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# Biometric Identification based on the Multidimensional Transient Functions of the Human Oculo-Motor System

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# Biometric Identification based on the Multidimensional Transient Functions of the Human Oculo-Motor System

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**Abstract.** Recently, identification systems that use human biometric characteristics in solving the problem of access to information systems are becoming more common. The paper proposes a new method of biometric identification of users of computer systems based on the definition of integral Volterra models of the human oculomotor system (OMS) according to experimental research "input-output" using innovative technology of eye tracking. Developed in the Python IDLE programming environment software to identify OMS. Experimental studies of the OMS of two individuals were performed. Based on the data obtained using the TOBII PRO TX300 eye tracker, the transient functions of the first, second and third orders of the OMS are determined. There is a significant difference in the diagonal intersections of the transition functions of the second and third orders of the two individuals.

## 1. Introduction

The task of user authentication is quite important in today's world. The most popular method of solving it is input user login and password until now. Password protection alone is not reliable, as it cannot provide the required level of protection without the use of other security mechanisms. Identification systems that use human biometric characteristics to solve the problem of access to information systems are becoming more common [1]-[4].

Eye tracking technology is widely used in research and educational research [5]. A variety of software has been developed and various technologies have been used in research [5]-[7]. The human visual system has unique properties that are easy to identify. Eye movements largely depend on both physical and physiological characteristics, which makes forgery impossible [8], [9]. Computational intelligence approaches are widely adopted in establishing identity based on biometrics [10]-[15]. When tracking eye movements, two positions are suggested for identification. The first is the position of the eye at a specific point on the display. The second is the moment of movement of the eyes when moving the gaze from one point to another. The computer evaluates the data obtained and determines the unique characteristics for each case [16]-[23].

## 2. The Aim of the Research

Increase the efficiency (reliability) of information protection on the computer through the development of hardware and software identification of human oculo-motor system (OMS) based on nonlinear dynamic model and data of experimental input-output research using innovative eye tracking technology. The Volterra model in the form of multidimensional transient functions (MTF) is used for identification [24].

### *2.1 The object of research*

The process of biometric identification of a computer user on the basis of eye tracking data in dynamics - responses to given test visual stimuli (the process of eye tracking).

*2.2 The subject of research*
Software tools for constructing the Volterra model – evaluation of multidimensional transient functions of OMS according to the eye-tracking data, determination based on transient functions of informative features and construction of defining rules of optimal classification.

## 3. Volterra Model and the Method of the Identification OMS

The «input-output» relationship for a nonlinear dynamic system (NDS) with an unknown structure with one input and one output is represented by a discrete Volterra series in the form [25]:

$$y[m]=\sum_{n=1}^{\infty}y_n[m]=\sum_{k_1=0}^{m}w_1[k_1]x[m-k_1]+\sum_{k_1,k_2=0}^{m}w_2[k_1,k_2]x[m-k_1]x[m-k_2]+ \\ +\sum_{k_1,k_2,k_3=0}^{m}w_3[k_1,k_2,k_3]x[m-k_1]x[m-k_2]x[m-k_3]+\dots . \tag{1}$$

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

The Volterra series is replaced by a polynomial and is usually limited to the first few terms of the series in practice. In this study we limited ourselves to the first three terms of the series (we chose the degree of the Volterra polynomial model $N = 3$).

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

Test step signals are used to identify OMS. If the test signal $x[m]=\theta[m]$, where $\theta[m]$ is a unit function (Heaviside function), then the partial components of the response $y_1[m]$, $y_2[m]$, $y_3[m]$ are equal first order transition functions and diagonal sections of second and third order transition functions:

$$y_1[m]=h_1[m]=\sum_{k_1=0}^{m}w_1[m-k_1], \\ y_2[m]=h_2[m,m]=\sum_{k_1,\,k_2=0}^{m}w_2[m-k_1,m-k_2], \\ y_3[m]=h_3[m,m,m]=\sum_{k_1,\,k_2,\,k_3=0}^{m}w_3[m-k_1,m-k_2,m-k_3]. \tag{2}$$

