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ПРОГРЕССИВНЫЕ ИНФОРМАЦИОННЫЕ ТЕХНОЛОГИИ

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METHOD OF DEFINING FREE PLACES IN VIDEO CONTENT FOR IMPOSITION TYPHLOCOMMENTS

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ABSTRACT

Context. The problem of accessibility of video content is one of the most pressing problem for people with visual impairments. To solve this problem, the methods and means of construction, editing and adaptation of video content for visually impaired persons are development.

Objective. The goal of the work is to develop the method of searching silent areas in the scale for the imposition of typhlocomments and improve the search modules in the software-algorithmic complex of adaptation of video content for visually impaired persons.

Method. The method of searching for places that free from dialogues and other important sounds in video content is implemented. These places of video content are used for inserting typhlocomments. The algorithms of scanning and filtration modules for arrays and searching places available for the imposition of the typhlocomments are developed. This will allow for additional smoothing of the spectrum. Smoothing runs in the forward direction, then in reverse. After calculating the correlation of these two smoothed arrays, we see that almost all the short signals are deleted. For the useful signal, the values that smoothed in the forward and reverse direction overlap and therefore remain in the array. Next, the correlation between the smoothed arrays is compared with the set threshold, and if it does not match the set value, then this element of the array is 0. As a result of the algorithm, we have a list of places. For each item in the list, the beginning of the silence place and its length are specified.

Results. On the basis of the developed method of finding places to insert typhlocomments and improved modules, the testing of software-algorithmic complex was performed in standard configuration, and with the additional smoothing module. The first version of the software-algorithmic complex gave the next result: 120 useful pauses. Version with the additional module found 140 useful pauses.

Conclusions. The results of the experiment make it possible to evaluate the developed method and improved modules of scanning, filtration and smoothing. These modules giving a significant gain of results (about 13%), searching for the places for the imposition of typhlocomments, which improves the adapted video content for people with visual impairments.

KEYWORDS: audiodescription, typhlocomments, video content for visually impaired persons, scale, WaveLet transform of signals.

ABBREVIATIONS

HPF is a high-pass filter;
LPF is a low-pass filter;
SAC is a software-algorithmic complex.

NOMENCLATURE

F_i is a set of typhlocomments describing i-th plot;
K is a threshold of signal energy;
P_i is a number of plot;
S^0 is a top-level subsystem;
S^1 is a bottom-level subsystem;
$Sem(P_i)$ is a semantics of the i-th plot;
$t(f_i^j)$ is a duration of the i-th plot;
V is a video content;
W is a set of information signal;
X is a set of coordination signal;
θ is a set of parameters (the position on the time axis, amplitude, width).

INTRODUCTION

More than 80 % of the information from the outside world, a person receives from the vision. Loss of vision

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becomes a real information barrier for people with visual impairments throughout their lives. The availability of video content plays an important role in the social adaptation of such people. Nowadays, in Ukraine there are no laws, government programs that aimed at accessing the video content for this people.

As a result of the conducted researches it was found that in Ukraine more than 600 thousand of blind and visually impaired people and only 10% of them are aware of the possibility access to the heritage of culture, art, sports through viewing video content that is adapted for the visually impaired people.

Typhlocomment is a text that describes what is happening at that moment on the screen and read in special pauses with off-screen voice.

In general, typhlocomments are conceived to allow access to video content to people with visual impairments, but at present, potential users of video content with audio description can be anyone.

That's why it is necessary to develop specific software tools for providing video content for people with visual impairments. The scientists of the Information systems and networks department of Lviv Polytechnic National University are working on the developing software-algorithmic complex of access to video content for persons with visual impairments. They developed the method and improved the modules for finding places in the video content, which has allowed to improve the quality of the search places that available for the imposition of typhlocomments by 13%.

The object of study is the process of video content submission for visually impaired persons.

The subject of study is methods and tools for constructing, editing and adapting video content for visually impaired persons.

The purpose of the work is to develop and improve the method of searching silent areas in the scale for the imposition of typhlocomments.

1 PROBLEM STATEMENT

The research objective is to develop and improve SAC modules for the adaptation of video content for visually impaired persons.

To achieve this, the following tasks must be solved:

1) to analyze the developed software-algorithmic complex;

2) to develop the method of searching silent areas in audio data for the imposition of typhlocomments;

3) to construct the algorithms of the necessary modules for finding places in the scale;

4) to carry out an experimental comparison of the results of searching places for the insertion of typhlocomments of the software-algorithmic complex with the new places search module.

Any P_i plot is described by a set of typhlocomments $F_i = \{f_i^1, f_i^2,..., f_i^{n_i}\}$. We must select from the set F_i the following j-th typhlocomment determined by formula (1):

$$t(f_i^j) \le t(P_i), \quad (1)$$

and then the corresponding semantics are almost equivalent by formula (2):

$$Sem(P_i) \cong Sem(f_i^j). \quad (2)$$

The realization of condition (1) required that the typhlocomment was not imposed on the dialogues of the plot, and the implementation of condition (2) required the expert assessments.

The i-th plot is divided into sub-plots $S_i \supseteq S_1 \cup S_2 \cup ... \cup S_{m_i}$ without dialogues, so that the typhlocomment does not overlap with dialogues or other important to understand the plot sounds. Then $t(P)_i = t(P_1) + t(P_2) + ... + t(P_{m_i})$.

Also required a set of conditions by formula (3):

$$t(f_k^j) \le t(P_k), k = 1,2,..., m_i. \quad (3)$$

From the set F_i we must select those elements for which condition (3) holds.

2 REVIEW OF THE LITERATURE

The problem of adapting video content for visually impaired persons has been studied from 80s of the last century. The scientists [1, 2] worked on information accessibility for visually impaired people in video format, but adaptation of the video content (finding places for insertion of typhlocomments) has always been performed with the person help.

There are many systems that help visually impaired people in everyday life. In [3] an indoor guidance system for helping blind people is presented. This system provided output instructions to the user by means of a speech synthesizer, was tested in a university building and has shown encouraging results.

In another work [4] system is designed to provide context-dependent guidance messages to blind people while they traverse local pathways. This system is tested under various local pathway scenes, and the results confirm its efficiency in assisting blind people to attain autonomous mobility.

The problem of adaptability of films for visually impaired people is considered in the works [5, 6].

A project DVS Theatrical [7] has been developed in the USA, where 25% of all big screen movies are accessible to people with visually impairments.

A new mobility assistive information and communication technologies for the visually impaired people are described in [8]. Methods for formative and summative evaluations of mobility devices are also discussed.

The most popular software for typhlocomments creation is Media Subtitler [9].

In work audio subtitling as a modality of audiovisual localisation which is positioned at the interface between subtitling, audio description and voice-over are described [10].

The author [11] presents a study aimed at assessing an application offering audio description for mobile devices. The results indicated positive ratings of the assessed features such as usability, utility and quality. The application can be used as a tool for providing improved access to cinema content for people with visually impairments.

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The conception, development, and an initial usability evaluation of a software suite for audio description are presented in [12]. The proposal pursues to facilitate and widen a comprehension of videos for people with visual disabilities by using synthesized voice. The authors developed a video player (ADVPlayer) that synchronizes the original video with a second audio containing a text-to-speech version of an audio description script. The evaluation of usability of ADVPlayer revealed a high comprehension and acceptance in terms of satisfaction and confidence.

In [13] a prototype software (audio-vision manager) that uses many computer-vision technologies to automatically extract visual content, associate textual descriptions and add them to the audio track with a synthetic voice is presented. The technology that automatically processes a film offline, extracts visual information such as shot transitions, key-texts, key-places, key-faces and the action of actors, assigns a text to each visual element added to the audio band, and optionally reads it using a voice synthesizer has been implemented.

To search for places in the scale, free from important sounds (replicas of actors, noise mechanisms, etc.), spectral analysis and WaveLet transform are used.

The WaveLet transform of signals [14–16] is a generalization of spectral analysis, the typical representative of which is the classical Fourier transform. The bases used for this purpose are called WaveLet-functions of two arguments – scale and offset. They were introduced in the 80's of the XX century, but later received fast theoretical development and significant application in various spheres of processing signals and images. In contrast to the traditional Fourier transform, WaveLet transform provides a two-dimensional representation of the investigated signal in the frequency domain in the frequency-position plane. In this case, the analog of frequency is the scale of the argument of the basic function (most often – the time), and the position is characterized by its offset. This allows splitting large and small details of the signals simultaneously to locate them on a timeline. In other words, WaveLet analysis can be described as a localized spectral analysis. WaveLet transform is used in the processing and coding of signals and images of different types (language, satellite images, radiographs of internal organs), image recognition, during studying the properties of crystals and nanobjects surfaces, and in many other cases [17, 18].

3 MATERIALS AND METHODS

Processing signal is the process of transformation and evaluation of its informative characteristics by any technical system. Any signal can be characterized by some generalized values – energy, power, moments or other function, for example, a signal auto-correlation function. The signal can also be presented as a sum of simple oscillations (for example, a sinusoid) and characterized by its set of numbers, called the spectrum, which determines the proportion of each oscillation in the signal. If the signal model is known, then it is characterized by the vector (set) of parameters θ of this model. Any signal parameter carries useful information about the studied object. Therefore, the task of processing is to select these parameters and evaluate their values, from which then the information about the investigated processes is extracted.

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The process of inserting the typhlocomment is hierarchical. Hierarchy of layers is shown on Fig. 1. There are three components: top-level subsystem S^0 (audiodescription), bottom-level subsystem S^1 (choosing the place for typhlocomment) and video content V. For mathematical support of the audio description process the coordination theory is used.

The elements of the set X are the coordinating signals that subsystem S^0 uses to operate of bottom-level subsystem S^1. Top-level subsystem S^0 called a coordinator because its outputs $x \in X$ are signals for coordinating system S^1. The subsystem S^0 has one input – information ω, which is obtained from bottom-level subsystem using feedback. This input used to form a coordination action x. That is described by formula (5):

$$S^0 : W \to X. \qquad (5)$$

The top-level subsystem defines where to insert the typhlocomment and starts the module of typhlocomment reading.

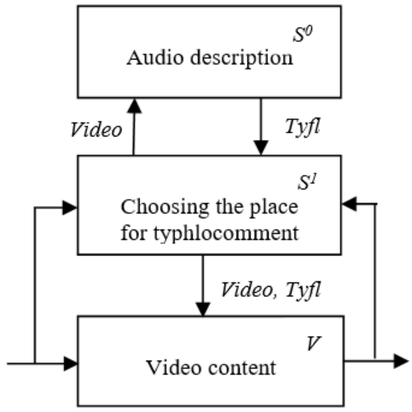

Figure 1 – The hierarchy of audio description process

The search process in the software-algorithmic complex of places for the imposition of typhlocomments includes the following parameters (Fig. 2):

1. K, % – is the threshold of signal energy, in case of exceeding of signal the search algorithm begins its operation.

2. Spectrum density, % – is the density spectrum threshold. If this threshold is exceeded, then the program passes to the next analysis. This parameter indicates the presence of explicitly expressed certain frequency bands in the spectrum relative to others.

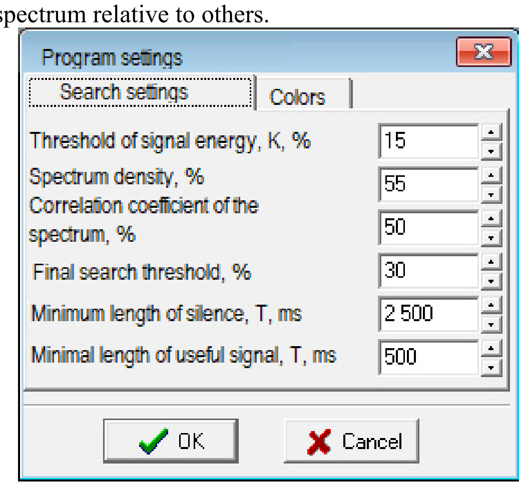

Figure 2 – Options settings window

3. Correlation coefficient of the spectrum, % – is the spectral correlation threshold in each section of the sound signal to the set standard spectrum.

4. The final search threshold, % – is the threshold on the resulting graph of the algorithm's operation. When the signal is below this threshold, the program considers that corresponding area is a silent and lists it.

5. The minimum length of silence, T, ms – is the time that compares the length of the found area of silence.

6. Minimal length of the useful signal, T, ms – is the time that compares the interval between neighboring areas of silence.

The method of searching silent areas in audio data consists of four steps, which are applied consistently for each 10-ms plot. For this, the audio row preliminary broken up.

Step 1. For each 10 ms plot, the spectrum is calculated due to the WaveLet transform.

Step 2. For analysis, the program takes 1024 samples of audio data and divides into 10 parts of length 1, 2, 4, 8, 16, 32, 64, 128, 256 and 512 samples respectively using WaveLet recursive method. Each part corresponds to its frequency strip.

Step 3. After that, the energy is calculated for each part. Thus, get 10 values of level in accordance with frequency strips for each sound.

Step 4. Each section of the audio track is scanned in four stages:

1. Filtering of the sound section by means of the LPF and HPF passing the frequency range from 50 to 300 Hz. The energy of the received signal is calculated and compared with the passing threshold.

2. For each section of the audio track, if the corresponding element of the array is 255, checking is executed for the density of the spectrum.

3. For each section of the audio track, if the corresponding element of the array is 255, a correlation of its spectrum with the reference spectrum is performed.

If, as the result of the three stages, short signals that had the spectrum similar to the set passed verification, or the short pause between the words of the actor failed the check (there will be a value 0 in the array for this section), then the fourth step of verification is applied.

4. To delete sudden values of 0 or 255, smoothing the array is performed. Initially, the search is performed for sections of the array with values "0", whose length does not exceed 500 ms. Such sections are considered false, and the value of the array in them is changed to 255. The search of section of array with values "255", whose length does not exceed 150 ms, is executed. Such plots are considered false and the value of the array in them is changed to 0.

The algorithms of the scanning and filtration modules for arrays and searching places available for the imposition of typhlocomments are developed (Fig. 3–4). This will allow for additional smoothing of the spectrum.

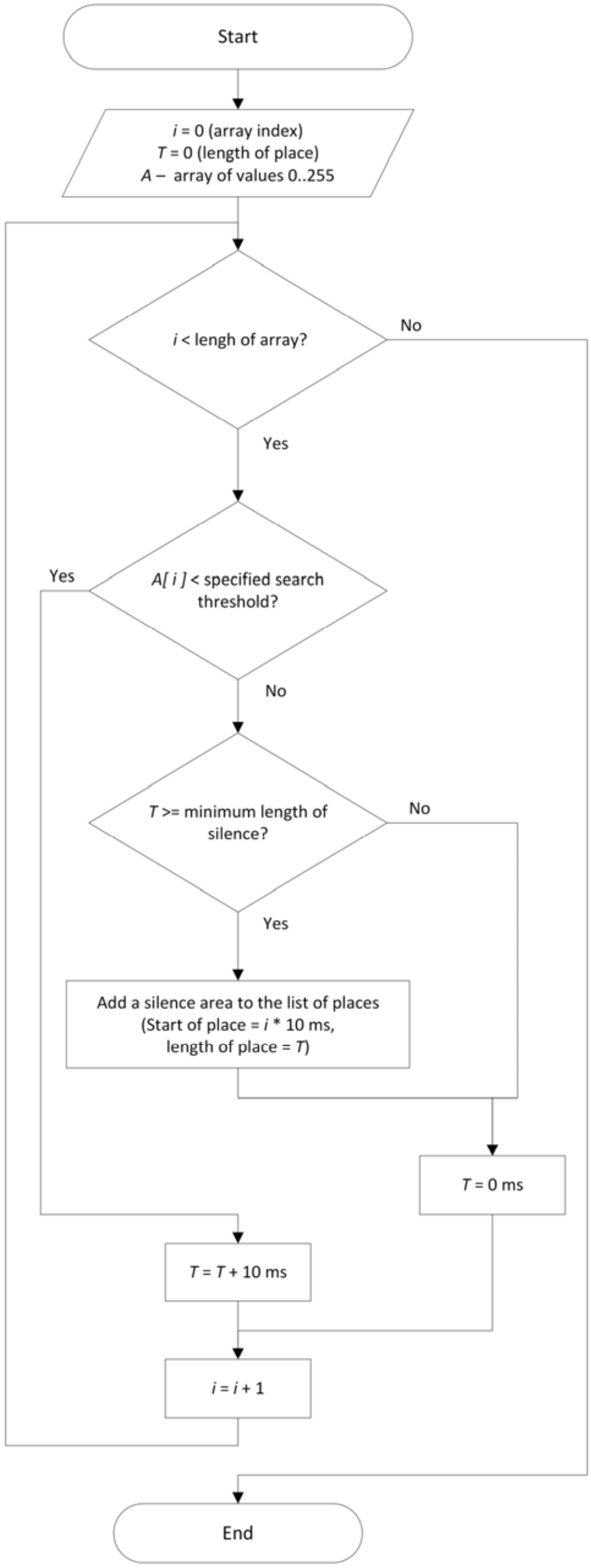

Figure 3 – The function of scanning the array and searching the places for inserting the typhlocomments

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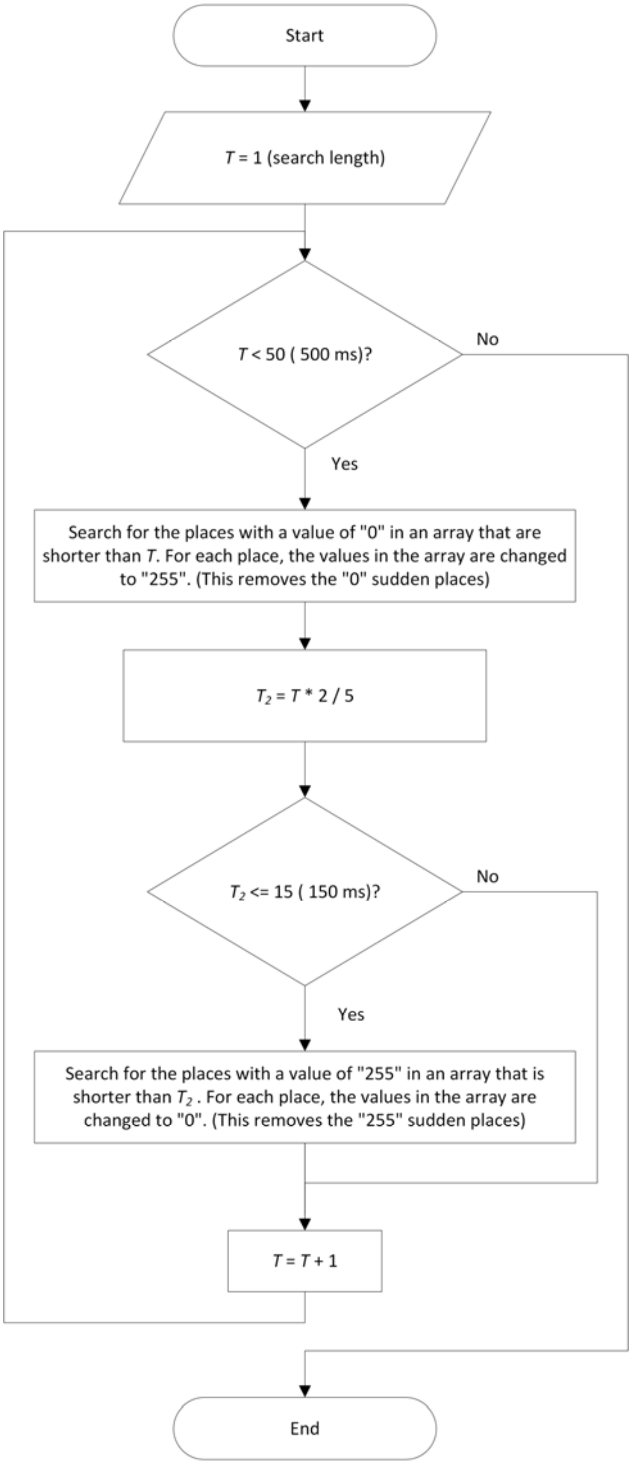

Figure 4 – The array filtration

Smoothing runs in the forward direction, then in reverse. After calculating the correlation of these two smoothed arrays, we see that almost all the short signals are deleted. For the useful signal, the values that smoothed in the forward and reverse direction overlap and therefore remain in the array. Next, the correlation between the smoothed arrays is compared with the set threshold, and if it does not match the set value, then this element of the array is 0.

The work of the algorithm of SAC "Audio editor" (mode "Visualization of charts of searching places") is graphically presented in Fig. 5–6.

After applying the search algorithm, we have an array of values: 0 – a silent / non-useful signal, for each section of 10 ms in length, or 255 – a signal that respond all requirements. Accordingly, the developed module of software-algorithmic complex scans the array and finds the parts of the array that are fully filled with a value of 0 and have a length of at least that set in the parameters (for example, 2000 ms, that corresponding to 200 elements of the array). After searching places with the value of 0, the last stage of the algorithm is executed – each place with the value of 255, that situated between neighboring places with the value of 0, is verified. If the length of the place with the value of 255 is shorter than specified in the parameters of the program (for example, 200 ms, that corresponding to 20 elements of the array), then such a place is considered accidentally entered into the useful signal, and it is equal to 0 and combined with neighboring places.

Consequently, as a result of the algorithm, we have a list of places. For each item in the list, the beginning of the silence place and its length are specified.

The module for writing a voice comment directly into an audio file of video content has been developed.

4 EXPERIMENTS

On the basis of the research, developed and improved the method of searching silent areas in audio data for the imposition of typhlocomments. The testing of software-algorithmic complex was performed in standard configuration, and with the additional smoothing module.

The check was carried out on the example of the film by Sergei Loznitsy "Donbass" (2018).

The first version of the software-algorithmic complex gave the next result: 120 useful pauses. Version with the additional module found 140 useful pauses.

The software-algorithmic complex detected pauses [19], and after that it is possible to use the module's function to read out the typhlocomments immediately into the audio track file. This process is depicted in Fig. 7.

The window contains a stopwatch that shows hours, minutes, seconds, hundredth of the second, and progress that allows you to visually navigate within time, and also buttons of management the record. If the original sound in the silence place obstructs the overlay, you can reduce its volume.

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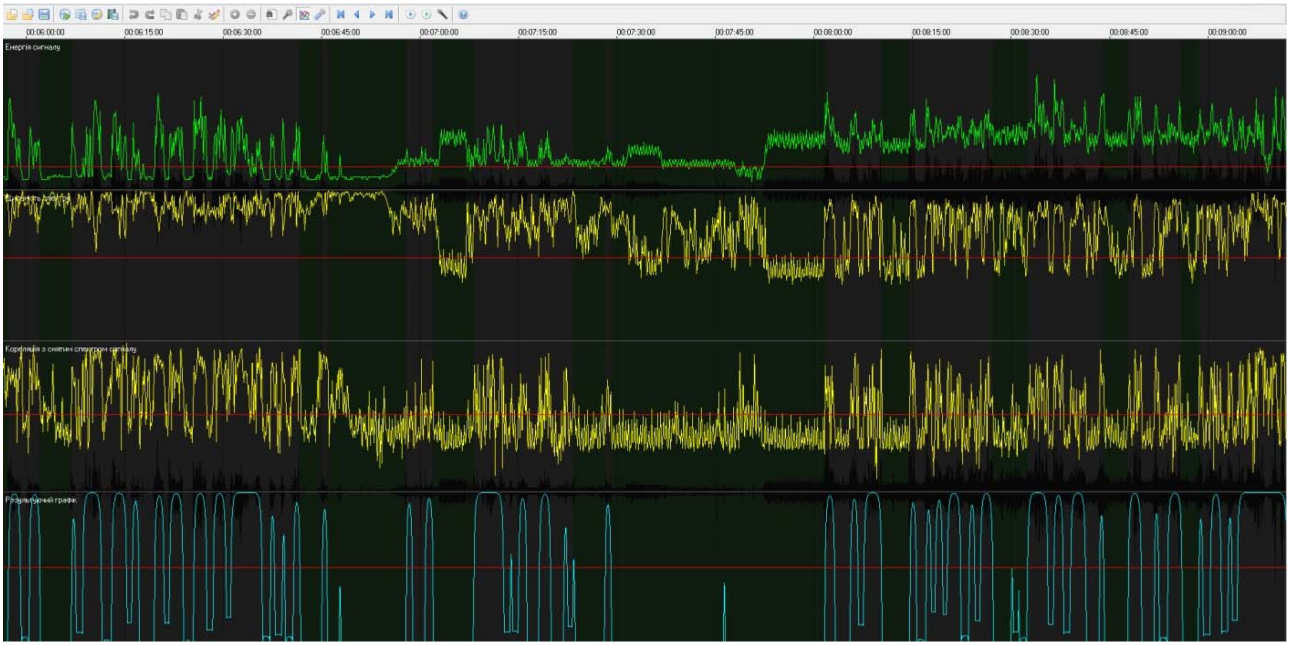

Figure 5 – Visualization of the search algorithm

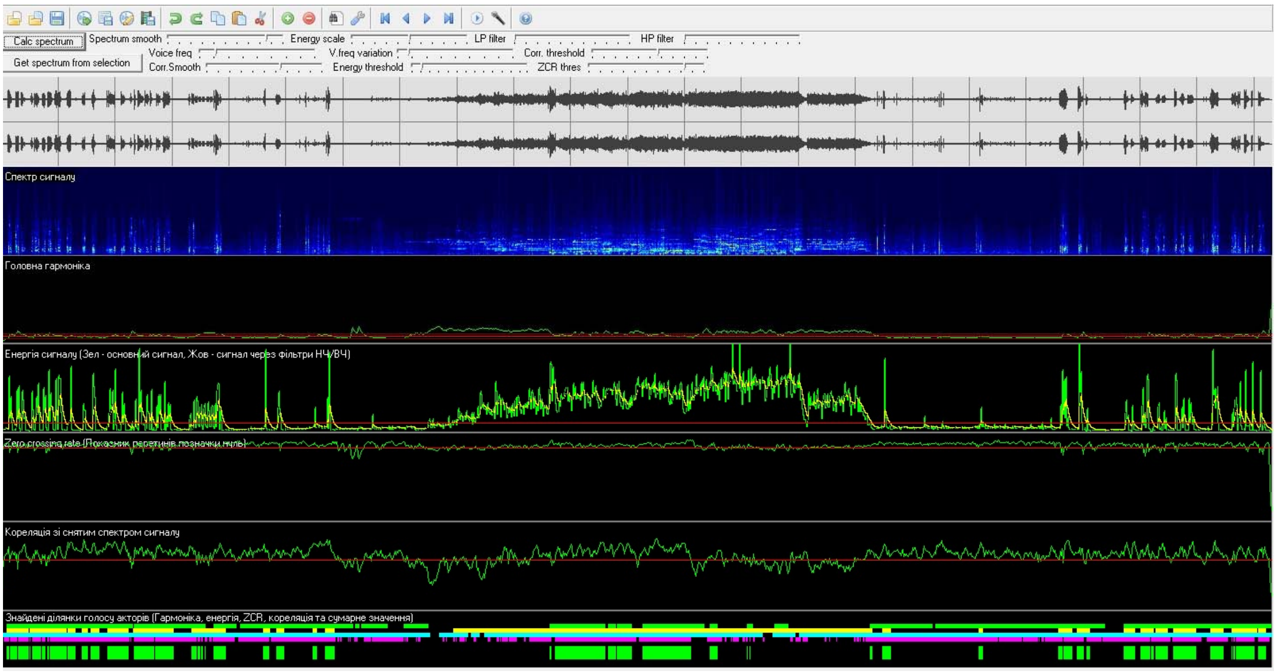

Figure 6 – Visualization of the search algorithm

5 RESULTS

The results of the experiment (see Fig. 8) make it possible to evaluate the developed and improved modules of scanning, filtration and smoothing. These modules giving a significant gain of results (about 13%), searching places for the imposition of typhlocomments, which improves the adapted video content for people with visual impairments.

6 DISCUSSION

Today, scientists around the world are developing information technologies and software that help people with physical disabilities interact with other people and computers and provide themselves with the necessary information. The problem of information availability for the visually impaired people is caused by a poor quality presentation of information on sites and small-adapted modern television for the needs of such people.

There are no developed information systems in the world that would provide a full range of adaptation process of video content for visually impaired people. There are single systems that only perform some functions, but they are commercial and they have some disadvantages. This is due to the complexity of a daptation and integ-

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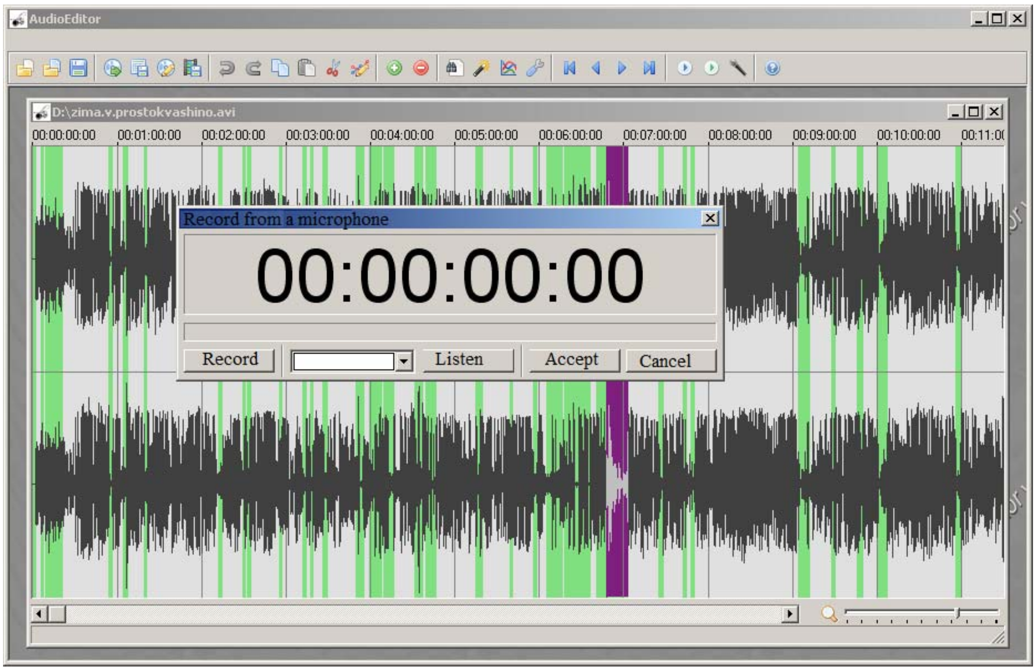

Figure 7 – Window of choice of the audio file area with the ability to record the typhlocomments

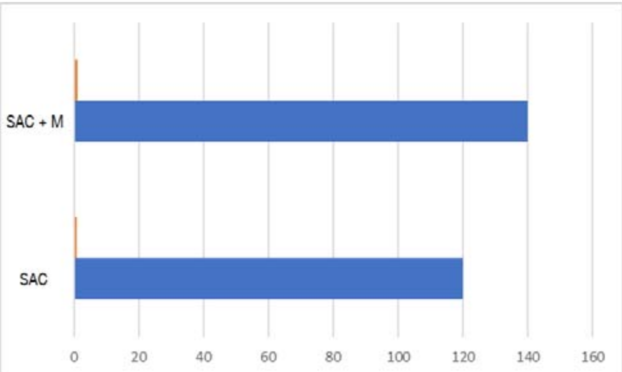

Figure 8 – Number of useful pauses that SAC can detected with the module and without it

rating different software and hardware into one system. As a result, there are no valuable software-algorithmic tools that would provide the solution to the formulated problem.

The experimental results, that have been achieved using the special module, show significant increase about 13% of search quality of the places available for the imposition of typhlocomments in comparison with results of software developed in [20]. This result was achieved by using the method of searching silent areas in audio data for the imposition of typhlocomments and the algorithms of the scanning and filtration modules for arrays. This will allow for additional smoothing of the spectrum.

Smoothing runs in the forward direction, then in reverse. After calculating the correlation of these two smoothed arrays, we see that almost all the short signals are deleted. Next, the correlation between the smoothed arrays is compared with the set threshold, and if it does not match the set value, then this element of the array is 0.

Consequently, as a result of the algorithm, we have a list of places. For each item in the list, the beginning of the silence place and its length are specified.

CONCLUSIONS

This article demonstrated efficient method and algorithms of the scanning and filtration modules for arrays and searching places available for the imposition of the typhlocomments. This method allowed to improve the quality of the search for available places for the imposition of typhlocomments by 13%.

Audio description, as an opportunity to adapt video content for people with visual impairments, is really a method of reporting the plot that is currently happening on the screen.

The scientific novelty of obtained results is that the method of searching places available for the imposition of the typhlocomments are firstly proposed.

The practical significance of obtained results is that the software-algorithmic complex of access to video content for persons with visual impairments realizing the modules for finding places in the video content. The check of SAC was carried out on the example of the film by Sergei Loznitsy “Donbass”. Version with the additional module found 140 useful pauses.

Prospects for further research are to focus on implementation developed methods and algorithms for audio description of video content for people with visual impairments.

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МЕТОД ВИЗНАЧЕННЯ ВІЛЬНИХ ДІЛЯНОК У ВІДЕОКОНТЕНТІ ДЛЯ НАКЛАДАННЯ ТИФЛОКОМЕНТАРІВ

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АНОТАЦІЯ

Актуальність. Проблема доступності відеоконтенту є однією з найактуальніших проблем для людей із вадами зору. Для вирішення цієї проблеми, розроблено методи та засоби побудови, редагування та адаптації відеоконтенту для осіб з вадами зору.

Мета роботи. Метою роботи є розроблення методу пошуку вільних від діалогів ділянок у звукоряді для вставки тифлокоментарів та вдосконалення модулів пошуку цих ділянок у програмно-алгоритмічному комплексі адаптації відеоконтенту для осіб з вадами зору.

Метод. Реалізовано метод пошуку вільних від діалогів та інших важливих звуків місць у відеоконтенті. Ці знайдені ділянки відеоконтенту використовуються для вставки тифлокоментарів. Розроблено алгоритми модулів сканування та фільтрації масивів та пошуку у них ділянок, доступних для накладання тифлокоментарів. Це дало змогу провести додаткове згладжування спектру.

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Виконується згладжування в прямому напрямку, далі у зворотньому. Розрахувавши кореляцію цих двох згладжених масивів ми побачимо, що короткі сигнали практично всі видаляються, а для корисного сигналу, згладжені в прямому і протилежному напрямку значення перекриваються, і тому залишаються в масиві. Далі кореляція між згладженими масивами порівнюється з встановленим порогом, і якщо він не відповідає встановленому значенню, то цей елемент масиву дорівнює 0.

В результаті роботи алгоритму отримано список ділянок для вставки тифлокоментарів. Для кожного елемента списку задається початок ділянки тиші та її довжина.

Результати. На основі розробленого методу пошуку місць для вставки тифлокоментарів та вдосконалених модулів, було проведено тестування програмно-алгоритмічного комплексу у стандартній комплектації, та з модулем додаткового згладжування. Перша версія програмно-алгоритмічного комплексу дала результат у 120 корисних пауз. Версія з додатковим модулем – 140 корисних пауз.

Висновки. Результати експерименту дають змогу оцінити, що розроблений метод та вдосконалені модулі сканування, фільтрації масивів та згладжування, дають суттєвий приріст результатів (близько 13%) пошуку ділянок для накладання тифлокоментарів, що у свою чергу покращує створюваний адаптований відеоконтент для осіб з порушеннями зору.

КЛЮЧОВІ СЛОВА: тифлокоментування, тифлокоментар, відеоконтент для осіб з вадами зору, звукоряд, Вейвлет-перетворення сигналів.

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МЕТОД ОПРЕДЕЛЕНИЯ СВОБОДНЫХ УЧАСТКОВ В ВИДЕОКОНТЕНТЕ ДЛЯ НАЛОЖЕНИЯ ТИФЛОКОММЕНТАРИЕВ

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АННОТАЦИЯ

Актуальность. Проблема доступности видеоконтента является одной из самых актуальных проблем для людей с нарушениями зрения. Для решения этой проблемы, разработаны методы и средства построения, редактирования и адаптации видеоконтента для лиц с нарушениями зрения.

Цель работы. Целью работы является разработка метода поиска свободных от диалогов участков в звукоряде для вставки тифлокоментариев и усовершенствование модулей поиска этих участков в программно-алгоритмическом комплексе адаптации видеоконтента для лиц с нарушениями зрения.

Метод. Реализован метод поиска мест, свободных от диалогов и других важных звуков в видеоконтенте. Эти места видеоконтента используются для вставки тифлокомментариев. Разработаны алгоритмы модулей сканирования и фильтрации массивов и поиска в них участков, доступных для наложения тифлокомментариев. Это позволило провести дополнительное сглаживание спектра.

