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Non-numerical information processing in biotechnical systems with biofeedback

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ABSTRACT

The paper considers issues of coordinating functional and cybernetic models when creating biotechnical systems with biological feedback. It is noted that the functional model of a biological object, built on the imperative principle of achieving a useful result, has a number of features, the most important of which is the ambiguity of the response to the input impact. The principle of the constancy of the output response of a technical object to the same input stimulus is fundamental for the construction and testing of hardware and software. The reasons for the emergence of uncertainty in the output feature space of a biological object as a response to an input stimulus are analyzed. The necessity of processing the output feature information of a biological object in real time by means of non-numerical transformation of a sequence of samples with the determination of the Kameni median and decision-making based on the sign criterion is substantiated. The effectiveness of using a non-numerical approach for statistical processing of data with a limited sample size and the presence of anomalous outliers is demonstrated. As an application, the developed method and an infrared peloidotherapy chamber with radiation intensity control based on the reaction of a person in a biological feedback loop are used. The output feature space of a biological object is analyzed, and the feasibility of using skin resistance indicators is justified and modeled. The results of experimental studies of the relationship between skin resistance and heart rate indicators and the intensity of infrared radiation are presented. The possibility of controlling the permeability of human skin using a technical component of the system is demonstrated.

Keywords: Biotechnical system; model matching; feature space; ambiguity of response; non-numerical processing

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INTRODUCTION

The main purpose of human-machine systems was to expand human capabilities and increase machine intelligence. Biotechnical systems contain significantly heterogeneous components, and their properties depend not only on specific elements and connections, but also on operating conditions, external influences, and background history. Subsequently, these tasks have expanded significantly in the areas of intensifying the internal reserves of biological objects using technical means in medical applications, training, and the use of analogues of biological methods of information processing in artificial intelligence systems. The technical part of control systems is based on proven methods of automatic control theory, based on cybernetic modelling in the form of mathematical or logical formalization. The interaction of system elements is presented in the form of input and output data models, transformation results, transmission channel parameters, and external influences. Structural decomposition is carried out not only according to the criterion of a finite mathematical description but also taking into account the preservation of the integrity of the object, which is usually impossible for biological objects. The exception is a statistical biological object (poultry farms with infrared heating, which describe chicks with a physical or mathematical model), and the biological system is reduced to a cybernetic model. A biological system differs significantly from a technical one, since a living organism is a self-regulating open system that exchanges information and matter with the external environment. The reaction to a standard impact of a technical object is constant, which is the basis for testing hardware and software. For biological systems, the principle of uniqueness does not apply, and the output response varies significantly. The reason for this is that information is perceived through receptors, whose signals are transmitted to the central nervous system and manifested through effectors that determine behavioral responses. At the same time, receptors, the central nervous system, and effectors, united by the physiological system, depend on the metabolic level associated with energy and substrate supply.

By focusing solely on the informational component, it is impossible to obtain a uniform response to uniform conditions if the metabolic state of the physiological system is unknown. Anokhin's functional model is used to describe a biological object, which considers the organism as a single whole, connecting the structures of a living organism responsible for afferent synthesis, decision-making, efferent reactions, and imperative useful adaptive results. If we consider the feature space of technical and biological systems as sets, then the interaction depends on the area of their intersection. The study of interaction is a complex problem that is determined by the consistency of cybernetic and functional models, since the system must have a unified representation at the interface level. The combination of cybernetic and functional approaches significantly increases the intellectual capabilities of the system by utilizing the advantages of each component.

