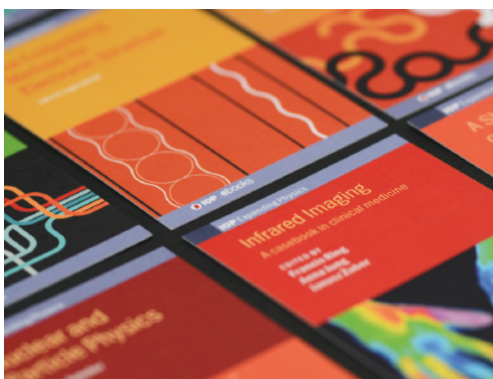


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Identification of the oculo-motor system based on the Volterra model using eye tracking technology

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Abstract. Instrumental algorithmic and software tools for constructing a nonparametric dynamic model of the human oculo-motor system (OMS) based on its inertial and nonlinear properties are developed in the paper on the basis of the experimental studies data of «input-output» in the form of the Volterra model. Taking into account the specificity of the object investigated, test multistage signals (visual stimulus) were used for identification. Based on the experimental data obtained using the developed computational algorithms and data processing software, a nonparametric dynamic model of OMS in the form of a transition function and transition functions of the 2nd and 3rd orders is constructed. Verification of the constructed model showed its adequacy to the object investigated – a practical coincidence (within the acceptable error) of the object and model feedback for the same test effect.

1. Introduction

Innovative technology of eye tracking which is rapidly developing nowadays is the process of determination of the view or of eye movements. This high-tech innovation has been further developed and effectively used in the construction of a mathematical model of process of tracking eye movement to detect anomalies in data tracking to quantify the motor symptoms of Parkinson's disease [1-4]. Using nonlinear dynamic Wiener and Volterra-Laguerre model for identification of OMS is based on a random effects test, which requires the application of methods of correlation analysis and generates a large amount of experimental data (long-term experimental studies).

In order to build the Volterra model of the human OMS, a person is encouraged to use the test deterministic effects; for example, step signals (the most appropriate for the study of the dynamics of OMS), which simplifies the computational algorithm to identify and significantly reduce the time of processing of experimental data [5-8]. There is a method and computer algorithms identifying deterministic nonlinear dynamical systems in the form of Volterra models using multi-step test signals [9].

The purpose of the work is the development of the method for constructing of the nonparametric dynamic model of OMS in the form of Volterra series based on experimental studies of "input-output" and also computational tools and software for the information technology processing experimental data.

2. The scope of application

The developed software enables support of the following tasks:



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- The relationship study of mental states and cognitive processes in educational activities, a post-traumatic stress disorder, the diagnosis of the Parkinson's disease stage, checking the psycho-physiological state of pilots and drivers, the professional suitability, the fatigue syndrome.
- The interaction of mental states and cognitive processes during the educational activities of students and schoolchildren, an objective assessment of their cognitive development level, assessment of the effectiveness of training to improve mental processes (ie. thinking processes) and for psychological correction of personality.
- Extension of the individual's creative life due to the early diagnosis of degenerative processes of cognitive functions of the brain. Identification of a gifted personality (building a psychological model of the personality) and evaluation of its abilities.
- Professional selection (the identification and education of leaders).
- The assimilation of scientific knowledge and their respective skills serves as the main goal and the main result of educational activities. The process of mastering knowledge is the central part of the learning process. Managing this process implies the existence of effective objective indicators for assessing an individual's intellectual abilities.

The methods of psychological identification of an individual proposed in the project, based on obtaining experimental data using eye tracking technology and computing means of processing them, allow monitoring and diagnostics of the state of cognitive processes during the educational activities of students and schoolchildren.

