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Article

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Reference: Shyshatskyi, Andrii/Pluhina, Tetiana et. al. (2023). The development of the method of evaluation of complex hierarchical systems based on improved alforitm of particle swarm. In: Technology audit and production reserves 6 (2/74), S. 15 - 19.
https://journals.uran.ua/tarp/article/download/288055/282018/665589.
doi:10.15587/2706-5448.2023.288055.

UDC 355/359
DOI: 10.15587/2706-5448.2023.288055

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THE DEVELOPMENT OF THE METHOD OF EVALUATION OF COMPLEX HIERARCHICAL SYSTEMS BASED ON IMPROVED ALFORITM OF PARTICLE SWARM

The scientific task, which is solved in the research, is to increase the efficiency of the evaluation of complex hierarchical real-time systems. Finding solutions to nonlinear optimization problems and especially global optimization problems is one of the most popular problems in computational mathematics. In applied problems, the objective function, as a rule, has a large number of variables, is not given in an analytical form and is calculated as some integral characteristic of a complex dynamic process. The development of effective methods, to a certain extent adaptive to the variability of the objective function, is especially relevant in connection with the development of computer technology and the possibility of using parallel computing systems. The conducted research was aimed at developing a method of evaluating complex hierarchical systems based on an improved particle swarm. At the same time, the object of research was complex hierarchical real-time systems. The subject of research is the functioning of real-time hierarchical systems.

The novelties of the proposed method consist in:

– creating a multi-level and interconnected description of complex systems of hierarchical real-time systems;

– increasing the efficiency of decision making while evaluating complex systems of hierarchical real-time systems;

– solving the problem of falling into global and local extremes while assessing the state of complex systems of hierarchical real-time systems;

– the possibilities of directed search by several individuals of the particles swarm in a given direction, taking into account the degree of uncertainty;

– the possibilities of re-analysis of the state of complex systems of hierarchical real-time systems;

– avoiding the problem of loops while visualizing the state of the national security system in real time.

It is advisable to implement the specified method in specialized software, which is used to analyze the state of complex systems of hierarchical real-time systems and make management decisions.

Keywords: *complex hierarchical real-time systems, responsiveness, particle swarm, global and local optimization.*

Received date: 24.07.2023
Accepted date: 18.09.2023
Published date: 29.09.2023

How to cite

Shyshatskyi, A., Pluhina, T., Plekhova, G., Binkovska, A., Pronin, S., Stasiuk, T., Nalapko, O., Protas, N., Pliushch, T., Burlak, D. (2023). The development of the method of evaluation of complex hierarchical systems based on improved alforitm of particle swarm. Technology Audit and Production Reserves, 6 (2 (74)), 15–19. doi: https://doi.org/10.15587/2706-5448.2023.288055

1. Introduction

Finding solutions to nonlinear optimization problems and especially global optimization problems is one of the most popular problems in computational mathematics. In applied problems, the objective function, as a rule, has a large number of variables, is not given in an analytical form and is calculated as some integral characteristic of a complex dynamic process.

The development of effective methods, to some extent adaptive to the variability of the objective function, is especially relevant in connection with the development of computer technology and the possibility of using parallel computing systems. General basic provisions on this topic are given in works [1–3], where original approaches and reviews of various numerical methods and their modifications for solving optimization and global optimization tasks are considered. Also, in works [4, 5], which present methods based on uneven coatings, implemented as parallel computing algorithms for global optimization.

The work [6] presents a method of analyzing large data sets. The specified method is focused on finding hidden information in large data sets. The method includes the operations of generating analytical baselines, reducing

ISSN 2664-9969

variables, detecting sparse features and specifying rules. The disadvantages of this method include the impossibility of taking into account different decision-making evaluation strategies, the lack of taking into account the type of uncertainty of the input data.

The work [7] gives an example of transformation mechanism of information models of construction objects to their equivalent structural models. This mechanism is designed to automate the necessary conversion, modification and addition operations during such information exchange. The disadvantages of the mentioned approach include the impossibility of assessing the adequacy and reliability of the information transformation process and the appropriate correction of the obtained models.

