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ENHANCING THE PROTECTION OF AUTOMATED GROUND ROBOTIC PLATFORMS IN THE CONDITIONS OF RADIO ELECTRONIC WARFARE

Purpose. Enhancing the protection of automated ground robotic platforms in the conditions of threats of the electromagnetic spectrum by implementing the developed mathematical model of the reliability of information processing and control systems in the system of residue class.

Methodology. The research applies non-traditional methods for increasing the reliability of information processing for ground robotic platforms based on the use of system of residue class codes. The process of creating a reliable mathematical model of the information processing and control systems functioning in the non-positional numeral system in the residue class has been researched. The work used a complex of research methods, which includes the theory of reliability and the theory of interference-resistant coding in the system of residue class. The research is based on the methodology of data reservation of non-positional code structures, which provides for the simultaneous presence of three types of reservation: structural, informational, and functional ones.

Findings. Calculations and a comparative analysis of the reliability of information processing and control systems are provided, namely, fault tolerance according to the indicator of the probability of failure-free operation of the triplicated majority positional (binary) system and system synthesized on the basis of codes of the system of residue class, which is 0.96724 and 0.99986, respectively. It was proved that the information processing and control system operating in the system of residue class with one reserve computational path and a reliability automaton has better reliability indicators than the triplicated positional structure, taking into account the influence of the majority element. The results of calculations of the amount of equipment required for the implementation of the considered model show that the gain is 4, 27, 38 and 42 % for one-, two-, three- and four-byte bit grids; it leads to a decrease in hardware costs, price and energy consumption of the system, which is extremely important for ground robotic platforms.

Originality. A reliable mathematical model is proposed, which, under the condition of using functional data reservation in non-positional code structures, differs from analogues in the possibility of replacing one or more inoperable information tracts with a control one. This allows us to consider information processing and control system as a highly reliable system with dynamic reservation without stopping the computing process, which is a rather important parameter for ground robotic platforms operating in real time.

Practical value. The proposed solution can be used to create highly reliable information processing and control systems of robotic platforms. The use of the proposed model will increase survivability and resistance to threats of the electromagnetic spectrum of the robotic platform and ensure a high level of its protection in the conditions of increased radio-electronic warfare. The practical application of the proposed model, especially with an increase in the bit grid of information processing systems, leads to a significant reduction in the amount of necessary equipment, which will enable developers to balance cost and quality, provide the necessary functionality with specified reliability indicators, and also create a robotics platform that meets modern requirements and standards.

Keywords: *robotic platform, fault tolerance, survivability, spectrum threats, system of residues*

Introduction. Modern warfare challenges necessitate the development of innovative military technologies incorporating artificial intelligence. In the context of military operations digitalization, electromagnetic spectrum manipulation accompanying such operations gains particular significance. Electronic warfare (EW) is a key component of modern military confrontation, providing both protection of one's own forces and destabilization of enemy command and control systems. The integration of artificial intelligence into EW systems contributes to increased accuracy, efficiency, and autonomy of combat operations. This includes automated analysis of electromagnetic signals, forecasting of enemy actions, and adaptive management of EW resources in real time. Such an approach is critically important for strengthening Ukraine's defense capabilities. In this regard, ensuring the fault tolerance, survivability, and resilience to electromagnetic spectrum threats of military technologies, particularly robotic platforms, through the improvement of reliable mathematical models, which significantly reduces the impact of electromagnetic spectrum threats on the information environment, is undoubtedly a priority research direction.

Problem statement. Ground-based robotic platform control is carried out under unstable conditions, leading to a decrease in the operational efficiency and reliability of the overall control process [1]. This necessitates the development and implementation of innovative control methods for automated robotic platforms based on the reliable operation of the information processing and control system (IPCS) [2] and allowing one to ensure the protection of robotic platforms in electronic warfare (EW) conditions.

