NATIONAL ACADEMY OF SCIENCES OF UKRAINE
INTERNATIONAL RESEARCH AND TRAINING CENTER FOR INFORMATION TECHNOLOGIES AND SYSTEMS OF THE NAS OF UKRAINE AND OF MES OF UKRAINE
V.M. GLUSHKOV INSTITUTE OF CYBERNETICS OF THE NAS OF UKRAINE

Cybernetics and Computer Engineering

2 (196)/2019

SCIENTIFIC JOURNAL ▪ FOUNDED IN 1965 ▪ PUBLISHED 4 TIMES PER YEAR ▪ KYIV

CONTENTS

The journal is included in the List of Scientific Professional Editions of the Ministry of Education and Science of Ukraine (MESU) for PhD applicants in technical and physical-mathematical sciences (order of the MES of Ukraine № 1528, 29.10.2014),
biological and medical sciences (order of the MES of Ukraine № 261, 06.03.2015)

The journal is included in Google Scholar, information resource Scientific Periodicals of Ukraine (V.I. Vernadsky NLU), ULRICHS WEB, Crossref (DOI), ROAD, Electronic Journals Library (Germany)

Certificate of State Registration КВ № 12649-1533Р, 14.05.2007

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Editor *N.A. Charchiyan*

Computer layout *A.V. Tupalskiy*

Підп. до друку 21.06.2019. Формат 70×108/16. Гарн. Times New Roman.
Ум. друк. арк. 10,33. Обл. вид. арк. 9,84. Тираж 72. Зам. №

Віддруковано ВД “Академперіодика” НАН України
01004, Київ 4, вул. Терещенківська, 4.

Свідоцтво про внесення до Державного реєстру суб’єкта видавничої справи

Серії ДК № 544 від 27.07.2001 р.

НАЦІОНАЛЬНА АКАДЕМІЯ НАУК УКРАЇНИ
МІЖНАРОДНИЙ НАУКОВО-НАВЧАЛЬНИЙ ЦЕНТР
ІНФОРМАЦІЙНИХ ТЕХНОЛОГІЙ ТА СИСТЕМ НАН УКРАЇНИ І МОН УКРАЇНИ
ІНСТИТУТ КІБЕРНЕТИКИ ІМ. В.М. ГЛУШКОВА НАН УКРАЇНИ

Кібернетика та обчислювальна техніка

2 (196)/2019

НАУКОВИЙ ЖУРНАЛ ▪ ЗАСНОВАНИЙ У 1965 р. ▪ ВИХОДИТЬ 4 РАЗИ НА РІК ▪ КИЇВ

ЗМІСТ

DOI: https:// 10.15407/kvt196.02.003

UDC 004.021

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LINGUISTIC APPROACH FOR ESTIMATION OF ELECTROCARDIOGRAMS'S SUBTLE CHANGES BASED ON THE LEVENSTEIN DISTANCE

Introduction. *The linguistic approach, based on the transition from electrocardiogram (ECG) to codogram, gained fame for the analysis of heart rhythm. To expand the functionality of the method, it is advisable to study the possibility of simultaneously monitoring the dynamics of changes in the duration of cardiac cycles and the indicator of simmetry T-wave that carries information about ischemic changes in the myocardium.*

The purpose of the article *is to develop algorithmic and software components to solve this problem and conduct experimental studies on model and real data.*

Methods. *ECG of certain groups was automatically encoded, Levenshtein distance was calculated between ECG pairs for group and the reference codogram of the group was constructed. The evaluation of the results of experimental studies was carried out on the basis of traditional methods of statistical analysis.*

Results. *It is shown that based on the Levenshtein distance between all pairs of codograms of the test group, the reference codogram of the group of patients with coronary artery disease (CAD) and the group of healthy volunteers can be determined. It was established that making decisions based on the comparison of the ECG codogram of the person with the reference codogram allows for the separation of representatives of the indicated groups with sensitivity S_E = 72% and specificity C_P = 79% even in those cases when the traditional analysis of the ECG in 12 leads is not informative.*

Conclusions. *The proposed approach allows to obtain additional diagnostic information when solving actual problems of practical medicine.*

Keywords: *linguistic approach, diagnostic sign of ECG, Levenshtein distance.*

INTRODUCTION

The physiological processes occurring in biological systems are often repetitive in time. Such processes generate specific signals, which are commonly called cyclical in the scientific literature [1, 2]. A typical example of a cyclical signal is an electrocardiogram (ECG), reflecting the cyclical nature of the circulatory system and respiratory organs of a living organism.

Despite the fact that electrocardiography for over a hundred years has been the most common method of functional diagnostics in cardiology, the sensitivity and specificity of traditional ECG examinations are not high enough. Thus, in work [3] it was shown that resting ECG, assessed by generally accepted criteria, remains normal in approximately half of patients with chronic coronary artery disease (CAD), including during episodes of chest discomfort.

Modern digital electrocardiographs, which implement traditional approaches to the analysis and interpretation of ECG, also do not provide the required reliability of diagnostic results. Moreover, experienced clinicians still prefer visual interpretation of ECG, not completely trusting computer algorithms, which, because of the complexity of real signals, often lead to errors at the stage of recognition of informative fragments [4].

Therefore, scientists are constantly looking for alternative approaches to computer processing of cyclic signals, in particular, ECG. One of these approaches is based on the transformation of the original signal into a word (sequence of characters), for the analysis of which the concepts of formal languages are used. Such an approach in various publications is called linguistic [5, 6], structural [7] or syntactic [8].

In cardiology practice, the linguistic approach has become famous for analyzing heart rhythm [9, 10]. It has long been known that the heart rhythm is a universal reaction of the organism to any influence from the external and internal environment [11]. Mathematical analysis of the heart rhythm allows you to obtain important information about the functional state of all parts of the regulation of human life, both in normal conditions and in various pathologies [12]. Computer technologies of mathematical analysis of heart rate variability of the heart rate (HRV) are still actively used to assess the state of the autonomic nervous system and adaptive reserves of the body [13].

However, only on the basis of control over the sequence of lengths of the $R-R$ -intervals it is impossible to judge the functional state of the heart itself as the main system-forming organ, in particular, the ischemia of the heart muscle. To increase the credibility of the conclusion about the functional state of the body, it is reasonable to supplement the analysis of the dynamics of the $R-R$ -intervals with an analysis of the dynamics of other ECG indicators.

In [14, 15], a method for analyzing an ECG signal was proposed, which provides for encoding ECG symbols of a given alphabet that carry information about the increment signs of both the $R-R$ -interval lengths and the amplitudes of R -wave of adjacent cycles. As a result, the observed ECG generates words (codograms), the processing of which by machine learning methods expands the capabilities of the mathematical analysis of heart rhythm.

The International Scientific and Training Center for Information Technologies and Systems of the National Academy of Sciences of Ukraine and the Ministry of Education and Science of Ukraine has developed an innovative method for processing electrocardiograms (ECG), which is called fasegraphy [16, 17]. A distinctive feature of the method is the use of intelligent IT for processing the observed time signal $z(t)$ on the phase plane $z(t), \dot{z}(t)$, where $\dot{z}(t)$ is the rate of change of the electrical activity of the heart [18]. This difference made it possible for the *first time* to implement a procedure for reliably determining the novel ECG feature (indicator β_T) characterizing the symmetry of the T-wave of the cardiac cycles [19].

Large-scale clinical studies conducted with the help of the FASEGRAPH® software and hardware complex, which implements fasegraphy method, confirmed that measuring the indicator β_T and evaluating its standard deviation RMS β_T makes it possible to increase the accuracy of detecting the initial signs of myocardial ischemia, even in cases where the analysis of traditional ECG features in 12 leads is not informative [20].

It follows that, remaining within the framework of linguistic analysis, it is advisable to study the possibility of simultaneously analysis the dynamics of changes $R-R$- intervals and dynamics of changes β_T-indicator on the sequence of cardiac cycles.

The purpose of the article is to develop algorithmic and software components for solving this problem.

BASIC COMPONENTS OF LINGUISTIC ECG ANALYSIS

Recall that the general scheme of linguistic analysis of the time signal $z(t)$ suggests segmentation $z(t)$ into a sequence of separate fragments, reflecting the alternation of elementary events during the development of the process under study [6]. Thus, a transition is made from the k-implementation of the signal $z_k(t)$ observed on a limited time interval $t \in [0,T]$ to the word $S_k = \alpha_1 \alpha_2 \cdots \alpha_K$ as *finite* chain of *characters* $\alpha_j \in \mathrm{A}$, $j = 1,...,K$ from the alphabet of the "names" of the fragments. A set of all-possible words (not necessarily finite) forms a formal language for which the grammar is built [21]:

$$G = \langle \Omega_0, \Omega_T, P_G, \omega_0 \rangle, \tag{1}$$

where Ω_0 is a set of *non-terminal* symbols (variables); Ω_T — a set of *terminal* symbols (constants), $\Omega_T \cup \Omega_0 = \mathrm{A}$, $\Omega_T \cap \Omega_0 = \varnothing$; P_G — a set of *grammatical rules* (substitution rules); $\omega_0 \in \Omega_0$ — *initial* (root) non-terminal character.

In the majority of works devoted to linguistic analysis of signals, it is assumed that the alphabet of reference fragments is known in advance [22], and the construction of grammar makers adequate to the set of observed signals is carried out by man on the basis of informal knowledge of an expert in the subject area.

Despite the fact that in a number of papers, particular, in [23], the main theoretical concepts of the general formulation of the problem of restoring grammars on a training set of observations were revealed, it should be stated that there are still no universal methods for practical solution of this difficult problem.

Therefore, following the works [14, 15], we will make the transition from the k-th observed signal $z_k(t)$ to the word $S_k = \alpha_1\alpha_2\cdots\alpha_K$, analyzing the sequence of sign differences in the values of ECG indices on adjacent cycles.

Let we have N ECG cycles and values of several indicators are determinedon on each of cycles , for example, the duration of RR intervals and the index β_T of T wave symmetry.

Denote each of these sequences as:

$$x_1, x_2, \ldots x_N . \tag{2}$$

Let us determine the values of the indicator variable V_i, $i = 2,\ldots,N$, by the signs of the increments of the quantities on each cycle in relation to the previous cycle:

$$V_i = \begin{cases} +1, \text{ if } & x_i - x_{i-1} > 0, \\ -1, \text{ if } & x_{i-1} - x_i > 0. \end{cases} \tag{3}$$

As a result, for the indicators RR and β_T , we will get two sequences of indicator variables $V_i^{(RR)}$ and $V_i^{(\beta)}$ respectively, and each ECG cycle will be encoded with one of the four symbols of the alphabet $\mathrm{A} = \{a, b, c, d\}$ as follows (Tabl. 1).

The sequence of characters received in accordance with Table 1 forms a N-bit word S_k (codogram) that uniquely encodes the k-th processed ECG.

For illustration, a flowchart of the codogram's generation S, where N is the total number of registered cardiac cycles (Fig. 1).

The proposed method of linguistic analysis and interpretation of ECG is based on the Levenshtein distance $L(S_1, S_2)$ between two words S_1, S_2 of N and M symbols, respectively. Recall that the Levenshtein distance is equal to the minimum number of editing operations such as insertion, deletion, and replacement of a character for converting a word S_1 into a word S_2 [24, 25].

The algorithm for calculating the Levenshtein distance is as follows.

Table 1. **Principle of ECG cycle coding**

The value of the indicator variable $V_i^{(RR)}$	+1	+1	-1	-1
The value of the indicator variable $V_i^{(\beta_T)}$	+1	-1	+1	-1
Symbol	***a***	***b***	***c***	***d***

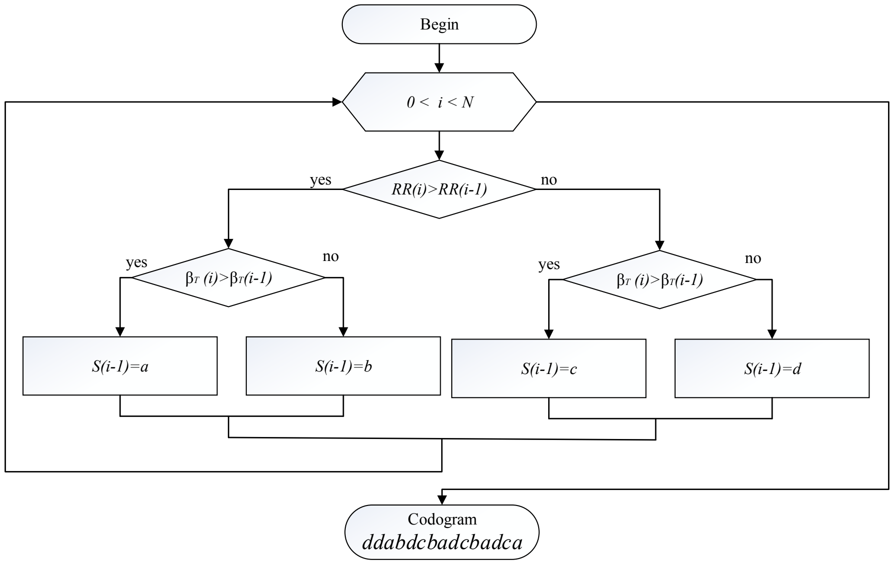


Fig. 1. The algorithm's block diagram for the formation of codograms

We form a matrix D of dimension $N+1,\ M+1$ and fill the first row and first column of the matrix D as follows:

$$
\begin{aligned}
&D(i,0)=i, \quad \forall i=0\ldots N,\\
&D(0,j)=j,\ \forall j=0\ldots M.
\end{aligned} \tag{4}
$$

The remaining elements of the matrix D ($i>0,\ j>0$) is filled in accordance with the rule:

$$D(i,j)=\min\{D(i,j-1)+1,\ D(i-1,j)+1,\ D(i-1,j-1)+m(S_1(i),S_2(j)\}, \tag{5}$$

where

$$m(S_1(i),S_2(j))=\begin{cases}0, \text{ if } & S_1(i)=S_2(j),\\ 1, \text{ if } & S_1(i)\neq S_2(j).\end{cases} \tag{6}$$

As a result the value $D(N,M)$ determines the Levenshtein distance.

In general, there may be several optimal paths from cell $D(1,\ 1)$ to cell $D(N,M)$ that provide the minimum number of editing operations. Figure 2 illustrates this fact and shows the "optimal" sequence of transition from the word

$$S_1 = \text{ddabdcbadcbadca} \tag{7}$$

to the word

$$S_2 = \text{bacdaaacdadccbb}. \tag{8}$$

		d	d	a	b	d	c	b	a	d	c	b	a	d	c	a
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
b	1	1	2	3	3	4	5	6	7	8	9	10	11	12	13	14
a	2	2	2	2	3	4	5	6	6	7	8	9	10	11	12	13
c	3	3	3	3	3	4	4	5	6	7	7	8	9	10	11	12
d	4	3	3	4	4	3	4	5	6	6	7	8	9	9	10	11
a	5	4	4	3	4	4	4	5	5	6	7	8	8	9	10	10
a	6	5	5	4	4	5	5	5	5	6	7	8	8	9	10	10
a	7	6	6	5	5	5	6	6	5	6	7	8	8	9	10	10
c	8	7	7	6	6	6	5	6	6	6	6	7	8	9	9	10
d	9	8	7	7	7	6	6	6	7	6	7	7	8	8	9	10
a	10	9	8	7	8	7	7	7	6	7	7	8	7	8	9	9
d	11	10	9	8	8	8	8	8	7	6	7	8	8	7	8	9
c	12	11	10	9	9	9	8	9	8	7	6	7	8	8	7	8
c	13	12	11	10	10	10	9	9	9	8	7	7	8	9	8	8
b	14	13	12	11	10	11	10	9	10	9	8	7	8	9	9	9
b	15	14	13	12	11	11	11	10	10	10	9	8	8	9	10	10

Fig. 2. Possible ways to ensure the optimal transition from the word S_1 to the word S_2

Table 2. **The optimal transition from word S_1 to word S_2**

Step	**Source word**	**Operation**	**Result of editing**
1	S_1 = ddabdcbadcbadca	Replacement d → b	S_1 = bdabdcbadcbadca
2	S_1 = bdabdcbadcbadca	Deletion *d*	S_1 = babdcbadcbadca
3	S_1 = babdcbadcbadca	Replacement b → c	S_1 = bacdcbadcbadca
4	S_1 = bacdcbadcbadca	Deletion *c*	S_1 = bacdbadcbadca
5	S_1 = bacdbadcbadca	Replacement b → a	S_1 = bacdaadcbadca
6	S_1 = bacdaadcbadca	Replacement d → a	S_1 = bacdaaacbadca
7	S_1 = bacdaaacbadca	Replacement b → d	S_1 = bacdaaacdadca
8	S_1 = bacdaaacdadca	Replacement a → c	S_1 = bacdaaacdadcc
9	S_1 = bacdaaacdadcc	Insertion *b*	S_1 = bacdaaacdadccb
10	S_1 = bacdaaacdadccb	Insertion *b*	S_1 = bacdaaacdadccbb

The step on i symbolizes the removal of the next symbol from the word S_1, the step on j — inserting the next word S_1 symbol into the word S_2, and the step on both indices symbolizes the replacement of the S_1 symbol with the next S_2 symbol or the absence of changes.

Table 2 demonstrates one of the optimal options shown in Fig. 2.

In addition to the classic Levenshtein distance, a number of its modifications are known, for example, the Damerau-Levenshtein distance, in which an additional editing operation in the form of transposition - permutation of two adjacent symbols, or the Levenshtein extension where different prices for elementary editing operations is introdused.

INFORMATION TECHNOLOGY OF LINGUISTIC ECG ANALYSIS

A number of important tasks can be formulated based on the calculation of the Levenshtein distance between the ECG codograms, including:

Task 1. Study of the properties of the Levenshtein distance based on the analysis of model signals generating an ECG of a realistic shape

Task 2. Decision making on the affiliation of the examined person one of two groups, for example, a group of patients or a group of conditionally healthy people, a group of trained or untrained, etc.

Task 3. Evaluation of the intra-individual characteristics of the codograms of one person over a sufficiently large segment of observations.

Task 4. Study of the possibility of using Levenshtein distance to assess changes in the functional state of the body under the influence of physical and emotional stress, medication, surgery, etc.

To perform the necessary research, an information technology (IT) has been developed, the structure of which is shown in Fig. 3.

To study the properties of the Levenshtein distances a software simulator that implements a stochastic model of generating artificial electrocardiograms of a realistic form [26] was uncluded in the IT. The generative model generates a sequence of ECG cycles, built on the basis of the sum of asymmetric Gaussian functions.

$$z_0(t) = \sum_k A_i \exp\left[-\frac{(t-\mu_k)^2}{2[b_k(t)]^2}\right] \tag{9}$$

with a given level of distortion of parameters that characterize the shape of the k-th fragment $k \in \{P, Q, R, S, ST, T\}$

Studies of the possibilities of the proposed approach for solving other problems were carried out on the basis of real ECGs accumulated in the database of the FASEGRAPH® complex. The complex consists of an ECG recorder with finger electrodes and a computer program that provides automatic ECG processing and determination of traditional and original diagnostic features, in particular, the duration of RR- intervals and parameters β_T beat to beat.

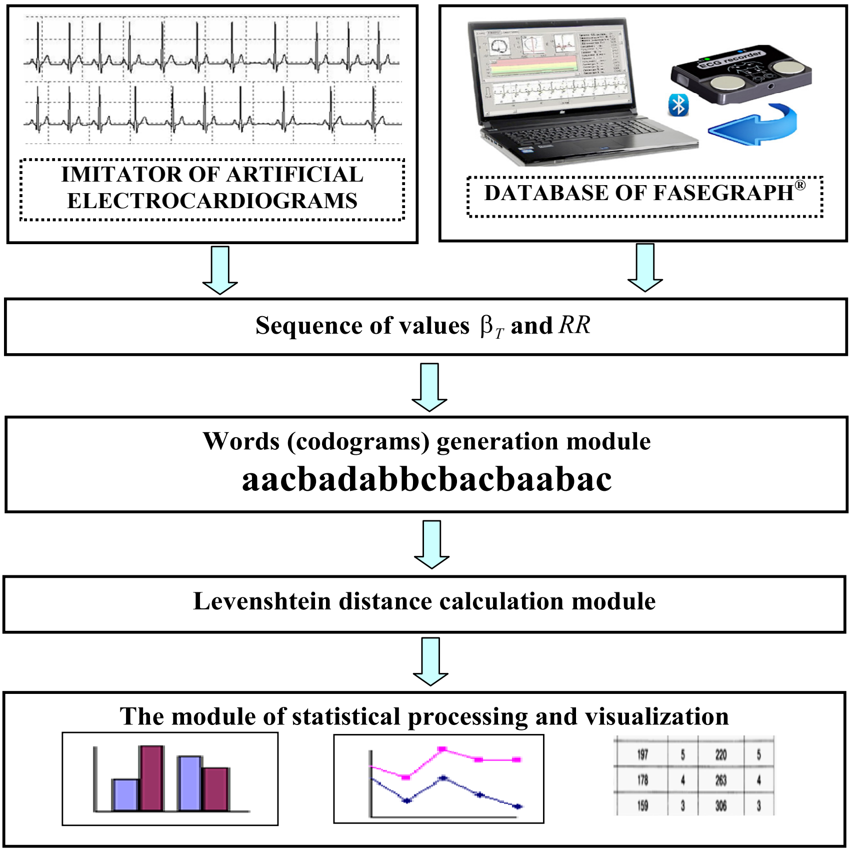


Fig. 3. Structure of information technology

According to the accumulated data, corresponding codograms were formed and *reference codograms* of individual groups of subjects were determined, for example, reference codograms of verified patients and conditionally healthy volunteers, athletes and people who are not actively involved in sports, etc.

The algorithm for constructing reference ECG codograms is as follows.

Let Q_1 and Q_2 ECG which represent one of the two studied groups was recorded as a result of the experiments. Each of Q_1 ECG of the first group (for example, a group of patients) is encoded in words $S_q^{(1)}$, $q = 1,...,Q_1$, in accordance with Table 1. According to formulas (4) - (6), the Levenshtein distance $L_{\mu\nu}(S_\mu^{(1)}, S_\nu^{(1)})$ between each pair $S_\mu^{(1)}, S_\nu^{(1)}$, $\mu = 1,...,Q_1$, $\nu = 1,...,M_1$ encoded ECG is determined.

Next, we form a square $Q_1 \times Q_1$-matrix of distances $L_{\mu\nu}(S_\mu^{(1)}, S_\nu^{(1)})$, $\mu = 1,...,Q_1$, $\nu = 1,...,Q_1$ between all pairs of words corresponding to the ECG of the first group of subjects

$$\Lambda = \begin{pmatrix} L_{11}, & L_{12}, \ldots, L_{1Q_1} \\ L_{21}, & L_{22}, \ldots, L_{2Q_1} \\ & \ldots \\ L_{Q_1 1}, & L_{Q_1 2}, \ldots, L_{Q_1 Q_1} \end{pmatrix}.$$

The row of this matrix, the sum of the elements of which is minimal, defines the reference word $S_0^{(1)}$ of the first group, i.e.

$$S_0^{(1)} = \arg\min_{1 \le \nu \le Q_1} \sum_{\mu=1}^{Q_1} L_{\mu\nu} . \quad (10)$$

The reference word $S_0^{(2)}$ of the second group is determined in a similar way by analyzing the sum of the elements of the Levenshtein distance matrix $L_{\mu\nu}(S_\mu^{(2)}, S_\nu^{(2)})$, $\mu = 1,\ldots,Q_2$, $\nu = 1,\ldots,Q_2$ constructed for all pairs of codograms of the second group, i.e.

$$S_0^{(2)} = \arg\min_{1 \le \nu \le Q_2} \sum_{\mu=1}^{Q_2} L_{\mu\nu} . \quad (11)$$

Reference codograms (10), (11) allow solving various tasks, for example, relating the analyzed ECG to the first or second groups based on a comparison of the Levenshtein distance between the code word S_t of the analyzed ECG and the reference words $S_0^{(1)}$ and $S_0^{(2)}$:

$$\text{ECG belongs to the first group, if } L(S_t, S_0^{(1)}) \le L(S_t, S_0^{(2)}), \quad (12)$$

$$\text{ECG belongs to the second group, if } L(S_t, S_0^{(1)}) > L(S_t, S_0^{(2)}). \quad (13)$$

A similar rule can be used to make a decision about the level of fitness of a person on the basis of Levenshtein's distance between his codogram S_t and reference words $S_0^{(1)}$ and $S_0^{(2)}$, constructed separately for groups of athletes and people who are not actively involved in sports.

To assess the intraindividual features of the codograms (task 3), the data of the concrete person was extracted from the database, which were registered for a sufficiently large period of time. We analyzed only those persons who had no serious organic cardiac abnormalities during the observation period.

On the basis of processing the Q codograms of a concrete person we determined a reference word S_0 for this person and calculated the Levenshtein distance $L(S_1, S_0)$ $L(S_2, S_0)$, … , $L(S_Q, S_0)$ relative to S_0. The values $L(S_1, S_0)$ $L(S_2, S_0)$, … , $L(S_Q, S_0)$ were considered as the implementation of a random value for which an estimate of the distribution was constructed and its statistical characteristics were determined.

For the study of changes in Levenshtein distances in the course of physical and emotional loads, drip injections of drugs and other experimental studies (task 4), we used the electrocardiogram accumulated in the database, recorded during the corresponding observation period T_0, and plotted the changes of the distances $L(S_t, S_0)$ during the experiment relatively discrete time $t = 1,2,..., T_0$.

RESULTS OF EXPERIMENTAL RESEARCHES

Let us briefly review the first practical results obtained using the developed IT.

Figure 4 shows graphs of test signals generated by an artificial ECG simulator. The first signal (the signal A) is a periodic function - a sequence of ECG cycles of a given shape without distortion. Obviously, the codogram of such a signal contain only one letter:

$$S_A = \boldsymbol{dddd \ldots dddd.}$$

The codogram S_A was used as a reference for calculating the Levenshtein distances to the codograms of two other test signals: a signal B that simulated a sequence of reference cycles with distortions of the shape of the wave T only, and a signal C that additionally distorted the durations RR - intervals. The standard deviation of β_T for both signals was RMS β_T = 0,3 units, and the standard deviation of the RR -duration (the standard indicator of the mathematical analysis of heart rate variability) was $SDNN = 140$ ms.

The codograms constructed for the distorted signals had the form:

$$S_B = \boldsymbol{aacddccbaabdccbacabbcaaddcddadbbcaabbdaddadbabcc\ldots}$$

$$\boldsymbol{\ldots babccdbabbdccbabcbababdcdacbabadcbadcdcbaddcd}$$

$$S_C = \boldsymbol{bbabcbcabccaabddcbdcabdcaaabddcabdcbabbcbccabdccabdc\ldots}$$

$$\boldsymbol{\ldots bccbabdcbdcbcabdcbdcbdcabddcbcabcaabddca.}$$

Table 3 summarizes the results of the comparison of distorted signals B and C with the reference signal A.

