Modeling and Planning of Parallel Information Processing in a Computing System Operating in Extremely Conditions

Aleksander Basyrov[a], Anatoly Khomonenko[a, b] and Igor Koshel[a]

[a] *Military Space Academy named after A.F. Mozhaisky, st. Zhdanovskaya, 13, St. Petersburg, 197198, Russia*
[b] *Emperor Alexander I St. Petersburg State Transport University, 9 Moskovsky pr., Saint. Petersburg, 190031, Russia*

Abstract
Considers the functioning of a parallel computing system (PCS) as part of a robotic complex that is exposed to external extremely destructive influences (EDI), leading to its destruction. A model of parallel computations under the conditions of possible EDI is proposed. Examples of modeling the functioning of the PCS of a robotic complex with estimates of the maximum possible efficiency of its functioning for various implementations of parallel computation plans are given. Conclusions are made and proposals are formulated for planning parallel processing of information in terms of EDI on a robotic complex. On the basis of modeling the functioning of a robotic complex, the analysis of known algorithms for planning parallel computations with estimates of the quality indicator of the functioning of PVS for various implementations of plans for parallel computations is carried out. A new algorithm for planning parallel information processing in a computing system is proposed, taking into account the probable destruction of a robotic complex, and the results of its study presented.

Keywords
Onboard computing system, planning of parallel information processing, maximum possible efficiency, extreme destructive impact.

1. Introduction

[1] One of the topical areas of application of robotic systems is their use in extreme conditions of destructive environmental influences, in which human work is impossible or extremely dangerous.

Trends in the development of robotic systems for various purposes are associated with the need to implement a significant amount of computation and require a scientifically based approach to modeling and planning computational processes occurring in their computing systems. As is known [1-3], the main way to improve the performance of computing systems is the use of methods and technologies of parallel computing.

The problem of modeling and planning parallel computing processes (PCP) under normal functioning of a computing system (CS) is successfully solved [4-6], however, under conditions of extreme destructive influences (EDI), it needs modeling approaches that provide preventive (proactive) planning of parallel calculations aimed at achieving the maximum possible efficiency of the CS functioning in conditions of its possible destruction.

External destructive effects on the robotic complex can be of a different nature (high temperature, critical shock loads, radiation exposure). Without losing the generality of modeling the processes of functioning of robotic complexes in various conditions of destructive influences, the article discusses EDI, the implementation of which leads to a complete loss of the robotic complex's performance.

Based on the concept of preventive functional-parametric configuration of the CS [7], it is necessary to plan the computational pro-

[1] Intelligent Transport Systems. Transport Security – 2021, May 14, St. Petersburg, Russia.
EMAIL: alexanderbas@mail.ru (A.G. Basyrov); khomon@mail.ru (A.D. Khomonenko); kin1470@mail.ru (I.N. Koshel)
ORCID: 0000-0002-3258-8529 (A.G. Basyrov); 0000-0003-0411-258X (A.D.Khomonenko); 0000-0002-2059-3216 (I.N. Koshel)

cess in it, taking into account the possible destruction of the CS and, accordingly, abnormal termination of the computational process.

The issues of planning parallel information processing have been given sufficient attention [5, 6]; various formulations of the problem of planning parallel computations are known. The purpose of planning is to develop a plan (schedule) of the computational process that ensures either the completion of computations by a given (target) date, or by the minimum possible. The article will consider a new formulation of the task of scheduling parallel computations, which is involved in performing the maximum possible amount of computational work with a random or indefinite deadline for the completion of computations caused by the destruction of the CS due to the EDI on the robotic complex. Under these conditions, when scheduling computations, it is necessary to synthesize such a plan of the computational process, in accordance with which the maximum possible amount of computations will be performed before the onset of the breakup of the CS.

2. Features of the functioning of a parallel computing system in conditions of extreme destructive influences

Let us consider the functioning of the CS of a robotic complex, consisting of several computational modules (processors or separate computers) under the conditions of possible EDI.