LITERATURE REVIEW

A significant feature of complex systems is their indivisibility and the impossibility of reducing their properties to their constituent elements [1]. This is most clearly evident in systems involving humans in a biological feedback loop, which allows the technical part of the system to intensify the internal properties of the organism [2] and the technical part to enhance intellectual properties [3]. The most sought-after applications are in medicine: joint treatment [4], psychology [5, 6], post-surgical rehabilitation [7], and cardiology [8]; in sports: in hockey [9], in sports requiring precision [10], in assessing the ability of athletes to decentralize [11], in improving psychological skills to enhance athletic performance [12]; in education [13]. Biotechnical control systems with biological feedback allow for higher performance compared to technical and biological systems in adaptive control in the design of interactive immersive environments [14], in the treatment of disorders associated with psychoactive substance use [15], and in improving brake control in older people [16]. However, invasive methods of reading feature information are rarely used in treatment [17], which significantly reduces the available feature space of a biological object. The output feature space is limited to electroencephalograms [18], electrocardiograms [19], eye movements [20], skin resistance [21], heart rate variability [22], or a complex of features [23]. The ambiguity of the feature space of a biological object significantly limits the capabilities of biotechnical systems [24]. The consequence of the absence of information necessary for control in the features is the inability to ensure high-quality control [25]. To solve this problem, it is important to obtain high-quality primary information [26] and pre-process the data after reading the features [27]. The significant features for each specific task differ and require detailed analysis in relation to the requirements of a specific system [28]. However, the ambiguity of the biological object's response and the coordination of biological and technical models remain significant problems. An attempt to reconcile cybernetic and functional models has been made in [29], but the complexity of the problem means that its solution remains relevant.

PURPOSE AND OBJECTIVES OF THE STUDY

The aim of this work is to reconcile cybernetic and functional models of a biotechnical system through the use of non-numerical data processing.

To achieve this goal, the following tasks must be solved:

1) analyses the properties of the feature space of a biological object and propose ways to reconcile the biological and technical components of a specific biotechnical system of infrared heating based on the reaction of a human being included in the biological feedback loop;

2) propose an approach to the preliminary processing of data from the output feature space of a biological object that takes into account the characteristics of the physiological model and the influence of external factors on the body's response.

ANALYSIS OF SYMPTOM SPACE

The functioning of a control system with biological feedback presupposes the presence of an output response from a biological object that adequately reflects the connection with the input influence in accordance with the target function. The feature space highlights the information that is related to the input influence and is determined by the task being solved by the biotechnical system. The requirement for adequacy is difficult to implement for a biological object, and moreover, the most informative invasive means of reading information are practically unacceptable for most systems with biological feedback. This limits the methods and means of obtaining feature space.

Without claiming to provide a general analysis of the feature space of a biological object, we consider as an example the task of analyzing the feature space for an infrared peloidotherapy system designed to treat the musculoskeletal system. A person in a peloidotherapy chamber, on which sensors for reading signs are located, is included in the biological feedback loop, and the output data via the Bluetooth channel is sent to the processing unit. The greatest therapeutic effect is achieved when the person is thermally stabilized at the phase cooling level. Sweating is an effective means of heat transfer, since 0.58 kcal/hour is consumed to evaporate 1 g of water. This level is individual for each organism, therefore, a stable heating control process is only possible based on the reaction of a specific person included in the biological feedback loop.

Infrared radiation from the external environment is perceived by human thermal sensors, which serve as information inputs for the body. The heat obtained during energy absorption leads to a local increase in skin temperature by 1–20°C and causes a vascular reaction, which manifests itself in a short-term spasm of blood vessels (up to 30 seconds). Followed by an increase in the diameter of blood vessels up to 6 times and a change in blood flow velocity by 2-20 times. Under infrared exposure, the main indicators of a biological object are heart rate, skin resistance, respiratory rate, blood pressure, and surface temperature.

The correlation analysis showed that the most significant indicators are skin resistance, which characterizes skin hydration during phase cooling, and heart rate, which is associated with heat redistribution by blood flow.

To determine the relationship between the intensity of infrared exposure to the human surface and the body's physiological response, experiments were conducted in a peloidotherapy chamber (Fig. 1). The human body mass and the associated heating dynamics, as well as the inertia of infrared emitters, were taken into account.

