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ELECTRONIC SYSTEM OF BIOMETRIC CONTROL OF PSYCHOPHYSIOLOGICAL STATE OF PILOTS

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Abstract: The physical phenomena underlying the methods of pulse oximetry and electrocardiography used in medical diagnostics of blood vessels are analyzed. While studying the data processing algorithms, we selected the most optimal one that is based on nonparametric criteria of mathematical statistics. This allowed us to conduct a real-time diagnosis of the physiological state in the complex under development.

Key words: syncope condition, pulsometry, electrocardiography, monitoring, pulse oximeter, diagnostic complex, psychophysiological state.

1. Introduction

In recent years, more than 80 % of air crashes are related to the so-called “human factor” – i.e. inadequate actions of pilots, caused by their negative psycho-emotional or stressful physiological state, impaired movement coordination and short-term loss of consciousness in extreme situations. This relates to both routine mass passenger transportation by air and modern military aviation/aircraft. In order to prevent syncope conditions and, thus, air crashes, the development of methods and technical means for operational control and monitoring of the pilot's body state throughout the flight is certain to be relevant. In this regard, it is advisable to create a compact device that is placed on the body of the operator of high-speed motion and provides rapid collection and processing of data from biometric sensors. At the same time, existing modern electronic technologies allow the use of standard superminiature low power sensors able to quickly read the entire complex of human biometric characteristics and send the received information through wireless communication for processing and decision making.

2. Statement of problem

The development of modern aviation in terms of the creation of high-speed aircraft of high maneuverability is resulted from the improvement of technical means, which provide the increase in the tactical and technical characteristics of the aircrafts [1]. At the same time, the physiological capabilities of the human operator become one of the main barriers to the further development of aircraft technology due to the restrictions imposed by pressure drops, lack of oxygen and large overloads during the flight [2]. The deterioration of pilots’ state is caused by a temporary disruption of normal blood flow and oxygen supply to the brain, up to a short-term loss of consciousness (syncope conditions), which ultimately leads to air crashes and the death of the aircraft crew and passengers. The average duration of the unconscious state is 15 seconds or more, it takes a few more seconds to regain consciousness. Therefore, the entire period of loss and restoration of consciousness takes about 25 seconds.

Due to the widespread use of high-speed technology in recent years, both in our country and abroad, there has been an increase in the proportion of aviation accidents that are directly or indirectly caused by the syncope conditions.

The most sensitive methods for early detection of the initial signs of impaired normal functioning of the human body under stress are the recording of the frequency of blood pulsation in the arteries and the assessment of oxygen saturation (pulsometry), the determination of the frequency and regularity of heart beats (ECG). Here it should be noted that the choice of informative parameters for controlling the psychophysiological state of the person (in this case – the pilot) is still not the ultimately solved problem, therefore our choice is largely a controversial proposal.

3. Literature review

The problem of ensuring the safety of flights, and the prevention of air crashes depend to a great extent on the state of health, the uninterrupted preservation of performance and the adequacy of the pilot’s behaviour in extreme conditions. It is practically impossible to solve this problem without the use of modern technical means for monitoring the functional state of the pilot's body during the entire flight. However, despite numerous attempts to develop different systems of continuous direct and indirect determination of indicators of the physiological state of the pilot [3, 4], the problem remains unresolved.

Disadvantages of pulse oximetry are usually considered in terms of restrictions directly to plethysmography and spectrophotometry [5]. The error of indicators is observed at insufficient blood flow or insufficient hemoglobin level in the blood in anemia (tissues may suffer from hypoxia despite high oxygen saturation in the blood); during the movement of the patient (for example, when coughing, muscle tremor, convulsions, distance and optical density between the LED and the photodetector change resulting in to the appearance of artifacts); in carbon monoxide poisoning, which binds more quickly to hemoglobin and may delay hypoxia recognition. The most common cause of measurement errors is electromagnetic interference, including mobile phones, nearby equipment. Bright light in the room may also distort the pulse oximeter signal.