In this case, the responses of the Volterra model of the OMS are calculated based on the expression:

$$\tilde{y}_i[m]=a_i\hat{y}_1[m]+a_i^2\hat{y}_2[m]+a_i^3\hat{y}_3[m],\quad i=\overline{1,N}\,, \tag{3}$$

where $\hat{y}_1[m]=\hat{h}_1[m],\ \hat{y}_2[m]=\hat{h}_2[m,m],\ \hat{y}_3[m]=\hat{h}_3[m,m,m]$ are obtained estimates of the partial components of the model (MTF).

The research uses an approximation identification method [26]. The approximation method of identification in domain time is based on the allocation of the $n$-th partial component in the OMS response by constructing linear combinations of responses to test signals with different amplitudes [26], [27].

Let at system input test signals are given successively $a_1x[m]$, $a_2x[m],\dots,a_Nx[m]$ ($N$ is approximation model order, $a_1$, $a_2,\dots,a_N$ are different real numbers, which satisfy the term $|a_j|\leq 1$ for $\forall j$=1,2,...,N; $x[m]$ is arbitrary function). Then the linear combination of the OMS responses with the coefficients $c_j$ is amount to the $n$-th partial component of the OMS response to the input signal $x[m]$. In this case, a methodical error arises in the selection of the $n$-th partial component, due to the partial components of the OMS response of higher orders $n>N$:

$$\sum_{j=1}^{N} c_j\, y(a_j x[m]) = y_n(x[m]) + \sum_{j=1}^{N} c_j \sum_{n=N+1}^{\infty} y_n(a_j x[m])\,, \tag{4}$$

where

$$y_n(x[m]) = y_n[m]\,;$$

$$y(a_j x[m]) = \sum_{n=1}^{\infty} a_j^n \sum_{k_1=0}^{m} \ldots \sum_{k_n=0}^{m} w_n[k_1,\ldots,k_n] \prod_{i=1}^{n} x[m-k_i]\,;$$

if $c_j$ is real coefficients such that

$$\mathrm{A}_N\, \mathrm{c} = \mathrm{b}\,, \tag{5}$$

where

$$\mathrm{A}_N = \begin{bmatrix} a_1 & a_2 & \ldots & a_N \\ a_1^2 & a_2^2 & \ldots & a_N^2 \\ \ldots & \ldots & \ldots & \ldots \\ a_1^N & a_2^N & \ldots & a_N^N \end{bmatrix},\quad \mathrm{c} = \begin{bmatrix} c_1 \\ c_2 \\ \ldots \\ c_N \end{bmatrix},\quad \mathrm{b} = \begin{bmatrix} b_1 \\ b_2 \\ \ldots \\ b_N \end{bmatrix},$$

and $b_l = 1$ at $l = n$ and $b_l = 0$ at $l \neq n$, $\forall l \in \{1, 2, \ldots, N\}$.

For example, for $N$=2:

$$\begin{bmatrix} a_1 & a_2 \\ a_1^2 & a_2^2 \end{bmatrix} \cdot \begin{bmatrix} c_1^{(1)} \\ c_2^{(1)} \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix},$$

$$\begin{bmatrix} a_1 & a_2 \\ a_1^2 & a_2^2 \end{bmatrix} \cdot \begin{bmatrix} c_1^{(2)} \\ c_2^{(2)} \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix};$$

for $N$=3:

$$\begin{bmatrix} a_1 & a_2 & a_3 \\ a_1^2 & a_2^2 & a_3^2 \\ a_1^3 & a_2^3 & a_3^3 \end{bmatrix} \cdot \begin{bmatrix} c_1^{(1)} \\ c_2^{(1)} \\ c_3^{(1)} \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix},$$

$$\begin{bmatrix} a_1 & a_2 & a_3 \\ a_1^2 & a_2^2 & a_3^2 \\ a_1^3 & a_2^3 & a_3^3 \end{bmatrix} \cdot \begin{bmatrix} c_1^{(2)} \\ c_2^{(2)} \\ c_3^{(2)} \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix},$$

$$\begin{bmatrix} a_1 & a_2 & a_3 \\ a_1^2 & a_2^2 & a_3^2 \\ a_1^3 & a_2^3 & a_3^3 \end{bmatrix} \cdot \begin{bmatrix} c_1^{(3)} \\ c_2^{(3)} \\ c_3^{(3)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}.$$