The execution of a set of programs in real time is realized according to the plan of a parallel computational process. We will assume that PCP planning is aimed at ensuring the execution of programs (tasks) on a given set of computational modules (CM) by a given directive date. The implementation of PCP under the conditions of external destructive influences can be interrupted by the destruction of the CS, which leads to a reduction in the completion time of calculations and the execution of not all planned tasks, but only some of them.

The PCP plan (Fig. 1) can be represented as an array of tuples containing the task number, the number of the computing module that will execute the task, and the scheduled start (end) time of the task. The figure shows the interval [0, t_D] of the normal functioning of the CS and the interval [0, t_p] of functioning, limited by the extreme destructive effect (EDE) on the complex.

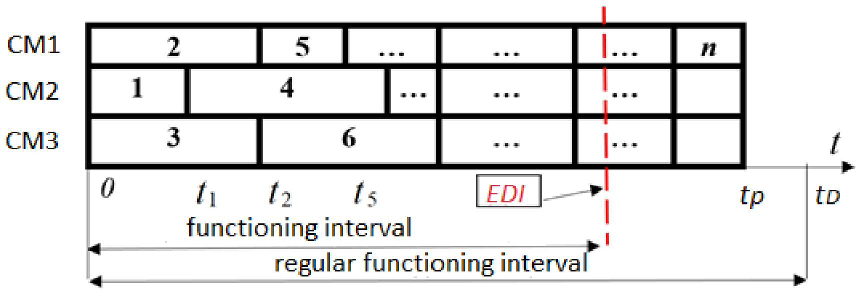

Figure 1: Parallel Computing Process Plan

In the context of a possible abnormal completion of the solution of target tasks by external EDI (destruction of the CS), it is advisable to assess the use of the CS with the maximum possible efficiency of its functioning [8]. The maximum possible efficiency of the CS functioning is the degree of the CS reaching the state of performing the greatest amount of computational work on the interval (regular or abnormal) of the CS functioning.

$$S(\xi) = \frac{\sum_{i=1}^{n} x_i(\xi)\cdot\tau_i}{\min\left(\xi, \max_i\{t_i\}\right)}, \quad (1)$$

where τ_i – is the execution time of the i-th task;

t_i – time of completion of the i-th task;

ξ – the time moment of the destruction of the CS.

Note that in the absence of EDI, this indicator coincides with the acceleration factor of parallel computations [9].

The task of organizing the functioning of the CS of the robotic complex under the conditions of EDI can be formulated as follows. For the given task parameters, the parameters of the CS of the robotic complex, the parameters of the possible EDI on the CS, find

the dependence of the value of the maximum possible efficiency of the functioning of the BCS on the plan of the computing process (modeling task);

a plan for a parallel computing process that ensures the maximum value of the CS performance factor (scheduling problem).

Mathematical formulation of the problem.

Given: 1) a set *Z* of tasks with parameters: $\{\tau_i\}, i = 1,..,n$; τ_i – is the time of solving the i-th task, *n* is the number of tasks;

2) the distribution function *F(t)* of the moments of time for the implementation of the EDI on the CS;

Find: the plan of the computational process, where, $\Xi = \{t_1, t_2,.., t_n\}$ are the planned time points for the completion of tasks, such that

$$\Xi^* = \arg \max_{\Xi^* \in \Xi^{admis}} \overline{S}_{\Xi}(Z, F),$$

where $\overline{S}_{\Xi}$ is the mathematical expectation of the CS performance factor, Ξ^{admis} is the set of admissible plans.

3. A model of a parallel computational process during the operation of a computing system under conditions of extreme destructive influences

If, in accordance with the PCP plan, the i-th task, i = 1, 2,..., n, ends at the moment of time t_i and the distribution function *F(t)* of the moment of completion of calculations caused by the EDI is known, then problems will be solved with probability $\overline{F}(t_i) = 1 - F(t_i)$, the planned completion time of which is not is superior t_i (Fig. 2).