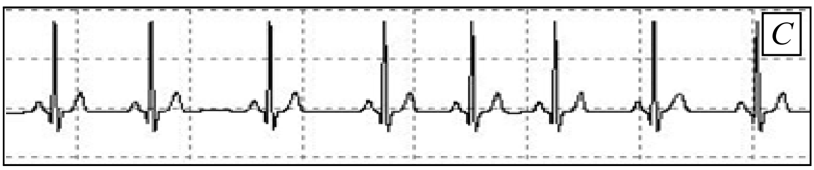
As can be seen from Table 3, the Levenshtein distance increases as the level of ECG cycle distortion increases. However, it was established that the statistical dependence of the distance $L(S_t, S_0)$ of the analyzed codogram S_t relative to the reference one S_0 and index $SDNN$ is substantially nonlinear: the coefficient of determination of the linear dependence $R^2 < 0,5$.

Table 3. **The results of the comparison with the test signal** ***A***

SIGNAL	Increment of RMS β_T, un.	Increment of $SDNN$, ms	Levenshtein distance, un.
B	0,03	0	$L(S_B, S_A) = 46$
C	0,03	140	$L(S_C, S_A) = 71$

RMS $\beta_T = 0$, $SDNN = 0$

RMS $\beta_T = 0{,}03$, $SDNN = 0$



RMS $\beta_T = 0{,}03$, $SDNN = 140$ ms

Fig. 4. Test signals: A — without distortion, B — distortion of β_T only, C — both distortion β_T and RR -intervals

Interesting results were obtained for athletes and people who are not actively involved in sports. The studies were conducted on the basis of real ECG, obtained when testing young volunteers of both sexes aged 18–24, which were divided into two groups:

• **Group 1:** $Q_1 = 47$ highly qualified athletes who are engaged in boxing, various types of wrestling and triathlon;

• **Group 2**: $Q_2 = 113$ people not involved in sports.

Investigations were carried out while performing the Martin test: 20 squats in 30 seconds. We recorded ECG all person from each group before the load, at the height of the load, and after a 3-minute rest. The values of the average heart rate (HR) and the average index β_T characterizing the symmetry of the T wave were determined in these three states.

Following the previously obtained results [26], we will assume that an adequate response of the organism to the load is that with the load both indicators increase, and after resting they return to their original state, i.e.

$$(HR^{(2)} - HR^{(1)}) > (HR^{(3)} - HR^{(1)}), \tag{14}$$

$$(\beta_T^{(2)} - \beta_T^{(1)}) > (\beta_T^{(3)} - \beta_T^{(1)}), \tag{15}$$

where $\eta^{(1)}, \eta^{(2)}, \eta^{(3)}$ — the value of the corresponding indicator in the initial state, at the height of the load and after a 3-minute rest.

We studied the differences in the body's response to exercise in athletes and people who are not actively involved in sports, based on conditions (14), (15), and also based on an estimate of the Levenshtein distance $L(S^{(2)}, S^{(1)})$ and $L(S^{(3)}, S^{(1)})$ between the codogram $S^{(2)}$ at load height and codogram $S^{(3)}$ after resting with respect to to the original codogram $S^{(1)}$.

As a working hypothesis, it was assumed that the condition

$$L(S^{(2)}, S^{(1)}) > L(S^{(3)}, S^{(1)}) \tag{16}$$

also confirms an adequate response of the organism to the load.

The results of the research are summarized in Tables 4 and 5, in the cells of which the symbol "+" and "-" denote fulfillment or non-fulfillment of conditions (14) – (16).

As can be seen from the data given in Tables 4 and 5, the athletes and non-athletes observed small differences in the frequency of occurrence of events W_i, $i = 1,...,8$, which form a complete group. To confirm the reliability of the detected differences, additional data processing was carried out on the basis of the calculation of confidence intervals.

From probability theory it is known [29] that the frequency P^* of a random event, calculated from a sample of observations by volume Q, with reliability of inference γ determines the confidence interval $\mathbf{I} = [P^{(1)}, P^{(2)}]$ of probability P, the boundaries of which are determined by formulas:

Table 4. **Athletes reaction to load**

Random event	**Indicator's recovery after the load**			**Event frequency, %**
	HR	**β_T**	***L* ($S^{(2)}$, $S^{(2)}$)**	
	Condition (14)	**Condition (15)**	**Condition (16)**	
W_1	+	+	+	23,40
W_2	-	+	+	2,13
W_3	+	-	+	2,13
W_4	-	-	+	2,13
W_5	+	+	-	36,17
W_6	-	+	-	10,64
W_7	+	-	-	14,89
W_8	-	-	-	8,51

Table 5. **The response of non-athletes to the load**

Random event	Indicator's recovery after the load			Event frequency, %
	HR	β_T	$L\,(S^{(2)}, S^{(2)})$	
	Condition (14)	Condition (15)	Condition (16)	
W_1	+	+	+	26,55
W_2	-	+	+	6,19
W_3	+	-	+	8,85
W_4	-	-	+	2,65
W_5	+	+	-	34,51
W_6	-	+	-	7,08
W_7	+	-	-	11,50
W_8	-	-	-	2,65

$$P^{(1)} = \frac{P^* + \frac{1}{2}\frac{t_\gamma^2}{Q} - t_\gamma \sqrt{\frac{P^*(1-p^*)}{Q} + \frac{1}{4}\frac{t_\gamma^2}{Q^2}}}{1 + \frac{t_\gamma^2}{Q}} \qquad (17)$$

$$P^{(2)} = \frac{P^* + \frac{1}{2}\frac{t_\gamma^2}{Q} + t_\gamma \sqrt{\frac{P^*(1-P^*)}{Q} + \frac{1}{4}\frac{t_\gamma^2}{Q^2}}}{1 + \frac{t_\gamma^2}{Q}}, \qquad (18)$$

where $t_\gamma = \arg\Phi^*\left(\frac{1+\gamma}{2}\right) > 0$, and $\Phi^*(x) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x} e^{-\frac{\tau^2}{2}} d\tau$.

On the basis of expressions (17), (18), according to the data of Tables 4 and 5, taking into account the volumes $Q_1 = 47$ and $Q_2 = 113$ of the respective samples, the confidence intervals of the probability of random events $W_i, i = 1,...,8$ are determined. It has been established that with reliability of inference $\gamma = 99\,\%$ the reliability intervals of the probability for events W_2, W_3, W_8 do not overlap in the group of athletes and people who are not actively involved in sports (Table 6). And this with high credibility indicates that the probabilities of these events are different. For example, in athletes $P(W_2) < 0{,}397$, while $P(W_2) > 0{,}498$ in people who are not actively engaged in sports.

Table 6. **Significant differences in confidence intervals of probabilities**

Random event	Confidence intervals of probabilities		Reliability of inference γ
	Athletes	Non-athletes	
W_2	[0,100 ; 0,397]	[0,498 ; 0,727]	99 %
W_3	[0,100 ; 0,397]	[0,786 ; 0,941]	99 %
W_8	[0,675 ; 0,940]	[0,173 ; 0,383]	99 %

Note that the indicators HR and β_T represent the averaged values of the parameters of individual ECG cycles, and the condition (16) characterizes the dynamics of the RR-intervals and the index β_T beat to beat. Therefore, condition (16), to a greater extent than conditions (14), (15), characterizes transient processes when performing load tests.

The found statistically significant differences in the response of the body of athletes and non-athletes to the load test may be related both to the athlete's overloads at previous trainings and also to indicate that in the process of regular workouts the athlete's body learns to more economically adapt to the load test. Both are reflected in the features of the dynamics of change HR, β_T and $L(S^{(2)}, S^{(1)})$. Of course, the study of the found fact requires further deeper investigations on representative samples of observations.

Recently, scientists have paid attention to intraindividual ECG changes of a healthy person at rest [29], which is not a precursor of any pathology. In this regard, it is interesting to study the intra-individual changes in the codograms of the same person over a fairly long observation period.

The basis of such studies was based on the analysis of the ECG series of two subjects, registered for six years. $Q_1 = 26$ codograms of the first test subject (male) and $Q_2 = 25$ codograms of the second test subject (woman) are analyzed.

Based on the processing of the available codograms, the reference codogram of the first person

$$S_0^{(1)} = \boldsymbol{bccabcbadabdcadcabcabccbdcbbcabccaddcbbdaba\ldots}$$

$$\boldsymbol{\ldots cbccbdabadadccdbcadccbaccbdcabdabbcabcabdcbacabbcadccbda}$$

and the second person

$$S_0^{(2)} = \boldsymbol{addaddacdadadcbdabcaddacbdcadabdadcadcadacd\ldots}$$

$$\boldsymbol{\ldots adbccadcbbcadbcdadcadcdcdbcdaddacbacbcdacdadaacbabbcada}$$

was constructed using the method described above.

Levenshtein distance between reference codograms is

$$L(S_0^{(1)}, S_0^{(2)}) = 52\,.$$

Estimates of distributions of random variables $L(S_t^{(1)}, S_0^{(1)})$ and $L(S_t^{(2)}, S_0^{(2)})$, $t = 1,\ldots,Q_2$ (histograms) corresponding to ECG's codograms recorded during the observation period are presented in the (Fig. 5).

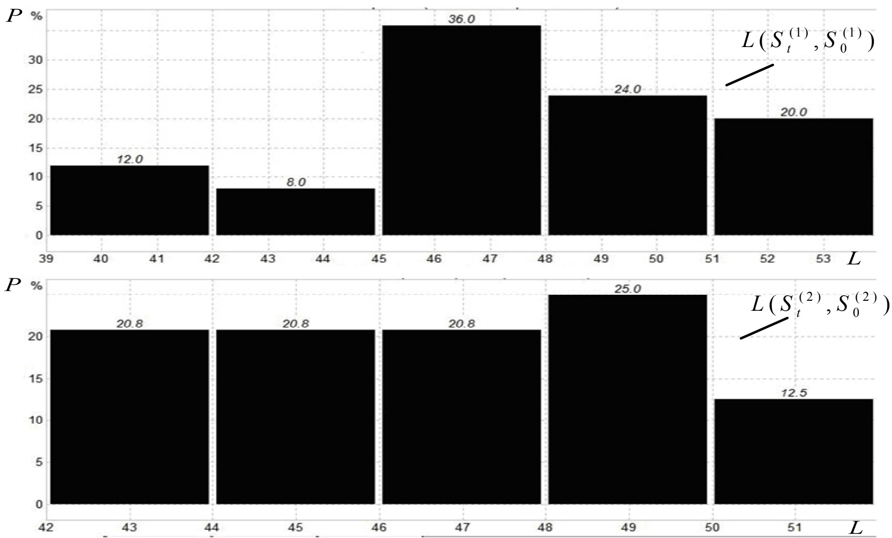


Fig. 5. Histograms of distance distributions $L(S_t^{(1)}, S_0^{(1)})$ and $L(S_t^{(2)}, S_0^{(2)})$

As can be seen from Fig. 5, Levenshtein distances $L(S_t^{(1)}, S_0^{(1)})$ $L(S_t^{(2)}, S_0^{(2)})$ varied over a fairly wide range of values for both individuals during the observation period. For comparison, we note that during this period there were also significant fluctuations in traditional indicators β_T and standard deviation of RR -intervals which amounted

$$\beta_T^{(1)} = 0{,}771 \pm 0{,}079,\ \beta_T^{(2)} = 0{,}752 \pm 0{,}125,\ SDNN^{(1)} = 37{,}9 \pm 16{,}1,$$
$$SDNN^{(2)} = 32{,}5 \pm 10{,}5.$$

The study of the diagnostic capabilities of the proposed method was carried out using a database of real ECG recorded at the Ischemic Heart Diseases Department of the V.D. Strazhesko's Research Institute of Cardiology Academy of Medical Sciences of Ukraine (Kyiv) and four clinics in Germany — Essen University Hospital (Essen), Katholical Hospital "Phillpusstift" (Essen), German Heart Center (Berlin).

The clinical material consisted of 100 ECG records of patients with chronic ischemic heart disease (CAD), whose diagnosis was previously established by coronary angiography (class V_1), and 100 ECG records of healthy volunteers included in the control group (class V_2)

By the formulas (10), (11) two reference codograms for the specified classes are defined: the reference codogram of patients with ischemic heart disease

$$S_0^{(1)} = \boldsymbol{adcbdadcadabdabcadabdadcbdab}$$

and reference codogram of a healthy volunteers

$$S_0^{(2)} = \boldsymbol{cbcdcabdcabddcaadcaa}.$$

The Levenshtein distance between these codograms was

$$L(S_0^{(1)}, S_0^{(2)}) = 15.$$

Based on the processing of the available data, it has been established that decision making according to the rules (12), (13) provides sensitivity $S_E = 72\%$ and specificity $C_P = 79\%$.

For illustration, we present the results of the ECG evaluation for two patients — a verified patient (male, 69 years old), whose codogram was

$$S_t^{(1)} = \textbf{\textit{adcabdadcadabdaddabdaadabdbdda}}$$

and a representative of the control group — a male, 54 years old, whose codogram was

$$S_t^{(2)} = \textbf{\textit{bdcbbcdcabcdcabcdcbaa.}}$$

It is easy to verify that $L(S_t^{(1)}, S_0^{(1)}) = 13$ and $L(S_t^{(1)}, S_0^{(2)}) = 15$, i.e.

$$L(S_t^{(1)}, S_0^{(1)}) < L(S_t^{(1)}, S_0^{(2)})$$

and in accordance with the rule (12), the survey must be reduced to the CAD-group.

Similarly, for the second person we have $L(S_t^{(2)}, S_0^{(1)}) = 14$ and $L(S_t^{(2)}, S_0^{(2)}) = 8$, i.e.

$$L(S_t^{(2)}, S_0^{(1)}) > L(S_t^{(2)}, S_0^{(2)})$$

and in accordance with the rule (13) the person should be reduced to a healthy group.

It is important to note that traditional signs of myocardial ischemia (elevation or depression of the ST segment) not observed on all patient's ECG. And this means that conventional electrocardiography would classify all processed ECG into healthy group.

At the same time experiments show that it is possible to classify representatives of the classes even on such "complex" clinical material on the basis comparison of the Levenshtein distances.

Fig. 6 presents estimates of the conditional distributions $P(L(S_t, S_0^{(1)}))$ and $P(L(S_t, S_0^{(2)}))$ of Levenshtein distances with respect to the reference codograms of the sick and the healthy person.

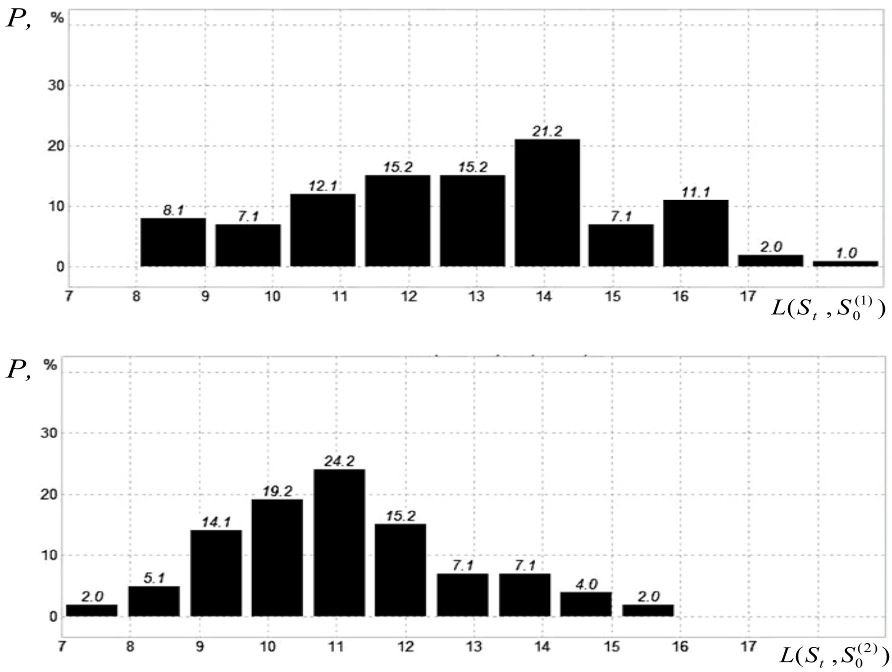


Fig. 6. Conditional distributions of Levenshtein distances to patient (top) and healthy (bottom) standards

Testing the hypothesis of homogeneity of conditional distributions $P(L(S_t, S_0^{(1)}))$ and $P(L(S_t, S_0^{(2)}))$ according to the Kolmogorov-Smirnov criterion showed that the hypothesis of equality of distributions should be rejected with high statistical significance $(p < 0{,}001)$. The similar fact was confirmed by Mann-Whitney U test.

Consequently

$$P(L(\cdot)\,|\,V_1) \not\equiv P(L(\cdot)\,|\,V_2). \tag{19}$$

If also the diagnostic sign $L(\cdot)$ is conditionally independent of indicators $SDNN$ and RMS, i.e.

$$P(L, SDNN, RMS\ \beta_T\,|\,V_k) \equiv P(L\,|\,V_k)P(SDNN, RMS\ \beta_T\,|\,V_k),\quad k = 1{,}2, \tag{20}$$

then, according to a theorem proved in [30], the Levenshtein distance is guaranteed a useful diagnostic sign in conjunction with $SDNN$ and RMS in terms of reducing the probability of erroneous decisions.

The analysis of the Levenshtein distances was also useful for illustrating the dynamics of ECG changes during the drug treatment of cardiovascular pathologies.

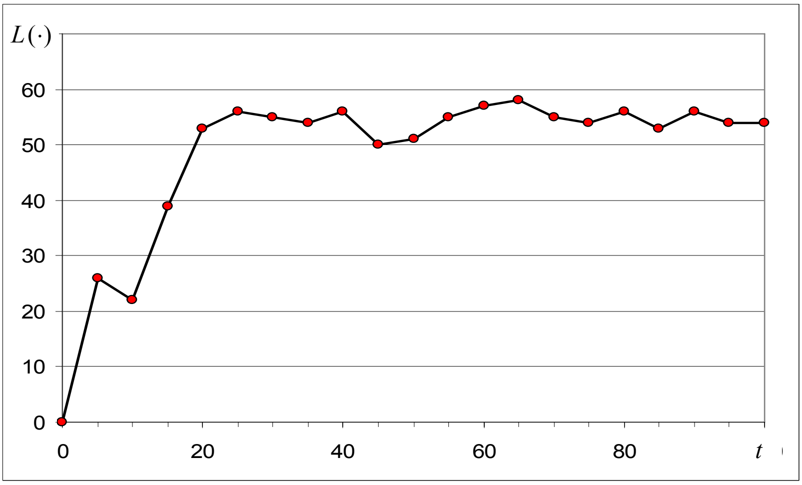


Fig. 7. Schedule of changes in the distance *L* (S_t, S_0) in the process of intravenous drug infusions

Fig. 7 is a graph of the change in the distance $L(S_t, S_0)$ between ECG codograms, which were recorded during intravenous infusion of drugs to patient R. (male, 72 years old), diagnosed with atrial fibrillation.

Patient R. was hospitalized at the Scientific and Practical Center for Prevention and Clinical Medicine (Kyiv). ECGs were recorded every 5 minutes for 1 hour and 20 minutes in the process of intravenous infusion of Tivomax preparations followed by the addition of the drug Armadin.

Before the administration of the drugs, there was a pronounced extrasysitivity on the patient's ECG, which decreased significantly to 20-th minute. With the further administration of drugs, the heart rhythm gradually normalizes. By the end of 100 minutes, the standard deviations of the RR -interval were within the functional norm ($SDNN = 30$ ms). As can be seen from Fig. 7, the positive dynamics of intravenous infusion of drugs is clearly illustrated by the graph of Levenshtein distances $L(S_t, S_0)$ changing.

The analysis of the Levenshtein distance was also used to monitor the condition of patient S. (male, 61) diagnosed with atrial fibrillation combined with arterial hypertension, who was hospitalized for 47 days in a hospital for scientists of the National Academy of Sciences of Ukraine. Monitoring was carried twice a day (Fig. 8).

The patient was treated with antiarrhythmic drugs (Digoxin et al.) and blood pressure lowering drugs (Captopres, etc.). Periodically intravenous infusions of a number of drugs were conducted.

During the entire period of treatment, the patient's condition was stable, which was reflected only by insignificant fluctuations of the Levenshtein distance between codograms except for some moments of time (Fig. 8). One of such measurements, marked by an arrow in Fig. 8, was associated with the treadmill study, when the heart rate was 139 beats / min, and the T -wave symmetry index assumed an excessively high value $\beta_T = 2{,}05$ unit.

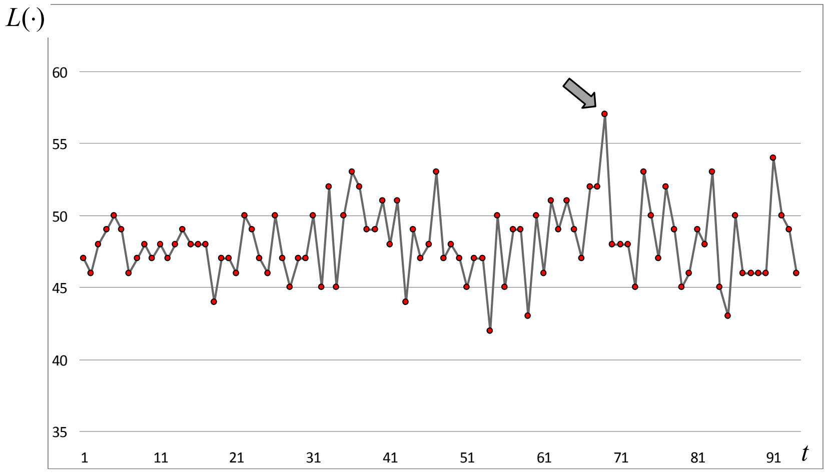


Fig. 8. Monitoring of state patient S

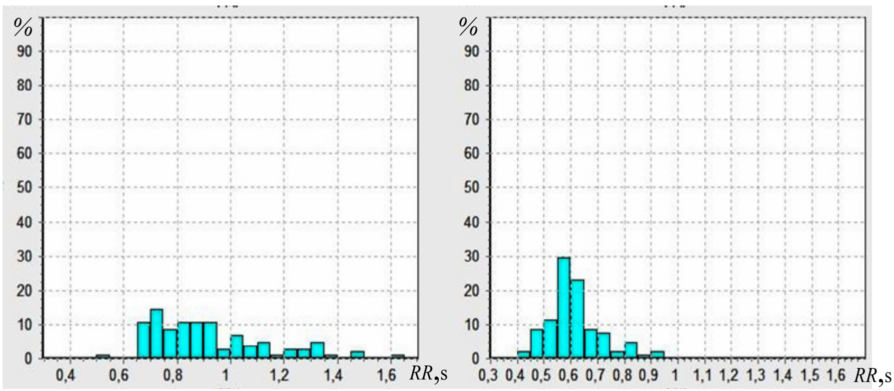


Fig. 9. Histograms *RR*- intervals before (left) and after (right) treatment of patient S

Daily monitoring of ECG indices using the method fasegraphy combined with monitoring of Levenshtein distances, confirmed the effectiveness of the medical treatment of the patient B.: the index decreased from the initial value of ms to the value of ms. heart rate variability decreased by 73%, what clearly illustrates the comparison of the histograms of the durations of the RR -intervals (Fig. 9).

In conclusion we note that the considered approach of ECG coding with subsequent analysis of the Levenshtein distance between codograms can naturally be generalized to the cases when not only the intervals $R-R$ and indicator β_T are used for ECG coding, but also other informative indicators, in particular, amplitudes of R and T waves.

CONCLUSIONS

The proposed approach is based on converting sequences of parameters that characterize the form of individual electrocardiogram cycles into a word — a finite string of characters of a given alphabet. The words (codograms) obtained in this way are analyzed on the basis of the Levenshtein distance, which determines the minimum number of editing operations (inserting, deleting, and replacing a character) to convert one word into another.

The calculation of the Levenshtein distances between all pairs of codograms of the group of subjects allows one to determine the reference codogram of this group. Comparison of the Levenshtein distances, including the analysis of the editorial distance between the current codogram and the reference codogram, makes it possible to make diagnostic decisions about patient ownership of the corresponding group.

An information technology based on the implementation of the components of the proposed approach has been developed. Experimental studies conducted using model and real data confirmed the potential diagnostic effectiveness of the proposed approach for obtaining additional information in solving actual applied problems. Of course, from the point of view of evidence-based medicine, such research should be continued on a significantly larger amount of clinical material.

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Received 01.04.2019

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Отримано 01.04.2019

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ЛІНГВІСТИЧНИЙ ПІДХІД ДЛЯ ОЦІНЮВАННЯ ТОНКИХ ЗМІН ЕЛЕКТРОКАРДІОГРАМИ НА ОСНОВІ ВІДСТАНІ ЛЕВЕНШТЕЙНА

Вступ. Лінгвістичний підхід, оснований на переході від ЕКГ до кодограми, здобув популярність для аналізу серцевого ритму. Для розширення функнальних можливостей методу доцільно вивчити можливості одночасного контролю динаміки тривалості серцевих циклів і оригінального показника, який несе інформацію про ішемічні зміни міокарда.

Мета статті — розробити алгоритмічні і програмні компоненти для розв'язання цього завдання і провести експериментальні дослідження за модельними і реальними даними.

Методи. Забезпено автоматичне кодування ЕКГ, обчислення відстаней Левенштейна між парами ЕКГ певної групи випробовуваних і побудова референтної кодограми групи. Оцінювання результатів експериментальних досліджень проводилося на основі традиційних методів статистичного аналізу.

Результати. Показано, що на основі відстаней Левенштейна між усіма парами кодограм групи випробовуваних можна визначити референтну кодограму групи хворих на ішемічну хворобу серця (ІХС) і групи здорових добровольців. Встановлено, що прийняття рішень на основі порівняння кодограми ЕКГ випробуваного з еталонною кодограмою забезпечує поділ представників зазначених груп з чутливістю S_E = 72% і специфічністю C_P = 79% навіть в тих випадках, коли традиційний аналіз ЕКГ у 12 відведеннях виявляється неінформативним.

Висновки. Запропонований підхід дає змогу отримати додаткову діагностичну інформацію для вирішення актуальних завдань практичної медицини.

Ключові слова: *лінгвістичний підхід, діагностична ознака ЕКГ, відстань Левенштейна.*

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ЛИНГВИСТИЧЕСКИЙ ПОДХОД ДЛЯ ОЦЕНИВАНИЯ ТОНКИХ ИЗМЕНЕНИЙ ЭЛЕКТРОКАРДИОГРАММЫ НА ОСНОВЕ РАССТОЯНИЯ ЛЕВЕНШТЕЙНА

Введение. Лингвистический подход, основанный на переходе от ЭКГ к кодограмме, получил известность для анализа сердечного ритма. Для расширения функциональных возможностей метода целесообразно изучить возможности одновременного контроля динамики изменения продолжительности сердечных циклов и оригинального показателя, несущего информацию об ишемических изменениях миокарда.

Цель статьи — разработать алгоритмические и программные компоненты для решения этой задачи и провести экспериментальные исследования на модельных и реальных данных.

Методы. Обеспечивалось автоматическое кодирование ЭКГ, вычисление расстояний Левенштейна между парами ЭКГ определенной группы испытуемых и построение референтной кодограммы группы. Оценка результатов экспериментальных исследований проводилась на основе традиционных методов статистического анализа.