3. Intelligent it of diagnostics neuronal processes

An intelligent information technology for diagnosing the states of neural processes based on nonparametric identification of OMS in the form of nonlinear dynamic Volterra models is proposed. The technology involves a consistent solution of the following tasks:

- **Identification of OMS. The goal** is to construct an information model of OMS in the form of multidimensional transient functions (MTF) – integral transformations of Volterra kernels. **Stages** of the implementation: submission of test signals with different amplitude to the inputs of OMS (horizontal, vertical, diagonal); measurement of OMS responses to test signals using an eye tracker; calculation of MTF based on the data of the experiment «input-output» type.
- **Construction of diagnostic model of OMS. The goal** – formation of the feature space. Stages of the implementation: compression of MTF; determination of the diagnostic features; selection of optimum system features (reduction of the diagnostic model).
- **Construction of the classifier** of the individual's psychophysiological state on the basis of the OMS model. **The goal** is to build a family of decision rules for optimal classification. **Stages** of the implementation: construction of decision rules based on the results of OMS identification (training); assessment of classification reliability (examination); optimization of diagnostic model.
- **Diagnosis of neural processes. The goal** is to assess the state of the individual. **Stages** of the implementation: identification of OMS; evaluation of diagnostic features; classification - classification of the individual under study to a certain class.

4. Eye tracking technology for identification of OMS

Information technology of the constructing a nonparametric dynamic model of the human OMS taking into account its inertial and nonlinear properties based on the data of experimental studies "input-output" was developed. As a basic OMS model - the Volterra model is used in the form of multidimensional transition functions.

Methods and tools for the identification of OMS have been developed using the help of eye tracking technology, and building a features space and optimal classification human states using

machine learning. In the Laboratory of Motion Analysis and Interface Ergonomics at the Lublin University of Technology (Lublin, Poland), joint studies of the human OMS were performed to obtain diagnostic information for solving urgent problems in the neuro informatics and the computational neuroscience. Experimental research was carried out using eye tracking technology with the use of the video based Tobii TX300 (300 Hz sampling rate) eye tracker and appropriate software.

5. Computing method of transient functions for identification of OMS

Taking into account the specificity of the object investigated, test multistage signals were used for identification. If a $x(t)$ test signal represents a unit function (the Heaviside function) – $\theta(t)$, it will result in identification of the transition function of the first order and the diagonal section of the n -th order.

To determine the sections of subdiagonal transition of functions of the n -th order ($n \geq 2$) OMS was tested using the n step test signal with the specified amplitude and different intervals between signals. With appropriate processing responses get a subdiagonal section of n -dimensional transition functions $h_n(t_1, \dots, t_n)$, which represent the n -dimensional integral of the Volterra kernel n -order $w_n(t_1, \dots, t_n)$ [9, 10]:

$$h_n(t_1, \dots, t_n) = \int_0^\infty \dots \int_0^\infty w_n(t_1 - \lambda_1, \dots, t_n - \lambda_n) d\lambda_1 \dots d\lambda_n. \quad (1)$$

Based on the experimental data obtained using the developed computational algorithms and data processing software, a nonparametric dynamic model of the human-eye apparatus in the form of a transition function and transition functions of the 2nd and 3rd orders is constructed [9].

5.1. Method for constructing of an approximation Volterra model of the nonlinear dynamical system

The method for constructing an approximate Volterra model of the OMS is developed. The method of identification is based on the $y(t)$ approximation at an arbitrary $x(t)$ deterministic signal in the form of the Volterra polynomial of the N -th order (N – the order of the approximation model) [9]:

$$\tilde{y}_N(t) = \sum_{n=1}^N \hat{y}_n(t) = \sum_{n=1}^N \int_0^t \dots \int_0^t w_n(\tau_1, \dots, \tau_n) \prod_{i=1}^n x(t - \tau_i) d\tau_i, \quad (2)$$

where $\hat{y}_n(t)$ – the partial components in the human OMS approximation model.