Выполняется сглаживание в прямом направлении, дальше в обратном. Рассчитав корреляцию этих двух сглаженных массивов, мы увидим, что короткие сигналы практически все удаляются, а для полезного сигнала, сглаженные в прямом и обратном направлении значение перекрываются, и поэтому остаются в массиве. Далее корреляция между сглаженными массивами сравнивается с установленным порогом, и если он не соответствует установленному значению, то этот элемент массива равен 0.

В результате работы алгоритма получено список участков для вставки тифлокомментариев. Для каждого элемента списка задается начало бесшумного участка и ее длина.

Результаты. На основе разработанного метода поиска мест для вставки тифлокоментариев и усовершенствованных модулей, было проведено тестирование программно-алгоритмического комплекса в стандартной комплектации, и с модулем дополнительного сглаживания. Первая версия программно-алгоритмического комплекса дала результат в 120 полезных пауз. Версия с дополнительным модулем – 140 полезных пауз.

Выводы. Результаты эксперимента позволяют оценить, что разработанный метод и усовершенствованные модули сканирования, фильтрации массивов и сглаживания, дают существенный прирост результатов (около 13%) поиска участков для наложения тифлокоментариев, что в свою очередь улучшает создаваемый адаптированный видеоконтент для лиц с нарушениями зрения.

КЛЮЧЕВЫЕ СЛОВА: тифлокомментирование, тифлокомментар, видеоконтент для лиц с нарушениями зрения, звукоряд, Вейвлет-преобразование сигналов.

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CONCEPTION AND APPLICATION OF DEPENDABLE INTERNET OF THINGS BASED SYSTEMS

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ABSTRACT

Context. The problem is in the design, development, maintenance and commisioning of interoperable dependable systems using on the Internet of Things based on von Neumann paradigm of "building reliable systems from unreliable components" for dependable service-oriented systems and infrastructures.

Objective. The goals of the paper are in the development of concepts and principles and assessment technologies for creation and maintenance of complex critical systems based on Internet of Things (IoT) as well as implementation of research in various domains.

Method. In the paper the concept of development of dependable systems on the basis of the Internet of things is described. The multisectoral analysis of methods and models of reliability and cybersecurity (dependability) evaluation of information and control systems of critical applications using the Internet of things has been performed for different domains: power, healthcare, industrial, etc. The analysis has shown that some software failures and malfunctions, cyberattacks and consequences of influence of attacks are identical for all domains, but there are specific features for each domain, which are necessary to consider at working out of methodology of maintenance of denepdability of reliability of systems of critical applications using the Internet of things.

Results. The developed conception, methods, tools and technologies for the creation and implementation of dependable information & control systems for critical applications based on the Internet of Things.

Conclusions. The paper proposes a conception that includes a set of scientific and applied tasks for the development of methods, tools and technologies for the creation and implementation of dependable information & analytical and information & control systems for critical applications based on the Internet of Things. The prospects for further research may include the detailing of the developed models, methods and technologies to ensure the dependability of complex information & control systems for critical applications based on the Internet of Things.

KEYWORDS: Information and control systems of critical applications, Internet of Things, dependability, cybersecurity, functional safety.

ABBREVIATIONS

DDoS – Distributed Denial of Services;

ICSIoT – Information & Control Systems based on Internet of Things;

ICT – Information and Communication Technologies;

IoT – Internet of Things;

LAN – Local Area Network;

USB – Universal Serial Bus.

NOMENCLATURE

λij is a failure rate or attack rate;

μij is a recovery rate;

$Pi(t)$ is a probability of finding the ICSIoT system in each of the states;

$AC(t)$ is an availability function.

INTRODUCTION

One of the promising areas of modern information and telecommunication technologies development is the IoT. The infrastructure of interconnected objects, people, systems and information resources together with intelligent services allowing them to process information, combine the physical and virtual world is a paradigm of IoT, which ensures the integration of any electronic device into the Internet environment. Areas of application of IoT are information & analytical and information & control systems of manufacturing, energy, defense, transport, construction, healthcare, smart cities and buildings.

IoT-based technologies are implemented both in everyday life, where they increase comfort and quality of life, and in the so-called critical systems, which must provide a high level of reliability, safety for long-term use, and meet strict national and international standards. Information & analytical and information & control systems of critical applications (energy, aerospace and transport complexes, medical equipment and communications) based on the ICSIoT are a separate class of such systems [1].

Failures of such systems are possible due to software design defects, physical defects of hardware, attacks on system vulnerabilities. Adverse effects and attacks on vulnerabilities in ICSIoT components, software, and databases can occur at each of these levels. The target of at-

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tackers can be data, video and audio recordings, disabling hardware and software components.

It is important for ICSIoT to ensure the protection and tolerance of systems to failures of various natures, i.e. to ensure their dependability. Dependability is a complex property of the system to perform appropriate functions and provide services that can be justifiably trusted [2]. Dependability combines reliability, functionality and cybersecurity, which is very important in the requirements regulation, evaluation, creation and use of critical systems in general as much as systems based on the IoT in particular. It should be emphasized that systems based on IoT technologies consist of hardware, software, communication components of different reliability and security levels. Therefore, there is a contradiction between the requirements for dependability (reliability and safety) of ICSIoT and the level of characteristics of the dependability of their components in an aggressive physical and information environment, between the capabilities of appropriate technologies and inspiring methods and means of creating critical systems using IoT. Therefore, it is necessary to consider the concept of ensuring the dependability of critical systems based on IoT, which combines the principles, methods and tools of analysis, evaluation and ensuring the reliability, security and dependability of these systems as a whole.

1 PROBLEM STATEMENT

The purpose of the paper: development of concepts and principles, systematization of models and methods to ensure ICSIoT compliance with reliability and safety requirements, review of assessment technologies, creation and maintenance of such systems and implementation of research results of authors in creating ICSIoT in various domains.

The scientific novelty and applied task, which is solved in the work, is the development of methods, means and technologies of creation and introduction of capable information-analytical and information-control systems of critical application on the basis of the IoT.

In accordance with the purpose of the work the following tasks are solved:

1. The concept, principles of dependable ICSIoT are offered.
2. The normative profile of ICSIoT is developed, which takes into account and harmonizes the list and content of requirements of international and national standards for reliability, availability, functional and cybersecurity and modernization.
3. Mathematical models and methods for assessing the performance, availability, functionality and cybersecurity of ICSIoT, which take into account various types of failures and cyberattacks on systems, allow to analyze their functional behavior and formulate recommendations for the choice of hardware and software components, architecture, interaction protocols and more.
4. Methods of development of capable ICSIoT for various complexes (medical, power, industrial, communication, etc.) and maintenance of their reliability and safety at creation, modernization and use are offered.
5. Developed and implemented information technologies to support decision-making in the creation, modernization and maintenance of ICSIoT.

To solve the set tasks, it is necessary to create models and methods that will allow assessing the reliability, availability, and reliability of the system. The apparatus of Markov models has proven itself well in assessing ICSIoT system availability. The following assumptions were made when creating the models and simulations. Assumptions in Markov model development:

– current system hardware failures are subject to Poisson distribution;

– the flow of subsystem failures is governed by Poisson's distribution law because the results of monitoring and diagnostics, antivirus software testing have corrected a secondary error (the result of the accumulation of primary errors and defects, software bookmarks) and to correct software failures or failures, troubleshooting or consequences code, attacks on DoS – and DDoS – the number of primary software defects constantly. Therefore, it is true to assume that the flow of software failures is subject to Poisson propagation, the failure rate is constant;

– the model does not take into account that the elimination of software vulnerabilities and design errors change the parameters of the failure flow (and recovery). Markov's model theory is used to study the reliability of ICSIoT, because the failure rate of hardware and software and the presence of software vulnerabilities are constant.

The main parameters indicated on the graph of Markov model – the transition rates from one state to another: λij, μij. Several models are used to create the conception and application of dependable IoT based systems. The initial data for the models, which are used in conception, are different for different models. For the model, described in this paper, initial data are: $\lambda1317=5{,}7\cdot10^{-4}$ 1/h; $\lambda1517=1\cdot10^{-5}$ 1/h; $\lambda1617=1\cdot10^{-6}$ 1/h; $\lambda218=1\cdot10^{-5}$ 1/h; $\lambda318=1\cdot10^{-5}$ 1/h; $\lambda1320=1\cdot10^{-6}$ 1/h; $\lambda1520=1\cdot10^{-6}$ 1/h; $\lambda2017=1{,}14\cdot10^{-3}$ 1/h; $\lambda120=1\cdot10^{-6}$ 1/h; μ67=60 1/h; μ141=0,125 1/h; μ111=0,5 1/h; μ32=40 1/h; μ42=30 1/h; μ52=30 1/h; μ1513=50 1/h; μ1613=60 1/h; μ71=0,02 1/h; μ87=2 1/h; μ81=30 1/h; μ101=1 1/h; μ121=5 1/h; μ181=1 1/h; μ191=0,02 1/h; μ91=1 1/h; μ171=1 1/h; μ188=60 1/h; μ61=0,02 1/h; μ2021=60 1/h; μ221=20 1/h; μ211=30 1/h; μ1722=60 1/h; μ201=40 1/h; μ2113=20 1/h.

2 REVIEW OF THE LITERATURE

The analysis of known proceedings, projects and experience of such systems operation allows formulating the purpose and objectives of research conducted by the authors over the past 10 years. Currently, there are publications of many authors who have conducted research in the following areas: critical application systems reliability, IoT systems cybersecurity, Web-services dependability, critical application systems dependability, IoT systems, IoT systems dependability.

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The issues of research and development of dependable systems were considered in the following scientific proceedings. In [1] the basic methods of modeling, design and evaluation, as well as providing dependable IoT systems described, their architecture and the particular implementation are introduced. In [2] the basic concepts of dependability are introduced, and it is shown that it combines the system's reliability and cybersecurity, the classification of different types of failures, threats and their attributes.

In [3] the modified taxonomic scheme of system dependability taking into account the changes of functional requirements, dependability requirements, computer systems environment characteristics, including an operating cycle and levels of maintenance of fault tolerance is offered, the taxonomy of multiversion calculations in dependable systems is generalized.

Study of the design and architecture of IoT systems and their dependability were considered in next scientific proceedings: in [4] the analysis and the classification of technologies, protocols and applications of IoT and their interaction with big data technologies and cloud and fog computing is performed. In [5] the depedability assessment of energy-efficient IoT devices is held.

In [6] Markov model of applications for ICT systems dependability is provied, taking into account redundancy.

In [7] the problem of applications of the IoT dependability regardless of their size and area of use is reseached. In [8] to ensure IoT system dependability it is adviced to use a simple formal "Mirror model" to transmit data from sensors in the IoT network, using the assets of the trust in blockchain.

In [9] a study of dependability of edge computing is conducted and challenges of deploying IoT systems in view of failures as hardware (crashing, hanging, and so on) and software, and vulnerabilities of IoT devices with decentralized control are included.

In [10] the methods and tools to predict dependability and improve the reliability of IoT are provided. The authors of this article propose the concept of creating dependable critical systems using IoT.

Thus, there is a large number of scientific publications that present the results of research, including analysis, evaluation and assurance of the reliability and cybersecurity of critical infrastructure systems, the dependability of these systems, as well as individual components of IoT systems. The known publications do not include generalized methodological results that would take into account certain contradictions between IoT capabilities and certain security deficiencies that may occur in their implementation in critical systems.

3 MATERIALS AND METHODS

The conception of interoperable systems based on the IoT is based on the well-known von Neumann paradigm of "building reliable systems from unreliable components" and its developed variants for dependable service-oriented systems and infrastructures [1].

For ICSIoT, it can be formulated as the construction of dependable IoT systems from insufficiently dependable (reliable and secure) nodes (embedded digital media, intelligent sensors, etc.), communications and cloud (server) resources in an aggressive environment with uncertain characteristics.

The scheme, which reflects the structure and interrelation of methodology elements of dependable systems, based design on the IoT, namely the concept, principles, models, methods, tools and technology, is shown in Fig. 1.

The conception of dependable systems based on the IoT is grounded on the next principles:

1. The principle of comprehensive consideration and assessment of various failure types of components, communications, services due to software defects and attacks on ICSIoT.

2. The principle of case-oriented formation and analysis and assessment of compliance with the requirements of ICSIoT dependability [11].

3. The principle of selection and implementation of measures to ensure dependability at all the life-cycle stges by the criterion – "acceptable risk – costs".

The conception and principles are implemented through the development of relevant models and methods of assessment and dependability implementation. In particular, the following groups of models have been developed:

1. Models of ICSIoT functional behavior, which are divided into:
   a. distributed intellectual energy ICSIoT models;
   b. dynamic ICSIoT based on cybergraphs model;
   c. functional behavior of medical ICSIoT [12] model.

The use of models allows to get a clear idea of how the system works (ICSIoT subsystem) in different situations and under the influence of various factors, including cyberattacks.

2. Models of dependability which include:
   a. theoretical-multiple model of dependability assessment [13];
   b. ICSIoT dependability assessment under cyberattacks influence [14]–[16];
   c. dependability assessment taking into account the power consumption modes of ICSIoT components [24].

The use of them allows a detailed assessment of the performance indicators of ICSIoT (availability functions, etc.) and its subsystems.

The models take into account two properties of dependability – cybersecurity and reliability of ICSIoT and its subsystems considering different types of cyberattacks.

3. ICSIoT reliability and cybersecurity models, including:
   a. ontological ICSIoT cybersecurity assessment mo-del;

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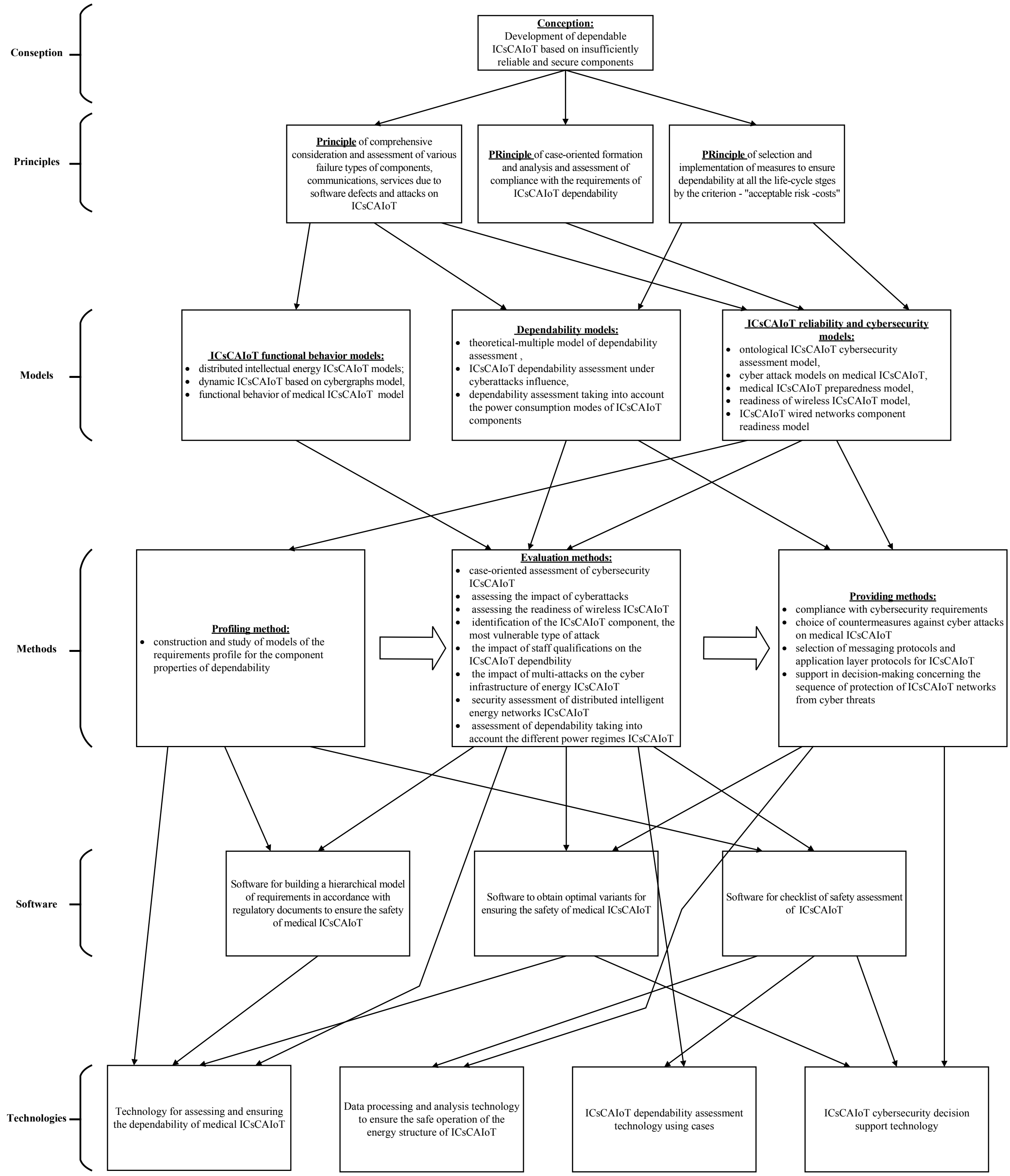

Figure 1 – Structure and interrelation of methodology elements of dependable systems, based design on the IoT

b. cyber attack models on medical ICSIoT [17], medical ICSIoT preparedness model, taking into account attacks on vulnerabilities of infrastructure components [18];

c. availability of wireless ICSIoT model taking into account the coverage factor;

d. ICSIoT wired networks component availability model [19].

These models allow to assess separately the reliability (coefficient or availability function) of ICSIoT and its subsystems, and separately the indicators of cybersecurity of ICSIoT and its subsystems.

Security models allow to identify the requirements for cybersecurity and assess the availability of ICSIoT under the influence of cyber attacks.

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These security models are the basis for a number of profiling, evaluation and assurance of ICSIoT methods. The profiling method is based on the construction and study of models of the requirements profile for the component properties of dependability [20]. Evaluation methods are based on the development and study of models of all the above types. Methods of ensuring security are based on the use of models of dependability and models of reliability and cybersecurity for ICSIoT [21].

On the basis of the profiling and evaluation methods, software ools for constructing a hierarchical model of requirements in accordance with the normative documents to ensure the safety of medical ICSIoT [21] are proposed. Based on security methods and evaluation methods, the best options for cybersecurity for the entire range of attacks have been developed [18]. Based on the profiling method and assessment methods, the software is developed for the ICSIoT security checklist assessment [20, 21].

Developed software tools have been integrated into information technology. Based on the best cybersecurity options for the entire range of attacks and the construction of a hierarchical model of requirements in accordance with regulatory documents to ensure the safety of medical ICSIoT, as well as the above relevant models and methods, the technology for assessing and ensuring the dependability of medical ICSIoT [21] was obtained.

Basing on the usage of software to form options for cybersecurity for the entire range of attacks there were proposed:

a) data processing and analysis technology to ensure the safe operation of the energy structure of ICSIoT;

b) ICSIoT dependability assessment technology using cases [20].

In addition, ICSIoT cybersecurity decision support technology is proposed, which is based on the use of security methods and software for ICSIoT security assessment checklists to obtain optimal cybersecurity options for the entire range of attacks [21].

4 EXPERIMENTS

To create the concept of dependable systems of critical applications based on the IoT, several models for assessing the reliability of the system, models of the functional behavior of the ICSIoT, models of reliability and cybersecurity were developed by authors of this paper. For so many models, different assumptions apply, and their input to the simulation. Based on the proposed models, methods for assessment, functional behavior, reliability and cyber security have been developed. Let's consider several examples of simulation of the obtained models.

The Markov model (Fig. 2) [14] describes the states of ICSIoT, which takes into account the reliability of system's software and hardware, attacks on the system and different modes of power consumption of the server and router. The simulation results are shown in Fig. 3 and Fig. 4.

The Markov model considering DDoS attacks and server's and router's energy modes without patches on possible vulnerabilities, which has the following states: good-working state (1); the server is fully used with high power consumption S0 (2); the server is fully used, the hardware, that are not used, can enter the low-power mode S1 (3); sleep mode of the server with low power consumption, a computer can wake up from a keyboard input, a LAN network or USB device S2 (4); server appears off, power consumption is reduced to the lowest level S3 (5); server failure (6); switching to the backup server device after the server failure (7); restarting of the server after the software fail (8); successful DDoS attack on the server after the firewall failure (9); firewall software or hardware failure (10); attack on the power supply system after the firewall failure, that lead the failure of general power system (11); technical state of switch from the general power system after its failure on the alternative energy sources (solar, diesel generator, wind turbine) (12); router status active – sending packages with high power consumption (13); successful DDoS attack on the router (14); good-working state of the router with transmitting packets – normal idle (15); good-working state of the router without packet transmission low-power idle (16); router software or hardware failure (17); server software or hardware fail (18); router hardware or software fail (20); switching to the backup router device after the router failure (21); restarting the router software after the router software fail (22).

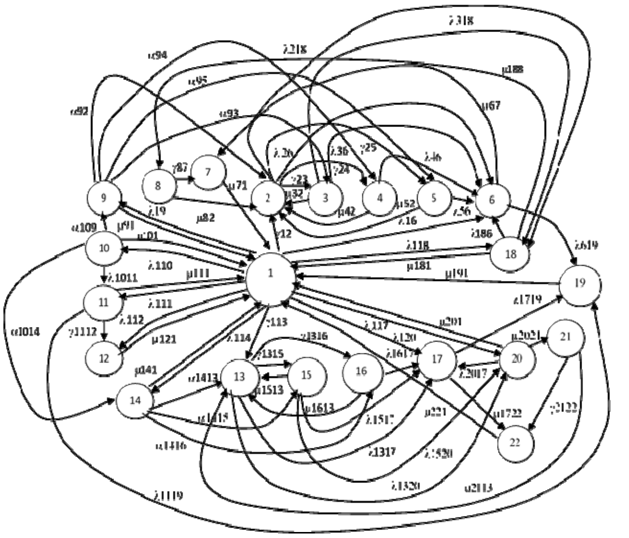

Figure 2 – Graph of the Markov model of the ICSIoT system states [14]

The model takes into account the rates to the states of the power consumption modes of the server and router (from state 2 to 3, 4, 5 and from states 14 to 13, 15, 16). Timely installation of a patch on firewall software vulnerabilities can reduce or stop the impact of DDoS attacks, which primarily affects the reliability of the ICSIoT server, router, and firewall (as a separate network device). When a DDoS attack affects ICSIoT subsystems, they cannot go into a state of reduced power consumption. For the Markov model (different variants of firewall software patching) the system of Kolmogorov-Chapman differential linear equations was presented and investigated, the

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value of the availability function $AC(t)$ ICSIoT with normalization conditions was calculated and analyzed [14]:

$$AC(t) = P1(t) + P2(t) + P3(t) + P4(t) + P5(t) + P12(t) + \\ + P13(t) + P15(t) + P16(t) + P21(t),$$

where

$$\sum_{i=1}^{22} Pi(t) = 1; \quad P1(0) = 1.$$

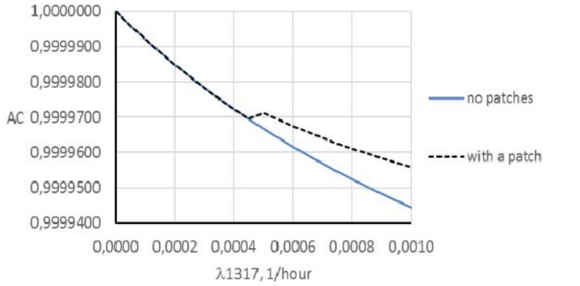

Figure 3 – Graphical dependences of AC ICSIoT on rate λ1317 for models with patching of firewall software vulnerabilities and without patches, if $\lambda 1317 = 0...1 \cdot 10^{-3}$ 1/h [14]

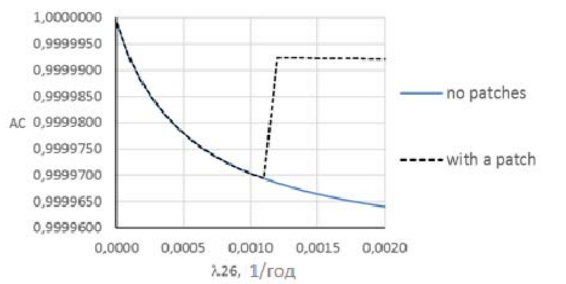

Figure 4 – Graphical dependences of AC ICSIoT on rate λ26 with patcherization of vulnerabilities in firewall software (*AC10*) and server and router firewalls (*AC*9_14), if λ26 changes values within $0... 2 \cdot 10^{-3}$ 1/h [14]

5 RESULTS

If the transition rate λ26 changes from 0 to 0.001 1/h, the *AC* value decreases from 1 to 0.99997 for the unpatched model and to 0.9999925 for the model with the firewall software patch installed (Fig. 4) [14]. The *AC* value is decreased by 0.999945 for the model without patch. If the values of λ1317 change in the range of 0… 10^{-3} 1/h, the *AC* value for the model with the firewall software patch will decrease from 1 to 0.999957 (Fig. 3). Installing a patch on the firewall (Fig. 3) allows you to obtain the same *AC* values (1 ... 0.93) at λ1317 = 0 ... 10^{-3} 1/h, but this value is significantly higher than in the model without patches: *AC* = 1 ... 0.9999553 (Fig. 3).

If no patches are installed on the firewall software, then *AC* decreases from 1 to 0.9999553 at λ26 = 10^{-3} 1/h. Installing a patch on the server firewall does not significantly change the AC value. If you install a patch on the firewall software, the AC value increases compared to the case without patches, with the same initial data, from 0.9999553 to 0.9999925. If the transition rate λ26 changes from 0 to 0.001 1/h, the *AC* value decreases from 1 to 0.99997 for the unpatched model and to 0.9999925 for the model with the firewall software patch installed (Fig. 4).

The *AC* value is decreased by 0.999945 for the model without patch. If the values of λ1317 change in the range of 0… 10^{-3} 1/h, the *AC* value for the model with the firewall software patch will decrease from 1 to 0.999957 (Fig. 3).

Installing a patch on the firewall allows to obtain the same *AC* values (1 ... 0.93) at λ1317 = 0 ... 10^{-3} 1/h, but this value is significantly higher than without patches: *AC* = 1 ... 0.9999553.

If no patches are installed on the firewall software, then *AC* decreases from 1 to 0.9999553 at λ26 = 10^{-3} 1/h. Installing a patch on the server firewall does not significantly change the *AC* value. If you install a patch on the firewall software, the *AC* value increases compared to the model without patches, with the same initial data, from 0.9999553 to 0.9999925.

If the transition rate value λ26 is changed from 0 to 0.001 1/h, the *AC* value decreases from 1 to 0.99997 for the model without patching and to 0.9999925 for the case with the patch installed on the firewall.

Decrease in the *AC* value occurs 0.999945 for a model without a patch. If the values of λ1317 change within the range 0…10^{-3} 1/h, value of *AC* for the case with patch on firewall decrease from value 1 to 0.999957.

Establishing a patch on the firewall allows to obtain the same *AC* values (1…0.999553) at λ1317 = 0…10^{-3} 1/h, but this value is significantly higher than in the case without patch: *AC* = 1…0.9999553. If patches are not installed on the firewalls, then the AC decrease from value 1 to 0.9999553 at λ26 = 10^{-3} 1/h. Patch installation on server firewall not significantly changes the *AC* of ICSIoT value.

Under the influence of DDoS attacks, the server, which is in one of the energy-saving modes, will switch to the mode of increased power consumption.

6 DISCUSSION

It was researched and analyzed the function availability of ICSIoT, taking into account the reliability of components, recovery rates, and different kinds of energy modes of server and router OS, DDoS attacks on the router and the server, and setting patches on firewalls vulnerabilities. Therefore, it is necessary to analysis of graphical dependences of the AC on the change of values of transition rates from one ICSIoT state to another showed that timely introduction of patches on software vulnerabilities of ICSIoT components significantly increases the value of the *AC* of the whole system and allows to increase system availability.

Markov models of ICSIoT system operation, in contrast to the existing ones, take into account the power regimes of the router and server, the impact of DDoS attacks, failures and failures of software and hardware, patching vulnerabilities of router software.

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The study results made it possible to develop and implement appropriate principles, methods, models and information technologies for assessing and ensuring the viability of ICSIoT in the fields of energy, medicine, mechanical engineering, aerospace, transport systems, etc.

The results of research of this proceeding are implemented on the follwoing enterprises (Table 1):

– at the enterprises of energy engineering (nuclear domain), RPC Radics LLC (Kropyvnytskyi, Ukraine) and PJSC SRPA Impulse (Severodonetsk, Ukraine);

– on the development of medical equipment, LLC “XAI-MEDICA” (Kharkiv, Ukraine);

– on the development of transport systems, LLC “SPC” Railwayautomatics” (Kharkiv);

– at machine-building enterprise, PJSC “FED” (Kharkiv);

– on the development of aerospace systems, scientific and technical design bureau “POLISVIT” (Kharkiv);

– on the development of state regulations by the State Service for Special Communications and Information Protection of Ukraine (Kyiv);

– on the development of methodological documents and requirements for the safety of critical infrastructure, PJSC “Institute of Information Technologies” (Kharkiv);

– in the educational process of the National Aerospace University “KhAI” (Kharkiv), Pukhov Institute for Modelling in Energy Engineering (Kyiv), Volodymyr Dahl East Ukrainian National University (Severodonetsk);

Table 1 – Summary of practical implementation of research and development results

Areas, enterprises (organizations), systems			**Results of research and development**							
			Models of non-functional characteristics			Methods of working with requirements			Automation technologies	
			Dependability models	Functional and behavior models	Reliability and cybersecurity models	Requirements profiling methods	Evaluation methods	Providing methods	Tools	Information technologies
Energy	RPC Radics LLC	ICSIoT components			+	+			+	
		Regulations			+	+				
	PJSC SRPA Impulse	ICSIoT components		+	+		+	+		
		Software								+
Medicine	LLC “XAI-MEDICA”	Telemedicine systems		+		+			+	
Transport systems	LLC “Scientific and Production Company” Railwayautomatics”	Microprocessor systems					+			
Engineering	PJSC “FED”	ICSIoT					+	+		
Aerospace systems	EDB “POLISVIT” SSPE “Kommunar Corporation”	Embedded systems				+	+	+		
State regulations	State Service for Special Communications and Information Protection of Ukraine	Critical Infrastructure Asset		+			+	+		+
	PJSC “Institute of Information Technologies”	Critical Infrastructure Asset				+	+	+	+	
Higher education	National Aerospace University “KhAI”, Pukhov Institute for Modelling in Energy Engineering, Volodymyr Dahl East Ukrainian National University	Learning process	+	+	+	+	+	+	+	+
International projects	TEMPUS international projects	MASTAC, SAFEGUARD, GREENCO, SEREIN, CABRIOLET	+	+	+	+	+	+	+	+
	ERASMUS+ international project	ALIOT	+	+	+	+	+	+	+	+
	FP7 scientific project	KhAI-ERA	+	+	+	+	+	+	+	+
	Horizon 2020 scientific project	ECHO, COST Action DigForAsp, SPEAR	+		+	+	+	+	+	+

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– in the educational process of the universities of EU countries: Institute of Informatics and Technology Alessandro Faedo of the National Research Council of Italy ISTI-CNR (Pisa, Italy), Tallinn Technical University TalTech (Tallinn, Estonia), Leeds Beckett University LBU (Leeds, UK);

– within the implementation of international projects under the European programs TEMPUS MASTAC, SAFEGUARD, GREENCO, SEREIN, CABRIOLET, ERASMUS + (ALIOT), FP7 (KhAI-ERA) [22], Horizon 2020 (ECHO) [23], COST Action DigForAsp [24], SPEAR [25], as well as in the implementation of national projects commissioned by the Ministry of Education and Science, the National Academy of Sciences of Ukraine in 2010–2020.The implementation in RPC Radics LLC has reduced the risks of cybersecurity violations in the development and implementation of NPP information and management systems. The implementation in PJSC SRPA Impulse allowed increasing the competence of operational personnel to ensure the protection of components of distributed intelligent power systems from cyberthreats. The completeness of cybersecurity increases by 20–30 %. The implementation of the results in LLC “XAI-MEDICA” allowed automating the process of the medical device functional behavior modeling, to reduce the evaluation time and to provide recommendations for ensuring the warranty and selection of evaluation tools. The implementition in LLC “SPCompany” Railwayautomatics” allowed reducing the risks of cybersecurity violations during the development and implementation of the software and hardware set “TEMP”. While using it in PJSC “FED” it was possible to reduce time costs, automate the process and increase the credibility of assessing the reliability of industrial IoT, to provide recommendations for ensuring the dependability and choice of assessment tools. The implementation of the research results in scientific and technical design bureau “POLISVIT” allowed reducing the time spent on assessing the security of systems, increasing the credibility of the assessment and confirming compliance with the requirements of technical and regulatory documentation. The implementation of the results at the PJSC “Institute of Information Technologies” has reduced the risks of cybersecurity violations in the development and implementation of cryptographic information security systems.

The use of research results at enterprises allowed obtaining technical and economic indicators that correspond to the level and exceed the best domestic and world counterparts.

The use of research results in the educational process and scientific work of the National Aerospace University “KhAI”, Pukhov Institute for Modelling in Energy Engineering, Volodymyr Dahl East Ukrainian National University, Tallinn Technical University, Institute of Informatics and Technology “Alessandro Faedo” of the National Research Council of Italy ISTI-CNR (Pisa, Italy), Leeds Beckett University (Leeds, UK), as well as in the implementation of international projects of the European programmes TEMPUS and ERASMUS+, the seventh framework program to support research activities FP7, the framework program of the European Union for Research and Innovation “Horizon 2020” funded by the EU, as well as state budget projects allowed to increase the fundamentality, clarity and practical orientation of the educational process and scientific activity.

Further research of the authors is aimed at detailing the developed models, methods and technologies to ensure the dependability of complex ICSIoT.

Research currently continues withing the ECHO project (creation of the European Network of Cyber Security Centers and the Center of Competence for Innovation and Operations). The developed methods of ensuring the dependability of complex ICSIoT s form the basis for identifying intersectoral and transversal challenges and opportunities in cybersecurity in various sectors as health, transport, manufacturing, telecommunications, energy, finance, management, space, defense.

The results of the research, presented in this paper, will be further used and developed in the doctoral dissertation on “Methodology for ensuring the dependability of IIoT systems”, in research projects under the funding program Horizon 2020 – ECHO and STARC and in public research proceedings commissioned by the Ministry of Education and Science of Ukraine.

CONCLUSIONS

The paper proposes a conception that includes a set of scientific and applied tasks for the development of methods, tools and technologies for the creation and implementation of dependable information & analytical and information & control systems for critical applications based on the Internet of Things. The following results were obtained:

1. The conception principles of ensuring the reliability of Information and control systems of critical applications based on Internet of Things, which are based on the development of von Neumann’s paradigm of creating reliable and secure systems based on insufficiently reliable and secure components.

2. The normative profile of ICSIoT was developed, which takes into account and harmonizes the list and content of requirements of international and national standards, which allow to make decisions on compliance of such systems with requirements in terms of reliability, availability, functional and cybersecurity, as well as to take them into account during development and modernization of ICSIoT.

3. Mathematical models and methods for assessing the performance, availability, functional and cybersecurity of ICSIoT were developed and researched, taking into account different types of failures and cyberattacks on systems that allow to analyze their functional behavior, improve assessment accuracy and formulate recommendations for selection hardware and software components, architecture, interaction protocols, etc.

4. Methods of creating dependable I ICSIoT for various complexes (medical, energy, industrial, communica-

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tion, etc.) and ensuring their reliability and safety in the development, modernization and use were developed.

5. Tools and information technologies to support decision-making in the creation, modernization and maintenance of ICSIoT for medical, energy, industrial, communication systems and complexes were developed and implemented.

In general, the authors obtained a number of technical and economic indicators, which are provided by the implementation of the results of scientific proceeding, correspond to the level and exceed the best domestic and world analogues.

The results of the presented study were implemented at eight enterprises of Ukraine in the fields of energy, medicine, mechanical engineering, aerospace industry, transport systems, as well as in the development of state regulations in the field of critical infrastructures. The obtained results are used in the educational process of three universities of Ukraine, two universities of the European Union (Estonia, Italy) and the University of Great Britain, as well as in the implementation of eleven international projects funded by the EU.

Some results of the study were also used in the development of draft regulations at the state level on the classification of critical information infrastructure by criticality and the criteria and procedure for classifying critical information infrastructure as critical. The implementation of the developed documents is an important step in building the Ukrainian state system of protection of critical information infrastructure.