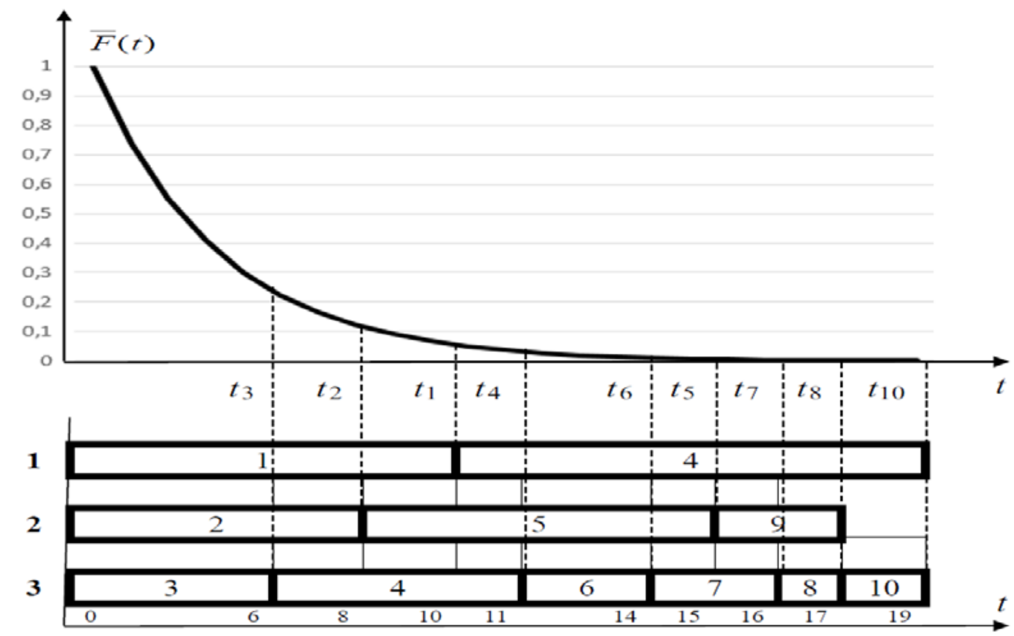

Figure 2: Computation completion time distribution function

The average volume of work performed by onboard computing system (OCS) will be

$$R_W = \sum_{i=1}^{n} \tau_i \cdot (1 - F(t_i)),$$

in this case, the value of the CS performance coefficient at the moment of time is determined by the expression

$$S(t_i) = \frac{1}{t_i}\sum_{i=1}^{n} \tau_i \cdot (1 - F(t_i)) \qquad (2)$$

The values t_i, and hence the value of expression (2) for a given distribution function *F(t)* of the completion time of calculations, depend on the duration and order (sequence) of task execution.

To find the mathematical expectation of the CS performance coefficient for the entire time of its operation, we divide the calculation scheduling interval into q intervals $\left[0,\chi_1\right), \left[\chi_1,\chi_2\right),..., \left[\chi_{q-1},\chi_q\right)$ so that the right boundary of each interval corresponds to the time of completion of at least one task.

Then the mathematical expectation $\overline{S}_{\Xi}$ of the CS performance coefficient for the entire time of its operation will be

$$\overline{S}_{\Xi} = \sum_{i=1}^{q} \frac{\sum_{i=1}^{n} \tau_i \cdot x_i(\chi_i)}{\chi_i} \cdot \left(F(\chi_{i+1}) - F(\chi_i)\right). \qquad (3)$$

Note that $F(\chi_{q+1}) = 1$ since computations end at a moment in time χ_q.

Indicator (3) is the average value of the coefficient of performance of the CS and can be used as a generalized indicator of the quality of functioning of the CS of the robotic complex in the conditions of EDI.

Note that in the absence of destructive effects on the CS $F(\xi) = 0$, the indicator (3) coincides with the "traditional" coefficient of acceleration of parallel information processing [9].

The analysis shows that the type of EDI distribution and the procedure for assigning tasks to computational modules affect the performance indicators of the CS functioning. The difference in the value of the CS productivity factor can reach 20%.