Let the input test signals of OMS be fed alternately: $a_1x(t)$, $a_2x(t)$, \dots , $a_Lx(t)$; a_1, a_2, \dots, a_L – distinct real numbers satisfying the condition $|a_j| \leq 1$ for $\forall j=1, 2, \dots, L$; then minimization of the criterion:

$$J_N = \sum_{j=1}^L (y[a_jx(t)] - \tilde{y}_N[a_jx(t)])^2 = \sum_{j=1}^L \left(y_j(t) - \sum_{n=1}^N a_j^n \hat{y}_n(t) \right)^2 \rightarrow \min \quad (3)$$

is reduced to solving the system of normal equations of Gauss, which in the vector-matrix form can be written as:

$$\mathbf{A}'\mathbf{A}\hat{\mathbf{y}} = \mathbf{A}'\mathbf{y}, \quad (4)$$

where:

$$\mathbf{A} = \begin{bmatrix} a_1 & a_1^2 & \dots & a_1^N \\ a_2 & a_2^2 & \dots & a_2^N \\ \dots & \dots & \dots & \dots \\ a_L & a_L^2 & \dots & a_L^N \end{bmatrix}, \mathbf{y} = \begin{bmatrix} y_1(t) \\ y_2(t) \\ \dots \\ y_L(t) \end{bmatrix}, \hat{\mathbf{y}} = \begin{bmatrix} \hat{y}_1(t) \\ \hat{y}_2(t) \\ \dots \\ \hat{y}_N(t) \end{bmatrix}.$$

From (4) we obtain:

$$\hat{\mathbf{y}} = (\mathbf{A}'\mathbf{A})^{-1}\mathbf{A}'\bar{\mathbf{y}} \quad (5)$$

5.2. Software tools

The following instrumental algorithmic and software tools are developed to achieve the goal of the research:

- Formation of test signals in the form of bright dots on the computer monitor screen at different distances from the initial position horizontally, vertically and diagonally.
- Preprocessing (bringing the OMS responses to a common start and rationing to one) and analyzing the data obtained from the eye tracker.
- Constructing an identification model of OMS in the form of multidimensional transitional functions (integral transformations of Volterra kernels).
- Constructing a feature space for designing the status classifier of a human using machine learning.
- Visualization of data and processing results of experimental research.
- Classifiers construction using deterministic and statistical methods of learning the pattern recognition based on the data obtained using eye tracking technology.

5.3. Organization and methodology of experimental research using eye tracking technology

When conducting experimental studies, such actions are carried out:

- The subject is placed in front of the computer so that his eyes are at the center of the monitor at a distance of 40-50 cm from him.
- The subject's head is fixed in order to prevent its movements during the study and to ensure the same experimental conditions.
- On the subject's readiness, the Signal Manager of the test visual stimulus program is launched (Figure 1).
- A red circle appears in the center (or from its edge) – of the screen in the starting position (Figure 1, *a*).
- After a short pause (2-3 sec.), the circle in the starting position disappears and a circle of a different color appears at the point with the specified coordinates (Figure 1, *b*) – a visual stimulus (test signal), which is displayed in this position for a specified duration (1-2 sec.) – the action makes the eye move in the direction of the visual stimulus.
- Then this stimulus circle disappears and a red circle appears in the starting position – this makes the eye move in the opposite direction to the starting position, after these actions the experiment ends.
- Using the eye tracker, the coordinates of the pupil of the eye are determined during its movement (reaction to the visual stimulus) in the period between the starting positions and the coordinate values are stored in the xls file.

