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EYE-TRACKING TECHNOLOGY IN THE STUDY OF COGNITIVE PROCESSES

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Abstract. *Instrumental algorithmic and software tools for building a non-parametric dynamic model of the oculo-motor system (OMS) of a person, taking into account its inertial and nonlinear properties, based on the data of «input-output» experimental studies using eye-tracking technology, have been developed. Information technology and software for obtaining experimental data for the identification of OMS using test visual stimuli and the use of eye-tracking to track eye movements have been developed. Experimental studies of OMS have been carried out and first-, second- and third-order transient functions have been determined on the basis of oculographic research data. An analysis of the variability of transient functions corresponding to different psychophysiological states of the individual was carried out.*

Key words: *oculo-motor system, identification, Volterra model, multidimensional transition functions, test visual stimuli, eye-tracking technology.*

Introduction.

Studies of human eye movements and the trajectory of their movement allow us to reveal the structure of the individual's relationship with the environment. Analysis of the relationship between oculo-motor and the central nervous system, with the content of mental processes, with various forms of activity (behavior, activity, communication), contributes to the study of the mechanisms of brain work and their disorders, the identification of the dynamics of psychophysiological states of a person, patterns of perception, thinking, ideas, differentiation personal intentions [1].

The acquisition of scientific knowledge and corresponding skills is the main goal and the main result of educational activity. The process of acquiring knowledge is a central part of the educational process. Management of this process implies the availability of effective objective indicators for assessing a person's intellectual abilities. The methods of non-linear dynamic identification of the oculo-motor system (OMS) of an individual proposed in our project, which are based on obtaining experimental data using innovative eye-tracking technology and computing tools for their processing, allow monitoring and diagnosis of the state of cognitive processes during the educational activities of students. At the same time, an integral nonlinear dynamic model is used the Volterra polynomial, for the construction of which the data of experimental studies of «input-output» OMS using test visual stimuli are used [2, 3].

The purpose of the work is developing a method and instrumental algorithmic and software tools for building a mathematical model of the OMS based on the Volterra polynomial according to the data of experimental studies of the OMS «input-output» using test visual stimuli and eye-tracking technology, applying the obtained models to assess the psychophysiological state of the individual with the aim of increasing efficiency educational activity.

Theoretical and practical significance of research.

The scientific novelty of the obtained results lies in the development and in-depth theory and methodology of building Volterra models of the human oculo-motor system and their application in studies of cognitive processes.

Formal relations that represent universal expressions for estimating diagonal intersections of multidimensional transition functions (*n*-dimensional integrals from Volterra kernels) of OMS in the form of a linear combination of OMS responses to test visual stimuli with different distances from the starting position have been proposed and theoretically substantiated, which made it possible to algorithmize and simplify the software implementation of the identification procedure.

A new method of building an approximation model of the OMS based on the Volterra polynomial using test visual stimuli displayed on the monitor screen at different distances from the starting position is proposed, which, unlike known methods, uses a regularized method of least squares to determine the diagonal intersections of multidimensional transition functions, which allows improve the accuracy and computational stability of the identification procedure.

OMS models were built based on Volterra polynomials of the second and third orders according to eye-tracking data in the form of diagonal intersections of the corresponding transition functions, which differ from the known ones in that they provide the possibility of modeling OMS in a given interval of input signals beyond the radius of convergence of the Volterra series. Models are involved in the construction of classifiers of human psychophysiological states.

The information technology of diagnosing psychophysiological states of a person has received further development due to the use as a source of primary data of information models of the OMS of the «input-output» type based on Volterra polynomials. Eye-tracking technology is used to build models. This makes it possible to increase the accuracy of OMS modeling and, as a result, to increase the reliability of diagnosis in the space of the proposed heuristic features, which are determined using integral and differential transformations of multidimensional transition functions of OMS, which greatly simplifies the identification of features and the practical implementation of Bayesian classifiers.

The practical significance of the obtained results lies in the creation of instrumental software tools that implement computational algorithms of deterministic nonlinear dynamic identification of the OMS in the form of multidimensional transition functions and their implementation in scientific research and the educational process.