4. Algorithm for scheduling parallel computations in a computing system operating under extreme destructive influences

Let us show the influence of the parallel computation plan on the value of the indicator of the quality of the CS functioning (3) by the example of the distribution of 10 tasks with the execution time correspondingly 1, 2, ..., 9, 10 units of time by three different scheduling algorithms: the list scheduling algorithms [6] LTM and GTM, and the Multi-Fit algorithm [10]. These three computation plans are schematically shown in Figure 3. The computation time w (schedule length) in accordance with the indicated plans is 22, 19 and 19 time units, respectively.

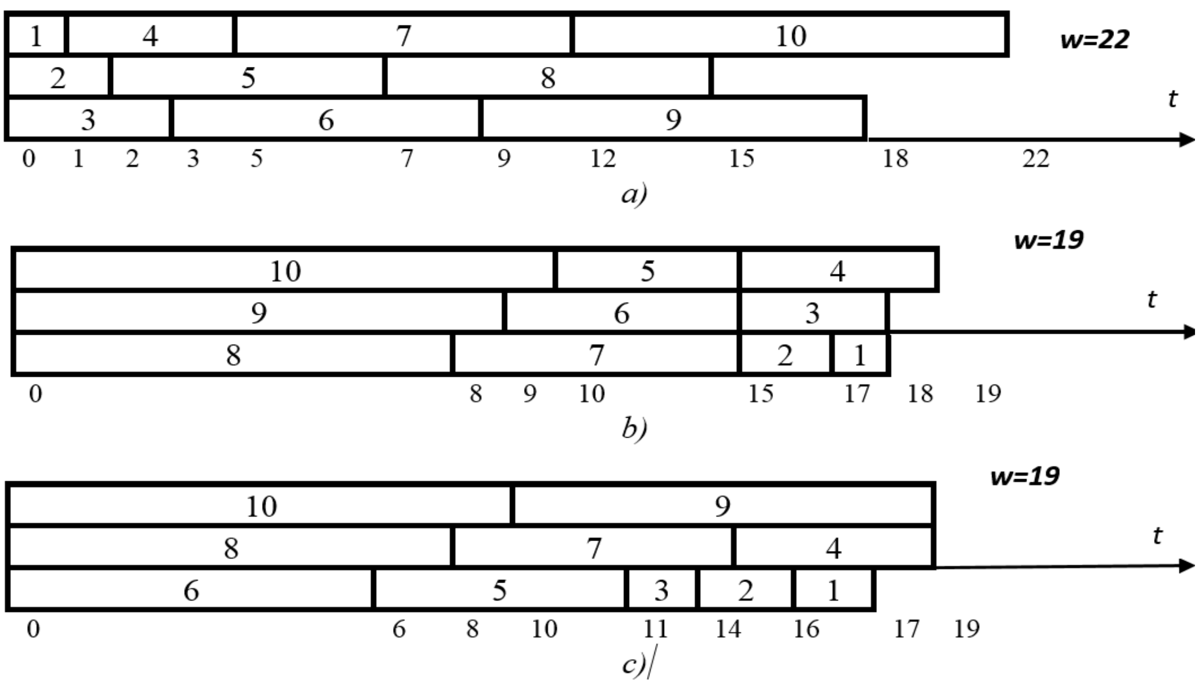

Figure 3: Plans of PCP built by algorithms a - LTM, b - GTM, c - Multi-Fit

Table 1 shows the average values of the CS productivity factor for different laws of distribution of the EDI time points on the CS for each of the three marked plans.

Table 1
The mathematical expectation of the value of the CS performance coefficient

DI distribution option	LTM	GTM	MultiFit
Without DI	**2,5**	**2,8947**	**2,8947**
Uniform $F(t)=\frac{1}{b}t,\ 0\le t\le b$			
b =25	2,0427	1,7300	1,8124
b =50	2,2713	2,3124	2,3536
b =100	2,3857	2,6036	2,6242
Exponential $F(t)=1-e^{-\lambda t}$			
λ=0.1	1,7932	1,0995	1,2161
λ=0.01	2,3924	2,6189	2,6387
λ=0.001	2,4886	2,8658	2,8678
Normal $F(t)=0.5+\Phi\left(\frac{t-\mu}{10}\right)$, where $\Phi(x)$ – **the Laplace function**			
μ=10	1,7384	1,4483	1,5365
μ=20	2,2565	2,4022	2,4273
μ=30	2,4463	2,8105	2,8049

The graphs of the dependence of the efficiency factor of the CS on the time of its destruction for various algorithms for planning VFD are shown in Fig. 4.