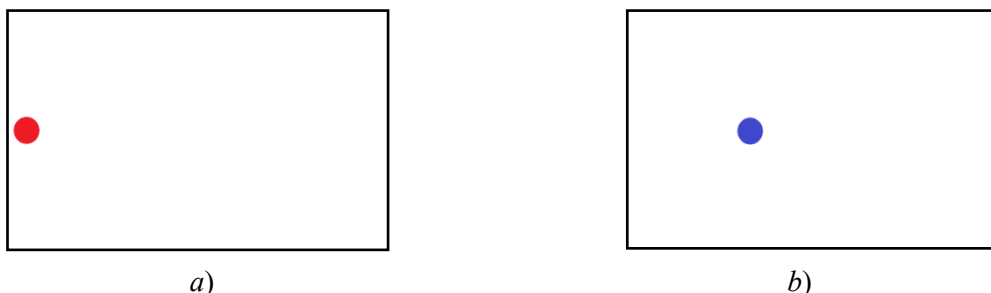


Figure 1. Test visual incentives: *a*) starting position; *b*) position of the stimulus

In the studies of each respondent, three experiments were successively implemented for three amplitudes of test signals in the horizontal direction. The distance between the starting position and the test incentives is equal to: $0.33 l_x$, $0.66 l_x$, $1.0 l_x$, where l_x is the length of the monitor screen. Coordinates of the starting position ($x = 0$, $y = 0.5 l_y$), l_y – mean the width of the monitor screen. The obtained results of measurements of the OMS responses at $L=3$ obtained with using the Tobii TX300

eye tracker in one study cycle (“Horizontally”) are shown in Figure 2. Transient process in the OMS response to the test signal $a_1 = 0.33$ are illustrated on Figure 3.

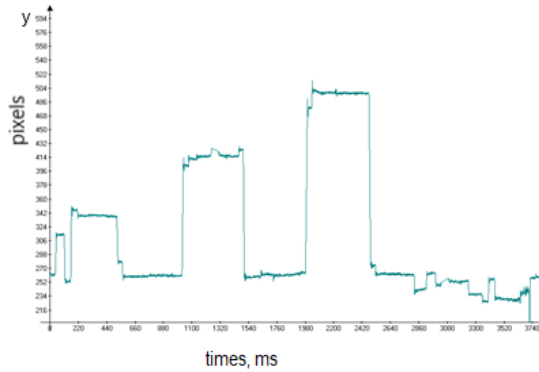


Figure 2. OMS responses at $L=3$ obtained using the Tobii TX300 eye tracker

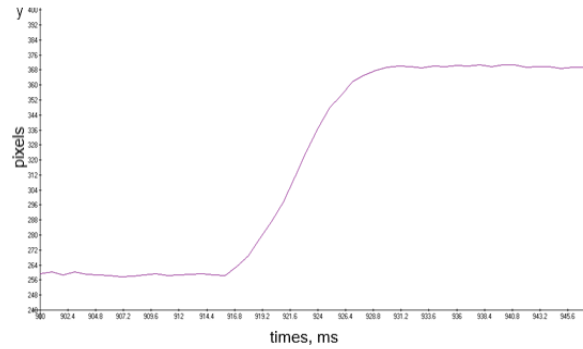


Figure 3. Transition process in the OMS response to the test signal: $a_1 = 0.33$

6. Research results

The experiments were organized in order to classify subjects by the state of fatigue. The data for constructing the model – the OMS responses to the same test signals, were obtained using the Tobii Pro TX300 eye tracker at different times of the day: "In the Morning" (before work) and "In the Evening" (after work). The average values of the OMS responses obtained from the eye tracker at various amplitudes of the test signals "In the Morning" and "In the Evening" are shown in Figure 4.

According to averaged data of OMS responses on visual stimuli with a different distance from the start position on the basis of formula (5) the functions of the OMS were defined when approximation models of degrees $N = 3$ were used. Graphs of the transition functions estimates for the "In the Morning" and "In the Evening" states of the subject based on model (1) are shown in Figure 5.