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КОНЦЕПЦІЯ І ВПРОВАДЖЕННЯ ҐАРАНТОЗДАТНИХ СИСТЕМ НА ОСНОВІ ІНТЕРНЕТУ РЕЧЕЙ

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АНОТАЦІЯ

Актуальність. Проблема проектування, розробки, обслуговування та введення в експлуатацію гарантоздатних систем, побудованих з використанням інтернету речей на основі парадигми фон Неймана про «створення надійних систем з ненадійних компонентів» для надійних сервіс-орієнтованих систем та інфраструктур.

Метод. В статті запропоновано концепцію побудови ґарантоздатних систем на основі інтернету речей, проведений мультисекторальний аналіз методів і моделей оцінки надійності та кібербезпеки (ґарантоздатності) інформаційно-керуючих системи критичного застосування на основі інтернету речей для різних доменів: енергетичного, медичного, індустріального та ін. Аналіз показав, що деякі відмови і збої технічних засобів і програмного забезпечення, кібератаки і післядія впливу атак однакові для всіх доменів, але існують специфічні особливості для кожного домену, які необхідно враховувати при розробці методології забезпечення ґарантоздатності інформаційно-керуючих системи критичного застосування на основі інтернету речей.

Результати. Розроблена концепція, методи, засоби та технології створення та впровадження гарантоздатних інформаційно-керуючих систем критичного застосування на основі інтернету речей.

Висновки. У статті запропоновано концепцію, яка включає набір наукових та прикладних завдань щодо розробки методів, засобів та технологій для створення та впровадження гарантоздатних інформаційно-аналітичних та інформаційно-керуючих систем критичного застосування на основі інтернету речей. Перспективи подальших досліджень можуть включати деталізацію розроблених моделей, методів та технологій для забезпечення надійності складних інформаційно-керуючих систем критичного застосування на основі інтернету речей.

КЛЮЧОВІ СЛОВА: інформаційно-керуючі системи критичного застосування, інтернет речей, ґарантоздатність, кібербезпека, функційна безпечність.

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КОНЦЕПЦИЯ И ПРИМЕНЕНИЕ ГАРАНТОСПОСОБНЫХ СИСТЕМ НА ОСНОВЕ ИНТЕРНЕТА ВЕЩЕЙ

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АННОТАЦИЯ

Актуальность. Проблема проектирования, разработки, обслуживания и ввода в эксплуатацию гарантоспособных систем, построенных с использованием Интернета вещей на основе парадигмы фон Неймана о «создании надежных систем из ненадежных компонентов» для надежных сервис-ориентированных систем и инфраструктур.

Метод. В статье предложена концепция построения гарантоспособных систем на основе Интернета вещей, проведенный мультисекторный анализ методов и моделей оценки надежности и кибербезопасности (гарантоспособности) информационно-управляющих систем критического применения на основе Интернета вещей для разных доменов: энергетического, медицинского, промышленного и др. Анализ показал, что некоторые отказы и сбои программного обеспечения, кибератаки и последействие влияния атак одинаковы для всех доменов, но существуют специфические особенности для каждого домена, которые необходимо учитывать при разработке методологии обеспечения гарантоспособности систем притического применения на основе Интернета вещей.

Результаты. Разработана концепция, методы, средства и технологии создания и внедрения гарантоспособных информационно-управляющих систем критического применения на основе Интернета вещей.

Выводы. В статье предложена концепция, которая включает набор научных и прикладных задач по разработке методов, средств и технологий для создания и внедрения гарантоспособных информационно-аналитических и информационно-управляющих систем критического применения на основе Интернета вещей. Перспективы дальнейших исследований могут включать детализацию разработанных моделей, методов и технологий для обеспечения надежности сложных информационно-управляющих систем критического применения на основе Интернета вещей.

КЛЮЧЕВЫЕ СЛОВА: информационно-управляющие системы критического применения, Интернет вещей, гарантоспособность, кибербезопасность, функциональная безопасность.

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ERP-SYSTEM RISK ASSESSMENT METHODS AND MODELS

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ABSTRACT

Context. Because assessing information security risks is a complex and complete uncertainty process, and non-appearance is a major factor influencing the effectiveness of the assessment, is advisable use vague methods and models that are adaptive to non-computed data. The formation of vague assessments of risk factors is subjective, and risk assessment depends on the practical results obtained in the process of processing the risks of threats that have already arisen during the functioning of the organization and experience of information security professionals.

Objective. The object of the study are neural models that combine methods of fuzzy logic and artificial neural net-works and systems, that is, human-like style considerations of fuzzy systems with training and simulation of mental phi novena of neural networks.

Method. The paper analyzes modern areas of research in the field of information protection in information systems, methods and technologies of information security risk Assessments, use of vague models to solve problems of information security risk assessment, as well as concept and con-struction of ERP systems and analyze problems of their security and vulnerability.

Results. Identified factors influencing risk assessment suggest the use of linguistic variables to describe them and use fuzzy variables to assess their qualities, as well as a system of qualitative assessments. The choice of parameters for the development of the structure of a fuzzy product model of risk assessment and the basis of the rules of fuzzy logical conclusion justified.

Conclusions. A vague risk assessment model of ERP systems is considered. You have selected a list of factors that affect information security risk. The methods of assessment of risks of information resources and ERP-systems in general, assessment of financial losses from the implementation of threats, determination of the type of risk according to its assessment for the formation of recommendations for their processing in order to maintain the level of protection of the ERP-system are considered. The list of linguistic variable models is considered. The structure of the database of fuzzy product rules – MISO-structure is selected. Fuzzy variable models are considered.

KEYWORDS: information security, fuzzy logic, risk assessment, security, ERB-system.

ABBREVIATIONS

ALE – Annualized Loss Expectancy;

ARO – Annualized Rate of Occurrence;

ANFIS – Adaptive Network-based Fuzzy Inference System;

DB – Database;

DSTU – State standard of Ukraine;

CVE – Common Vulnerabilities and Exposures;

CVSS – Common Vulnerability Scoring System;

ERP – Enterprise Resources Planning;

ERP – System-Enterprise Recourses Planning System;

FIS– Fuzzy Inference System;

IES – International Electro-technical Commission;

ISO – International Organization for Standardization;

MIMO – Structure (Multi Inputs – Multi Outputs);

MISO – Structure (Multi Inputs – Single Output);

SISO – Structure (Single Input – Single Output);

NVD – National Vulnerability Database;

RDBMS – relational database management system;

SUN TZY – Normative document on technical protection of information.

NOMENCLATURE

A – financial loss from the single threat implementations;

P_e – the probability of an event;

R – risk of threat implementation;

P_t – probability of threat;

V – vulnerability level;

$<\alpha, X, C(\alpha)>$ fuzzy variable: α – name of the variable, $\alpha \in A$; X – universal set (α definition area);

$C(\alpha)=\{\mu_\alpha(x) \vdots x \in X\}$ – indistinct set on *X*, describing the limit on the possible values of fuzzy variable α; μ– accessory function;

$< X, T(X), E, G, M >$ linguistic variable;

X – the name of the linguistic variable;

T (*X*) – a set of values of linguistic variable (termplural), which imagines the name of fuzzy variables, the area of definition of each of which is a lot of *E*;

E – area definition variable (all range of its values);

G – a syntactic procedure that generates the names of a fuzzy variable, allows you to operate elements of the term set T(X), in particular, to generate new terms;

M – a semantic rule, which in accordance with each fuzzy variable *X* its value $\mu(x)$.

R – set of actual numbers;

$\mu_{A_{ij}}(x_j^1)$ – feature affiliations.

$M=\{\mu_i(x_j^1) \vdots i=\overline{1,n}\}$ –a set of functions of belongings;

$\mu_i(x_j^1)$ – the function of the *i*-th belonging to the Variable x_j^1 the i-th segment of the variable Value area;

i – number of segments area of the variable value.

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INTRODUCTION

Risk implies a combination of the probability of damage by overcoming the system of protection using vulnerabilities and the severity of such damage. Minimizing the risks is done by developing a "security policy" (behavioral scheme) and managing it. Thus, the concept of "risk of information breach" is based on an analysis of "causes of information security Brea chess "and" consequences of information security breaches".

Risk assessment is carried out in the simplest case by two factors: the probability of accident and the severity of possible consequences.

Object of research in this paper is the information security of ERP-systems.

Subject of research – models and methods for assessing information security risks.

The purpose of this work is to improve the quality of information security and ERP systems risk assessment with fuzzy neural models.

1 PROBLEM STATEMENT

As part of the business risk of an enterprise, the risk of information security is defined as a product of loss (financial) from breach of confidentiality, integrity, authenticity or availability of information resources (the severity of consequences) for the likelihood of such infringement (probability of event):

$$R = A \cdot P_e, \quad (1)$$

Vulnerability:

$$P_e = P_t \cdot V. \quad (2)$$

The level of systemic risk is calculated as the sum of risks for all assets and each threat, taking into account the vulnerabilities and the effect of the taken countermeasures as the difference between the amount of planned costs for countermeasures and the total loss assessment at the determined system risk level.

Security risk assessment is an important element in the overall security risk management process, which is the process of ensuring that the organization's risk position was within the acceptable limit of the senior management, and consists of four main steps: Assessment of security risks, testing and oversight, risk mitigation and operational security.

Risk managers and decision-making organizers use risk assessments to determine which risks are reduced through control and which to take or transmit.

The assessment of information security risks is the process of identifying the vulnerable situations, threats, the probability of their occurrence, the level of risks and consequences related to organizational assets, as well as the control that can mitigate these threats and their consequences. It offers readers:

1) Assess the probability of threats and vulnerabilities that are possible; 2) Calculation of an impact that may that are possible; 3) Calculation of an impact that may have a threat to each asset; 4) Determination of quantitative (measurable) or qualitative (described) cost of risk.

Information security risk assessment is divided into three general stages:

1).Risk identification; 2).Riskanalysis;3).Risk Assessment.

Risk assessment includes seven steps: identification of system protection facilities; identification of the threat; identification of vulnerability; control analysis; determination of probability; analysis of consequences; identification of risk.

Complete risk assessment process should also include two more steps: Recommendations for monitoring and documentation of results.

According to the results of the risk assessment, it is decided that the choice of means to influence the risk in order to minimize the damage from the implementation of threats in the future. The following methods of exposure to risk are used.

The following methods of exposure to risk are used. Risk reduction – reduction of possible damage or probability of adverse events. This can be achieved as this: exclusion of risk; reducing the likelihood of risk; reduction of possible losses.

Preservation of risk (acceptance) – provides for the refusal of actions aimed at compensation (without Financing), compensation of it from the sources of the Organization (Risk fund, self-insurance Fund), or with the involvement of external sources (subsidies, loans etc.). The most commonly refers to threats with low damage and low probability of occurrence.

Risk transfer – transfer of responsibility for it to third parties (most often for remuneration) while maintaining the existing level of risk.

2 REVIEW OF THE LITERATURE

There are two main approaches to assessing risk: qualitative and quantitative approaches. The third approach, called mixed or hybrid, combines elements of qualitative and quantitative approaches.

Quantitative assessments of the risk of information security use mathematical formulas for determining the exposure factor and the expected loss of one or every threat, as well as the probability of a threat implementation, called the annual rate of ARO. These figures are used to estimate the amount of resources (money) that will be lost annually to vulnerabilities used, called the annual duration of ALE loss. By using the received figures, the organization can plan to monitor this risk if the countermeasure is available and cost effective. These numbers allow for the analysis of costs and benefits for each countermeasure and the threat to the asset. Countermeasures that reduce the annual duration of damages more than their annual costs should be applied if there is sufficient resource to use the countermeasure.

The advantages of using this approach are the ability to quantify the consequences of incidents, analyze costs and benefits when choosing remedies and get a more accurate definition of risk.

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The disadvantages include the dependence of quantitative indicators on their volume and accuracy of the measurement scale, inaccuracy of results, the need to enrich quality description, a large cost of the analysis, which requires more experience and modern tools.

Qualitative risk assessments of information security use experience, judgment and intuition, not mathematical formulas. Qualitative risk assessment may use surveys or questionnaires, interviews and group sessions to determine the level of threat and the annual loss duration. This type of risk assessment is very useful when it is too difficult to attribute values to a particular risk. Qualitative assessments of information security risks tend to be well perceived because they involve many people at different levels of the organization; they do not require a large number of mathematical computing, but the results tend to be less accurate than the results achieved by quantitative evaluation.

The disadvantages of approach are the inability to determine the probability and results, using numerical measures and approximate overall nature of the results.

It is possible to use a mixed approach to information security risk assessments. This approach combines some elements of both quantitative and qualitative assessments.

This approach is to assess greater credibility through presenting difficult facts, but it also engages people inside the organization to obtain an individual understanding. The disadvantage of this approach is that its implementation may take longer. However, a mixed approach can lead to better data than what these two methods can get separately.

Information risk assessment involves the use of various technologies, documents or software tools.

The methodology for assessing information security risks involves a sequence of actions that are necessary, as well as a tool (software product) to assess the risks at the enterprise.

Information risk assessment is carried out using various technologies, documents or software. The methodology for assessing information security risks is understood by a systematized sequence of actions (step-by-step instructions) that need to be done and a tool (software product) for risk assessment at the enterprise.

Currently, the following standards are operating in Ukraine: ISO 27001, ISO 27002, ISO 27003, ISO 27004 and ISO 27005 [1–5].

Based on the differences in risk analysis approaches, ways to review risk elements, functionality and other assessment methods, all risks vary as follows:

1. Graphical – methods that involve visualization of objects of analysis and processes of interaction between them, while graphs, trees or diagrams are built, allowing different ways to display information about the objects studied. In most cases, these methods only allow identification of risk elements and methods of interaction between them.

2. Mathematical methods, which define the properties of objects and their interaction with the help of some formal languages describing the laws of functioning, changes of properties, etc. These methods allow not only identifying elements, but also to analyze their behavior, changing their properties and influencing on other elements.

3. Linguistic – Methods that do not involve any tools and programs, and require only a team of person is responsible for risk analysis. At the same time, all the stages of risk assessment, as possible, assume only oral communication between groups of persons, during which the elements of risk are identified, the assumptions about their behavior are made and an approximate assessment of opportunities and losses is carried out. This class of methods is most popular and easy to use, but is not always able to lead to an adequate assessment of the situation.

In recent years, highly intensively developed methods of analysis and risk assessment, which are based on the elements of Fuzzy logic. Such methods allow to change the close tabular methods of rough assessment of risks on a mathematical method, as well as to significantly expand the possibilities of mathematical risk analysis methods [6–8].

The mechanism of risk assessment through fuzzy logic in general is imagines with itself the expert system. The knowledge base of such system will make rules that reflect the logic of the relationship of input values of risk factors and risk level. In the simplest case, a table describs this logic in general, which more accurately reflects the real relationships of factors and consequences. Such connections are formalized and described by the production rules of the "if-something" type. In addition, the fuzzy logic mechanism provides for the formation of factor ratings levels and their representation in the form of fuzzy variables. The process of shaping this type of assessments in general is quite complex, because it requires a large number of sources of information, consideration of their quality and the use of experts experience.

To determine the level of risk, it is advisable to use the theory of fuzzy sets, which allows you to describe vague concepts and knowledge, operate them and draw vague conclusions. The theory of fuzzy models used to solve problems in which inputs are unreliable and poorly formalized, as in the case of the problem solved in this work. To assess the risk, it is appropriate to use the mechanism of a vague logical conclusion – obtaining a conclusion in the form of a fuzzy set corresponding to the current values of input variables, using a fuzzy knowledge base and fuzzy operations.

There are developed models of fuzzy conclusion of Mamdani, Sugeno, Larsen and Tsukamoto [9]. The most commonly used in practice are Mamdani and Sugeno algorithms. The main difference between them is the method of specifying the values of the output variable in the rules constituting the knowledge base. In systems such as Mamdani, values of input variables are given in fuzzy volumes, in Sunio-type systems – as linear coexistence of input variables. For tasks, which are identifications that are more important, it is advisable to use the algorithm Sugeno, and for tasks in which more important is the explanation and justification of the decision, the Mamdani algorithm will have an advantage.

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3 MATERIALS AND METHODS

A fuzzy plural (fuzzy set) is a set of arbitrary elements that cannot be accurately stated whether these elements have some distinctive properties used for fuzzy values.

Therefore, the fuzzy set *A* is defined as many ordered pairs consisting of elements of *X* universal set *X* and relevant degrees of belonging to the

$$\mu_A : A = \{(x, \mu_A(x)) \vdots x \in X\},$$

μ_A – is the indicator affiliation feature (or just a feature of belonging) that takes value in the ordered plural *M* = [0; 1] and indicates the degree (or level) of the element *x* subset of *A*.

The degree of belonging μ_A is a subjective measure of , as the $x \in X$; element, corresponds to the notion whose meaning is formalized by *A* [10] fuzzy set.

Classical logic cannot work with vague concepts because all statements in formal logical systems can have only two mutually exclusive rules: "True" with the meaning of Truth "1" and "not true" with the meaning of truth "0".

One of the attempts to escape from the double-digit binary logic to describe uncertainty was the introduction of Lukasevich [11] three-digit logic with a third State "may" with the value Truth "0.5". By typing fuzzy sets in the review, Zade [12] suggested summarizing the classical binary logic based on the consideration of the infinite number of truth-values.

In the suggested version of vague logic, the meanings of true statements are summarized to the interval [0; 1], that is, include both individual cases of classical binary logic and Lukasevich's trivial logic. This approach allows us to consider statements with different values of truth and to perform reasoning with uncertainty.

"Perhaps true", "perhaps wrongly", etc. The higher the confidence in the truth expression, the closer the value of the degree of truth to "1". In the boundary cases "0", if there is absolute certainty in the false statement, and "1", if there is an absolute sure of the truth statement. The fuzzy reflection of *T*: Ω → [0, 1] acts on a multitude of fuzzy statements Ω = *A, B, C*. In this case, the value of the Ω $A \in$ [0, 1] and is an estimate of uncertainty [10].

Like normal logic, fuzzy logic uses operations to construct complex statements.

1. Logical objection – "Not *A*", "false as *A*", the value of truth of which: $T\neg A = 1 - TA$.

2. Logical Conjunction – "*A* and *B*", who's meaning is truth:

$$TA \cap B = \min(TA; TB). \quad (3)$$

3. Logical disjunction – "*A* or *B*", whose meaning is truth:

$$TA \cup B = \max(TA; TB). \quad (4)$$

4. Fuzzy momentum is "with *A* should *B*", " if *A*, then *B*", whose truth-values are:

$$TA \supset B = \max(\min(TA; TB); 1 - TA).$$

5. Indistinct equivalence – "*A* is equivalent to *B*", whose truth-values are? $TA \equiv B = \min(\max(T\neg A; TB); \max(TA; T\neg B))$.

In describing objects and phenomena by means of Fuzzy sets, the concept of fuzzy and linguistic variables [10, 13, and 14] is used.

Fuzzy variable characterized by the following expression

$$<\alpha, X, C(\alpha)>.$$

Fuzzy plural on X, which describes the limitations on possible values of a fuzzy variable α, has a drawer:

$$C(\alpha) = \{\mu_\alpha(x) \vdots x \in X\}.$$

Linguistic variable is a subjective assessment of a person, which is expressed as a natural language, regarding a specific value of a numerical variable.

Linguistic variable is called set

$$< X, T(X), E, G, M >. \quad (5)$$

For example, the expert determines the thickness of the manufactured product using the concepts of "low thickness", "average thickness" and "high thickness", with the minimum thickness equal to 10 mm, and the maximum – 80 mm.

Formalization of this description can be carried out with the help of the following linguistic variable (5):

We will present: *X* – thickness of the product; *T* (*X*) – {"Small thickness", "average thickness", "high thickness"}; *E* – [10, 80]; *G* –procedure for the formation of new term with the help of connections "i", "or" and modifiers such as "very", "not"", ""slightly"" etc. For example: ""Small or medium thickness", "Very small thickness", etc.; *M* – Task Procedure *X* = [10, 80] fuzzy subsets, A_1 = "small thickness", A_2 = "average thickness", A_3 = "large thickness".

4 EXPERIMENTS

The term-many and extended term set in the conditions of an example can be characterized by the functions of belonging (see Fig. 1–2).

Fuzzy numbers are fuzzy variables defined in the metric axis, which is a fuzzy number A defined as fuzzy for a set of real R numbers with function affiliation *R* with feature affiliations $\mu_{A_x}(x) \in [0,1]$, *x* is a real number, i.e. $\in A$.

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The system of Fuzzy logic conclusion is the process of obtaining fuzzy conclusions in the necessary management object based on fuzzy conditions or preconditions, representing information about the current state of the object.

The basis for a fuzzy logical conclusion is the indistinct system, which consists of linguistic rules. Let *x* and *y* are input and output linguistic variable; *A* and *B* are some fuzzy sets (feature affiliations) taken from the term sets of *x* and y variables, respectively.

The linguistic rule of vague conclusion "if any" looks like: R = "$x \in A$, then $y \in B$", where R "$x \in A$" is a vague statement, called the rule

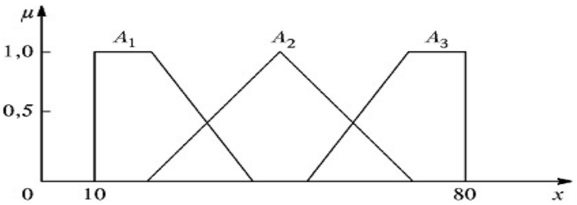


Figure 1 – The accessories of fuzzy sets: "small thickness" = A_1, "average thickness" = A_2, "high thickness" = A_3

Condition, "$y \in B$" is a vague statement called the conclusion rules.

Fuzzy logical conclusion combines all basic concepts of the theory of fuzzy sets: Functions of belonging, Linguistic variables, methods of fuzzy implication, etc.

The fuzzy output system consists of five functional blocks [9, 15 and 16].

1. Block of Phazyfication. Phazyfication (introduction of fuzziness) is the setting of the correspondence between the numerical value of the input variable of the fuzzy Output system and the value of the function of belonging to the corresponding term of the linguistic variable. At the stage of phazyfication the value of all input variables of the system fuzzy output, received externally with respect to the system of fuzzy output method.

In case of a clear value of the input variable $x_j^{'1}$ the degree truth fuzzy saying "$x_j^{'1} \in A_{ij} \, x_j^1$" is determined by the.

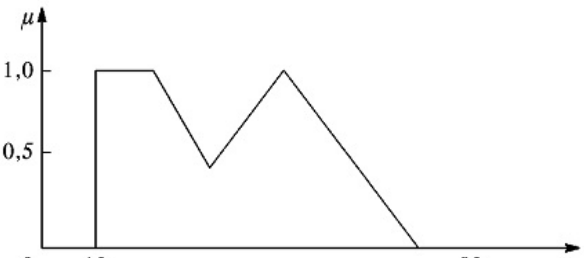


Figure 2 – The function of the fuzzy set "small or average thickness" = $A_1 \cup A_2$

Value of the $\mu_{A_{ij}}(x_j^1)$ function. When the same fuzzy value is specified, the input variable $\tilde{x}_j^1$ the degree of truth of the appropriate fuzzy statement "$\tilde{x}_j^1 \in A_{ij}^1$" in the premise is determined based on one of the fuzzy conjunction operations (3), e.g. operation min – conjunction $\mu_{A_{ij}^1}(x)$ = min $\{\mu_{\tilde{x}_j}(x_j),\ \mu_{A_{ij}}(x_j)\}$, or the operation of algebraic product $\mu_{A_{ij}^1}(x_j) = \{\mu_{x_i}(x_j) * \mu_{A_{ij}}(x_j)\}, \forall x_j \in X_j$.) For an example of fuzziness, see Fig. 3 [16].

2. The base of the system rules of fuzzy output is intended for the formal presentation of empirical knowledge of experts in a particular subject area in the form of fuzzy product rules. Thus, the base of fuzzy product rules of fuzzy output system is a system of fuzzy product rules; reflecting expert's knowledge on methods of management of the object in different situations, nature of its functioning in different conditions, etc. i.e., contains the formalized human knowledge.

Depending on the number of fuzzy statements in the prerequisites and the conclusions database of the fuzzy product model, the structure of one of the following types can be represented [17]:

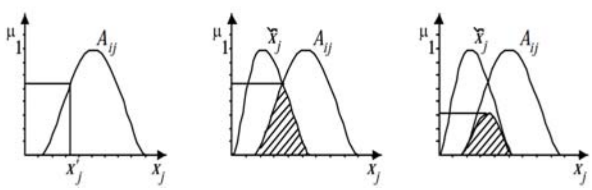
– SISO-Structure;
– MISO-Structure;
– MIMO Structure.

3. Database. It contains definition of the belonging to the fuzzy sets function used in fuzzy rules:

$$M = \{\mu_i(x_j^1) \vdots i = \overline{1, n}\}.$$

4. Decision-making unit (block of vague logical conclusion). Performs withdrawal operations based on existing rules: aggregation of conditions – the procedure for determining the level of truthfulness of the rules of the system of fuzzy conclusion. Activation of conclusions – the procedure for determining the level of truthfulness of the conclusions of the product rules. Accumulation – the procedure for finding the function of belonging for each of the original linguistic variables specified by the set of rules [9].

5. Block of Dephazyfication. Dephazyfication in fuzzy output systems is the process of transition from the function of the source linguistic variable to its clear (Numeric) value. The purpose of dephazyfication is to obtain quantitative values for each output variable used by external means in relation to the fuzzy output system using the results of accumulating all outgoing linguistic variables [10].



A B C

Figure 3 – Examples of entering a fuzzy with the use of clear values of the input variable x_j^1 (A) and fuzzy value of the input variable $\tilde{x}_j^1$ operation min-conjunct (B) and algebraic equal (C)

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Neural fuzzy networks have fuzzy values in different components of traditional neural networks based on the theory of fuzzy sets and fuzzy logic. Different types of intelligent systems have their own characteristics, for example, regarding the possibilities of learning, generealization and getting results, which makes them the most suitable for solving some classes of problems and less suitable for others.

Neural networks are convenient for the problems of pattern recognition, but are very inconvenient to explain how they perform recognition. They can automatically gain knowledge, but the process of their learning is often slow enough, and the analysis of the trained network is very complex (trained network is usually "black box" for the user). At the same time, some priori information (expert knowledge) to accelerate the learning process in the neural network is difficult to enter.

Systems with fuzzy logic, opposite, are easy to explain obtained with their help of conclusions, but they cannot automatically gain knowledge for their use in mechanisms Vive den. The need to break the universal sets into separate areas, as a rule, limits the number of input variables in such systems a small value.

Hayashi and Imura [18] have shown that a direct-spread neural network can approximated any system based on vague rules, and any direct-spread neural network can be aproximized by a system based on vague rules. In theory, systems with fuzzy logic and artificial neural networks are similar to each other, but in practice, they have their own advantages and shortcomings. This understanding has formed the basis for the creation of the apparatus of fuzzy neural networks, in which the output is made based on fuzzy logic, but the relevant affiliation functions are adjusted using methods of teaching neural networks, for example, method of reverse propagation error. Such systems not only use a priori information, but also can acquire new knowledge, being logically transparent.

Neuro-fuzzy network is the presentation of a fuzzy output system in the form of a neural network convenient for learning, analyzing and using. The structure of the neuro-fuzzy network corresponds to the main blocks of fuzzy output systems [19, 20].

Fuzzy models and algorithms of fuzzy output on their basis can be presented in the form of fuzzy products networks, in the structure of identical multilayered neural networks with direct signal distribution (feed forward), elements of each layer (or combination of layers), implementing a separate stage of fuzzy output in a fuzzy production model:

The first layer of neurons performs the function of introducing fuzziness (phazyfication); Hidden layers display a combination of fuzzy rules and implement the fuzzy output algorithm; The last layer performs the function of bringing to clarity (dephazyfication) of the original variable.

At present, a large number of different architectures of neuro-fuzzy networks are known [21, 22]:

– Fuzzy neural systems (fuzzy neural systems): In neural networks, fuzzy logic principles are applied to speed up the configuration process or improve the parameters;

– Fuzzy logic is only an instrument of neural networks and such a system cannot be interpreted in fuzzy rules, since it represents the "black box";

– Competing neuro-fuzzy systems (concurrent neuro-fuzzy systems): A fuzzy system and a neural network are working on one task without affecting each other's parameters;

– Parallel neuro-Fuzzy systems (cooperative neuro-fuzzy systems): Settings executed are with the help of neural networks, after which the fuzzy system functions in-dependently;

– Integrated (hybrid) neuro-fuzzy systems (Integrated neuro-fuzzy systems) – systems with close interaction of fuzzy logic and neural networks.

ERP is understood to be the concept of a coherent solution for accounting, control, planning and management of industrial and financial resources of the enterprise. Research firm Gartner Group to describe management systems that provide automation of planning, forecasting and financial management processes, production, logistics and marketing, accounting, product design, development of technological processes, etc. introduced the term. ERP is a global management standard proposed by the U.S. Manufacturing and Reserves Management Community.

5 RESULTS

ERP-System is a corporate integrated information system that implements the ERP concept, creating a single information environment for automation of planning, accounting, control, management and analysis of the main business processes of the enterprise.

The purpose of the ERP-system is to integrate all departments and structures of the company into a single information and technological computer network to meet all the needs of individual units.

The most common ERP systems are SAP, Oracle E-Business Suite, and Microsoft Dynamics.

The term ERP-system used in the following two meanings as:

1) information system for identification and planning of all resources of the enterprise, which are necessary for the sale, production, purchase and accounting in the process of fulfillment of client orders;

2) Methodology for effective planning and management of all resources of the enterprise, which are necessary for the sale, production, procurement and accounting when fulfilling customers orders in the spheres of production, distribution and service provision.

The typical ERP-system ensures the following tasks:

– financial management;
– Production management;
– Managing inventory formation and distribution;
– Management implementation and marketing;
– Management of customer retention;
– Supply management;

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– Project management;
– Personnel management;
– Service management;
– Quality assurance procedures.

In addition, the ERP-systems can support electronic data exchange with other software applications, as well as simulate situations that are related to planning and forecasting.

The use of ERP-Systems has the following advantages for the enterprise:

– Saving business in the long term by optimizing processes;
– Reducing operating expenses due to simplified business processes and best practices;
– Improve user collaboration;
– Reducing risk by increasing data integrity and financial control;
– Reducing management and operation costs through single-form and integrated systems;
– Providing a unified system that reduces IT, workforce and training costs;
– Obtaining real-time information by business;
– Facilitating the reporting and planning process with improved data and analytics;
– Increase accountability and security by controlling user rights.

In addition to advantages, the use of ERP-Systems has its drawbacks:

– deploying and maintaining the ERP-system can be very expensive;
– System deployment is a long and complicated process;
– Deploying a system of significant changes in management;
– ERP-systems are often less complex than specialized software and may not be used or replaced.

The objectives and tasks of information security in ERP-systems are as follows:

– mitigation of the risks of loss/disclosure;
– Compliance with state and intra corpo-rate standards of information protection;
– Data integrity protection;
– Guarantee of confidentiality of company's internal information.

ERP-systems have a complex architecture that combines various technologies, such as application servers, databases, inter-platform software, Web server, operating systems, ID management systems, etc. This complexity creates additional threats in terms of information security, which can occur in the design and development stages of the ERP-system, and during the implementation and operation stages [24].

The typical ERP-system consists of three components, connected through the client-server architecture (see Fig. 4):

– DB level;
– Application level;
– View level ((assigned to the user).

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Data storage is carried out in the database (level DB), their processing is done on the server application (application level), and user interaction occurs through the client application (presentation layer). The environment, which unites all the components that are on different architectural levels of the ERP, is the network infrastructure.

Figure 4 – Three level environment of ERP-systems

The three tiered client-server architecture can be deployed to a multilevel system.

Thus, the main aspects of security to consider when using the ERP-system, are:

– network security;
– Operating system security;
– DB security;
– application-level security;
– Protection of information on the client computer.

Ensuring security of information is necessary at each of the selected levels of the ERP-system, with the choice of information security mechanisms at the above levels depends on the specifics of a particular project and the risk level of each threat.

ERP systems are generally developed as large, complex, homo geneous, critical applications, and are usually developed and marketed as commercial extraordinary software by large software vendors such as SAP, Oracle, and Microsoft. ERP application development is theoretically based on the best industry practices, and they are designed to meet the broad business requirements covering a wide range of industries.

The functionality provided by commercial ERP-systems is designed in such a way that it can be configured to enable customers to incorporate their own business rules to meet specific business or industrial requirements. However, even after the configuration is completed, gaps often remain between the standard functions provided and specific requirements of the organization. Aiming to improve user adoption, most ERP systems customers complete the development of extensions and settings to make sure the app better supports business processes.

As ERP systems handle and store confidential personal and commercial information relating to employees, customers, suppliers, prospects and projects, further development beyond the original scheme exposes the application to increased risk of data breaches and non-compliance with the rules.

Custom development tends to constitute a very small portion of the entire application, but since they are accessing and processing the same sensitive data as the un-derlying program, they pose a significant security risk, which can potentially cost an organization's loss from a security breach. Extension and configuration of ERP applications is a specialized technical effort that requires, apart from the necessary development skills, to understand the architectural, functional and security model of the program, including proposed by the manufacturer best practices for product expansion. Here are some key aspects of security that enterprise developers must take into account when using ERP-applications:

1) Access Management. ERP application access control refers to the identification and management of authorized users, including giving them the appropriate roles needed to access processes and data. Access control is crucial for protecting data against unauthorized disclosure and change at the same time, maintaining appropriate availability levels for authorized users for operational purposes.

2) Database level security. At the heart of the ERP-system is RDBMS, which manages data entry/output and storage on the database server. The ability to customize data objects for different users is the key to any application and the basis for the security architecture to control access to data. Different database platforms provide tools for creating logical data objects that allow various users to view and handle common business objects differently.

3) Data encryption/ Data masking. In addition to functional access and data access controls, ERP data can be encrypted to mitigate exposure risks. Encryption is the most important tool for protecting sensitive information, more commonly used to transmit data, ensuring privacy and data integrity. For static data, encryption is not required for all security scenarios, but for sensitive personal data such as credit card numbers or passwords, this is an important tool. Data masking is a technique that is used to protect further data when encryption is not necessary. This allows you to move sensitive information in a way that will not prevent ordinary operations with a database such as maintaining reference integrity and limiting data types. Data values change but meet the schema requirements, allowing extracts from a database that usually contain sensitive data used for development purposes and testing. Data masking can be done using scripts, or special tools from developers of ERP systems.

Among the most common security problems, ERP-system can specify the following threats:

– The delay of updates that are necessary mainly to eliminate the vulnerabilities found in the software, and the installation of which is vital to prevent the possibility of using these vulnerabilities;

– Insufficient control of access rights, which, in the wrong setting, become potential internal risks to the system and threaten the integrity and confidentiality of information;

– Insufficient training of personnel working with the system, especially for new employees, who do not have deep knowledge of internal processes and errors, which may violate the principles of business processes execution;

– Insufficient checking of personnel having unimpeded access to system processes and ability to change the functionality of the ERP-system software;

– Use of unlicensed programs that can be used together with the ERP-system to achieve a single goal (for example, support for sales data in the ERP system, but run reports using Excel);

– Errors in implementation and configuration of the platform (customization, incorrect credentials, open ports, etc.) ERP system, which has many configuration files, can also potentially compromise the functioning of the process and data;

– Failure to comply with the regulatory norms and regulations intended to protect confidential information entails financial and reputational consequences.

Here is a list of common vulnerabilities of ERP-systems:

1) Complexity. ERP systems handle transactions and implement procedures to ensure that users have different access privileges. For example, in SAP R/3 system, there are actually automated object objects that allow to perform various actions on systems. In an organization of medium size can be created about one hundred types of transactions, each transaction usually requires that the smallest, two-object authorization. On the example of the SAP system, if the company has 200 users, there are approximately 800 000 (100 * 2 * 20 * 200) methods for configuring the security parameters of ERP-systems [25].

As complexity increases, the possibility of errors and conflicts of authority also increases [26].

2) Specificity of the software. Software vendors regularly correct the vulnerabilities because hackers track business applications to find and use security issues: SAP Monthly releases a hot fix, Oracle issues security fixes to quarterly, moreover, business applications become increasingly exposed to Internet or migrate to the cloud [27].

Internal business applications close to prying eyes, and this leads to the illusion of "safe as classified", but in specific business applications find trivial and extremely dangerous security vulnerabilities that are rare in popular products.

3) Lack of competent specialists. Most ERP system training programs are designed to teach how to use system capabilities and pay little attention to ERP security and auditing [25]. The majority of companies understand the threats of ERP systems by the security service at best superficially [28]. Many companies do not pay proper attention to the security of the ERP system. The implementation consultants tend to be concerned only by having to deploy the system in time and invest in a pre-determined budget. Safety issues are considered secondary. Because of this, the security of the system turns out to be weak, and to identify and fix safety problemsa difficult and costly measure.