Trainings held in the the hydro pool at Yu. Gagarin Cosmonaut Training Centre aimed at practicing methods of extravehicular activity at the orbital stations “Mir” and “Alpha” established that in the loss of consciousness, the instantaneous pulse values reach 180-200 beats per minute, the electrocardiogram may show single extrasystoles and the appearance of tachycardia or fibrillation All these factors dramatically change the oscillatory mode of the cardiac muscle and thus disrupte the sequence of cardiointervals [6]. In this case, the main ECG-signs of extrasystoles are: extensive QRS complexes, differing in form from the “correct”; absence of the tooth *P*; absence of the prolonged diastolic pause (distance *R-R* between extrasystoles is equal to two “correct” distances). In the case of tachycardia or fibrillation, the frequency of heart beats increases, there is a chaotic contraction of the fibers of the myocardium at a frequency of 250-480 per minute. In this case, the electrocardiogram does not define the tooth *P*, the *QRS* complex is changed.

According to the results of the experiments and given the significant influence of overloads on cardiac rhythm and its oscillatory mode of operation, [7] has proposed a method for determining the adequacy of the load P_{load}, calculated as follows:

$$P_{load} = k \cdot \mathrm{M} / (\mathrm{N} \cdot \sigma),$$

where k is the coefficient taking into account the individual characteristics of the state of the pilot's body in the region of high levels of tension and is within $\mathrm{k}=(1,0-1,25)\cdot \mathrm{s}$; M – stands for the number of the most common R-R-intervals; N – represents the number of the measured R-R-intervals (sample size); σ – denotes the estimation of standard deviation of R-R-interval.

Hypoxia is observed when the partial pressure of oxygen in the inhaled air is lowered when flying at high altitudes. It is noted that with height increasing, the partial pressure of oxygen in the human alveolar air decreases much faster than in the atmospheric air. Thus, with the partial pressure of oxygen in the atmospheric air being reduced by 1/3, in the alveolar air, it decreases by 1/2. The rate of arterial blood oxygen saturation (saturation) (SaO_2) is 95 %. In critical cases of hypergravatsia or, conversely, of oxygen deficiency (in the case of altitude illness), saturation can decrease to 65 %. Acute hypoxia is also accompanied by an increase in the frequency and depth of breath and an increase in the frequency of heart beats [8].

Overload affects almost all systems of the body. Consequences of accelerations, in particular, manifest themselves in disruption of cerebral circulation, which can cause complete loss of vision, loss of consciousness, and, with significant overloads, possible fatality. The main cause of the physiological conditions described above is considered to be cerebral hypoxia and cardiac arrhythmias. It is advisable to use non-invasive instrumental research methods for the rapid detection of critical states of pilots. The most promising ones are: pulse oximetry and electrocardiography.

4. Basic part

A Texas Instruments ADS1294R microcircuit was selected to receive the electrocardiogram. It contains:

– 8 low noise amplifiers with programmable gain and low noise (PGAs);

– 4 parallel operating ADCs with 24-bit resolution;

– a built-in amplifier for the right leg electrode;

– built-in amplifiers for central Goldberg electrodes (GCT) and Wilson electrode (WCT);

– continuous determination of the availability of contact between the electrodes and the human body;

The ADS1294 has a noise level down to the 4-uVpp input that is significantly better than the limits set in IEC60601-2-27/51, providing more precise measurements in portable applications and professional high-density ECG equipment;

– the ECG circuit does not require multiple external filters, they are included in the ADC circuit.

– the ability to measure tissue impedance at frequencies of 32 kHz and 64 kHz.

An AFE4490 microcircuit manufactured by Texas Instruments was also used to receive signals from the pulse oximeter. The AFE4490 is a fully integrated analogue device designed for the use in pulse oximetry. It consists of a driver of emitting LEDs and input cascades with amplifiers and ADCs to register a photocurrent from 2 input channels that operate at different wavelengths. A controlled LED driver allows you to set the required current passed through red and infrared LEDs, as well as to vary the brightness of each channel individually. It is also possible to set up an algorithm for polling photodiodes and to realize the possibility to reduce the level of external noise overload.

