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THE RELIABILITY IMPROVING OF COMPUTER SYSTEM ELEMENTS WITH USING MODULAR ENCODING

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ABSTRACT

Context. Computing systems are implemented in many industries and economies of the modern world. The quality indicators of the systems in which they are used depend on the reliability of their work. The reliability of a computing system consists of the reliability of the construction and functioning of its elements. It is not always possible to ensure reliability in the design by choosing a high-quality element base, structural redundancy, or other well-known methods. Therefore, important and critical elements of computing systems are protected by built-in control schemes. They allow you to detect errors that occur when performing basic data operations. An effective way of constructing such circuits is to use actions on the remainder of the division of the operands by a selected module or by several modules (modular coding). Especially the task of choosing the most accurate and least redundant means of control is relevant for a wide range of basic elements of modern computing systems.

Objective. The aim of the work is research and development of recommendations on the use of modular coding to improve the reliability of the functioning of elements of modern computing systems in various hardware and software basis.

Methods. A method for numerical control of the correctness of performing basic arithmetic and logical operations by computing devices is selected and analyzed. On its basis, a schematic model of a computing system was built and verified in the MatLab Simulink environment, which uses modular coding as a means of ensuring the reliability of the functioning of elements. The analysis of the probabilistic characteristics of decision-making is carried out, estimates of the probability of an erroneous decision-making are given. A software implementation of the simulation algorithm in the Visual Basic for Applications environment has been created, which made it possible to plot the dependence of reliability indicators on coding parameters.

Results. A schematic model of a computing system has been developed. It allows study various combinations of faults in the functioning of elements and errors in their operations. An algorithm for simulating all kinds of malfunctions and errors in the functioning of elements of computing systems when they perform basic operations is implemented in software. The qualitative dependences of the probabilistic characteristics of reliability on the coding parameters are determined. Based on the analysis of the characteristics obtained, conclusions are drawn and practical recommendations are given on the use of modular coding in the elements of computing systems in order to achieve the specified reliability indicators.

Conclusions. To improve the reliability of the functioning of the elements of computing systems, it is effective to use built-in control schemes using modular coding. Taking into account the recommendations for choosing the parameters of the codes will ensure the required reliability with minimal redundancy of circuits and the computational complexity of the calculation algorithms.

KEYWORDS: computing system, element, reliability, diagnostics, modular coding, module, deduction, reliability indicators, error detection probability, simulation, circuit, built-in control.

ABBREVIATIONS

AES is an Advanced Encryption Standard;
ASIC is an Application Specific Integrated Circuits;
CAS is a Chemical Abstracts Service;
CS is a Computing System;
ECS is an Element of Computing System;
FPGA is a Field-Programmable Gate Array;
IDEA is an International Data Encryption Algorithm;
RCS is a Residual Class System;
RSA is a public key cryptographic algorithm (authors are Rivest, Shamir, Adleman);
SoC is a System on Crystal.

NOMENCLATURE

A is a first operand;
B is a second operand;
C is a result of operation;
f is a total function;
i is an index of information module;
j is an index of control module;
k is a number of control modules;
k_j is a modulo;
m is a number of information modules;
n is a total number of modules;
N is a amount of non-found errors;
P is a probability of error detection;
Pc is a working range;
P_{nf} is an error probability;
$P(P_{nf}/P_j)$ is a conditional probability of missing an error;
p is a probability of error at one digit;
pc is a module for modulo calculation;
p_j is a value of control module with index j;
pk_j is a control module with index j;
pm_i is a information module with index I;
;r_a is a remainder (modulo) after dividing the number A by the module p;
r_b is a remainder (modulo) after dividing the number B by the module p;
r_c is a remainder (modulo) after dividing the number C by the module p;
r'_c is a result of control by the module p;
R is a redundancy rate;
R_{I} is a first redundancy rate;
R_{II} is a second redundancy rate.

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INTRODUCTION

CS play an important role in solving specialized problems in many areas of industry and economy of the modern world. Most of the quality indicators of the processes they serve depend on the reliability of their work.

Reliability is determined by the following main components: failure-free operation, maintainability, durability and storability [1]. One of the main ways to ensure reliability is the use of built-in control schemes using modular coding [2].

Modular (arithmetic) codes detect and correct errors arising from the action of noise during the storage and processing of information in the elements of computing systems, as well as during the transfer of data between them. The main problem here is the economical use of redundancy to achieve the required reliability (noise immunity) of data transmission over a noisy channel or when they are stored on some medium. Knowledge of the theory and practice of coding is necessary for developers of both hardware and software of modern computing systems [3].

In the process of calculations, there is a constant transfer and transformation of information in the memory of computing devices. Thus, when designing an ECS, it is necessary to provide for both error detection and correction measures. This function is assigned to the control system. Control system – a set of hardware and software methods and tools that ensure the determination of the correct operation of the device as a whole or its individual units, as well as automatic correction of detected errors. There are the following types of computational errors arising [4]:

– due to errors in the initial data;

– due to methodological errors;

– due to malfunctions in the operation of devices.

Therefore, important and urgent tasks are a reasonable choice of parameters and an effective hardware and software implementation of modular coding methods in ECS.

The object of study is modular coding methodology in ECS control schemes.

The subject of the study is development of methods for assessing the probabilistic characteristics of modular codes and recommendations for their implementation in the selected hardware-software basis.

The purpose of the work is increasing the reliability of computing systems elements with using a modular coding in the built-in control circuits.

1 PROBLEM STATEMENT

The basis of CS is computers (information converters). Let us single out two directions of ensuring reliability – improving reliability during their operation and increasing the reliability of information transfer between them [5].