4) Lack of security auditing tools. ERP security Audit is done manually, as various tools with ERP, packages do not provide system security auditing tools. Manual audit

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is a complex and laborious process that increases the possibility of error [26].

5) A large number of settings. In the default, system settings there are many parameters and subtle settings that include the differentiation of rights for different Objects, such as transactions and tables. In all these mass settings, the task of securing is not easy even for a system. In addition, the customer somehow sharpens a large part of the ERP system settings, so that there are no two identical ERP systems. In addition, they develop their programs, safety of which should also be taken into account in the comprehensive assessment of the [29]. For this reason, it is difficult to develop a consistent approach or methodology for security audits.

We provide a list of vulnerabilities of ERP systems, according to the level of architecture [30].

Network layer:

1. Ability to intercept and modify traffic:

– lack of data encryption – data transfer between the client and the server client-server requests containing critical information can be intercepted or modified;

– password transfer in the open form.

2. Vulnerabilities in the encryption or authentication protocol:

– ash authentication;

– XOR password encryption;

– Introduction of the use of old authentication protocols;

– Non correct authentication algorithms.

3. Using a network protocol vulnerability would cause legitimate users to be denied access so that an attack could be carried out:

– Error in RFC the YSTEM_-CREATE_INSTANCE function (exploit the vulnerability allows arbitrary code);

– Error in RFC RFC_START_GUI function (exploiting the vulnerability also allows arbitrary code);

– Error in RFC the RFC_START_PROGRAM function (exploit the vulnerability could allow arbitrary code or learn about the RFC server configuration);

– Error in RFC the TRUSTED_SYSTEM_SECURITY function (exploit the vulnerabilities allows information about existing users and groups on the RFC server).

Operating system level:

1) OS software vulnerabilities: Any vulnerability in the OS used to access applications.

2) Weak OPERATING OS passwords:

– possibility of remote selection of passwords;

– Empty passwords for remote control tools such as RAdmin and VNC.

3) Unsafe OS settings:

– NFS and SMB (data can be accessed by an anonymous user via NFS or SMB);

– File permissions;

– The unsafe settings of the hosts (trusted hosts can be set by servers that can easily be captured by an attacker.

Application vulnerabilities.

– All possible vulnerabilities in web applications;

– Buffer overflow and format string in web servers and application servers;

– Dangerous access rights.

6 DISCUSSIONS

Modern scientific directions in the field of information protection in information systems, methods and technologies of information security risk assessment, use of fuzzi models to solve problems of information security risk assessment, as well as concepts and developments of ERP systems and problems of their security and vulnerability.

According to the results of the survey, the proposed factors influencing risk assessment use linguistic variables to qualities, and determine the system of qualitative assessments describe them and use fuzzy variables to assess their.

CONCLUSIONS

The approach to information security risk assessment of ERP systems may be further developed and lie the basis of the development of information risk management systems.

Ensuring security of information is necessary at each of the selected levels of the ERP-system, with the choice of information security mechanisms at the above levels depends on the specifics of a particular project and the risk level of each threat. Assessment of information security risks when using the ERP-system is necessary to develop recommendations for reducing the level of risks, as well as taking effective measures to ensure the information security of the entire enterprise.

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МЕТОДИ І МОДЕЛІ ОЦІНКИ РИЗИКІВ ERP-СИСТЕМИ

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АНОТАЦІЯ

Актуальність. Оскільки оцінка ризиків інформаційної безпеки є складним і повним невизначеності процесом, а невизначеності є основним фактором, що впливає на ефективність оцінки, доцільно використовувати нечіткі методи та моделі, що є адаптивними до нечислових даних. Формування нечітких оцінок факторів ризиків носять суб'єктивний характер, а оцінка ризику залежить від практичних результатів, отриманих у процесі обробки ризиків загроз, що вже виникали у процесі функціонування організації та досвіду фахівців з інформаційної безпеки.

Мета роботи – дослідження нейронечітких моделей, що комбінують методи нечіткої логіки та штучних нейронних мереж і систем, тобто людиноподібного стилю міркувань нечітких систем з навчанням та моделюванням розумових явищ нейронних мереж.

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Метод. У роботі оглянуто сучасні напрямки досліджень в сфері захисту інформації в інформаційних системах, методи та технології оцінювання ризиків інформаційної безпеки, використання нечітких моделей для вирішення задач оцінки ризиків інформаційної безпеки, а також концепцію та побудову ERP-систем та проаналізовано проблеми їх безпеки та вразливості.

Результати. Визначено фактори, що впливають на оцінку ризиків, запропоновано використання лінгвістичних змінних для їх опису та використання нечітких змінних для оцінки їх якостей, а також системи якісних оцінок. Обґрунтовано вибір параметрів для розробки структури нечіткої продукційної моделі оцінювання ризиків та бази правил нечіткого логічного висновку.

Висновки. Розглянуто нечітку модель оцінки ризику ERP-систем. Вибрано список факторів, що впливають на ризик інформаційної безпеки. Розглянуто методи оцінки ризиків інформаційних ресурсів та ERP-систем загалом, оцінки фінансових втрат від реалізації загроз, визначення виду ризику за його оцінкою для формування рекомендацій щодо їх обробки з метою підтримання рівня захисту ЕРП-системи. Розглянутий перелік лінгвістичних змінних моделей. Вибрано структуру бази даних нечітких правил продукту – MICO-структура. Розглядаються нечіткі змінні моделі.

КЛЮЧОВІ СЛОВА: інформаційна безпека, нечітка логіка, оцінка ризиків, захищеність, ERB-система.

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МЕТОДЫ И МОДЕЛИ ОЦЕНКИ РИСКОВ ERP-СИСТЕМЫ

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АННОТАЦИЯ

Актуальность. Поскольку оценка рисков информационной безопасности есть сложным и полным неопределенности процессом, а неопределенности есть основным фактором, что влияет на эффективность оценки, целесообразно использовать нечеткие методы и модели, что есть адаптивными до нечисловых данных. Формирование нечетких оценок факторов рисков имеют субьективный характер, а оценка рисков зависит от практических результатов, полученных в процессе обработки рисков погроз, что уже возникали у процессе функционирования организации и опыта специалистов с информационной безопасности.

Цель работы – исследования нейронечетких моделей, что комбинируют методы нечеткой логики и искусственных нейронных сетей и систем, то есть человекоподобного стиля мышлений нечетких систем с обучением и моделированием умственных свойств нейронных сетей.

Метод. В работе рассмотрены современные направления исследований в сфере защиты информации в информационных системах, методы и технологии оценивания рисков информационной безопасности, использования нечетких моделей для решения задач оценки рисков информационной безопасности, а также концепцию и построения ERP-систем и проанализировано проблемы их безопасности и уязвимости.

Результаты. Определены факторы, что влияют на оценку рисков, предложено использование лингвистических переменных для их описания и использования нечетких переменных для оценки их качеств, а также системы качественных оценок. Обоснован выбор параметров для разработки структуры нечеткой продукционной модели оценивания рисков и базы правил нечеткого логического заключения.

Выводы. Рассмотрено нечеткую модель оценки рисков ERP-систем. Выбрано список факторов, что влияют на риск информационной безопасности. Рассмотрены методы оценки риску информационных ресурсов и ERP-систем вообще, оценки финансовых втрат от реализаци погроз, определение типа риску за его оценкою для формирования рекомендаций относительно их обработки для поддержания уровня защищенности ERP-системы. Определен список лингвистических переменных модели; выбрано структуру базы нечетких продукционных правил – MISO-структура. Рассмотрено структуру нечеткой модели. Определены нечеткие переменные модели.

КЛЮЧЕВЫЕ СЛОВА: информационная безопасность, нечеткая логика, оценка рисков, защищенность, ERB-система.

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ALGORITHMS AND SOFTWARE SUITE FOR RELIABILITY ASSESSMENT OF COMPLEX TECHNICAL SYSTEMS

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ABSTRACT

Context. One of the most essential properties of technical systems is their reliability, i.e. the ability of the system to perform intended functions, preserving with time the values of operation indicators within the predefined boundaries. The failure cost for modern complex technical system can be very high, which can result in events of different severity ranging from economic losses to harm to human life and health. Hence, the requirements for their reliability constantly increase. The reliability assessment of complex technical systems can be simplified by the combination of analytical research methods with computational capabilities of modern computers. The most widely used analytical methods are based on the theory of Markov processes which in turn provide the possibility to determine the time dependencies of probabilities of the system to be in defined states (operating, recovering, failure etc.), and thus the values and time dependencies of the reliability indices needed. These methods can be successfully used for the reliability analysis of different kinds of technical systems: both non-recovered and recovered; non-redundant and redundant of different redundancy types, maintenance priorities etc. However, the application of these methods for complex technical systems containing large number of elements meets the high dimensional calculation problem, which makes it impossible to perform these tasks manually. Hence the problem of automation of complex technical system reliability modeling using modern computational systems is very relevant research topic. To solve this problem, one can use specific algorithmic and software techniques described in this paper.

Objective. The goal of this article is to develop the algorithms for automated RBD processing and reliability indices assessment of complex technical systems along with the software suite for automated reliability assessment.

Method. To perform the reliability analysis the RBD approach is used which allows one to represent and visualize each element of the system in the form of a rectangle, joined by the lines in parallel or in series with other elements of the system. To obtain the reliability indices values the mathematical model of technical system reliability behavior using Markovian random process was suggested. The algorithm of RBD processing and automatic determination of operability conditions of a technical system was further considered. To calculate the minimum and maximum number of operational and failure states for the system of n elements and r recoveries the paper introduces a mathematical model based on combinatorial approach. To develop the software suite the object-oriented approach was used.

Results. The algorithms and software suite allows us to easily construct RBD for a technical system, to automatically determine the operability condition with execution time of about 10 sec for 1,000 elements with mixed type of connection, to form automatically a state-and-transition matrix along with the corresponding differential equation system and solve it with total execution time of about 35 sec for 109 states and, thus to obtain the numerical values of reliability indices for the technical system studied. A case study of the reliability assessment for the system consisting of 22 elements using RBD shows that the total time of software execution is 36.712 sec. During executing of this test case the most time (35.168 sec) was spent for execution of the algorithm for construction of a state-and-transition graph consisting of 52,694 states.

Conclusions. The algorithms and methods for automated reliability indices assessment of complex technical systems based on RBD approach, as well as model for estimating the number of total and working system states are presented. The modular structure of the developed software suite makes it flexible and gives an opportunity to add and make modifications of modules fast and without significant program changes.

KEYWORDS: software, reliability, RBD, states and transitions graph.

ABBREVIATIONS

RBD is a reliability block diagram.

NOMENCLATURE

$P_i(t)$ is the probability of a system being at time t in the state x_i;

t is time;

x_i is a system state;

$\lambda_{ij}(t)$ is an intensity of transition from state x_i to state x_j;

N is the number of possible states of a system;

n is the number of elements (modules) in a system;

r is the number of recoveries for each element in a system.

INTRODUCTION

Development of complex technical systems sets new and still more complicated issues before design engineers. The majority of modern technical systems are hardware-software, multicomponent and thus difficult in engineering and development. Besides they are classified as restorable and unrestorable, of long and short operation time, standby and simplex, which also complicates the process of their design. One of the most important devel-

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opment tasks especially in designing of such systems is the calculation of their reliability because the lives of dozens or even thousands of people depend on the operational activity of the above mentioned systems, their breakdown can lead to millions of losses and numerous deaths of people [1, 2]. Therefore, reliable design is one of the most important stages of technical system development in general and complex high-duty technical systems in particular.

The object of the study is the process of reliability assessment of complex technical systems.

The subject of the study is algorithms and software tools for automated reliability assessment using reliability block diagram.

The purpose of the work is to develop the algorithms and software suite for automated reliability assessment of complex technical systems using the RBD approach and Markov processes formalism.

1 PROBLEM STATEMENT

The main problem of designing of reliability models of complex technical systems based on Markovian processes is their large dimension, which reach hundreds of thousands of states even for a system consisting of relatively small number of elements, in particular if one or more of the following conditions are satisfied: (i) the elements are of different types; (ii) the elements can be recovered with a limited number of times; (iii) there are different maintenance teams and the teams are not universal (i.e. a particular team can repair only particular element types)[3].

Reliability behavior of a system in time can be interpreted as a random process with a discrete range of values (states) and continuous change of parameter (time), i.e. as a discrete-continuous stochastic process. Time dependences of the probabilities of random process can be described by the system of Kolmogorov – Chapman differential equations of the following type [4]:

$$\frac{dP_i(t)}{d(t)} = -\sum_{i=1}^{N}\lambda_{ij}(t)P_i(t) + \sum_{j=1}^{N}\lambda_{ij}(t)P_j(t), \quad i,j = 1,2,\ldots,N. \tag{1}$$

A set of states and system transitions as well as the values of transition intensities (i.e. the failure and recovery intensities) are the input data for Kolmogorov–Chapman differential equations (1). These values are partially obtained directly from the user's input (failure and recovery intensities) and partially are formed automatically by the developed software suite based on a RBD provided by user [5].

The solution of equation system (1) allows us to determine the following reliability indices: probability of failure-free operation, the availability coefficient and availability function, the average failure-free operating time (Time-To-Failure), the average recovery time, etc. Thus, these values and theirs time dependencies are the output of the discussed software suite.

2 REVIEW OF THE LITERATURE

Reliability assessment of complex technical systems, including both purely hardware and with a software component, is often carried out using Markovian models. The essence of these models is in considering the system reliability behavior as a random process which can be described as a set of discrete states changing in time [6]. The time can be considered both discrete and continuous. The mentioned models can be characterized by relevant state vectors of system elements.

The reliability model of a modern complex technical system can contain up to several thousands of elements being in turn in different states (e.g. operating, failure, recovering) [7]. This results in large space of possible states in the corresponding Markov model [8]. It is convenient to describe the system reliability behavior by a graph, the nodes of which are attributed to the states of the system, and the edges to possible transitions from one state to another [9].

One of the classical approaches to the reliability calculations is a structurally logical analysis of technical systems. This approach for calculation of reliability parameters implies the use of structurally logical RBD [10] of technical systems, which graphically display the interconnection of elements and their influence on the system operability on the whole. Structurally logical diagram is a collection of previously allocated elements, connected between each other in series or in parallel. The criterion for the determination of the joint kind of the elements is the influence of their failure on the system operability. Under this approach the condition of the system operability can be defined with the help of the algebraic function of logics, i.e. in analyzing of the diagram topology it is first needed to determine such segments, which form the serial connection of elements and thus the joint method of the allocated segments between each other is being considered. In serial connection the elements are connected by the logical operation AND, in parallel connection – by the logical operation OR [11].

From the first sight it might seem that the execution of the above described operations is a quite simple task, which does not require special skills and knowledge and is of polynomial complexity. In reality it is not so, because even the construction of the operability condition for the technical system is not a simple task, especially in case of the availability of a collection of elements with diversified joints between them, while solving which manually there is a very high probability of a human error, particularly among designers with insufficient work experience. In its turn the construction and visualization of a state and transition graph is a sophisticated problem, because the number of possible states of the system depending on the number of elements, the number of element recoveries is growing exponentially which is in its turn reflected upon the complexity of the differential equation system.

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By reference to the abovementioned the process of the reliable designing of complicated technical systems requires the automation of all its stages, starting from the construction of the RBD and ending with the visualization of the obtained results respectively and the task of automated calculation of the reliability indexes of the technical systems is currently central.

The next step, after the analysis of RDB and definition of a condition of the system operability of system, is a construction of a state matrix of a technical system. It contains the information on the operation of the system from the viewpoint of reliability [12]. Every matrix line is a vector, the components of which are the indicators of the state, in which each element remains, when the system itself is in state n. The element can be present only in two states: operating or restoring, it can also be found in a standby state, which can be caused by different reasons [13].

With reference to the availability of failures and recoveries the system randomly transits from one state to another and as such in the process of a long-term use it can be found in each of the possible states not once. In this case the process of its operation can be easily defined with the help of graphs, where the states of the system correspond to the graph nodes, and possible transitions from state to state (to the graph edges) [14, 15]. The use of Kolmogorov–Chaman differential equation system, see Eq. (1) allows to explain the reliability behavior of the system with time as a random process with the finite number of values and continuous replacement of the argument (time), i.e. the discrete-continuous stochastic process [16]. The solution of this equation system allows us to determine the reliability indices mentioned in the Sec. 1.

3 MATERIALS AND METHODS

Besides, for the solving of the problem for automation of reliability indexes calculation we have developed the method of automated formulation of operability condition of the technical systems based upon the RBD [17]. This method is based on three algorithms, each of them performs a specific functional role in the method operation and on the whole they allow to obtain the operability condition, based on the RBD for systems with undefined configuration of joints between the elements of the system (Fig. 1.)

As detailed above a state and transition graph is a convenient method for visual analysis of the system operating process, which allows to obtain the information on all possible states, the system can be found in (operating, standby, failure) as well as particular joints between the elements [18].

Thus, the algorithm of constructing a state and transition graph [18] was developed, which uses the operability condition of the system as an input parameter for the processing and determination of all possible states and joints between them based upon successive failures and recoveries of the system elements (Fig. 2).

We have also developed the algorithm [19] for the automation of the process for the workup of the Kolmogorov-Chapman differential equation system, which being based on the set of all system states and transitions allows to automatically generate and solve such equation systems without involvement of specialized software products (Matlab, Mathcad) for the analysis of structural RBD and automated determination of reliability indexes of complex technical systems (Fig. 3).

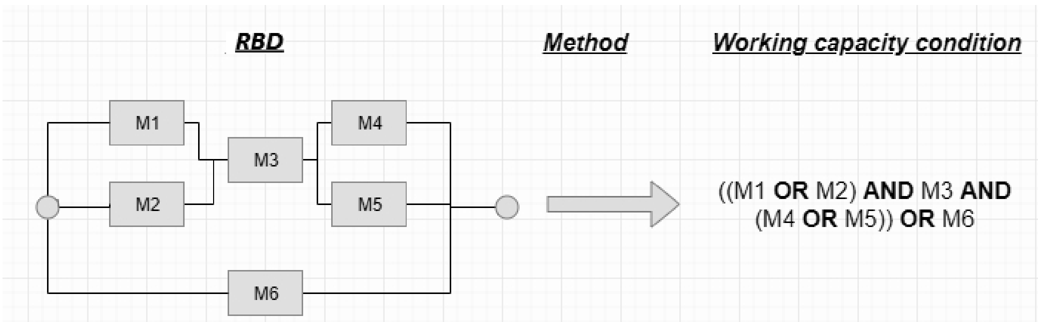

Figure 1 – The diagram of the operating method for the automated formulation of the operability condition of technical systems based on RBD

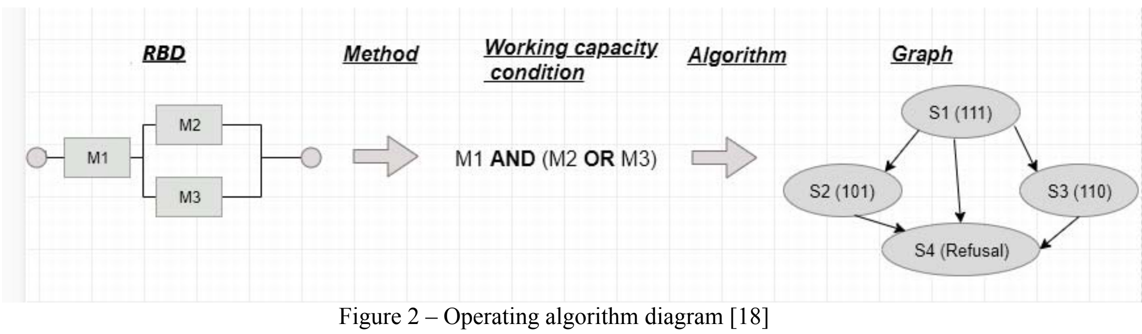

Figure 2 – Operating algorithm diagram [18]

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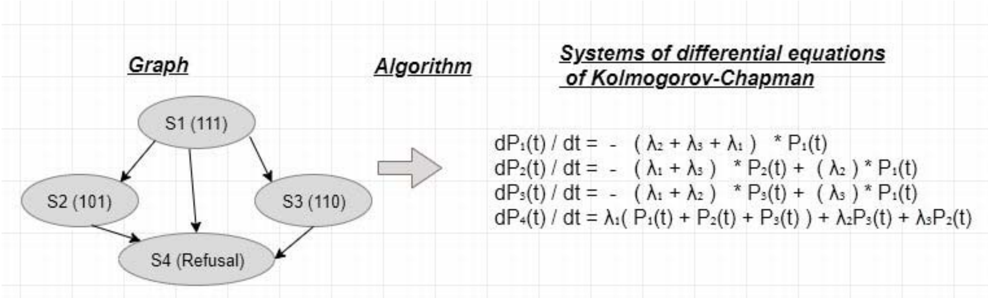

Figure 3 – Operating algorithm diagram

Thus it has become necessary to develop a number of algorithms and methods, that provide opportunities to automate the process for calculation of reliability indexes of complicated technical systems based upon RBD [17–19], as well as for the integration of already developed program modules [20] into the holistic software suite, which would allow to build RBD in an automated way for the description of operation of technical systems with different configuration and level of complexity and to formulate the operability conditions of such systems based upon them.

The software suite must provide the opportunity to construct a state and transition graph in an automated way as well as the differential equation system for the description of technical system operation. It also has to be able to make the calculations of reliability indexes of complex technical systems automatically as well as to visualize the obtained results.

As a result of analysis (RBD and Graph states and transitions) the formulas for the calculation of the minimum and maximum number of acceptable states for the system of n elements and r recoveries were derived:

– minimum number of acceptable states for the system of *n* elements and *n* recoveries – the number of states for serial connection of each of n elements and r recoveries, Eq. (2);

– maximum number of acceptable states for the system of *n* elements and *r* recoveries – the number of states for parallel connection of each of n elements and r recoveries, Eq. (3);

– the number of acceptable states for the system of *n* elements for the mixed type of connection between the system elements – this value is variable between the maximum and minimum permissible values depending on the configuration of joints between the elements in the system;

$$(2\cdot(r+1) - 1)^n + 1 \quad (2)$$

$$(2\cdot(r+1))^n \quad (3)$$

Let us consider the derivation of equations 2 and 3 in detail.

We have got a system of n elements (modules), which are arranged in parallel and each of the elements can be recovered r times (r is the same for each module).

The operation of this system can be represented with the help of a numeral, where n is the digit capacity, and r is an index – for each digit position order of module recovery (how many times it was already recovered).

So the operating state of the module corresponds to numeral 1 and the failure state to 0, but we should also take into account the index of the current recovery ($1_0\ 1_1\ 1_2\ 0_0\ 0_1\ 0_2\ ...\ 1_r\ 0_r$), when increasing the number of recovery for the system by 1 ($r = r+1$), the set of elements for placement increases by 2, because the values $1_{r+1}\ 0_{r+1}$, therefore to determine the set of all possible states for parallel connection (consider – operating states – one of the elements in the system is operating, standby states – one or more elements are in the standby state and the others are in the state of failure or critical failure – all elements of the system are failed and cannot be recovered any more) we can use a specially adapted to this case combinatorial formula of arrangement with repetition:

$$A_n^m = n^m . \quad (4)$$

Therefore, Eq. (3) takes the following form:

$A_n^m = n^m = (2\cdot(r+1))^n$ – operating states, standby states, critical failure.

Eq. (3) also gives the opportunity to derive the equations for particular subsets of operating states and standby states, critical failure (this is always one state out of the overall set).

The state of critical failure for the system with n parallel arrangement of elements and with r recovery is as follows: $0_r\, 0_r\, 0_r\, ...\, 0_r$.

As mentioned above – the states of standby – when one or more elements are in the standby state, and others are in the state of failure. Then out of the set $\{0_0\ 0_1\ 0_2\ ...\ 0_r\}$we can perform the repeated arrangement, which will include all standby states and one state of critical failure, therefore the formula for the determination of the number of standby states for the system with n parallel arrangement of elements and with r recovery is as follows (5):

$$(r+1)^n - 1 . \quad (5)$$

Then we need to subtract the number of operating states from the overall number of states to determine the number of operating states (6).

$$\begin{aligned}&(2\cdot(r+1))^n - ((r+1)^n - 1) - 1 = \\ &= 2^n \cdot (r+1)^n - (r+1)^n + 1 - 1 = (2^n - 1)\cdot(r+1)^n .\end{aligned} \quad (6)$$

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Let us consider the example. We have got a system of 3 (n = 3) elements, which are arranged in parallel with the recovery value 1 (r = 1).

Then the set $\{1_0\, 1_1\, 0_0\, 0_1\}$ – of all possible elements for arrangement, and as far as in the system n = 3 – the number of elements that need to be arranged, that is why the number of states for this system is equal to:

$$A_n^m = n^m = (2\cdot(r+1))^n = (2\cdot(1+1))^3 = 64.$$

This value is the maximum value of all possible states for the system with n = 3 and r = 1, for systems with the same n and r values, but with serial or mixed element connection – the set of states will be less because this value is maximum for parallel connection between all elements of the system.

$(2\cdot(r+1))^n-(r+1)^n-2=(2\cdot2)^3-2^n-2=64-8-2=54$ – operating states out of 64 states

$(r+1)^n-1=(1+1)^3-1=8-1=7$ – standby states out of 64 states

For the system with serial arrangement of elements the formula for the determination of the set of states is calculated as follows.

We have a system with n elements (modules), which are arranged in serial and each of the elements can be recovered r times (r is the same for each module).

An important condition for a system with serial arrangement of elements is that we consider the operating states (all elements of the system are operating), standby states (one or more elements are in standby state and the others are operating), critical failure state (one element of the system is failed and cannot be recovered). It means that for the arrangement with repetition, which will also be used to derive the formula for the determination of the set of states for serial connection of elements in the system, the set of all possible elements for arrangement $\{1_0\, 1_1\, 1_2\, 0_0\, 0_1\, 0_2\, ...\, 1_r\, 0_r\}$will be less by one, because we do not take into account $\{0_{r\ index\ =\ r\ max}\}$. $\{1_0\, 1_1\, 1_2\, 0_0\, 0_1\, 0_2\, ...\, 1_r\}$; out of this set we can define the arrangement for all operating and downtime states and the system will have 1 critical failure state, so the Eq. (2) will look as follows:

$$A_n^m = n^m = (2\cdot(r+1)-1)^n + 1.$$

Eq. (2) also gives the opportunity to derive the formulas for particular subsets of operating states and downtime states, critical failure (this is always one state out of the overall set).

Operating states for a system with n serial arrangement of elements and with r recoveries will consist of the arrangement with repetition out of the set of values $\{1_0\, 1_1\, 1_2\, ...\, 1_r\}$, therefore the formula for the determination of the number of operating states for a system with serial arrangement of elements will look as follows

$$(r+1)^n. \qquad (7)$$

The equation $(2\cdot(r+1)-1)^n$ allows to determine the total sum of operating and standby states for the system therefore the formula for the determination of the number of standby states with serial arrangement of elements will look like:

$$(2\cdot(r+1)-1)^n-(r+1)^n=(2r+1)^n-(r+1)^n. \qquad (8)$$

Let us consider an example. We have got a system of 3 (n = 3) elements, arranged in parallel with the recovery value 1 (r = 1).

Then the set {10 11 00 } – of all possible elements for arrangement (as far as 01 in arrangement for a serial system is not taken into account), and n = 3 is the number of elements that need to be arranged, therefore the number of states for this system is equal to: $A_n^m = n^m = (2\cdot(r+1)-1)^n+1=(2\cdot(1+1)-1)^3+1=28$.

This value is the minimum value of possible states for a system with n = 3 and r = 1, for a system with the same n and r values but with parallel or mixed connection of elements – the set of states will be greater.

$(r + 1)^n = 2^3 = 8$ – operating states out of 28 states

$(2r+1)^n-(r+1)^n=3^3-2^3=19$ – standby states out of 28 states

The equations (2) and (3) as well as the corresponding equations (5)–(8) are suitable for fast estimation of the system for the maximum and minimum permissible number of states of the system with the determinate n and r values as far as we do not need any special methods, complicated calculations, etc. These equations were also tested in software via the software system, described in this article.

4 EXPERIMENTS

It has been decided that the developed software suite must have a modular architecture, where each of the modules allows to make calculations of particular features of a technical system (operability condition, state and transition graph, equation system, diagrams) independently of each other. A modular structure of the complex makes it flexible and allows to update or make modifications of necessary modules fast and without significant program changes (Fig. 4).

The suite contains one basic module, which is responsible for the interconnection and transfer of data between all other elements of the system. These modules can be divided into two groups:

1. Modules, responsible for the processing of particular features determination:
   – Operability condition;
   – State and transition graph;
   – Differential equation system;
   – Diagrams of numeric values of reliability indexes.
2. Modules, responsible for the visualization of information and configurations of graphic components.

For the implementation of functional capabilities of the software suite a flexible hierarchy of classes was de-

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veloped. It allows making modifications easily by adding new functionality and modules.

The main class of the software suite is the class Reliability Schema. It allows us to make manipulations in the working space and in the space of system configurations. This is the basic class responsible for the entire operating of the system and its certain modules, included into it.

WorkabilityCondition – is the class, responsible for the construction of operability condition, it uses the algorithm of the reliability diagram bypass, the algorithms of successive and parallel joints of segments for the determination of an operability condition.

NodePath – is the class for the description of reliability diagram segments: the start and the end segment node, partial operability condition, segment modules, succession of a segment

SystemState – is the class for the determination of all possible states and transitions, in which the technical system under study might be present.

State – is the class for the description of the system state. It contains information on the type, order number, elements, which lead to failure.

SystemConfiguration – is a static class, that contains the information on the system configurations and features: system recovery; number of modules; deleted elements; construction of a state and transition graph; equation system composition; construction of diagrams and values of their definition.

We have processed the software with the help of Microsoft Visual Studio 2017 using the programming language C# and WPF technology for Windows platform (the software product works on the operating system Windows XP and higher). The initial stage of the software work is the creation and configuration of a structural scheme which describes the operation process of a technical system. The main window (Fig. 5) consists of a working space (Fig. 6) and configuration space.

The working space is intended for the RBD formulation. There are initialization nodes at the start and at the end of the window; the scheme must start and end at these points. The joint of elements in the scheme must be arranged from left to right.

The working space is represented by RBD for 12 elements with different joint types, which corresponds to the real technical system of a low complexity level. The configuration space is indented for the tracking and control of the RBD constructing process.

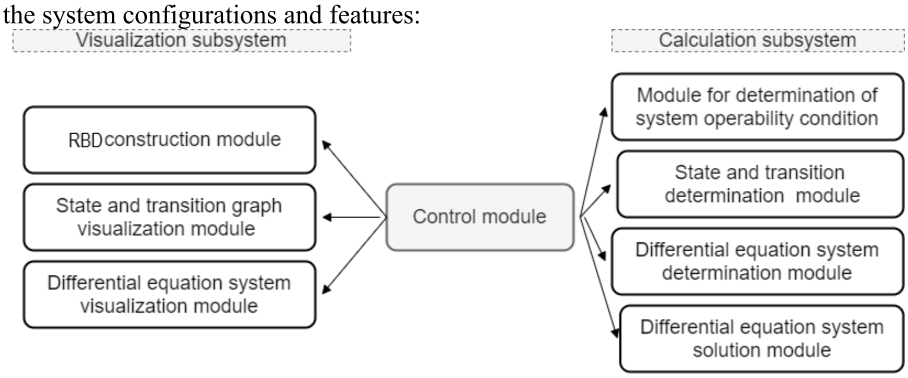

Figure 4 – The diagram of software package modules

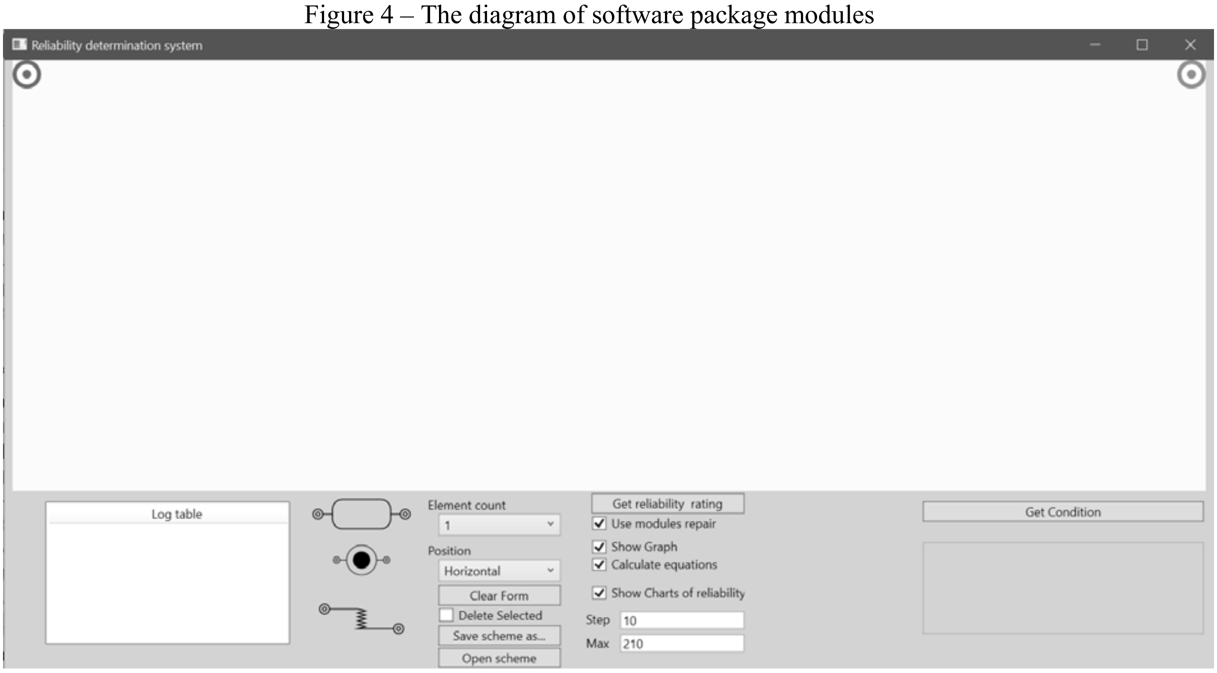

Figure 5 – The main window of the software suite

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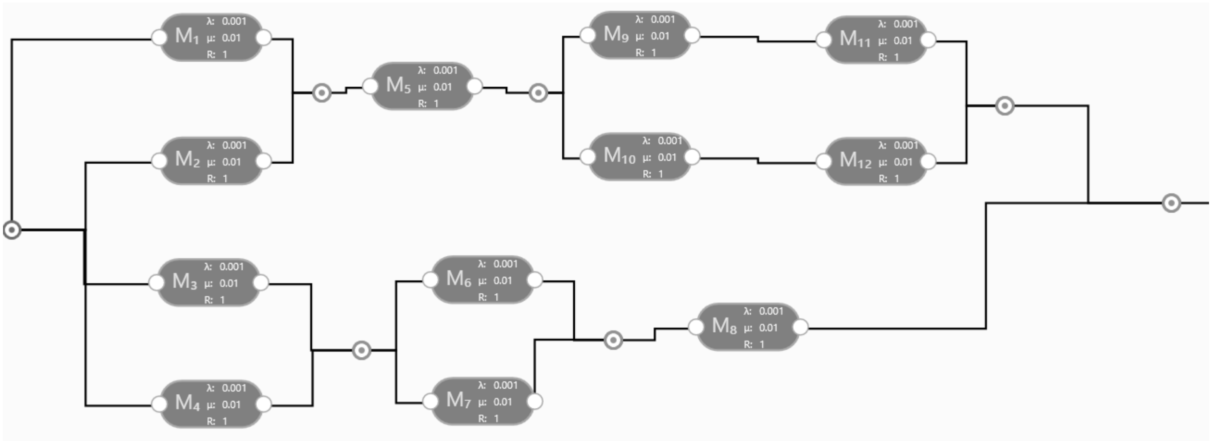

Figure 6 – Working space of the software suite

It includes the chronological chart of RBD graphic components creation (Fig. 7). This is a convenient method, which allows to track the process of adding components, the RBD consists of as well as it displays the time of their adding.