The following software tools have been developed:

- the «SignalManager» program (C#) – allows to generate deterministic or random test visual stimuli of any configuration on the computer monitor screen for conducting «input-output» identification experiments with human OMS using innovative eye-tracking technology;
- the «eSmart» program (Java Android) – instrumental software for Android smartphones, which perform automatic recognition of images of objects (face, eye, pupil) on the sequence of video registration frames and calculation of pupil coordinates in the dynamics of the eye movement process;
- the «VolterraApp» program (Matlab) – implements computational algorithms for nonlinear dynamic identification of OMS based on the Volterra polynomial in the form of multidimensional transition functions (MTF);
- the «FeatureSpace» program (Matlab) – implements computational algorithms

for determining heuristic features, which are used to build spaces of diagnostic features.

The intelligent information technology for diagnosing psychophysiological conditions of a person.

The proposed intelligent information technology for diagnosing states of neural processes, which is based on non-parametric identification of the oculo-motor system in the form of non-linear dynamic Volterra models. The technology involves the sequential solution of the following tasks:

1. Identification of OMS. The goal is to build an information model of the OMS in the form of MTF – integral transformations of Volterra kernels. Stages of implementation: supply of test signals with different amplitudes at the input of the OMS horizontally, vertically, diagonally); measurement of OMS responses to test signals using an eye tracker; calculation of OMS based on the data of the «input-output» experiment.

2. Building a diagnostic model of OMS. The goal is to form a space of features. Stages of implementation: MTF compression; determination of the diagnostic significance of signs; selection of the optimal system of signs (diagnostic model reduction).

3. Building a classifier of the individual's psychophysiological state based on the OMS model. The goal is to build a set of decision rules for optimal classification. Stages of implementation: construction of decisive rules based on the results of identification OMS (training); classification reliability assessment (examination); optimization of the diagnostic model.

4. Diagnostics of neural processes. The goal is to assess the state of the individual. Stages of implementation: identification of OMS; evaluation of diagnostic signs; classification – assignment of the studied individual to a certain class.

The stages of implementation of model-oriented classification technology are illustrated in fig. 1.

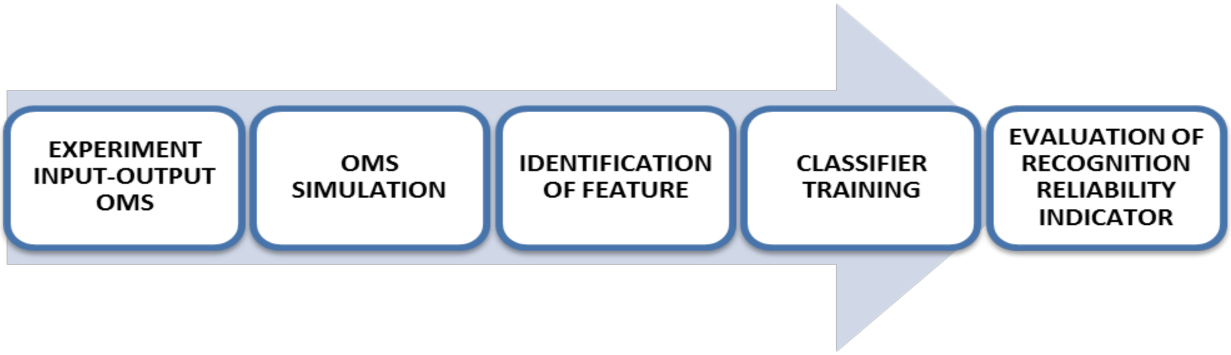

Figure 1 – Stages of implementation of model-oriented classification technology OMS model as multidimensional transient functions (MTF).

The research uses an method of constructing approximate Volterra model of the nonlinear dynamical system (NDS), which is based on the allocation of the *n*-th partial component in the OMS response by processing responses to test signals with different amplitudes [4, 5].

The «input-output» ratio for the NDS with an unknown structure (such as a «black box») with a single input and a single output can be represented by a discrete cubic Volterra polynomial in the form:

$$y[m]=\sum_{n=1}^{3} y_n[m]=\sum_{k_1=0}^{m} w_1[k_1]x[m-k_1]+\sum_{k_1,k_2=0}^{m} w_2[k_1,k_2]x[m-k_1]x[m-k_2]+ \\ +\sum_{k_1,k_2,k_3=0}^{m} w_3[k_1,k_2,k_3]x[m-k_1]x[m-k_2]x[m-k_3], \quad (1)$$

where $w_1[k_1]$, $w_2[k_1,k_2]$, $w_3[k_1,k_2,k_3]$ are discrete weight functions (Volterra kernels) of the 1st, 2nd and 3rd orders; $x[m]$, $y[m]$ are input (stimulus) and output (response) function (signals) of the system, respectively; $y_n[m]$ is partial components of the response (convolution of *n*-th order sequences); *m* is a discrete time variable.