The first direction is the choice of effective circuit solutions, materials, production technologies, etc. But this does not always help, therefore, when using them in critical infrastructure facilities (aviation, space, security, energy, etc.), it is necessary to provide additional control of the correct functioning. An effective solution is to control the execution of operations (modulo a prime number or their product – modular coding). This is especially true for the implementation of your own basic elements (with your own production of integrated circuits of various degrees of integration) and in programmable logic devices in a configurable hardware-software basis (FPGA, ASIC, SoC, etc.) [6].

The second direction is redundant coding. Advantages of modular codes: simple and, as a consequence, less resource-intensive (the number of operations, the length of the operands, etc.) encoding and decoding algorithms. This is especially true when implementing ESCs under resource constraints such as fieldbus programmable logic controllers. Also, when the transmission medium is noisy, it is usually required to use complex methods of error-correcting coding (Reed-Solomon codes, convolutional codes, turbo codes and their cascading), which have such complex decoding algorithms that it is difficult and sometimes unrealistic to implement them in ECS [7].

Mathematical formulation of the problem: the length of the informational part of the message m is known. It is necessary to determine the dependence of the probabilistic indicator of reliability on the number and values of control modules:

$$P = f(k, p_j), j \in [1; k]. \quad (1)$$

Also, an important characteristic for choosing the parameters of the modular code is the dependence of the probabilistic indicator of reliability on redundancy:

$$P = f(R). \quad (2)$$

The task is to select the number and values of modules for better reliability (with a fixed redundancy) and less redundancy (with a fixed value of the reliability indicator).

2 REVIEW OF THE LITERATURE

The basis of modular coding is number theory (Fermat, Bernoulli, Leibniz, Euler, Gauss) [8]. It is based on the comparison of two integers modulo a natural number – a mathematical operation that allows you to answer the question of whether two selected integers, when divided by one number, give the same remainders. Arithmetic operations with the remainder of numbers in a fixed modulus form modular arithmetic or modular arithmetic, which is widely used in mathematics, computer science, and cryptography [9].

Work on the use of redundant coding to improve the reliability of computing devices began in the middle of the 20th century. The introduction of redundancy at the hardware and / or software levels has been recognized as the main way to build reliable computing systems [10]. In particular, modular coding is used in many built-in control schemes in the structure of computing devices [11].

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Redundant coding is used at all levels of interaction between elements of computing systems. Depending on this, different coding methods are used – both relatively simple (parity check [6], codes for some combinations [12], modular codes [13]), and more complex (binary cyclic codes [14], nonbinary Reed codes -Solomon [15], non-block convolutional codes [16], soft decision codes [17], packet error correction codes [18], etc.). The redundancy and computational complexity of the coding and decoding algorithms are determined based on the requirements for the reliability of the functioning of a particular computing system or its device [19–21].

To determine errors when entering an international bank account number, a comparison modulo 97 is used. This allows you to detect arithmetic errors of a sufficiently high frequency.

In cryptography, comparisons can be found in public-key systems using, for example, the RSA algorithm or the Diffie-Hellman protocol. Also, modular arithmetic provides finite fields, over which elliptic curves are then drawn, and is used in various symmetric key protocols (AES, IDEA).

In chemistry, the last digit in the CAS serial number is the checksum value, which is calculated by adding the last digit of the number multiplied by 1, the second digit from the right multiplied by 2, the third digit multiplied by three, and so on up to the first digit from the left, ending with the remainder of division by 10.

It should be noted that the literature does not describe ways of justifying the choice of a module when controlling logical operations (usually 3 is used in practice, but it is possible that other modules or a composite module are more efficient) [18]. There are no publications on the assessment of probabilistic indicators of reliability when deciding on the frequency and place of arithmetic errors when controlling operations in computing devices.

Also, the results of studies of the application of modular coding to ensure reliability in data transmission, to compare efficiency with other error-correcting codes are not presented. This explains the relevance of this work.

3 MATERIALS AND METHODS

Consider arithmetic codes using numerical control modulo a prime number, which is widely used in computing systems to control all basic arithmetic and logical operations [3]. These include addition, subtraction, multiplication, logical addition (disjunction), logical multiplication (conjunction), negation of equivalence (addition mod 2), inversion, shift operations of various kinds (arithmetic and logical left-right shift, cyclic shift). A generalized block diagram that implements numerical control in modulus is shown in Fig. 1.

The essence of control is as follows. Let us denote the main controlled operation on operands A and B by *, and the residues of operands A and B by r_a and r_b respectively: $A \equiv r_a \pmod{pc}$; $B \equiv r_b \pmod{pc}$.

The process of forming a deduction (remainder) is called the convolution of a number. In parallel with the main operation * on operands A and B a certain operation is performed in the controlling device # on the operands r_a and r_b. Then the result of the operation C is collapsing, and value r_c is compares with result r'_c received in the control device. The equality of r_c and r'_c indicates the correct performance of the operation.

Taking into account that the bit depth of the deduction is much less than the dimension of the operand, it can be expected that the total complexity of the controlling device and convolution devices will be less than the complexity of the device duplicating the main (controlled) device.

The objects of control are devices that implement the above operations: adders, counters, shifters, arithmetic devices, etc.

Let us give a number of mathematical operations on residues in the numerical method of controlling the basic operations for converting information in computing devices.