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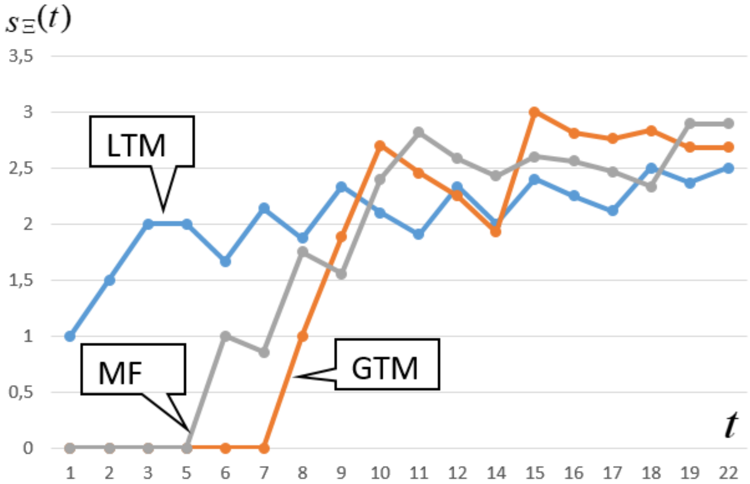


Figure 4: Dependence of the productivity factor on the CS destruction time for various parallel processing scheduling algorithms

The analysis of the data presented in Table 1 shows that the type of EDI distribution and the algorithm for assigning tasks to computational modules affect the value of the selected indicator of the quality of the CS functioning.

For the example under consideration, for various planning algorithms, the maximum difference in the value of the mathematical expectation of the CS performance coefficient is more than 18% for a uniform distribution, more than 63% for an exponential distribution, more than 20% for a normal distribution.

4.1. A two-phase algorithm for planning parallel computing processes in a CS operating under extreme destructive influences

PCP scheduling algorithms minimize the number of computational modules to complete computations by a given (directive) deadline or minimize the computation completion time for a given structure of the computing system. Under the conditions of the functioning of the OCS described above, its degradation is possible before the planned completion date of calculations, therefore, it is required to construct a plan that maximizes the value (3). This formulation of the problem of scheduling parallel computations, which consists in performing the maximum possible amount of computational work with an indefinite deadline for the completion of computations, is new.

PCP scheduling algorithms that provide an optimal result belong to the class of NP-complete, therefore, in practice, real-time systems use heuristic algorithms for assigning tasks to CMs [1,3,4].

The analysis of the results of the application of the known algorithms for planning PCP under the conditions of CS degradation showed that the value of the performance coefficient (3) strongly depends on the time of CS degradation.

Four algorithms were analyzed

two list algorithms: LTM - a task with a shorter duration is assigned earlier than others and GTM - a task with a longer duration is assigned earlier than others;

Multi-Fit algorithm - FFD-procedure (First-Fit-Decreacing) for packing objects into containers with iterative selection of the container volume;

Multi-Fit algorithm with tasks reordering in increasing duration (MF +).

The analysis consisted in calculating the indicator (3) for the VFD plan constructed by the selected algorithm for a given distribution function of the time of degradation of the CS. A random variable was simulated - the time of degradation of the air force, distributed according to uniform, exponential and normal distribution laws.

Regardless of the law of the distribution of the time ξ of degradation of the CS, it was found that with a mathematical expectation $\bar{\xi}$ close to the beginning of the PCP plan, a greater value of the residual productivity is provided by the LTM algorithm, and if it is close to the end of the PCP plan - by the Multi-Fit algorithms.

The idea of the proposed algorithm is based on a combination of two scheduling procedures for a parallel computational process: the LTM list scheduling and the Multi-Fit reordering algorithm.