Результаты. Показано, что на основе расстояний Левенштейна между всеми парами кодограмм группы испытуемых можно определить референтную кодограмму группы больных ишемической болезнью сердца (ИБС) и группы здоровых добровольцев. Установлено, что принятие решений на основе сравнения кодограммы ЭКГ испытуемого с эталонной кодограммой обеспечивает разделение представителей указанных групп с чувствительностью $S_E = 72\%$ и специфичностью $C_P = 79\%$ даже в тех случаях, когда традиционный анализ ЭКГ в 12 отведениях оказывается неинформативным.

Выводы. Предложенный подход позволяет получить дополнительную диагностическую информацию при решении актуальных задач практической медицины.

Ключевые слова: *лингвистический подход, диагностический признак ЭКГ, расстояние Левенштейна.*

DOI: https:// 10.15407/kvt196.02.027

UDC 616.89-07-08(035):616-036.82:355.11:355.721

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USING SEMANTIC MODELING TO IMPROVE THE PROCESSING EFFICIENCY OF BIG DATA IN THE INTERNET OF THINGS DOMAIN

Introduction. *The development of the Internet of Things (IoT), equipped with various electronic sensors and controllers that distantly operate with these things is an important step of a new technical revolution. In this article we look at the features of Big Data generated by the Internet of Things (IoT) technology, and also present the methodology for processing this Big Data with use of semantic modeling (ontologies) at all stages of the Big Data life cycle. Semantic modeling allows to eliminate such contradictions in these technologies as the heterogeneity of devices and things that causes the heterogeneity of the data types produced by them. Machine learning is used as an instrument for Big Data of analyzes: it provides logical inference of the rules that can be applied to processing of information generated by Smart Home system.*

The purpose *of the article is to use deep machine learning, based on convolutional neural networks because this model of machine learning corresponds to processing of unstructured and complex nature of the IoT domain.*

Results. *Proposed approach increases the efficiency of IoT Big Data processing and differs from traditional processing systems by using NoSQL database, distributed architectures and semantic modeling.*

Conclusion. *The conceptual architecture of the Big Data processing system for IoT and describe it on on the example of the NoSQL database for Smart Home were given. This architecture consists of five independent levels. At each of these levels, a combined approach of semantic modeling and data mining methods can be used. Currently, this platform can be combined with a lot of open source components.*

Keywords: *Industry 4.0, Big Data, Internet of Things, ontology, Semantic Web, non-formal and informal learning.*

INTRODUCTION

Industry 4.0 is defined in [1] as a process of the digital transformation of industrial markets with smart manufacturing currently on the forefront.

The new capabilities of Industry 4.0 deal with intellectualization of digital technolologies used in industrial processes. Specialists say about the phenomena of 'smart anything' in environment of people: from smart grid, smart buildings and smart plants, smart services and smart manufacturing and so on. Internet of things also is influenced by this tendency.

Various advanced digital technologies are already used in manufacturing for realization of Industry 4.0. It will lead to greater efficiencies and change traditional relations among suppliers and customers. In [2] nine most important technologies that build Industry 4.0 are defined:

- Big data and analytics;
- The cloud computing;
- Autonomous robots;
- Simulation;
- Horizontal and vertical system integration;
- The industrial Internet of things;
- Cybersecurity;
- Additive manufacturing;
- Augmented reality.

Industry 4.0 actively uses digital context for industrial objective therefore the tasks of collection and comprehensive evaluation of data from various distributed sources—production equipment and systems as well as enterprise- and customer-management systems— now become standard to semantic support of decision making processes in real-time mode.

Competencies can be used for adaptation of Industry 4.0 for semantic management of personnel.

Now a lot of research works, deal with this problem, are provided. For example, in [3] authors try to analyze the most significant aspects of the new forms of human work that they face in this Industry 4.0 revolution in order to know what is currently being done. With all the advances that have been made over time in the problem of knowledge age, the participation of organizations requires them to create and maintain environments that foster learning.

The development of the Internet of Things (IoT), equipped with various electronic sensors and controllers that distantly operate with these things is an important step of a new technical revolution.

The term «Internet of Things» was proposed in 1999 by K. Ashton. Now IoT signigies a complex system of interrelated computing devices, mechanical and digital machines, objects, animals or people that are provided with unique identifiers and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction. IoT has evolved from the convergence of wireless technologies, microelectromechanical systems, microservices and the Internet. IoT components (devices — sensors, actuators, mobile devices etc. — and services) are heterogeneous and dynamic, with unknown nature of the network topology.

IoT proposes new technological infrastructure that expands the technology of wireless sensors, involves the Internet connecting for a lot of things around a person and distance management of these things [4].

However, IoT is a complex and heterogeneous environment that should evolve towards creating a more structured set of solutions, where “things” should be represented in some uniform way and be equally detectable, able to communicate with other objects, and also be directly integrated with the Internet infrastructure and with Web services irrespective of the specific method of connection [5].

Data collected by different sensors and devices is usually polysemantic (temperature, light, sound, video, etc.).

The Internet of Things is widely used in various areas of society. Health, environment, traffic, vehicles, aviation, manufacturing, defense, home automation, telecommunications are the most known examples of IoT applications. The number of electronic devices connected to the IoT is increasing every year. Analysts expect that the number of electronic devices connected to the IoT will grow up by 2020 from 50 to 100 billion. It is expected that the total amount of data generated as a result of mass usage of such devices will become than 35 zettabyte [6] and can be considered as Big Data.

The development of IoT devices, systems and solutions, huge amounts of heterogeneous and unstructured data is a contiguous process. This Big Data needs to be analyzed and processed in order to acquire hidden knowledge. The heterogeneity of IoT devices and systems causes additional problems in processing and analyzing Big Data generated by IoT.

ANALYSIS OF NON-FORMAL AND INFORMAL LEARNING

Among the key modern innovations in the world today is the concept of non-formal and informal education [7]. The current problem is the study of the systematic combination of all forms of education: formal, non-formal and informal. The UNESCO Education Glossary [8] contains the following definitions:

Learning — individual acquisition or modification of information, knowledge, understanding, attitudes, values, skills, competencies or behaviours through experience, practice, study or instruction.

Formal education is an institutionalized, deliberate and planned education through public organizations and recognized private institutions and, in their totality, creates a system of formal education of the state.

Non-formal education — education that is institutionalized, intentional and planned by an education provider. The defining characteristic of non-formal education is that it is an addition, alternative and/or a complement to formal education within the process of the lifelong learning of individuals. It is often provided to guarantee the right of access to education for all. It caters for people of all ages, but does not necessarily apply a continuous pathway-structure; it may be short in duration and/or low intensity, and it is typically provided in the form of short courses, workshops or seminars. Non-formal education mostly leads to qualifications that are not recognized as formal qualifications by the relevant national educational authorities or to no qualifications at all. Non-formal education can cover programmes contributing to adult and youth literacy and education for out-of-school children, as well as programmes on life skills, work skills, and social or cultural development.

Informal learning — forms of learning that are intentional or deliberate but are not institutionalized. They are less organized and structured than either formal or non-formal education. Informal learning may include learning activities that occur in the family, in the work place, in the local community, and in daily life, on a self-directed, family-directed or socially-directed basis.

These definitions are intended to provide a general understanding of the concepts, but today they are not yet fully enshrined in Ukrainian legislation and do not satisfy the principle of legal certainty. These definitions indicate the key differences that distinguish one type of education from another. In particular, the main difference between formal and non-formal education is that the latter is an addition or alternative to the formal, as well as in the official recognition or non-recognition by the state or authorized non-state bodies of qualifications obtained on the basis of educational achievements. The main difference between information education and other types is that it is not institutionalized.

The Law of Ukraine "On Education" (Article 9. Forms of Education) [9] contains the norms concerning formal, non-formal and informal education:

1. A person exercises his right to education throughout his life through formal, and informal education. The state recognizes all these types of education, supports educational actors providing relevant educational services, and encourages the acquisition of education of all kinds.

2. Formal education — education acquired through educational programs in accordance with the levels of education, branches of knowledge, specialties (occupations) prescribed by the legislation, envisages the achievement of the results of the education of the corresponding level of education and the recognition of qualifications recognized by the state determined by the students of education.

3. Non-formal education — education acquired through educational programs and does not stipulate the awarding of state-recognized qualifications to the levels of education and obtaining an education document established by the legislation.

4. Informational education (self-education) — education, which involves the self-organized acquisition of certain competencies by the person, in particular during everyday activities related to professional, community or other activities, family or leisure activities.

5. Qualifications and learning outcomes acquired through non-formal and informal education can be confirmed and recognized in the system of formal education or in other cases stipulated by the legislation of Ukraine.

In Ukraine, as in other countries of the world today, the task is to legalize non-formal and informal education, as well as to create legislative preconditions for official recognition of educational results obtained in these types of education.

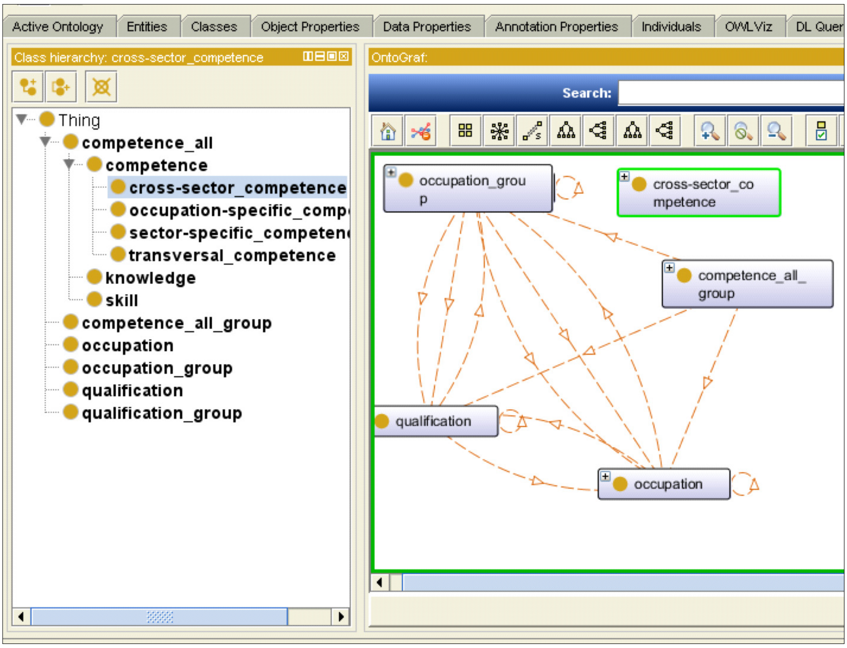

Fig.1. Ontology of competences (fragment).

EU Council Recommendation 2012 [7] highlights the issue of creating a systematic approach to "validation", increasing the visibility and value of learning beyond the formal education and training systems. The document developed 4 phases of validation for non-formal and informal learning. To specify the main features of validation, the recommendation defines four distinct phases: *identification*; *documentation*; *evaluation*; and *certification*.

The national qualifications frameworks are now being implemented in Europe. These frameworks can contribute to the implementation and integration of validation.

Today, the transformation of a market economy into a knowledge economy is taking place. Highly skilled professionals are the greatest value for the IT industry. In the process of learning, students study and apply in practice a variety of tools and Internet technology things, including: IoT devices and physical objects, equipped with IoT, consumer devices, sensors, gadgets and a wide range of Internet applications. [4]. Devices used for different learning systems generate a stream of Big Data that needs to be efficiently handled for decision making and the creation of intelligent learning systems.

We use for analysis an ontology of competences that use such main componentsand their types as it represented (Fig.1.)

This ontology spesifies the types of competences, their level ets. and can be used as as base either for matching of various natutal-languige texts, or for their semantic mark-up.

We propose to use an additional ontology class — atomic competence [10], which is meant for correlating instances of different IO classes by assessing their semantic proximity. Atomic competence has the following properties:

– $a \in C$, where K is the set of IO class "Competence" and C_{atomic} is the set of atomic competences, i. e. $C_{atom} \subseteq C$;

– every competence can be represented by a set of atomic competences $\forall c \in C \exists a_i \in C_{atomic}$, $i = \overline{1,n}, k = \bigcup_{i=1}^{n} a_i$;

– no atomic competence is a subset of another atomic competence $\forall a, b \in C, a \subseteq b \Rightarrow b \notin C_{atomic}$.

SEMANTICS IN IOT

The distribution of the IoT sensors gives rise to various data types, data formats and time measurements specifications that cause of problems deal with data integration. This problem can be overcome by Semantic Web solutions used for data representation with the single knowledge model. RDF, RDF Schema and OWL are the main means for knowledge representing on the Semantic Web [11, 12]. These languages represent only the conceptual data model and rules, but do not specify the particular formats of serialization.

Now some specific languages for semantic data representation such as Turtle, N3 and JSON-LD are developed. [13] emphasizes the importance of semantics for the knowledge representation of the IoT domain and provides an assessment of the various knowledge representation languages in terms of efficiency of their use (in the field of data exchange and processing). The author evaluates all actual semantic formats: extensible Markup Language (XML), Resource Description Framework (RDF), SenML, Notation3 (N3), Turtle, N-Triples and JavaScript Object Notation for Linked Data (JSON-LD). The latter — JSON-LD is an effective and modem solution for experimental results.

Unfortunately, semantic data representation alone is not enough to solve the IoT heterogeneity problem. We also need general dictionaries for representation of domain semantics. Ontologies are used in the Semantic Web domain to provide a common language for representation of various “things”, their relationships, etc. The Ontology Semantic Sensor Network (SSN) developed by the W3C Semantic Sensor Network Incubator Group is the first step on this path. SSN ontology is used to represent sensors, their properties and observations (generated data), domains, etc. in very simple general terms and it is assumed that they will be used by all types of sensors all over the world.

A number of papers deal with attempts of development of IoT ontologies. A common knowledge base for IoT domain that supports semantic detection of IoT sensors and their service infrastructure is offered in [14]. Ontologies for an IoT domain consisting of ontologies of devices, domains and computations are offered in [15]. The development an IoT ontology that covers the following aspects of the IoT domain: IoT resources, IoT services, observation and measurement, physical locations, deployment platform, QoS, and tests for IoT services is described in [16].

In addition, some researchers propose semantic structures and IoT platforms. Barbero et al. [17] offers the conceptual IoT platform that uses such languages as XML and OWL.

INTERNET OF THINGS AND BIG DATA IN SMART LEARNING ENVIRONMENTS

Smart learning environments are equipped with digital components that create better, more efficient, and smoother learning process. Ideally, they create a perfect synergy between physical and digital realities, allowing students to absorb information from their environment and creating opportunities for seamless transitions between a variety of learning approaches: individual and group learning, formal and informal settings, in analog and digital formats. IoT can track whether homework was done and collect data about how much time a student needed to complete an assignment. This data can help teachers better understand whether their methods are working, which students need additional help, and which tasks they struggle with the most.

Big Data may provide the chance to say goodbye to much-maligned standardized testing. Data collected during routine tasks and classwork – processed with the help of AI tools – may offer greater insights into the skills and abilities of individual students compared to any standardized test. This alone could produce a tremendous restructuring of the entire education sector.

BIG DATA AND MACHINE LEARNING IN IOT

We propose to use machine learning (ML) algorithms to acquire the semantics of Big Data generated by IoT devices. IoT data should be considered as Big Data if it has some specific Big Data features from 5V set [18]:

- Volume — the large amounts of data;
- Velocity — the high-speed generation of new data;
- Variety — the heterogeneous data representation (various formats and types);
- Veracity — the level of data conformity to facts;
- Value — the pertinence to user needs.

Big Data in IoT differs from traditional Big Data by its specific characteristics in terms of data generation, data interoperability and data quality.

Speed, scalability, dynamics and heterogeneity are important issues for IoT data creating. Data quality can be measured using signs of uncertainty, redundancy, ambiguity and inconsistency of data [19].

These characteristics of IoT data should be considered in process of development of new model or structure for Big Data processing. In addition, streaming data transmission causes another big problem that should be considered in new IoT structures and models: streaming data also has its typical characteristics such as continuity, unordered data flow, unlimited data, and the absence of persistent data objects. Technological platforms and solutions for storing large IoT data have been developed only recently. Methods of Big Data storage also differ from traditional data storage methods. Such critical factors should be considered for IoT data storing: consistency, availability and sensitivity to data partitioning [20]. For example, Jiang et al. [21] offer an IoT-based storage environment that runs on cloud computing platforms. Li et al. [22] propose a solution for storing large IoT data based on NoSQL. Cecchinel et al. [23] develop an IoT architecture that collects and processes IoT sensor data using MongoDB as storage mechanism for Big Data.

The literature also describes the use of machine learning algorithms in areas related to IoT. Khan et al. [24] and Altun et al. [25] use an artificial back-propagation neural network to recognize human activity, such as walking, sitting, running, etc. Choi et al. [26] use a neural network of reverse propagation for Smart Home applications. Lane et al. [27] offer deep learning networks and convolutional neural network models for processing data from IoT sensors.

Thereby, machine learning algorithms are widely used in areas related to IoT. However, these research works solve local and limited problems, and they are not suitable for data processing from heterogeneous IoT sensors and devices.

PROBLEM DEFINITION

The main idea of paper — we propose to use of competence ontology for retrieval and analyzing of Big Data from individual digital devices (mobile telephones etc.). Such data can characterize the level of person's competence for concrete proposal in situations with informal and non-formal education. We propose to match atomic competencies that are integrated into domain ontology.

Semantic representation (ontologies) that simulate the behavior and characteristics of IoT things is essential for the interoperability of these things, their discovery and selection for specific tasks.

The external ontology of IoT-things sensors (SSN ontology) for preliminary processing of heterogeneous unstructured and semi-structured Big Data generated by these sensors at the Extraction-Transformation-Loading (ETL) stage can be used. Methods of machine learning and logical inference can help in generation of the rules for Big Data processing.

REQUIREMENTS FOR SEMANTIC-ORIENTED IoT BIG DATA PROCESSING ARCHITECTURE

Overview of existing IoT platforms indicates the main directions of development of their functionality:

- Simulation of semantic data. Semantic Web allows to describe IoT domain by standard protocols and dictionaries. New frameworks support various aspects of semantic-oriented modeling, storage and processing of data oriented to semantics. However, one of their missing features is the use of logical inferences on knowledge and rule-based inference.
- Big Data analytics and machine learning: Big Data generated by IoT (as opposed to previous sensor systems with limited data storage and processing capabilities) needs in analysis of large volumes of data. Therefore, we plan to use not only Big Data analytics, but also modem ML approaches, such as deep learning.

The implementation of above functionalities can be realized if the following non-functional requirements are fulfilled:

- common IoT standards that increase requirements for interoperability. Therefore, the new IoT structure should be based only on common standards and refrain from developing its own solutions.
- system openness: higher interconnection and interoperability are possible only on base of open systems. Nowadays, a service-oriented approach where the functionality of the system can be accessed through standard Web services or by open API is required. Web services provide interconnectivity and openness.

Semantic data modeling is very suitable for IoT. To solve the problems of data modeling and management in complex information systems, recent works use innovative solutions based on Semantic Web technologies.

The Semantic Web use for sensors is analyzed in [28]. IoT is the next target for the Semantic Web, where heterogeneity is inherent in many types of sensor devices and their output signals, multiple communication protocols and data formats, etc.

MACHINE LEARNING FOR BIG DATA ANALYTICS

Deep learning is a particular learning model that combines well with unstructured and complex nature of the IoT domain. Deep neural networks are basically multilayered ones with a large number of cascading layers that have learning capabilities for hierarchical features. Deep learning works well in cases where the data set is huge and there has a large number of functions (for example, individual image pixels, individual elements or time series sequences, signals, etc.).

The main reason that makes deep learning the preferred choice for data researchers is that traditional neural network models are not scalable enough to provide solutions for Big Data. Meanwhile, deep neural networks usually do not require domain knowledge and characteristics, and also work well with Big Data, so directly submitting of raw data to deep learning model provides fast, scalable and more accurate data analysis solutions.

ARCHITECTURE OF THE SEMANTIC PROCESSING OF IOT BIG DATA

We propose the conceptual architecture of the system intended for semantic processing of IoT Big Data. It has multilevel structure for performing different independent tasks. System contains five basic levels, namely:

(1) data collection,
(2) extraction-transformation-loading (ETL),
(3) logical inference based on semantic rules,
(4) machine learning,
(5) the result of the work of the levels from the lowest to the highest.

System processes the raw data from the sensors, adds semantics and rules, executes machine learning, and finally, carries out some actions.

The first level in the structure is the level of data collection,

which is responsible for collecting all kinds of data from various sources, in particular from sensors. It can be considered as an input layer, since the platform uses this level to interact with sensors.

The incoming data is raw data, and the only task that this level performs is receiving and transmitting the raw data to the ETL level for processing.

$$\forall x \in T \exists d = ETL(x)$$

The second level in the structure is the level of ETL (Extract- Transform-Loading). Incoming data from the acquisition level is accepted by the ETL level for analysis. Since sensors of different types send data of different types and formats, the ETL level contains sensor drivers to receive and analyze data accordingly. For example, a humidity sensor and a temperature sensor send data in different formats.

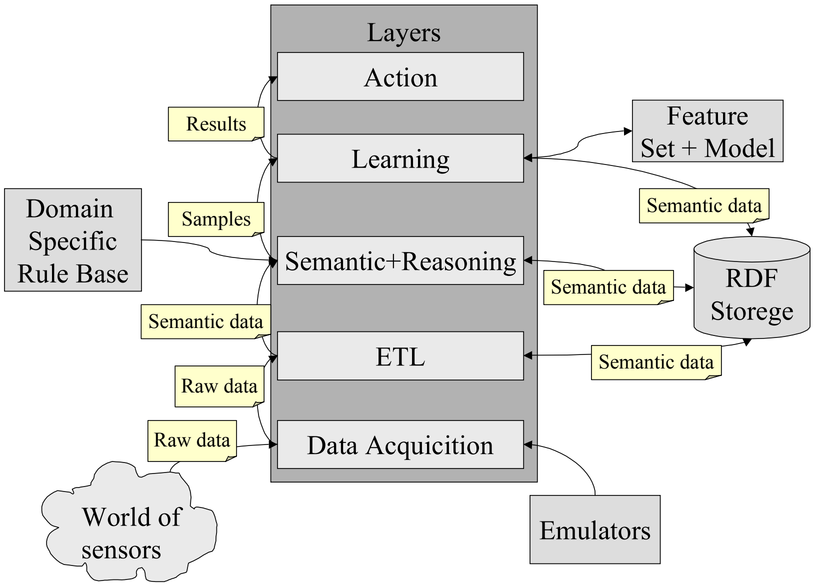

Fig. 2. Multilevel architecture of the semantic processing of IoT Big Data.

In addition, each sensor driver is responsible for receiving data in the correct form, the correct block and format, depending on the sensor, its type and version. For example, a temperature sensor from supplier A may provide data in units of degrees Celsius, while another sensor from supplier B may provide data in units of Fahrenheit. For this purpose, the ETL level is responsible for storing data in the correct type and format, regardless of the type of sensor, with the help of semantic technologies.

Data is converted to a semantic format RDF that is a basic language for describing statements. At this stage, artifacts from the sensor network ontology SSN are used together with ontology constructs.

The third level is the level of inference based on semantic rules. This layer uses semantically enriched data from the ETL layer that analyzed with the help of parsing rules defined by the corresponding drivers. The main purpose of the reasoning layer is to mark the domain boundaries and draw basic conclusions from the RDF data by use of the built- in reasoning mechanism. Two types of rules are used for semantization of data from sensors. The first one is the rules of logical inference characteristic for RDF, RDFS and OWL (these oriented on particular language rules are automatically processed by inference engine). The second type are the rules specific to the domain or user.

For example, in a smart home environment, we can maintain a temperature of between 25 and 45 degrees Celsius. For this purpose, you can enter a domain rule "If the temperature is above 45 degrees Celsius, then activate the air conditioner or, if it is below 25, activate the heater." Domain-specific rules are just important for system as semantic ones. The fourth level is the level of learning. This level basically acquires features from data by machine learning techniques. This level consists of two sub-steps — preprocessing and learning. Various deep learning algorithms can be used for this purposes.

The last level is the action layer. The results of learning are used for selection of appropriate actions. For example, if the learning algorithm produces three different results using data of meteorological indications to determine the probability of rain, such as “low probability”, “average probability”, and “high probability” then user decides what actions are caused by each result - if rain has high probability then take an umbrella.

CONCLUSION

Implementing the new IoT infrastructure is a challenge. There are many options for this architecture and its components, but choosing the right technology and method is a difficult task. Now we can choose many open source components to create such structure. New features of such platform have two directions: semantics and analysis of Big Data.

In this article we reviewed and discussed the requirements for the Big Data processing platform architecture coming from IoT using new approaches to using Big Data semantics and analysis. The platform will combine the semantic infrastructure and Big Data and machine learning capabilities that will be implemented based on semantic data.

This platform is designed to provide effective support for all types of sensors in order to preserve data, substantiate the semantic rules for inferring these data and then use machine learning methods to obtain the best results from Big Data processing.

We plan to implement the structure with the above tools and methods. We will also use real-life examples of use in such areas as smart grids, e-health’s, smart home, etc.

AKNOWLEDGMENTS

"The work was prepared in accordance with the thematic plan of scientific research of the Tavria State Agrotechnological University named after D.Motorny (project of applied research at the expense of the State Budget "Theoretical foundation and development of the information system of semantic identification, documentation and processing of the results of non-formal and informal learning").

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Received 10.01.2019

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Отримано: 10.01.2019

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ВИКОРИСТАННЯ СЕМАНТИЧНОГО МОДЕЛЮВАННЯ
ДЛЯ ОБРОБ ОБРОБЛЕННЯ BIG DATA В ДОМЕНІ ІНТЕРНЕТУ РЕЧЕЙ

Вступ. Важливим кроком нової технічної революції є розвиток Інтернету речей (IoT), обладнаного різними електронними давачами та контролерами, які дистанційно працюють з цими речами. У статті розглянуто особливості Big Data, створених за технологією Інтернету речей, а також презентовано методологію оброблення цих великих даних з використанням семантичного моделювання (онтології) на всіх етапах життєвого циклу великих даних. Семантичне моделювання дає змогу усунути такі суперечності в цих технологіях, як неоднорідність пристроїв і речей, що зумовлює неоднорідність типів даних, які їх виробляють. Машинне навчання використовують як інструмент для аналізу великих даних: він забезпечує логічне виведення правил, які можуть бути застосовані до оброблення інформації, що генерується системою Smart Home.

Метою статті є використання глибокого машинного навчання, основаного на згорткових нейронних мережах, оскільки ця модель машинного навчання відповідає обробленню неструктурованого та складного домену IoT.

Результати. Запропонований підхід підвищує ефективність оброблення великих даних IoT і відрізняється від традиційних систем оброблення за допомоги бази даних NoSQL, розподілених архітектур і семантичного моделювання. Запропоновано використовувати глибоке машинне навчання, що базується на нейронних мережах, пристосованих для неструктурованих даних IoT.Запропоновану концептуальну архітектуру системи оброблення великих даних для IoT описано на прикладі бази даних NoSQL для Smart Home.

Висновки. Запропонована архітектура системи оброблення великих даних для IoT складається з п'яти незалежних рівнів. На кожному з цих рівнів можна використовувати комбінований підхід семантичного моделювання та методів інтелектуального аналізу даних. Зазначену платформу можна поєднувати з великою кількістю відкритих компонентів.