The work [8] developed an analytical web-platform for the research of 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 of assessing the adequacy and reliability of the information transformation process, and high computational complexity. Also, one of the shortcomings of the mentioned research should be attributed to the multidirectionality of the search for a solution.

The work [9] developed a method of fuzzy hierarchical evaluation 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 of assessing the adequacy and reliability of the assessment and, accordingly, determining the assessment error.

The work [10] carried out an analysis of 30 algorithms for processing large data sets. Their advantages and disadvantages are shown. It has been established 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 their high computational complexity and the impossibility of checking the adequacy of the obtained estimates.

The work [4] presents an approach for evaluating input data for decision making support systems. The essence of the proposed approach consists in the clustering of the basic set of input data, their analysis, after which the system is trained based on the analysis. The disadvantages of this approach are the gradual accumulation of assessment and training errors due to the lack of an opportunity to assess the adequacy of the decisions made.

The following deterministic, stochastic and heuristic methods are most in demand in software applications:
- the methods based on various variants of the genetic algorithm (GA), evolutionary calculations and their modifications;
- the methods based on a particles swarm – Particle Swarm Optimization (PSO) with the introduction of adaptive modifications;
- the methods of random search and annealing simulation;
- the method of averaging coordinates and methods based on inverse regressions, etc.

Existing mathematical methods of global optimization are poorly adapted to real-time dynamic systems and do not have sufficient universality, which prevents their widespread implementation.

The aim of the research is the development of a method for evaluating complex hierarchical systems based on an improved particle swarm.

The object of the research is the complex hierarchical real-time system.

The subject of the research is functioning real-time hierarchical system.

2. Materials and Methods

The research problem is to increase the efficiency and reliability of decision making regarding the state of real-time hierarchical systems. Modeling was carried out using MathCad 14 (USA). Aser Aspire based on the AMD Ryzen 5 processor was used as hardware. The particle swarm algorithm was chosen as the basic mathematical apparatus in the proposed research.

3. Results and Discussion

3.1. The development of a method for evaluating complex hierarchical systems based on an improved particle swarm. In this work, a method for evaluating complex hierarchical systems based on an improved particle swarm based on a combination of the coordinate averaging method and PSO is proposed.

It allows the coordinate averaging method to move from the random selection of test points to the use of current coordinates of a swarm of particles, the collective movement of which occurs adaptively, adapting to the nature of the change in the target function. While moving a swarm of particles, to take into account their displacement in the direction of the found averaged center based on the coordinate averaging method. An additional mechanism that accelerates the convergence process of the hybrid algorithm is the inclusion in the calculation process of several steps of the Hook-Jeeves procedure, which specify the current coordinates of the best and/or worst particle in the swarm.

In this work, the main attention is paid to a number of «zero-order» methods. For approximate estimates of the variability of the objective function, the maximum values obtained as the ratio of the difference of the objective function values to the distance for all pairs of sample points are used (the lower estimate of the Lipshitz constant).

A bounded continuous function $f(x):\Omega\rightarrow\mathbb{R}$ is considered, where $x=(x_1, x_2, \ldots, x_n)\in\Omega\subset\mathbb{R}^n$. The set Ω is the domain of admissible values of the variables and in the simplest case represents an n-dimensional parallelepiped with given sides, $[x_i^{[0]}-d_i, x_i^{[0]}+d_i]$, $i=1,2,\ldots,n$.

It is necessary to find an approximate value of the global minimum f^* and at least one point x^* in which this value is reached with a given permissible error ε_f for the values of the objective function:

$$f_{\min}=\min f(x),\ x\in\Omega,\ f^*-\varepsilon_f\le f_{\min}\le f^*,\ f^*=f(x^*). \quad (1)$$