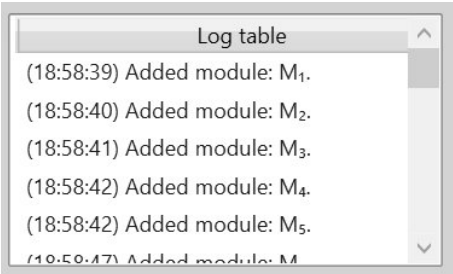

Figure 7 – The chronological chart of the diagram graphic components creation

Besides, the configuration space allows to select the graphic element which is needed at a particular moment of time by clicking the mouse (1 – Module, 2 – Node, 3 – Line) (Fig. 8).

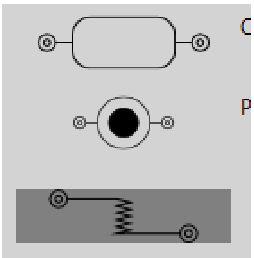

Figure 8 – Selection of a current graphic element for the RBD construction

As a matter of convenience, it is also possible to select the number of elements, which must be added simultaneously, the direction of their composition, clearing of the diagram completely or deleting of its particular elements (Fig. 9): element count – determines how many elements are built on the working frame by one click (refers to the module nodes); position – the direction of element composition: vertical or horizontal; clear form – complete clearing of the working window and all elements in it; delete selected – if a tick is put opposite this mark, then after clicking the right mouse button pointed at a particular element of the working window, it will be deleted; save schema as an open schema – allows to save and open a file with the saved RBD.

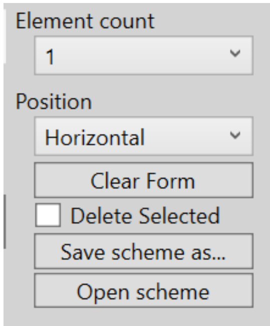

Figure 9 – Configurations of a diagram construction

The option of saving the RBD configuration is a convenient functionality while working with large systems, which allows to accelerate and improve the analysis process, because it makes it possible to get back to work over the analysis of a particular diagram fast at any convenient time.

The basic RBD component is a module. By default, each module has the following feature values (Fig. 10): probability of failure = 0.005; intensity of recovery =0.05; the number of recoveries = 1.

The user can change them by selecting a suitable module. To select the module, you need to click on it by the right mouse button (you should consider if the flag indicator next to Delete select is not selected).

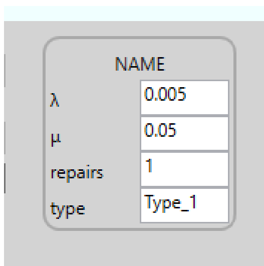

Figure 10 – Module features

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After constructing the RBD for a particular system you can review the operability condition for this system (Fig. 11). To do this you need to click the button "Get Condition" in the configuration space and the result of the diagram analysis will appear in the window.

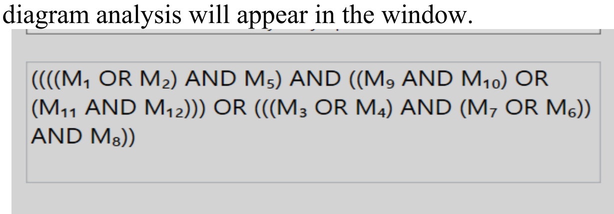

Figure 11 – Operability condition for RBD

For further work with the saved RBD in a separate configuration window you can select the following options (Fig. 12):

– Use modules repair – use modules repair: if selected the modules repair is considered;

– Show graph – display state and transition graph;

– Calculate equations – build and solve the Kolmogorov-Chapman equation system;

– Show chart of reliability – construct the charts of reliability index number changes with the specification of tab spacing and timeline.

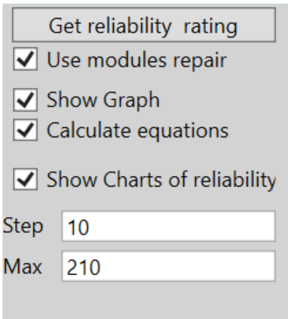

Figure 12 – Configuration window of reliability analysis parameters

After construction of RBD and selection of suitable calculation parameters you need to click "Get reliability rating" button. After a certain period the calculations will be made, the time of execution will be displayed in the logging window. Then the window with an open tab "Graph of states" will appear – this tab allows to display all existing states, the system can be found in as well as to view the general and detailed state and transition graph (Fig. 13).

This window is divided into three sections: state review section (1) – you can view the exact number of states, the system can be found in, and their description with the specified type; state details section (2) – allows to view each state in a more detailed interpretation with the description of states, which enter and leave it, as well as the states, which lead to a critical failure; state and transition graph review section (3) – this section allows you to see all possible states and transitions between them in a graphic representation, zoom in and scale down using the mouse wheel.

The software suite also provides the possibility to transit to a window, which allows to review the differential equation system and the chart of reliability index values of the system under study (Fig. 14). This window consists of two sections:

1. Section of the equation system view;
2. Section of the chart view:

– probabilities of failure-free operation;
– standby function;
– probability of failure.

For the detailed review and analysis of solutions for the differential equation system you can transit to the tab "Runge-Kutta method". Here you can review the information on the dependence of probability of system operation for the states at a particular moment of time (this chart is a detailed description of the equation system solutions). There is also an option of saving the chart data to a file or clipboard.

The program suite also provides an option to select the interface language from two possible variants: English and Ukrainian. To set the interface language you need to indicate which language you want to select in the App.config file (en-US or uk-Ua).

5 RESULTS

For verification of correct operation and validation of the developer software suite an integrated testing of all complex components and modules was carried out as well as the analysis of the developed algorithms operation was conducted [17–19] for a different set of input data with the estimation of the operation highspeed response. As far as the estimation of the highspeed response is one of the basic features of this kind of software which works with schemes, consisting of hundreds or thousands of elements.

The main parameters that influence the highspeed response of the algorithms were determined as well as the analysis with different configuration and combination of these parameters was carried out. These parameters include the number of modules in the system, the number of joints between the modules in the system and the number of recoveries for one module. Testing of the system was carried out on a local machine with the following features: OS Windows 10, Intel Core i7, max 2.7 GHz, RAM 8 Gb DDR4 2133 MHz, 256 Gb SATA SSD, NVIDIA GeForce 940MX 2 Gb.

The analysis of the dependence of the highspeed response of method operation on the number of modules in the system for serial, parallel and mixed joints was carried out on three different system configurations:

– serial connection – all elements in the system are arranged in series one after another;

– parallel connection – all elements in the system are arranged in parallel;

– mixed connection – all elements in the system are arranged in different combinations of serial and parallel joints.

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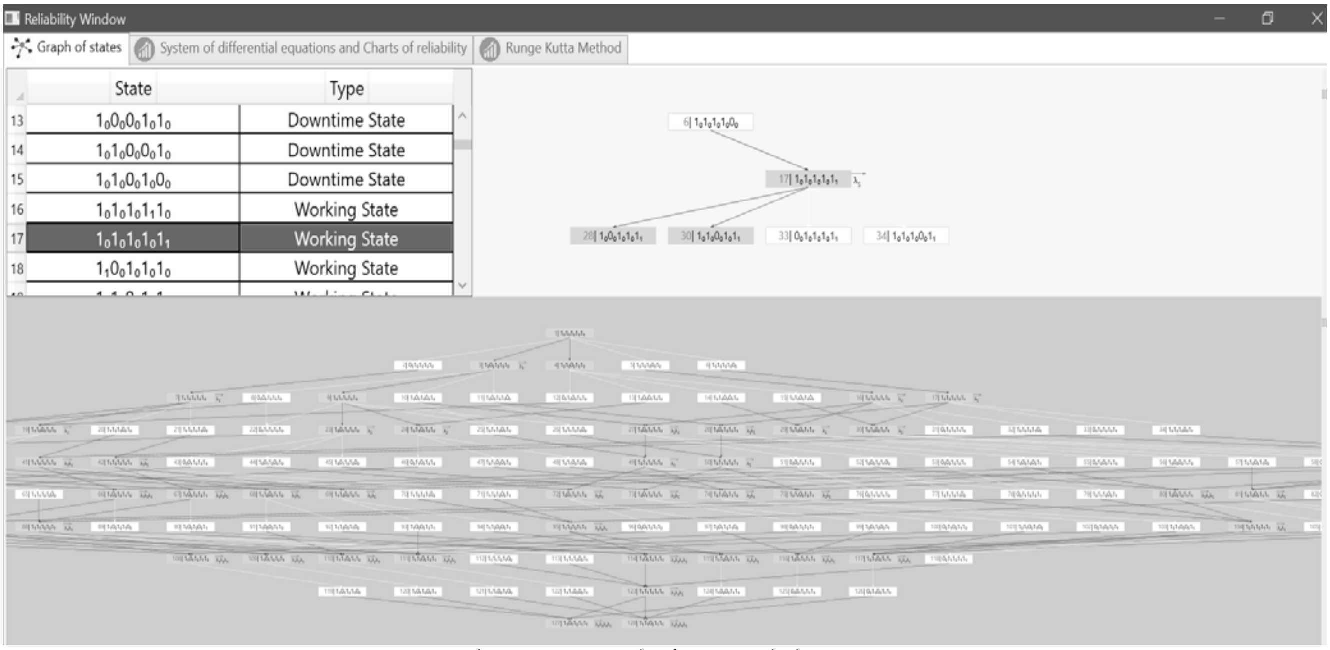

Figure 13 – "Graph of states" window

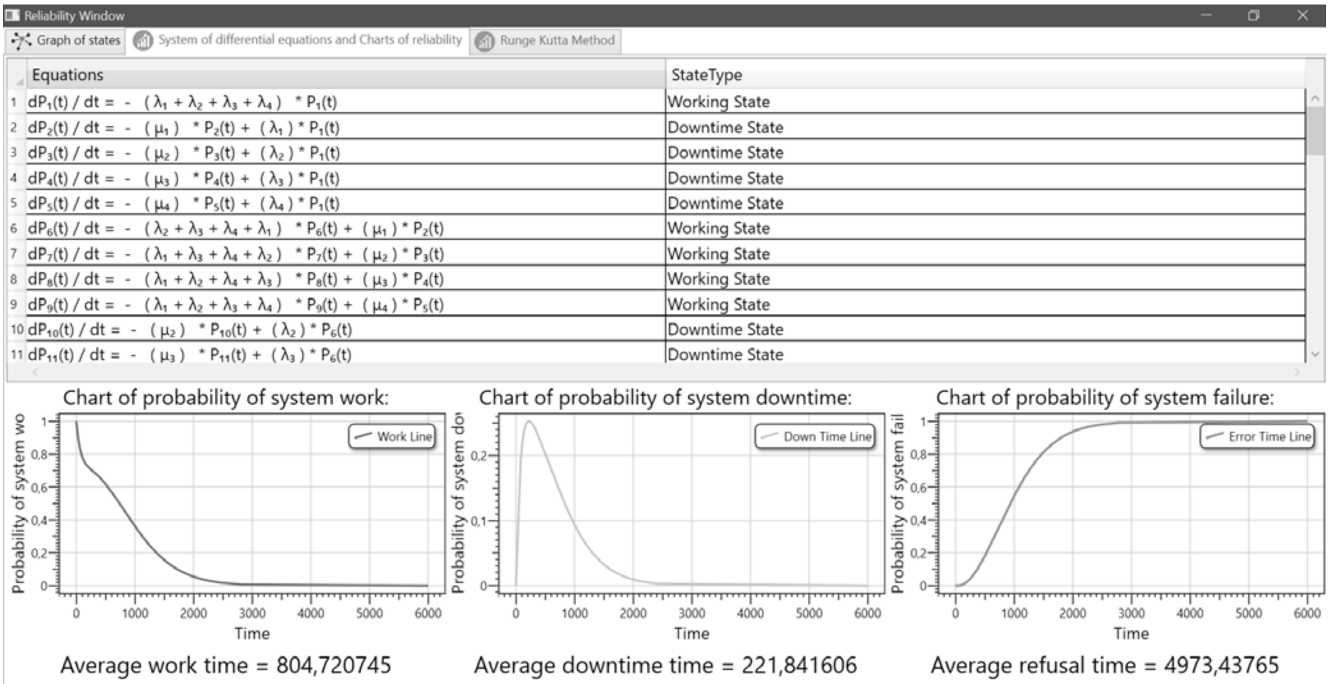

Figure 14 – The view window of the differential equation system and the chart of reliability index values

For program implementation of the method for automated formulation of operability condition of technical systems based upon the RBD the analysis with different number of modules in the system and different configuration of joints between the modules (parallel and serial) was carried out. The results of the measurement of the operating time are represented in the Table 1 and Fig. 15. The number of recoveries for this method is not a determining factor that influences the operation highspeed response, as it is not taken into account at this step.

In its turn the operation analysis of the program implementation for the algorithm of construction a state and transition graph was carried out for the schemes of different configurations, but this kind of analysis implies that the number of system module recoveries should be considered, because this factor has a strong effect on the number of states and transitions between them. The Table 2 and Fig. 16 displays the effect of the number of recoveries for the system of 5 modules with serial and parallel connection on the number of states in a graph (operating state, standby and critical failure are considered).

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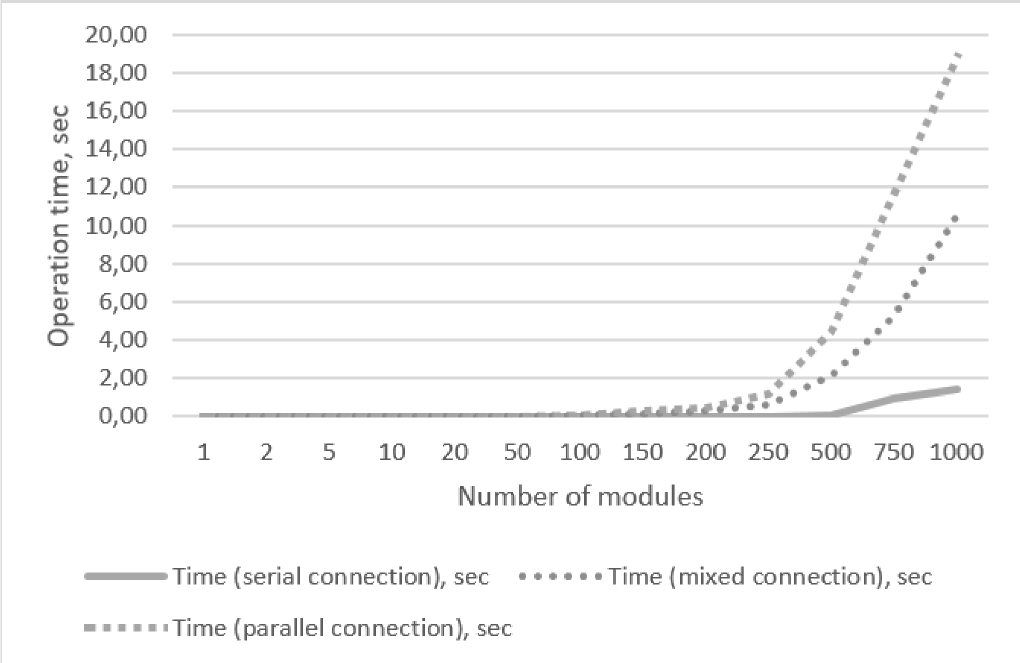

Figure 15 – Diagram of dependence of the operating time of method operation on the number of modules in the system for serial, parallel and mixed connections

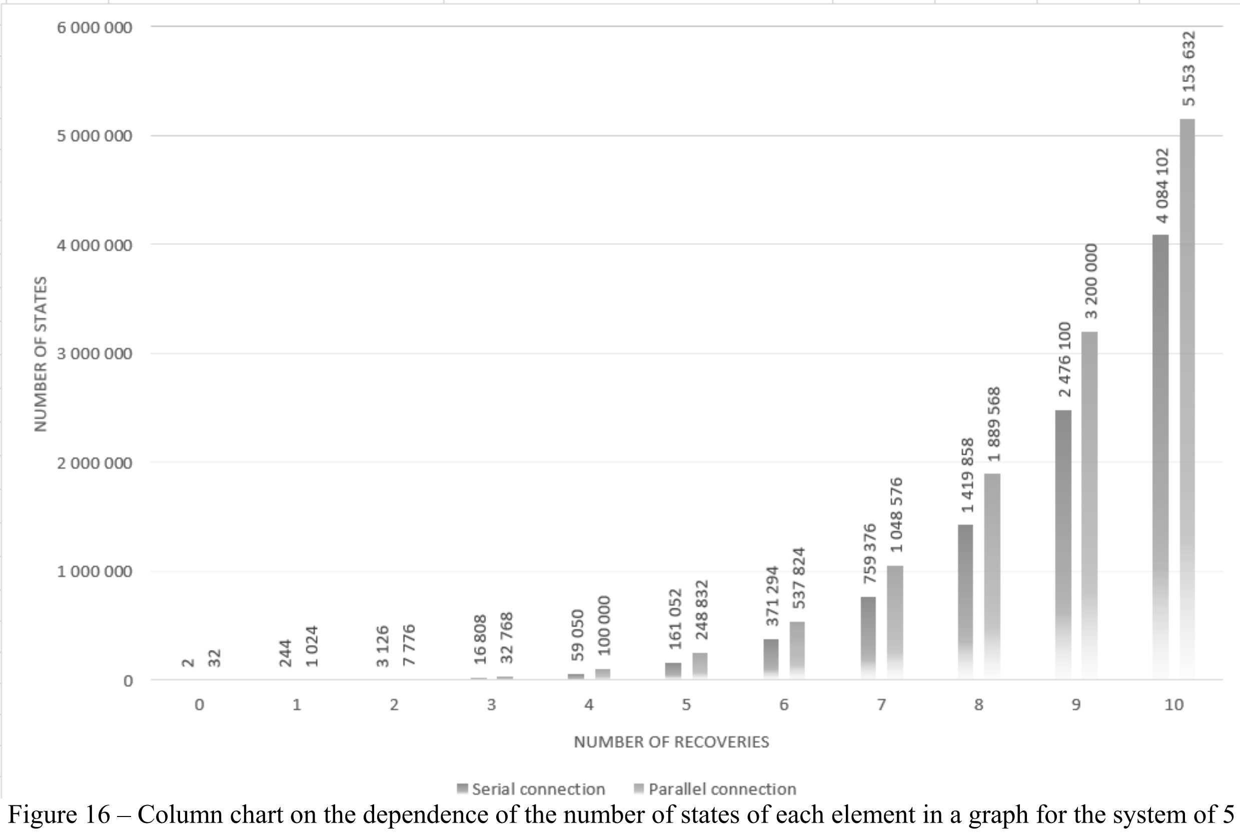

Figure 16 – Column chart on the dependence of the number of states of each element in a graph for the system of 5 modules on the number of recoveries for parallel and serial connection between the elements of the system

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Table 1 – Operation time analysis of the method for automated formulation of technical systems working condition implementation.

№	Number of modules	Time (serial connection), sec	Time (mixed connection), secc	Time (parallel connection), sec
1	1	0.0000308	0.0000321	0.0000330
2	2	0.0000474	0.0000484	0.0000488
3	5	0.0000791	0.0000821	0.0000922
4	10	0.0001703	0.0002093	0.0002418
5	20	0.0002004	0.0004931	0.0007001
6	50	0.0003784	0.0058938	0.0037932
7	100	0.0004165	0.0486683	0.0571824
8	150	0.0004484	0.1509184	0.2522243
9	200	0.0005171	0.3154700	0.4550050
10	250	0.0060551	0.6377826	1.1881978
11	500	0.0106783	2.1342265	4.4533016
12	750	0.9105432	5.2297644	11.6021298
13	1000	1.4004321	10.5671256	18.8623663

Table 2 – The number of states in a graph upon the recoveries number of each element for the system of 5 modules

№	Number of recoveries	Number of states in serial connection	Number of states in parallel connection
1	0	2	32
2	1	244	1 024
3	2	3 126	7 776
4	3	16 808	32 768
5	4	59 050	100 000
6	5	161 052	248 832
7	6	371 294	537 824
8	7	759 376	1 048 576
9	8	1 419 858	1 889 568
10	9	2 476 100	3 200 000
11	10	4 084 102	5 153 632

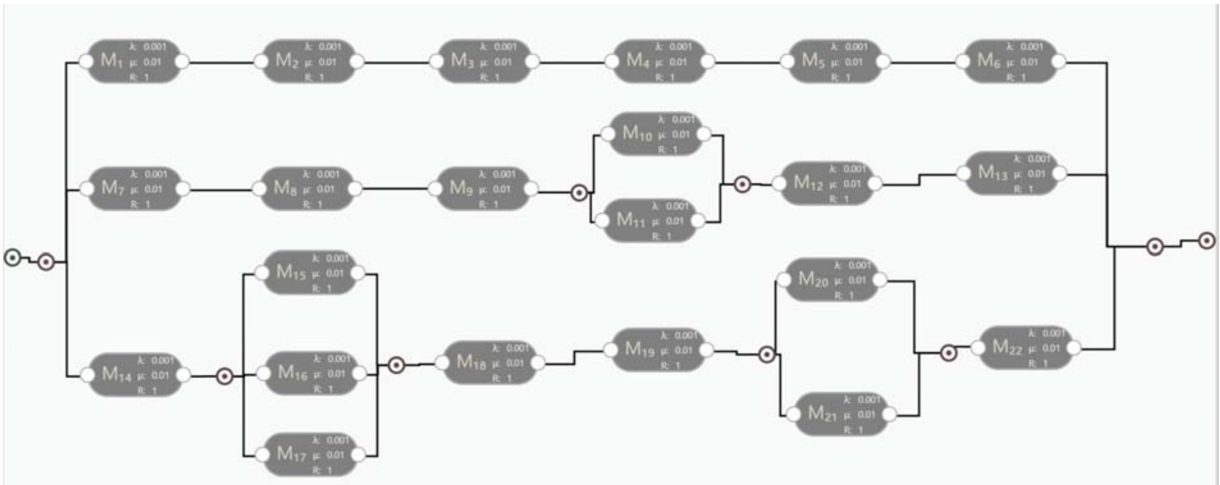

Figure 17 – The reliability block diagram for the unrecoverable system of 22 elements

The analysis of the operation time of software implementation of the algorithm for the construction of a state and transition graph was carried out for a system with parallel connection of modules without the recovery of the module states with the increase of the number of modules in the system (Table 3).

Table 3 – The operation time of software implementation of the algorithm for construction of state and transition graph

№	Number of modules	Number of states	Algorithm operating time, sec
1	1	2	0.0451121
2	2	4	0.0119204
3	5	32	0.3929208
4	10	1024	3.3207597
5	15	32768	8.6198466
6	20	1048576	58.1923007
7	25	33554432	> 6 min

In its turn the operation of the algorithm for processing of the Kolmogorov–Chapman differential equation system consists of two parts:

– determination of equations – this process consists of the determination of equations based on the Eq. (1) – for each state of the system.

– solving the equation system using the Runge-Kutta method.

The operation time of software implementation of the algorithm for processing of the Kolmogorov-Chapman differential equation system is presented in the Table 4 for systems with the number of states varying from 1,000 up to 1,000,000. It is easy to notice that the developed software suite can solve the differential equation system for 106 states in a quite short time (near 35 sec).

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Table 4 – The operation time of the equation workup process

№	Number of states	Processing time, sec.
1	1,000	0.023
2	10,000	0.586
3	50,000	1.127
4	100,000	2.012
5	250,000	4.827
6	500,000	10.142
7	750,000	18.721
8	1,000,000	35.299

6 DISCUSSION

As seen from the Table 1 of the dependence of the method's operation time on the number of modules in the system for serial, parallel and mixed connections the developed software suite provides the opportunity to formulate the working condition for the system of 1000 elements (modules) with a mixed type of connection (Fig. 15) during the short time, which corresponds to a rather complex technical system with the most widely used type of connection between the system elements (mixed).

The obtained data (see Table 2 and Table 3) allow us to conclude that the visualization of a state and transition graph for technical systems with a large number of modules is a sophisticated task (depending on the configuration of the system; for example the number of possible states for a system of 30 elements, arranged in parallel is about 1.07 10^9). The time of operation of the software suite is growing, and thus there is a need of decomposition of such technical systems into smaller subsystems.

For example, Fig. 17 displays the RBD for an unrecoverable system of 22 elements. Time for determination of working condition for this technical system is about 0.0004 sec. Time for execution of the algorithm for construction of a state and transition graph (the number of determined states is 52 694) is 35.168 sec. Time for processing of the Kolmogorov-Chapman differential equation system for this system is 1.544 sec.

Total time for execution of a particular task for the reliability assessment of technical system consisting of 22 elements using RBD is 36.712 sec. The most time was given to the construction of a state and transition graph and this should be improved to increase the operation time of the developed software suite.

CONCLUSIONS

This paper presents algorithms and methods, that provide opportunities to automate the process for calculation of reliability indexes of complicated technical systems based upon RBD , as well as formulas for estimating the total and working number of system states based on input indicators about the system *n* and *r*.

According to the mathematical apparatus, a software was developed for the calculation of reliability indexes of complicated technical systems, which provides opportunities to automate the process of their reliability analysis, reduces the influence of a human factor and thus reduces the probability of making errors on early stages of reliability indexes calculation.

The developed software package has a modular architecture, where each of the modules makes it possible to carry out the calculation of particular reliability features of a technical system (operability condition, a state and transition graph, equation system, graphs of results visualization) independently of each other. Modular structure of the software suite makes it flexible and gives an opportunity to add and make modifications of modules fast and without significant program changes.

This software suite allows us to easily construct RBD for a technical system, to determine the operability condition automatically (execution time ≈ 10 sec for 1,000 elements with mixed type of connection), to form a state/transition matrix (up to 10^9 states), to form the differential equation system automatically and solve it (execution time ≈ 35 sec for 10^9 states) and, thus to obtain the numerical values of reliability indexes (probabilities of failure-free operation and probabilities of failure and standby).

Besides, the developed software suite is cross-platform, it has a convenient and ergonomic interface, Ukrainian and English localization, and other additional functions for the convenience of a design engineer.

The scientific novelty of the results presented in the paper lies in the further development of Markov reliability modelling and in firstly obtained model for the number of operational and failure states for the system of *n* elements and *r* recoveries using RBD approach.

The practical significance of the described study lies in the developed algorithms and software suite which makes it possible the automated reliability assessment of complex technical systems with up to 1,000 elements forming up to 1,000,000 states during the time less than one minute.

The future research will be focused on improvement the calculational speed of the developed software suite by developing appropriate methods and algorithms.

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АЛГОРИТМИ ТА ПРОГРАМНИЙ ЗАСІБ ДЛЯ ОЦІНЮВАННЯ НАДІЙНОСТІ СКЛАДНИХ ТЕХНІЧНИХ СИСТЕМ

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АНОТАЦІЯ

Актуальність. Однією з найважливіших властивостей технічних систем є їх надійність, тобто здатність системи виконувати задані функції, зберігаючи в часі значення експлуатаційних показників в заданих межах. Вартість відмови для сучасних складних технічних систем може бути дуже високою, що може призвести до подій різного ступеня тяжкості, починаючи від економічних збитків і закінчуючи шкодою для здоров'ю і життя людей. Отже, вимоги до їх надійності постійно зростають. Процес оцінки надійності складних технічних систем можна спростити поєднанням аналітичних методів дослідження з обчислювальними можливостями сучасних комп'ютерів. Найпоширеніші аналітичні методи базуються на теорії марковських процесів, яка в свою чергу дають можливість визначити часові залежності ймовірностей перебування системи у визначених станах (працездатності, відновлення, відмови), а отже, значення і часові залежності необхідних показників надійності. Ці методи можуть бути використані для аналізу надійності технічних систем різного типу: невідновлюваних та відновлюваних; резервованих та нерезервованих з різним видом резервування чи типом обслуговування та ін. Однак застосування цих методів для складних технічних систем, що містять велику кількість елементів вимагає виконання великої кількості розрахунків, що унеможливлює виконання цих завдань вручну. Отже, проблема автоматизації моделювання надійнос-

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ті складної технічної системи з використанням сучасних обчислювальних систем є дуже актуальною темою дослідження. Для вирішення цієї проблеми можна використовувати конкретні алгоритмічні та програмні прийоми, описані в цій роботі.

Мета. Метою даної статті є розробка алгоритмів автоматизованої обробки структурних схем надійності (ССН) та оцінки показників надійності складних технічних систем поряд із набором програм для автоматизованої оцінки надійності.

Метод. Для проведення аналізу надійності використовується підхід ССН, який дозволяє представляти та візуалізувати кожен елемент системи у вигляді прямокутника, з'єднаного лініями паралельно або послідовно з іншими елементами системи. Для отримання значень показників надійності запропоновано математичну модель поведінки надійності технічної системи з використанням випадкового марковського процесу. Далі розглянуто алгоритм обробки ССН та автоматичного визначення умови працездатності технічної системи. Для розрахунку мінімальної та максимальної кількості робочих станів та станів відмов для системи з n елементів та r відновлення в роботі вводиться математична модель, заснована на комбінаторному підході. Для розробки програмного комплексу був використаний об'єктно-орієнтований підхід.

Результати. Набір алгоритмів та програмного забезпечення дозволяє нам легко побудувати ССН для технічної системи, автоматично визначити стан працездатності з часом виконання близько 10 сек. для 1000 елементів із змішаним типом з'єднання, автоматично сформувати матрицю станів та переходів разом із відповідною системою диференціальних рівнянь та вирішити її із загальним часом виконання близько 35 сек. для 109 станів і, таким чином, отримати числові значення показників надійності для досліджуваної технічної системи. Дослідження оцінки надійності для системи, що складається з 22 елементів із використанням ССН, показує, що загальний час виконання програмної реалізації становить 36,712 сек. Під час виконання цього тестового випадку найбільше часу (35,168 сек.) було витрачено на роботу алгоритму побудови графа станів та переходів, що складається з 52 694 станів.

Висновки. Представлені алгоритми та методи автоматизованої оцінки показників надійності складних технічних систем на основі підходу ССН, а також модель для визначення кількості станів системи(також включає визначення працездатних станів і станів відмови). Модульна структура розробленого набору програм робить його гнучким та дає можливість додавати та вносити модифікації модулів швидко та без значних змін програми.

КЛЮЧОВІ СЛОВА: програмне забезпечення, надійність, структурна схема надійності, граф станів та переходів.

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АЛГОРИТМЫ И ПРОГРАММНОЕ СРЕДСТВО ДЛЯ ОЦЕНИВАНИЯ НАДЕЖНОСТИ СЛОЖНЫХ ТЕХНИЧЕСКИХ СИСТЕМ

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АННОТАЦИЯ

Актуальность. Одним из важнейших свойств технических систем является их надежность, то есть способность системы выполнять заданные функции, сохраняя во времени значения эксплуатационных показателей в заданных пределах. Стоимость отказа для современных сложных технических систем может быть очень высокой, что может привести к событиям различной степени тяжести, начиная от экономических убытков и заканчивая ущербом для здоровья и жизни людей. Итак, требования к их надежности постоянно растут. Процесс оценки надежности сложных технических систем можно упростить сочетанием аналитических методов исследования с вычислительными возможностями современных компьютеров. Самые распространенные аналитические методы базируются на теории марковских процессов, которая в свою очередь дает возможность определить временные зависимости вероятностей нахождения системы в определенных состояниях (работоспособности, восстановления, отказа), а следовательно, значение и временные зависимости необходимых показателей надежности. Эти методы могут быть успешно использованы для анализа надежности различных технических систем: как невосстанавливаемых, так и восстанавливаемых; без резервирования и с резервированием различных типов, приоритетов обслуживания и т. д. Однако применение этих методов для сложных технических систем, содержащих большое количество элементов требует выполнения большого количества расчетов, делает невозможным выполнение этих задач вручную. Итак, проблема автоматизации моделирования надежности сложной технической системы с использованием современных вычислительных систем является очень актуальной темой исследования. Для решения этой проблемы можно использовать конкретные алгоритмические и программные приемы, описанные в этой работе.

Цель. Целью данной статьи является разработка алгоритмов автоматизированной обработки структурных схем надежности (ССН) и оценки показателей надежности сложных технических систем наряду с набором программ для автоматизированной оценки надежности.

Метод. Для проведения анализа надежности используется подход ССН, который позволяет представлять и визуализировать каждый элемент системы в виде прямоугольника, соединенного линиями параллельно или последовательно с другими элементами системы. Для получения значений показателей надежности предложена математическая модель поведения надежности технической системы с использованием случайного марковского процесса. Далее рассмотрен алгоритм обработки ССН и автоматического определения условия работоспособности технической системы. Для расчета минимального и максимального количества рабочих состояний и состояний отказов для системы с n элементов и r восстановлений в работе вводится математическая модель, основанная на комбинаторном подходе. Для разработки программного комплекса был использован объектно-ориентированный подход.

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Результаты. Набор алгоритмов и программного обеспечения позволяет нам легко построить ССН для технической системы, автоматически определить состояние работоспособности со временем выполнения около 10 сек на 1000 элементов со смешанным типом соединения, автоматически сформировать матрицу состояний и переходов вместе с соответствующей системой дифференциальных уравнений и решить ее с общим временем выполнения около 35 сек для 109 состояний и, таким образом, получить числовые значения показателей надежности для исследуемой технической системы. Исследование оценки надежности для системы, состоящей из 22 элементов с использованием ССН, показывает, что общее время выполнения программной реализации составляет 36,712 сек. Во время выполнения этого тестового случая больше времени (35,168 сек) было потрачено на работу алгоритма построения графа состояний и переходов, состоящего из 52 694 состояний.

Выводы. Представленные алгоритмы и методы автоматизированной оценки показателей надежности сложных технических систем на основе подхода ССН, а также модель для определения количества состояний системы (также включает определение трудоспособных состояний и состояний отказа). Модульная структура разработанного набора программ делает его гибким и позволяет добавлять и вносить модификации модулей быстро и без значительных изменений программы.

КЛЮЧЕВЫЕ СЛОВА: программное обеспечение, надежность, структурная схема надежности, граф состояний и переходов.

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УПРАВЛІННЯ У ТЕХНІЧНИХ СИСТЕМАХ

CONTROL IN TECHNICAL SYSTEMS

УПРАВЛЕНИЕ В ТЕХНИЧЕСКИХ СИСТЕМАХ

УДК 681.518:004.93

ІНФОРМАЦІЙНО-ЕКСТРЕМАЛЬНЕ ІЄРАРХІЧНЕ НАВЧАННЯ СИСТЕМИ КЕРУВАННЯ ПРОТЕЗОМ КІСТІ РУКИ З НЕІНВАЗИВНОЮ СИСТЕМОЮ ЗЧИТУВАННЯ БІОСИГНАЛІВ

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АНОТАЦІЯ

Актуальність. Розв'язана актуальна задача інформаційного синтезу здатної навчатися системи керування протезом кісті руки з неінвазивною системою зчитування біосигналів.

Мета роботи – підвищення функціональної ефективності системи керування протезом кісті руки з неінвазивною системою зчитування біосигналів на основі машинного навчання, що дозволяє при функціонуванні системи в робочому режимі розпізнавати з високою достовірністю і оперативністю когнітивні команди користувача протезу.

Метод. У рамках інформаційно-екстремальної інтелектуальної технології (ІЕІ-технології) аналізу даних, яка базується на максимізації інформаційної спроможності системи розпізнавання в процесі машинного навчання, запропоновано метод інформаційного синтезу інтелектуальної системи керування протезом кісті руки з неінвазивною системою зчитування біосигналів. На відміну від існуючих методів інтелектуального аналізу даних метод інформаційно-екстремального машинного навчання розроблено в рамках функціонального підходу до моделювання когнітивних процесів, притаманних людині при формування та прийняття класифікаційних рішень. Такий підхід дозволяє наділити систему керування протезом властивостями адаптивності до довільних початкових умов формування когнітивних команд і перенавчання при розширенні словника ознак та алфавіту класів розпізнавання. Крім того, вирішальні правила, побудовані за отриманими в процесі машинного навчання геометричними параметрами гіперсферичних контейнерів класів розпізнавання є практично інваріантними до багато вимірності простору ознак розпізнавання. На основі запропонованої категорійної моделі розроблено алгоритм машинного навчання з оптимізацією ієрархічної структури даних. При цьому досліджено вплив на функціональну ефективність машинного навчання структур даних, побудованих у вигляді дихотомічного і декурсивного дерев. Як критерій оптимізації параметрів машинного навчання використовується модифікація інформаційної міри Кульбака, яка є функціоналом точнісних характеристик рішень, що приймаються.

Результати. Побудовані в процесі ієрархічного інформаційно-екстремального машинного навчання вирішальні правила дозволяють розпізнавати в реальному темпі часу когнітивні команди з достатньо високою повною ймовірністю прийняття правильних класифікаційних рішень. За результатами фізичного моделювання доведено, що при використанні ієрархічної структури даних у вигляді декурсивного дерева функціональна ефективність машинного навчання збільшується у порівнянні із структурою даних у вигляді дихотомічного бінарного дерева.