The evaluation of transient functions can be set in general as follows:

$$\begin{aligned} \hat{h}_n^{(N)}[m,\ldots,m] &= \hat{y}_n[m] = \sum_{j=1}^{N} c_j^{(n)} y(a_j \theta[m]) = \\ &= c_1^{(n)} y_{a_1}[m] + c_2^{(n)} y_{a_2}[m] + \ldots + c_N^{(n)} y_{a_N}[m],\quad n = 1,2,\ldots,N, \end{aligned} \tag{6}$$

where $y_{a_j}[m] = y(a_j \theta[m])$ – OMS response to a test signal with an amplitude $a_j$.

Some cases of recording transient functions for $N$=3 and $\forall m \geq 0$:

$$\hat{h}_1[m] = c_1^{(1)} y_{a_1}[m] + c_2^{(1)} y_{a_2}[m] + c_3^{(1)} y_{a_3}[m],$$

$$\hat{h}_2[m,m] = c_1^{(2)} y_{a_1}[m] + c_2^{(2)} y_{a_2}[m] + c_3^{(2)} y_{a_3}[m],$$
$$\hat{h}_3[m,m,m] = c_1^{(3)} y_{a_1}[m] + c_2^{(3)} y_{a_2}[m] + c_3^{(3)} y_{a_3}[m]. \quad (7)$$

Model responses at $N$=3 to step test signals with amplitudes $a_1$, $a_2$, $a_3$:

$$\tilde{y}_1[m] = a_1\hat{h}_1^{(3)}[m] + a_1^2\hat{h}_2^{(3)}[m,m] + a_1^3\hat{h}_3^{(3)}[m,m,m],$$
$$\tilde{y}_2[m] = a_2\hat{h}_1^{(3)}[m] + a_2^2\hat{h}_2^{(3)}[m,m] + a_2^3\hat{h}_3^{(3)}[m,m,m], \quad (8)$$
$$\tilde{y}_3[m] = a_3\hat{h}_1^{(3)}[m] + a_3^2\hat{h}_2^{(3)}[m,m] + a_3^3\hat{h}_3^{(3)}[m,m,m],$$

model responses at $N$=2:

$$\tilde{y}_2[m] = a_1\hat{h}_1^{(2)}[m] + a_1^2\hat{h}_2^{(2)}[m,m],$$
$$\tilde{y}_2[m] = a_2\hat{h}_1^{(2)}[m] + a_2^2\hat{h}_2^{(2)}[m,m]. \quad (9)$$

## 4. Results

To identify the OMS in the form of MTF according to the data eye tracking program Signal Manager was created to generate test visual stimuli on the computer monitor screen. The obtained physiological features of the OMS, in experiments on eye movement tracking, step signals (bright dots) with different distances $a_j$ ($j$ = 1,2,…,$N$; $N$ is number of experiments) from the starting position are used. Thus, visual stimuli can be considered as functions $x_j[m]= a_j\theta[m]$, where $\theta[m]$ is a unit Heaviside function. With the help of an eye tracker, the responses of the OMS are recorded, which are used to determine the MTF [28].

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 conducted using high-tech equipment – eye tracker TOBII PRO TX300 (300 Hz) [29].

In Figure 1 and Figure 2 OMS responses to test visual stimuli with amplitudes $a_1$, $a_2$ and $a_3$. in two individuals are shown that were obtained on different days and at different times of the day.