This type of control is based on the use of identities known from the theory of numbers for the comparability

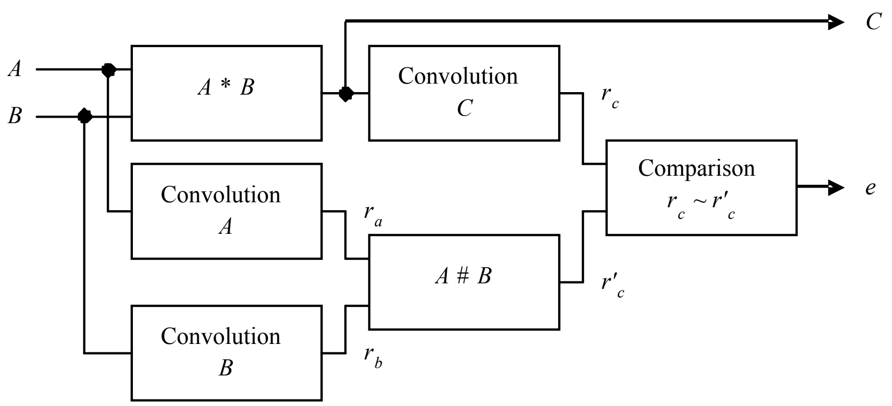

Figure 1 – Element structure of the developed test diagnostics system

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of the sum (product) of numbers with the sum (product) of the remainders of the same numbers by some modulus:

$$\sum_{i=1}^{n} A_i \equiv \sum_{i=1}^{n} r_{a_i} (\mathrm{mod}\, pc); \quad (3)$$

$$\prod_{i=1}^{n} A_i \equiv \prod_{i=1}^{n} r_{a_i} (\mathrm{mod}\, pc). \quad (4)$$

There are some formulas for control the basic arithmetical and logical operations of operands A and B and the result C:

addition: $r'_c \equiv (r_a + r_b) \bmod pc$; (5)
multiplication: $r'_c \equiv (r_a \cdot r_b) \bmod pc$; (6)
disjunction: $r'_c \equiv (r_a + r_b - r_{(A\,\&\,B)}) \bmod pc$; (7)
conjunction: $r'_c \equiv (r_a + r_b - r_{(A+B)}) \bmod pc$. (8)

A more difficult and more accurate control method is the error detection method that works with numbers in RSC. Let us define a series of positive coprime numbers $p_1, p_2, \ldots, p_n$, which we call the bases of the number system in the residual classes. Let $p_1 < p_2 < \ldots < p_n$. To represent the number A in the selected RCS we find the set of the smallest residuals r_i (i = 1, 2, …, n) for $A \equiv r_i$ (mod p_i).

Thus, each number will be uniquely represented by its own set of residuals: $A = (r_1, r_2, \ldots, r_{n-1}, r_n)$. The range of positive integers at RCS is limited to:

$$Pc = p_1 p_2 \ldots p_n. \quad (9)$$

The range of numbers [0, Pc–1] will be called “working”. All operands and results within this range will be called «correct» and outside of it will be called “incorrect”.

For the code provided in RCS to be able to detect and correct arithmetic errors, redundancy must be introduced. The main method for constructing redundant RCSs is to expand the original system by adding modules $p_{m+1}, p_{m+2}, \ldots, p_{m+k}$ that pairwise simple with each other and with the modules of the original system. Thus, in the representation of a number in RCS, one can distinguish m information modules и k redundant modules, tolat n modules. This means that a number in RCS can be represented through the totality of residues (modulus) for all declared modules:

$$A = \{r_{m1}, r_{m2}, \ldots r_{mi}, \ldots, r_{mm}, r_{k1}, r_{k2}, \ldots, r_{kj}, \ldots, r_{kk}\}; \quad i \in [1; m]; j \in [1; k]. \quad (10)$$

Redundancy can be estimated as the ratio of the number of redundant modules to the total number of modules (R_{I}) or through the bit representation of the lengths of the corresponding parts of the code (R_{II}):

$$R_{\mathrm{I}} = \frac{k}{m+k} = \frac{k}{n}; \quad (11)$$

$$R_{\mathrm{II}} = \frac{\sum_{j=1}^{k} [\log_2 k_j]}{\sum_{i=1}^{m} [\log_2 m_i] + \sum_{j=1}^{k} [\log_2 k_j]}. \quad (12)$$

An analytical model [3] was used to determine the reliability characteristics, a schematic model (in the MatLab Simulink package) and a software model (in the Visual Basic for Applications environment) were developed.

Analytical model. We will assume that errors in each of the digits of the number code appear independently of each other and obey the binomial probability distribution. Then the probability of occurrence of errors of the j-th multiplicity in an n-bit number:

$$P(j,n) = P(j) = \binom{n}{j} p^j (1-p)^{n-j}. \quad (13)$$

Determine the probability of not detecting an error:

$$P_{nf} = 1 - P = \sum_{j=1}^{n} P(j,n) P\left(P_{nf} \middle/ P_j \right). \quad (14)$$

This formula is universal, that is, it is valid for any control method.

Schematic model. The block diagram of the model in Matlab Simulink [22], which implements the control of arithmetic operations (multiplication, addition, subtraction), is shown in Fig. 2. The values of the operands A and B are entered, as well as the operating mode of the device. The elements «Display» illustrates the results of the operation and control the correctness of its execution. Distortion can be set in the block to define variants of detectable and undetectable errors.

The block diagram of the model in Matlab Simulink, which implements the control of logical operations (conjunction, disjunction, summation modulo two), is shown in Fig. 3.

To study the properties of modular coding in the system of residual classes a block diagram of the model in MatLab Simulink was developed (Fig. 4). The main components are implemented in the model:
– source of information;
– encoder;
– information transmission channel;
– source of interference;
– decoder;
– the recipient of the information.