Висновки. Експериментально підтверджено достатньо високу функціональну ефективність запропонованого методу інформаційно-екстремального машинного навчання системи керування протезом кісті руки з неінвазивною системою зчитування біосигналів. Отримані наукові результати відкривають новий напрям створення інтелектуальних протезів руки з неінвазивною системою зчитування біосигналів на основі машинного навчання та розпізнавання образів

КЛЮЧОВІ СЛОВА: інформаційно-екстремальна інтелектуальна технологія, машинне навчання, інформаційний критерій, система керування, протез кісті руки, електроміографічний датчик.

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НОМЕНКЛАТУРА

H – кількість ярусів декурсивної ієрархічної структури;

S – кількість страт h-го ярусу, $h=\overline{1,H}$;

M – кількість класів розпізнавання;

N – кількість ознак розпізнавання;

n – кількість векторів ознак класів розпізнавання в навчальній матриці;

$x_{h,s,m}$ – двійковий усереднений вектор ознак класу розпізнавання $X^o_{h,s,m}$;

$d_{h,s,m}$ – кодова відстань, яка визначає радіус гіперсферичного контейнера класу розпізнавання $X^o_{h,s,m}$;

P – ієрархічна декурсивна структура алфавіту класів розпізнавання

$E^{(s)}_{\max}$ – інформаційний критерій оптимізації параметрів машинного навчання розпізнавати реалізації класів розпізнавання s-ї страти фінального ярусу;

S_f – кількість фінальних страт декурсивної ієрархічної структури;

G – множина вхідних факторів;

T – множина моментів часу одержання інформації;

Z – простір ознак розпізнавання;

H – множина декурсивних ієрархічних структур;

Y – вхідна навчальна матриця;

X – робоча бінарна навчальна матриця;

f_1 – оператор формування матриці Y;

f_2 – оператор формування матриці X;

L – кількість статистичних гіпотез;

S_h – кількість страт на h-му ярусі;

G_P – область допустимих значень структури P;

G_E – робоча (допустима) область визначення функції інформаційного критерію;

$K^{(k)}_{1,h,s,m}(d)$ – кількість подій, при яких реалізації класу розпізнавання $X^o_{h,s,m}$ помилково не відносяться до свого класу;

$K^{(k)}_{2,h,s,m}(d)$ – кількість подій, при яких «чужі» реалізації помилково відносяться до класу розпізнавання $X^o_{h,s,m}$;

10^{-r} – достатньо мале число, яке вводиться для уникнення поділу на нуль;

$\overline{D}_1$ – усереднена за алфавітом класів розпізнавання перша достовірність;

$\overline{\beta}$ – усереднена за алфавітом класів розпізнавання помилка другого роду ;

$\overline{P}_t$ – усереднена за алфавітом класів розпізнавання повна ймовірність правильного прийняття рішень;

$d^*_{h,s,m}$ – оптимальний радіус контейнера класу розпізнавання $X^o_{h,s,m}$;

$x_{h,s,c}$ – двійковий усереднений вектор ознак сусіднього класу розпізнавання $X^o_{h,s,c}$.

ВСТУП

Створення інтелектуальних протезів руки на основі машинного навчання та розпізнавання образів дозволяє суттєво розширити їх функціональні можливості, забезпечити реабілітацію людини з інвалідністю та її адаптацію до повноцінного життя. У порівнянні з протезами руки з інвазивною системою зчитування біосигналів протези з неінвазивною системою зчитування є суттєво дешевшими та зручнішими при їх використанні. Але через високу зашумленість біосигналів і суттєвий перетин в просторі ознак класів розпізнавання, які характеризують окремі рухи протезу, розробка інтелектуальних протезів вимагає подолання ускладнень науково-методологічного характеру. Саме через ці причини алгоритми машинного навчання системи керування протезом руки з використанням відомих методів технології Data Mining не забезпечують високу точність виконання когнітивних команд. Тому підвищення функціональної ефективності здатної навчатися системи керування протезом руки набуває важливого науково-практичного значення.

1 ПОСТАНОВКА ЗАДАЧІ

Розглянемо формалізовану постановку задачі інформаційно-екстремального машинного навчання системи керування протезом руки з неінвазивною системою зчитування сигналів. Нехай кожний клас розпізнавання характеризує біосигнал, який зчитується з електроміографічного датчика при виконанні відповідної когнітивної команди. Дано ієрархічну структуру алфавіту $\{X^o_{h,s,m}\,|\,h=\overline{1,H}, s=\overline{1,S}, m=\overline{1,M}\}$ класів розпізнавання, для якого за результатами моніторингу сигналів з датчика інформації сформовано для кожної страти тривимірну навчальну матрицю $\| y^{(j)}_{h,s,m,i} \|, i=\overline{1,N}, j=\overline{1,n} \|$.

Необхідно в процесі машинного навчання шляхом цілеспрямованої перестановки класів розпізнавання в заданій ієрархічній структурі даних оптимізувати параметри машинного навчання, які забезпечують максимальне значення усередненого за фінальними стратами інформаційного критерію

$$\overline{E}_{\max} = \frac{1}{S_f}\sum_{s=1}^{Sf} E^{(s)}_{\max} , \qquad (2)$$

На етапі екзамену необхідно прийняти рішення про належність біосигналу, що розпізнається, одному із класів заданого алфавіту.

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2 ОГЛЯД ЛІТЕРАТУРИ

Основною тенденцією сучасного розвитку протезів руки є підвищення їх функціональної ефективності шляхом використання методів інтелектуального аналізу даних [1–3]. Найбільш досконалими є протези руки з інвазивною системою зчитування біосигналів [4], але вони вимагають хірургічного втручання, незручності при користуванні та мають високу собівартість. В працях [5–7] наведено опис протезів, здатних розпізнавати та відчувати поверхню предмету, тобто наділених тактильною функцією. Але існуючі біонічні протези, керовані сигналами від пасивних електроміографічних сенсорів мають не достатньо високу точність. Тому в працях [8, 9] запропоновано підвищувати точність виконання когнітивних команд шляхом додаткової системи оптичного трекінгу руху очей, але такий підхід суттєво підвищує собівартість протезу та ускладнює умови його використання. Алгоритми машинного навчання для встановлення відповідності між біосигналами та командами на основі нейронних мереж [10–12] та методу опорних векторів [13–15] через багато вимірність словника ознак і суттєвий перетин класів розпізнавання не дозволяють досягти достатньо високу точність розпізнавання біосигналів. Наприклад, точність розпізнавання руху окремих пальців навіть при непошкодженій м'язовій тканині не перевищує 62% [15]. В праці [16] розглядається можливість застосування для розпізнавання сигналів нечітких нейронних мереж, але при цьому так само існує проблема багато вимірності. В працях [17–19] для зменшення впливу багатовимірності пропонується використовувати побудовані на штучних мережах екстрактори вхідних даних, що не виключає втрате інформації. Як перспективний напрям слід розглядати використання ідей і методів так званої інформаційно-екстремальної інтелектуальної технології аналізу даних, яка ґрунтується на максимізації інформаційної спроможності системи в процесі її навчання [20–22]. Основною парадигмою інформаційно-екстремального машинного навчання як і в нейроподібних структурах є адаптація вхідного математичного опису системи до максимальної достовірності розпізнавання образів. Але на відміну від нейроподібних структур вирішальні правила, побудовані в рамках геометричного підходу, є практично інваріантними до багато вимірності словника ознак. З метою зменшення впливу потужності алфавіту класів розпізнавання на достовірність і оперативність розпізнавання в праці [23] запропоновано алгоритм інформаційно-екстремального ієрархічного машинного навчання. Але в цій праці не досліджувалася задача оптимізації в інформаційному розумінні ієрархічної структури даних. Одне з ускладнень машинного навчання системи керування протезом руки полягає в необхідності нормалізації біосигналів, отриманих з датчиків, розташованих симетрично на пошкодженій і непошкодженій руках. Для розв'язання цієї задачі перспективним є застосування методу нормалізації сигналів, запропонованого в працях [24, 25].

В статті розглядається задача підвищення функціональної ефективності інформаційно-екстремального ієрархічного машинного навчання системи керування протезом кісті руки з неінвазивною системою зчитування біосигналів шляхом оптимізації ієрархічної структури даних.

3 МАТЕРІАЛИ І МЕТОДИ

Категорійну модель оптимізації ієрархічної структури класів розпізнавання представимо у вигляді орієнтованого графу відображення множин, що застосовуються в процесі інформаційно-екстремального машинного навчання. Категорійна модель включає вхідний математичний опис I_B у вигляді структури

$$I_B = < G, T, \Omega, Z, H, Y, X; f_1, f_2 > .$$

На рис. 1 показано категорійну модель інформаційно-екстремального машинного навчання системи керування протезом кінцівки руки з оптимізацією ієрархічної структури алфавіту класів розпізнавання.

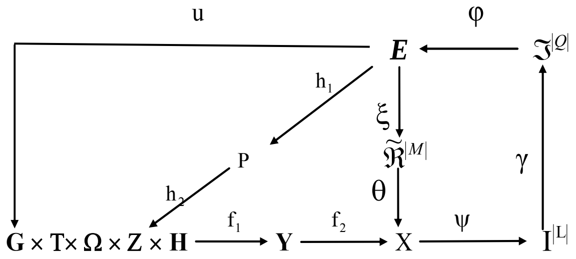

Рисунок 1– Категорійна модель машинного навчання

На рис. 1 декартовий добуток $G \times T \times \Omega \times Z \times H$ задає універсумум випробувань, який є джерелом інформації. Терм-множина E значень інформаційного критерію оптимізації параметрів машинного навчання є загальною для всіх контурів оптимізації. Оператор ξ на кожному кроці машинного навчання відновлює в радіальному базисі простору ознак контейнери класів розпізнавання, які утворюють в загальному випадку нечітке розбиття $\tilde{\Re}^{|M|}$. Оператор θ проекцирує побудоване розбиття $\tilde{\Re}^{|M|}$ на розподіл двійкових векторів ознак бінарної навчальної матриці *X*, а оператор ψ перевіряє основну статистичну гіпотезу про належність векторів ознак відповідному класу розпізнавання. За результатами статистичної перевірки гіпотез формується множина статистичних гіпотез $I^{|L|}$, а оператор γ формує множину точнісних характеристик $\Im^{|Q|}$, де $Q = L^2$. Оператор φ обчислює множину E значень інформаційного критерію оптимізації параметрів машинного навчання. В категорійній моделі контур оптимізації контрольних допусків на ознаки розпізнавання замикається через терм-множину D – систему контрольних допусків, які використовуються як рівні квантування ознак розпізнавання при формуванні робочої бінарної навчальної матриці.

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Наявність бінарної навчальної матриці дозволяє шляхом квантування за рівнем ознак розпізнавання адаптувати вхідний математичний опис до максимальної достовірності класифікаційних рішень. Крім того, категорійна модель має додатковий контуру оптимізації ієрархічної структури даних P, вершини якої містять атрибути класів розпізнавання із заданого алфавіту у вигдяді їх навчальних матриць.

Згідно з категорійною моделлю (рис. 1) алгоритм машинного навчання системи керування протезом з оптимізацією структури P представимо у вигляді процедури

$$P^* = \arg\max_{G_P}\{\max_{G_R \cap \{s\}} \overline{E}_S\}\}, \qquad (3)$$

Розглянемо основні етапи реалізації алгоритму оптимізації ієрархічної структури даних в процесі машинного навчання системи керування протезом кінцівки руки.

1) обнуління лічильника варіантів ієрархічних структур (кроків навчання): $r := 0$.

2) ініціалізація лічильника варіантів ієрархічних структур: $r := r + 1$.

3) обнуління лічильника ярусів структури даних: $h := 0$.

4) ініціалізація лічильника ярусів структури даних: $h := h + 1$.

5) обнуління лічильника страт яруса: $s := 0$.

6) ініціалізація лічильника страт яруса: $s := s + 1$.

7) для кожної s-ї страти h-го ярусу r-ї ієрархічної структури реалізується базовий алгоритм інформаційно-екстремального машинного навчання, який реалізує оператори правого контуру категорійної моделі (рис. 1).з метою оптимізації геометричних параметрів контейнерів класів розпізнавання за усередненим по всім фінальним (кінцевим) стратам інформаційного критерію $\overline{E}^*_{r,h,s}$.

8) якщо $s \le S_h$, то виконується пункт 6, інакше – пункт 9.

9) якщо $h \le h_{\max}$, де $h_{\max}$ – кількість ярусів r-ї структури даних, то виконується пункт 4, інакше – пункт 10.

10) обчислюється усереднене за фінальними стратами максимальне значення інформаційного критерію оптимізації $\overline{E}^*_{r,h}$.

11) якщо $r \le r_{\max}$, де $r_{\max}$ – кількість ієрархічних структур даних, то виконується пункт 2, інакше – пункт 12.

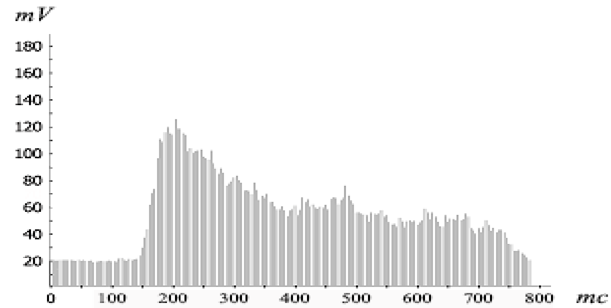
12) визначається за процедурою (3) оптимальна ієрархічна структура даних:

13) ЗУПИН.

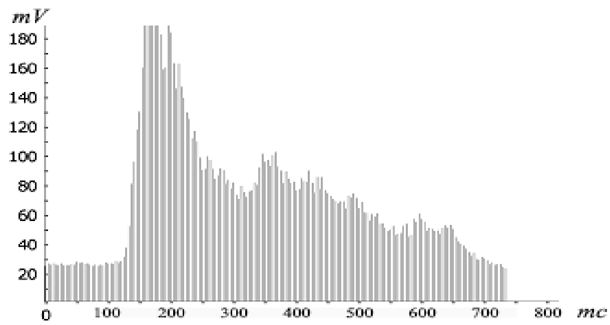
Таким чином, у рамках ІЕІ-технології алгоритм машинного навчання реалізує цілеспрямований пошук глобального максимуму інформаційного критерію (2) для різних варіантів ієрархічної структури алфавіту класів розпізнавання.

4 ЕКСПЕРИМЕНТИ

Як приклад реалізації вище наведеного алгоритму оптимізації ієрархічної структури даних розглядалося машинне навчання системи керування протезом кісті руки. для чотирьох класів розпізнавання: клас X_1^o характеризував функціональний стан «Згинання долоні», клас X_2^o – «Стискання долоні при утриманні предмету», клас X_3^o – «Розгинання долоні» і клас X_4^o – «Згинання вказівного пальця». На рис. 2 показано приклади квантованих за часом зчитування з електроміографічного датчика біосигналів, які отримано при реалізації когнітивних команд «Згинання долоні» (клас розпізнавання X_1^o) і «Стискання долоні при утриманні предмету» (клас розпізнавання X_2^o).



а



б

Рисунок 2 – Приклади зображень типових біосигналів: а – клас розпізнавання X_1^o; б — клас розпізнавання X_2^o

При формуванні навчальної матриці крок квантування біосигналів складав 10 милисекунд, а інтервал квантування – 1,2 с. Таким чином, структурований вектор-реалізація одного класу розпізнавання складався із 120 ознак розпізнавання, які дорівнювали дискретним значенням біосигналів, що зчитувалися послідовно з електроміографічного датчика. При цьому з метою усунення фонового шуму вектор ознак складався з дискрет, значення яких були більше 30 *mV*.

При інформаційно-екстремальному машинному навчанні системи керування протезом досліджувалися дві ієрархічні структури даних. Першою розглядалася

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дихотомічна бінарна ієрархічна структура, за якою спочатку оптимізувалися геометричні параметри одного класу розпізнавання, а до другого входили вектори ознак всіх інших класів. Після оптимізації параметрів першого класу розпізнавання його вектори ознак видалялися із вхідної навчальної матриці. Потім аналогічно оптимізувалися параметри одного класу розпізнавання із трьох класів, які залишилися в алфавіту. І нарешті здійснювалася оптимізація параметрів машинного навчання для двох останніх класів розпізнавання. Іншою досліджувалася так звана декурсивна ієрархічна структура у вигляді направленого графу, в якому атрибути вершини вищого ярусу передаються у вершину своєї страти нижнього ярусу. Для наочності розглядалися показані на рис. 3 три варіанти декурсивних структур даних для заданого алфавіту класів розпізнавання.

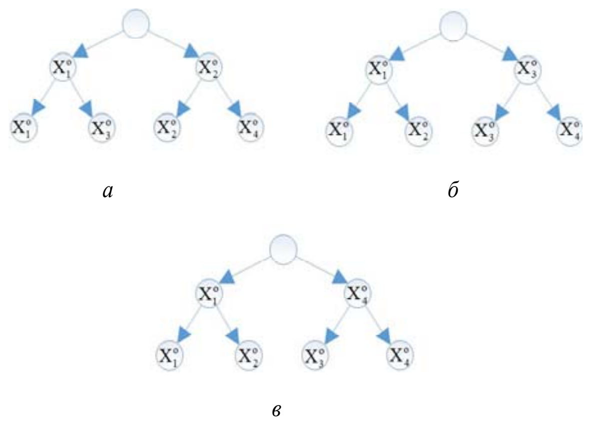

Рисунок 3 – Варіанти декурсивних ієрархічних структур даних

Машинне навчання системи керування протезом кінцівки руки за ієрархічними структурами , показаними на рис. 3, здійснювалося для того самого алфавіту класів розпізнавання, що і в попередньому випалку. Оптимізація в інформаційному розумінні ієрархічної структури даних здійснювалася за алгоритмом (3), за яким визначалися оптимальні значення радіусів гіперсферичних контейнерів класів розпізнавання при заданому параметрі поля контрольних допусків $\delta = 10\ mV$. Як критерій оптимізації параметрів машинного навчання системи керування протезом використовувалася модифікована міра Кульбака, яка для двох альтернативних апріорно рівноймовірних рішень має вигляд

$$E_{h,s,m}^{(k)}(d) = \frac{1}{n}\{n - [K_{1,h,s,m}^{(k)}(d) + K_{2,h,s,m}^{(k)}(d)]\} \times \\ \times \log_2 \frac{2n - [K_{1,h,s,m}^{(k)}(d) + K_{2,h,s,m}^{(k)}(d)] + 10^{-p}}{[K_{1,h,s,m}^{(k)}(d) + K_{2,h,s,m}^{(k)}(d)] + 10^{-p}}. \quad (4)$$

Критерій (4) обчислювався при обсязі навчальної вибірки $n = 25$ і $p = 2$. При цих значеннях максимальне значення критерію дорівнює 4,40.

5 РЕЗУЛЬТАТИ

В табл 1 показано результати оптимізації ієрархічних структур даних в процесі інформаційно-екстремального машинного навчання системи керування протезом кісті руки з неінвазивною системою зчитування біосигналів для заданого алфавіту з чотирьох класів розпізнавання.

Таблиця 1 – Результати машинного навчання системи керування протезом

Номер варіанту	$\overline{E}^*$	$\overline{D}_1$	$\overline{\beta}$	$\overline{P}_t^*$
1	3,99	0,88	0,07	0,91
2	3,50	0,80	0,11	0,84
3	3,55	0,82	0,12	0,85
4	4,40	1,00	0,00	1,00

У табл. 1 як перший варіант розглядається дихотомічна бінарна ієрархічна структура даних, другий варіант – структура, показана на рис. 3а, третій варіант – структура (рис. 3б) і четвертий варіант – структура (рис. 3в). На рис. 4 показано графіки залежності інформаційного критерію оптимізації (4) від радіусів контейнерів класів розпізнавання першої фінальної страти ієрархічної структури, показаної на рис. 3в.

На рис. 5 показано графіки залежності критерію (4) від радіусів контейнерів класів розпізнавання другої фінальної страти структури (рис. 3в).

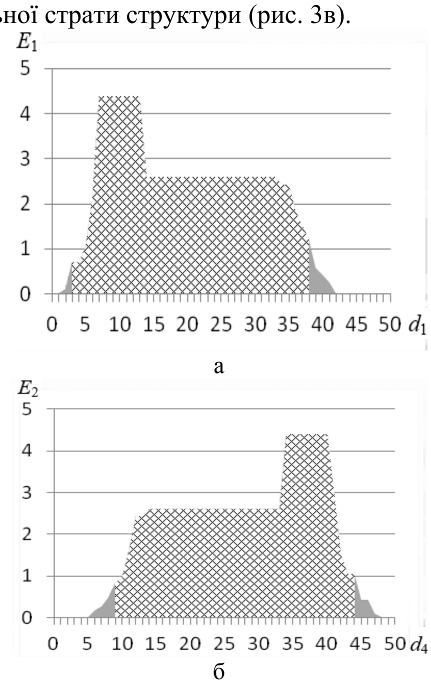

Рисунок 4 – Графіки залежності критерію від радіусів контейнерів класів розпізнавання першої фінальної страти (рис. 3в): а – клас X_1^o ; б –клас X_4^o

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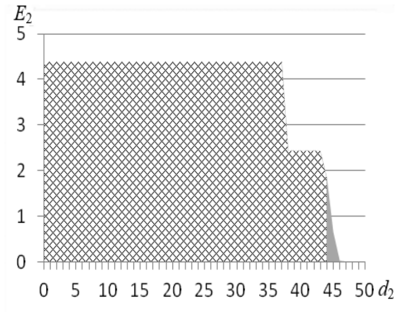
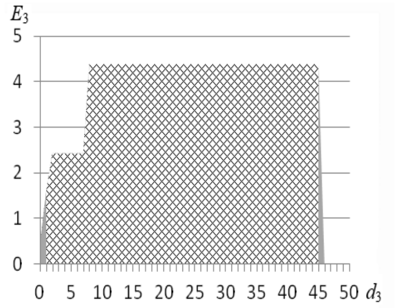


а



б

Рисунок 5 – Графіки залежності критерію від радіусів контейнерів класів розпізнавання другої фінальної страти структури (рис. 3в): а – клас X_2^o ; б –клас X_3^o

Аналіз рис. 4 і рис. 5 показує, що середнє значення критерію оптимізації (4) для фінальних страт дорівнює максимальному значенню критерію $\overline{E}^* = 4,40$. Оскільки графіки на цих рисунках мають ділянки типу "плато", то визначення оптимальних радіусів контейнерів класів розпізнавання здійснювалося за умови мінімальних значень коефіцієнта нечіткої компактності який має вигляд

$$\eta = \frac{d^*_{h,s,m}}{d(x_{h,s,m} \oplus x_{h,s,c})}. \qquad (5)$$

Визначені згідно з виразом (5) оптимальні радіуси контейнерів класів розпізнавання відповідно дорівнювали: $d_1^* = 11$ (тут і далі в кодових одиницях бінарного простору Хеммінга), $d_2^* = 25$, $d_3^* = 29$ і $d_4^* = 15$.

За отриманими в процесі машинного навчання оптимальними в інформаційному розумінні геометричними параметрами контейнерів класів розпізнавання було побудовано вирішальні правила, які в предикативній формі мають вигляд

$$(\forall X_m^o \in \Re^{|M|})(\forall x^{(j)} \in \Re^{|M|})[if\ (\mu_m > 0)\,\&\,(\mu_m = \max\{\mu_m)$$
$$then\ x^{(j)} \in X_m^o\ \ else\ x^{(j)} \notin X_m^o], \qquad (5)$$

де $x^{(j)}$ – вектор ознак, що розпізнається; μ_m – функція належності вектора $x^{(j)}$ контейнеру класу розпізнавання X_m^o.

У виразі (5) функція належності для гіперсферичного контейнера класу розпізнавання X_m^o визначається за формулою [22]

$$\mu_m = 1 - \frac{d(x_m \oplus x^{(j)})}{d_m^*},$$

де d_m^* – оптимальний радіус гіперсферичного контейнера класу розпізнавання X_m^o.

Таким чином, при функціонуванні системи керування в режимі екзамену, на якому оцінюється функціональна ефективність машинного навчання, або безпосередньо в робочому режимі за вирішальними правилами (5) визначається належність вектору ознак, що розпізнається, одному із класів із заданого алфавіту. При цьому вирішальні правила через малу обчислювальну трудомісткість відрізняються високою оперативністю.

6 ОБГОВОРЕННЯ

Аналіз табл. 1 показує, що оптимальною в інформаційному розумінні виявилася ієрархічна структура, показана на рис. 3в, яка забезпечила максимальну граничну повну ймовірність правильного розпізнавання когнітивних команд. Тобто можна стверджувати, що при виборі оптимальної ієрархічної структури побудовано безпомилкові за навчальною матрицею вирішальні правила. Цей факт є необхідною умовою високої функціональної ефективності машинного навчання системи керування протезом Достатньою умовою високої функціональної ефективності машинного навчання слід вважати наближене до одиниці значення повної ймовірності правильного розпізнавання когнітивних команд, отримане при функціонуванні системи керування протезом в режимі екзамену, коли розпізнаються вектори ознак, сформовані безпосередньо на етапі екзамену. Отримана за результатами екзамену середня повна ймовірність правильного розпізнавання когнітивних команд для заданого алфавіту класів розпізнавання дорівнювала $\overline{P}_t = 0,95$. При цьому найменше значення $P_t = 0,85$ мала повна ймовірність правильного розпізнавання когнітивних команд класу розпізнавання X_4^o, який характеризував біосигнал когнітивної команди «Згинання вказівного пальця». Такий показник є достатньо високим, оскільки він знаходиться на рівні показників протезів із інвазивною системою зчитування біосигналів.

ВИСНОВКИ

Запропонований метод інформаційно-екстремального машинного навчання є практично інваріантний до багато вимірності словника ознак і алфавіту класів розпізнавання і є гнучкий до перенавчання системи керування при розширенні алфавіту класів розпізнавання. Крім того, побудовані за результатами машинного навчання в рамках геометричного підходу вирішальні правила дозволяють приймати класифіка-

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ційні рішення в реальному темпі часу, що підтверджується експериментальними результатами, отриманими на дослідному зразку. При цьому оперативність виконання протезом кінцівки руки когнітивних команд буде в основному визначатися сталою часу перехідного процесу сервоелектромоторів як виконавчих пристроїв.

Застосування отриманих наукових результатів для машинного навчання протезу руки із більшою кількістю ступенів свободи пов'язано із необхідністю збільшення інформації шляхом розташування електроміографічних датчиків біосигналів на різних ділянках системи м'язів, які реагують на відповідні когнітивні команди. У цьому випадку виникає необхідність збільшення потужностей словника ознак і алфавіту класів розпізнавання. При цьому для забезпечення високої функціональної ефективності машинного навчання може виникнути необхідність збільшенням глибини машинного навчання шляхом оптимізації додаткових параметрів функціонування системи керування, включаючи параметри оброблення біосигналів.

ПОДЯКА

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ИНФОРМАЦИОННО-ЭКСТРЕМАЛЬНОЕ ИЕРАРХИЧЕСКОЕ МАШИННОЕ ОБУЧЕНИЕ СИСТЕМЫ УПРАВЛЕНИЯ ПРОТЕЗОМ КИСТИ РУКИ С НЕИНВАЗИВНОЙ СИСТЕМОЙ СЧИТЫВАНИЯ БИОСИГНАЛОВ

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АННОТАЦИЯ

Актуальность. Решена актуальная задача информационного синтеза обучающейся системы управления протезом кисти руки с неинвазивной системой считывания биосигналов.

Цель работы – повышение функциональной эффективности системы управления протезом кисти руки с неинвазивной системой считывания биосигналов на основе машинного обучения, что позволяет при функционировании системы в рабочем режиме распознавать с высокой достоверностью и оперативностью когнитивные команды пользователя протезом.

Метод. В рамках информационно-экстремальной интелдектуальной технологии (ИЭИ-технологии) анализа данных, основанной на максимизации информационой способности системы распознавания в процессе машинного обучения, предложен метод информационого синтеза интеллектуальной системы управления протезом кисти руки с неинвазивной системой считывания биосигналов. В отличии от существующих методов интеллектуального анализа данных метод информационно-экстремального машинного обучения разработан в рамках функционального подхода к моделированию когнитивных процессов, свойственных человеку при формировании и принятии классификационных решений. Данный подход позволяет наделить систему управления протезом свойствами адаптивности к произвольным начальным условиям формирования когнитивных команд и переобучения при расширении словаря признаков и алфавита классов распознавания. Кроме того, решающие правила, построенные по полученным в процессе машинного обучения геометрическим параметрам гиперсферических контейнеров классов распознавания являются практически инвариантными к многомерности пространства признаков распознавания. На основе предложенной категорийной модели разроботан алгоритм машинного обучения с оптимизацией иерархической структуры данных. При этом исследовано влияние на функциональную эффективность машинного обучения структур данных, построенных в виде дихотомического и декурсианого деревьев. В качестве критерия оптимизации параметров машинного обучения используется модификация информацилннлй меры Кульбака, являющаяся функционалом точностных характеристик классификационных решений.

Результаты. По экспериментальним данным, полученным с электромиографического датчика, сформирована входная структурированная обучающая матрица для алфавита с четырёх классов распознавания. Построенные в процессе иерархического информационно-экстремального машинного обучения решающие правила позволяют распознавать в реальном темпе времени когнитивные команды с достаточно высокой полной вероятностью принятия правильных классифицирующих решений. Результатами физического моделирования доказано, что при использовании иерархической структуры данных в виде декурсивного дерева функциональная эффективность машинного обучения увеличивается в сравнении с структурой данных в виде дихотомического бинарного дерева.

Выводы. Результатами физического моделирования подтверждена достаточно высокая функциональная эффективность предложенного метода информационно-экстремального машинного обучения системы управления протезом кисти руки с неинвазивной системой считывания биосигналов. Полученные научные результаты открывают новое направление создания интеллектуальных протезов руки с неинвазивной системой считывания биосигналов на основе машинного обучения и распознавания образов.

КЛЮЧЕВЫЕ СЛОВА: информационно-экстремальная интеллектуальная технология, машинное обучение, информационный критерий, система управления, протез кисти руки, электромиографический датчик.

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INFORMATION-EXTREME HIERARCHICAL MACHINE LEARNING OF THE HAND BRUSH PROSTHESIS CONTROL SYSTEM WITH A NON-INVASIVE BIO SIGNAL READING SYSTEM

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ABSTRACT

Context. The actual problem of the information synthesis of learning and control systems for the prosthesis of the hand with a non-invasive system for reading biosignals has been solved.

Objective. The goal of the work is to increase the functional efficiency of the control system for the prosthesis of the hand with a non-invasive system for reading biosignals based on machine learning, which allows the system to operate in the operating mode to recognize the cognitive commands of the user of the prosthesis with high reliability and efficiency.

Method. Within the framework of informational and extreme intellectual technology (IEI technology) of data analysis based on maximizing the informational ability of a recognition system in machine learning, a method of informational synthesis of an intelligent control system for a prosthetic hand with a non-invasive biosignal reading system is proposed. In contrast to the existing methods of data mining, the method of information-extremal machine learning was developed as part of a functional approach to modeling the cognitive processes inherent in humans in the formation and adoption of classification decisions. This approach makes it possible to endow the prosthesis management system with adaptability properties to arbitrary initial conditions for the formation of cognitive teams and retraining while expanding the vocabulary of signs and the alphabet of recognition classes. In addition, the decision rules based on the geometric parameters of hyperspherical containers of recognition classes obtained during machine learning are almost invariant to the multidimensionality of the recognition feature space. Based on the proposed category model, a machine learning algorithm has been developed with optimization of the hierarchical data structure. At the same time, the influence on the functional efficiency of machine learning of data structures constructed in the form of dichotomous and decursion trees was studied. As a criterion for optimizing machine learning parameters, a modification of the informational Kullback measure is used, which is a functional of the accuracy characteristics of classification decisions.

Results. According to the experimental data obtained from the electromyographic sensor, an input structured learning matrix for the alphabet with four recognition classes is formed. The decision rules constructed in the process of hierarchical informational and extreme machine learning make it possible to recognize cognitive teams in real time with a rather high total probability of making correct classifying decisions. The results of physical modeling proved that when using a hierarchical data structure in the form of a decursive tree, the functional efficiency of machine learning increases in comparison with the data structure in the form of a dichotomous binary tree.

Conclusions. The results of physical modeling confirmed a sufficiently high functional efficiency of the proposed method of information-extreme machine learning for the control system of the prosthesis of the wrist with a non-invasive system for reading biosignals. The obtained scientific results open up a new direction in the creation of intellectual prostheses of the hand with a non-invasive system for reading biosignals based on machine learning and pattern recognition.

KEYWORDS: information-extreme intellectual technology, machine learning, information criterion, control system, prosthesis, electromyographic sensor.

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OPTIMAL STABILIZATION ALGORITHM FOR PRODUCTION LINE FLOW PARAMETERS

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ABSTRACT

Context. A method for constructing an algorithm for stabilizing the interoperability of a production line is considered. The object of the study was a model of a multi-operational production line.

Objective. The goal of the work is to develop a method for constructing an optimal algorithm for stabilizing the flow parameters of a production line, which provides asymptotic stability of the state of flow parameters for a given quality of the process.

Method. A method for constructing an algorithm for stabilizing the level of interoperative backlogs of a multi-operational production line is proposed. The stabilization algorithm is based on a two-moment PDE-model of the production line, which made it possible to represent the production line in the form of a complex dynamic distributed system. This representation made it possible to define the stabilizing control in the form of a function that depends not only on time but also on the coordinates characterizing the location of technological equipment along the production line. The use of the method of Lyapunov functions made it possible to synthesize the optimal stabilizing control of the state of interoperation backlogs at technological operations of the production line, which ensures the asymptotic stability of the given unperturbed state of the flow parameters of the production line at the lowest cost of technological resources spent on the formation of the control action. The requirement for the best quality of the transition process from a disturbed state to an unperturbed state is expressed by the quality integral, which depends both on the magnitude of the disturbances that have arisen and on the magnitude of the stabilizing controls aimed at eliminating these disturbances.

Results. On the basis of the developed method for constructing an algorithm for stabilizing the state of flow parameters of a production line, an algorithm for stabilizing the value of interoperation backlogs at technological operations of a production line is synthesized.

Conclusions. The use of the method of Lyapunov functions in the synthesis of optimal stabilizing control of the flow parameters of the production line makes it possible to provide asymptotic damping of the arising disturbances of the flow parameters with the least cost of technological resources spent on the formation of the control action. It is shown that in the problem of stabilizing the state of interoperative backlogs, the stabilizing value of the control is proportional to the value of the arising disturbance. The proportionality coefficient is determined through the coefficients of the quality integral and the Lyapunov function. The prospect of further research is the development of a method for constructing an algorithm for stabilizing the productivity of technological operations of a production line.

KEYWORDS: PDE-model of a production line, multi-moment equations, Lyapunov function, quality integral, optimal control, stabilization problem.

ABBREVIATIONS

PDE is a partial differential equation.

NOMENCLATURE

$[\chi]_0(t,S)$ is a density of inter-operational backlog of parts (WIP) at the time moment t for the position of the production route with the coordinate S;

$[\chi]_1(t,S)$ is a flow of parts at a time t through the position of the technological route with a coordinate S;

$[\chi]_{1\psi}(t,S)$ is a normative productivity of the production equipment at the moment time t for the position of the technological route with the coordinate S;

$\Upsilon_0(t,S)$ is a program control of the state of interoperation backlogs at the time moment t for the position of the technological route with a coordinate S, which ensures the transition of the production system from one state of the production system to another state of the production system;

$\Upsilon_1(t,S)$ is a program control of the normative productivity of production equipment at the time moment t for the position of the technological route with a coordinate S, which ensures the transition of the production system from one state of the production system to another state of the production system;

T_d is a characteristic time of the transfer of the production system from one state of parameters to another state of streaming parameters;

$u_k(t,[y]_0,[y]_1)$ is a control action, providing stabilization of flow parameters $[\chi]_k(t,S)$ relative to the undisturbed state $[\chi]_k^*(t,S)$;

$\omega(t,[y]_0,[y]_1,u_0,u_1)$ is a function that determines the requirements for the lowest possible cost of technological resources (energy, raw materials, labour resources, etc.) spent on the formation of control actions $u_0(t,[y]_0,[y]_1)$, $u_1(t,[y]_0,[y]_1)$.

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INTRODUCTION

The time factor plays a decisive role in planning the operation of a production line and the operational control of its flow parameters [1]. At the same time, the main requirement for the process of planning and operational control of production is to ensure the continuity and rhythm processing of parts along the technological route [2]. In this regard, mathematical methods of planning and operational control of the flow parameters of the production line are exceptional importance [3]. The most important and least studied among them are the dynamic problems of the optimal use of the technological resources of the enterprise to ensure a steady-state of the flow parameters of the production line [4].