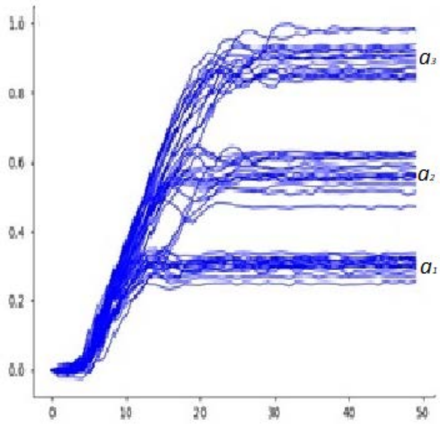


**Figure 1.** OMS responses to visual stimuli with amplitudes $a_1$, $a_2$, $a_3$ for 1st student

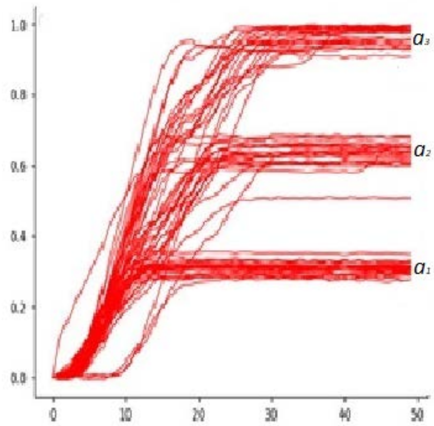


**Figure 2.** OMS responses to visual stimuli with amplitudes $a_1$, $a_2$, $a_3$ for 2nd student

According to the averaged data of OMS responses to visual stimuli (Figure 3), the transient functions of OMS when using Volterra models of different degree $N$ ($N$=1,2,3) were determined. Graphs of transient functions for two individuals based on the model at $N$=1 are presented in Figure 4, at $N$=2 – in Figure 5 and at $N$=3 – in Figure 6. As it can be seen from Figure 4 – Figure 6, the obtained transient functions of the 1st order almost coincide for two individuals. However, the diagonal sections of the transient functions of the 2nd (Figure 5) and third (Figure 6) orders in two individuals change significantly in values, therefore, can be effectively used as a source of primary data in building a system of recognition of individuals with application of machine learning.