In the encoder and decoder (Fig. 5), the number and values of information and redundant modules are set, and the conversion to RCS is also implemented. In the communication channel model, distortions are introduced into the transmitted message. An error detection procedure is implemented in the decoder. It is based on the inverse transformation of the number representation in RCS and checking if it is within the working range.

The constructed models make it possible to carry out experiments on introducing arbitrary distortions and analyzing the detecting ability of a code with given characteristics.

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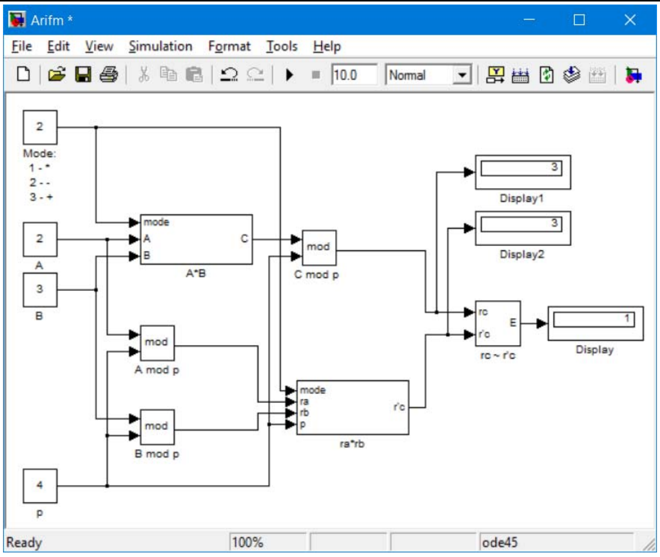

Figure 2 – The model for arithmetical operation control

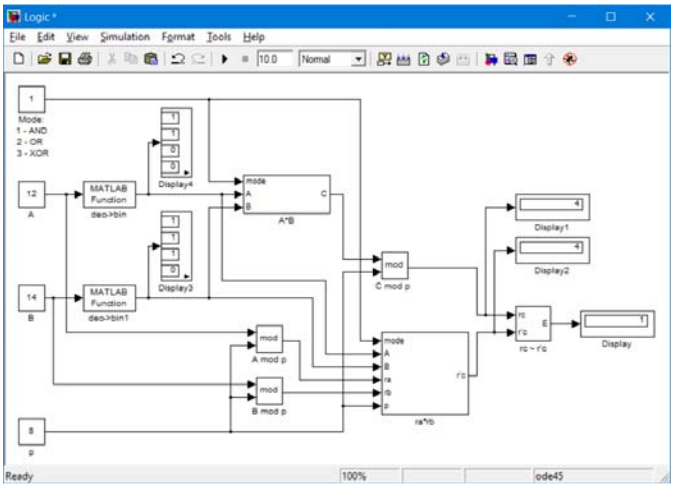

Figure 3 – The model for logical operation control

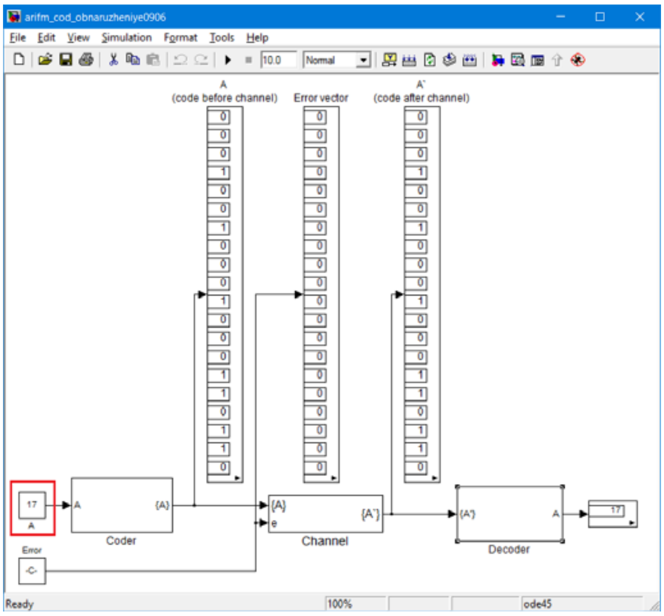

Figure 4 – The model for computing system with encoding with RCS

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Programming model. To study the dependences of reliability indicators on code parameters, a program model was developed in the Visual Basic for Applications language for Microsoft Excel (Fig. 6). It allows you to set the type of the checked operation, the required parameters of the code and to carry out simulation modeling of the full set of faults. As a result, the number of detected and undetected errors is calculated. The software simulation algorithm is shown in Fig. 7.

The number of undetected errors $N \in [N_{min}; N_{max}]$ (div – whole division operation):

$$N_{min} = (2^m \text{ div } pc);\ N_{max} = (2^m \text{ div } pc) + 1. \qquad (15)$$

The probability of undetected errors:

$$P_{nf} = N_{max} / 2^m = (2^m \text{ div } p + 1) / 2^m. \qquad (16)$$

4 EXPERIMENTS

As a result of the study of the analytical model (14), a dependence was built (Fig. 8). When analyzing distortions, we assume that errors of different signs are equally probable and in the i-th bit of the binary positional number are equal $\pm 2^i$.