To measure a respiratory phase, a flexible variable resistance sensor was used. A conductive track is applied on a polymeric basis. As the sensor bends, the conductivity of the track changes, and the total resistance of the sensor changes. The additive technologies used contributed to the design of a device intended for determining the change in the volume of the chest by measuring the resistance of the bending sensor (Fig. 1). Breath registration was performed by determining the change in the chest volume, the corresponding sensor being attached with belts at the top of the chest.

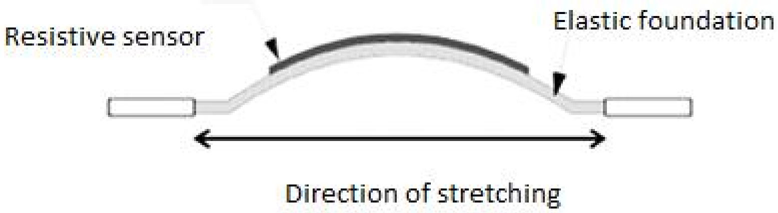
The main element of the breathing sensor was a sensor that changes its electrical resistance in proportion to the degree of bending. In order to measure linear deformation (increase in chest volume during inhalation) and apply a resistive bend-sensing sensor using additive technologies, a special plastic spring was used – Fig. 1.

The resistive sensor was glued to the plastic spring, and in the process of linear stretching of the spring, there occured a bend of the resistive sensor. Due to the fact that the bend of the sensor led to insignificant changes in its resistance, it was necessary to use a device of pre-amplification of the useful signal. To amplify the signal, a device based on the OPA2348 operational amplifier switched on in the differential amplifier mode was used. A signal from the resistive sensor was fed to the non-inverting input, and a signal from the voltage divider with a potentiometer installed on one of their sides to select a point of relative gain was received at the inverting input. The output of the operational amplifier was protected by diodes to prevent the output voltage from going out of the given range. The block diagram of an electronic device of the diagnostic complex based on the ECG, pulse oximeter and breathing sensor is shown in Fig. 2.

For the organization of synchronous work of the described specialized chips and pre-processing of the received data, a 32-bit ARM Cortex-M4 microcontroller STM32F407 was used. Transmission of the received data to the personal computer was carried out via an interface chip FTDI 2232H. The chip was chosen because it allowed high-speed data transfer from the peripheral device to the personal computer via USB interface. During operation, this chip was configured to transfer data through an asynchronous buffer, by recording data being downloaded into the EEPROM chip.

The speed of the interface chip in this mode can reach 30 Mbps. Connection to specialized microcircuits of the electrocardiogram and pulse oximeter was performed using the universal serial data interface SPI.

The chest volume sensor has an analogue output at which the voltage set is proportional to the current respiratory phase of the person under examination. Subsequent digitization of the analogue signal was carried out by a 12-bit analogue-to-digital converter built into the STM32F407 microcontroller. A 2-line LCD display was used to indicate the current status of the device and output individual settings, and an incremental encoder was provided for controlling the device during operation.



a

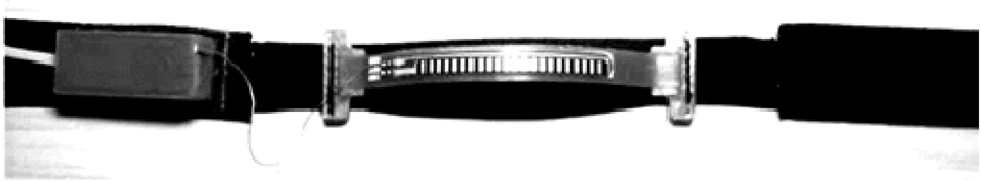


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Fig. 1. Schematic representation of the principle of the breathing sensor operation (a) and the appearance of the breathing sensor (b).