The problem of identification consists in choosing test signals $x[m]$ and developing an algorithm that allows to identify partial components $y_n[m]$, (n = 1, 2, 3) based on the responses received $y[m]$ and determine on their basis multidimensional Volterra kernels: $w_1[k_1]$, $w_2[k_1,k_2]$, $w_3[k_1,k_2,k_3]$.

Taking into account the specifics of the studied OMS, test step signals are used for identification. If the test signal $x[m]=\theta[m]$, where $\theta[m]$ is a unit function (Heaviside function), then the partial components of the response $y_1[m]$, $y_2[m]$, $y_3[m]$

will be equal to the transient function of the first order $h_1[m]$ and diagonal sections of the transient functions of the second and third orders $h_2[m,m],\ h_3[m,m,m]$, respectively [6]:

$$y_1[m] = h_1[m] = \sum_{k_1=0}^{m} w_1[m-k_1],$$
$$y_2[m] = h_2[m,m] = \sum_{k_1,\,k_2=0}^{m} w_2[m-k_1, m-k_2], \tag{2}$$
$$y_3[m] = h_2[m,m,m] = \sum_{k_1,\,k_2,\,k_3=0}^{m} w_3[m-k_1, m-k_2, m-k_3].$$

Determination of subdiagonal intersections of transient functions is based on the NDS test using L test step signals with given amplitudes a_j, j=1,2,…,L ($L \ge N$, N is the degree of the Volterra polynomial). In this case the responses of the NDS are denoted by $y_1[m]$, $y_2[m]$, …, $y_L[m]$. Reviews of the Volterra model will be view

$$\widetilde{y}_j[m] = a_j \hat{y}_1[m] + a_j^2 \hat{y}_2[m] + a_j^3 \hat{y}_3[m],\ j = \overline{1, L}, \tag{3}$$

where $\hat{y}_1[m] = \hat{h}_1[m], \hat{y}_2[m] = \hat{h}_2[m,m], \hat{y}_3[m] = \hat{h}_3[m,m,m]$ – obtained estimates of the partial components of the model – multidimensional transition functions.

To determine the transient functions $h_1[m], h_2[m,m], h_3[m,m,m]$, the method of least squares (LSM) is used which provides the minimum standard error of the deviation of the model responses from the responses of the OMS to the same stimulus:

$$J_N = \sum_{j=1}^{L} \left(y_j[m] - \sum_{n=1}^{N} a_j^n \hat{y}_n[m] \right)^2 \to \min. \tag{4}$$

The minimization of criterion (4) is reduced to solving a system of normal Gaussian equations, which in vector-matrix form can be written as

$$\mathrm{A}'\mathrm{A}\hat{\mathrm{y}} = \mathrm{A}'\,\mathrm{y}, \tag{5}$$

where $\mathrm{A} = \left\| \alpha_{jn} \right\|, \alpha_{jn} = a_j^n,\ j, n = \overline{1, N}.$

In the studies of each respondent, three experiments were performed sequentially for the three amplitudes a_1, a_2, a_3 (N=3) of the test signals in the horizontal direction. The distance between the starting position and the test stimuli is: (1/3)lx, (2/3)lx and (1.0)lx, where lx is the length of the monitor screen. Coordinates of the starting position (x=0, y=(1/2)ly), where ly is the width of the monitor screen.

Experimental studies of OMS were carried out using a high-tech device, the Tobii Pro TX300 (300 Hz) eye tracker, given by the Center for Innovation and Advanced Technologies of the Lublin Technological University (Lublin, Poland) [6].

Construction of a Bayesian classifier for assessing the psychophysiological state of a person.