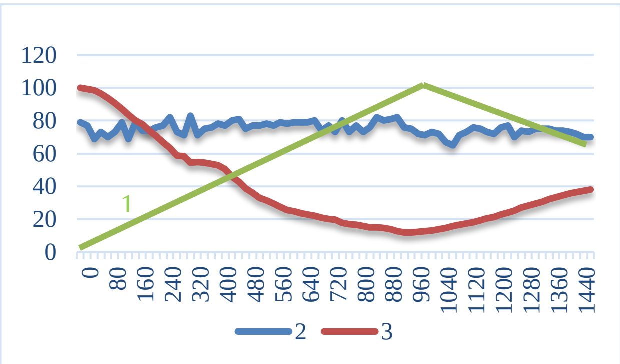

Fig. 1. **Response to changes in infrared radiation power:**
1 – radiation power; 2 – heart rate; 3 – skin resistance
Source: **compiled by the authors**

To conduct model experiments and develop a biological feedback control system, a model of the skin was developed for the purpose of peloid therapy. Ignoring internal processes or focusing solely on the characteristics of the sensory element leads to results whose value cannot be achieved by any further processing. Thus, the models of skin resistance by Frike, Morse, Petrov, and Schwann [30] assume the constancy of the electronic conductivity of the skin, since the epidermis is a scaly layer of dead cells.

The developed model takes into account electrolyte penetration and ion conductivity of the epidermis layer in addition to the electronic conductivity of the dermis. The hypothesis of a porous structure of the layer and uniform wetting by electrolyte throughout the entire volume is accepted. This is expressed by the modulation coefficient *d*, which varies from zero for dry epidermis to one for 100% moisture content. In general, terms, the skin resistance model is represented as a parallel connection of the ionic conductivity of the epidermis *A/d* and the electronic conductivity of the dermis *R*. Comparison of the experimentally obtained curve with the model shows that the difference between them in the active zone does not exceed 3–5%.

Analysis of the curves obtained shows that the informative value of skin resistance for this task is higher than that of heart rate. The curve is monotonic, which makes it possible to use it to control the radiation power within the narrow range of therapeutic significance of the experiment. The phase cooling power range is 10-20 %, and the delay in sweating from the start of heating does not exceed 8-10 seconds, which in the first approximation determines the dynamic characteristics of the system.

Heat absorption by the body is not the only reason for changes in skin resistance. During the experiment, the influence of other factors that could affect the results was analyzed. These irritating factors include sound and mechanical effects that are present during the procedures. To test the effect of this impact, the resistance of the skin was increased to 50-60 kOhm by changing the intensity of the radiation, and a sharp sound was emitted while the intensity of the radiation remained unchanged. The results obtained show that after irritating exposure, the resistance decreases by 15-30 % for 1-2 minutes and returns to its initial state after 2-4 minutes.

The results obtained clearly influence the results of managing the technical part of the system with biological feedback and the technology for reading primary information.

CONTROL OF A BIOLOGICAL OBJECT

Another task is to manage a specific function of a biological object in order to achieve the goal of a biotechnical system.

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As an example, let us consider its solution for the task of peloid therapy. The simplest of these is to maintain the patient in a state of phase cooling. To do this, in accordance with Fig. 1, it is necessary to set and maintain the radiation power at a level of approximately 80-90 conventional units.

Let's complicate the task. It is necessary to quickly turn off phase cooling, because when the sweat glands stop activating, the flow of fluid changes direction and penetrates into the subcutaneous layer. This treatment method, proposed by Dr. Slynko, opens up new possibilities for treatment when administering drugs through the skin. To implement this process, it is necessary to bring the body to active sweat secretion and briefly (for tens of seconds) lower the temperature until phase cooling stops.

It is obvious that switching off infrared emitters and natural cooling cannot achieve this effect due to the low cooling rate, the mass of the emitters and the person. The solution is a separate compression or cryogenic cold chamber with nitrogen cooling, whose energy consumption exceeds 2-3 kW.

When analyzing this problem from the point of view of information technology, the task of interrupting the phase cooling process can be transformed as follows. We have a data source, a communication channel or transmission medium, and a data recipient, which must be combined into a single structure.