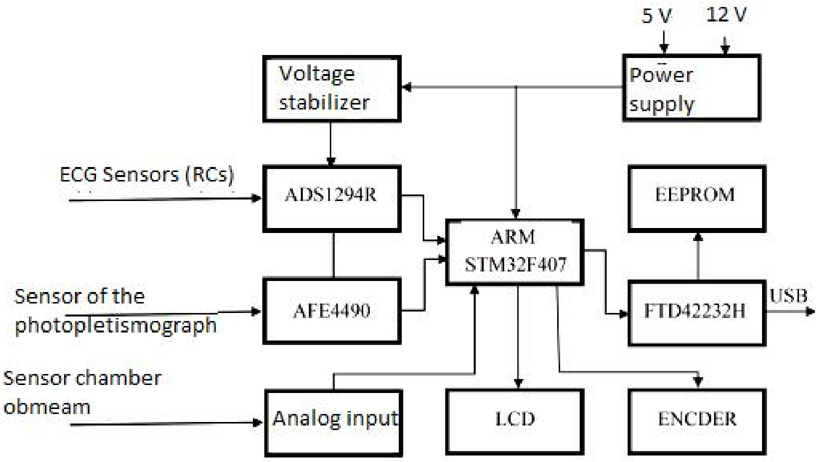


Fig. 2. Block diagram of the electronic device of the diagnostic complex.

Particular attention was paid to the organization of noise immunity of the device. Microcircuits of an electrocardiogram and a pulse oximeter are highly sensitive to interference produced by a power supply, so when developing the device, several stages of input voltage filtration and low-noise voltage stabilizers were used. Also, in the area of the printed circuit located near the sensitive chips, a separate fill was implemented, combined with a global “ground” at one junction point to eliminate current loops and reduce the antenna effect.

5. Experiment

The waveform of the variable pulse component may be associated with a change in the volume of arterial blood that occurs during inhalation, changes in blood flow, changes in the activity of the nervous system, etc. The waveform of the signal should also change when exposed to external overloads due to changes in transmural pressure (pressure difference on both sides of the vessel wall). Thus, it is necessary to analyze the graphic waveforms of the received signals and the values of parameters at different states of the body.

Fig. 3 shows the input data synchronously fed from the electrocardiogram and pulse oximeter. The upper graph represents the result of the ECG, taken from the 1st classic deflection. The two lower graphs represent the changes in the intensity of red and infrared light, respectively, reflected from the measured volume of tissues on the front of the operator's head.

For further processing several parameters were selected to characterize the functional state of operators in real time (Fig. 3).

Results. Currently, there are many methods that determine the functional state of the operator in terms of heart rate. These methods are based on the recognition and measurement of time intervals between R – ECG teeth (R – R intervals), on the construction of dynamic series of cardiointervals (CI) and subsequent analysis of numerical series by various mathematical methods. To evaluate the heart rate variability, a series of successive KIs are recorded, their duration is measured and a mathematical processing of the dynamic range of the obtained values CI is performed. The methods of time (statistical) and frequency (spectral) analysis of cardiac rhythm variability are the most widely used in practice.

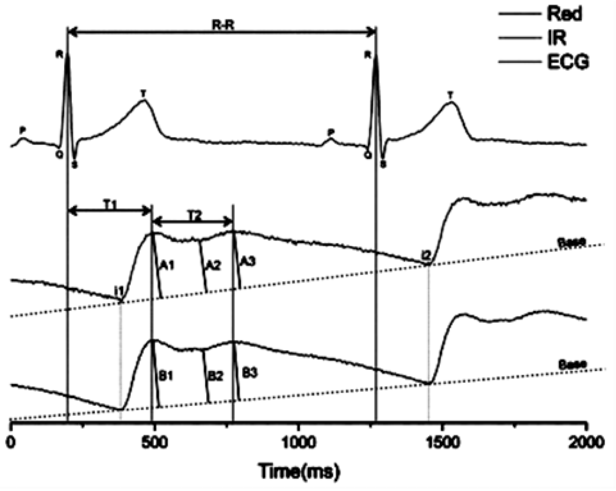


Fig. 3. Graphical representation of synchronously received ECG signals and their defined parameters.

The statistical analysis of the duration of the CI involves presentation of the law of the distribution of the random process – the heart rhythm in the form of a histogram, characterized by a set of statistical parameters and diagnostic indicators that reflect the activity of the autonomic nervous system.