At the same time, despite significant technological progress in the development of modern hardware and software and technologies used in control and communication systems, a number of problems in this area remain unresolved [3, 4]. These problems are primarily related to:

- high requirements for the operational efficiency and reliability of decision-making in the control of spatially distributed systems, which must be ensured by the organization of processes for highly reliable, high-performance, high-speed acquisition, analysis, processing, and exchange of large volumes of data in real time, with a given quality over communication channels with limited bandwidth and energy resources, under the influence of various types of interference [5];
- limited capabilities of existing methods, algorithms, and models to perform high-reliability, high-performance, high-speed, parallel implementation of processes for analyzing, acquiring, processing, and transmitting large volumes of data, including video information required for the operation of such systems in real time, with a given quality, over communication channels with limited bandwidth and energy resources, under the influence of interference [6];

- the analysis of existing solutions shows that the issue of developing information processing and control systems for robotic platforms that take into account research ideas on improving the technical characteristics of structures using the non-positional numeral system in the residue class has not been fully considered.

The solution to these problems is possible both on the basis of the application of already developed and tested approaches and methods for the rational organization of operational information exchange processes, which are based on the accumulated experience in the operation of communication systems and means, and on the basis of the application of promising methods based on the achievements of modern information technologies and scientific developments in the field of management and communication.

Literature review. A comprehensive analysis of numerous publications indicates promising new directions for the construction and application of real-time IPCSs, thus requiring computational systems with a high degree of parallel data processing. Neurocomputers, built on innovative approaches such as system of residue class (SRC), are increasingly finding application as such specialized computing devices [7].

In work [8], it is emphasized that the increasing complexity of electronic countermeasures has made sorting and identification of radar signals a crucial part of information processing systems. To meet the demands of shipboard information infrastructure, a multi-computer architecture for information processing is proposed. Based on timestamp-based parallel processing planning strategy and a task priority processing method, a real-time parallel signal scheduling algorithm has been developed for this architecture. However, there is a common drawback of multi-computer systems, which lies in the need for additional hardware, software, and control resources.

In [9], parallelization of two widely used implicit numerical solvers for solving partial differential equations on structured grids is presented. Both solvers were parallelized using a hardware-software parallel computing architecture, which allows for a significant increase in computational performance through the use of graphics processing units. However, the proposed approach is technically challenging to implement given the current element base (electronic components).

In research [10], a bit-serial processing approach is proposed to enhance the computational efficiency of neural processing without sacrificing accuracy. This is achieved through a simple design, dynamic precision adjustment, and reduced computations. The paper introduces elements of a serial/parallel systolic array for processing, which is designed to improve computational efficiency.

Many research works in the field of information and control systems focus on improving data security, often implemented based on Complex Event Processing (CEP) systems. CEP systems allow for the detection of predefined patterns in event streams, such as potential software threats, in real time. Reference [11] presents a parallel CEP approach based on flexible decomposition of CEP queries. The idea is to manage the decomposition with a stable throughput of each processor to maximize overall performance. However, the problem of CEP query evaluation, which is computationally intensive, is not fully solved.

To enhance the efficiency of data processing, a method is proposed utilizing a computer system with a multi-core architecture and the Message Passing Interface (MPI) library, employing two parallel algorithms [12]. The first algorithm is based on the classical average values filter, while the second algorithm utilizes partial sums for improved performance. The research demonstrates that increasing the number of parallel processes reduces the measured processing time. However, this observation holds only when the number of parallel processes does not exceed the number of processing cores, which imposes certain limitations on this research.

In [13], a method based on a parallel distributed Kalman filter is proposed to enhance the efficiency of wireless systems by enabling simultaneous data exchange among all nodes and parallel processing with previous time indices. Additionally, sequential time stamp confirmation of each block by all nodes ensures seamless operation. The developed parallel distributed linear Kalman filter architecture is applicable only to non-stationary (mobile) systems and wireless networks.

The analysis of the aforementioned studies related to modern approaches to creating efficient control systems for spatially distributed real-time objects and the degree of development of technical solutions in this field allows us to conclude that a comprehensive approach is necessary to solve these problems, requiring the development of appropriate scientific and methodological principles and the implementation of regulatory measures [14]. Such a comprehensive approach includes the development of methods, models, and algorithms for creating IPCSs and a specialized control computing complex, which allows for the organization of the implementation of control process components in real time. This can be achieved through the application of advanced methods for improving the performance and fault tolerance of specialized computers, based on the use of SRC, which will improve the efficiency and reliability of the overall control process [15].