Ключові слова: *Індустрія 4.0, Великі дані, Інтернет речей, онтологія, семантичний Web, неформальне та інформальне навчання.*

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ИСПОЛЬЗОВАНИЕ СЕМАНТИЧЕСКОГО МОДЕЛИРОВАНИЯ ДЛЯ ОБРАБОТКИ BIG DATA В ДОМЕНЕ ИНТЕРНЕТА ВЕЩЕЙ

Рассмотрена специфика Big Data, которые генерирует технология Интернет вещей, а также представлена методология их обработки семантического моделирования (онтологий) на всех этапах жизненного цикла больших данных. Семантическое моделирование позволяет устранить такие противоречия в технологиях, как гетерогенность устройств и данных. Предлагается использование машинное обучение для анализа Big Data, создаваемых информационной системой умного дома. Предложено использовать глубокое машинное обучение, базирующееся на сверточных нейронных сетях, приспособленных для неструктурированных данных IoT. Представлены новые подходы для обработки больших данных, которые повышают эффективность обработки Big Data в IoT. Представлена концептуальная архитектура системы обработки больших данных для Интернета вещей на примере сгенерированной базы данных NoSQL для умного дома. Данная архитектура состоит из пяти независимых уровней, каждый из которых может использовать семантическое моделирование.

Ключевые слова*: Индустрия 4.0, Большие данные, Интернет вещей, онтология, семантический Web, неформальное и информальное обучение.*

DOI: https:// 10.15407/kvt196.02.043

UDC 550:531; 681.51

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TOPOLOGICAL ANALYSIS OF ANGULAR MOMENTUM RANGE VALUES OF THE GYRO MOMENT CLUSTERS BASED ON COLLINEAR GYRODINES PAIRS

Introduction. *To ensure the high dynamic characteristics of Earth remote sensing satellites in their orientation systems, the gyro moment clusters (GMCs) based on excessive number (more than three) two-gimbals control moment gyrodines (GDs) can be used as actuators. The attitude control by GD actuators task is the most difficult among the tasks of spacecraft (SC) reorientation control. The central issue in solving this task is the synthesis of the control laws for precession angles of individual GDs when there are excessive. Success in solving the control problem is substantially determined by the choice of the GMC structure, it means the number of GDs used and their mutual positions of the precession axes. From this choice depends on the possibility of forming by GMC the necessary control momentum, the existence and number of special GMC states, the complexity of the control laws for the precession angles of the individual GDs included in the GMC. This is because in order to maintain the desired SC orientation for a long time and to perform its turns with the required angular rate, the GMC must have a sufficient margin of angular momentum. The allowable values of the total angular momentum created by the GDs form a certain area that is bounded by a closed surface of complex shape in a coordinate system rigidly attached to main SC body. Inside this area there are particular surfaces on which the control of the GDs is complicated or unfeasible. These surfaces are called singular. In this regard, for SC attitude control in addition to control the precession rate of individual GDs it is also necessary to control the mutual orientation of the angular momenta of the GDs in GMC. That is why one of the most important problems of the control laws synthesis with the use of GMC is the identifying singular surfaces (topological analysis) in the area allowable angular momentum of the GMC.*

The purpose *of the article is to develop a technique for detecting singular states in GMC based on three collinear pairs.*

Results. *The analysis was carried out and the singular states of the GMC with three collinear pairs were revealed.*

Conclusion. *An original technique of a topological analysis of GMC based on collinear GD's pairs is proposed. This technique may be useful to developers of SC attitude control systems.*

Keywords: *spacecraft, gyrodine, singular vector, singular surface.*

INTRODUCTION

The task of a SC attitude control is the control by angular motion around CS mass center. Nowadays this task is very actual due to the ever-increasing requirements for the dynamic characteristics of CS angular maneuvers. The turns must run from any current position to any given position. Wherein the attitude accuracy after turning should be angular minutes, and the angular rates can attain the values 2–3 degrees per second. For example, the French SC Spot 7 for shooting the Earth's surface with high-resolution launched on June 30, 2014, provides the following dynamic characteristics of spatial maneuvers:

- angular orientation accuracy — 1,7 arcmin;
- the maximum angular rate — 2,1 deg/s.

The assurance of such high dynamic characteristics is complicated by the fact that the mass increase trend is observed for high resolution Earth remote sensing satellites. If the mass of the earlier satellites Ikonos, OrbView-3 was 720 and 304 kg, respectively, then the mass of the subsequent satellites QuickBird-2, WorldView-1, Geoeye-1, WorldView-2 exceeds 2000 kg. It is known that for SC with a considerable mass the most effective actuators of attitude control systems are the GMCs based on excessive number (more than three) two-gimbals control moment GDs [1, 2]. The main advantage of GMC is that they have the best "created control moment /own mass" ratio among other actuator types and at the same time allow for complex rotational movements of the SC necessary for solving many practically important attitude control tasks. The tasks of controlling angular motion with the help of GMC are one of the most difficult tasks among the SC attitude control tasks. The general approaches to the solution of these tasks and some fundamental results were first presented in the domestic publications by papers of Ye. N. Tokar in the 1970s – 1980s. A significant contribution to the development of this subject matter was also made by the results presented in [3, 4, 5, 6]. The modern approaches to the development SC attitude control algorithms using GDs are considerd in [7, 8].

In order to maintain the SC given orientation for a long time and to turn with the required angular rate the GMC must have a sufficient angular momentum store. Possible summary angular momentum generated by the GDs form a certain area S_H in SC body fixed frame. This area is bounded by a closed surface of complex shape. Inside area S_H there are particular surfaces on which the control of the GDs is complicated or unfeasible. These surfaces are called singular. There are two types of singular surfaces: passable and impassable. Passable are called surfaces that can be passed by changing the mutual configuration of GDs angular momenta without changing the summary angular momentum of GMC. If this is not possible, then the surface is called impassable. In the class of GDs systems, the most rational are the GMC on the base of collinear pairs. The aggregating of GDs into so-called collinear groups, in which the precession axes are arranged in parallel, gives one very important advantage: if there are six or more GDs, all the singular surfaces of such schemes are strictly passable [9]. Quite a lot of work has been devoted to the problem of analyzing singular surfaces. As an example, one can cite the works [10, 11], in which singular passable and impassable surfaces were classified based on analytical criteria for GMC arbitrary schemes, and a technique for the type surface determining was proposed. The works [12–16] deserve attention, where the attitude control problems using GMC are studied in detail. Despite the fact that a lot of work has been devoted to the problem of GMC topological analysis, interest to this problem continues unabated today.

The main goal of this paper is to develop an analytical technique for identifying singular surfaces for GMC based on collinear GD's pairs and to carry out a topological analysis of such GMC built on six GDs.

FORMULATION OF THE PROBLEM

The SC will be considered as a rigid body containing arbitrarily mounted collinear pairs of GDs. Let us introduce the right orthogonal coordinate system B rigidly attached to main SC body or Body Frame (BF) and the right orthogonal coordinate system G_i rigidly attached to mounting plains of the GDs in the i^{th} pair. Let us determine the position of the basis G_i relative to the basis B by the transition matrix C_{BG_i}. We assume that all the GDs have the same proper angular momenta $h_0 = \text{const}$.

For the GDs angular momenta vectors h_{2i-1} , h_{2i}, $i = 1, 2, \cdots, N$ in the i^{th} collinear pair, the following relationships are valid:

$$\begin{aligned} h_{2i-1_B} &= C_{BG_i} h_{2i-1_{G_i}}, \\ h_{2i_B} &= C_{BG_i} h_{2i_{G_i}}. \end{aligned} \qquad (1)$$

Hereinafter, the subscript in the vector designation indicates what basis it is projected.

Introduce the vector $\alpha = (\alpha_1, \ldots, \alpha_{2N})^{\mathrm{T}}$ and Jacobi gradient matrix

$$L(\alpha) = \begin{pmatrix} \dfrac{\partial h_{1B}}{\partial \alpha_1} & \cdot & \cdot & \cdot & \dfrac{\partial h_{2NB}}{\partial \alpha_{2N}} \end{pmatrix}. \qquad (2)$$

To ensure SC angular motion complete controllability it is necessary that the rank of the Jacobi gradient matrix $L(\alpha)$, which is determined by the dimension of its column space, is three. Consider the following problem: to find restrictions on the vector of the GDs precession angles α in the scalar equations form (equations of special surfaces)

$$f_k(\alpha) = 0, \; k = 1,2\ldots K \;,$$

where K is the number of singular surfaces in GMC at which the rank of the Jacobi gradient matrix $L(\alpha)$ is less than three

$$\operatorname{rang} L(\alpha) < 3 \tag{3}$$

The solution of the problem. If the condition (3) is satisfied, then the columns of the matrix $L(\alpha)$ lie in the same plane. In this case GMC cannot generate control torque components along unit vector λ_B of the normal to this plane. Such an unit vector $\lambda_B = (\lambda_{1B}, \lambda_{2B}, \lambda_{3B})^{\mathrm{T}}$ is called the GMC singular vector and is determined from the condition

$$\lambda_B^T L(\alpha) = 0 . \tag{4}$$

This task can be reformulated as follows: to find all the restrictions on the GDs precession angles vector, for which the homogeneous overdetermined system of equations (4) has nonzero solutions. Equation (4) taking into account expressions (1) and (2) can be represented as follows:

$$\begin{pmatrix} \frac{\partial}{\partial \alpha_1} h_{1_{G_1}}^{\mathrm{T}} C_{G_1 B} \\ \frac{\partial}{\partial \alpha_2} h_{2_{G_1}}^{\mathrm{T}} C_{G_1 B} \\ \vdots \\ \frac{\partial}{\partial \alpha_{2N-1}} h_{2N-1_{G_{N-1}}}^{\mathrm{T}} C_{G_{N-1} B} \\ \frac{\partial}{\partial \alpha_{2N}} h_{2N_{G_{2N}}}^{\mathrm{T}} C_{G_{2N} B} \end{pmatrix} \lambda_B = 0 . \tag{5}$$

Denote by $g_i = \frac{h_i}{h_0}$ the angular momenta of the GDs in relative units. Then equation (5) can be represented as:

$$\begin{pmatrix} \frac{\partial}{\partial \alpha_1} g_{1_{G_1}}^{\mathrm{T}} C_{G_1 B} \\ \frac{\partial}{\partial \alpha_2} g_{2_{G_1}}^{\mathrm{T}} C_{G_1 B} \\ \vdots \\ \frac{\partial}{\partial \alpha_{2N-1}} g_{2N-1_{G_{N-1}}}^{\mathrm{T}} C_{G_{N-1} B} \\ \frac{\partial}{\partial \alpha_{2N}} g_{2N_{G_{2N}}}^{\mathrm{T}} C_{G_{2N} B} \end{pmatrix} \lambda_B = 0 . \tag{6}$$

Suppose R_i is the coordinate system associated with i^{th} GD rotor. The axis x_R of this system coincides with the precession axis of the i^{th} GD, the axis y_R coincides with the rotor rotation axis of i^{th} GD and the z_R axis complements the system to a right-hand one. Further assume that the mutual orientation of the bases G_i and R_i corresponds to Fig. 1.

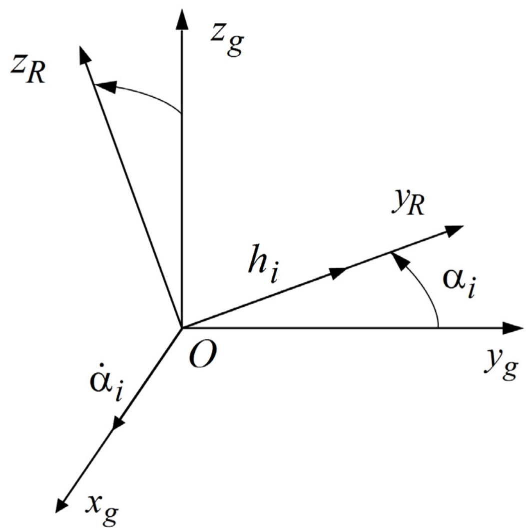

Fig. 1. Mutual orientation of the bases G_i and R_i

In this case, for the i^{th} collinear pair GDs angular momenta in the relative units, the following expressions are valid:

$$g_{G_j} = \begin{pmatrix} 0 \\ \cos\alpha_j \\ \sin\alpha_j \end{pmatrix} = \begin{pmatrix} 0 \\ y_j \\ z_j \end{pmatrix}, \; j = 1,2,\ldots,2N. \quad (7)$$

It follows from (7) that

$$\frac{\partial g_{G_j}}{\partial \alpha_j} = \begin{pmatrix} 0 \\ -\sin\alpha_j \\ \cos\alpha_j \end{pmatrix} = \begin{pmatrix} 0 \\ -z_j \\ y_j \end{pmatrix}. \quad (8)$$

By substituting (8) into (6), we obtain N subsystems

$$\begin{pmatrix} 0 & -z_{2i-1} & y_{2i-1} \\ 0 & -z_{2i} & y_{2i} \end{pmatrix} \lambda_{G_i} = 0, \; i = 1,2,\ldots,N, \quad (9)$$

where

$$\lambda_{G_i} = C_{G_i B} \lambda_B. \quad (10)$$

Consider the matrices

$$A_{2i-1,2i} = \begin{pmatrix} -z_{2i-1} & y_{2i-1} \\ -z_{2i} & y_{2i} \end{pmatrix}. \quad (11)$$

Denote by $D_{2i-1,2i}$ the determinant of the matrix $A_{2i-1,2i}$. Finding this determinant, we obtain

$$D_{2i-1,2i} = z_{2i}y_{2i-1} - z_{2i-1}y_{2i} = sin\,\alpha_{2i}\,cos\,\alpha_{2i-1} - cos\,\alpha_{2i}\,sin\,\alpha_{2i-1} = \\ = sin(\alpha_{2i} - \alpha_{2i-1}) \tag{12}$$

The solution of the systems (9) depends on the values of the determinants and is determined by the expression:

$$\lambda_B = C_{BG_i}\lambda_{G_i} = \begin{cases} \begin{pmatrix} \pm 1 \\ 0 \\ 0 \end{pmatrix}, & D_{2i-1,2i} \neq 0; \\ \begin{pmatrix} \sin\varepsilon_i \\ y_{2i}\cos\varepsilon_i \\ z_{2i}\cos\varepsilon_i \end{pmatrix} = \begin{pmatrix} \sin\varepsilon_i \\ \pm y_{2i-1}\cos\varepsilon_i \\ \pm z_{2i-1}\cos\varepsilon_i \end{pmatrix}, & D_{2i-1,2i} = 0; \end{cases}, \tag{13}$$

where ε_i is an arbitrary angle. The geometric interpretation of the solution (13) is as follows. According to equation (9), the vector λ_{G_i} is a singular vector of the i^{th} collinear pair. If the angular momenta of the included in the collinear pair GDs do not lie on one straight line, then the singular vector λ_{G_i} is perpendicular to the plane passing through the vectors $g_{G_{2i-1}}$, $g_{G_{2i}}$ and parallel to the GDs of precession axes, which, according to Fig. 1, is the axis x_i. If the angular momenta of the included into collinear pair GDs lie on one straight line, then they form a straight line to which an infinite number of perpendiculars can be drawn, which position in the basis G_i is determined by the angle ε_i. Since, if the condition $D_{2i-1,2i} = 0$ is satisfied, the angular momenta in the i^{th} collinear pair are related by the relationship $g_{G_{2i-1}} = \pm g_{G_{2i}}$, hereafter only vectors $g_{G_{2i}}$ are considered. Then, taking into account expressions (7) and (10), for a singular vector λ_B it is true the relationship

$$\lambda_B = C_{BG_i}\lambda_{G_i} = \begin{cases} \pm c_1^{BG_i}, & D_{2i-1,2i} \neq 0; \\ c_1^{BG_i}\sin\varepsilon_i + c_2^{BG_i} y_{2i}\cos\varepsilon_i + c_3^{BG_i} z_{2i}\cos\varepsilon_i, & D_{2i-1,2i} = 0; \end{cases}, \tag{14}$$

where $c_k^{BG_i}, k = 1,2,3$ are the columns of matrix C_{BG_i}. N relationships (14) define the same vector λ_B, therefore, if λ_B is not a zero solution to system (4), then for any $i \neq j$, $i, j = 1,2,\ldots,N$, the equalities should be satisfied

$$C_{BG_i}\lambda_{G_i} = C_{BG_j}\lambda_{G_j}. \tag{15}$$

Thus, if there are the GDs precession angles vector α and angles ε_i for which all $N(N-1)/2$ equalities (15) hold, then there exist nonzero solutions of system (4) and there is a singular state. If there are no such angles, then $\lambda_B = 0$ and there is no singular state.

TOPOLOGICAL ANALYSIS OF THE 3-SPE SCHEME

As an example of the application of the proposed technique, consider the GMC containing three collinear pairs. In the original work of J.W.Crenshaw [17], the excessive multiple scheme based on three collinear GDs pairs was named as 3-Scissored Pair Ensemble (3-SPE).

We will assume that the precession axes of the GDs of the first group coincide with the axis z_B, the precession axes of the second group coincide with the axis y_B and the precession axes of the third group coincide with the axis x_B (Fig. 2). For such a GMC scheme the transition matrixes C_{BG_i}, $i=1,2,3$ have the forms:

$$C_{BG_1}=\begin{pmatrix}0&0&-1\\0&1&0\\1&0&0\end{pmatrix},\quad C_{BG_2}=\begin{pmatrix}0&-1&0\\1&0&0\\0&0&1\end{pmatrix},\quad C_{BG_3}=\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}.$$

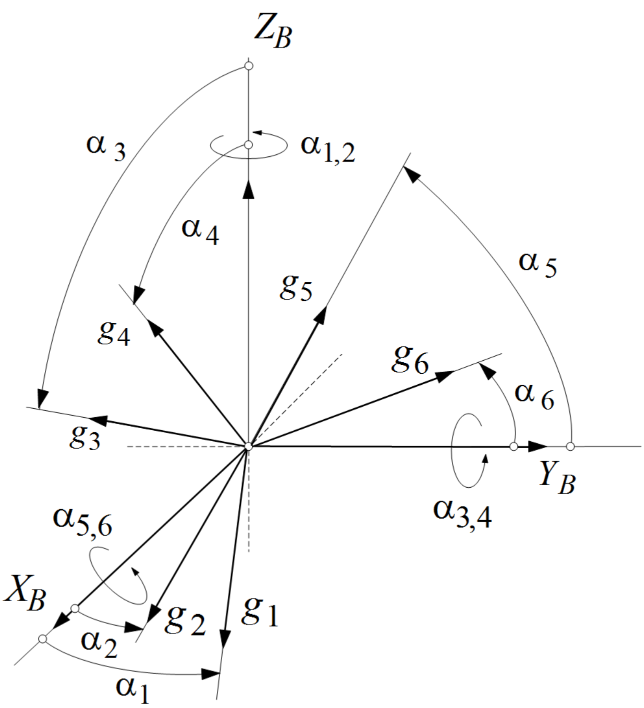

Fig. 2. Precession axes arrangement of GDs in 3-SPE scheme

In this case, for the projections of the relative angular momenta along the axes of B basis, the following expressions are valid:

$$g_{1B} = \begin{pmatrix} -\sin\alpha_1 \\ \cos\alpha_1 \\ 0 \end{pmatrix} = \begin{pmatrix} -z_1 \\ y_1 \\ 0 \end{pmatrix} = \begin{pmatrix} x_{1B} \\ y_{1B} \\ 0 \end{pmatrix}, \quad g_{2B} = \begin{pmatrix} -\sin\alpha_2 \\ \cos\alpha_2 \\ 0 \end{pmatrix} = \begin{pmatrix} -z_2 \\ y_2 \\ 0 \end{pmatrix} = \begin{pmatrix} x_{2B} \\ y_{2B} \\ 0 \end{pmatrix},$$

$$g_{3B} = \begin{pmatrix} -\cos\alpha_3 \\ 0 \\ \sin\alpha_3 \end{pmatrix} = \begin{pmatrix} -y_3 \\ 0 \\ z_3 \end{pmatrix} = \begin{pmatrix} x_{3B} \\ 0 \\ z_{3B} \end{pmatrix}, \quad g_{4B} = \begin{pmatrix} -\cos\alpha_4 \\ 0 \\ \sin\alpha_4 \end{pmatrix} = \begin{pmatrix} -y_4 \\ 0 \\ z_4 \end{pmatrix} = \begin{pmatrix} x_{4B} \\ 0 \\ z_{4B} \end{pmatrix}, \qquad (16)$$

$$g_{5B} = \begin{pmatrix} 0 \\ \cos\alpha_5 \\ \sin\alpha_5 \end{pmatrix} = \begin{pmatrix} 0 \\ y_5 \\ z_5 \end{pmatrix} = \begin{pmatrix} 0 \\ y_{5B} \\ z_{5B} \end{pmatrix}, \quad g_{6B} = \begin{pmatrix} 0 \\ \cos\alpha_6 \\ \sin\alpha_6 \end{pmatrix} = \begin{pmatrix} 0 \\ y_6 \\ z_6 \end{pmatrix} = \begin{pmatrix} 0 \\ y_{6B} \\ z_{6B} \end{pmatrix}.$$

To determine the conditions under which the homogeneous system (4) has a nonzero solution, we analyze the dependence of the solution of this system on the values of the determinants $D_{1,2}$, $D_{3,4}$, $D_{5,6}$. According to (12) these determinants are defined by the formulae

$$D_{1,2} = \sin(\alpha_2 - \alpha_1), \qquad D_{3,4} = \sin(\alpha_4 - \alpha_3), \qquad D_{5,6} = \sin(\alpha_6 - \alpha_5).$$

Depending on the numerical values of the determinants $D_{1,2}$, $D_{3,4}$, $D_{5,6}$, the following different options are possible:

1) $D_{1,2} \neq 0$, $D_{3,4} \neq 0$, $D_{5,6} \neq 0$.

In this case, according to (15), the condition for the existence of a nonzero solution of system (4) is $\begin{pmatrix} 0 \\ 0 \\ \pm 1 \end{pmatrix} = \begin{pmatrix} 0 \\ \pm 1 \\ 0 \end{pmatrix} = \begin{pmatrix} \pm 1 \\ 0 \\ 0 \end{pmatrix}$.

But obviously equalities are impossible. Therefore, $\lambda_B = 0$ and no singular state.

2) $D_{1,2} = 0$, $D_{3,4} \neq 0$, $D_{5,6} \neq 0$.

From relationships (14) and (15) it follows that for the existence of a nonzero solution the equalities

$$\begin{pmatrix} -z_2\cos\varepsilon_1 \\ y_2\cos\varepsilon_1 \\ \sin\varepsilon_1 \end{pmatrix} = \begin{pmatrix} 0 \\ \pm 1 \\ 0 \end{pmatrix} = \begin{pmatrix} \pm 1 \\ 0 \\ 0 \end{pmatrix}$$

must be satisfied, which is impossible and there is no singular state.

3) $D_{1,2} \neq 0$, $D_{3,4} = 0$, $D_{5,6} \neq 0$.

In this case, for the existence of a nonzero solution the equalities

$$\begin{pmatrix} 0 \\ 0 \\ \pm 1 \end{pmatrix} = \begin{pmatrix} -y_4 \cos\varepsilon_2 \\ \sin\varepsilon_2 \\ z_4 \cos\varepsilon_2 \end{pmatrix} = \begin{pmatrix} \pm 1 \\ 0 \\ 0 \end{pmatrix}.$$

must be satisfied, which is impossible and there is no singular state.

4) $D_{1,2} \neq 0$, $D_{3,4} \neq 0$, $D_{5,6} = 0$.

In this case, for the existence of a nonzero solution the equalities

$$\begin{pmatrix} 0 \\ 0 \\ \pm 1 \end{pmatrix} = \begin{pmatrix} 0 \\ \pm 1 \\ 0 \end{pmatrix} = \begin{pmatrix} \sin\varepsilon_3 \\ y_6 \cos\varepsilon_3 \\ z_6 \cos\varepsilon_3 \end{pmatrix}$$

must be satisfied. These equalities are not satisfied, $\lambda_B = 0$, therefore there is no single state.

5) $D_{1,2} \neq 0$, $D_{3,4} = 0$, $D_{5,6} = 0$.

A necessary condition for the existence of a nonzero solution for this case is the validity following equalities:

$$\begin{pmatrix} 0 \\ 0 \\ \pm 1 \end{pmatrix} = \begin{pmatrix} -y_4 \cos\varepsilon_2 \\ \sin\varepsilon_2 \\ z_4 \cos\varepsilon_2 \end{pmatrix} = \begin{pmatrix} \sin\varepsilon_3 \\ y_6 \cos\varepsilon_3 \\ z_6 \cos\varepsilon_3 \end{pmatrix}.$$

These equalities are possible when $\varepsilon_2 = 0, \pi$; $\varepsilon_3 = 0, \pi$; $y_4 = 0$, $y_6 = 0$, $z_4 = \pm 1$, $z_6 = \pm 1$. Therefore $\lambda_B \neq 0$ and there is a singular state. Let us find the equation of the surface in the basis B on which this state arises. From the equalities of the determinants $D_{3,4}$ and $D_{5,6}$ to zero and expressions (16) it follows that $y_3 = \pm y_4 = -x_{3B} = \mp x_{4B} = 0$, $y_5 = \pm y_6 = y_{5B} = \pm y_{6B} = 0$. Then

$$x_{3B}^2 + x_{4B}^2 + y_{5B}^2 + y_{6B}^2 = 0. \tag{17}$$

The constraint (17) defines a surface in the basis B in the form of a unit circle lying in a plane $OX_B Y_B$, to which the singular vector $\lambda_B = (0, 0, \pm 1)^{\mathrm{T}}$ corresponds.

6) $D_{1,2} = 0$, $D_{3,4} \neq 0$, $D_{5,6} = 0$.

In this case, the condition for the zero solution existence is

$$\begin{pmatrix} -z_2 \cos\varepsilon_1 \\ y_2 \cos\varepsilon_1 \\ \sin\varepsilon_1 \end{pmatrix} = \begin{pmatrix} 0 \\ \pm 1 \\ 0 \end{pmatrix} = \begin{pmatrix} \sin\varepsilon_3 \\ y_6 \cos\varepsilon_3 \\ z_6 \cos\varepsilon_3 \end{pmatrix}.$$

It is satisfied if $\varepsilon_1 = 0, \pi$; $\varepsilon_3 = 0, \pi$; $y_2 = \pm 1$, $y_6 = \pm 1$, $z_2 = 0$, $z_6 = 0$. From the conditions $D_{1,2} = 0$ and $D_{5,6} = 0$, the equalities follow: $y_1 = \pm y_2 = -x_{1B} = \mp x_{2B} = 0$, $z_5 = \pm z_6 = z_{5B} = \pm z_{6B} = 0$. A nonzero solution will occur if there is a constraint

$$x_{1B}^2 + x_{2B}^2 + z_{5B}^2 + z_{6B}^2 = 0 . \tag{18}$$

To the constraint (18) corresponds a circle lying in a plane $OX_B Z_B$ of the basis B and a singular vector $\lambda_B = (0, \pm 1, 0)^T$.

7) $D_{1,2} = 0$, $D_{3,4} = 0$, $D_{5,6} \neq 0$.