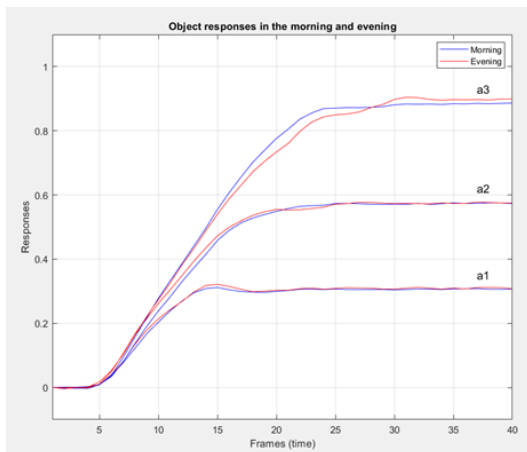


Figure 4. Averaged OMS responses at various amplitudes of test signals “In the Morning” and “In the Evening”

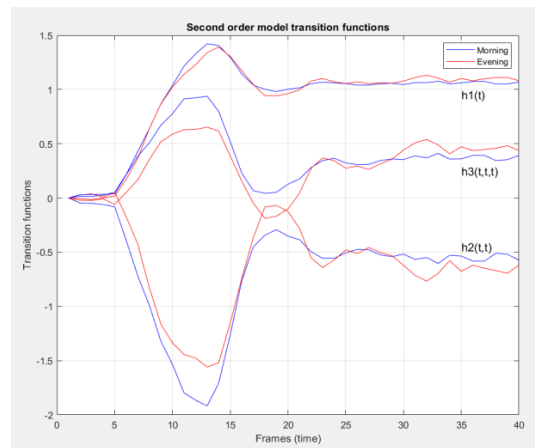


Figure 5. Transition function estimates at $N = 3$ “In the Morning” and “In the Evening” states of the subject based on model (1)

Received responses with the help of calculations on models at $N = 3$ from various amplitudes of test signals "In the Morning". Graphs these are presented in comparison with similar responses OMS in Figure 6. Graphs of responses of the model OMS at $N = 3$ at various amplitudes of the test signals “In the Morning” and “In the Evening” are illustrated in Figure 7.

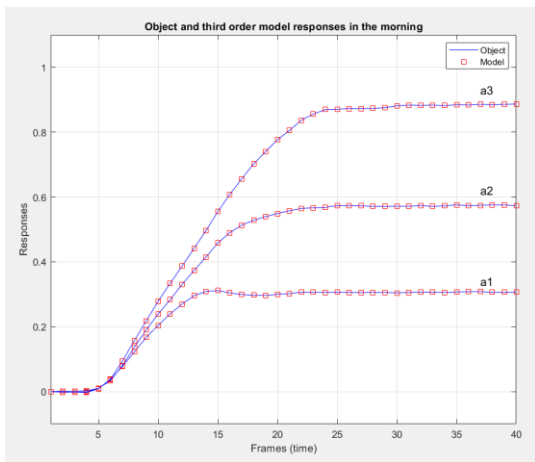


Figure 6. Responses of the OMS and the model at $N = 3$ at various amplitudes of the test signals "In the Morning"

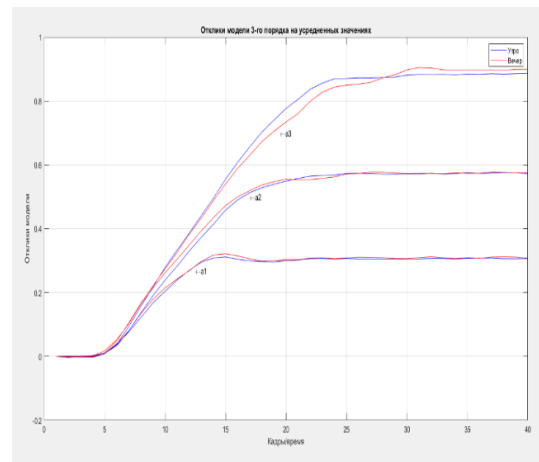


Figure 7. The responses of the model at $N = 3$ at various amplitudes of the test signals "In the Morning" and "In the Evening"

6.1 Deviation of the multidimensional transient functions

The variability (deviation) of the multidimensional transient functions of different orders n of the approximation model of OMS for the states of the respondent "In the Morning" and "In the Evening" is quantified using the indicators:

σ_{nN} - maximum deviation:

$$\sigma_{nN} = \max_{m \in \{0, M\}} |\hat{y}_{ne}[m] - \hat{y}_{nm}[m]|, \tag{6}$$

ϵ_{nN} – normalized standard deviation:

$$\epsilon_{nN} = \left(\frac{\sum_{m=0}^M (\hat{y}_{ne}[m] - \hat{y}_{nm}[m])^2}{\sum_{m=0}^M (\hat{y}_{nm}[m])^2} \right)^{1/2}, n = 1, 2, \dots, N. \tag{7}$$

The deviation indicators of multidimensional transient functions of different orders of the OMS approximation model for respondent states "In the Morning" and "In the Evening" are given in Table 1 and are represented by diagrams in Figure 8 and Figure 9.

Table 1. The deviation indicators of multidimensional transient functions

N	ϵ_{1N}	σ_{1N}	ϵ_{2N}	σ_{2N}	ϵ_{3N}	σ_{3N}
1	0.019	0.03	–	–	–	–
2	0.051	0.078	0.232	0.109	–	–
3	0.04	0.1	0.199	0.387	0.322	0.291

As can be seen from figure 5, the obtained transition function of the 1st order for the "In the Morning" and "In the Evening" are virtually independent of the status of the subject. However, the diagonal cross section of the transition functions of the second and third order change significantly in

magnitude and, therefore, can be effectively used as the primary data source when building models of classifiers of psychophysiological conditions of the person using machine learning.

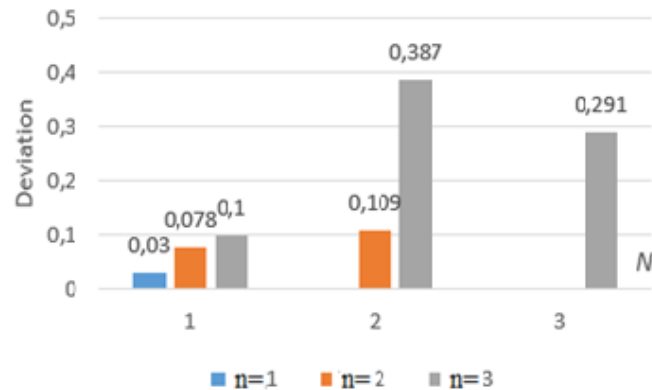


Figure 8. Diagram of deviations indicators σ_{nN}

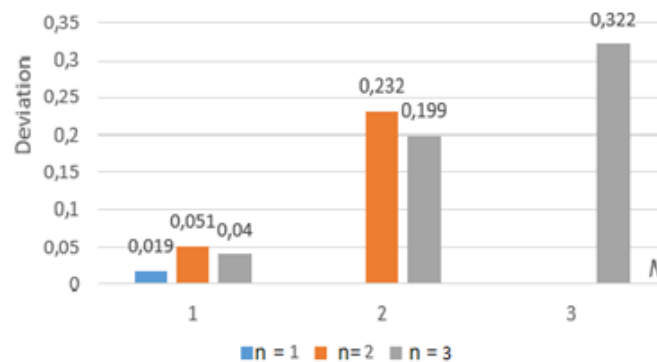


Figure 9. Diagram of deviations indicators ϵ_{nN}

7. Conclusions

The developed methodology and tools for building the non-parametric dynamic model of the OMS of the person based on the data of experimental research "input-output" test using the visual stimuli and eye tracking technology. Experimental studies of the OMS made of the same subject before and after the working day. Based on the data using the eye-tracker, transition functions of the 1st, 2nd and 3rd orders of the OMS has obtained. The revealed variability of the transition functions of the 2nd and 3rd orders for different psychophysiological states of the respondent (level of fatigue) has observed. Thus, they can be used in diagnostic studies in the field of the neuroscience and psychology.

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