In research [16], a new terminology, concept, and a complex classification system for fault tolerance mechanisms within the framework of a non-positional numeral system in the residue class is presented and developed. The integration of this numeral system can lead to increased redundancy and fault tolerance, which are necessary to maintain operational integrity under unforeseen system failures.

Unsolved aspects of the problem. The works by the authors [8–13] converge on a single fact: no one has fully explored the development of efficient and highly reliable data processing systems based on alternative numeral systems. This is the main problem with existing research, which is based on the positional numeral system (PNS). Meanwhile, there are two main approaches to increasing the reliability of IPCSs:

- improving reliability indicators through the use of the latest FPGA schemes and other logical structures and elements (for example, as a result of introducing an updated element base into the structure of the IPCSs);

- the use of various types of reservation (implementation of all known types of redundancy), which determine the reliability of systems.

Given that the reliability level of logic elements primarily depends on the existing technology level, the introduction of redundancy in the case of using any known element base will be most effective in terms of increasing the reliability of IPCSs. At the same time, the most effective practical way to improve reliability indicators is structural reservation, which can be implemented using majority-voted duplicated or triplicated structures. However, the use of structural reservation significantly complicates the structure of the IPCS. In addition, it significantly increases energy consumption, system weight and size, as well as production costs and operating expenses. Moreover, a number of other characteristics of the IPCSs as a whole deteriorate, resulting in a limitation of the scope and conditions of operation when processing information in critical information and control systems.

Studies [15, 16] explore methods for improving the speed and reliability of IPCSs operating in SRC. However, the question of creating a reliable model, which is confirmed by a comparative analysis of the proposed solutions and existing ones, is not considered.

Purpose and tasks statement. The purpose of this work is to develop a mathematical model of reliability for an information processing and control system operating in a system of residue class, taking into account the influence of switching devices.

To achieve this purpose, the following tasks were set:

1. To create a mathematical model of an IPCS operating in a non-positional numeral system using residue class.

2. To conduct a comparative analysis of the reliability (fault tolerance), mean time to failure, of triplicated IPCS in the PNS and IPCS synthesized based on SRC codes.

3. To propose recommendations for implementing the proposed solutions in a ground-based robotic platform.

Description of the research methodology. Based on the attributes of the SRC, namely the independence, equality, and low-bitness of residues, the use of which provides a number of advantages in data processing [17], are exploited in this research to identify three types of reservation in IPCS.

Structural reservation is as follows: the mathematical model of reliability of the IPCS in the SRC is implemented taking into account the use of secondary structural redundancy [18, 19].

Information computational paths i and supervisory (control) computational paths s function as components of the reserve system, while reserve computational paths r function as reserve components [20].

Information reservation is implemented based on additional data that becomes available when introducing into the code structure of supervisory computational paths s according to the bases of the SRC b_{i+1}, b_{i+2}. When errors appear, as a result of a failure in one of the computational paths of the IPCS on one of the i informational (working) or s supervisory b_q $(q=\overline{1,\ i+2})$ bases of the SRC, it eliminates errors by known methods [21, 22].

Therefore, the IPCS in the SRC, synthesized according to the known mathematical model, has a probability of failure-free operation of a computational path with an arbitrary base b_z $(z=\overline{1,\ i+s})$, that is insensitive to failures (similar to a triplicated majority structure in the PNS) [23]

$$P_z^{(0)}(t)=e^{-\lambda_z t}=e^{-a_z\lambda_z t}=e^{-\left[\log_2(b_z-1)+1\right]\lambda_l t}=e^{-\left[\log_2(b_{i+s}-1)+1\right]\lambda_l t}, \quad (1)$$

where λ_z is the intensity of failures of the equipment of the computational path in the SR on the largest bases b_{i+s}, λ_l is the intensity of failures attributed to one of the binary digits, i.e. for a positional l-byte IPCS, the probability of failure-free operation is equal to $P_0(t)=e^{-\lambda_0 t}$, where $\lambda_0 = 8l\lambda_l$, or $P_0(t)=e^{-8l\lambda_l t}$.