Making the transformations similar to those performed in cases 6) and 7), we obtain the following equation for the singular surface:

$$y_{1B}^2 + y_{2B}^2 + z_{3B}^2 + z_{4B}^2 = 0 . \tag{19}$$

The constraint (19) defines a circle lying in a plane $OY_B Z_B$ of the basis B and a singular vector $\lambda_B = (\pm 1, 0, 0)^T$.

The spatial positions of singular planes for cases 5) – 7) are shown in Fig. 3, [14].

8) $D_{12} = 0$, $D_{13} = 0$, $D_{23} = 0$.

The condition for the existence of a nonzero solution in this case is

$$\lambda_B = \begin{pmatrix} -z_2 \cos\varepsilon_1 \\ y_2 \cos\varepsilon_1 \\ \sin\varepsilon_1 \end{pmatrix} = \begin{pmatrix} -y_4 \cos\varepsilon_2 \\ \sin\varepsilon_2 \\ z_4 \cos\varepsilon_2 \end{pmatrix} = \begin{pmatrix} \sin\varepsilon_3 \\ y_6 \cos\varepsilon_3 \\ z_6 \cos\varepsilon_3 \end{pmatrix} . \tag{20}$$

Considering that the sines of angles ε_k, $k = 1,2,3$ are the coordinates of the vector λ_B:

$$\lambda_{1_B} = \sin\varepsilon_3 , \quad \lambda_{2_B} = \sin\varepsilon_2 , \quad \lambda_{3_B} = \sin\varepsilon_1 \tag{21}$$

and λ_B is the normalized vector, then from the equality of its norm to one follows the condition for the existence of a nonzero solution

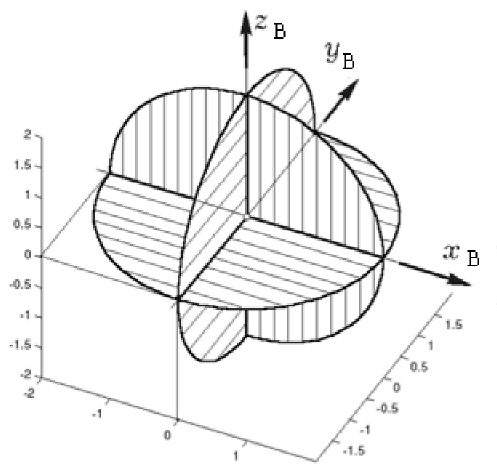

Fig. 3. The set of special GMC surfaces when two pairs GDs are in singular state

$$\sin^2\varepsilon_1 + \sin^2\varepsilon_2 + \sin^2\varepsilon_3 = 1. \tag{22}$$

To satisfy equalities (20), it is necessary that the following relationships hold for the coordinates of vectors g_{2i}:

$$y_2 = \frac{\sin\varepsilon_2}{\cos\varepsilon_1}, \quad z_2 = -\frac{\sin\varepsilon_3}{\cos\varepsilon_1};$$
$$y_4 = -\frac{\sin\varepsilon_3}{\cos\varepsilon_2}, \quad z_4 = \frac{\sin\varepsilon_1}{\cos\varepsilon_2}; \tag{23}$$
$$y_6 = -\frac{\sin\varepsilon_2}{\cos\varepsilon_3}, \quad z_6 = \frac{\sin\varepsilon_1}{\cos\varepsilon_3}.$$

Consider a few special cases:

a) $\varepsilon_1 = 0,\ \varepsilon_2 \neq 0,\ \varepsilon_3 \neq 0;$

b) $\varepsilon_1 \neq 0,\ \varepsilon_2 = 0,\ \varepsilon_3 \neq 0;$

c) $\varepsilon_1 \neq 0,\ \varepsilon_2 \neq 0,\ \varepsilon_3 = 0;$

d) $\varepsilon_1 = 0,\ \varepsilon_2 = 0,\ \varepsilon_3 = \pm\frac{\pi}{2}.$

In the case a) from conditions (22–23) we have the following relationships:

$$\sin^2\varepsilon_1 + \sin^2\varepsilon_2 + \sin^2\varepsilon_3 = \sin^2\varepsilon_2 + \sin^2\varepsilon_3 = 1,$$

$$\sin^2\varepsilon_2 = 1 - \sin^2\varepsilon_3 = \cos^2\varepsilon_3,\ \sin\varepsilon_2 = \pm\cos\varepsilon_3,\ \cos\varepsilon_2 = \pm\sin\varepsilon_3,$$

$$y_2 = \frac{\sin\varepsilon_2}{\cos\varepsilon_1} = \pm\cos\varepsilon_3, \quad z_2 = -\frac{\sin\varepsilon_3}{\cos\varepsilon_1} = -\sin\varepsilon_3,$$

$$y_4 = -\frac{\sin\varepsilon_3}{\cos\varepsilon_2} = \pm 1, \quad z_4 = \frac{\sin\varepsilon_1}{\cos\varepsilon_2} = 0,$$

$$y_6 = -\frac{\sin\varepsilon_2}{\cos\varepsilon_3} = \pm 1, \quad z_6 = \frac{\sin\varepsilon_1}{\cos\varepsilon_3} = 0,$$

$$y_1 = \pm y_2, \quad z_1 = \pm z_2,$$

$$y_3 = \pm y_4, \quad z_3 = \pm z_4,$$

$$y_5 = \pm y_6, \quad z_5 = \pm z_6.$$

By substituting these relationships into (16) we find

$$g_{1B} = \begin{pmatrix} x_{1B} \\ y_{1B} \\ 0 \end{pmatrix} = \begin{pmatrix} \pm z_2 \\ \pm y_2 \\ 0 \end{pmatrix} = \begin{pmatrix} \mp\sin\varepsilon_3 \\ \pm\cos\varepsilon_3 \\ 0 \end{pmatrix}, \quad g_{2B} = \begin{pmatrix} x_{2B} \\ y_{2B} \\ 0 \end{pmatrix} = \begin{pmatrix} -z_2 \\ y_2 \\ 0 \end{pmatrix} = \begin{pmatrix} \sin\varepsilon_3 \\ \pm\cos\varepsilon_3 \\ 0 \end{pmatrix},$$

$$g_{3B} = \begin{pmatrix} x_{3B} \\ 0 \\ z_{3B} \end{pmatrix} = \begin{pmatrix} -y_3 \\ 0 \\ z_3 \end{pmatrix} = \begin{pmatrix} \pm 1 \\ 0 \\ 0 \end{pmatrix}, \; g_{4B} = \begin{pmatrix} x_{4B} \\ 0 \\ z_{4B} \end{pmatrix} = \begin{pmatrix} -y_4 \\ 0 \\ z_4 \end{pmatrix} = \begin{pmatrix} \pm 1 \\ 0 \\ 0 \end{pmatrix},$$

$$g_{5B} = \begin{pmatrix} 0 \\ y_{5B} \\ z_{5B} \end{pmatrix} = \begin{pmatrix} 0 \\ y_5 \\ z_5 \end{pmatrix} = \begin{pmatrix} 0 \\ \pm 1 \\ 0 \end{pmatrix}, g_{6B} = \begin{pmatrix} 0 \\ y_{6B} \\ z_{6B} \end{pmatrix} = \begin{pmatrix} 0 \\ y_6 \\ z_6 \end{pmatrix} = \begin{pmatrix} 0 \\ \pm 1 \\ 0 \end{pmatrix}.$$

In this case, the singular surface is a unit circle lying in a plane OX_BY_B.

Having done the similar calculations for cases b) and c), we obtain that in case b) the singular surface is a unit circle in the plane OX_BZ_B, and in case c) it is a unit circle lying in the plane OY_BZ_B.

For the case d) a nonzero solution will exist if the following equalities hold

$$\lambda_B = \begin{pmatrix} -z_2 \\ y_2 \\ 0 \end{pmatrix} = \begin{pmatrix} -y_4 \\ 0 \\ z_4 \end{pmatrix} = \begin{pmatrix} \pm 1 \\ 0 \\ 0 \end{pmatrix},$$

from which it follows that $y_2 = y_{2B} = 0$, $z_2 = -x_{2B} = \pm 1$, $y_4 = -x_{4B} = \pm 1$, $z_4 = z_{4B} = 0$ and the singular surface is a straight line coinciding with the axis OX_B. Similarly, it can be shown that when $\varepsilon_1 = \pm\frac{\pi}{2}$, $\varepsilon_2 = 0$, $\varepsilon_3 = 0$ the singular surface is transformed into a straight line that coincides with the axis OZ_B, and as $\varepsilon_1 = 0$, $\varepsilon_2 = \pm\frac{\pi}{2}$, $\varepsilon_3 = 0$ the singular surface is transformed into a straight line that coincides with the axis OY_B.

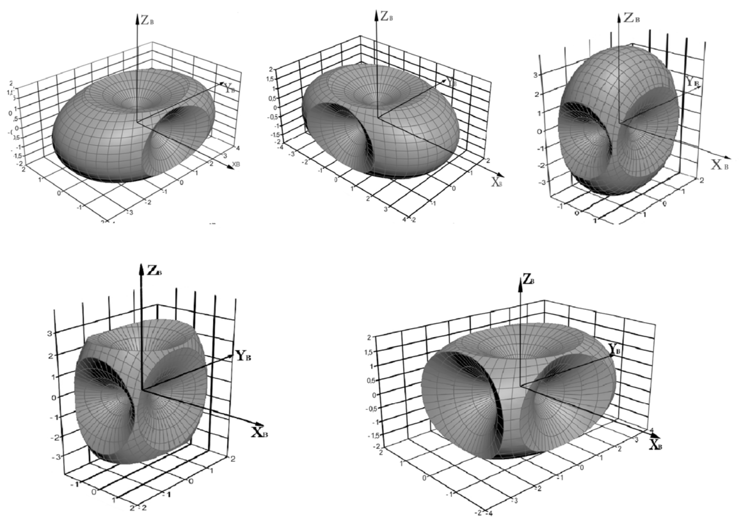

Fig. 4. The set of special GMC surfaces when three pairs GDs are in singular state

Thus, when one of the angles ε_k, $k = 1, 2, 3$ tends to zero or to π, the singular surface is transformed into a circle lying in one of the coordinate planes, and when one of the angles ε_k tends to $\frac{\pi}{2}$ or to $\frac{3\pi}{2}$ the singular surface is transformed into a straight line coinciding with one of the BF axes. In the general case, when $D_{12} = 0$, $D_{13} = 0$, $D_{23} = 0$, the singular surface has a quite complex shape. The boundary of this shape has six cavity ("craters"), the axes of which coincide with the BF axes. The set of possible native singular states of the 3-SPE scheme is shown in Fig. 4.

CONCLUSION

An original technique of a topological analysis of GMC based on collinear GD's pairs is proposed. Using this technique, the analysis was carried out and the singular states of the GMC containing three collinear pairs were revealed. The proposed technique may be useful to developers of SC attitude control systems.

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Received 15.02.2019

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Отримано 15.02.2019

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ТОПОЛОГІЧНИЙ АНАЛІЗ ОБЛАСТІ ДОПУСТИМИХ ЗНАЧЕНЬ КІНЕТИЧНОГО МОМЕНТУ СИЛОВИХ ГІРОСКОПІЧНИХ КОМПЛЕКСІВ КРАТНИХ СХЕМ

Вступ. Для забезпечення високих динамічних характеристик супутників дистанційного зондування Землі в їхніх системах орієнтації в якості виконавчих органів можуть використовуватися силові гіроскопічні комплекси (СГК), які є надлишковою (більше 3) системою двоступеневих силових гіроскопів (гіродінов). Завдання гіросилового керування кутовим рухом є одними з найскладніших серед завдань керування переорієнтацією КА. Центральним питанням під час вирішення цих завдань є питання синтезу законів керування кутами прецесії окремих гіродінов за їх надлишковості. Успіх у розв'язанні завдання керування багато в чому визначається вибором структури СГК, під якою розуміється кількість використовуваних гіродінов і взаємне розташування їхніх осей прецесії. Від такого вибору залежить можливість формування СГК необхідного керуючого моменту, наявність і кількість особливих станів СГК, складність законів керування кутами прецесії окремих гіродінов входять в СГК. Це зумовлено тим, що для тривалого підтримання постійної орієнтації апарата і виконання ним розворотів з необхідною кутовою швидкістю СГК повинен мати достатній запас кінетичного моменту (КМ). Допустимі значення сумарного КМ, створюваного гіродінами, утворюють в системі координат, жорстко пов'язаної з КА, деяку область, яка обмежена замкнутою поверхнею складної форми. Усередині цієї області розташовуються особливі поверхні, на яких керування гіродінами ускладнено або взагалі неможливе. Ці поверхні прийнято називати сингулярними. У зв'язку з цим, у разі керуванні орієнтацією КА за допомоги СГК, крім керування швидкістю прецесії окремих гіродінов, необхідно керувати і взаємною орієнтацією кінетичних моментів гіродінов, що входять в СГК. Водночас одним з найважливіших завдань синтезу законів керування з використанням СГК є завдання виявлення сингулярних поверхонь (топологічного аналізу) області допустимого кінетичного моменту СГК.

Мета роботи — розроблення методики виявлення сингулярних поверхонь в СГК кратних схем.

Результат — проведено аналіз та виявлено сингулярні стани схеми СГК, що містить три Колінеарні пари.

Висновки. Запропоновано оригінальну методику проведення топологічного аналізу СГК кратних схеми. Методика може бути корисна розробникам систем орієнтації КА.

Ключові слова: *космічний апарат, гіродін, сингулярний вектор, сингулярна поверхня.*

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ТОПОЛОГИЧЕСКИЙ АНАЛИЗ ОБЛАСТИ ДОПУСТИМЫХ ЗНАЧЕНИЙ КИНЕТИЧЕСКОГО МОМЕНТА СИЛОВЫХ ГИРОСКОПИЧЕСКИХ КОМПЛЕКСОВ КРАТНЫХ СХЕМ

Введение. Для обеспечения высоких динамических характеристик спутников дистанционного зондирования Земли в их системах ориентации в качестве исполнительных органов могут использоваться силовые гироскопические комплексы (СГК), представляющие собой избыточную (более 3) систему двухстепенных силовых гироскопов (гиродинов). Задачи гиросилового управления угловым движением являются одними из наиболее сложных среди задач управления переориентацией КА. Центральным вопросом при решении этих задач является вопрос синтеза законов управления углами прецессии отдельных гиродинов при их избыточности. Успех в решении задачи управления во многом определяется выбором структуры СГК, под которой понимается количество используемых гиродинов и взаимное расположение их осей прецессии. От такого выбора зависит возможность формирования СГК требуемого управляющего момента, наличие и количество особых состояний СГК, сложность законов управления углами прецессии отдельных гиродинов, входящих в СГК. Обусловлено это тем, что для продолжительного поддержания заданной ориентации аппарата и выполнения им разворотов с требуемой угловой скоростью, СГК должен обладать достаточным запасом кинетического момента (КМ). Допустимые значения суммарного КМ, создаваемого гиродинами, образуют в системе координат, жестко связанной с КА, некоторую область, которая ограничена замкнутой поверхностью сложной формы. Внутри этой области располагаются особые поверхности, на которых управление гиродинами усложнено или вообще неосуществимо. Эти поверхности принято называть сингулярными. В связи с этим, при управлении ориентацией КА с помощью СГК, кроме управления скоростью прецессии отдельных гиродинов, необходимо управлять и взаимной ориентацией кинетических моментов гиродинов, входящих в СГК. При этом одной из важнейших задач синтеза законов управления с использованием СГК является задача выявления сингулярных поверхностей (топологического анализа) области допустимого кинетического момента СГК.

Цель работы — разработка методики выявления сингулярных поверхностей в СГК кратных схем.

Результат — проведен анализ и выявлены сингулярные состояния схемы СГК, содержащей три коллинеарные пары.

Выводы. Предложена оригинальная методика проведения топологического анализа СГК кратных схем. Методика может быть полезна разработчикам систем ориентации КА.

Ключевые слова*: космический аппарат, гиродин, сингулярный вектор, сингулярная поверхность.*

DOI: https:// 10.15407/kvt196.02.059

UDC 577.169; 616.1 – 616.7

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THE METHOD OF DETERMINING CONDUCTIBILITY FOR CORONARY VESSELS BY TERMOGRAPHY

Introduction. *The character of the distribution of temperature in the heart is determined by the process of heat exchange between the myocardium and coronary vessels, as well as the state of microhemodynamics of the coronary vessels of the heart. For quantitative estimation of changes in temperature distribution on the surface of the heart, the algorithm for calculating a quantitative criterion, that may be an objective marker for effective protection of the heart and brain, is proposed. The method of determining the conductibity of coronary vessels is implemented on the basis of the algorithm for determining the thermal contours, calculated from the gradients of the temperature field on the image of the heart in the infrared spectrum. The improvement of the previously developed method for determining the thermal contours on the basis of Canny's algorithm consists of the transition from qualitative to quantitative assessment of the rate of change in temperature on the surface of the myocardium.*

The purpose of this study *is to evaluate the conductibity of coronary vessels for the study of blood flow in the surface layer of the myocardium during warming up and cooling of the heart in conditions of cardiopulmonary bypass.*

Results. *The numerical value of the quantitative criterion obtained is calculated by determining the difference in temperature between the blood and the myocardium, calculated as the difference between the geometric areas under the temperature distribution curves in the temperature field equation for the constant and the current fluxing temperature. The contouring method for determining the conductibity of coronary vessels allows to select areas on the surface of the myocardium, in which the change in temperature significantly lags behind the average temperature on the surface during warming or cooling of the heart, which indirectly allows evaluating the state of small coronary vessels in the myocardium.*

Conclusions. *The method for determining the conductivity of coronary vessels for the study of blood flow in the surface layer of the myocardium is proposed, which allowed to allocation contours of sites on the surface of the myocardium with uneven distribution of temperature during warming up and cooling of the heart. Scientific novelty of the method consists of the allocation of thermal contours of sites in which the temperature change significantly lags behind the average temperature on the surface during warming up or cooling of the heart.*

Keywords: *mathematical modelling, the algorithm of detector Canny, heart temperature, temperature profiles, hypothermia, hyperthermia, cardiopulmonary bypass.*

INTRODUCTION

During controlled cooling and warming on thermography images, the uneven distribution of temperature in tissues is become visible. In inflammatory processes in the myocardium, areas of hyperthermia that correspond to the area of infiltration, that indicate a difference in temperature with adjacent tissues are determined. In chronic inflammation, the temperature difference is 0,7–1°C, with acute illness 1–1,5°C, and in the destructive process reaches 1,5–2°C [1, 2]. When the blood temperature changes in the circulatory circuit, the body temperature of the patient also changes. Moreover, the temperature difference between the blood in the contour and the patient's body should not differ by more than 15°C [3, 4].

The temperature field recorded by the thermographic system reflects the unique morphological and biophysical characteristics of the myocardium [19]. The main reason for violations of local temperature in the heart is the microcirculation in the tissues of the myocardium due to inflammatory processes. The regulation of temperature in the myocardium is mainly carried out by changing the lumen of the coronary vessels [20, 21]. When cooling the heart, there is a slowing of blood flow and narrowing of the surface vessels. In another situation, with warming the heart, blood flow is redistributed to the surface of the vessels, which facilitates the removal of heat into the external operating field. In this case there is a so-called transverse temperature gradient that is the difference in temperature between the surface and deep layers of tissue of the myocardium.

TASKS OF THE RESEARCH

Analytical studies of temperature distribution on the surface of the heart are based on the developed model of the system of myocardium- coronary vessels [5, 6], the model of heat exchange for the process of cooling the blood and heart, and the model of heat flux propagation in the myocardium in the process of hypothermia and hyperthermia [7, 8], for calculating which used the methods of theoretical and mathematical physics (solving the boundary value of thermal conductibility) with the involvement of experimental data on the distribution of thermal fields in areas of temperature anomalies on the surface of the heart and methods of the statistical analysis and processing of experimental data [22–24].

The development of the method of contouring temperature inhomogeneities for determining the conductivity of coronary vessels on the basis of the algorithm of detector Canny is a promising task for the implementation of information technology for non-invasive control of heart temperature during conduction of thermography studies in cardiology.

The introduction of the method for assessing the conductibility of coronary vessels in cardiac surgery will allow in the long run non-invasively control the blood temperature in blood vessels and determine the efficiency of the operation of distal septum vessels after coronary bypass surgery in conditions of controlled cooling and warming during cardiopulmonary bypass.

THE PURPOSE OF THERMAL CONDUCTIBILITY STUDY

The purpose of study is to evaluate the conductibility of coronary vessels for the study of blood flow in the surface layer of the myocardium during warming up and cooling of the heart in conditions of cardiopulmonary bypass.The development of the method for contouring temperature inhomogeneities is associated with obtaining information on the state of the blood supply to the myocardium by separating the geometric boundaries between the cooled and warmed areas of the heart by using the algorithm of Canny's detecting and Gaussian filters for the video frames of the thermograms.

METHODS AND MEASURES OF THE RESEARCH

The temperature between the myocardium and the blood in the circuit of artificial blood circulation, which is cooled and warmed up in the heat exchanger, is measured using the thermograph FLIR ThermaCAM E300 having a temperature sensitivity of 0,1°C and a measurement error of $\pm 1\%$ of the range of measurements. The technical capabilities of the thermograph allow to determine the minimum difference in temperature between the heart and blood in the circuit of cardiopulmonary bypass from 0,5°C to 10°C.

The contouring method for determining the conductibility of coronary vessels is realized on the basis of the contours algorithm of Canny detector that allows to distinguish the contours of the boundaries between different sections of the thermograms and divide them [9]. According to the algorithm, the selection of Canny detector is modified to study temperature gradients on the surface of the myocardium for analysis the stream of video data in the form of frames of thermograms that is recorded by the thermal imager and stored in the database of thermography images.

Clinical researches and researches on the basis of the method of mathematical modeling were conducted for estimation of efficiency of work of the algorithm of allocation of contours on the images of open heart.

RESEARCH OF TEMPERATURE GRADIENTS ON THE HEART SURFACE

For determine temperature gradients in conditions of cardiopulmonary bypass, it is necessary to control the temperature difference between coronary vessels and myocardium. The temperature difference at a distance from the vessel wall can be found from the equation for the amount of heat Q_m that is transmitted to the myocardium through the surface of the vessel over an area of time τ [10–13]:

$$Q_m = q \cdot S \cdot \tau = \frac{\lambda}{\delta}\left(T_c - T_m\right) \cdot S_c \cdot \tau, \qquad (1)$$

where q — the density of the heat flow through the surface of the vessel, W/m^2, S_c — the surface area of the vessel, m^2, δ — the distance from the vessel wall, m, T_c – blood temperature in the vessel, ^oC, T_m — the temperature of the tissue of myocardium, ^oC.

From the equation we find the temperature difference between the vessel and the myocardium:

$$\Delta T = T_c - T_m = \frac{\delta}{\lambda} q. \tag{2}$$

The ratio δ/λ characterizes the thermal conductibility of the myocardium, and the value determines the full temperature pressure from the vessels to the myocardium. For the current temperature of the blood ΔT_i, that cools or warms up to a temperature T_i, it is possible to write the expression:

$$\Delta T_i = T_i - T_m = \Delta T - \frac{\Delta T}{\delta} l, \tag{3}$$

where l — the distance from the vessel wall, through which the heat travels from the vessel to the depth of the myocardium, m.

The ratio $\Delta T/\Delta T_i$ is a dimensionless excess temperature that characterizes the temperature distribution from the vessel wall to the blood in the tissue of myocardium:

$$\theta = \frac{\Delta T}{\Delta T_i} = 1 - \frac{l}{\delta}. \tag{4}$$

This expression is a temperature field equation in the assumption that the coefficient of thermal conductibility for the myocardium is a constant value. For determine the conditions for blood supply to the heart in small coronary vessels, it is advisable to estimate the change in the value S_i/S_m, which is the ratio of the warmed area of the myocardium to the total surface area S_m at the same time intervals Δt during hyperthermia:

$$\theta = \frac{\Delta T}{\Delta T_i} = 1 - \frac{S_i}{S_m}, \tag{5}$$

where S_m — total area of the surface of the myocardium, m^2, S_i — surface area of the myocardium, through which the process of heat transfer occurs, m^2.

With the thickness of the atrial walls 2–3 mm and the thickness of the walls of the left ventricle of the heart11–14 mm, which has the greatest thickness of the myocardium, the dependence of the coefficient of thermal conductibility on temperature $\lambda(T)$ has a virtually linear character [25, 26]:

$$\lambda(T) = \lambda_m(1 + bT), \tag{6}$$

where λ_m — the value of the coefficient of thermal conductibility of the myocardium for the temperature $T = 0{,}0^oC$ at the cooling of the heart, $W/(m \cdot K)$, b — the empirical coefficient of the temperature curve.

For the arithmetic mean temperature at the area of myocardium — coronary vessels, the expression for the coefficient of thermal conductivity has the form:

$$\lambda(T) = \lambda_m \left[1 + \frac{b}{2}(T_c - T_m)\right] = \lambda_m \left[1 + \frac{b}{2}\Delta T\right]. \tag{7}$$

In this case, the expression for the density of the heat flux q on the surface of the myocardium is as follows:

$$q = \frac{\lambda(T)}{\delta}(T_c - T_m) = \frac{\lambda_m}{\delta}(T_c - T_m)\left[1 + \frac{b}{2}(T_c - T_m)\right]. \tag{8}$$

From this equation we find that the temperature difference ΔT in the layer of the myocardium is a nonlinear function, even for linear dependence of the coefficient of thermal conductivity of the myocardium $\lambda(T)$:

$$\Delta T = \sqrt{\frac{1}{b^2} - \frac{2\delta}{b}\frac{q}{\lambda_m}} - \frac{1}{b}. \tag{9}$$

If the heat flow from the vessels is transmitted to the myocardium due to heat transfer from the blood in the vessels, the specific heat flux is determined from the Newton-Richman equation [10]:

$$q = \frac{\lambda_C(T)}{\delta}(T_c - T_m) = \alpha_c (T_i - T_m), \tag{10}$$

where α_c — the value of the coefficient of heat transfer in the blood vessels.

Substituting the value of the heat flux in the expression for the temperature field, we obtain the dependence for the relation S_i/S_m :

$$\frac{S_i}{S_m} = 1 - \frac{\Delta T}{\Delta T_i} = 1 + \frac{1}{b\Delta T_i} - \sqrt{\left(\frac{1}{b\Delta T_i}\right)^2 - \frac{2\delta}{b}\frac{\alpha_c}{\lambda_m \Delta T_i}}. \tag{11}$$

Thus, the resulting dimensionless value $F = S_i/S_m$ is determined by the rate of change in blood temperature in the vessels – the thermal conductibility of the blood λ_C, the thermal conductibility of the myocardium λ_m, the difference in temperature between the blood and the myocardium ΔT_i, as well as the sign and numerical values of the coefficient b for the temperature curve. The deviation of the values of the ratio F from the linear dependence for the temperature field equation θ characterizes the uneven distribution of the temperature in the myocardium owing to the different rate of heat propagation in the medium (Fig. 1):

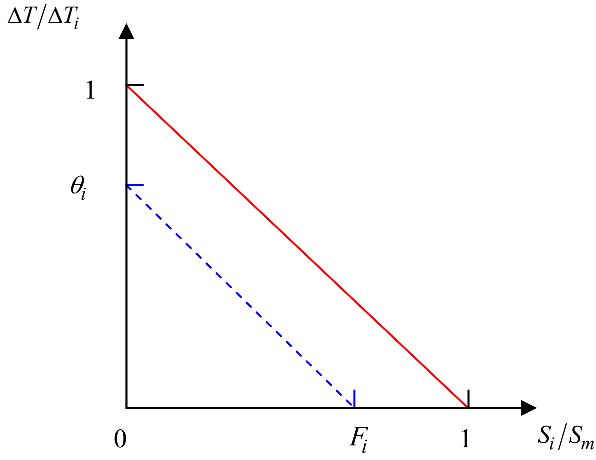


Fig. 1. Curves of temperature distribution in the layer of the myocardium for the temperature field equation

The relative deviation Δ_F from the linear dependence in the temperature field equation for the current temperature flux is calculated as the difference between the areas under the temperature distribution curves:

$$\Delta_F = \left(1 - F_i \cdot \theta_i\right) < 1. \tag{12}$$

where θ_i — the current value of the ratio $\Delta T/\Delta T_i$, F_i — the current value of the ratio S_i/S_m .