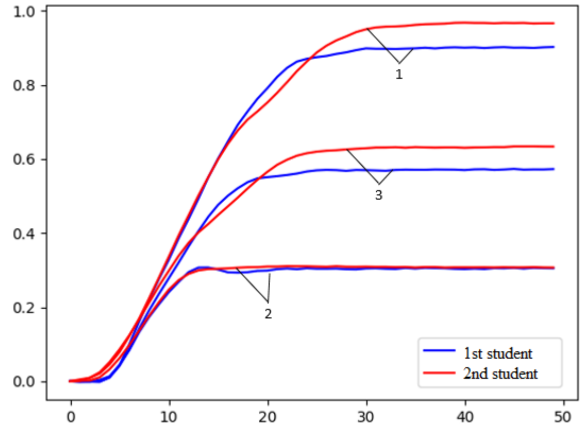


**Figure 3.** Average responses of OMS of two individuals

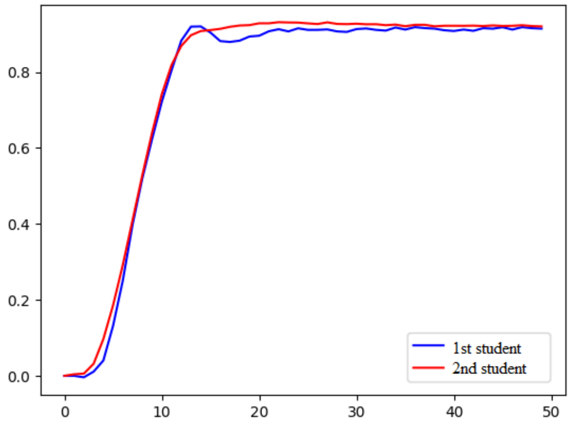


**Figure** 4. Transient functions 1st orders of two individuals

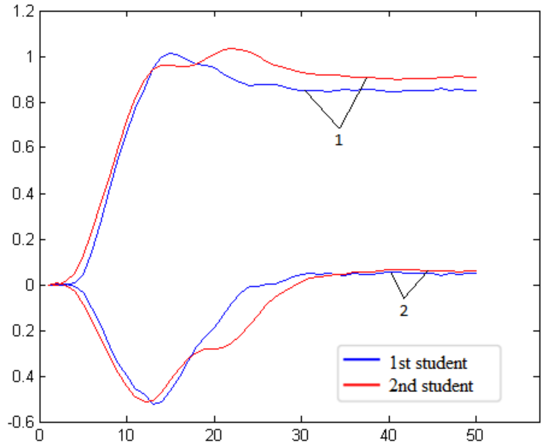


**Figure 5.** Transient functions: *1* – 1st; *2* – 2nd orders of two individuals

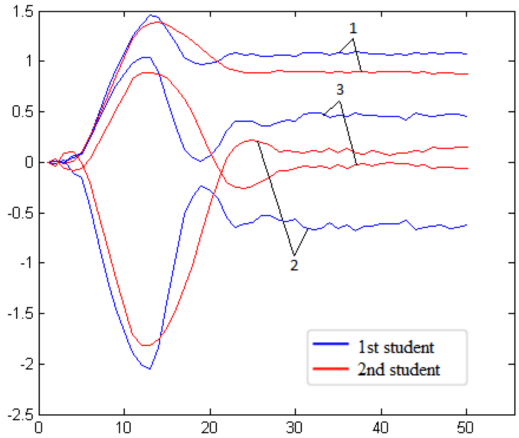


**Figure 6.** Transient functions: *1* – 1st; *2* – 2nd; *3* – 3rd orders of two individuals

Received responses with the help of calculations on models at $N = 3$ from various amplitudes of test signals. Graphs these are presented in comparison with similar responses OMS for premier and second of the students in Figures 7 and 8, respectively.

*4.1 Building a classifier of the individuals*

For identity recognition of the individuals based on the OMS nonlinear dynamical model conducted research:

*4.1.1 Building a feature space for designing classifier of the individual with using machine learning.* Classifiers construction with using statistical methods of learning the pattern recognition based on the data obtained using eye tracking technology.

The analysis of the reliability of personality recognition in the space of features calculated on the basis MTF consists in forming various combinations of features and evaluating their informativeness based on the classification results on the data sample under study using criterion for the probability of correct recognition (PCR). Thus, all possible pairs of features were investigated by the exhaustive search method. For studies of the informativeness, the features presented in the table (Appendix) are used.