Ratio (1) can be applied to determine the probability of failure-free operation of the IPCSs of ground robotic platforms under the following conditions:

- failures in the elements of the IPCSs correspond to the parameters of a simple flow. In this case, an exponential distribution is used to determine the failure rate of the system, which is justified theoretically and proven experimentally by data on the level of failure intensity of components of the information processing system [24];

- the switching device is considered ideal, i.e., assuming that the probability of failure-free operation of the switch is equal to 1;

- all computational paths of the IPCSs are equally reliable, respectively, its probability of failure-free operation will be equal to the probability of failure-free operation of the IPCS path with the largest SRC S base b_{i+s}, which is as close to 1 as possible;

- the ability to restore failed paths is not taken into account.

Functional reservation allows a working computational path to simultaneously take over the r failed functions under the condition [25]

$$b_q \ge \prod_{z=1}^{r} b_z. \quad (2)$$

In the analyzed mathematical model (1), this type of reservation is accounted for by adding r additional reserve paths to the value of s. It should be noted that the actual reliability of the IPCS operating in the SRC is significantly higher than that established by the ratio (1), since under condition (2) the possibility is not taken into account of replacing one or more non-functioning i paths by only one path s.

Presentation of the main material and obtained scientific results. The above-considered reliability model (1) of the IPCS in the SRC does not take into account the reliability of the switch. This circumstance does not always allow for an accurate assessment of the IPCS reliability in the SRC under real-world conditions.

In this regard, the reliability of the IPCS in the SRC can be considered as a model of sliding reservation, where reserve computational paths are in an unloaded mode (idle state) before being activated [26]. In this case, the IPCS consists of: a primary system containing i information computational paths; a reserve system containing r reserve computational paths; and an additional system consisting of two supervisory (control) computational paths ($s = 2$); a reliability automaton (RA) that performs the functions of identifying failed information computational paths, disconnecting it, and connecting reserve computational paths.

It is necessary to consider the following conditions to accurately perform a quantitative assessment of the probability of failure-free operation:

- the primary system, which contains b_q $(q=\overline{1,\ i+2})$ paths, during time t in an operational state;

- there is a simultaneous failure of no more than r reserve computational paths, and RA, which determines the reliability of switching devices, functions without failure.

Considering the mathematical expression characterizing the probability of failure-free operation of a sliding reservation IPCS with an unloaded (idle) reserve and an ideal (in terms of reliability) RA, and considering that each term of the sum under the finite integral will contain as a factor the probability of failure-free operation of the RA in the time interval from the beginning operation of the IPCS to extreme failure, we obtain

$$\begin{aligned} P_{SRC}^{(r)}(t) &= P^i(t)iP^{i-1}(t)\int_0^t a(\tau)P(t-\tau)P_{RA}(\tau)d\tau + i^2P^{i-1}(t)\int_0^t a(\tau)\left\{\int_\tau^t a(\xi-\tau)P(t-\tau)P(t-\xi)P_{RA}(\xi)d\xi\right\}d\tau+\ldots+ \\ &+i^rP^{i-1}(t)\int_0^t a(\tau)\left\{\int_0^t a(\delta-\tau)\left\{\int_\delta^t a(\varphi-\delta)\left\{\cdots\left\{\int_x^t a(\varphi-x)P(t-\varphi)P_{RA}(\varphi)d\varphi\right\}\cdots\right\}d\varphi\right\}d\delta\right\}d\tau. \end{aligned} \quad (3)$$