The data receiver is the decision-making center for regulating temperature balance – the hypothalamus, whose temperature-sensitive nerve cells are capable of detecting blood temperature changes of 0.01°C flowing through the brain. The concentration of the decision-making center for temperature regulation and the high sensitivity of the receiver indicate that there is a potential possibility of influencing the interruption of phase cooling.

A distinctive feature of a biological object is that it functions according to its own program, in which the target program of the biotechnical system exists only as one of the external components. The decision-making center for maintaining temperature homeostasis analyses not only information about the external environment temperature, but also information about the state of the physiological system components. Blood temperature carries such information, including information about the internal state of the body, which is why a hypothesis has been proposed about the possibility of influencing the physical indicator of sweat gland control.

The method involves converting code into current, current into temperature difference, transmitting the temperature difference to the decision-making center, stimulating a decision to change the form of temperature homeostasis control, and transmitting a control signal to block the sweat glands.

A thermoelectric cooler is used as a converter of current into a negative temperature difference. The developed mathematical models relate the cooling capacity Q and the relative operating current B to the time required to reach a steady state τ [31].

The possibility of forming a cooling pulse of a given intensity and duration is demonstrated:

$$Q_0 = nI^2_{max} R(2B - B^2 - \Theta),$$

$$\tau = \frac{\sum_i m_i C_i}{K_K\left(1 + 2B_K \frac{\Delta T_{max}}{T_0}\right)} \ln \frac{\gamma B_H (2 - B_H)}{2B_K - B_K^2 - \Theta},$$

where n is the number of thermocouples; I_{max} is the maximum operating current; R is the electrical resistance of the branch; B is the relative operating current; Θ is the relative temperature difference, ΔT_{max} is the maximum temperature difference; $m_0 c_0$ is the product of the mass and heat capacity of the cooling object; T_0 is the temperature of the heat-generating junction; γ is the relative power on the thermocouple; K is the low temperature coefficient.

The generated cooling impulse transmits a start signal to the vessel, which serves as a communication channel between the information input point and the biological decision-making center. The bloodstream to the decision-making center in the brain transmits the cooling impulse. If the temperature difference and the duration of the thermal impulse correspond to the decision-making levels, the center for maintaining temperature homeostasis perceives this as cooling of the body. The result is the formation of control commands to shut down the most effective mechanism of phase cooling of the body, including the deactivation of sweat glands.

The communication channel is analogue, and energy is lost when the cooling pulse is introduced into the bloodstream and when the information pulse is transported through the vessel and the branched network of vessels in the brain. It follows that in order to minimize losses, it is necessary to determine the injection site, which includes the thickness of the skin, the subcutaneous layer, and the thickness of the vessel walls. The carotid arteries best meet these requirements (Fig. 2).

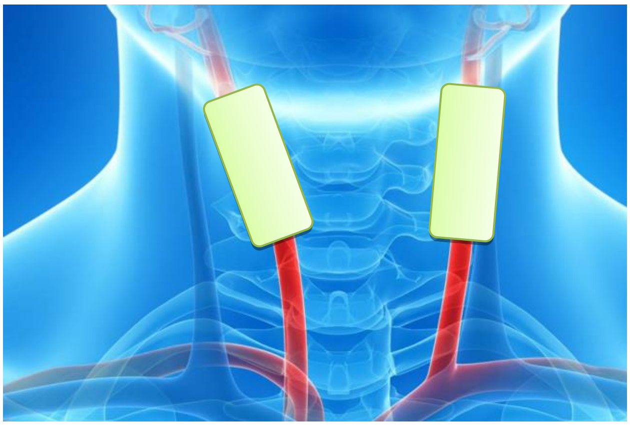

Fig. 2. **Entering information into the communication channel**
***Source:* compiled by the authors**

A model of losses in the skin, subcutaneous tissue, and vessel walls has been analyzed, which shows that losses depend on their diameter and that small vessels have virtually no effect on losses. In large-diameter vessels, which include the carotid artery, the temperature difference between the blood and the environment should be 0.5-0.80°C with pulse duration of 20-30 seconds, which is sufficient to trigger a response to interrupt sweating. The mass of blood compared to the mass of the human body that needs to be cooled allows the dynamic characteristics of interruption to be increased by 5-10 times and energy costs to be reduced by 1-2 orders of magnitude. Thus, using information technology methods, the problem of transferring data from a technical system to the decision-making system of a biological object for a specific application has been solved.