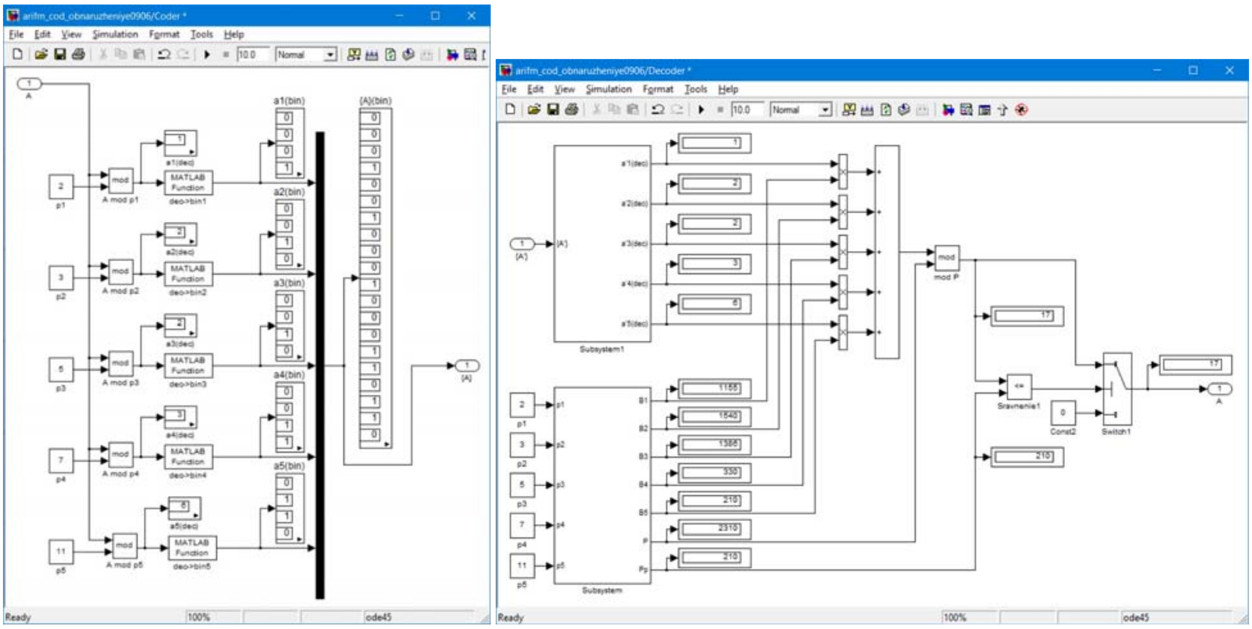

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Figure 5 – Encoder (a) and decoder (b) of model RCS

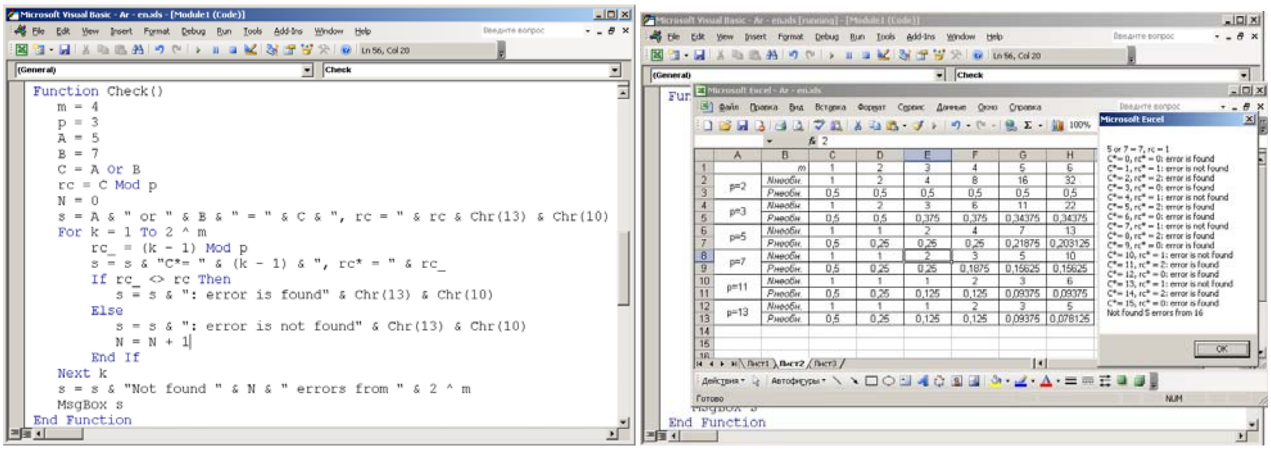

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Figure 6 – The main program module (a) and the example of simulation results (b)