To assess the psychophysiological state of an individual based on the OMS model in the form of transition functions of the 1st order – $h_1(m)$, and diagonal intersections of transition functions of the 2nd and 3rd order – $h_2(m,m)$, $h_3(m,m,m)$, according to [7], was constructed:

- feature space for developing a classifier of the psychophysiological status of a person using machine learning;
- classifiers using statistical methods of pattern recognition training based on data obtained using eye-tracking technology.

On the basis of training samples of data for objects of classes A («in the morning») and B («in the evening»), the discriminant function d(x) is successively calculated. To separate two classes (case of dichotomy), the discriminant function of the Bayesian (Gaussian) species classifier is used:

$$d(\mathrm{x})=\frac{1}{2}\mathrm{x}'(\mathrm{S}_2^{-1}-\mathrm{S}_1^{-1})\mathrm{x}+(\mathrm{S}_1^{-1}\mathrm{m}_1-\mathrm{S}_2^{-1}\mathrm{m}_2)'\mathrm{x}+\frac{1}{2}(\mathrm{m}_1'\mathrm{S}_1^{-1}\mathrm{m}_1-\mathrm{m}_2'\mathrm{S}_2^{-1}\mathrm{m}_2+\ln\frac{|\mathrm{S}_2|}{|\mathrm{S}_1|})+\lambda_{\max}, \qquad (6)$$

where x=(x_1,x_2,…,x_n)' is a vector of features, n is the dimension of the space of features, m_i is a vector of mathematical expectations of features of class i, i=1, 2; S_i=M[(x-m_i)(x-m_i)' is the covariance matrix for class i (M[ ] is a mathematical expectation operation). S_i^{-1} is the matrix inverted to S_i, |S_i| is the determinant of the S_i matrix, $\lambda_{\max}$ is the object classification threshold, which ensures the maximum value of the criterion of the probability of correct recognition (PCR).

An analysis of the informativeness of various combinations of features was carried out on the basis of the PCR criterion. A Bayesian classifier of human fatigue was built. In the two-dimensional space of features, the maximum PCR P = 0.9375 is achieved by combinations of the following features:

$$\left(x_3 = \sum_{m=0}^{M} \left| h_3(m,m,m) \right| \; \& \; x_{14} = \min_{m \in [0,M]} h_2^{'}(m,m) \right) \text{, or} \tag{7}$$

$$\left(x_3 = \sum_{m=0}^{M} \left| h_3(m,m,m) \right| \; \& \; x_{15} = \min_{m \in [0,M]} h_3^{'}(m,m,m) \right) \text{, or} \tag{8}$$

$$\left(x_{14} = \min_{m \in [0,M]} h_2^{'}(m,m) \; \& \; x_{15} = \min_{m \in [0,M]} h_3^{'}(m,m,m) \right) \text{, or} \tag{9}$$

$$\left(x_{14} = \max_{m \in [0,M]} h_2^{'}(m,m) \; \& \; x_{15} = \max_{m \in [0,M]} h_3^{'}(m,m,m) \right) \text{, or} \tag{10}$$

$$\left(x_6 = \arg\max_{m \in [0,M]} h_3^{'}(m,m,m) \; \& \; x_{11} = \max_{m \in [0,M]} h_2^{'}(m,m) \right) \text{, or} \tag{11}$$

$$\left(x_8 = \arg\min_{m \in [0,M]} h_2^{'}(m,m) \; \& \; x_{11} = \max_{m \in [0,M]} h_2^{'}(m,m) \right) . \tag{12}$$

Conclusion. A method of experimental research of the human oculo-motor system (OMS) was developed and implemented using innovative eye-tracking technology to obtain empirical data for the identification of OMS in the form of multidimensional transient functions (MTF) using video recording of responses to test visual stimuli; introduced methods and computational algorithms for building OMS models based on polynomials and the Volterra series in the form of MTF with the use of test visual stimuli and determining feedback using eye-tracking technology; developed instrumental software tools for deterministic nonlinear dynamic identification of OMS «input-output» based on Volterra models in the form of MTF and means of applying the obtained models in information systems for diagnosing the psychophysiological state of a person and recognizing a person.

The obtained scientific and practical results are aimed at solving the problem of identifying a gifted personality in the education system, diagnosing and monitoring the development of its potential in the educational process, supporting and accompanying a gifted personality in the educational environment and society. The implementation that took place is an effective implementation of the modern STEM/STEAM approach, which covers natural sciences, technology, engineering, art and mathematics.

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