PRELIMINARY NON-NUMERICAL INFORMATION PROCESSING

The functional model of a biological object is characterized not only by its non-linear transformation of information, but also by the various paths that information takes. This is done to increase the reliability of the system, priorities to ensure response speed, perform intermediate processing of data along the path, and form temporary local goals. A biological object involves a significant number of processes that exist independently of the target function of the biotechnical system and must be perceived by it as abnormal emissions. The consequence is that the characteristic information of a biological object cannot be unambiguous, which must be taken into account during processing. Ambiguity leads to the fact that standard mathematical methods, which are successfully used for modeling and testing technical systems, are ineffective.

Communication channels of biological objects also play an important role in systems, as they have low bandwidth compared to technical systems, but ensure the functioning of the organism in real time. Receptor signals have a complex structure, contain signs of the beginning and end of exposure, their frequency and amplitude change as they are perceived, and they adjust their activity during prolonged stimulation. It is obvious that neither the frequency of biological impulses, nor their amplitude, nor their phases are capable of carrying all the information about the input impact due to the limitations of their range. The output feature space of biological object signals is statistical in nature, which is due to the small values of the currents and potentials of the output signals and their comparability with external and internal interference. The problem is that a single sample does not reflect the real response to the controlled stimulus, and multiple averaging of a sequence of samples increases accuracy only for stationary processes. This circumstance leads to the need to identify quasi-stationary local sections of dependencies for which statistical processing methods are acceptable.

The simplest and most effective way to improve the signal-to-noise ratio is the sliding window method, which consists of sequentially averaging samples within the window. The degree of smoothing is determined by the width of the window, and the delay refers to the middle of the window, which can be significant for control systems.

In addition, characteristic signals, such as skin resistance, obtained at different parts of the body, vary considerably due to the density of gland distribution and the thickness of the skin. Furthermore, there is no direct relationship between skin resistance and gland activation, and a twofold change in resistance does not mean that the heating intensity has increased proportionally. It follows that, in relation to biotechnical systems, the output signs of a biological object carry information about the processes in the body, but this data is qualitative rather than quantitative. A quantitative representation is justified for diagnostic systems with large amounts of data, such as stress testing and Holter monitoring.

Anokhin's functional model is based on the imperative principle of achieving a useful result by a biological system, which involves controlling intermediate local goals and correcting them at all stages of activity. In a biological object, the response

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to each reaction is accompanied by the formation of an elementary goal, verification of its achievement, correction of the goal, and so on. These actions take place within the framework of a higher-level goal, such as maintaining the temperature conditions for the functioning of the entire organism. Obviously, this is an extremely simplified representation, but it can serve as a basis for reconciling mathematical and functional models.

In terms of qualitative or non-numerical representation of output features, this can be interpreted as step-by-step decision-making by a technical system after each elementary act. The term 'non-numerical' means that the structure of the space in which the observation results are located is not a structure of real numbers, vectors or functions, and in general not a structure of linear space [32].

A feature of non-numerical data processing is the inability to perform addition and multiplication operations, since the results obtained lose their semantic content. This changes the approaches to pre-processing, since a moving filter involves performing an invalid addition operation to obtain the arithmetic mean.