The object of study is model of a production multi-operation production line.

The production lines of modern industrial enterprises contain~10^3 technological operations [5], in the interoperation reserves of which are ~10^5 parts [6]. The structure of the production line can be highly branched [7], consisting of separate sections of the technological route with a sequential position of technological operations [8]. The presence of a branched structure imposes additional difficulties on the construction of a production line model, and, as a consequence, construction of an algorithm for stabilization of the production line flow parameters. For this reason, the construction of an algorithm for stabilizing the flow parameters will be carried out for a production line with a sequential position of technological operations [9] (Fig. 1).

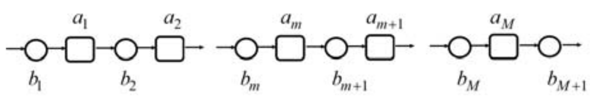

Figure 1 –Serial production line

This simplification will allow us to focus on the key design points of the stabilization algorithm. The obtained results can be used to design control systems for flow parameters of complex branched production lines.

The subject of study is a method for constructing an algorithm for stabilizing the production line flow parameters, based on the PDE model of the production line.

The control problem of the production line flow parameters is often considered as the task of building program control (production schedule of the output plan [11]). Methods for constructing a programmed control using the equations of the fluid–model and the PDE–model are presented in [12, 13]. However, in the presence of disturbances, the programmed control will be implemented without additional stabilizing effects only in the case of asymptotic stability of the production line flow parameters. This circumstance requires the development of methods for designing algorithms for stabilizing the production line flow parameters.

The purpose of the work is to develop a method for constructing an algorithm for optimal stabilizing the production line flow parameters, which ensures the asymptotic stability of the state of flow parameters.

1 PROBLEM STATEMENT

To describe the serial production line (Fig. 1), let's use a two-moment PDE-model, the equations of which have the form [4, 10]:

$$\frac{\partial[\chi]_0(t,S)}{\partial t}+\frac{\partial[\chi]_1(t,S)}{\partial S}=\Upsilon_0(t,S), \tag{1}$$

$$\frac{\partial[\chi]_0(t,S)}{\partial t}+\frac{[\chi]_{1\psi}(t,S)}{[\chi]_0(t,S)}\frac{\partial[\chi]_1(t,S)}{\partial S}=\Upsilon_1(t,S). \tag{2}$$

with a control program $\Upsilon_0(t,S)$, $\Upsilon_1(t,S)$ for transferring production systems from a state with parameters $[\chi]_0(0,S)$ to a state with parameters $[\chi]_0(T_d,S)$ for a time $t\in[0,T_d]$.

Let the production line flow parameters $[\chi]_0(t,S)$, $[\chi]_1(t,S)$ receive unknown random small disturbances:

$$[y]_0(t,S)=[\chi]_0(t,S)-[\chi]_0^*(t,S), \tag{3}$$

$$[y]_1(t,S)=[\chi]_1(t,S)-[\chi]_1^*(t,S), \tag{4}$$

with respect to given program control $\Upsilon_0^*(t,S)$, $\Upsilon_1^*(t,S)$ unperturbed parameters $[\chi]_0^*(t,S)$, $[\chi]_1^*(t,S)$. To eliminate the disturbances $[y]_0(t,S)$, $[y]_1(t,S)$ that have arisen, it is required to develop control actions $u_0(t,[y]_0,[y]_1)$, $u_1(t,[y]_0,[y]_1)$, which should ensure the asymptotic stability of a given unperturbed state of flow parameters $[\chi]_0^*(t,S)$, $[\chi]_1^*(t,S)$, satisfying the system of equations (1), (2). It is assumed that the function $u_0(t,[y]_0,[y]_1)$, $u_1(t,[y]_0,[y]_1)$ satisfies the equalities

$$u_0(t,0,0)=0,\ u_1(t,0,0)=0. \tag{5}$$

The given functions are defined and continuous in the area under consideration and are not constrained by any additional inequalities.

When setting the problem of stabilization of production line flow parameters, we supplement the requirement of asymptotic stability of the unperturbed state of flow parameters with the requirement of the best quality of the transient process

$$I=\int_0^\infty \omega(t,[y]_0,[y]_1,u_0,u_1)dt. \tag{6}$$

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2 REVIEW OF THE LITERATURE

Common models that are used for the synthesis of optimal control of the production line flow parameters are Clearing-function models [14, 15], queue theory [16], discrete-event models [17, 18], Fluid– models [12, 13], system dynamics models [3], PDE– models [4, 5].

Clearing-function models and queue theory models are used when the input or output parameters of the production line are controlled. This class of models determines the relationship between input and output parameters using approximate relationships or precise analytical expressions that take into account, with a given accuracy, the state of distributed parameters along the production line. At the same time, there is no control over the state of flow parameters along the production line. Effective use of the Clearing-function model is presented in [19]. However, such cases of effective use of Clearing-function models are very rare.

Discrete-event models make it possible to sufficiently accurately simulate the process of processing products at technological operations of a production line. This class of models is used to build control systems of the flow parameters of technological operations of production lines. A significant disadvantage of their application for the design of control systems for the production line parameters is that the construction of effective control systems requires large expenditures of computing resources. When constructing multi-operational models of production lines [5] for batches with a large number of parts [6], the computational time of the model parameters exceeds the time allotted for making a decision on the formation of control actions.

Fluid models, system dynamics models and PDE models are most suitable for describing a production line. Fluid models and models of system dynamics are recommended for describing production lines containing several tens of technological operations [20]. For a large number of technological operations, the most effective way to describe a production line is to use a PDE model. In the paper [19], the limit transition from the PDE-model equation to the Clearing-function equation is provided. The Clearing Equation for a conveyor system determines the relationship between the input and output streaming parameters of the transport system. In the paper [20], the limit transition from the PDE-model equations to the equations of system dynamics is given.

PDE-models are significant practical interest for the control systems design for the parameters of many operational production lines. Further development of the PDE-models class, associated with the development of methods for constructing algorithms for optimal control of production line flow parameters, providing asymptotic stability of the flow parameters state, opens up new prospects for using this class of models in control systems of flow production.

3 MATERIALS AND METHODS

Balance equations (1), (2) determine the state of the multi-operation production line flow parameters $[\chi]_0(t,S)$, $[\chi]_1(t,S)$ (Fig. 1). The main mode of operation of production lines for enterprises with a flow method of organizing production is a synchronized mode, in which the performance of technological equipment is the same for each technological operation [21, 22]. Synchronization of technological equipment is taken into account as an additional condition

$$\frac{\partial[\chi]_{1\psi}(t,S)}{\partial S} \cong 0 \,. \tag{6}$$

Then the system of equations for the parameters of the production line corresponds to a linearized system of equations in small perturbations $[y]_0(t,S)$, $[y]_1(t,S)$:

$$\frac{\partial[y]_0(t,S)}{\partial t} + \frac{\partial[y]_1(t,S)}{\partial S} = q_{00}u_0 + q_{01}u_1 , \tag{7}$$

$$\frac{\partial[y]_1(t,S)}{\partial S} + \frac{\partial[y]_1(t,S)}{\partial S}B + [y]_1(t,S)\frac{\partial B}{\partial S} +$$

$$+ \frac{\partial[y]_0(t,S)}{\partial S}AB + [y]_0(t,S)\frac{\partial(AB)}{\partial S} = q_{10}u_0 + q_{11}u \,,$$

$$A = \left.\frac{[\chi]_{1\psi}(t,S) - [\chi]_1(t,S)}{[\chi]_0(t,S)}\right|_0 , \; B = \left.\frac{[\chi]_{1\psi}(t,S)}{[\chi]_0(t,S)}\right|_0 ,$$

$$q_{00}u_0 + q_{01}u_1 = \Upsilon_0(t,S) - \Upsilon_0^*(t,S) \,,$$

$$q_{10}u_0 + q_{11}u = \Upsilon_1(t,S) - \Upsilon_1^*(t,S) \,.$$

Functions $q_{nm} = q_{nm}(t)$ are limited and continuous functions of time. The period of existence of the disturbance T_v of the flow parameters ranges from several days to several weeks, while the period of change in the coefficients A and B, determined by the strategic management of the enterprise, ranges from several months to several years [23]. In this regard, let's assume that the coefficients A and B during the period of existence of the disturbance T_v do not explicitly depend on time, and their changes in time are much less than the values of the coefficients themselves:

$$\frac{A}{T_v} >> \frac{\partial A}{\partial t}, \; \frac{B}{T_v} >> \frac{\partial B}{\partial t} \,. \tag{8}$$

Inequality (8) allows us to assume that the coefficients A and B in equations (7) depend only on the coordinate S. Let's assume that during control it is possible to measure the current values of the macro parameters $[\chi]_0$ and $[\chi]_1$. On the basis of measurements, the control device develops influences $u_0 = u_0(t,[y]_0,[y]_1)$, $u_1 = u_1(t,[y]_0,[y]_1)$ on the flow parameters of the production line $[\chi]_0(t,S)$, $[\chi]_1(t,S)$. These influences should ensure the asymptotic stability of the given unperturbed

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state of the flow parameters. The problem of the stabilizing production line flow parameters $[\chi]_0(t,S)$, $[\chi]_1(t,S)$ can be reduced to the control problem interoperable stocks or to the control problem the productivity of technological equipment. In this paper, let's consider the control problem of inter-operational backlogs.

Correction, coordination and approval of the production plan require accurate information about the distribution of parts by technological operations along the technological route. The problem of tactical production planning is closely related to the problem of reserve placement of stocks. For a production line consisting of two technological operations in the paper [24], a solution to the problem of tactical planning at the level of individual elements is proposed using linear programming methods. In paper [8], the application of a fluid model for tactical production planning is considered, which optimizes the amount of safety stock to ensure the normative functioning of a multi-flow line. A nonlinear problem of planning the safety stock is formulated, which can be used to stabilize the flow parameters of a multi-flow production line with an objective function that minimizes the total cost of the safety stock.

Along with the planning problem, the value of the optimal safety stock, the stabilizing the parameters by a multi-flow line is no less urgent. The solution of the problem makes it possible to find the optimal control actions that ensure the asymptotic stability of the planned given unperturbed state of flow parameters with the least cost of technological resources spent on the formation of the control action $u_0 = u_0(t,[y]_0,[y]_1)$. Suppose that in a synchronized operation mode of the production line, the productivity of the technological equipment is equal to the standard value

$$[\chi]_{1\psi}(t,S) \cong [\chi]_1(t,S),$$

and the parts are evenly distributed over the technological operations

$$\frac{\partial[\chi]_0(t,S)}{\partial S} \cong 0.$$

Then, when using only the management of inter-operational reserve $u_0 = u_0(t,[y]_0,[y]_1)$ the system of two-moment balance equations (7) can be represented in the form

$$\frac{\partial[y]_0(t,S)}{\partial t} + \frac{\partial[y]_1(t,S)}{\partial S} = q_{00}u_0, \quad \frac{\partial[y]_1(t,S)}{\partial t} + \frac{\partial[y]_1(t,S)}{\partial S}B = 0. \tag{9}$$

It is assumed that if the amount of inter-operative backlogs deviates from the undisturbed state $[\chi]_n = [\chi]_n^*(t,S)$ it is possible to compensate for this deviation with intensity $q_{00}\cdot u_0$ at the expense of external sources of replenishment or from insurance backlogs. The absence of a control action $u_0 = u_0(t,[y]_0,[y]_1)$ in the equation for the productivity of technological equipment позволяет утверждать, allows us to assert that there is no source of change in the productivity of technological equipment, $q_{10} \equiv 0$. The change in the value of inter-operative backlogs occurs due to desynchronization in the performance of technological equipmen $\frac{\partial[y]_1(t,S)}{\partial S}$, which is ultimately compensated by the source of insurance backlogs $q_{00}\cdot u_0$. The negative value of the receipt of parts from the source of insurance reserves $q_{00}\cdot u_0$ indicates the formation of an excessive inter-operational reserve, which is taken from the technological operation reserve. When $[y]_0(t,S) < 0$, additional costs are required to replenish the deviations of the inter-operative backlog. Since the system of equations (9) contains only one multiplier q_{00}, so let's put $q_{00} = 1$, thereby taking into account the considered coefficient directly in the unknown function u_0.

As a criterion evaluating the quality of the flow parameters operational control (6), let's choose the condition that determines the minimum of the integral:

$$I = \int_0^{\infty}\int_0^{S_d} \left(\alpha([y]_0)^2 + \beta(u_0)^2\right) dSdt. \tag{10}$$

where α, β are the coefficients characterizing the costs associated with the deviations of the flow parameters and the costs associated with the control actions necessary to eliminate these deviations do not depend on S. Taking into account the expansion of small disturbances $[y]_0(t,S)$, $[y]_1(t,S)$ of the flow parameters $[\chi]_0(t,S)$, $[\chi]_1(t,S)$ and control actions $u_0(t,[y]_0,[y]_1)$ in a Fourier series, the integrand ω for the quality integral takes the form

$$\omega = \\ = \alpha\left(\{y_n\}_0 + \sum_{j=1}^{\infty}\{y_n\}_j \sin[k_jS] + \sum_{j=1}^{\infty}[y_n]_j \cos[k_jS]\right)^2 + \\ + \beta\left(\{u_n\}_0 + \sum_{j=1}^{\infty}\{u_n\}_j \sin[k_jS] + \sum_{j=1}^{\infty}[u_n]_j \cos[k_jS]\right)^2. \tag{11}$$

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Let us perform integration the quality criterion (10) by the coordinate S

$$I = \int_0^\infty \alpha\left(\{y_0\}_0^{\,2} + \frac{1}{2}\sum_{j=1}^{\infty}\left(\{y_0\}_j^{\,2} + [y_0]_j^{\,2}\right)\right)dt + \\ + \int_0^\infty \beta\left(\{u_0\}_0^{\,2} + \frac{1}{2}\sum_{j=1}^{\infty}\left(\{u_0\}_j^{\,2} + [u_0]_j^{\,2}\right)\right)dt . \quad (12)$$

Substituting into the system of equations (9) the expansion of small perturbations $[y]_0(t,S)$, $[y]_1(t,S)$ of the flow parameters and control action $u_0(t,[y]_0,[y]_1)$ in the Fourier series, the system of equations in small perturbations is obtained:

$$\frac{d\{y_0\}_0}{dt} = \{u_0\}_0 , \ \frac{d\{y_1\}_0}{dt} = 0 , \\ \frac{d\{y_0\}_1}{dt} + k[y_1]_1 = \{u_0\}_1 , \ \frac{d[y_0]_1}{dt} + k\{y_0\}_1 = [u_0]_1 , \quad (13) \\ \frac{d\{y_1\}_1}{dt} - [y_1]_1 kB = 0 , \ \frac{d[y_1]_1}{dt} + \{y_1\}_1 kB = 0 .$$

When constructing the system of equations (13), for clarity of demonstrating the method of constructing the stabilization algorithm, the expansion in the Fourier series is limited by the first two terms. Let's seek the Lyapunov function in the quadratic form:

$$V^0 = \int_0^{S_d} \left(c_0([y]_0)^2 + c_1([y]_1)^2\right)dS , \ \frac{\partial V^0}{\partial t} = 0 \quad (14)$$

with constant coefficients c_0, c_1. Then Lyapunov function V^0 can be written in terms of the coefficients $\{y_n\}_0$, $\{y_n\}_j$, $[y_n]_j$

$$V^0 = c_0\left(\{y_0\}_0^{\,2} + \frac{1}{2}\sum_{j=1}^{\infty}\left(\{y_0\}_j^{\,2} + [y_0]_j^{\,2}\right)\right) + \\ + c_1\left(\{y_1\}_0^{\,2} + \frac{1}{2}\sum_{j=1}^{\infty}\left(\{y_1\}_j^{\,2} + [y_0]_j^{\,2}\right)\right). \quad (15)$$

Let us define the Hamiltonian $B[V^0]$ for the system under study in the following form:

$$B[V^0] = \sum_{n=0}^{1} \frac{\partial V^0}{\partial \{y_n\}_0}\frac{d\{y_n\}_0}{dt} + \\ + \sum_{j=1}^{\infty}\left(\sum_{n=0}^{1}\frac{\partial V^0}{\partial \{y_n\}_j}\frac{d\{y_n\}_j}{dt} + \sum_{n=0}^{1}\frac{\partial V^0}{\partial [y_n]_j}\frac{d[y_n]_j}{dt}\right) + \omega . \quad (16)$$

Under optimal control $u_0 = u_0^{\,*}(t,[y]_0,[y]_1)$ the value $B[V^0]$ should have a minimum and thus become zero. Hence the first equation for determining the form of the Lyapunov function V^0 and the optimal control action $u_0 = u_0^{\,*}(t,[y]_0,[y]_1)$:

$$B[V^0] = 0 . \quad (17)$$

4 RESULTS

Differentiating $B[V^0]$ by $\{u_0\}_0$, $\{u_0\}_j$, $[u_1]_j$ and equating the results to zero, we obtain the missing equations for determining the form of the Lyapunov function V^0 and the optimal control action $u_0 = u_0^{\,*}(t,[y]_0,[y]_1)$:

$$\frac{\partial B[V^0]}{\partial \{u_0\}_0} = \sum_{n=0}^{1} \frac{\partial V^0}{\partial \{y_n\}_0}\frac{\partial}{\partial \{u_0\}_0}\left(\frac{d\{y_n\}_0}{dt}\right) + \\ + \sum_{j=1}^{\infty}\sum_{n=0}^{1} \frac{\partial V^0}{\partial \{y_n\}_j}\frac{\partial}{\partial \{u_0\}_0}\left(\frac{d\{y_n\}_j}{dt}\right) + \quad (18) \\ + \sum_{j=1}^{\infty}\sum_{n=0}^{1} \frac{\partial V^0}{\partial [y_n]_j}\frac{\partial}{\partial \{u_0\}_0}\left(\frac{d[y_n]_j}{dt}\right) + 2\beta\{u_0\}_0 = 0.$$

$$\frac{\partial B[V^0]}{\partial \{u_0\}_m} = \sum_{n=0}^{1} \frac{\partial V^0}{\partial \{y_n\}_0}\frac{\partial}{\partial \{u_0\}_m}\left(\frac{d\{y_n\}_0}{dt}\right) + \\ + \sum_{j=1}^{\infty}\sum_{n=0}^{1} \frac{\partial V^0}{\partial \{y_n\}_j}\frac{\partial}{\partial \{u_0\}_m}\left(\frac{d\{y_n\}_j}{dt}\right) + \quad (19) \\ + \sum_{j=1}^{\infty}\sum_{n=0}^{1} \frac{\partial V^0}{\partial [y_n]_j}\frac{\partial}{\partial \{u_0\}_m}\left(\frac{d[y_n]_j}{dt}\right) + \beta\{u_0\}_m = 0 ,$$

$$\frac{\partial B[V^0]}{\partial [u_0]_{\mathrm{m}}} = \sum_{n=0}^{1} \frac{\partial V^0}{\partial \{y_n\}_0}\frac{\partial}{\partial [u_0]_{\mathrm{m}}}\left(\frac{d\{y_n\}_0}{dt}\right) + \\ + \sum_{j=1}^{\infty}\sum_{n=0}^{1} \frac{\partial V^0}{\partial \{y_n\}_j}\frac{\partial}{\partial [u_0]_{\mathrm{m}}}\left(\frac{d\{y_n\}_j}{dt}\right) + \quad (20) \\ + \sum_{j=1}^{\infty}\sum_{n=0}^{1} \frac{\partial V^0}{\partial [y_n]_j}\frac{\partial}{\partial [u_0]_{\mathrm{m}}}\left(\frac{d[y_n]_j}{dt}\right) + \beta[u_0]_{\mathrm{m}} = 0 .$$

Substituting (13) into the above equations (18)–(20), the following equations are obtained:

$$c_0\{y_0\}_0 + c_0\{y_0\}_0 + \beta\{u_0\}_0 = 0 , \quad (21) \\ c_0\{y_0\}_m + \beta\{u_0\}_m = 0 , \\ c_0[y_0]_m + [\beta]_0[u_0]_m = 0 .$$

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The system of equations (21) is solvable with respect to coefficients $\{u_0\}_0$, $\{u_0\}_m$, $[u_0]_m$:

$$\{u_0\}_0 = -\frac{c_0}{\beta}\{y_0\}_0, \tag{22}$$

$$\{u_0\}_m = -\frac{c_0}{\beta}\{y_0\}_m,$$

$$[u_0]_m = -\frac{c_0}{\beta}[y_0]_m.$$

The coefficient c_0 can be determined from equation (17). If it is possible to find a limited particular solution of the equation for determining the coefficient c_0, such that form V^0 (15) turns out to be definitely positive, then the control actions (22) will ensure the asymptotic stability of the given unperturbed state of the flow parameters due to equations (9).

5 DISCUSSION

The system of equations (22) determines the algorithm for the optimal stabilization of the inter-operational backlogs of the production line. Taking into account the relation for the expansion coefficients of functions $[y]_0(t,S)$, $u_0(t,S)$ (22), the stabilization algorithm can be represented in the form

$$u_0(t,S) = -\frac{c_0}{\beta}[y]_0(t,S). \tag{23}$$

The stabilizing action is proportional to the disturbance that has arisen and is opposite to it in sign. The optimal control $u_0 = u_0^*(t,[y]_0,[y]_1)$ is set by the value of the coefficient c_0, which is calculated taking into account the given form of the function of the quality criterion of the process of stabilization of the flow parameters (6). Substitution of function (23) into equation (9)

$$\frac{\partial[y]_0(t,S)}{\partial t} + \frac{\partial[y]_1(t,S)}{\partial S} = -\frac{c_0}{\beta}[y]_0(t,S). \tag{24}$$

allows a qualitative analysis of the obtained solution. The stabilizing action (23) compensates for the desynchronization of technological equipment The minimum value of the constant c_0 in the Lyapunov function can be determined from the condition

$$\frac{c_0}{\beta}[y]_0(t,S) + \frac{\partial[y]_1(t,S)}{\partial S} \ge 0. \tag{25}$$

Inequality (25) must hold for any values of t and S. If the condition is satisfied

$$\left|\frac{c_0}{\beta}[y]_0(t,S)\right| >> \left|\frac{\partial[y]_1(t,S)}{\partial S}\right|,$$

the solution of equation (24) takes the form

$$[y]_0(t,S) \sim \exp\left(-\frac{c_0}{\beta}t\right).$$

The resulting deviation of inter-operative backlogs decreases exponentially with characteristic decay time $t_d = \beta / c_0$. An increase in the value of the coefficient c_0 leads to an increase in the rate of the damping process of the arisen disturbance and, accordingly, decreases the characteristic time of the process of stabilization of the arisen disturbances. Condition (25), which determines the minimum value of the coefficient c_0, which the asymptotic damping of the arising disturbances of the inter-operational reserve is ensured, can be represented in the following form

$$\frac{c_0}{\beta}[y]_0(t,S) - \frac{1}{B}\frac{\partial[y]_1(t,S)}{\partial t} \ge 0. \tag{26}$$

Inequality (26) must be satisfied for any values of t and S. The reasons for the disturbance can be different. The main cause of disturbances is desynchronization of technological equipment. The technological time for processing a part with technological equipment is not a deterministic value. The processing time is a random variable, which is determined by a given law of distribution of a random variable with a mathematical expectation inversely proportional to the standard productivity of technological equipment $[\chi]_{1\psi}(t,S)$ [25]. Thus, a stochastic process of processing parts with an average processing time $[\chi]_{1\psi}^{-1}(t,S)$ leads to the emergence of a function gradient $[y]_1(t,S)$, and, accordingly, to desynchronization of technological equipment along the production line. Also, a significant source of deviations in the value $[y]_0(t,S)$ is the presence of a source of defective products. The occurrence of this situation can be caused by both random factors and systemic factors associated, for example, with the wear of a tool or technological equipment. Such a source leads both to the loss of parts due to the impossibility of their further processing and to a decrease in the productivity of technological equipment for processing modes of illiquid parts.

CONCLUSIONS

A method for constructing an algorithm for stabilizing the production line flow parameters was proposed.

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The scientific novelty of obtained results is that for the first time a method for constructing an algorithm for stabilizing the production line flow parameters was proposed. The stabilization algorithm makes it possible to provide asymptotic damping of the arising disturbances of inter-operative reserves, provided that the stabilization proceeds in accordance with a given quality criterion. This makes it possible to ensure a given production output in accordance with planned indicators with a minimum expenditure of technological resources. The algorithm for stabilizing the flow parameters allows you to avoid equipment downtime due to the lack of parts in the inter-operational bunkers or due to their overflow.

The practical significance lies in the use of the developed methodology for the design of highly efficient systems for stabilizing the production line flow parameters of industrial enterprises with the flow method of organizing production.

Prospects for further research are the development of a method for constructing an algorithm for stabilizing the productivity of technological operations of a production line.

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АЛГОРИТМ ОПТИМАЛЬНОЇ СТАБІЛІЗАЦІЇ ПОТОКОВИХ ПАРАМЕТРІВ ВИРОБНИЧОЇ ЛІНІЇ РОЗМІРНОСТІ

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АНОТАЦІЯ

Актуальність. Розглянуто метод побудови алгоритму стабілізації меж-операційних заділів виробничої лінії. Об'єктом дослідження була модель виробничої багато-операційної потокової лінії.

Мета роботи. Метою роботи є розробка методу побудови оптимального алгоритму стабілізації потокових параметрів виробничої лінії, при якому забезпечується асимптотична стійкість стану потокових параметрів при заданому якості процесу ліквідації виниклих збурень..

Метод.. Запропоновано метод побудови алгоритму стабілізації рівня міжопераційних заділів багатоопераційної виробничої лінії В основу побудови алгоритму стабілізація покладена двох моментная PDE-модель виробничої лінії, що дозволило представити виробничу лінію у вигляді складної динамічної розподіленої системи. Таке уявлення дало можливість визначити стабілізуючий управління у вигляді функції, яка залежить не тільки від часу, але і координати, що характеризує місце розташування технологічного обладнання уздовж виробничої лінії. Використання методу функцій Ляпунова дозволило синтезувати оптимальне стабілізуючий управління станом меж-операційних заділів на технологічних операціях виробничої лінії, яка забезпечує асимптотичну стійкість заданого невозмущенного стану потокових параметрів виробничої лінії при найменших витратах технологічних ресурсів, що витрачаються на формування керуючого впливу. Вимога про найкращій якості перехідного процесу від обуреного стану до незбурених виражено інтегралом якості, який залежить як від величини виникли збурень, так і від величини стабілізуючих управлінь, націлених на ліквідацію даних збурень.

Результати. На основі розробленого методу побудови алгоритму стабілізації стану потокових параметрів виробничої лінії синтезований алгоритм стабілізації величини меж-операційних заділів на технологічних операціях виробничої лінії.

Висновки. Використання методу функцій Ляпунова при синтезі оптимального стабілізуючого управління потоковими параметрами виробничої лінії дозволяє забезпечити асимптотическое загасання виникають збурень потокових параметрів при найменших витратах технологічних ресурсів, що витрачаються на формування керуючого впливу. Показано, що в задачі стабілізації стану міжопераційних заділів стабілізуючий управління по величині пропорційно величині виникає обурення. Коефіцієнт пропорційності визначається через коефіцієнти інтеграла якості і функції Ляпунова. Перспективою подальших досліджень є розробка методу побудови алгоритму стабілізації продуктивності технологічних операцій виробничої лінії

КЛЮЧОВІ СЛОВА: PDE-модель виробничої лінії, багато-моментні рівняння, функція Ляпунова, інтеграл якості, оптимальне управління, стабілізація..

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АЛГОРИТМ ОПТИМАЛЬНОЙ СТАБИЛИЗАЦИИ ПОТОКОВЫХ ПАРАМЕТРОВ ПРОИЗВОДСТВЕННОЙ ЛИНИИ

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АННОТАЦИЯ

Актуальность. Рассмотрен метод построения алгоритма стабилизации межоперационных заделов производственной линии. Объектом исследования являлась модель производственной многооперационной поточной линии.

Цель работы. Целью работы является разработка метода построения оптимального алгоритма стабилизации потоковых параметров производственной линии, при котором обеспечивается асимптотическая устойчивость состояния потоковых параметров при заданном качестве процесса ликвидации возникших возмущений.

Метод. Предложен метод построения алгоритма стабилизации уровня межоперационных заделов многооперационной производственной линии. В основу построения алгоритма стабилизация положена двух моментная PDE–модель производственной линии, что позволило представить производственную линию в виде сложной динамической распределенной системы. Такое представление дало возможность определить стабилизирующее управление в виде функции, которая зависит не только от времени, но и координаты, характеризующей место расположения технологического оборудования вдоль производственной линии. Использование метода функций Ляпунова позволило синтезировать оптимальное стабилизирующее управление состоянием межоперационных заделов на технологических операциях производственной линии, которое обеспечивает асимптотическую устойчивость планового заданного невозмущенного состояния потоковых параметров производственной линии при наименьших затратах технологических ресурсов, расходуемых на формирование управляющего воздействия. Требование о наилучшем качестве переходного процесса от возмущенного состояния к невозмущенному выражено интегралом качества, который зависит как от величины возникших возмущений, так и от величины стабилизирующих управлений, нацеленных на ликвидацию данных возмущений.

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Результаты. На основе разработанного метода построения алгоритма стабилизации состояния потоковых параметров производственной линии синтезирован алгоритм стабилизации величины межоперационных заделов на технологических операциях производственной линии.

Выводы. Использование метода функций Ляпунова при синтезе оптимального стабилизирующего управления потоковыми параметрами производственной линии позволяет обеспечить асимптотическое затухание возникающих возмущений потоковых параметров при наименьших затратах технологических ресурсов, расходуемых на формирование управляющего воздействия. Показано, что в задаче стабилизации состояния межоперационных заделов стабилизирующее управление по величине пропорционально величине возникающего возмущения. Коэффициент пропорциональности определяется через коэффициенты интеграла качества и функции Ляпунова. Перспективой дальнейших исследований является разработка метода построения алгоритма стабилизации производительности технологических операций производственной линии.

КЛЮЧЕВЫЕ СЛОВА: PDE-модель производственной линии, много-моментные уравнения, функция Ляпунова, интеграл качества, оптимальное управление, стабилизация.

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IMPROVING THE ACCURACY OF AUTOMATIC CONTROL WITH MATHEMATICAL METER MODEL IN ON-BOARD CONTROLLER

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ABSTRACT

Context. The article discusses the issues of increasing the accuracy of automatic control of a moving object using a mathematical model of a meter and a device observing measurement errors in the on-board controller of the control system. The object of the research is the processes of automatic control of a moving object with a mathematical model of a meter and a device observing measurement errors in the on-board controller of the control system. The subject of the research is a method and algorithms for increasing the accuracy of automatic control of a moving object with a mathematical model of a meter and a device observing measurement errors in the on-board controller of the control system.

Objective. The aim of research is an improving the accuracy of automatic control of a moving object.

Method. This aim is achieved through the use in the on-board controller of the control system of the mathematical meter model and the observing device built on its basis, the estimation of the useful component and the systematic error, depending on the motion parameters of the controlled object, using only the useful component for control, without systematic error.

Results. A method and algorithms for increasing the control accuracy of a moving object through the use in the on-board controller of a mathematical meter model and an observer of systematic measurement errors, built on its basis, have been developed. The efficiency and effectiveness of the developed method and algorithms were confirmed by mathematical modeling in the MATLAB environment of the control processes of a moving object in a closed circuit with a control system.

Conclusions. The results of mathematical modeling confirmed the operability and efficiency of the proposed method and algorithms and allow them to be used for practical purposes in the development of mathematical support for high – precision automatic control systems.

KEYWORDS: automatic control, control accuracy, movement control systems, measurement errors, observing device, mathematical model.

ABBREVIATIONS

GCS $OX_2Y_2Z_2$ is a Gyroscopic Coordinate System;

GSE is a Gyrocompass Sensing Element.

NOMENCLATURE

$\mathbf{f}_n(\bullet)$ is a mathematical model of the control object;

$\mathbf{X}_n$ is a control object state vector;

$\mathbf{C}_n$ is a vector of control object constants;

$\mathbf{f}_{jm}(\bullet)$ is a j-th meter component of mathematical model;

$\mathbf{X}_m$ is a meter state vector;

$\mathbf{C}_m$ is a vector of meter constants;

$\mathbf{f}_u(\bullet)$ is a control law;

$\mathbf{U}$ is a control vector;

$\mathbf{X}_m^*$ is a vector of required movement parameters;

$\mathbf{C}_u$ is a vector of control law constants;

$\mathbf{F}$ is a quality control function;

$\hat{\mathbf{X}}_m$ is a measurement evaluation vector;

$\hat{\mathbf{X}}_{0m}$ is a vector of estimation of useful component of measurements;

$\hat{\mathbf{X}}_{jm}$ is an estimate vector j-th component of the systematic measurement error;

$\boldsymbol{\lambda}_j$ is a j-th observer coefficient vector;

$\mathbf{H}$ is a kinetic moment vector of the gyrocompass sensing element;

$\boldsymbol{\Omega}$ is an angular rate of kinetic moment vector;

$\mathbf{M}^j$ is a j-th vector of disturbance moment;

Θ_m is a measured deflection angle of gyrocompass sensetive element in vertical plane;

$\hat{\Theta}_m$ is an assessed deflection angle of gyrocompass sensetive element in vertical plane;

$\hat{\Theta}_{0m}$ is an assessed usefull components of deflection angle in vertical plane;

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$\hat{\Theta}_{jm}$ is an estimation of the j-th component of the systematic measurement error from $\mathbf{M}^j$ – disturbance moment;

Ψ_m is a measured deflection angle of gyrocompass sensetive element in horizontal plane;

$\hat{\Psi}_m$ is an assessed deflection angle of gyrocompass sensetive element in horizontal plane;

$\hat{\Psi}_{0m}$ is an assessed usefull components of deflection angle in horizontal plane;

$\hat{\Psi}_{jm}$ is an estimation of the j-th component of the systematic measurement error from $\mathbf{M}^j$-disturbance moment in the horizontal plane;

$\mathbf{f}_0^{\Theta}$ is a mathematical model of the useful component in vertical plane;

$\mathbf{f}_j^{\Theta}$ is a mathematical model of the j-th deviation component in the vertical plane;

$\mathbf{f}_0^{\Psi}$ is a mathematical model of the useful component in horizontal plane;

$\mathbf{f}_j^{\Psi}$ is a mathematical model of j-th deviation component in horizontal plane;

λ_j^{Θ} is a j-th observer coefficient in vertical plane;

λ_j^{Ψ} is a j-th observer coefficient in horizontal plane;

ω_3 is an Earth rate;

σ is a geographic latitude;

l is a gravity center displacement;

m is a displaced mass;

g is a free fall acceleration;

a is a vessel acceleration or deceleration;

V is a speed of the controlled object;

R is a radius of the Earth;

K is a course of the controlled object;

V_r is a speed of course change;

r is a radius of course change;

ω_z is a yaw rate;

ω_{zm} is a measured yaw rate;

ω_{zw} is an assessed yaw rate;

ψ is a yaw angle;

ψ_m is a measured yaw angle;

ψ_w is an assessed yaw angle;

δ is a rudder deflection angle.

INTRODUCTION

The quality of the control system as a whole is determined by the quality of the mathematical, algorithmic and software of the on-board controller designed to solve the set functional task, the quality of input information coming to the on-board controller from the measuring devices, as well as the quality of processing the output signals from the on-board controller by the executive devices.

Information from measuring devices, in addition to the useful component, also contains fluctuation and systematic measurement errors [1–4]. Fluctuating measurement errors cannot be completely eliminated, but can be reduced by hardware or software processing in the meter itself or on-board controller of the control system using bandpass filters. There are also more complex processing methods using a mathematical model of the control object for filtering and simultaneous observation of parameters of the state vector that are inaccessible to direct observation [5–7], including those that are optimal in noise [8]. Mathematical models of the controlled object are also used to predict the movement of the controlled object, determine failures [9], and other purposes [10–15].

Automation of control processes allows to exclude the human factor as much as possible [16–17], which is the cause of a large number of accidents and catastrophes, and to significantly reduce the human influence on the control processes of mobile objects [18–21].

This article discusses the issues of increasing the accuracy of automatic control of a moving object through the use of a mathematical meter model in the on-board controller. Existing solutions, as will be shown below in the review, do not use the capabilities of mathematical meter models in the on-board controller for improving the accuracy. Therefore, the development of such systems is actual scientific and technical task.

The object of the research is the processes of automatic control of a moving object with a mathematical model of a meter and a device observing measurement errors in the on-board controller of the control system.