Based on the fact that the probability of failure-free operation of one computational path of the IPCS is $P_1(t)=e^{-\lambda_1 t}$, the probability of failure-free operation of the RA is $P_{RA}(t)=e^{-\lambda_{RA}t}$, then based on formula (3) we obtain an expression for calculating the probability of failure-free operation of the IPCS in the SRC

$$\begin{aligned} P_{SRC}^{(r)}(t) &= e^{-i\lambda_1 t}\sum_{z=0}^{r}\left(i\frac{\lambda_1}{\lambda_{RA}}\right)^z - \\ &-i\frac{\lambda_1}{\lambda_{RA}}e^{-(\lambda_{RA}+i\lambda_1)t}\cdot\sum_{z=0}^{r-1}\sum_{q=0}^{r-1-z}\left(i\frac{\lambda_1}{\lambda_{RA}}\right)^q\frac{(i\lambda_1 t)^z}{z!}, \end{aligned} \quad (4)$$

where $\lambda_{RA} = \lambda_{SD} + s\lambda_1$ is the intensity of RA failures; λ_{SD} is the intensity of failures of the switching device (SD); $s\lambda_1$ is the intensity of failures s supervisory (control) computational paths. λ_1 is the intensity of failures of one computational paths, which is determined by the formula

$$\lambda_1 = a\lambda_l = \left\{ \left] \frac{1}{i+s+r} \left(\sum_{z=1}^{i+s+r} \left[\log_2(b_z - 1) \right] + 1 \right) \right[\right\} \lambda_l. \quad (5)$$

Considering that the researched IPCS consists of two supervisory (control) computational paths $(s = 2)$, the intensity of RA failures is calculated using the formula $\lambda_{RA} = \lambda_{SD} + 2\lambda_1$, and formula (5) takes the form

$$\lambda_1 = a\lambda_l = \left\{ \left] \frac{1}{i+2+r} \left(\sum_{z=1}^{i+2+r} \left[\log_2(b_z - 1) \right] + 1 \right) \right[\right\} \lambda_l.$$

Based on the fundamental requirements for the IPCS in the research of the proposed reliability model, we will assume that $r = 1$. In this case, the mathematical reliability model (4) is presented in the form

$$P_{SRC}^{(1)}(t) = e^{-i\lambda_1 t} \left[1 + i\frac{\lambda_1}{\lambda_{RA}} \left(1 - e^{-i\lambda_{RA} t} \right) \right].$$

Mathematical expression (4) accounts for the impact of functional reservation, i.e. the ability of one computational path s to perform the functions of up to r simultaneously failed paths under condition (2). At the same time, in formula (4) it is necessary to take into account the fact that, in some cases, supervisory (control) computational paths act as reserve paths, i. e. $r + s$. This fact is not considered in formula (1). The proposed reliability model (4) allows for the determination of IPCS reliability indicators based on known and relatively simple ratios. Mathematical model (4) makes it possible to consider the influence of all examined types of reservation, which are conditioned by the attributes of the SRC. Under this condition, the reliability model expression (4) can be represented as

$$P_{SRC}^{(r+s)}(t) = e^{-i\lambda_1 t} \sum_{z=0}^{r+s} \left(i\frac{\lambda_1}{\lambda_{RA}} \right)^z - i\frac{\lambda_1}{\lambda_{RA}} e^{-(\lambda_{RA} + i\lambda_1)t} \cdot \sum_{z=0}^{r+s-1} \sum_{q=0}^{r+s-1-z} \left(i\frac{\lambda_1}{\lambda_{RA}} \right)^q \frac{(i\lambda_1 t)^z}{z!}. \quad (6)$$

To determine the reliability level of the IPCS, the following input data must be specified:

- the number i of the SRC paths, which depends on the size of the bit grid, that is, it is determined by the l-byte machine word;
- the intensity of failures of one computational path of the IPCS $\lambda_1 = a\lambda_l$ (5);
- the intensity of RA failures $\lambda_{RA} = \delta\lambda$ (or the value of the conversion factor $\left.\delta^* = \frac{\lambda_1}{\lambda_{RA}} = \frac{a}{\delta}\right)$.

Additionally, based on a comparative analysis of the reliability of the IPCS in the SRC and the triplicated majority positional (binary) system, it is necessary to consider the intensity of failures for:

- l-byte positional system $\lambda_0 = 8l\lambda_l$;
- the majority element $\lambda_M = \varphi\lambda_l\,\lambda_M = \varphi\lambda_l$ (or the value of the conversion factor $\left.\varphi^* = \frac{\lambda_0}{\lambda_M} = \frac{8l}{\varphi}\right)$ [27].