In non-numerical statistics, the problem of processing a sequence of samples $x_1, x_2, \ldots, x_n$ of a set X is solved by introducing a difference index $d : X^2 \to [0, +\infty]$, which indicates that the greater is, the more *x* and *y* differ. In this case, it is not the arithmetic mean that is determined, but the empirical mean $E_n(d)$, which denotes minimization $E_n(d) = Arg \min \left\{ \sum_{1 \le i \le n} d(x_i, x), x \in X \right\}$ and is represented by the difference function $f(x, y)$, and its minimum value is the median for Kameni's ranked samples. With the difference function $f(x, y) = |x - y|$ and an odd number of samples $\bar{x} = x_{k+1}$, the value of the empirical mean according to Kemeny will be equal to , i.e. the specific value of the sample at the *(k+1)* ranked position according to the non-decreasing sequence. According to the Hinchin theorem, the Kameni mean does not differ from the mathematical expectation for a number of samples $n \to \infty$, but the most interesting problems are those for a small number of samples.

Another feature of the physiological model is that increasing the sample size does not lead to a more reliable estimate, since it is impossible to speak of the stationary and centeredness of the processes. This circumstance is critical for real-time systems, since the sample size introduces a delay that is usually half the time interval of the sampling window. A small sample size leads to a significant spread of control actions and negatively affects control stability indicators.

If we consider stability as immunity to permissible deviations, then the reaction of a biological object of the type 'cold–warm' or 'comfortable–uncomfortable' is more stable than the perception of ambient temperature values. Each person perceives the sensation of warmth individually, and its quantitative description is secondary.

Due to the reasons $x_1, x_2, \ldots, x_n$ mentioned X above, the sample of characteristics of the output random variable of a biological object cannot have a known distribution function $F(x)$. As the sample size increases, in accordance with the central limit theorem, the distribution function tends towards a normal distribution. For a non-parametric model, the two criteria most relevant to decision-making are the sign criterion and the rank criterion. For the sign criterion $F(m) = 0{,}5$, i.e. each of the random variables is uniformly greater than the other sample:

$$R_j = \begin{cases} -1, & if \quad x_j < m_0 \\ +1, & if \quad x_j > m_0 \end{cases}.$$

If the value m_0 corresponds to the sensor response during the active part of the process, the relationship shown reflects the decision made in the active therapeutic zone. A decision of '-1' indicates that the radiation intensity needs to be increased, '+1' indicates that it needs to be decreased, and '0' indicates $x_j = m_0$ that it should remain unchanged.

This approach is known as the tracking balancing principle, which is characterized by high noise immunity at a low signal-to-noise ratio. The disadvantage is the low speed of entering the mode, which can be compensated for by the primary output with sequential conversion from the higher orders followed by operation on the lower order. In particular, in the developed peloidotherapy chamber, the active phase control mode occupied 10–20% of the total heating range and was carried out by low-inertia near- and mid-range infrared emitters. The sampling period was determined by the time constants of the emitters and the human response time (0.5-0.8 seconds) to thermal exposure and was 2-5 seconds. Obviously, for rehabilitation tasks the parameters will be different.

The use of Zadeh's fuzzy methods can, to a certain extent, reduce the negative impact of fuzziness in control systems. However, when it comes to data conversion tasks in biofeedback control systems, the problem of ambiguity in the response to a known input is crucial. These differences can be considered as outliers.

Anomaly detection is not a new problem; it involves detecting and searching for new objects that differ from known ones. Anomaly detection includes statistical and model tests, iterative, metric, and machine learning methods that are tailored to a specific task. The most promising methods are based on calculating flow dispersion, trend formation, and threshold comparisons of forecasts and obtained values. Rejecting anomalous outliers is also a mandatory operation in stress analyses. The results of simulation experiments presented in the literature show that anomaly filtering works effectively for up to 18% of single outliers.

The characteristics of the feature space of a biological object are its non-numerical form, small number of samples, and large number of anomalous outliers. To verify the feasibility of using non-numerical approaches, a comparative analysis was performed of the processing of the feature space of a series of heart rate samples using a linear filter (arithmetic mean) and a nonlinear Kemeny filter (median). The data was recorded using a standard medical device with a sampling period of 20 s, and the processing was performed using a sliding 5-point window. In the absence of abnormal outliers, no noticeable difference was observed between processing with linear and nonlinear filters. However, in the presence of abnormal outliers, the situation changes significantly.