Assigning tasks to computational modules goes through two phases. In the first phase, some of the tasks with the shortest duration are distributed among computational modules (CM) in accordance with the list algorithm for assigning tasks with the LTM function. In the second phase, the remaining tasks are distributed across the CM using the Multi-Fit algorithm, after which, on each CM, the tasks are finally reordered according to their non-decreasing duration.

An important parameter of the proposed distribution of tasks is the ratio between the number of tasks (amount of computations) distributed by the LTM algorithm and by the Multi-Fit algorithm. This ratio can be formalized by the value

$$\Delta = \Sigma_{LTM} / \sum_{i=1}^{n} \tau_i ,$$

where Σ_{LTM} is the total duration of tasks distributed over the CM by the LTM algorithm. Let's call this parameter the “phase level” of the task distribution. The phase level Δ changes in the interval [0,1], and at $\Delta = 0$ the proposed algorithm completely coincides with the MF + algorithm, and at $\Delta = 1$ – with the LTM algorithm. By fitting in no more than *n* iterations of the phase level, you can "tune" the algorithm to obtain the maximum residual performance for specific initial data.

Let us give a formal description of a two-phase planning algorithm for a degrading PCP (let's call it LTM + MF).

Step 1. Ordering tasks in non-increasing duration: $\tau_1 \geq \tau_2 \geq \ldots \geq \tau_n$.

Step 2. Using the given value Δ, determine the maximum number k of the last tasks in this sequence with numbers $n-k+1,\ n-k+2, \ldots, n-1, n$ for which condition

$$\sum_{i=1}^{k} \tau_{n-i+1} / \sum_{i=1}^{n} \tau_i \le \Delta$$

is satisfied.

Step 3. Sequentially assign tasks numbered *n*, *n-1*,…, *n-k-1* to those CMs on which the next task will start its execution earlier than on other CMs.

Step 4. For the remaining *n-k* problems, apply the Multi-Fit assignment algorithm.

Step 5. In the resulting PCP plan, on each CM, reorder the tasks according to their non-decreasing duration.

For any initial data (the number and duration of tasks, the number of CMs, the mathematical expectation of the point in time $\bar{\xi}$ of PCP degradation), it is possible to determine the value of the phase level that provides the maximum average value of the CS performance factor.

4.2. Results of statistical tests of algorithms for planning parallel computing processes in a computing system operating under extreme destructive influences

To analyze the effectiveness of the application of the developed two-phase algorithm for planning parallel computational processes, an imitation model of the functioning of an CS of a robotic complex under conditions of destructive influences was created.

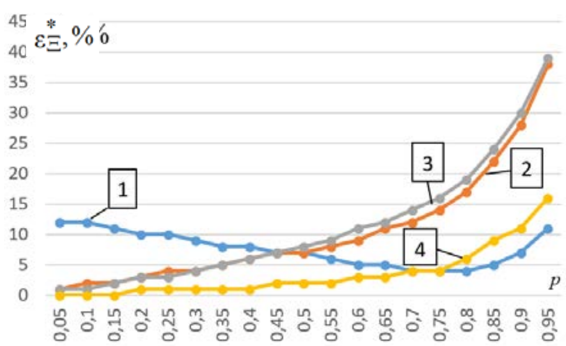
The modeling consisted of multiple generation of PCP plans by various planning algorithms (LTM, GTM, MF, MF + and the developed two-phase algorithm LTM + MF), generation of a random variable - the time of CS degradation, calculation and comparison of the average residual capacity of the CS, which implements different PCP plans ... When modeling the time of degradation of the CS, three distribution laws of a random variable were used - uniform, exponential, and normal [6]. The CS model included 2, 4, 6 and 8 CMs. The number of tasks to be distributed varied from 10 to 50, and the duration of each task was a random number in the range from 1 to 30.

