ant colony optimization algorithm	Proposed method
N	T, s	T, s	T, s
5	0.282	0.276	0.232
10	0.723	0.4	0.423
15	6.641	0.999	1.1
20	10.7	2.5	2.7
30	21.3	4.5	4.7
40	42	7.9	7.4
50	56	10.1	9.2
100	120	17.6	19.6
200	727	74.2	80.2
Complexity	$O\left(\frac{(N-1)!}{4}\right)=O(N!)$	$O(N^2+N)=O(N^2)$	$O(n^2)$

6. Discussion of the results of the development of the parametric control method

The results of increasing the efficiency of parametric control are explained by the use of the improved firefly algorithm in contrast to classical empirical expressions. The firefly algorithm is not used in its classical form, but by improving it with the help of evolving artificial neural networks.

The main advantages of the proposed parametric control method are as follows:

– it has a flexible hierarchical structure of indicators, which allows reducing the problem of multi-criteria evaluation of alternatives to one criterion or using expressions (1)–(3) to select a vector of indicators;

– unambiguity of the obtained assessment of the state of the control object, expressions (1)–(9);

– universality of application due to adaptation of the system of indicators during operation;

– it does not accumulate learning errors due to the use of learning procedures (step 8);

– taking into account the type of uncertainty and noise of the initial data while constructing the path metric (step 2);

– high reliability of the obtained solutions while searching for a solution in several directions (step 4–8);

– the ability to determine the need to involve additional network hardware resources (step 9).

The disadvantages of the proposed method include:

– lower accuracy of assessment and parametric control for a single parameter;

– loss of credibility of the obtained solutions while searching for a solution in several directions at the same time;

– lower assessment accuracy compared to other assessment methods.

The method makes it possible:

– to perform object state assessment and parametric control;

– to determine effective measures to improve control efficiency;

– to increase the speed of object state assessment and management decisions regarding the control of its parameters;

– to reduce the use of computing resources of decision support systems;

– to determine the need to involve additional computing resources.

The proposed method solves the problem of improving the efficiency of assessing the state of the control object and controlling its parameters using the synthesized firefly algorithm.

It is advisable to apply this method in decision support systems for assessing the state of the object and its parametric control as a software product. It is proposed to be used in the interests of combat management of the actions of troops (forces).

The limitations of the study are:

– the need to know the completeness of information about the state of the control object for determining correction factors;

– the need to know the amount of computing resources of the decision support system.

It is advisable to use the proposed approach for solving the problems of evaluating complex and dynamic processes and their parametric control, characterized by a high degree of complexity.

This study is a development of research aimed at developing methodological principles for increasing the efficiency of information and analytical support, published earlier [2, 4–6, 23, 34–36].

Areas of further research should be aimed at reducing computing costs while processing various types of data in special-purpose systems.

7. Conclusions

1. The mathematical model of parametric optimization based on the improved firefly algorithm in special-purpose information systems was developed. This formalization allows you to describe the processes taking place in

special-purpose information systems while solving the problems of parametric control of the object state. This approach makes it possible to effectively parallelize the process of searching for an optimal solution, which partially eliminates the problem of prior convergence of the algorithm and control the search process for finding optimal and quasi-optimal solutions. As a criterion for the effectiveness of the specified method, the efficiency of decision-making regarding the parametric control of the object state with a given reliability was chosen. This makes it possible to create a hierarchical description of a complex process by levels of generalization and conduct an appropriate analysis of its state.

2. The algorithm for implementing the method is defined, which allows you:

– to take into account the type of uncertainty and noise of data;

– to take into account available computing resources of the control object state analysis system;

– to determine the necessary computing resources of the system for an operational assessment of the object state;

– to carry out accurate training of individuals of a swarm of fireflies using the expressions developed in [2].

3. The application of the proposed method is given on the example of assessing the state of the operational situation of a group of troops (forces). The specified example showed a 17–20 % increase in the efficiency of data processing using additional improved procedures. The obtained data made it possible to conclude that the time complexity of the algorithm does not exceed the polynomial complexity.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship, or any other, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has associated data in the data repository.

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