Data for evaluating the proposed reliability model of the IPCS in the SRC, considering the actual reliability indicators of existing IPCS in the SRC, is presented in Table 1. Considering that the maximum probability of failure-free operation of a majority structure in the PNS, consisting of three IPCS units and a majority element, whose failure-free operation probability $P_M(t) = e^{-\lambda_M t}$, can be achieved only in a redundant structure [28].

Table 1

Reliability indicators of the IPCS in the SRC

$l\ (i)$	Basics of the SRC			δ^*	φ^*
	Informational $b_i(i = \overline{1,i})$	Supervisory $b_s(s = 2)$	Reserve $b_r(r = 1)$		
1(4)	$b_1 = 3$, $b_2 = 4$, $b_3 = 5$, $b_4 = 7$	$b_5 = 11$, $b_6 = 13$	$b_7 = 17$	7	4.3
2(6)	$b_1 = 2$, $b_2 = 5$, $b_3 = 7$, $b_4 = 9$, $b_5 = 11$, $b_6 = 13$	$b_7 = 17$, $b_8 = 19$	$b_9 = 23$	6.2	4.1
3(8)	$b_1 = 3$, $b_2 = 4$, $b_3 = 5$, $b_4 = 7$, $b_5 = 11$, $b_6 = 13$, $b_7 = 17$, $b_8 = 19$	$b_9 = 23$, $b_{10} = 29$	$b_{11} = 31$	5.9	3.8
4(10)	$b_1 = 2$, $b_2 = 3$, $b_3 = 5$, $b_4 = 7$, $b_5 = 11$, $b_6 = 13$, $b_7 = 17$, $b_8 = 19$, $b_9 = 23$, $b_{10} = 29$	$b_{11} = 31$ $b_{12} = 37$	$b_{13} = 41$	5.6	3.3

The probability of failure-free operation for the considered type of IPCS in the PNS is given by the formula

$$P_M(t) = \left[3P_0^2(t) - 2P_0^3(t) \right] \times \left[3P_M^2(t) - 2P_M^3(t) \right], \quad (7)$$

where $P_0(t) = e^{-\lambda_0 t} = e^{-8l\lambda_l t}$ is the probability of failure-free operation of the l-byte positional IPCS.

Example. On the condition that $\lambda_M \ll \lambda_0$, let us perform a comparative analysis of the reliability of a positional IPCS and an IPCS in the SRC with two supervisory computational paths $(s = 2)$ and one reserve path $(r = 1)$ Considering the criterion of minimal hardware redundancy for the IPCS in the SRC, we obtain the following set of basics of SRC $(i = 4)$: $b_1 = 3$, $b_2 = 4$, $b_3 = 5$, $b_4 = 7$, $b_5 = 11$, $b_6 = 13$, $b_7 = 17$, (see the first row of Table 1).

At the same time, $\prod_{i=1}^{4} b_i = 3 \cdot 4 \cdot 5 \cdot 7 = 420 > 2^8$ and the greatest common divisor is $(b_z, b_q) = 1$ for $z \neq q$; $q = \overline{1, i+s}$, $z = \overline{1, i+s+r}$.

To enhance the reliability requirements for the IPCS in the SRC, the following conditions are adopted:

- the intensity of failures of RA is only seven times lower than the intensity of failures of computational paths of the IPCS, i. e. $\lambda_1 = 7\lambda_{RA}$;
- the intensity of failures of the majority element is forty times less than the intensity of failures of one IPCS in the PNS, i. e. $\lambda_0 = 40\lambda_M$;
- the intensity of failures of the *RA* in the SRC is three times higher than the intensity of failures of the majority element of the positional IPCS, i. e. $\lambda_{RA} = 3\lambda_M$.