One of the important steps in determining statistical estimates is the choice of the size of the length of the sample to be processed, which may be fixed both during the analysis and determined by its results. Typical values of duration are in the interval of 20…60 ms, and with the physical or emotional load in the state of adequate mobilization, these values are reduced. This can cause a jump-like increase in the tension index, since the interval of the partition becomes less than the variational scale.

There is an optimal number of grouping intervals, which provides the best approximation of the step bypass histogram to the smooth distribution curve of the general population.

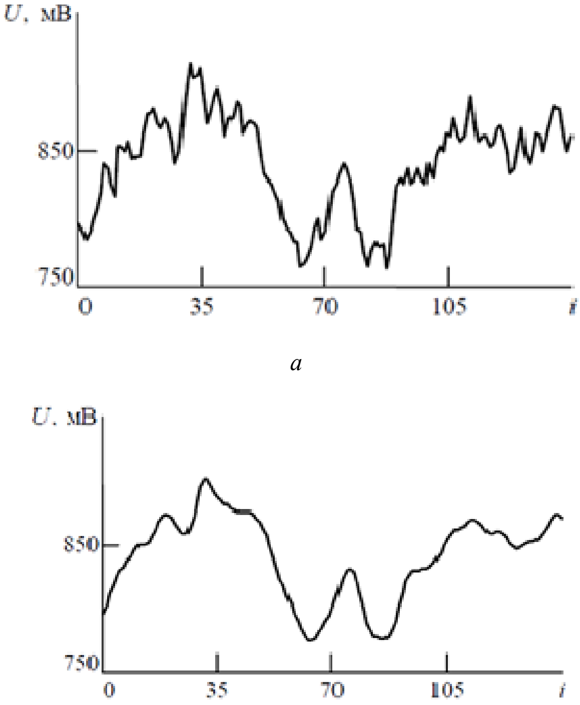
When the data is split into too many small intervals, some of them will be empty or underfilled resulting in a overly comb-shaped histogram.

On the contrary, the use of a small number of extended intervals can lead to the loss of characteristic distribution features that are lost in the determination of parameters within the intervals. In the extreme case, if the grouping interval is equal to the variational range of the experimental data, then any distribution will be reduced to a uniform one.

Also important is the accuracy of R-R-intervals calculation, which depends on the sampling rate of the electrocardiographic signal and the algorithm for selecting these teeth by software. At loads, the variational range substantially decreases and can be about 10 ms. The total accuracy of the allocation of the R-tooth should not exceed 10 % of this value, i.e. it should be no more than 1 ms, which corresponds to the sampling rate of the hardware of 2000 Hz. The hardware implementation of this value in electrocardiographic devices does not represent any technical complexity, therefore the accuracy of the allocation of such teeth is determined by the software tools for detecting the point of the vertex R-tooth on the background of various interferences.

The first operation of processing a series of KI is the removal of abnormal values, which due to single occurrence are not subject to statistical processing, but affect the resulting parameter estimates. This operation is performed by digital filtering, the algorithm of which allows unreliable estimates of R-R-intervals to be rejected from this sample. One of the algorithms that solve this problem is an interval rejection algorithm that stores the values of the intervals corresponding to the condition $\left|(RR_i - RR_{i-1})/RR_i\right| < 1 - a$, where a is the coefficient of filtration.

When using this algorithm, it is assumed that the filter coefficient is adjusted to the length of the R-R-interval. Such treatment is used, in particular, to remove perturbations caused by respiratory cycles. The original sample (Fig. 4a) is averaged over three neighboring branches (Fig. 4b). In the event that such processing is found to be inadequate, they are converted to averaging over five neighboring branches (Fig. 5), which significantly reduces the manifestations of narrow cardiac output.



a

b

Fig. 4. a – original sample of the ECG signal; b – averaged sample of three elements.