The appearance of abnormal emissions during contact methods of reading information is associated, among other things, with changes in the conductivity of the contact connections between the epidermis and the electrodes when a person moves in the infrared radiation zone, as provided for in the treatment protocol.

An analysis was carried out of the operation of linear and nonlinear filters when introducing abnormal single and paired abnormal emissions into experimentally obtained heart rate sample streams.

The analysis shows that when processing a time series with single anomalous outliers using a linear filter, the influence of the anomalous component is significant, since it is included in the arithmetic mean and shifts the filtered value towards the outlier. When processed with a nonlinear filter, anomalous outliers have virtually no effect on the results, since a single outlier is shifted from the median by ranking. Similarly, for a sequence of two anomalous outliers, the median depends only on the remaining samples. Accordingly, unlike the 18% threshold, the filter is effective for up to 40% of outliers for a nonlinear five-point filter. That is, a nonlinear filter with an odd number of samples $2n+1$ is effective provided that the number of consecutive anomalies does not exceed n.

Studies have been conducted on the effectiveness of pre-processing the flow of skin resistance values when exposed to infrared radiation and moving the patient in a peloidotherapy chamber. The analysis showed that linear processing does not provide stable intensity control in a structure with biological feedback. The effect of abnormal emissions depends significantly on their amplitude. Processing with a nonlinear filter better ensures the continuity of the control process.

It is obvious that non-numerical filtering, like non-numerical processing methods in biotechnical systems, needs detailed study, but even preliminary results indicate its promise.

CONCLUSIONS

The analysis of the biological and technical components of the biotechnical system showed that the main problem lies in the need to reconcile the functional and cybernetic models.

One of the main problems in coordinating the functional and cybernetic models is the ambiguity of the output feature space of the biological object.

Based on information technology, a variant of target control of a biological object is proposed.

The expediency of using non-numerical methods of information processing to coordinate the functional and cybernetic models is justified.

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Нечислова обробка інформації в біотехнічних системах з біологічним зворотним зв'язком

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АНОТАЦІЯ

У роботі розглянуто питання узгодження функціональної та кібернетичної моделей при створенні біотехнічних систем з біологічним зворотним зв'язком. Відзначено, що функціональна модель біологічного об'єкта, побудована на імперативному принципі досягнення корисного результату, має ряд особливостей, найважливішою з яких є неоднозначність реакції на вхідний вплив. Принцип незмінності вихідної реакції технічного об'єкта на однаковий вхідний вплив є основоположним для побудови та тестування апаратних і програмних засобів. Проаналізовано причини появи невизначеності у вихідному ознаковому просторі біологічного об'єкта, як реакції на вхідний вплив. Обґрунтовано необхідність обробки даних вихідної ознакової інформації біологічного об'єкта в реальному часі шляхом нечислового перетворення послідовності вибірок з визначенням медіани Кемені та прийняттям рішення за критерієм знаків. Показано ефективність застосування нечислового підходу для статистичної обробки даних з обмеженим обсягом вибірки та наявністю аномальних викидів. В якості додатка використано розроблений метод та камеру інфрачервоної пелоїдотерапії з керуванням інтенсивністю випромінювання за реакцією людини, що знаходиться в ланцюзі біологічного зворотного зв'язку. Проаналізовано вихідний ознаковий простір біологічного об'єкта та обґрунтовано доцільність використання показників опору шкіри, розроблено його модель. Представлено результати експериментальних досліджень зв'язку ознак опору шкіри та частоти серцевих скорочень від інтенсивності інфрачервоного випромінювання. Показано можливість управління функцією проникності шкірного покриву людини технічною складовою системи.

Ключові слова: біотехнічна система; узгодження моделей; ознаковий простір; неоднозначність реакції; нечислова обробка

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