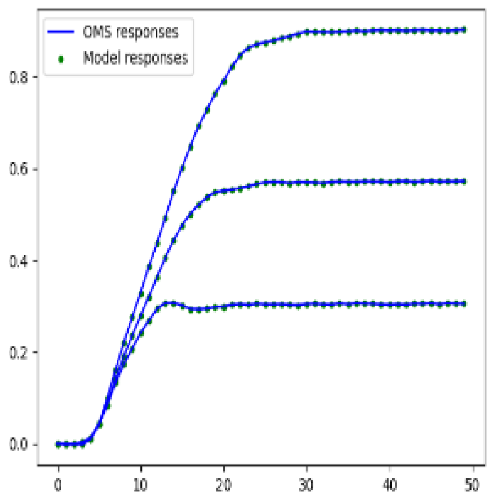


**Figure 7.** Average responses of the OMS and of the Volterra model for *N*=3 of first student

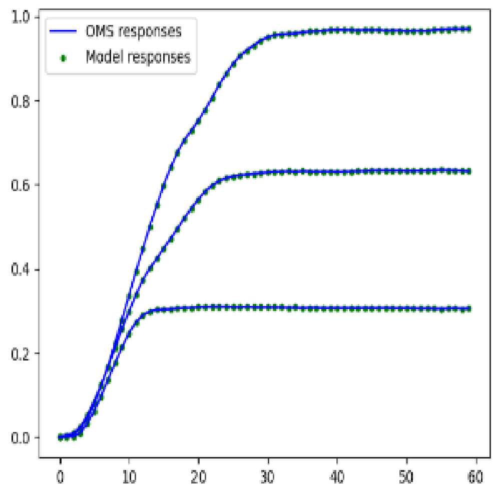


**Figure 8.** Average responses of the OMS and of the Volterra model for *N*=3 of second student

To locate features resistant to noise, we conducted the additional research which consisted of adding random 1% and 5% samples from a normal (Gaussian) distribution.

A complete enumeration of features was investigated by the method of statistical solutions for the PCR, from the set of values of which the average value of this indicator was calculated. The pair of features was chosen that maintained the stability of the indicator under perturbation.

The column chart of the maximum recognition reliability values of the best pair of features at different noise levels is presented in Figure 9. For comparison, a couple of features are presented that are less resistant to noise in Figure 10.

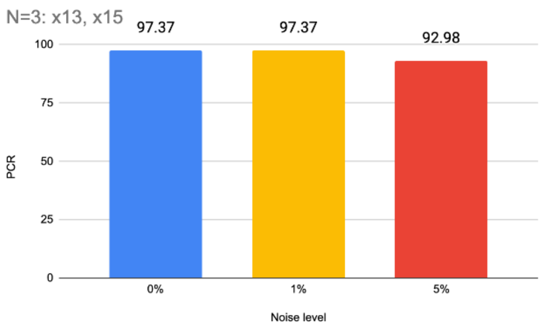


**Figure 9.** The column chart of the PCR of $x_{13}$, $x_{15}$ features

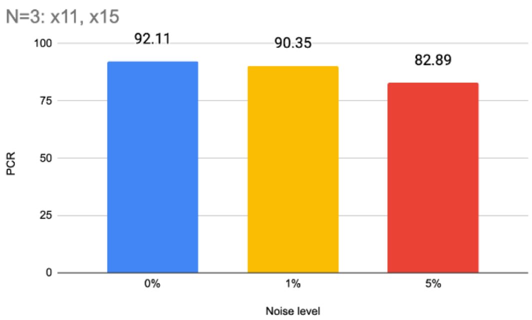


**Figure 10.** The column chart of the PCR of $x_{11}$, $x_{15}$ features

Moreover, separately features $x_{13}$ and $x_{15}$ gives the following results:

- $x_{13}$ yields the PCR $P$=0.8684;
- $x_{15}$ yields the PCR $P$=0.7368.

So, the best combination of two features with noise resistance that gives high PCR is:

$$x_{13} = \min_m h_1^{'}(m) \ \& \ x_{15} = \min_m h_3^{'}(m,m,m) \cdot \qquad (10)$$

Bayesian classifier of individuals in two-dimensional features space is provided of the maximum recognition reliability (*P*) at the combination by these features: the PCR is *P*=0.9737.

Analogic results were obtained by means of Support Vector Machine (SVM) [30]. The classifier is built using a 2nd order polynomial kernel:

$$K(x,x') = (\langle x,x' \rangle + 1)^d, \quad (11)$$

where *d* is determined by degree of the parameter, *d* =2.

Scikit-learn library was used (class sklearn.svm.SVC) to apply SVM. The location of the objects of the training sample in the space of features is show in Figure 11.