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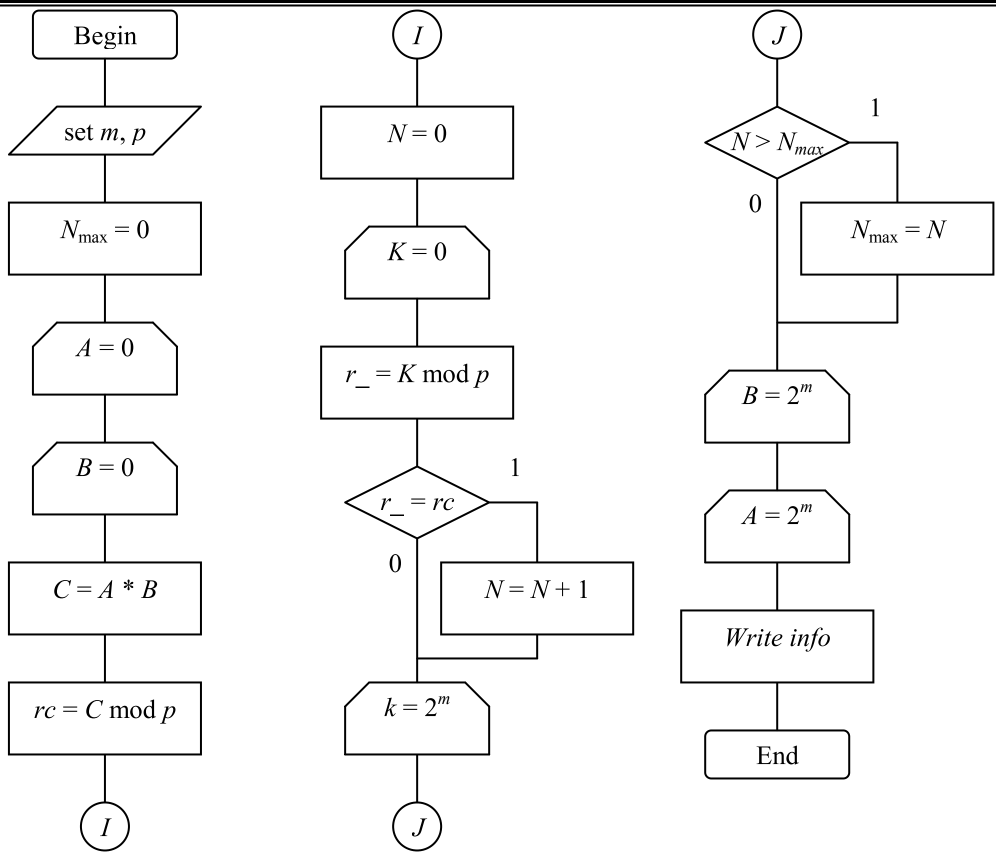

Figure 7 – Algorithm of program simulation

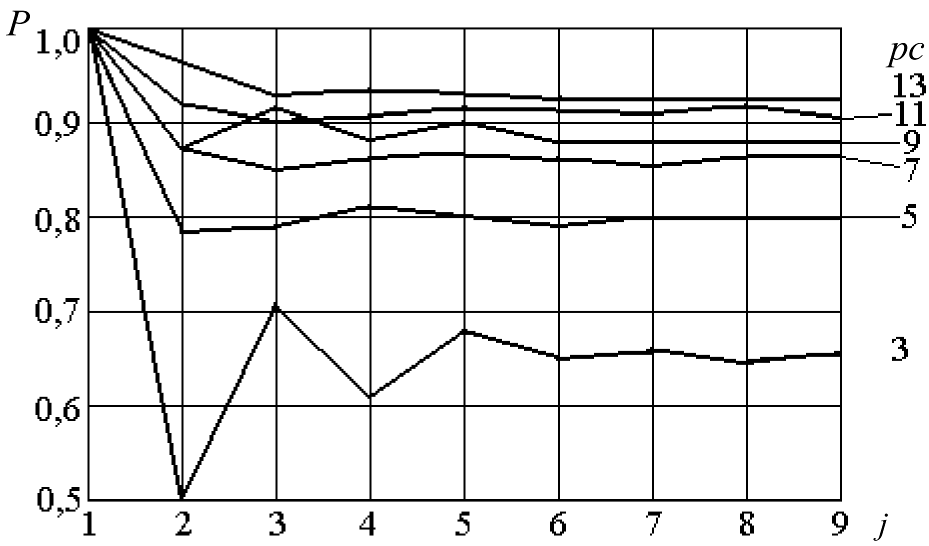

Figure 8 – Dependence of the conditional probability of error detection *P* on their multiplicity *j* for different modules *pc*

Fig. 9 shows the dependences of the error detection probability obtained from the results of the study of the software model:

– on the bit depth of the checked number for different modules *p*;

– from the value of the modulus *p* for different values of the digit capacity of the checked number.

Fig. 10 shows the results of circuit simulation for errors in one and two digits of the number representation in RCS.

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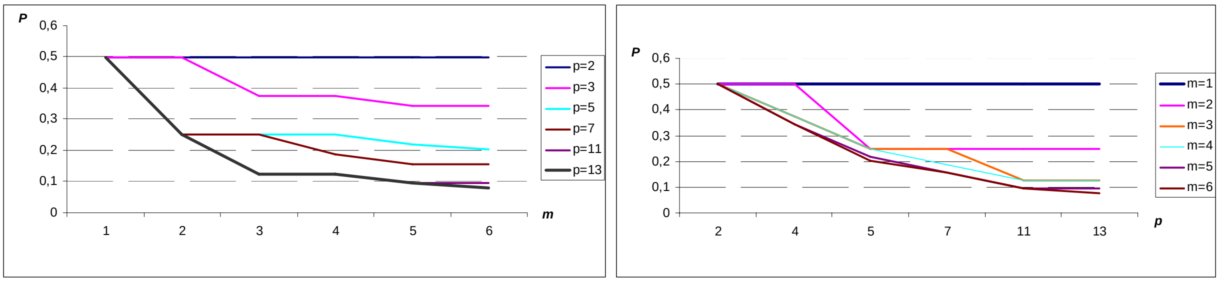

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Figure 9 – Experimental dependences: $P = f(m)$ with p = const (a) and $P = f(p)$ with m = const