According to mathematical expressions (6 and 7) and the given initial data, the calculated probability of failure-free operation for a one-byte ($l = 1$) reserved IPCS in the SRC with parameters $i = 4$, $r = 1$ is $P^{(1)}_{SRC}(t) = 0.99986$, and for a one-byte triplicated computational structure in the PNS is $P_M(t) = 0.96724$. It is evident that the IPCS in the SRC with one reserve computational path and *RA* is more reliable than a triplicated computational structure in the PNS, considering the influence of the majority element.

The research of the developed mathematical model revealed that the critical probability of failure-free operation for the IPCS in the SRC is 0.425, while for the triplicated positional IPCS it is 0.5 [29]. Thus, the use of the SRC expands the range of failure intensity values at which it increases reliability (uninterrupted) of the IPCS (compared to non-reserved positional IPCS).

Tables 2 and 3 present data on the amount of equipment required to implement the considered mathematical model for improving the reliability of the IPCS.

A comparative evaluation of the reliability of IPCSs with different parameters shows that the use of the SRC provides a significantly higher probability of failure-free operation compared to a triplicated positional IPCS with majority element for any l-byte machine words. The effectiveness of using SRC increases with the number of bits in the code words processed by the given IPCS. This fact confirms the opinion of experts that for promising IPCSs with large values of the l-bit grid, information coding in the SRC is extremely effective. Moreover, the use of the SRC reduces the critical probability of failure-free operation of the IPCS. Thus, SRC provides higher reliability of the IPCS even with lower hardware costs. As a result, the system reduces power consumption, size, and cost, which is important when designing and creating a robotic platform. This is achieved due to the fact that the considered models of IPCS reliability in the SRC more fully take into account the main attributes of non-positional code structures in the SRC.

From a practical standpoint, the proposed solution can be used to develop more reliable IPCSs for ground-based robotic platforms which are resistant to the influence of external factors. The benefits of implementing the developed reliability mathematical model during the design and manufacturing stages of robotic platforms include:

- reduced time for failure detection and forecasting;
- decreased operational memory usage during information processing;

Table 2

Comparative analysis of equipment in a one-byte ($l = 1$) positional IPCS and an IPCS in the SRC

Equipment volume, N	Binary PNS		SRC	
	One IPCS	Triplicated IPCS	Non-reserved IPCS	$r = 1$
Amount of equipment	8	24	23	24
Additional equipment (AE), %	–	200	193	196

Table 3

Comparative analysis of the gain in the amount of equipment

l	PNS			SRC		Gain in the amount of equipment, %
	One IPCS	Triplicated IPCS	AE, %	$r = 1$	AE, %	
1	8	24	200	24	196	4
2	16	48	200	35	173	27
3	24	72	200	45	162	38
4	32	96	200	55	158	42

- reduced amount of equipment for developing robotic platforms, allowing developers to balance the two primary indicators of cost and quality, ensuring the necessary functionality and reliability of robotic platforms that meet modern requirements and standards;
- the ability to scale the proposed solution for various classes of tasks;
- the fault tolerance of data processing systems will improve the efficiency of various sensors, i.e. it will ensure a reliable and accurate response of the robot to interrupt signals (since the delay between the occurrence of an interrupt and its processing is critical for real-time robotic platforms);
- the reliability of the IPCS operation will improve controllability (availability) of management, and consequently the maneuverability of robotic platforms;
- the residual representation of numbers allows the implementation of the IPCSs, where the processing of all digits (residues) is performed in parallel in time, which is important for the tasks of ground-based robotic platforms, where it is necessary to simultaneously control movement, process data from sensors and ensure communication with the operator.

The relevance of the above for strengthening the resistance of robotic platforms against electromagnetic spectrum threats is undeniable. Effective real-time processing of large arrays of data (video signals) will positively impact the functional features and quality of control of robotic platforms, as well as increase its survivability in electronic warfare environments.

Conclusions.

1. The task of creating a reliability mathematical model for IPCS operating in a non-positional numeral system in the residue class is solved by considering the reliability of the switch and switching devices. The proposed mathematical model (4), which takes into account the use of functional data reservation in the SRC, namely condition (2), which provides for the possibility of replacing one or more information computational paths in case of its failure with one reserve path. Based on the conducted research of the SRC attributes, a reliability mathematical model (8) was also presented, which allows taking into account information, functional, and structural reservation.