Obviously, in other equal conditions, the temperature in the myocardium ΔT_i varies so rapidly, the greater the density of the heat flux through the surface S_i, therefore, the current value of the ratio $F = S_i/S_m$ should approach the value $F_i \to 1$.

CONTOURING METHOD FOR DETERMINING CONDUCTIBILITYOF CORONARY VESSELS

In accordance with the contouring method of temperature inhomogeneities for the selection of Canny contours, modified to study the gradients of temperature on the surface of the myocardium, the stream of video data in the form of thermogram frames is recorded by the thermal imager and stored in the thermographic image database.

The first stage of treating the thermograms of the heart is the selection on the thermograms of temperature profiles, converted at the signal level. This procedure is carried out by applying threshold filtering. Since the level of thermal interference makes an error in determining the levels of temperature profiles that leads to distortion of the useful signal the interface of the Canny detector [14, 15] is used. The Canny boundary detector is a one-dimensional operator, which provides an optimal match between localization of thermal inhomogeneity and contour allocation. As criteria of optimality use to such criteria as probability of detection, high accuracy of localization, unambiguous response to one selection contours. The operator Canny maximizes the sum of two criterias: the probability of passage or false detection of the boundary, and the determination of the distance between the true and the isolated edges of the thermal heterogeneity. The first criterion leads to a reduction in the likelihood of the re-identification of the same edge heterogeneity. The second criterion allows you to determine the contrast margin and outline lines for the boundaries in the image using a certain threshold value, which use to compares the length of the gradient vector.

The algorithm for the operation for the circuit of Canny detector includes the following steps (Fig. 2):

1. Thermography image frames $I(x,y)$ are divided into segments for which the processing and detection of contours within each segment are performed:

$$I(x,y)=\sum_{k=1}^{N} I_k(\Delta x,\Delta y)\,, \tag{13}$$

where N — the number of segments of the representation of the image, $I(x,y)$ — the intensity of the pixels of the thermographic image, $I_k(\Delta x,\Delta y)$ — the segmentation of the image along the coordinates x and y.

2. The low frequency Gaussian Filtering. The each image segment is smoothed with use to Gaussian convolution:

$$G(x,y,\sigma)=\frac{1}{2\pi\sigma^2}\exp\left(\frac{x^2+y^2}{2\sigma^2}\right), \tag{14}$$

where σ — the degree of smoothing parameter.

3. Calculation of the gradient of the intensity of the pixels of the image in the vertical (axis x) $g(x)$ and horizontal (axis y) $g(y)$ directions with the help of the operators of the first derivative. Definition of the gradient module:

$$E_k(x,y)=\sqrt{g(x)^2+g(y)^2}\,. \tag{15}$$

3. Clarification of the contours found in the previous step is accomplished by resetting the gradient values $E_k(x,y)$ for those elements of the image that are not actually in the maximum of the gradient. The analysis starts from the point of maximum, that has a gradient value more than T_1 and lasts as long as the local maximum value does not become less than the threshold $T_2 < T_1$:

$$E_k(x,y)=\begin{cases} E_k(x,y), & T \ge T_1\,, \\ 0, & T \in \left(-\infty, T_1\right). \end{cases} \tag{16}$$

4. The resulting image is subjected to threshold processing using two temperature thresholds T_1 and T_2, moreover $T_1 > T_2$. Pixels of an image having an intensity value greater then, are defined as strong $p_k^{+}(x,y)$, and pixels whose values fall into an interval $\left[T_1, T_2\right]$ are defined as weak $p_k^{-}(x,y)$ pixels:

$$p_k(x,y)=\begin{cases} p_k^+(x,y), & T\in(T_2,\infty), \\ p_k^-(x,y), & T\in[T_1,T_2]. \end{cases} \tag{17}$$

5. Selecting the maximum response. For each image frame, the maximum response is determined as the value of the gradient module, which determines the affinity of the temperature profile to the given segment of the thermography image:

$$E(x,y)=\max_{k\to N}\left|E_k(x,y)\right| . \tag{18}$$

The algorithm for forming the contour ends with a morphological operation, in which the weak pixels are added to the strong pixels. Smoothing values of pixel intensity $I_k(x,y)$ increases the resistance of the Canny detector:

$$I_k(x,y)=\begin{cases} p_k^+(x,y)+p_k^-(x,y), & T\in(T_2,\infty), \\ p_k^-(x,y), & T\in[T_1,T_2], \\ 0, & T\in(-\infty,T_1). \end{cases} \tag{19}$$

According to the algorithm of the work of the Canny's limit detector, pixels of images are assigned to pixels of the boundary, which give the local maximum of the gradient in the direction of the temperature change vector. As a result, pixels marked white will be considered as a potential limit, all others will be excluded and marked with black. Pixels located in the immediate proximity to one of the vertical and horizontal directions are defined as the resulting contour of the boundary, and pixels lying alone or away from the boundary are removed.

In order to evaluate the efficiency of the algorithm for selecting the contours for open heart images in the presence of an additive obstacle, research was carried out using the mathematical modeling method. For this purpose, the model images of the area of the myocardium, containing an additive obstruction in the form of normal "white noise" with a given peak signal to noise ratio, were synthesized. The received noisy images were digitally processed according to the developed algorithm circuit of the Canny's detector at various values of the detector parameters, including the parameter σ characterizing the Gaussian linear filter, the values of the temperature thresholds T_1 and T_2 that determining the conditions for the segmentation of the images.

From the results of the numerical experiment it is clear that the procedure for determining the binary areas provides for the exclusion of false contours only when carefully selecting the parameter σ for filtering the original image. Therefore, the value of this parameter, which specifies the degree of image smoothing to filter interference, was selected experimentally and consisted of values:

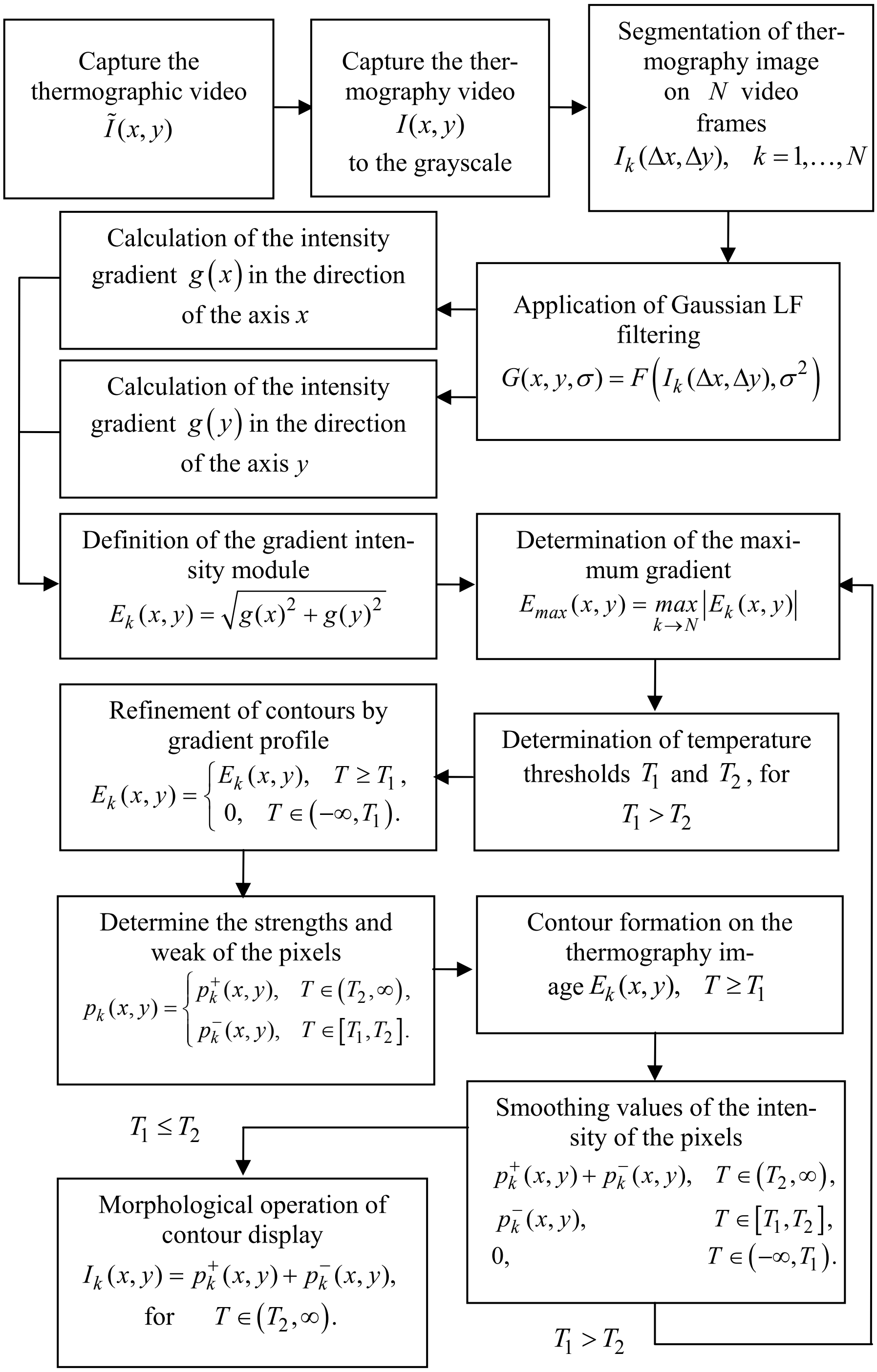


Fig. 2. Algorithm of the Canny's detector using the Gaussian filter, threshold filtering and smoothing values of the intensity of the pixels

$$\sigma = 1,4 \text{ for threshold } [T_1, T_2] = \left[14\,^0C, 18\,^0C\right] \text{ with hypothermia,}$$

$$\sigma = 2,0 \text{ for threshold } [T_1, T_2] = \left[32\,^0C, 36\,^0C\right] \text{ with hyperthermia.}$$

Thus, the Canny's limit detector determines how fast the brightness of the image changes at each point of the thermograms, which makes it possible to determine the boundaries of temperature heterogeneity and its orientation.

CLINICAL STUDIES

The clinical investigations of the method for conduction of coronary vessels were carried out at the clinical base of the Amosov National Institute of Cardiovascular Surgeryof NAMS of Ukraine to improve the efficiency of noninvasive control of human heart temperature in conditions of artificial blood circulation in the department of surgical treatment of aortic pathologies in sixteen open heart operations and in the department of surgical treatment of acquired heart defects in twelve open heart operations.

In clinical studies, the process of warming up and cooling myocardium is carried out through the cannulas, which are installed in the anterior part of the aorta in the region of the top of the heart. The cannula is installed in the branch of the right ventricular artery for pumping a cardioplegic solution along the right coronary artery, and the cannula is installed on the surface of the aortic bulb for pumping the solution along the left coronary artery.

The clinical studies on isolated heart show the feasibility of using the method of determining the conductibility of coronary vessels on the basis of noninvasive heart temperature control for assessing the conditions of blood supply to the vessels of the myocardium (Fig. 3).

When cooling the heart (Fig. 3 a), the coronary vessels are clearly distinguished at the temperature difference between the tissues of the myocardium and the solution 6°C and more (to a temperature of 10°C). Accordingly, when warming the heart (Fig. 3 b), the coronary vessels are released at a temperature difference of 9°C or more (up to 12°C). The initial temperature of the myocardium at the beginning of the cooling process was not less than 21–22°C, and at the beginning of the warming - no more than 25–26°C.

The assessment of the dynamics of temperature changes for the distribution of temperature in the myocardium can be performed for a sequence of thermograms of the heart that are performed for the state of hypothermia and hyperthermia in conditions of cardiopulmonary bypass (Fig. 4).

The application of the developed mathematical model of heat exchange for the surface layer of the myocardium [16 – 18] allows us to determine the boundaries between the warmed and cooled sections of the myocardium during hypothermia or hyperthermia of the heart. When cooling the heart (Fig. 4a) and warming the heart (Fig. 4b), the boundaries between the warmed and cooled areas are allocated due to the presence of a gradient on the surface of the myocardium at temperatures between 0.5°C and 4°C and more.

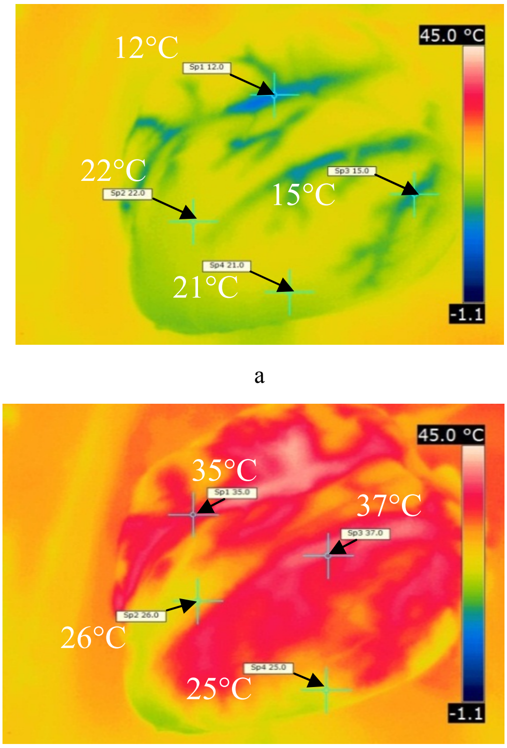
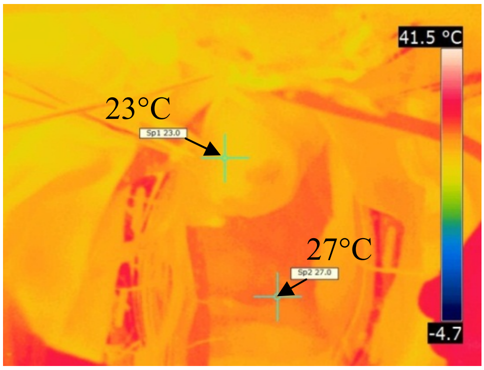


Fig. 3. Application of the thermographic method of contouring to determine the conductivity of coronary vessels: a — for cooled heart; b — for a warmed heart

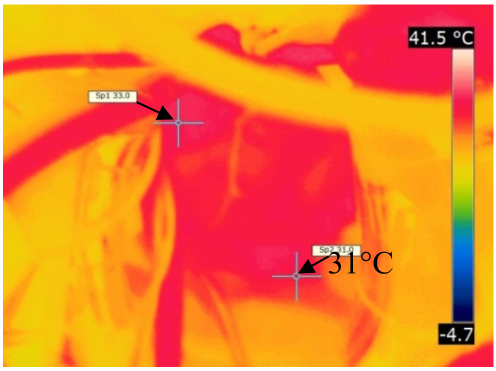
During hypothermia (Fig. 5), the area of the warm part of the myocardium decreases by compressing the cooling circuit S_{gipo} and, accordingly, increasing the area of the cooled area relative to the external cooling circuit limit S_o. The dynamics of temperature changes on the surface of the heart causes an increase in the magnitude of the ratio S_i/S_m and brings it closer to the value $F_i \to 1$.

During hyperthermia (Fig. 6) there is a decrease in the area of the chilled area of the myocardium by compressing the warming contour S_{giper} and, accordingly, increasing the area of the warmed area relative to the external warming circuit limit S_{gipo}. The dynamics of temperature changes on the surface of the heart causes an increase in the magnitude of the ratio $S \quad _o$ and brings it closer to the value $F_i \to 1$.

At the final stage of the processes of hypothermia and hyperthermia, the value $F_{gipo} = S_{gipo}/S_o$ is less than 1.3 times the value $F_{giper} = S_{giper}/S_o$, respectively, which is expressed in a more uniform warming of the studied area of the heart with hyperthermia in comparison with the process of its cooling under hypothermia in conditions of cardiopulmonary bypass.



a



b

Fig. 4. Thermograms of the heart for the state of hypothermia and hyperthermia: a — for a cooled heart; b — for a warmed heart

The developed method for determining the conductibility of coronary vessels provides the reliability of non-invasive control of open heart temperature, which is determined by the temperature sensitivity of 0,1°C of the thermometer FLIR ThermaCAM E300 and the measurement error ±1% of the range.In addition, the use of needle heaters and sensors in the oesophagus does not allow to determine the temperature of the inner wall of the myocardium without the introduction of invasive sensors in the opening between the aorta and the left ventricle, which is an additional factor for injury.

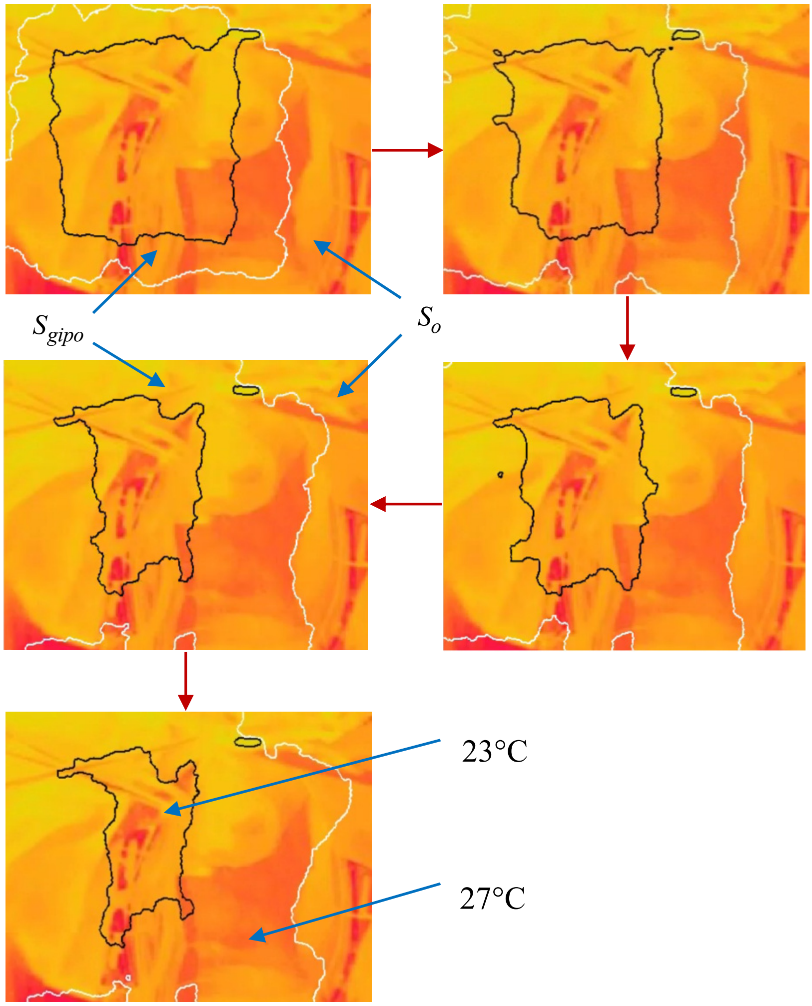


Fig. 5. Work of the Canny detector algorithm for hypothermia of the heart

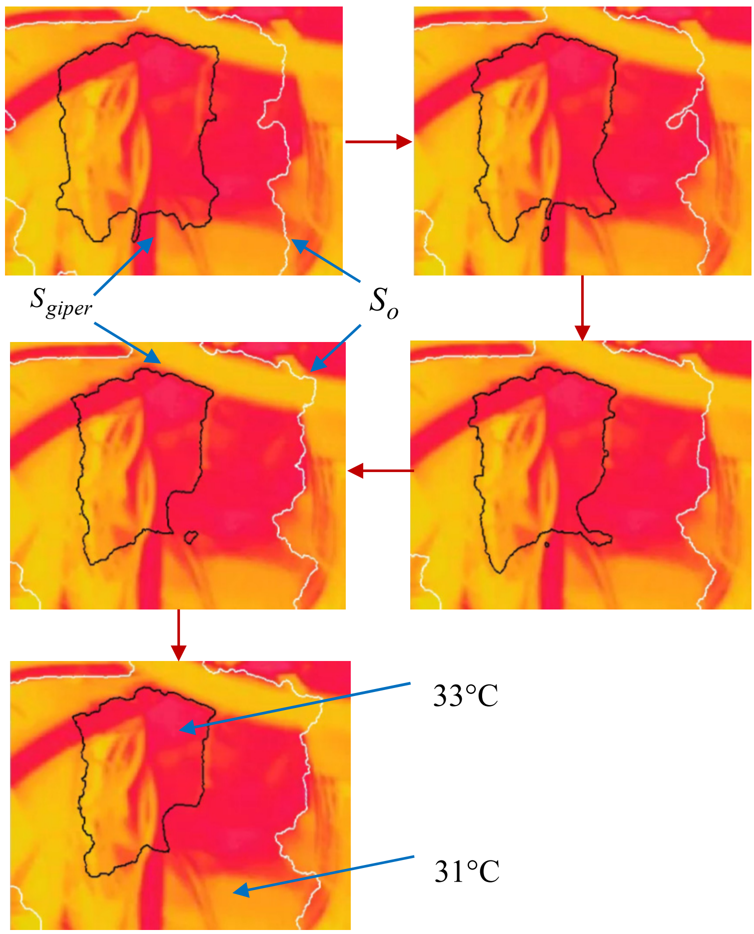


Fig. 6. Work of the Canny detector algorithm for hyperthermia of the heart

RESULTS

For compare the temperature data, that is measured using invasive needle sensors and the thermography method, the determination of regression dependence for the calculation of the dynamic changes in temperature, determined in real time. As a data examination class (C_1), the temperature value measured with the needle sensors $\Delta T_{MED}(t)$ is used. The investigated class (C_2) contains calculated temperature differences on the surface of the myocardium $\Delta T_{FLIR}(t)$, which are recorded during hypothermia and hyperthermia using the thermography.

The level of confidence in the obtained temperature data, measured by thermography means and needle sensors, reflects the value of confidence intervals. The obtained confidence intervals can be considered as an interval of values of the parameters, which does not contradict the true value of temperature. In determining the Euclidean distance by the K – mean method, the number of observations corresponding to the number of temperature measurements $k = 10$ is taken into account. The calculated Euclidean distance between the center of gravity of the examination class (C_1) and the studies class (C_2) is researched that equals $d(c_1, c_2) = 6,69$. The resulting value of the confidence interval is less than 15% shows the closeness between the data in the classes.

The reliability of determining the coefficient of correlation $r(c_1, c_2)$ depends on the number of measurements of temperature and the number of degrees of freedom $k = n - 2$. The value of the t-criterion for assessing the statistical significance of the correlation relationship between the samples is determined by the formula:

$$t(r) = \frac{\sqrt{r(c_1, c_2)^2}}{\sqrt{1 - r(c_1, c_2)^2}} \sqrt{n - k}, \tag{20}$$

where n — the number of temperature measurements, k — the number of degrees of freedom for pair regression.

The results of the regression analysis of the temperature measurement data are to determine the correlation coefficient $r(c_1, c_2) = 0,739$ and the regression equation on the basis of comparison of data x_i, y_i in the classes C_1 and C_2 to the studies (Table 1).

The critical value of Student's t-criterion is located $t_{crit} = 2,306$ for the sample $n = 10$ size and the number of degrees of freedom $k = 2$ at the level of significance $p < 0,05$. The calculated t-criterion $t(r) = 3,102$ for a specific correlation coefficient $r(c_1, c_2)$ is greater than the critical value $t(r) > t_{crit}$, hence the relationship between data in classes C_1 and C_2, is statistically significant. The resulting regression equation $y = 0,3829x + 0,2137$ (Fig. 7) has a large angle of inclination of the data interrelation $0,3829$ and linear dependence, and allows you to perform the conversion of temperature readings, measured with the help of needle sensors, to the temperature values obtained using the thermography method.

Table 1. **Results of regression analysis of temperature control data for the method of determining the conductibility of coronary vessels**

Evaluation criterion		**The value of the coefficient**
• Correlation coefficient	$r(c_1, c_2)$	0,739
• t-criterion value	$t(r)$	3,102
• Regression equation	$y = 0,3829x + 0,2137$	0,383

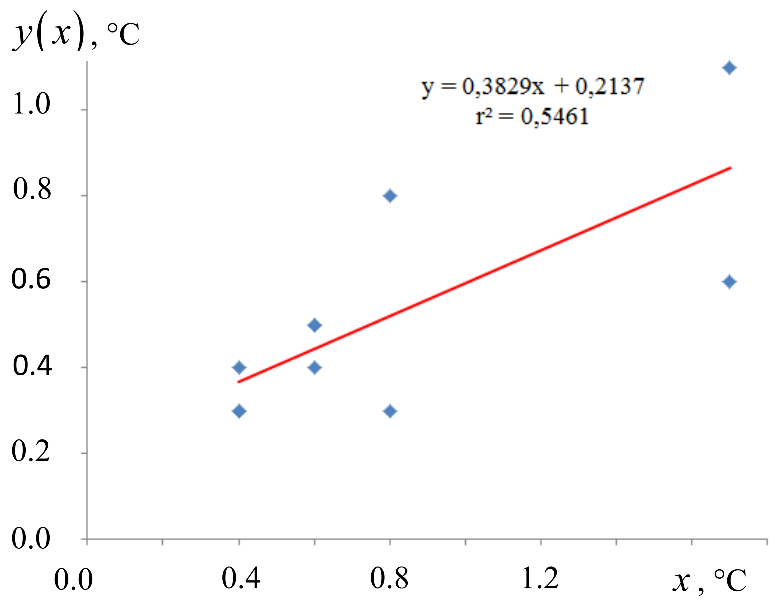


Fig. 7. Regression equation based on the comparison of data x_i, y_i in classes: x — data of the examination class C_1 of heat sensor, $\Delta T_{MED}(t)$, °C, y — class data C_2 for thermographic studies, $\Delta T_{FLIR}t)$, °C.

The proposed algorithm for obtaining contours of areas with nonhomogeneous temperature distribution on the surface of the heart, realized on the basis of the contours algorithm of Canny detector, allows receiving additional information on the state of the blood supply of the myocardium by using the Gaussian filter, and on the basis of the informative temperature profiles on thermographic images, separating the geometric boundaries between the cooled and warmed up areas of the myocardium by using the algorithm of Canny detecting for the video frames of thermograms.

The obtained regression dependences have the correlation coefficient of 0.75, that allows to perform the conversion of heart temperature readings, which are measured with the help of needle heaters in the temperature values, obtained using the thermography method. The reliability of the method for determining the conductibility of coronary vessels for the detection of myocardial areas with the ischemic regions with dimensions less than 2×2 mm can be increased by using modern medical thermographs with a sensitivity of 0,02°C and a measurement error of ±0,5% of the range.