The subject of the research is a method and algorithms for increasing the accuracy of automatic control of a moving object with a mathematical model of a meter and a device observing measurement errors in the on-board controller of the control system.

The purpose of research is an improving the accuracy of automatic control of a moving object.

This aim is achieved through the use in the on-board controller of the control system of the mathematical meter model and the observing device built on its basis, the estimation of the useful component and the systematic errors, depending on the motion parameters of the controlled object, using only the useful component for control, without systematic errors.

1 PROBLEM STATEMENT

A mathematical model of the control object is

$$\frac{d\mathbf{X}_n}{dt} = \mathbf{f}_n(\mathbf{X}_n, \mathbf{U}, \mathbf{C}_n), \quad (1)$$

mathematical model of a meters is

$$\frac{d\mathbf{X}_m}{dt} = \mathbf{f}_0(\mathbf{X}_n, \mathbf{C}_m) + \mathbf{f}_1(\mathbf{X}_n, \mathbf{C}_m) + \ldots \mathbf{f}_k(\mathbf{X}_n, \mathbf{C}_m) \quad (2)$$

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and the law of an object motion control is

$$\mathbf{U} = \mathbf{f}_u(\mathbf{X}_m, \mathbf{X}^*, \mathbf{C}_u) . \quad (3)$$

It is required to minimize the control error

$$F = \left\| \mathbf{X}_n - \mathbf{X}^* \right\| \to \min . \quad (4)$$

2 LITERATURE REVIEW

The article [22] discusses the issues of reducing an errors in measuring fluctuating concentrations for specific type of diffusion monitor. Observations have found that a significant error may be present in the estimates of the mean values of rapidly changing concentrations. Similar conclusions were also drawn from the numerical calculation of the error and its variance using the time-dependent field concentration data. The results indicate that when measuring substances with short-term exposure, excessive exposure estimates can be expected when sampling fluctuating concentrations. A simple modification of the sampler is proposed to reduce or eliminate this error.

In article [23] a method for eliminating the error in the results of measuring the surface shape of space structures with a high spatial resolution is proposed. When measuring the surface shape of a spherical mirror model, it turned out that measurement errors can be divided into systematic, depending on the projected gratings, and random, which are influenced by the optical properties of the object and the measuring system. A method for eliminating errors is proposed, including a band-pass filter to remove systematic errors and averaging procedures to reduce random errors. Using the example of measuring the surface shape of a spherical mirror model and a white plate model, it is shown that the proposed method can eliminate measurement errors by more than 50%. The effectiveness of the method is presented by the results.

In article [24] issues related to temperature drift and synchronous measurement error of the axial displacement sensor in an engine with a magnetic suspension are considered. There was proposed a configuration of the displacement sensor, consisting of three meters, a pair of meters is used to eliminate the synchronous measurement error, and the third sensor to take into account the temperature drift. A mechanism for generating a synchronous measurement error caused by incorrect assembly was presented, as well as an operational amplifier for obtaining the exact position of the axial center by adjusting the weighting coefficients of the readout signals of a pair of sensors. A temperature compensation circuit was also presented. An experiment was carried out on a test bench of an engine with a magnetic suspension, confirming the effectiveness of the proposed methods.

In article [25] the issues of eliminating the low-frequency vibrational disturbance in the constant component of the measurement of the Michelson interferometer, used to measure the communication signal with distributed polarization in fibers with high two-ray refraction, are considered. Compared to the space interferometer, the DC components in the interferograms of the all-fiber interferometer oscillate more intensely. These fluctuations are mainly caused by the disturbance of the motorized delay line in motion, which is confirmed by the corresponding models and experiments. A method for processing signals of group averages is proposed to eliminate low-frequency oscillatory disturbances, and the results of experimental confirmation are obtained.

The article [26] deals with the measurement of the flow rate of matter based on the phase method with homodyne frequency conversion. The principles of implementation of a contactless flow meter with compensation for fluctuations of electrophysical parameters in the flow are shown. The measuring device consists of a main channel, which extracts information about the flow rate of a substance, and a reference channel, to extract information about the electrophysical parameters of a substance in the flow. the minimum number of required adjustment elements, which has a positive effect on its reliability and stability in the presence of various external influences.

In article [27] the issues of motor speed control are considered. The quality of control largely depends on the accuracy of the speed feedback signal. The measuring method used in the incremental encoder is the most widely used due to its high theoretical accuracy. However, in practice, the internal error of the optical grating of the incremental encoder and the error of the analog-to-digital conversion make it difficult to achieve the theoretical accuracy of speed measurement. The article proposes a single-phase self-adaptive method for ideal suppression of the speed measurement error. The performed modeling and experiment confirm the efficiency of the proposed method.

In article [28] the issues of assessing the position of the rotor of synchronous machines with permanent magnets for medium and high speeds are considered. Describes an intelligent, non-touch speed control method for the entire speed range, which is especially suitable for pumps and fans. A simple method of observing the voltage of the reverse electromotive force was found, which is integrated into the control strategy. In addition, systematic errors and their effect on the accuracy of the calculated rotor position are systematically analyzed and documented. The theoretical results are confirmed by simulations and measurements.

In article [29] the issues of estimating deviations of the actual radar directional pattern from the ideal one for remote sensing of ocean surface currents are considered. A calibration method is proposed based on the time-averaged local spatial speed of coverage in order to reduce the influence of deviations of the actual radar radiation pattern on the measurements.

At the same time, as follows from the above review, the authors have not found solutions to improve control accuracy by using in the on-board controller of the motion

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control system a mathematical meter model and an observer, built on its basis, to determine of systematic measurement errors that depend on the parameters of the control object and taking them into account when control. Therefore, the solution of these issues is an urgent scientific and technical task.

3 MATERIALS AND METHODS

The right side of the mathematical model of the measurer (2) contains a vector – function $\mathbf{f}_0(\mathbf{X}_n,\mathbf{C}_m)$, determining the behavior of the useful component of the measured signal, and the vector of the function $\mathbf{f}_1(\mathbf{X}_n,\mathbf{C}_m)$, $\mathbf{f}_2(\mathbf{X}_n,\mathbf{C}_m)$, …, $\mathbf{f}_k(\mathbf{X}_n,\mathbf{C}_m)$, determining the behavior of the systematic components of measurement errors.

To estimate these components write the vector equation (2) in the form

$$\frac{d\hat{\mathbf{X}}_{0m}}{dt}=\mathbf{f}_0(\mathbf{X}_n,\mathbf{C}_m), \quad (5)$$

$$\frac{d\hat{\mathbf{X}}_{1m}}{dt}=\mathbf{f}_1(\mathbf{X}_n,\mathbf{C}_m), \quad (6)$$

$$\dots$$

$$\frac{d\hat{\mathbf{X}}_{km}}{dt}=\mathbf{f}_k(\mathbf{X}_n,\mathbf{C}_m), \quad (7)$$

$$\hat{\mathbf{X}}_m=\hat{\mathbf{X}}_{0m}+\hat{\mathbf{X}}_{1m}+\dots+\hat{\mathbf{X}}_{km}. \quad (8)$$

After numerical integration of the system of differential equations (5)–(7) in the onboard controller, we obtain the vector of estimates of the measured parameters $\hat{\mathbf{X}}_m$ and the vector of estimates of its components $\hat{\mathbf{X}}_{0m}$, $\hat{\mathbf{X}}_{1m}$, …, $\hat{\mathbf{X}}_{km}$. Due to the inaccuracy of the mathematical model, integration errors, and other factors, the vector of estimates $\hat{\mathbf{X}}_m$ over time will more and more differ from the measurement vector $\mathbf{X}_m$ and estimates $\hat{\mathbf{X}}_{0m}$, $\hat{\mathbf{X}}_{1m}$, …, $\hat{\mathbf{X}}_{km}$ from their actual values.

To prevent this from happening, cover equations (5)–(7) with feedback on the deviation of the estimate vector $\hat{\mathbf{X}}_m$ from the measured vector $\mathbf{X}_m$.

$$\frac{d\hat{\mathbf{X}}_{0m}}{dt}=\mathbf{f}_0(\mathbf{X}_n,\mathbf{C}_m)+\boldsymbol{\lambda}_0(\mathbf{X}_m-\hat{\mathbf{X}}_m), \quad (9)$$

$$\frac{d\hat{\mathbf{X}}_{1m}}{dt}=\mathbf{f}_1(\mathbf{X}_n,\mathbf{C}_m)+\boldsymbol{\lambda}_1(\mathbf{X}_m-\hat{\mathbf{X}}_m), \quad (10)$$

$$\dots$$

$$\frac{d\hat{\mathbf{X}}_{km}}{dt}=\mathbf{f}_k(\mathbf{X}_n,\mathbf{C}_m)+\boldsymbol{\lambda}_k(\mathbf{X}_m-\hat{\mathbf{X}}_m), \quad (11)$$

$$\hat{\mathbf{X}}_m=\hat{\mathbf{X}}_{0m}+\hat{\mathbf{X}}_{1m}+\dots+\hat{\mathbf{X}}_{km}. \quad (12)$$

The system of vector differential equations (9)–(11), together with the vector equation (12), ensure the retention of the vector of estimates $\hat{\mathbf{X}}_m$ near the measurement vector $\mathbf{X}_m$, and also an estimate of the vectors of the components $\hat{\mathbf{X}}_{0m}$, $\hat{\mathbf{X}}_{1m}$, …, $\hat{\mathbf{X}}_{km}$. Using in the control law (3) estimates of the vector $\hat{\mathbf{X}}_{0m}$ instead of a vector of dimensions $\mathbf{X}_m$

$$\mathbf{U}=\mathbf{f}_u(\hat{\mathbf{X}}_{0m},\mathbf{X}^*,\mathbf{C}_u)$$

allows to minimize control error (4)

$$F=\left\|\mathbf{X}_n-\mathbf{X}^*\right\|\to\min.$$

Consider a practical case of using this method on the example of a gyrocompass.The vector differential equation of the GSE motion has the form

$$\frac{d\mathbf{H}}{dt}=\frac{\partial\mathbf{H}}{\partial t}+\boldsymbol{\Omega}\times\mathbf{H}=\sum_{j=1}^{n}\mathbf{M}_j, \quad (13)$$

GCS is located in the center of the gyrocompass sensor suspension, the axis OX_2 is directed along the kinetic momentum vector of the GSE, the axis OY_2 is perpendicular to the axis OX_2, the axis OZ_2 complements the GCS to the “right” one.

Vector differential equation (13) in GCS has the form

$$H\dot{\Theta}=\sum_{j=1}^{n}M_{yj}, \quad (18)$$

$$-H\cos\Theta\dot{\Psi}=\sum_{j=1}^{n}M_{zj.}, \quad (19)$$

or after defining the right-hand sides

$$\dot{\Theta}=-\omega_3\cos\sigma\sin\Psi-\frac{V}{R}(\sin K\sin\Psi-\cos K\cos\Psi),$$

$$\dot{\Psi}=\omega_3(\cos\sigma\cos\Psi tg\Theta-\sin\sigma)+lmgtg\Theta-$$
$$-\frac{V}{R}tg\Theta(\cos K\sin\Psi-\sin K\cos\Psi)-\frac{V_r}{r}-$$
$$-mal(\cos K\cos\Psi+\sin K\sin\Psi).$$

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To simplify the obtained equations of the course meter sensitive element motion, denote

$$f_0^{\Theta} = -\omega_3 \cos\sigma \sin\Psi ,$$

$$f_1^{\Theta} = -\frac{V}{R}(\sin K \sin\Psi - \cos K \cos\Psi) ,$$

$$f_0^{\Psi} = \omega_3(\cos\sigma \cos\Psi tg\Theta - \sin\sigma) ,$$

$$f_1^{\Psi} = lmg\mathrm{tg}\Theta ,$$

$$f_2^{\Psi} = -\frac{V}{R} tg\Theta(\cos K \sin\Psi - \sin K \cos\Psi) ,$$

$$f_3^{\Psi} = -\frac{V_r}{r} ,$$

$$f_4^{\Psi} = -mal(\cos K \cos\Psi + \sin K \sin\Psi).$$

Through the integration errors, inaccuracies of mathematical models, other factors, estimates $\hat{\Psi}_m, \hat{\Theta}_m$ will deviate more and more from the measured values Ψ_m, Θ_m.

To keep the estimates $\hat{\Psi}_m, \hat{\Theta}_m$ near the measured values Ψ_m, Θ_m, a observation device with component estimation was used.

$$\frac{d\hat{\Theta}_{0m}}{dt} = f_0^{\Theta} + \lambda_0^{\Theta}(\Theta_m - \hat{\Theta}_m) , \qquad (20)$$

$$\frac{d\hat{\Theta}_{1m}}{dt} = f_1^{\Theta} + \lambda_1^{\Theta}(\Theta_m - \hat{\Theta}_m) , \qquad (21)$$

$$\frac{d\hat{\Psi}_{0m}}{dt} = f_0^{\Psi} + \lambda_0^{\Psi}(\Psi_m - \hat{\Psi}_m) , \qquad (22)$$

$$\frac{d\hat{\Psi}_{1m}}{dt} = f_1^{\Psi} + \lambda_1^{\Psi}(\Psi_m - \hat{\Psi}_m) , \qquad (23)$$

$$\frac{d\hat{\Psi}_{2m}}{dt} = f_2^{\Psi} + \lambda_2^{\Psi}(\Psi_m - \hat{\Psi}_m) , \qquad (24)$$

$$\frac{d\hat{\Psi}_{3m}}{dt} = f_3^{\Psi} + \lambda_3^{\Psi}(\Psi_m - \hat{\Psi}_m) , \qquad (25)$$

$$\frac{d\hat{\Psi}_{4m}}{dt} = f_4^{\Psi} + \lambda_4^{\Psi}(\Psi_m - \hat{\Psi}_m) , \qquad (26)$$

$$\hat{\Theta}_m = \hat{\Theta}_{0m} + \hat{\Theta}_{1m} , \qquad (27)$$

$$\hat{\Psi}_m = \hat{\Psi}_{0m} + \hat{\Psi}_{1m} + \hat{\Psi}_{2m} + \hat{\Psi}_{3m} + \hat{\Psi}_{4m} . \qquad (28)$$

The mathematical model of the GSE motion, represented by the system of differential equations (20) – (26), is numerically integrated in the on-board controller of the automatic motion control system.

Component $\hat{\Psi}_{0m}$ of equations (28) is a useful component of the course meter reading without inertial deviation components $\hat{\Psi}_{jm}, j = 1..4$. Substituting this value into the control law (3), obtain an increase in the accuracy of the course movement of the control object (1)

$$\delta = \mathbf{f}_u(\hat{\Psi}_{0m}, \Psi^*, \mathbf{C}_u) .$$

4 EXPERIMENTS

Fig. 1 presents the results of mathematical modeling of the GSE motion when bringing into meridian.

Initial experimental conditions are: longitudinal speed of the vessel is $V(0) = 0\ m/s$, angular yaw rate is $\omega_z(0) = 0\ {}^\circ/s$, course angle is $\psi(0) = 0^\circ$, initial deviation of the GSE frame from the meridian is $\Psi_m(0) = -40^\circ$.

As can be seen from the graphs $\Psi_m, \hat{\Psi}_m$, the reduction to the meridian occurred within 10000 s (about 2.8 hours).

Fig. 2 shows GSE motion during the acceleration of the vessel.

Initial experimental conditions are: longitudinal speed of the vessel is $V(0) = 0\ m/s$, angular yaw rate is $\omega_z(0) = 0\ {}^\circ/s$, course angle is $\psi(0) = 0^\circ$, initial deviation of the GSE frame from the meridian is $\Psi_m(0) = 0^\circ$. From the moment of time $t = 2000\ s$ the vessel began to increase the speed to $V = 10\ m/s$.

As can be seen from the graphs $\Psi_m, \hat{\Psi}_m$, the GSE deviation and its estimate change up to 10° from the action of disturbing moments during the acceleration of the vessel. At the same time, the deviation of the useful component $\hat{\Psi}_{0m}$ does not exceed 0.5°.

Fig. 3 shows the GSE motion during the braking of the vessel. Initial experimental conditions are: the longitudinal speed of the vessel is $V(0) = 0\ m/s$, angular yaw rate is $\omega_z(0) = 0\ {}^\circ/s$, course angle is $\psi(0) = 0^\circ$, initial deviation of the GSE frame from the meridian is $\Psi_m(0) = 0^\circ$. From the moment $t = 0\ s$ the vessel gradually increases a speed to $V = 10\,m/s$, further moves with constant speed $V = 10\,m/s$ to the moment $t = 2000\ s$, then carries out passive braking.

As can be seen from the graphs $\Psi_m, \hat{\Psi}_m$, the GSE deviates from the meridian by an angle of up to 5.0° from the action of disturbing moments during the braking of the vessel. At the same time, the deviation of the useful component $\hat{\Psi}_{0m}$ does not exceed 0.5°.

Fig. 4 shows the results of mathematical modeling of the GSE motion when changing the course of the vessel.

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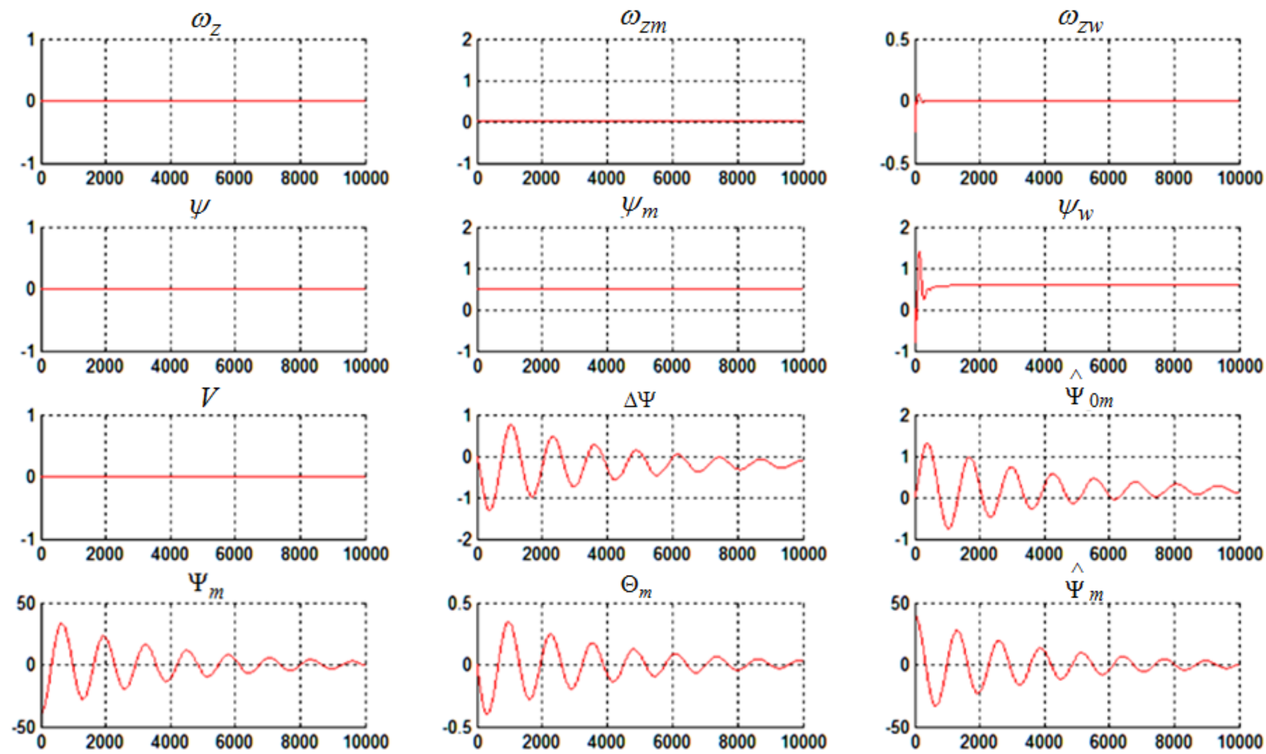

Figure 1 – The GSE motion when bringing into meridian

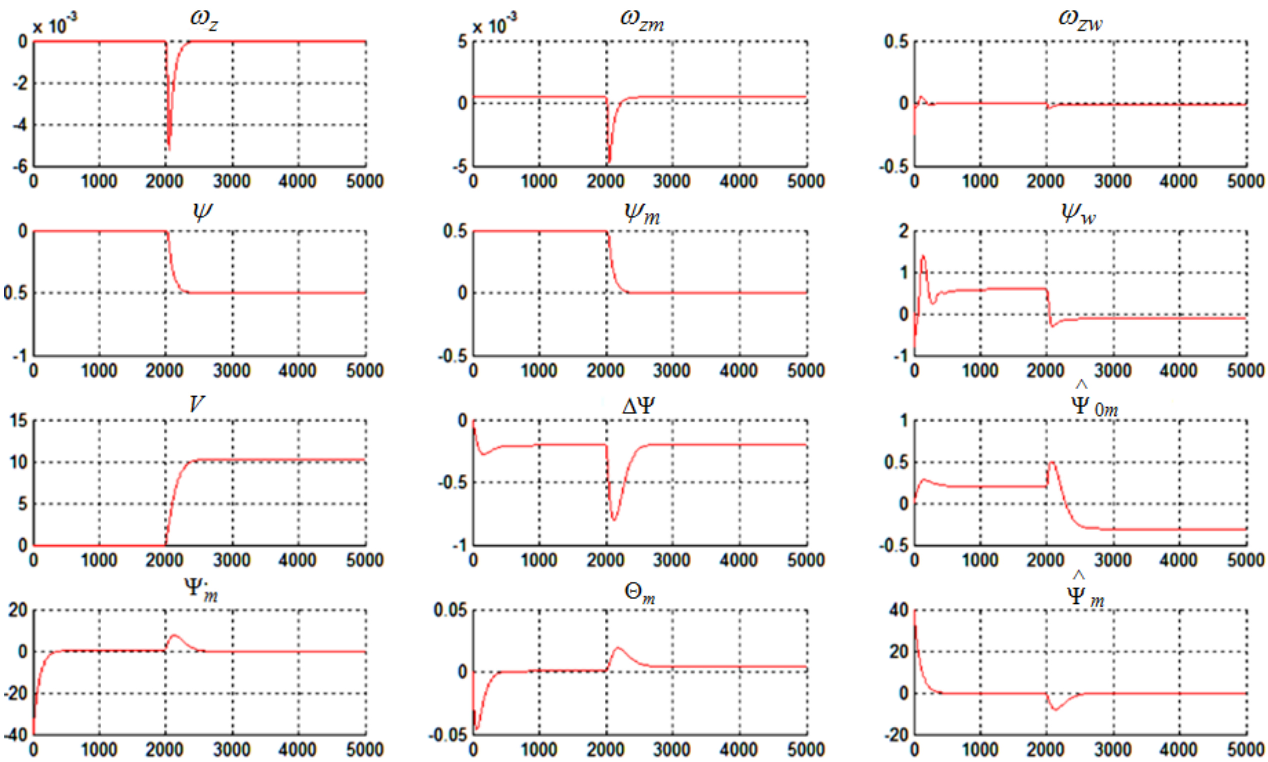

Figure 2 – The GSE motion during the acceleration of the vessel

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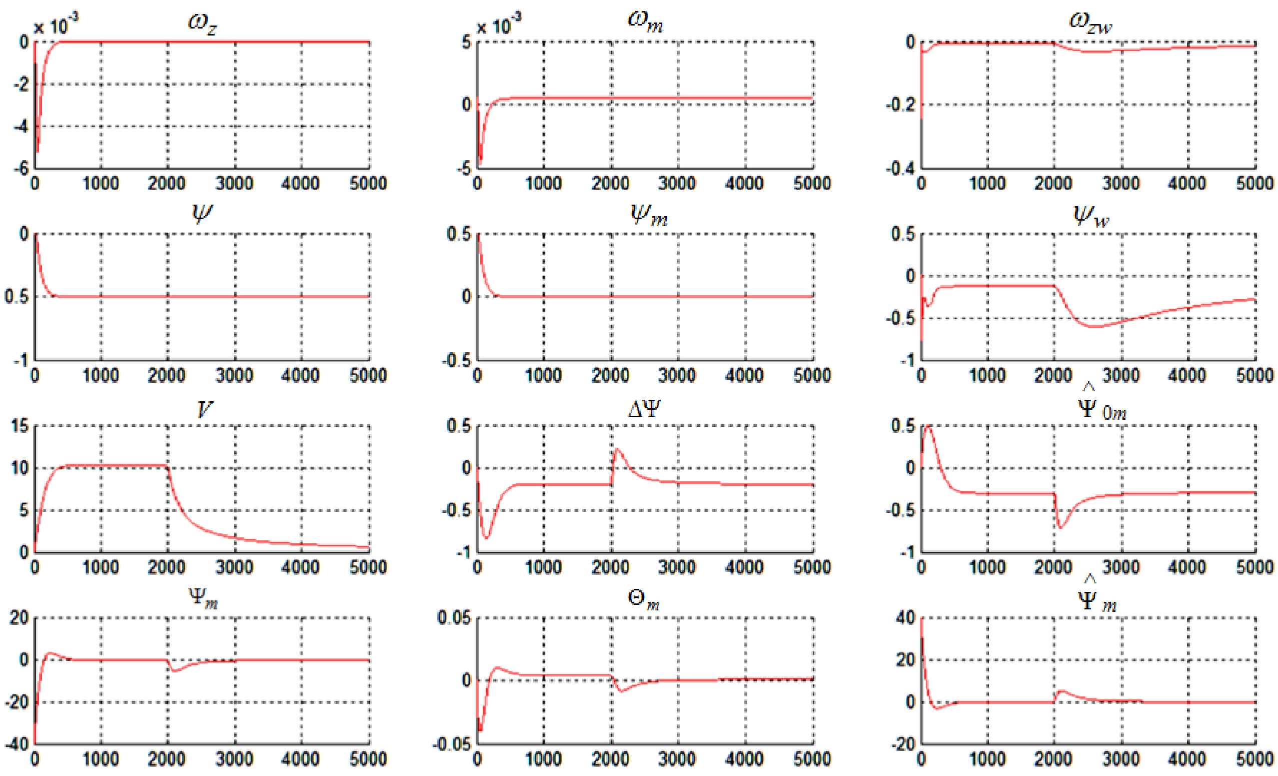

Figure 3 – The GSE motion during the braking of the vessel

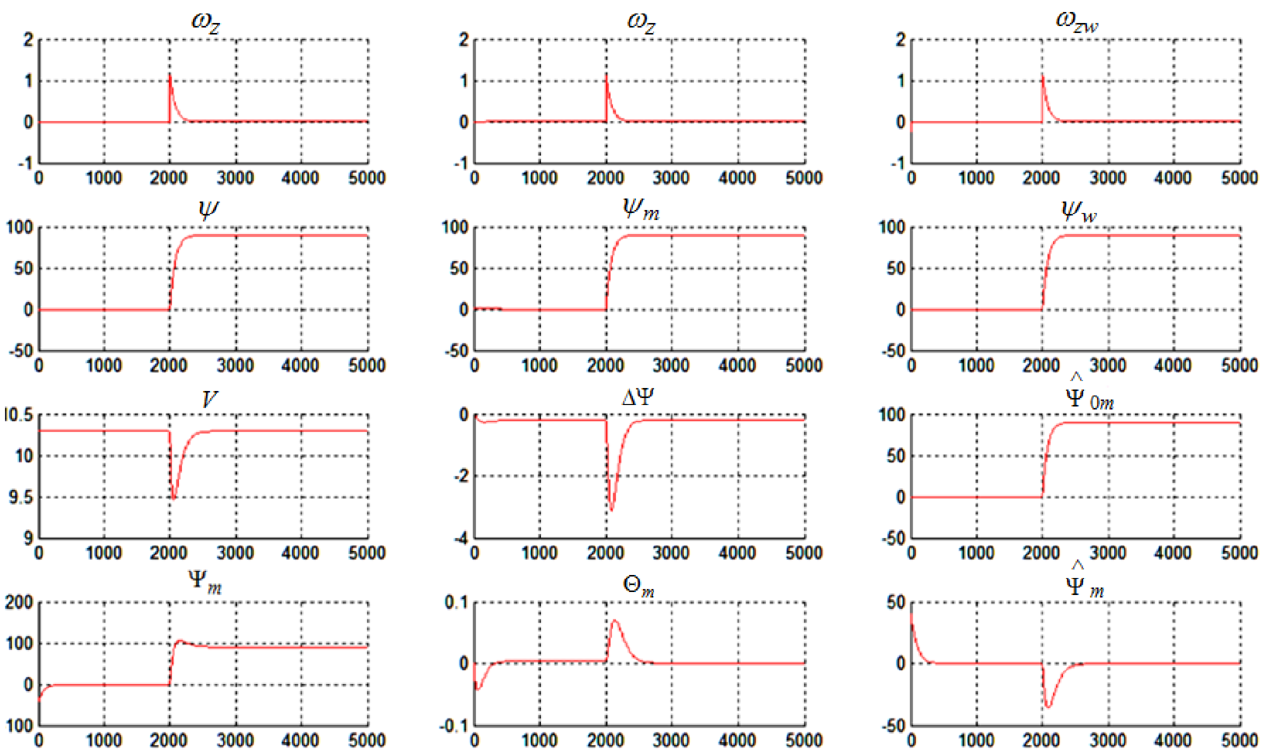

Figure 4 – The GSE motion during the course change

Initial experimental conditions are: longitudinal speed of the vessel is $V(0) = 10{,}4\ m/s$, angular yaw rate is $\omega_z(0) = 0\ ^\circ/s$, course angle is $\psi(0) = 0^\circ$, initial deviation of the GSE frame from the meridian is $\Psi_m(0) = 0^\circ$.

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From the time $t = 2000\ s$ the vessel began to change course from $\psi = 0^\circ$ to $\psi = 90^\circ$. As can be seen from the graphs $\Psi_m, \hat{\Psi}_m$, the GSE deviates from the meridian at an angle of up to 20° from the action of disturbing moments during the course change. At the same time the useful component $\hat{\Psi}_{0m}$ changes almost perfectly.

5 RESULTS

The article discusses the issues of increasing the accuracy of automatic control of a moving object using a mathematical model of a meter and a device observing measurement errors in the on-board controller of the control system.

The existing methods for solving this problem are analyzed, their shortcomings are revealed, the urgency of the problem being solved is formulated.

A method and algorithms for increasing the control accuracy of a moving object through the use in the on-board controller of a mathematical meter model and an observer of systematic measurement errors, built on its basis, have been developed.

A particular case of application of the developed method and algorithms for a vessel's gyrocompass was considered.

6 DISCUSSION

There were considered the method and algorithms for improving the control accuracy using the mathematical meter model in the on-board controller of the control system.

The analysis of the literature has shown that the known methods of increasing the control accuracy imply the improvement of the experimental conditions [22], the use of bandpass filters and averaging procedures [23, 25, 29], design solutions [24], the use of reference models [26], self-adjusting algorithms [27], mathematical models of the control object and observers [28]. However, in open sources, the authors failed to find methods and algorithms that increase the accuracy of controlling by using a mathematical meter model in the on-board controller of the control system.

The efficiency and effectiveness of the developed method and algorithms were confirmed by mathematical modeling in the MATLAB environment of the control processes of a moving object in a closed circuit with a control system.

As shown in Fig. 1–Fig. 4 simulation results, the proposed method and algorithms, in comparison with the known solutions, make it possible to increase several times the accuracy of automatic control of a moving object due to the use of a mathematical meter model and an observer built on its basis in the on-board controller of the control system, assessing systematic measurement errors and eliminating them when controlling a moving object.

This allows to assume that the considered method and algorithms can be recommended for use in the development of software for high – precision automatic control systems.

Further studies can be related to improving the accuracy of control movement with the Kalman filter.

CONCLUSIONS

A method and algorithms for improving the accuracy of automatic control with mathematical meter model in on-board controller were proposed.

The scientific novelty of the obtained results consists in the fact that for the first time a method and algorithms for improving the control accuracy using the mathematical meter model in the on-board controller of the control system, have been proposed.

This is achieved through the use in the on-board controller of the control system of the mathematical meter model and the observing device built on its basis, the estimation of the useful component and the systematic errors, depending on the motion parameters of the controlled object, using for control only the useful component, without systematic errors.

The practical value of the obtained results lies in the fact that the developed method and algorithms were tested by mathematical modeling in the MATLAB environment of the control object movement in a closed circuit with a control system.

The results of mathematical modeling confirmed the operability and efficiency of the proposed method and algorithms and allow them to be used for practical purposes in the development of mathematical support for high-precision automatic control systems.

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ПІДВИЩЕННЯ ТОЧНОСТІ АВТОМАТИЧНОГО КЕРУВАННЯ З МАТЕМАТИЧНОЮ МОДЕЛЛЮ ВИМІРЮВАЧА У БОРТОВОМУ КОНТРОЛЕРІ

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АНОТАЦІЯ

Актуальність. У статті розглянуті питання підвищення точності автоматичного керування рухомим об'єктом з використанням математичної моделі вимірювача та спостерігаючого за похибками вимірювання пристрою у бортовому контролері системи керування. Об'єктом дослідження є процеси автоматичного керування рухомим об'єктом з математичною моделлю вимірювача та спостерігаючого за похибками вимірювання пристрою у бортовому контролері системи керування. Предметом дослідження є метод і алгоритми підвищення точності автоматичного керування рухомим об'єктом з математичною моделлю вимірювача та спостерігаючого за похибками вимірювання пристрою у бортовому контролері системи керування.

Мета. Метою дослідження є підвищення точності автоматичного керування рухомим об'єктом.

Метод. Дана мета досягається за рахунок використання у бортовому контролері системи керування математичної моделі вимірювача і спостерігаю чого пристрою, побудованого на її основі, оцінки корисної складової і систематичної похибки вимірювання, що залежить від параметрів руху об'єкта керування, використання для керування тільки корисної складової без систематичної помилки вимірювання.

Результати. Розроблено метод і алгоритми підвищення точності автоматичного керування рухомим об'єктом за рахунок використання у бортовому контролері системи керування математичної моделі вимірювача і спостерігаючого пристрою, побудованого на її основі. Працездатність та ефективність розробленого методу і алгоритмів перевірені математичним моделюванням у середовищі MATLAB процесів керування рухомим об'єктом у замкнутій схемі із системою керування.

Висновки. Результати математичного моделювання підтверджують працездатність і ефективність запропонованого методу та алгоритмів і дозволяють рекомендувати їх для практичного застосування при розробці математичного забезпечення високоточних систем автоматичного керування рухом.

КЛЮЧОВІ СЛОВА: автоматичне керування, точність керування, система керування рухом, помилки вимірювання, спостерігаючий пристрій, математична модель.

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ПОВЫШЕНИЕ ТОЧНОСТИ АВТОМАТИЧЕСКОГО УПРАВЛЕНИЯ С МАТЕМАТИЧЕСКОЙ МОДЕЛЬЮ ИЗМЕРИТЕЛЯ В БОРТОВОМ КОНТРОЛЛЕРЕ

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АННОТАЦИЯ

Актуальность. В статье рассмотрены вопросы повышения точности автоматического управления подвижным объектом с использованием математической модели измерителя и наблюдающего за ошибками измерения устройства в бортовом контроллере системы управления. Объектом исследования являются процессы автоматического управления подвижным объектом с математической моделью измерителя и наблюдающего за ошибками измерения устройства в бортовом контроллере системы управления. Предметом исследования являются метод и алгоритмы повышения точности автоматического управления подвижным объектом с математической моделью измерителя и наблюдающего за ошибками измерения устройства в бортовом контроллере системы управления.

Цель. Целью исследования является повышение точности автоматического управления подвижным объектом.

Метод. Данная цель достигается за счет использования в бортовом контроллере системы управления математической модели измерителя и наблюдающего устройтва, построенного на ее основе, оценки полезной составляющей и систематической ошибки измерения, зависящей от параметров движения объекта управления, использования для управления только полезной составляющей без систематической ошибки измерения.

Результати. Разработан метод и алгоритмы повышения точности автоматического управления подвижным объектом за счет использования в бортовом контроллере системы управления математической модели измерителя и наблюдающего устройтва, построенного на ее основе. Работоспособность и эффективность разработанного метода и алгоритмов проверены математическим моделированием в среде MATLAB процессов управления подвижным объектом в замкнутой схеме с системой управления.

Выводы. Результаты математического моделирования подтверждают работоспособность и эффективность предложенного метода и алгоритмов и позволяет рекомендовать их для практического применения при разработке математического обеспечения высокоточных систем автоматического управления движением.

КЛЮЧЕВЫЕ СЛОВА: автоматическое управление, точность управления, система управления движением, ошибки измерения, наблюдающее устройство, математическая модель.

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