The calculation procedure for finding the approximate value of the coordinates of point x^* in the coordinate averaging method is built on the basis of an iterative process, which in a continuous form has such form [5]:

$$x_i^{[k+1]}=\left(\int_{\Omega^{[k]}} x_i p_s^{[k]}(x)\mathrm{d}x\right)\cdot\iota,\ i=1,2,\ \ldots,n, \quad (2)$$

$$p_s^{[k]}(x)=\frac{P_s^{[k]}(f(x))}{\int\limits_{\Omega^{[k]}} P_s^{[k]}(f(x))\mathrm{d}x},\qquad(3)$$

where k is the step number of the computational process; ι is the degree of uncertainty of the state of a complex dynamic real-time system (the value of uncertainty takes a value from 0 to 1); $\Omega^{[k]}$ is the coordinate averaging area at step k. It introduces a sequence of continuous functions $P_s(y)$, $s=1, 2, 3,...$, such that $\forall y\in\mathbb{R}$ value $P_s(y)\geq 0$ and for the sequence of the form $P_s(y)/P_z(y)$ the condition of monotonic unlimited growth is fulfilled when the selectivity parameter s and any fixed values of y, z with the condition $y<z$ increases. Examples of the functions $P_s(y)$, in particular, are the functions $\exp(-sy)$, s^{-y}, y^{-s} and the class of functions of the form $(1-y^r)^s$ for $y\in[0,1]$, $r=1,2,3,...$. For the following examples of numerical minimization, the function $(1-y^2)^s$ is used.

As s increases, the steepness of the cores $p_s^{[k]}$ increases, which in turn leads to an increase in the weight of the coordinates that correspond to the best values of the objective function (OF) and in the latter case, the sequence of averaged coordinates converges to a global minimum (the corresponding convergence theorem is proved in the work [5]).

For the numerical implementation of the coordinate averaging method, one of the effective ways to increase the accuracy of the calculation of integrals (2) is to successively increase the number of test points $x^{(j)[k]}$, $j=1,2,...,M^{[k]}$, at the k-th stage of the iteration process, so $M^{[k]}\geq M^{[k-1]}$. In order not to accidentally exclude the point of the global minimum, the area of averaging $\Omega^{[k]}$ in this case, it can be considered both adaptively variable [5] and constant.

In the proposed modification of the algorithm for iterative calculation of averaged coordinates, an adaptive displacement of the test points is introduced, which is implemented as the movement of a swarm of particles in the PSO method with FDR (fitness-distance ratio based PSO) modification [5]. At the same time, an additional elimination of the swarm particles to the found center of the averaged coordinates is introduced, which introduces a new factor of information exchange between particles into the PSO algorithm and additional stabilization of the process of collective search by the swarm of particles for the global minimum of the OF.

While calculating the integrals in formulas (2), (3), the summation of the values of the integral expressions on a set of test points is used, taking into account the volumes of the subregions of the discretization of the integration region $\Omega^{[k]}$.

In the proposed hybrid algorithm, the coordinates of the test points are identified with the coordinates of the particle swarm, which change during the collective search for the global minimum. At the beginning of the calculation process, random numbers with an uniform distribution on the intervals are set in the nodes of some calculation grid or generated by the sensor $[x_i^{[0]}-d_i, x_i^{[0]}+d_i]$, $i=1,2,...,n$. In the discrete form, relations (2), (3) take the following form:

$$x_i^{[k+1]}=\sum_{j=1}^{M^{[k]}} x_i^{(j)[k]} p_s^{[k]}\left(x^{(j)[k]}\right)V^{(j)[k]},\ i=1,2,...,n,\qquad(4)$$

$$p_s^{[k]}\left(x^{(j)[k]}\right)=\frac{P_s^{[k]}\left(g^{[k]}\left(x^{(j)[k]}\right)\right)}{\sum\limits_{j=1}^{M^{[k]}} P_s^{[k]}\left(g^{[k]}\left(x^{(j)[k]}\right)\right)V^{(j)[k]}},\qquad(5)$$

where $V^{(j)[k]}$ corresponds to the n-dimensional volume while dividing the region $\Omega^{[k]}$ on the subdomain associated with the family of integration points $x^{(j)[k]}$, $j=1,2,...,M^{[k]}$. Here $g^{[k]}(x)$ are the auxiliary functions that scale the objective function $f(x^{(j)[k]})$ to the range [0, 1], which are defined as:

$$g^{[k]}\left(x^{(j)[k]}\right)=\frac{f\left(x^{(j)[k]}\right)-f_{\min}^{[k]}}{f_{\max}^{[k]}-f_{\min}^{[k]}},\qquad(6)$$

where

$$f_{\min}^{[k]}=\min\left(f\left(x^{(1)[k]}\right), f\left(x^{(2)[k]}\right),..., f\left(x^{(M^{[k]})[k]}\right)\right),$$
$$f_{\max}^{[k]}=\max\left(f\left(x^{(1)[k]}\right), f\left(x^{(2)[k]}\right),..., f\left(x^{(M^{[k]})[k]}\right)\right).$$

Assuming that for the test points – the current coordinates of the swarm of particles – in formulas (4), (5) during the implementation of the approximate integration, it is possible to choose subregions so that their values $V^{(j)[k]}$, $j=1,2,...,M^{[k]}$, were approximately equal, the calculation formulas are simplified to the form:

$$x_i^{[k+1]}=\sum_{j=1}^{M^{[k]}} x_i^{(j)[k]} p_s^{[k]}\left(x^{(j)[k]}\right),\ i=1,2,...,n,\qquad(7)$$

$$p_s^{[k]}\left(x^{(j)[k]}\right)=\frac{P_s^{[k]}\left(g^{[k]}\left(x^{(j)[k]}\right)\right)}{\sum\limits_{j=1}^{M^{[k]}} P_s^{[k]}\left(g^{[k]}\left(x^{(j)[k]}\right)\right)}.\qquad(8)$$

It should be noted that for the computational algorithm of coordinate averaging [5] a specific type of subregions of the discretization of the integration region $\Omega^{[k]}$ is not significant, therefore the use of simpler ratios (7), (8) instead of (4), (5) in the numerical implementation is fully justified.

The adaptive change of the coordinates of the swarm of particles during the transition to the $(k+1)$-th step is carried out according to the PSO scheme [4, 5, 10] and the component of the movement to the averaged center of coordinates is additionally introduced $x^{[k]}$ for each j-th swarm particle in the following form:

$$x^{(j)[k+1]}=x^{(j)[k]}+\alpha Y^{(j)[k]}+D^{(j)[k]}+U^{[0,\beta_0]}\otimes\left(x^{[k]}-x^{(j)[k]}\right),\qquad(9)$$

where $Y^{(j)[k]}$ is the inertial component of the movement of the j-th particle; $D^{(j)[k]}$ is the vector of the adaptive displacement of the j-th particle, which is determined by three components of the random displacement of this particle [6, 11, 12]:

$$D^{(j)[k]}=d_1^{(j)[k]}+d_2^{(j)[k]}+d_3^{(j)[k]},\qquad(10)$$

where

$$d_1^{(j)[k]}=U[0,\beta_1]\otimes\left(x_b^{(j)[k]}-x^{(j)[k]}\right),$$
$$d_2^{(j)[k]}=U[0,\beta_2]\otimes\left(x_g^{(j)[k]}-x^{(j)[k]}\right),$$
$$d_3^{(j)[k]}=U[0,\beta_3]\otimes\left(x^{(q(j))[k]}-x^{(j)[k]}\right).\qquad(11)$$

In formulas (9)–(11) the notations are used:

– $x_b^{(j)[k]}$ are the best coordinates of the j-th particle for k iterations, determined by the value of the objective function ($d_1^{(j)[k]}$ is the cognitive component of particle elimination);

– $x_g^{(j)[k]}$ are the coordinates of the best part in the swarm with the minimum value of the objective function for k iterations ($d_2^{(j)[k]}$ is the social component of particle elimination);
– $x^{(q(j))[k]}$ are the coordinates of the particle with the number $q(j)$, in the direction of which the rate of decrease of the objective function is the largest ($d_3^{(j)[k]}$ is the component of the variability of the target function by the local estimate of the Lipshitz constant);
– $U[0,\beta]$ is the vector with components of uniformly distributed random numbers in the interval $[0,\beta]$;
– $\otimes$ is the component-wise multiplication of vectors;
– coefficients $\alpha, \beta_m, m=0,1,2,3$ are the parameters adjusted by the hybrid computational algorithm.