Comparison of the planning efficiency by different algorithms was carried out through the ratio of the average residual performance of the CS operating according to the PCP plan, formed by the developed two-phase algorithm LTM + MF, to the average residual productivity of the CS, operating according to the PCP plans, formed, respectively, by the LTM, GTM, MF, MF + algorithms:

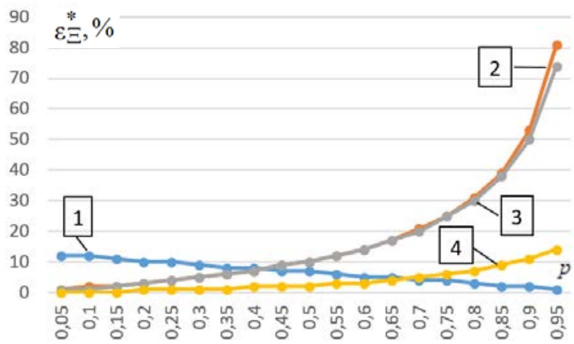
$$\varepsilon_{LTM} = \frac{\bar{S}_{LTM+MF}}{\bar{S}_{LTM}}; \ \varepsilon_{GTM} = \frac{\bar{S}_{LTM+MF}}{\bar{S}_{GTM}};$$

$$\varepsilon_{MF} = \frac{\bar{S}_{LTM+MF}}{\bar{S}_{MF}}; \ \varepsilon_{MF+} = \frac{\bar{S}_{LTM+MF}}{\bar{S}_{MF+}}.$$

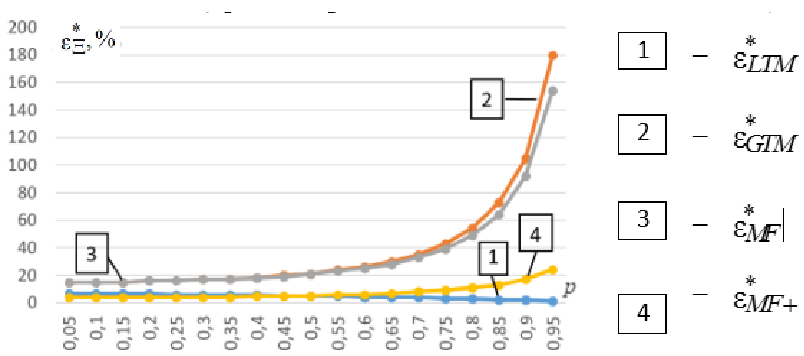
Figure 5 shows the dependences, where is the algorithm with which the two-phase LTM + MF algorithm is compared, on the value of p, which is equal to the ratio of the mathematical expectation of the time of the CS destruction to the planning interval of the PCP. The value represents the relative gain (in percent) in CS performance that can be obtained using the LTM + MF algorithm. This gain depends on the type and parameters of the distribution of the time of CS degradation.



a) uniform



b) exponential



c) normal

Figure 5: Relative gain in the average performance of the CS when using the developed algorithm for various distribution laws of the time of destruction of the CS

In the numerical experiment carried out, the smallest average gain was noted in comparison with the LTM algorithm: up to 9% with a normal distribution of the time of CS degradation, up to 12% – with an exponential one, and up to 13% – with a uniform one.

5. Conclusion

The proposed approach to modeling and planning the functioning of the computing system of a robotic complex provides a solution to computational problems in conditions of possible destruction of the robotic complex caused by EDI.

The novelty of the considered model lies in the ability to assess the value of the indicator of the quality of the functioning of the CS of the robotic complex - the productivity coefficient with stochastic EDI on it.

The proposed algorithm of polynomial complexity provides operational planning of parallel information processing in the CS of the robotic complex. The scientific novelty of the presented algorithm lies in the fact that, in contrast to the known ones, it allows you to rationally distribute the work (tasks) among the performers with a random or indefinite directive deadline for the total completion of all work.

An analysis of the results of simulation modeling of the functioning of a robotic complex under conditions of its possible destruction indicates the possibility of a significant increase in the value of the performance coefficient of parallel information processing in an CS based on the application of the proposed two-phase planning algorithm for PCP.

For an in-depth study of the state of research on the topics touched upon by us, it is recommended to familiarize yourself with works [13-15].

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