Thus, the use of the thermography method for determining the conductibility of coronary vessels in comparison with the use of needle heaters for the evaluation of microhemodynamics of coronary vessels can significantly increase the reliability of heart temperature control due to the possibility of obtaining additional information for the permissible difference in temperature on the surface of the myocardium during hypothermia and hyperthermia.

CONCLUSIONS

Thus, the method of contouring the cooled and warmed areas of the myocardium to determine the conductibility of coronary vessels using thermographic instruments for measuring the temperature of the heart, and an improved of the algorithm of detector Canny using the Gaussian filter, allows us to assess the conductibility of coronary vessels for the study of blood flow in the surface layer of the myocardium during warming up and cooling of the heart in conditions of cardiopulmonary bypass.

The application of the thermography method for determining the conductibility of coronary vessels in comparison with the use of needle heaters for the evaluation of microhemodynamics of coronary vessels provides non-invasive control of heart temperature and the possibility of obtaining additional information on the permissible difference in temperature on the surface of the myocardium during hypothermia and hyperthermia.

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Received 29.03.2019

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Отримано 29.03.2019

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МЕТОД ВИЗНАЧЕННЯ ПРОВІДНОСТІ КОРОНАРНИХ СУДИН ЗАСОБАМИ ТЕРМОГРАФІЇ

Вступ. Характер розподілу температури в серці визначається процесом теплообміну між міокардом і коронарними судинами, а також станом мікрогемодинаміки коронарного русла серця. Для кількісного оцінювання нерівномірності розподілу температури на поверхні серця запропоновано алгоритм розрахунку кількісного критерію, що може бути об'єктивним маркером ефективного захисту серця і мозку. Метод визначення провідності коронарних судин реалізовано на основі алгоритму визначення теплових контурів, що обчислюються за градієнтами температурного поля на зображенні серця в інфрачервоному спектрі. Вдосконалення розробленого раніше методу визначення теплових контурів на основі алгоритму Канні полягає в переході від якісного до кількісного оцінювання швидкості зміни температури на поверхні міокарда.

Метою дослідження є оцінювання провідності коронарних судин для дослідження кровоплину у поверхневому шарі міокарда під час зігрівання та охолодження серця в умовах штучного кровообігу.

Результати.Числове значення кількісного критерію отримано шляхом визначення різниці температур між кров'ю і міокардом, яке обчислюють як різницю геометричних площ під кривими розподілу температур у рівнянні температурного поля для постійного і поточного температурного напору. Метод контурування для визначення провідності коронарних судин дає змогу виділити ділянки на поверхні міокарда, в яких зміна температури значно відстає від середньої температури на поверхні під час зігрівання або охолодження серця, що уможливлює оцінювання стану дрібних коронарних судин в міокарді.

Ключові слова: *математичне моделювання, алгоритм детектування Канні, температура серця, температурні профілі, гіпотермія, гіпертермія, штучний кровообіг.*

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МЕТОД ОПРЕДЕЛЕНИЯ ПРОВОДИМОСТИ КОРОНАРНЫХ СОСУДОВ СРЕДСТВАМИ ТЕРМОГРАФИИ

Введение. Для количественной оценки неравномерности распределения температуры на поверхности сердца предложен алгоритм расчета количественного критерия, который может являться объективным маркером эффективной защиты сердца и мозга. Метод определения проводимости коронарных сосудов реализован на основе алгоритма Канни для определения тепловых контуров, которые вычисляются по градиентам температурного поля на изображении сердца в инфракрасном спектре.

Целью исследования является оценка проводимости коронарных сосудов для исследования кровотока в поверхностном слое миокарда во время согревания и охлаждения сердца в условиях искусственного кровообращения.

Результаты. Получено числовое значение количественного критерия, который рассчитывается путем определения разницы температур между кровью и миокардом, что косвенно позволяет оценивать состояние мелких коронарных сосудов в миокарде.

***Ключевые слова**: математическое моделирование, температура сердца, температурные профили, гипотермия, гипертермия, искусственное кровообращение.*

DOI: https:// 10.15407/kvt196.02.080

UDC 616.89-07-08(035):616-036.82:355.11:355.721

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PSYCHOMEDICAL INTERVENTION MODEL FOR SERVICEMEN BASED ON A STUDY OF MENTAL DISORDERS

Introduction. *Many domestic and foreign experts work under the problem of mental health at combat environment in various aspects, however, a lot of unsolved questions regarding to psychomedical consequences of hybrid war in Ukraine still exist.*

The purpose *of the article — is to assem and to analyze the influence of various harmful factors in combat environment on the psychological status and mental health of military personnel and ex-combatants for development of psychomedical intervention model.*

Materials and methods*. The materials of research were based on the study of more than 200 servicemen in different conditions and health state using own and adopted questionnaires with further descriptive and multivariate exploratory technics of data analysis. Bibliosemantic, information-analytical, comparative analysis of domestic publication from the last 4 years have been done for summarizing the national experience regarding to psychological aftereffects of armed conflict in Ukraine.*

Results*. A retrospective summarizing of available information on the medical and psychological consequences of hybrid war relating to the characteristics of their aftereffects in recent years among military and demobilized persons has been performed. An assessment of stress factors impact at combat environment (physical, informational, organizational and anticipation) on military personnel participated in military conflict has been done. The specific features and structure of mental disorders in the military personnel, which were treated in hospital conditions have been revealed. The decision support model for reliable ($p<0.001$) prediction further adjustment disorders after extreme conditions has been developed.*

Conclusions. *The greatest influence on the stress formation of combatants had "anticipation" factors as well as not much less pronounced "physical", "informational" and "organizational" environmental factors. Research permits to conclude that some of them significantly influence on the psycho-emotional state of military personnel and can be grouped into two main factors: the 1st - factor of negative future prediction and the 2nd - factor of negative impact of physical environment. The phenomenon of exaggerating of negative feelings* *among servicemen after the 4th-month impact of the stress factors has been discovered. The decision support model to predict further adjustment disorders (F43.2) after extreme conditions has been created for developing the Psychomedical Intervention Model in Ukrainian Armed Forces.*

Keywords: *psychomedical intervention model, decision support model, mental health, adjustment disorders, posttraumatic stress disorder, stress factors.*

INTRODUCTION

Military conflict in the East of Ukraine creates thousands of people who continue military service or return into civil society after demobilization with numerous features of militarized consciousness that significantly affect the further development of society and country.The occurring events in combatzone can be characterized by high intensity, tension, transience. The occupational activity in these extreme conditions requires from servicemen to perform work at the limits of their capabilities, which, as usual, affects mental health.

The World Health Organization made enormous strides [1–5] in developing effective health care for most of the mental disorders and further improvements in treatments are likely thanks to advances in the understanding of brain functioning and psychosocial factors particularly in health promotion, prevention and treatment, rehabilitation and restoration of health etc. The relevance of this is understandable, since mental health was, is and will be an important social criterion of growing development and prosperity of the country and society; it greatly affects demographic situation, national security, processes and results of economic, social and cultural development. That is why a forward mental health care is very important in NATO-led operations (SANAGs 2564, 2565, 2566, 2568, 2569, 2573, 2548) and many problems of it are still in study now.

Features of posttraumatic stress disorder (PTSD) of foreign armies' combatants has been comprehensively described in [6]. For example, it was found that the prevalence of PTSD varies in different social groups [7]. PTSD manifestations were higher in those who did not have high education and repeatedly killed during hostilities. Also, the level of PTSD manifestation increased depending on the deployment duration (the PTSD presence in military personnel fluctuated from 9% to 31% of those who were in combat zone for more than a year), as well as their trauma characteristics [8]. PTSD manifestations were observed in 18.3% of those who were exposed to heavy weapons, and this figure among the wounded was 23.9%. In 2013, the prevalence of PTSD and / or depression among war veterans in Iraq and Afghanistan was 20%. A number of researchers point out that this figure is much higher, justifying this by concomitant diagnoses of brain trauma (19% of veterans) which was not taking into account in the statistics of PTSD and other behavioral disorders. Among veterans of Iraq and Afghanistan, according to some studies, 39% of ex-combatants had problems with alcohol abuse and 3% drug use [8].

Unfortunately, there is no comprehensively summarizing information on relevant statistics of mental disorders and their observed effects among combatants and their families in available sources because of the high dynamics of situation in Ukraine. Furthermore, not only PTSD is the undesirable effect of combat stress, but also administrative and criminal offenses, suicide, violence in the family, addictive behaviors etc., which, at first, belong to the different areas of executive power, and secondly — some data are not fully presented (one by one) and out of the open access.

Many domestic and foreign experts work under the problem of mental health at combat environment in various aspects, however, a lot of unsolved questions regarding to psychomedical consequences of warfarein Ukraine are still exist.

The purpose of the article is assessment and analysis of influence of various harmful factors in combat environment on the psychological status and mental health of military personnel and ex-combatants for development of psychomedical intervention model.

MATERIALS AND METHODS

The materials of research were based on the study of more than 200 servicemen in different conditions and health state using own and adopted questionnaires with further descriptive and multivariate exploratory technics of data analysis.

The specially designed questionnaire, after examination by medical commission that confirmed their fitness to military service was filled in by 101 servicemen (20–30 years of old). The questionnaire was developed using an expert method. Ten combatants were invited upon their return from combat zone as experts who clarified the list and formulation of the questionnaire. As a result, there were formulated qualitative and quantitative measures of most important aspects of life in the combat environment. Evaluation of each stress factor was estimated on 19 questions (in % of strength of human fillings).

Resembling examination of 101 servicemen (20–35 years of age) using specially designed questionnaire for study adjustment disorders at hospital condition among combatants was also performed [9]. This method can assess the impact of physiological stress (10 questions), hardiness (commitment, control and challenge) (12 questions), intrusion (8 questions), avoidance of military personnel (7 questions) in situations that occur at combat zone. Evaluation of each question was performed in 10-point scale (from min to max manifestation).

The analysis of general morbidity on mental and behavior disorders among military personnel of Ukrainian Armed Forces in 2008-2016 years has been performed using official statistical data from automated information system of MTFs medical reports.

All examinations were performed in accordance with ethical standards of the responsible committee and the Helsinki Declaration and have been approved by the Bioethics Commission of Ukrainian Military Medical Academy.

Bibliosemantic, information-analytical and comparative analysis of domestic publication from the last 4 years have been done for summarizing the national experience regarding to psychological aftereffects of armed conflict in Ukraine.

Statistical analysis was performed by methods of descriptive statistic, multivariate exploratory technics (multiple regression, factor and discriminant analysis) using software STATISTICA 6.0 (license #AXX910A374605FA).

PROBLEM STATEMENT

*Features of mental and behavioral disorders among Ukrainian military personnel (background research).*According to the analysis of open sources of the medical information, provided by Ministry of Health of Ukraine and Ministry of Defense, 5327 combatants needed the treatment due to mental disorders, and 4876 of them were suffering from stress disorders in the period from April 2014 to September 2015 [10]. Among them: acute stress reaction (59.3%), PTSD (13.3%) and adjustment disorder (19%). Only 20.6% of soldiers could continue their military service after the treatment. The nosologic structure of hospitalized soldiers in 2014 showed that the majority of patients suffered from stress disorders (84.1%); mental disorders caused by psychoactive substances was diagnosed in 3.8% cases. Organic mental disorders had 6.2% of combatants, and psychotic disorders — 2.5%. Only 20.6% of servicemen could continue their military service after the treatment. Compared to 2014, in the first half of 2015 the percentage of soldiers, who were hospitalized due to stress disorders, reduced to 53.8%. At the same time, the percentage of persons with mental and behavioral disorders caused by drug abuse (mainly alcohol) increased in 8 times and reached the level of 34.0%.

From July 2014 to October 2016 Ukrainian scientists [11] found that mental and stress-related neurotic disorders were diagnosed in 37.5% of servicemen, than alcohol abuse (25.6%), organic, including symptomatic mental disorders (24.6%). Patients with schizophrenia amounted to 1.7%, acute transient delusional disorders — 5.6%, personality disorders — 1.3%.Thus, since 2015, the redistribution of mental disorders structure associated with addictive behavior has taken place.

Interesting results in 2014 were obtained from 96 combatants treated due to brain concussion, posttraumatic neuropathy, aggravation of chronic musculoskeletal diseases, the consequences of damaged limbs — defects of soft tissue and bone defects etc. [12]. In this study PTSD was combined mostly with the effects of different severity traumatic brain injury (TBI). Anxiety and depression scale (assessed by the HADS) were predominantly subclinical. 55% of servicemen had elevated levels of peritraumatic dissociation. The results of E. Vartegh drawing test, along with high adaptability, have shown such trends as: a sense of imbalance, high anxiety and tension, the presence of fear, the need of "self-I" protecting and outside support. This study indicated that 67% of combatants presented a high adaptability. Researchers observed the desire to withstand for illness and fight for health. It may be explained as a key to positive outlook on disease prevention and posttraumatic growth. However, at the same time, military personnel could be characterized by strong tension and dissatisfaction with the current situation.

In 92% cases the fears and concerns were hold inside and were not a point of discussion with anybody [12]. However, the sharpness of negative emotions (anxiety, loneliness, fear of the future) leading to a state of helplessness, reduced ability to cope with obstacles and difficulties in problems solving (58%), may demonstrate the need to protect and belonging to someone else or need for outside support.

The experts of Ukrainian Research Institute of Social and Forensic Psychiatry of Ukrainian Ministry of Health [13] found that 33.3% of mental disorders among hospitalized combatants defined by individual symptoms and did not reach the clinical level of mental illness. The main nosologies were presented as follows: organic emotionally labile [asthenic] disorder (F06.6) was detected in 6.8%, postconcussional syndrome (F07.2) in 4.0%, other personality and behavioral disorders due to physiological condition (F07.8) in 2.8%, PTSD (F43.1) — in 22.5%, adjustment disorder (F43.2) in 27.3%, neurasthenia (F48.0) in 5.2% of patients. Most cases of PTSD were often complicated by comorbidity with bipolar disorders, depression, disorders due to substance abuse, psychosis, personality disorders, and injuries to the formation of chronic pain. Despite the serious psychological circumstances, 30.4% of PTSD patient and 1.5% with adjustment disorder intend to return to their military units as soon as possible.

25.1% of military personnel were unfit to military service due to mental disorders in 2015 [14]. Injuries and traumas were inherent to 16.7%, cardiovascular system diseases — 15.4%; diseases of nervous system — 11.6%, and diseases of digestive system — 5.5%.

In addition to this, the index of psychogenic casualties reached almost to 80% and was significantly higher than was before military conflict (almost in 3 times) in 2014–2015. 30–40 % of these cases were ended by transformation of psychological health (borderline) disorders into psychiatric nosology that significantly increased the number of discharges from military service [15, 16].

Features of mental and behavioral disorders among Ukrainian ex-combatants. During reintegration of demobilized people into civilian life there were studied 63 ATO participants with PTSD in comparing with a group of 17 people who had only psychological problems. It was concluded that high levels of state anxiety were a reaction to experienced stress (group 1 — 100.0%, and group 2 — 88.2%) while significantly high level of trait anxiety prevailed in patients who had PTSD according to both objective (at 93,7% — 20,6 ± 2,3 points) and subjective evaluation (at 90,5% — 44,5 ± ±1,12 points) [17]. Both groups of people felt equally strong presence of depression in group 1 — 85.7% (15.1 ± 2.04 points) and in group 2 — 64.7 % (17 ± 1.3 points).

The first manifestations of PTSD polymorphism as clinical features came out after 2–12 months (in average 8.68 ± 0,46 months) [18]. The authors pointed out the presence of two surges in forming of PTSD first signs: 4–6 months- in 37.5 % and 11–12 months — in 46.4 % of patients. Formation of the expanded symptoms was occurred within 1–12 months from manifestation of the first signs of this disorder. In 39.3% of servicemen forming PTSD lasted 2-3months. It could be noted that PTSD had a chronic or delayed type of progression in the time.

In other study [19] of 112 ex-combatants who participated at combat zone in 2014–2015 there were revealed additional peculiarities of PTSD. At first, it was a complex of mental and behavioral disorders associated with underground structures. Anxiety, emotional tension, feeling of danger, a sense of warm inflow or cold inside the abdomen, chest and head incased in situation of approaching to underground structures (basement, cellar, subway, etc.) and disappeared while moving inside these structures. This complex disorder was named as “underground syndrome” and it was observed in 26.2% of cases.Secondly, “combatant nyctophobia” was observed in 19.3% of cases and it was manifested by increased anxiety, emotional stress, obsessive thoughts about finding safeshelter, and violent martial reminiscences at night caused by the combat past.Thirdly, “combatant nyctosensibilisation” was observed in 34.5% of cases and manifested by heightened alertness, suspicion, a willingness to appropriate defensive reactions, hyperacusis, lower threshold of plosive-aggressive outbursts, etc., difficulty falling asleep at night (dyssomnia). Fourthly, the psychogenic agrypnia ("Sleep self-deprivation") was indicated in 13.8% of cases as obtrusive fear of the night artillery fire or reconnaissance and subversive groups attack.The most common clinical manifestations of these disorders were intense negative feelings of traumatic event (100.0%) and sleep disorders (100.0%), often there were registered nightmares for military subjects in patients (82.7%), flashbacks (84.1%) physiological (autonomic) hyperactivation (79.4%), feelings of own future hopelessness beyond combat zone (84.5%), reducing emotional blunting (76.6%), efforts to avoid thoughts, feelings and conversations, reminiscent of the traumatic events (73,9%), hypervigilance (89,1%), irritation and outbursts of anger (82,4%). It should be noted that 57.7% of patients had reduced interest in previous activities or lost it completely. Performed studies indicated that there were such significant psychogenic factors as vital threat, the first battle stress and stress factors of combat environment in PTSD genesis [19].

*Influence of combat environment factors on combatants (own study).*It is known the life-threatening conditions affect the person on such way that subjective feelings often go ahead from the appearance of objective signs of performance decline [20]. Within the framework of the environmental psychology [21], it is relevant to study the influence of certain conditions of combat environmental and occupational activities of servicemen on their feelings.

It should be noted that such influence of environmental factors on human begins from the time of waiting for extreme situations, when people are intensively preparing for future challenges. Then, this effect is greatly enhanced in combat environment conditions. The servicemen' psychological state transformation can be changed into normal or wicked way at the reintegration period depending on individual stress coping strategy and possible presence of damages and injuries. In this case, it is important to get information about the severity of the impact of certain combat environmental factors on the healthy troops that have to continue their duty in various environmental conditions.

To streamline the description of the results there have been identified the following such groups of factors of combat environments as "physical", "informational", "anticipation" (foresight) and "organizational". This factors' separation was quite arbitrary. The group of "physical" factors were associated with the direct damage on the soldiers. The group of "informational" factors reflected the effects of situation assessment and cause some negative feelings, such as fear. The impact of the combat situation caused in some soldiers associated sensations with the assessment of the consequences of this situation.

Anticipation function, which estimates the likelihood of possible effects on any events in human and predicts the consequences of their actions, has been assessed also.

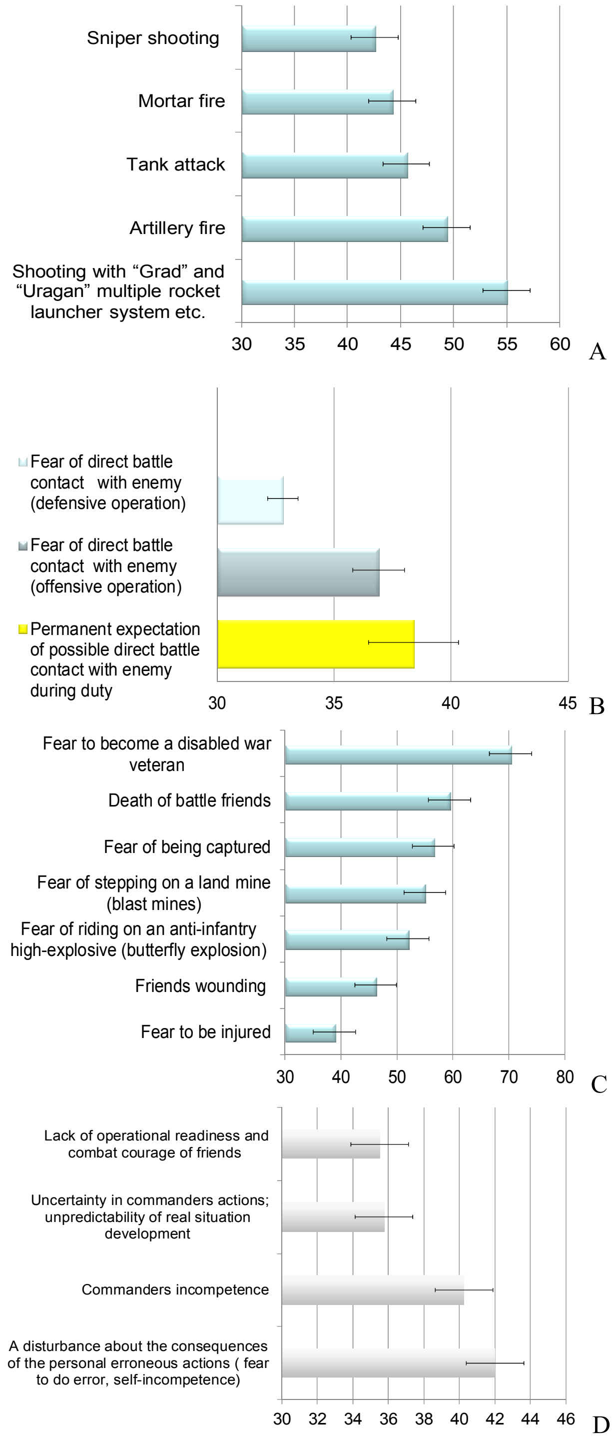

Fig 1. Influence of stress factors (estimated % of strength of feelings at combat environment on military personnel. A — “Physical”; B — “Informational”; C — “Anticipation”; D — “Organizational”.

Shooting with "Grad" and "Uragan" multiple rocket launcher system etc 55% was the most influenced factor among all physical factors, and the least one was "sniper fire" factor. Feasibly, these experiences were derived due to the total area of destruction, since both reactive systems can cause damage to many soldiers and sniper activity had more individually oriented effect.

FACTOR MODEL

Perception of "informational" stress factors was estimated by respondents as follows (Fig. 1B). First of all, the level of influence of these factors was much lower than "physical" factors ($p < 0.05$). Secondly, the impression caused by the constant expectation of possible direct contact with the enemy in duty time was very strong and accompanied by negative feelings of anxiety (38%) without observed circumstances of offensive or defensive operation.

The fact of direct contact with enemy infantry in the attack caused rather different feeling as fear. Expression of these emotions at the offensive operation reached to 37%, in terms of defensive operation — about 33% indicated the presence of greater emotional stress among military personnel in the offensive operation. This difference is not so significant, possibly due to the fact that the phase of positional fighting was more probable. Although the impact of the "informational" and "anticipation" factors on psychological state are close enough, each of these factors had its own specifics.

Specific features of the "anticipation" factors were forecasting of their action negative consequences in a combat environment. They are shown in Fig. 1 B. As anticipated consequences can be very noticeable to human, the level of their impact on people was higher than "physical" factors. This indicates that the risk to be captured, the death of combat friends and especially fear of becoming disabled were the most significant in the soldiers' lives due to anticipation effects.

The fact that excess fear of possible injured comrades was more expressed comparing to their own is very interesting. This psychological effect can be generated by existing of military team cohesion, the propensity of people to sacrifice in terms of protecting the state integrity, military patriotism. Formulated thesis was confirmed by the fact that the assessment of stress-related feelings due to the wounded friends was higher in comparison to stress feeling related to own injuries.

The impact of various factors on the development of organizational stress was also estimated among the ATO members (Fig. 1 D). It should be emphasized that all organizational factors did not influence equally on the development of stress. Some of them had a quite distinct effect (a disturbance about the consequences of possible personal erroneous actions (fear to do error, self-incompetence), commanders' incompetence, uncertainty in commanders' actions; unpredictability of real situation development, lack of operational readiness and combat courage of friends).

The impact of these factors on functional state of military personnel could not be compared with the majority of the "anticipation" or "physical" factors components.

Thus, uncertainties in commanders' actions, unpredictability of a real situation are fairly close in content to the commanders' incompetence factor in terms of further events prediction under uncertainty. Military personnel were less disturbed by combat preparation training and morale of colleagues.

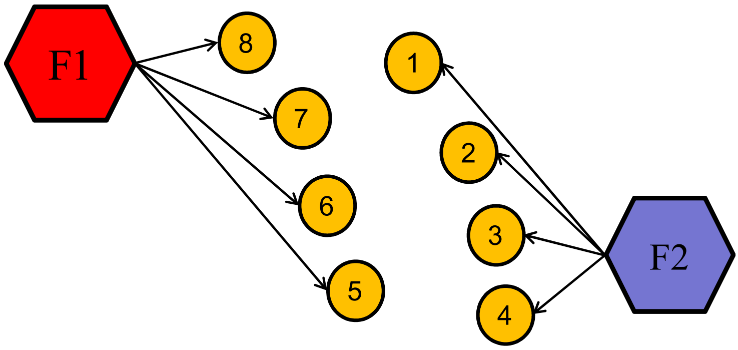

Fig. 2. The factor model influencing the development of adjustment disorders.1 — Shooting with "Grad" and "Uragan" multiple rocket launcher system etc., 2 — Mortar fire, 3 — Tank attack, 4 — Artillery shelling, 5 — Fear of getting injured, 6 — Fear of stepping on a land mine (blast mines), 7 — Fear of riding on an anti-infantry high-explosive (butterfly) mine, 8 — Fear to be captured.

Using factor analysis there were highlighted two factors that contribute adjustment disordersand explain 40% of total dispersion. As it is shown in Figure 2, there were the factor predicting the negative future effects (explaining 23% of total dispersion) and the factor of negative impact of physical environment (explaining 17% of total dispersion). The greatest influence on the formation of negative feelings among the environmental factors had "anticipation" factors as well as not much less pronounced "physical" factors. The analysis of those effect suggested that indirect impact on the soldiers' mind caused by anticipation of possible outcomes of events in some cases was more rapid than direct action of "physical" factors.

Of course, all manifestations of combat stress were not only depended on the intensity of warfare, but also on other external factors. Thus, according to research [19], critical external factors at the forefront were as follow: sleep deprivation (the average sleep duration was 2–4 hours at the forefront in 71.1% of cases); poor living conditions (bunkers and trenches in remote locations of the main forces — tents type as Uniform sanitary barrack tent with a capacity of 35–40 people (dated by 1956 year) and heated winter tent with a capacity of 20–25 people (dated by 1968), adjusted buildings (barns, abandoned manufacturing plants, schools) were indicated by 65.3% of respondents); problems with personal hygiene (in 36.6% of respondents conditions for natural personal care needs were absent and often associated with life-threatening because of the risk of plant mines or to be targeted by a sniper).