Thus, relations (4)–(11) after specifying the type of nuclei $P_s^{[k]}(y)$ with increasing selectivity parameter s and assignment of specific values of coefficients $\alpha, \beta_m, m=0,1,2,3$, fully define a hybrid computing algorithm for global optimization based on coordinate averaging and particle swarm methods. The selection of coefficients of the numerical algorithm of global optimization can be carried out by meta-optimization [13, 14] and is beyond the scope of this work.

3.2. Results of the analysis and discussion of the results. 100 runs of the algorithm were carried out, acceptable accuracy (of the order of 10^{-2}) in the values of the coordinates of the best particle was achieved in 10–15 iterations and then a consistent concentration of particles on the outskirts of the global minimum occurred. It should be noted that the method is statistical and in order to obtain an «acceptable result by probability» it is necessary to conduct multiple launches of the software application with changed values of random vectors $U[0, \beta]$.

The transition to large dimensions of the variables leads to the need for an exponential increase in the number of sample points or particles in the swarm. The possibility of parallel calculations indicates the expediency of using several families of particle swarms in the algorithm.

Computational experiments on the minimization of the function (9) at $n=100$ showed that if the total number of particles is not increased, the hybrid algorithm leads to one of the local minima. This is explained by the fact that this local minimum has the widest area of attraction (the last addition in formula (9)), as a result of which, with greater probability, at least one of the particles falls into the specified area and exerts the maximum influence on the subsequent behavior of the particle swarm.

It should be noted that the use of several families of particle swarms allows in a number of cases to simultaneously find both the global minimum and local minima of the objective function, which can be of interest while solving applied problems.

The proposed method differs from the existing ones:
– it creates a multi-level and interconnected description of complex hierarchical real-time systems;
– it increases the efficiency of decision making while assessing the state of complex hierarchical real-time systems;
– it solves the problem of falling into global and local extremes while assessing the state of complex real-time hierarchical systems;
– it allows to avoid the problem of the formation of loops while visualizing the state of complex hierarchical real-time systems;
– it enables directed search by several individuals of a swarm of particles in a given direction, taking into account the degree of uncertainty;
– it makes it possible to re-analyze the state of complex systems of hierarchical real-time systems.

The advantages of this research include:
– the possibility of performing calculations with source data that are different in nature and units of measurement;
– the possibility of avoiding the formation of loops while visualizing the state of the national security system;
– the possibility of directed search by several individuals of a swarm of particles in a given direction, taking into account the degree of uncertainty;
– the possibility of re-analysis of the state of complex systems of hierarchical real-time systems.

The shortcomings of the mentioned research should include the availability of appropriate computing power and time for calculations.

It is advisable to implement the specified method in specialized software used for condition analysis complex hierarchical real-time systems.

The direction of further research should be considered the further improvement of the specified method to take into account a greater number of factors during the analysis of the state system of ensuring national security and management decision making.

4. Conclusions

1. The research developed a method for evaluating complex hierarchical systems based on an improved particle swarm. The presented evaluation method is based on the combination of particle swarm and coordinates averaging methods and its modification using several particle swarms and including the Hooke-Jeeves procedure and the corresponding correction factors.

2. The novelty of the proposed method consists in:
– creating a multi-level and interconnected description of complex systems of hierarchical real-time systems;
– increasing the efficiency of decision making while evaluating complex systems of hierarchical real-time systems;
– solving the problem of falling into global and local extremes while assessing the state of complex systems of hierarchical real-time systems;
– the possibilities of directed search by several individuals of a swarm of particles in a given direction, taking into account the degree of uncertainty;
– the possibilities of re-analysis of the state of complex systems of hierarchical real-time systems;
– avoiding the problem of loops while visualizing the state of the national security system in real time.

3. It is advisable to implement the specified method in specialized software used for condition analysis complex systems of real-time hierarchical systems and management decision making.

Conflict of interest

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

Financing

The research was performed without financial support.

Data availability

The manuscript has no associated data.

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