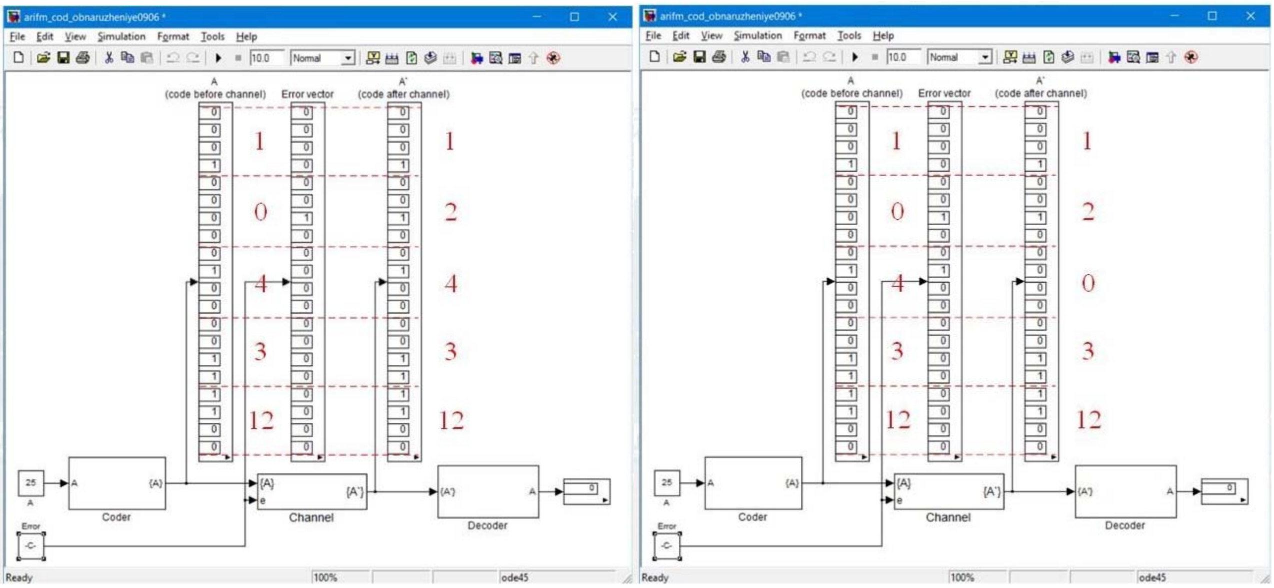

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Figure 10 – The simulation results of MatLab Simulink model RCS: one error (a) and two errors (b)

5 RESULTS

As a result of experimental studies, the dependences of reliability indicators (probability of error detection) on the parameters of the selected control method were constructed. This is done both to control the correctness of operations by the computing device and to detect errors with redundant modular codes.

It is shown that the greater the value of the controlling module pc, the greater the probability of detecting arithmetic errors, i.e. reliability of ECS functioning (Fig. 8). At the same time, according to the proposed formulas for assessing the redundancy, it is possible to select the optimal value at which the calculated detection probability will not exceed the specified (permissible) threshold value (Fig. 9).

With redundant modular coding, a direct relationship was determined between the number of monitoring modules and the probability of error detection (Fig. 10). It is shown that the detection of one arithmetic error in the i-th bit of the number representation in RCS can lead to the detection of up to mi bit errors. More bit errors can also be detected by increasing the number of detecting errors.

6 DISCUSSION

The developed models and the proposed experimental research methods make it possible to choose the required control method and code parameters in the presence of specified requirements and restrictions. This is especially important for the development of new devices in the modern hardware and software basis.

Most of the built-in control devices use no more then module 3 [6, 11, 21]. This requires a small bits amount of control device (no more than 2 bits). But research results and probability dependences (Fig. 8 and Fig. 9) are shown that an increase in the module value gives a significant increase in the probability of error detection (average 1.5–2 times: for example, for j = 5: $P_{pc=3}$ = 0.68 and $P_{pc=11}$ = 0.91). This, of course, requires an increase in the bits amount of the control device (for example, the module pc = 11 requires 4 bits). At the same time, it is important to gradually and reasonably introduce redundancy with the simultaneous fulfillment of reliability requirements.

Embedded control circuits require additional resources and can themselves be a source of errors. Therefore, maintaining a balance between reliability and redundancy is always an urgent task in the design and implementation of elements of modern computing systems.

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CONCLUSIONS

This article presents the results of the application of modular coding in solving problems of increasing the reliability of the functioning of the elements of computing systems. An approach to the implementation of control over the correctness of the execution of arithmetic and logical operations in computing devices has been studied. The application of modular coding to a data transmission channel both inside and between computing devices is considered. Analytical, schematic and software models of the investigated control, coding and decoding processes have been built.

The scientific novelty of the results is: an approach to assessing the dependence of reliability indicators on the control method and coding parameters is proposed. The dependences of the probabilistic characteristics on the coding parameters are constructed. Qualitative conclusions are made about their direction and the results of their influence on the main indicators of reliability.

The practical significance the results of the work consists in recommendations on the use of the obtained dependences and characteristics when choosing the method and parameters of modular coding. This has the prospect of being used both when implemented in computing devices:

– in the hardware basis (at the level of logical elements);

– in the software basis (microcontrollers, microprocessors);

– in hardware and software basis (FPGA).

Prospects for further research are prospects for the use of modular coding in information transmission systems as an effective way to correct transmission errors.

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ПІДВИЩЕННЯ НАДІЙНОСТІ ЕЛЕМЕНТІВ ОБЧИСЛЮВАЛЬНИХ СИСТЕМ З ВИКОРИСТАННЯМ МОДУЛЯРНОГО КОДУВАННЯ

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АНОТАЦІЯ

Актуальність. Обчислювальні системи запроваджено у багато галузей промисловості та економіки сучасного світу. Від надійності їхньої роботи залежать якісні показники тих систем, у яких вони використовуються. Надійність обчислювальної системи складається з надійності побудови та функціонування її елементів. Не завжди можна забезпечити надійність під час проектування вибором якісної елементної бази, структурною надмірністю або іншими відомими способами. Тому важливі та відповідальні елементи обчислювальних систем захищають схемами вбудованого контролю. Вони дозволяють виявляти помилки, які відбуваються під час виконання основних операцій із даними. Ефективним способом побудови таких схем є застосування дій над залишками від розподілу операндів за вибраним модулем або за декількома модулями (модулярне кодування). Особливо завдання вибору найточнішого та найменш надлишкового засобу контролю актуальне для широкого спектру базисних елементів сучасних обчислювальних систем.