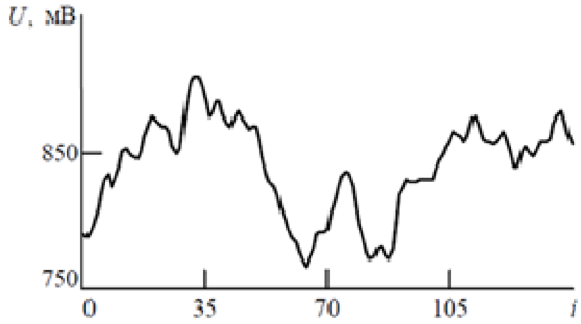


Fig. 5. Averaged sample of five neighboring elements.

6. Discussion

After the transformations of the initial series of R-R-intervals into a quasi-stationary one, it is possible to analyze the statistical parameters and system-forming characteristics of the psycho-physiological state and make a diagnosis.

It should be taken into account that the volume of the processed array of R-R-intervals (sample size) should be minimized to obtain values of the real-time stress index on board of a super-maneuverable aircraft, where aerial loading follows one after another and lasts only a few seconds. However, it is necessary to obtain reliable values of the statistical parameters reflecting the psychophysiological state of the operator in real time.

The algorithm satisfying the requirements set can be formed on the basis of nonparametric criteria of mathematical statistics. In assessing the differences between the two groups of observations in terms of mathematics, it is necessary to determine whether these groups belong to the same distribution (this would mean that there are no reliable differences between them) or whether they should be assigned to different distributions with a certain degree of probability. For the processing to be implemented on the basis of nonparametric criteria, an algorithmic support for carrying out research involving the use of the G – a criterion of signs, T– the Wilcoxon criterion, Q – the Rosenbaum criterion, and U – the Mann-Whitney criterion [9] have been developed.

The data processing algorithm based on G – the criterion of signs is presented in Fig. 6.

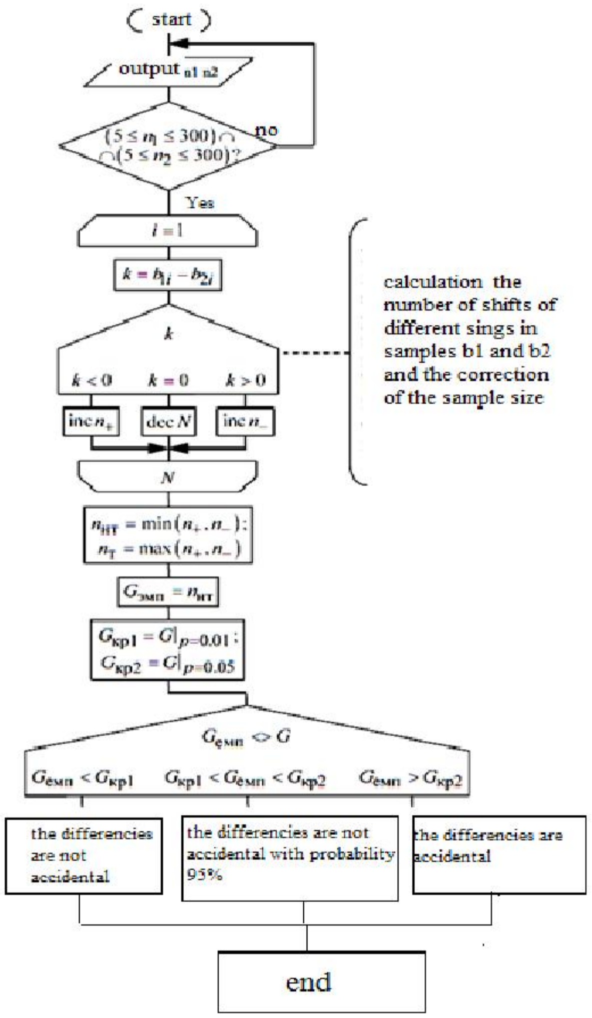


Fig. 6. Experimental data processing algorithm.

U is the G is the criterion of signs intended to compare the state of some property in the members of two dependent samples. The criterion is used to find out the shift direction in the transition from one measurement of the statistical parameter to another.

Mann-Whitney criterion intended to assess the difference between the values of R-R-intervals of two samples. This criterion is based on the calculation of the number of inversions U (permutations) of members in their general ordered series.