2. To evaluate the quantitative reliability indicators, one of the main reliability parameters was chosen, namely, the fault tolerance of the IPCS operation. A comparative analysis of the reliability (fault tolerance) based on the probability of failure-free operation of triplicated IPCS in the PNS and IPCS synthesized based on the SRC codes showed the advantages of the proposed mathematical approach over existing models. It was observed that with the expansion of the IPCS bit grid in the SRC, the probability of failure-free operation and the reliability of the robotic platform as a whole increase, which is quite relevant in the conditions of constantly growing data volumes.

3. The task of formulating recommendations for the implementation of the proposed reliability mathematical model in ground-based robotic platforms is solved by developing theoretical and practical solutions that significantly improve the key reliability indicators and other technical parameters critical for the fault tolerance and effective operation of ground-based robotic platforms in electronic warfare environments.

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Підвищення захищеності автоматизованих наземних робототехнічних платформ в умовах радіоелектронної боротьби

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Мета. Підвищення захищеності автоматизованих наземних робототехнічних платформ в умовах загроз електромагнітного спектру шляхом упровадження розробленої математичної моделі надійності системи обробки інформації та управління в системі залишкових класів.

Методика. Робота виконана із застосуванням нетрадиційних методів підвищення надійності обробки інформації наземних робототехнічних платформ на основі використання кодів системи залишкових класів. Досліджено процес створення надійної математичної моделі систем обробки інформації та управління, що функціонують у непозиційній системі числення в залишкових класах. У роботі використовувався комплекс методів дослідження, що включає теорію надійності й теорію завадостійкого кодування у системі залишкових класів. В основу досліджень покладена методика резервування даних непозиційних кодових структур, що передбачає наявність од-

ночасно трьох видів резервування: структурного, інформаційного й функціонального.

Результати. Наведені розрахунки й порівняльний аналіз надійності систем обробки інформації та управління, а саме відмовостійкості за показником імовірності безвідмовної роботи тройованої мажоритарної позиційної (двійкової) системи та синтезованої на основі кодів системи залишкових класів, що становить 0,96724 та 0,99986 відповідно. Було доведено, що система обробки інформації та управління, що функціонує в системі залишкових класів з одним резервним обчислювальним трактом та автоматом надійності, має кращі показники надійності за тройовану позиційну структуру з урахуванням впливу мажоритарного органу. Результати обрахунків кількості обладнання, необхідного для реалізації розглянутої моделі, показує, що виграш складає 4, 27, 38 та 42 % для одно-, дво-, три-, чотирибайтових розрядних сіток, тобто призводить до зменшення апаратурних витрат, вартості та енергоспоживанням системи, що надзвичайно важливо для наземних робототехнічних платформ.

Наукова новизна. Запропонована надійна математична модель, яка, за умови використання функціонального резервування даних у непозиційних кодових структурах, відрізняється від аналогів можливістю заміни одного чи кількох непрацездатних інформаційних трактів одним контрольним. Це дозволяє розглядати систему обробки інформації та управління як високонадійну систему з динамічним резервуванням без зупинки обчислювального процесу, що являється досить важливим параметром для наземних робототехнічних платформ, які функціонують у режимі реального часу.

Практична значимість. Запропоноване рішення може бути використано для створення високонадійних систем обробки інформації та управління робототехнічними платформами. Використання запропонованої моделі дозволить підвищити показники живучості та стійкості до загроз електромагнітного спектра робототехнічної платформи й забезпечити високий рівень її захищеності в умовах посилення радіоелектронної боротьби. Практичне застосування запропонованої моделі, особливо зі збільшенням розрядної сітки систем обробки інформації, веде до значного зменшення кількості необхідного обладнання, що надасть можливість розробникам збалансувати вартість та якість, забезпечити необхідну функціональність із заданими показниками надійності, а також створити робототехнічну платформу, що відповідає сучасним вимогам і стандартам.

Ключові слова: *робототехнічна платформа, відмовостійкість, живучість, загрози спектра, система залишків*

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