The obtained results were reflected on official statistical data of morbidity. Since 2014, the indexes of mental and behavior disorders for all categories of servicemen have increased by almost in 4 times (officers — 22.4 ‰, contracted solders — 28.4 ‰, conscripts — 20.4 ‰, which are significantly higher ($p \leq 0{,}001$) compared to 2013). The peak values were noted in 2015. In 2016, the morbidity of officers and conscripts decreased by almost 2 times (13.2 ‰ and 11.0 ‰ respectively); a slight decrease from 28.4 ‰ to 21.6 ‰ among contracted solders was noted.

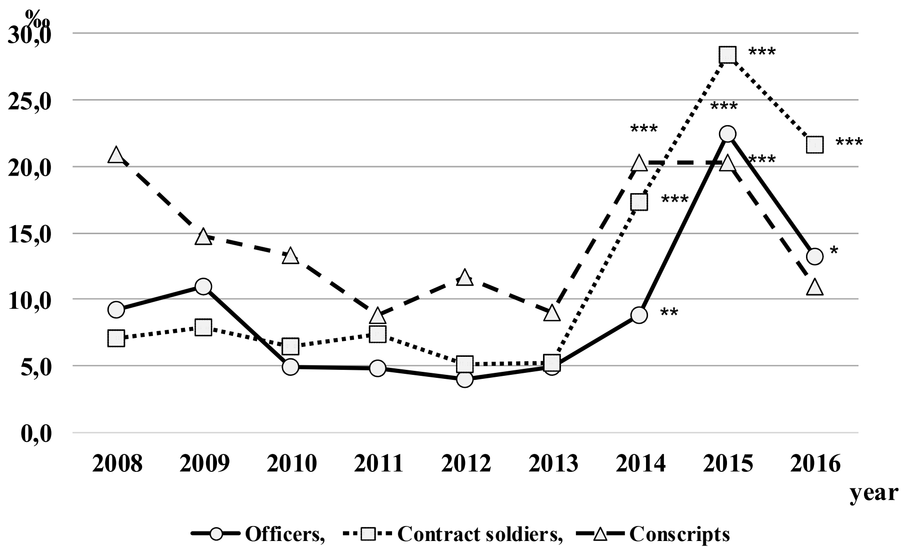

Fig. 3. Dynamics of general morbidity on mental and behavior disorders among military personnel of Ukrainian Armed Forces. *, **, *** — significant difference in overall general morbidity of mental and behavior disorders between 2013 year and 2014–2016 years according to Student's criterion corresponds to the levels $p < 0,05$, $p < 0,01$ and $p<0,001$

This increase in overall morbidity was affected by a number of factors: the execution of combat missions in the combat area mostly by officers and contracted solders who had acute or delayed response on combat stress; low quality of mobilized servicemen selection.

DISCRIMINANT MODEL OF MENTAL AND BEHAVIOR DISORDERS IN COMBATANTS

Patterns of mental disorders in combatants. The next own study was based on using specially designed questionnaire for study adjustment disorders at hospital condition. All data corresponded to normal distribution, so the residual analysis of multiple regressions between the deployment time and different negative psychophysiological feelings after returning from armed conflict zone during rehabilitation in hospital conditions showed such phenomenon as overstressing negative feelings after 4 months of stress impact. Present troubles in feelings of the patients overstress in the future (Fig. 4). Therefore, this period is also important for further psychological rehabilitation at the outpatient level of care and for appropriate detection of depression due to overstressing negative feelings by combatants after 4 months from traumatic events.

Using a cluster analysis (criterion was *K-means*) of adjustment disorders characteristics including intrusive thoughts and anxious avoidance it was selected two groups of people who had significantly ($p<0.001$) different their levels. After that, forward stepwise discriminant analysis of the physiological stress characteristics and hardiness (commitment, control and challenge) of these selected groups has been used to figure out the most informative indicators of adjustment disorders due to stress.

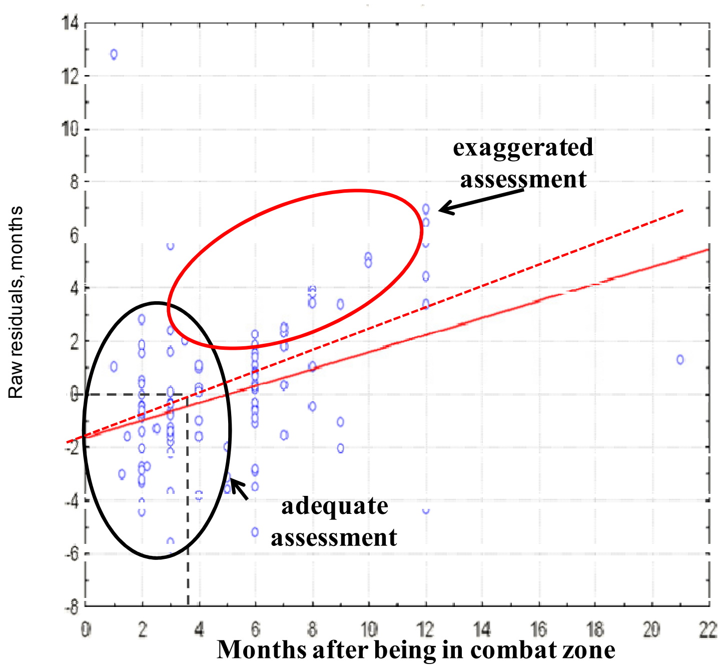

Fig. 4. Trends of enhancing negative feelings of military personnel after deployment in combat zone.

The resulting discriminant model has a high level of predictability ($p < 0.001$) for classification of individuals by their dividing into two groups with different levels of adjustment disorders due to stress using such 3 items in 10-point scale (from min to max manifestation) as:

- Rate of cases of Startle Reflex after Unpredictable Situation (SR is a brainstem reflectory reaction that serves to protect vulnerable parts, such as the back or the neck and facilitates escape from sudden stimuli);
- Feeling to be Alone Among Friends (FAAF);
- Apathy to Work due to Problems (AWP). .

The decision support model for predicting of further adjustment disorders after extreme conditions is as follows:

$$U1=-2,38+ 0,65* SR + 0,43* FAAF +0,45* AWP;$$

$$U2=-7,47+ 1,20* SR + 1,02* FAAF +1,03* AWP.$$

If U1 <U2 — respondent belongs to “risk group” of possible further adjustment disorders after extreme conditions. This model allows to determine the identity of the subject to a group of "risk" with high probability — 98% ($p < 0,001$).

According to research performed in our Institute [22] the structure of mental disorders among military personnel who were treated in hospital conditions had certain characteristics. Volunteers and mobilized people had mental disorders in 41–42% of all cases (Fig. 5.A).

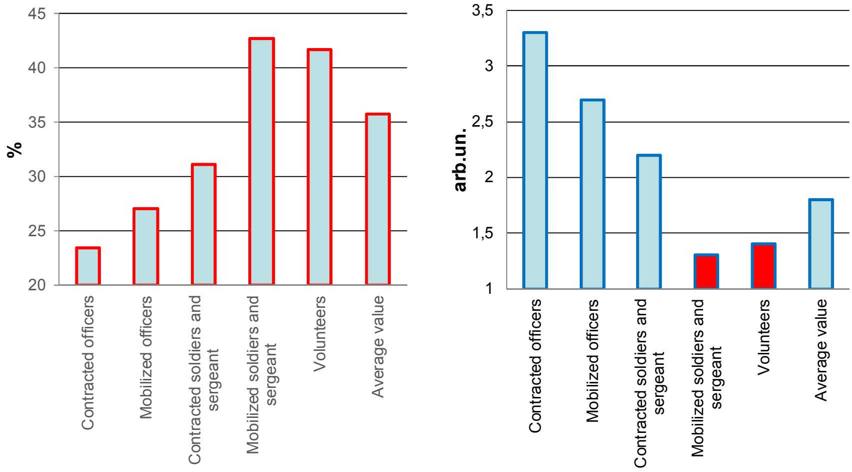

Fig. 5. Features of mental disorders among military personnel in hospital condition. A — with mental disorders, %; B — the relation of personnel without mental disorders to the number of those who had them.

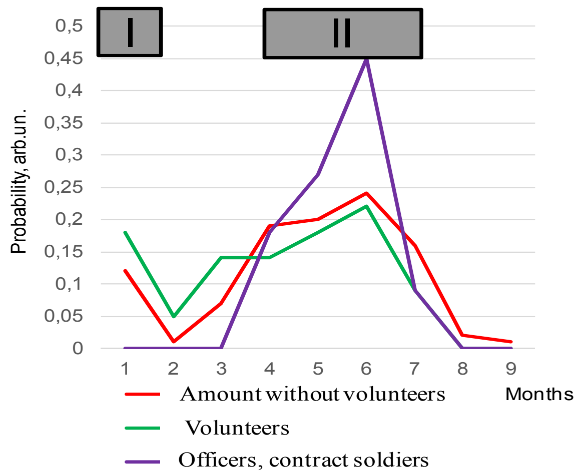

Fig. 6. Probability of mental disorders manifestation among warfare participants depending on the combat deployment time.

Moreover, among 13–14 volunteers, mobilized soldiers and sergeants nearly ten people had mental problems (the relations of personnel without mental disorders to the number of those who had it were 1:1,3 and 1:1,4; Fig. 5.B). Thus, the greatest manifestations of mental disorders were revealed in volunteers and mobilized people (71–77% of volunteers and mobilized soldiers and sergeants had mental problems) treated at hospital conditions in 2015.

The next stage of research was to find patterns of mental disorders in combatants depending on the deployment time in combat zone (Fig. 6).

The highest prevalence of mental disorders was found during the first and 6th months. It is important to note that officers and contract solders are the most vulnerable to the development of mental disorders while staying in combat zone around six months.

*Suicide problem.*In our research [23] the frequency of suicide in Ukrainian Armed Forces was 7.2% among all dead from March 2014 to January 2016 and this number was in 3 times higher in 2015 compared to 2014. 42.9 % of suicide were committing in combat area, 57.1% were committing outside combat zone. 68.4 % of suicides were committed at off-duty time. The largest number of suicides were committed by rank and file (65 %), sergeants committed suicide three times less (22%). 11 % of the suicides were officers and the lowest number was marked among civilian employees (2 %). Contracted military personnel could be characterized by more than half (55 %) suicide cases than mobilized solders (43 %). Most of the suicides among military personnel were committed as a result of firearms use (48 %) or by hanging (41 %), much less by blasting agents and other ways (7 %).

The crucial difference in monthly indicators of suicides was observed in June and December, when these rates in 2015 were higher almost in two times comparing with 2014. The highest rates of suicides in May, July, September and November were common features in annual suicides structure at the period of 2014–2015.Thus, combatants had both relatively high rates of hetero- and auto-aggression behavior in combat area and in reintegration period after demobilization.

Our data was also corresponded with official statistics of Ukrainian Prosecutor General's Office [24]. From April 2014 to June 2016 servicemen had committed 259 suicides, 148 deaths were corded due to the accident, 121 premeditated murder, 111 violations of weapons and ammunition handling, 40 cases of safety measures violations and 112 were traffic accidents. It is important that the length of participation in military conflict had an excessive impact on the number of completed suicides. So, at the period from May 2015 to October 2016 40.2% of suicides were committed by those who took part in combat environment more than half a year, 34.1% of suicides were committed by those who took part in the ATO for 3–6 months [24].

DEVELOPMENT OF THE PSYCHOMEDICAL INTERVENTION MODEL IN UKRAINIAN ARMED FORCES

The resulting patterns should be taken into account for developing the psychomedical intervention model. For it proper understanding I proposed the definition of psychomedical aid as a complex of general health measures carried out by mental health professionals in the event of combat stress, its consequences, as well as in order to prevent the maximum reduction of traumatic situations impact on human health, support and/or rapid recovery mental health and psychophysiological functions of servicemen in order to achieve a high level of mental and physical ability (combat proficiency).

The developed Psychomedical intervention model was based on Mental Health Continuum Model accepted by NATO countries. In the first stages of mental disorders progression, the most important role in preserving mental health belongs to the commanders (Fig. 7).

Psychomedical aid should be carried out on all levels of medical evacuation (levels of medical care) in accordance with the main measures of care for acute stress reaction. When moving from one level to another, the capacity of care increases, while the number of individuals requiring psychomedical aid decreases.

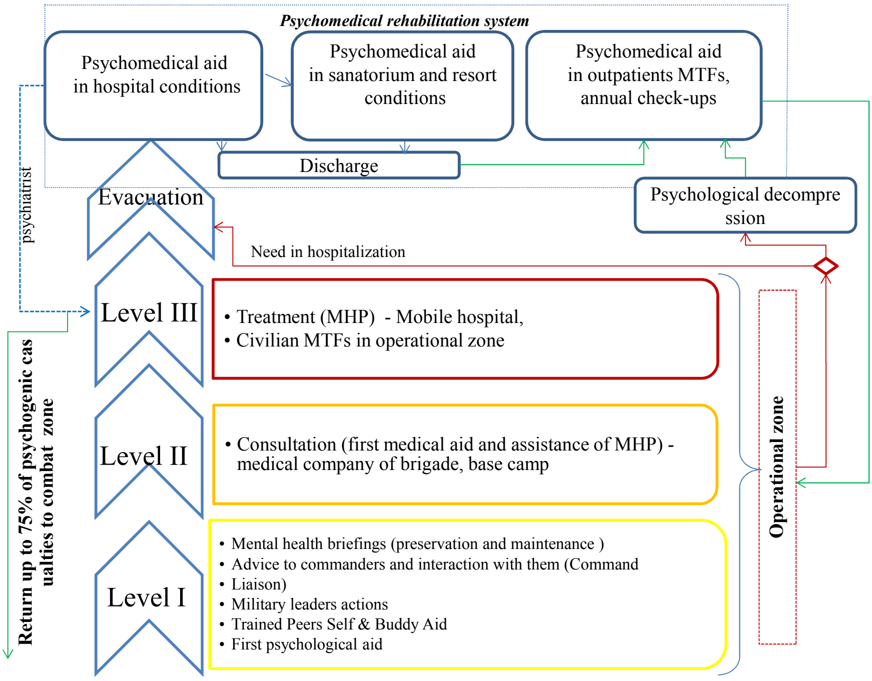

Fig. 7. Psychomedical intervention model in Ukrainian Armed Forces.

Level 1 support is the first line of support and includes leadership actions, self help and "buddy" support. This level normally occurs immediately following a potentially traumatic event and represents the most frequently in-demand level of support.

Level 2 support consists of a combination of medical and psychological assistance (provided by medical personnel of the military unit and mental health professionals).

And Level 3 support involves assessment and treatment services by mental health professionals.

After units' departure it is desirable to carry out measures of psychological decompression and the allocation of a group who need hospital medical care. I would like to note that due to the deployment of psychiatrists as reinforcement groups to the mobile hospitals, it was possible to significantly reduce (75% of cases were returned to their duties) the movement of patients with mental and behavioral disorders to the higher level MTFs for psychomedical rehabilitation.

The organization of psychomedical aid is based on the principles of timeliness and accessibility, in accordance with the current level of scientific knowledge; necessity and adequacy of medical measures with minimal social and legal restrictions; consistency (implementation of medical and psychological assistance at the following levels with increasing capacity); continuity (the relationship between the stages of medical care with the capacity of medical and psychological aid, the maintenance of medical documentation); legality, humanity.

Psychomedical aid should not be performed only in military conflict context, it must be ensured in peacetime daily activities, which will ultimately contribute to maintaining the combat capability of the troops.

DISCUSSION

In this study it was summarized available information on psychomedical consequences of warfare among military and demobilized persons through the last years. At the beginning of 2017 the situation has been slightly improved. At present time mental and behavioral disorders in the structure of therapeutic casualties among military personnel in combat zone were 4.9% at the beginning of 2017, 77.5% of them were neurotic, stress-related and somatoform disorders.

These data, on the one hand, can be explained by decreasing intensity of armed conflict and psychogenic casualties in turn, implementation of preventive measures, better organization of psychomedical care in combat area, but on the other hand — by "stigma". For example, in studies [25] carried out on 450 servicemen (aged from 19 to 54 years) that took part in military conflict from August 2014 to March 2015, it was indicated that the most of people avoided any talks about traumatic events which negatively affected their emotional, psychological and physiological state, and they often resorted to such defense mechanism as "avoidance"(41.6% of cases). Almost 36% of servicemen did not want "invasion" into their emotional sphere and they were not involved themselves emotionally in other situations. Some of ATO participants who were affected by psychological trauma displayed insomnia, excessive vigilance, exhaustion, escape into alcohol and others [25].

In this study at the first time the assessment of stress factors impact at combat environment (physical, informational, organizational and anticipation) on military personnel participated in military conflict has been done. The stability of working capacity is probably influenced by the expected threat, that is, the true or false prediction made by the person of some future collision with any dangerous situation and its assessment. The correlation of the anticipation factor with the manifestation of working capacity will be traced and also identified the conditions affecting it. Moreover, the decision support model to predict further adjustment disorders after extreme conditions has been created for developing the psychomedical intervention model in Ukrainian Armed Forces. The revealed 3 items including into discriminant model correspond with a new criteria of PTSD (ICD-11 for Mortality and Morbidity Statistics, class 6B40) and in addition give opportunity quantitatively predict further adjustment disorders after extreme condition. Presented research is not without flaws that are associated with the multidirectional vectors of the scientific searching of domestic authors. But, at the same time, an attempt was made to systematize them. Regarding own research, it contributed to the development of new pragmatic proposals to the military system of mental healthcare.

At the present time, we still don't have wide knowledge about the mechanisms of high reserves of working capacity manifested combat stress in extreme conditions. One can only assume that human reserves are hidden in the potentials of its redundancy (in the psychophysiological mechanisms of duplication of functions' regulation, in various forms of compensation).

Preliminary analysis of presented data allowed us to describe the set of the consequences of the trauma. These results may help for future reorientation of National mental health system, taking into account military needs. That's why the comprehensive National strategy for mental health care of veterans [26] should include continious systematic monitoring of mental health and risk assessment among military personnel, programs for prevention of drug addiction and alcohol abuse among soldiers and veterans, suicide prevention programs for military personnel etc.

THE PERSPECTIVE FOR THE FURTHER SCIENTIFIC RESEARCH

The research on recovery period is interesting because precisely in this period the psychophysiological mechanisms of compensation by regulatory functions are forming in the human body. For example, such complex concepts as tolerance, patience or resistance to the effects of stress factors, apparently, in some way are related to human serviceability, reliability and working capacity. And, if we understand this interaction, we can propose some measures aimed to overcoming the effects of stress.

CONCLUSIONS

The analysis of available information on psychomedical consequences of warfare among military and demobilized persons shows that 2015 was the year of the highest surge of mental disorders (adjustment disorders, drug abuse (mainly alcohol), suicides, hetero- and auto-aggression behavior etc.) and 25.1% of military personnel was unfit to military service due to mental health problems.

At the beginning of 2017 the situation has been slightly improved due to decreasing intensity of armed conflict and psychogenic casualties in turn, implementation of preventive measures, better organization of psychomedical care in combat area, and "stigma". The greatest influence on the stress formation of combatants had "anticipation" factors as well as not much less pronounced "physical", "informational" and "organizational" environmental factors. Research permits to conclude that some of them significantly influence on the psycho-emotional state of military personnel and can be grouped into two main factors: the 1st — factor of negative future prediction and the 2nd - factor of negative impact of physical environment.

The phenomenon of exaggerating of negative feelings among servicemen after the 4th-month impact of the stress factors has been discovered.

The decision support model to predict further adjustment disorders (F43.2) after extreme conditions has been proposed for developing the Psychomedical Intervention Model in Ukrainian Armed Forces.

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Resieved 04.03.2019

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Получено 04.03.2018

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УДОСКОНАЛЕННЯ МОДЕЛІ МЕДИКО-ПСИХОЛОГІЧНОЇ ДОПОМОГИ ВІЙСЬКОВОСЛУЖБОВЦЯМ НА ОСНОВІ ДОСЛІДЖЕННЯ МЕНТАЛЬНИХ РОЗЛАДІВ

Вступ. Багато вітчизняних і закордонних експертів вивчають різні аспекти проблеми психічного здоров'я в бойових умовах, проте все ще існує велика кількість невирішених питань щодо медико-психологічних наслідків гібридної війни в Україні.

Мета статті — дослідити вплив різних шкідливих чинників в бойовому середовищі на психологічний статус і психічне здоров'я військовослужбовців і колишніх комбатантів для розробки моделі медико-психологічної допомоги.

Матеріали та методи. Матеріали дослідження було засновано на вивченні понад 200 військовослужбовців в різних умовах і стані здоров'я з використанням власних і загальноприйнятих опитувальників з подальшою описовою статистикою і багатовимірним аналізом даних. Було проведено бібліосемантичний, інформаційно-аналітичний порівняльний аналіз вітчизняних публікацій за останні 4 роки для узагальнення національного досвіду щодо психологічних наслідків збройного конфлікту в Україні.

Результати. Проведено ретроспективне узагальнення наявної інформації про медичні і психологічні наслідки гібридної війни за останні роки, що стосується характеристик цих наслідків на військовослужбовців і демобілізованих осіб. Проведено оцінку впливу стресових факторів бойового середовища (фізична, інформаційна, організаційна та антиципаційна) на військовослужбовців, які брали участь у військовому конфлікті, які були згруповані в два основні чинники. Виявлено особливості та структуру психічних розладів у військовослужбовців, які проходили лікування в умовах стаціонару. Розроблена модель підтримки прийняття рішень для прогнозування подальших розладів адаптації після перебування в екстремальних умовах має високий ступінь достовірності ($p < 0{,}001$).

Висновки. Найбільший вплив на формування стресу у комбатантів надали чинники «антиципації», а також, що не менш виражені, «фізичні», «інформаційні» і «організаційні» чинники середовища. Дослідження дозволяють зробити висновок про те, що деякі з цих факторів істотно впливають на психоемоційний стан військовослужбовців і можуть бути згруповані в два основні чинники: 1-й — фактор негативного прогнозування майбутнього і 2-й — фактор негативного впливу фізичного середовища. Виявлено феномен перебільшення негативних відчуттів у військовослужбовців після впливу стресових факторів на 4-й місяць. Розроблена модель підтримки прийняття рішень для прогнозування подальших розладів адаптації (F43.2) після екстремальних умов доповнила розвиток сучасної моделі медико-психологічної допомоги в Збройних Силах України.

Ключові слова: модель медико-психологічної допомоги, модель підтримки прийняття рішення, психічне здоров'я, розлади адаптації, посттравматичний стресовий розлад, стресові фактори.

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УСОВЕРШЕНСТВОВАНИЕ МОДЕЛИ МЕДИКО-ПСИХОЛОГИЧЕСКОЙ ПОМОЩИ ВОЕННОСЛУЖАЩИМ НА ОСНОВЕ ИССЛЕДОВАНИЯ МЕНТАЛЬНЫХ РАССТРОЙСТВ

Ввведение. Многие отечественные и зарубежные эксперты изучают различные аспекты проблемы психического здоровья в боевой обстановке, однако все еще существуют многие нерешенные вопросы относительно медико-психологических последствий гибридной войны в Украине.

Цель статьи — исследовать влияние различных вредных факторов в боевой среде на психологический статус и психическое здоровье военнослужащих и бывших комбатантов для разработки модели медико-психологической помощи.

Материалы и методы. Материалы исследования были основаны на изучении более 200 военнослужащих в различных условиях и состоянии здоровья с использованием собственных и общепринятых опросников с дальнейшей описательной статистикой и многомерным анализом данных. Был проведен библиосемантический, информационно-аналитический сравнительный анализ отечественных публикаций за последние 4 года для обобщения национального опыта касательно психологических последствий вооруженного конфликта в Украине.

Результаты. Проведено ретроспективное обобщение имеющейся информации о медицинских и психологических последствиях гибридной войны за последние годы, касающееся характеристик этих последствий на военнослужащих и демобилизованных лиц. Проведена оценка воздействия стрессовых факторов боевой среды (физическая, информационная, организационная и антиципационная) на военнослужащих, участвовавших в военном конфликте. Выявлены особенности и структура психических расстройств у военнослужащих, проходивших лечение в условиях стационара. Разработанная модель поддержки принятия решений для прогнозирования дальнейших расстройств адаптации после пребывания в экстремальных условиях имеет высокую достоверность ($p < 0{,}001$).

Выводы. Наибольшее влияние на формирование стресса у комбатантов оказали факторы «антиципации», а также, не менее выраженные, «физические», «информационные» и «организационные» факторы среды. Исследования позволяют сделать вывод о том, что некоторые из этих факторов существенно влияют на психоэмоциональное состояние военнослужащих и могут быть сгруппированы в два основных фактора: 1-й — фактор негативного прогнозирования будущего и 2-й — фактор негативного воздействия физической среды. Обнаружен феномен преувеличения негативных ощущений у военнослужащих после воздействия стрессовых факторов на 4-й месяц. Разработанная модель поддержки принятия решений для прогнозирования дальнейших расстройств адаптации (F43.2) после экстремальных условий дополнила развитие современной модели медико-психологической помощи в Вооруженных Силах Украины.

Ключевые слова: модель медико-психологической помощи, модель поддержки принятия решения, психическое здоровье, расстройства адаптации, посттравматическое стрессовое расстройство, стрессовые факторы.

ДО УВАГИ АВТОРІВ!

У журналі надано результати досліджень в галузі теорії і практики інтелектуального керування, інформатики та інформаційних технологій, а також біологічної і медичної кібернетики.
Цільова аудиторія- науковці, інженери, аспіранти і студенти вищих навчальних закладів відповідного фаху.

Вимоги до рукописів статей

1. Рукопис надають на папері у двох примірниках (мова – англійська, українська, російська, 17-22 с.) та електронна версія. До рукопису додають:

• анотації – українською та англійською мовами (прізвище, ініціали автора/ів, місце роботи, місто, країна, назва статті, текст 250 -300 слів, з виділенням рубрик: вступ, мета, результати, висновки, ключові слова), російською мовою (УДК, прізвище, ініціали автора/ів, назва статті, 7-9 рядків тексту, ключові слова (5-8 слів);

• список літератури на мові оригіналу - в порядку згадування в тексті, за стандартом ДСТУ 8302:2015;

• список літератури - переклад джерел англійською мовою, прізвища та ініціали авторів - транслітерація:

• ліцензійний договір;

• відомості про автора/ів українською, англійською та російською мовами повинні містити: ПІБ, вчений ступінь, наукове звання, посада, відділ, місце роботи, поштова адреса організації, телефон (для зв'язку редактора), E-mail, авторські ідентифікатори ORCID або ResearcherID.

2. Текст статті подається з обов'язковими рубриками: вступ, постановка завдання/проблеми, мета, результати, чітко сформульовані висновки.

Вимоги до текстового файлу

Формат файлу * .doc, * .rtf. Файл повинен бути підготовлений за допомоги текстового редактора Microsoft Word.

Використовувані стилі: шрифт Times New Roman, 12 пт, міжрядковий інтервал – 1,5. Формат паперу А4, всі береги - 2 см.

Формули набирають у редакторі формул Microsoft Equation Editor 3.0. Опції редактора формул - (10,5; 8,5; 7,5; 14; 10). **Ширина формул -до 12 см**.

Рисунки повинні бути якісними, створені вбудованим редактором рисунків Word Picture або іншими Windows-додатками (рисунки надають окремими файлами відповідних форматів). **Ширина рисунків - до 12 см**.

Таблиці виконують стандартним вбудованим у Word інструментарієм «Таблиця». **Ширина таблиці - до 12 см**.

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