Мета роботи. Метою роботи є проведення досліджень та розробка рекомендацій щодо застосування модулярного кодування для підвищення надійності функціонування елементів сучасних обчислювальних систем у різному апаратурно-програмному базисі.

Методи. Вибрано та проаналізовано спосіб числового контролю правильності виконання основних арифметичних та логічних операцій обчислювальними пристроями. На його основі було побудовано та верифіковано схемотехнічну модель обчислювальної системи в середовищі MatLab Simulink, що використовує модулярне кодування як засіб забезпечення надійності функціонування елементів. Проведено аналіз імовірнісних характеристик ухвалення рішення, дано оцінки ймовірності помилкового ухвалення рішення. Створено програмну реалізацію алгоритму імітаційного моделювання у середовищі Visual Basic for Applications, яка дозволила побудувати залежності показників надійності від параметрів кодування.

Результати. Розроблено схемотехнічну модель обчислювальної системи, яка дозволяє досліджувати різні поєднання несправностей функціонування елементів та помилок у виконанні ними операцій. Програмно реалізований алгоритм імітаційного моделювання різноманітних несправностей та помилок функціонування елементів обчислювальних систем під час виконання ними базисних операцій. Визначено якісні залежності ймовірнісних характеристик надійності від параметрів кодування. На підставі аналізу отриманих характеристик зроблено висновки та надано практичні рекомендації щодо застосування модулярного кодування в елементах обчислювальних систем з метою досягнення ними заданих показників надійності.

Висновки. Для підвищення надійності функціонування елементів обчислювальних систем є ефективним застосування схем вбудованого контролю з використанням модулярного кодування. Облік рекомендацій щодо вибору параметрів кодів дозволить забезпечити необхідну надійність за мінімальної надмірності схем та обчислювальної складності алгоритмів розрахунку.

КЛЮЧОВІ СЛОВА: обчислювальна система, елемент, надійність, діагностика, модулярне кодування, модуль, відрахування, показники надійності, ймовірність виявлення помилки, моделювання, схема, вбудований контроль.

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ПОВЫШЕНИЕ НАДЕЖНОСТИ ЭЛЕМЕНТОВ ВЫЧИСЛИТЕЛЬНЫХ СИСТЕМ С ИСПОЛЬЗОВАНИЕМ МОДУЛЯРНОГО КОДИРОВАНИЯ

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АННОТАЦИЯ

Актуальность. Вычислительные системы внедрены во многие отрасли промышленности и экономики современного мира. От надежности их работы зависят качественные показатели тех систем, в которых они используются. Надежность вычислительной системы складывается из надежности построения и функционирования ее элементов. Не всегда можно обеспечить надежность при проектировании выбором качественной элементной базы, структурной избыточностью или другими известными способами. Поэтому важные и ответственные элементы вычислительных систем защищают схемами встроенного контроля. Они позволяют обнаруживать ошибки, которые происходят при выполнении основных операций с данными. Эффективным способом построения таких схем является применение действий над остатками от деления операндов по выбранному модулю или по нескольким модулям (модулярное кодирование). Особенно задача выбора наиболее точного и наименее избыточного средства контроля актуальна для широкого спектра базисных элементов современных вычислительных систем.

Цель работы. Целью работы является проведение исследований и разработка рекомендаций по применению модулярного кодирования для повышения надежности функционирования элементов современных вычислительных систем в различном аппаратурно-программном базисе.

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Методы. Выбран и проанализирован способ числового контроля правильности выполнения основных арифметических и логических операций вычислительными устройствами. На его основе была построена и верифицирована схемотехническая модель вычислительной системы в среде MatLab Simulink, использующей модулярное кодирование как средство обеспечения надежности функционирования элементов. Проведен анализ вероятностных характеристик принятия решения, даны оценки вероятности ошибочного принятия решения. Создана программная реализация алгоритма имитационного моделирования в среде Visual Basic for Applications, которая позволила построить зависимости показателей надежности от параметров кодирования.

Результаты. Разработана схемотехническая модель вычислительной системы, которая позволяет исследовать различные сочетания неисправностей функционирования элементов и ошибок в выполнении ими операций. Программно реализован алгоритм имитационного моделирования всевозможных неисправностей и ошибок функционирования элементов вычислительных систем при выполнении ими базисных операций. Определены качественные зависимости вероятностных характеристик надежности от параметров кодирования. На основании анализа полученных характеристик сделаны выводы и даны практические рекомендации по применению модулярного кодирования в элементах вычислительных систем с целью достижения ими заданных показателей надежности.

Выводы. Для повышения надежности функционирования элементов вычислительных систем эффективно применение схем встроенного контроля с использованием модулярного кодирования. Учет рекомендаций по выбору параметров кодов позволит обеспечить требуемую надежность при минимальной избыточности схем и вычислительной сложности алгоритмов расчета.

КЛЮЧЕВЫЕ СЛОВА: вычислительная система, элемент, надежность, диагностика, модулярное кодирование, модуль, вычет, показатели надежности, вероятность обнаружения ошибки, моделирование, схема, встроенный контроль.

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