Q is the Rosenbaum criterion used to assess thedifferences between two independent samples by the level of any feature or property measured quantitatively.

Two samples {b1} and {b2} of the same volume are allocated from the output array of R-R-intervals. This isdetermined by the previously stated restrictions on the duration and number of analysis intervals. It has been experimentally determined that within this problem this number lies in the interval $5 < N < 300$. Then the dominant tendency of changing intervals is determined in the transition from one sample to another. To do this in a variable k the difference between the values of the intervals having the same number in both samples is calculated, and then the variable sign is determined. For the variable n_+ the number of sample pairs giving a negative value of k is calculated, but for the variable n_- – the number of pairs giving a positive value. For the sign criterion, zero values are not significant. So if the value of k is zero, the sample volume is adjusted by a decrease in N, that is, with the exception of the corresponding pair of interval values under consideration. Of the two obtained values of the number of differences, the typical (nt) value is considered to be greater and the non-typical (nt) one – less.

Let us formulate the conditions: $H0$ – shift in the typical direction is random and *H1* – shift in the typical direction is non-random. The empirical value of G – the $G_{емп}$ criterion is set equal to the number of atypical shifts.

Table G – criterion [10], taking into account the adjusted sample volume N, determines the quantiles of distribution: $G_{кр1}$, which corresponds to the level 1 %; $G_{кр2}$, which corresponds to the level of 5 %. If $G_{емп} < G_{кр1}$, then the hypothesis $H0$ is rejected completely if $G_{кр1} < G_{емп} < G_{кр2}$, then $H0$ is rejected and $H1$ is accepted at the significance level of 5 %. In general, the smaller $G_{емп}$, the more likely that the shift in the typical direction is statistically significant.

If significant differences with the G-criterion can not be identified or their significance is considered insufficient, the use of other criteria considered may be possible.

Conclusions. A block diagram of the complex consisting of an electrocardiograph, a pulse oximeter and a respiratory sensor has been developed. The complex provides an opportunity to measure the degree of vascular blood flow at each time point and the current oxygenation of the blood; record the presence of respiratory reflexes, and process ECG signals.

Specialized integrated circuits are used to process input signals. The ADS1294R chip is selected to obtain an electrocardiogram. It implements specific functions that are characteristic of electrocardiographic measurements. The AFE4490 chip – a fully integrated analogue device designed for use in pulse oximetry is used as a device for receiving a signal from the pulse oximeter,

The most optimal algorithm, based on non-parametric criteria of mathematical statistics, was chosen. This made it possible to diagnose the physiological state in the developed complex in real time. Diagnosis of human condition is based on the recognition and measurement of time intervals between R-ECG teeth (R-R-intervals). The digital filtration of the ECG input signal and its statistical analysis with non-parametric criterion, namely the G-criterion of signs, is performed. An algorithm for data processing based on this criterion is presented.

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ЕЛЕКТРОННА СИСТЕМА БІОМЕТРИЧНОГО КОНТРОЛЮ ПСИХОФІЗІОЛОГІЧНОГО СТАНУ ПІЛОТІВ

Сергій Мещанінов, Анатолій Нельга

Виконано аналіз фізичних явищ, що лежать в основі методів пульсоксиметрії і електрокардіографії, застосовуються в медичній діагностиці кровоносних судин. У ході дослідження алгоритмів обробки інформації було обрано найбільш оптимальний алгоритм, що ґрунтується на основі непараметричних критеріїв математичної статистики. Це дало змогу проводити діагностику фізіологічного стану у розроблюваному комплексі в реальному часі.

Sergiy Meshchaninov – born in 1961, graduated from Oles Honchar Dnipropetrovsk National University. Doctor of Technical Sciences, Professor, Head of the Department of Electronics of Dnipro State Technical University. He is the author of more than 160 scientific and teaching works and patents, including 4 monographs, a textbook, scientific discovery (2000).

Anatoly Nelga – Senior Lecturer of the Department of Electronics, author of more than 170 scientific works, including 3 manuals, 12 patents for inventions