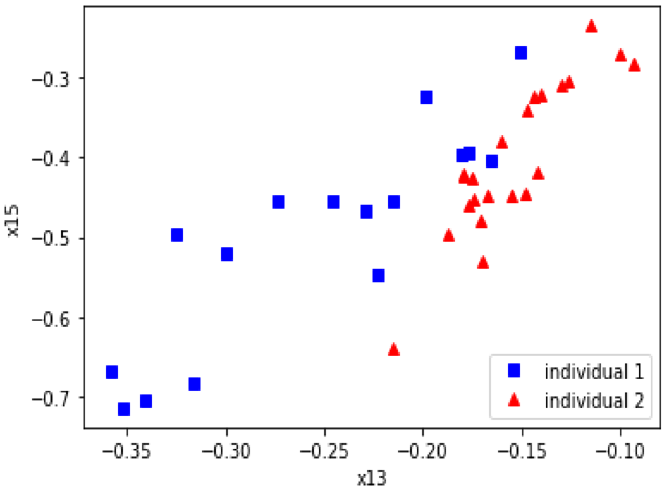


**Figure 11.** The location of the objects of the training set in the space of features $x_{13}$ and $x_{15}$

## 5. Conclusion

Management and differentiation of access to computer systems and their resources is an important aspect of information security. It can be done through user identification. A new method of biometric identification is proposed formed on the determination of integrated Volterra models of the human OMS based upon experimental research "input-output" using innovative eye tracking technology. There is data of two respondents applied in experimental studies. More individuals' data will be involved in future study to expand the research base.

The first, second and third orders transition functions of the OMS were determined based on the data received using the TOBII PRO TX300 eye tracker. Since there is a substantial difference between the diagonal intersections of the second and third order transition functions of two individuals, they can be used for feature space forming to build statistical classifiers for identity recognition.

Promising results were obtained in the problem of identification by behavioral characteristics of a person with a recognition accuracy of more than 97%. A pair of features was selected that are resistant to computational errors, which gives a high result of the probability of correct recognition.

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**Appendix.** Investigated heuristic features

| # | Features | Formal definition |
|---|---|---|
| **1** | $x_1$ | $x_1 = \sum_{m=1}^{M} \lvert h_1(m) \rvert$ |
| **2** | $x_2$ | $x_2 = \sum_{m=1}^{M} \lvert h_2(m,m) \rvert$ |
| **3** | $x_3$ | $x_3 = \sum_{m=1}^{M} \lvert h_3(m,m,m) \rvert$ |
| **4** | $x_4$ | $x_4 = \arg\max_m h_1^{'}(m)$ |
| **5** | $x_5$ | $x_5 = \arg\max_m h_2^{'}(m,m)$ |
| **6** | $x_6$ | $x_6 = \arg\max_m h_3^{'}(m,m,m)$ |
| **7** | $x_7$ | $x_7 = \arg\min_m h_1^{'}(m)$ |
| **8** | $x_8$ | $x_8 = \arg\min_m h_2^{'}(m,m)$ |
| **9** | $x_9$ | $x_9 = \arg\min_m h_3^{'}(m,m,m)$ |
| **10** | $x_{10}$ | $x_{10} = \max_m h_1^{'}(m)$ |
| **11** | $x_{11}$ | $x_{11} = \max_m h_2^{'}(m,m)$ |
| **12** | $x_{12}$ | $x_{12} = \max_m h_3^{'}(m,m,m)$ |
| **13** | $x_{13}$ | $x_{13} = \min_m h_1^{'}(m)$ |
| **14** | $x_{14}$ | $x_{14} = \min_m h_2^{'}(m,m)$ |
| **15** | $x_{15}$ | $x_{15} = \min_m h_3^{'}(m,m,m)$ |
| **16** | $x_{16}$ | $x_{16} = \max_m \lvert h_1(m) \rvert$ |
| **17** | $x_{17}$ | $x_{17} = \max_m \lvert h_2(m,m) \rvert$ |
| **18** | $x_{18}$ | $x_{18} = \max_m \lvert h_3(m,m,m) \rvert$ |
| **19** | $x_{19}$ | $x_{19} = \arg\max_m \lvert h_1(m) \rvert$ |
| **20** | $x_{20}$ | $x_{20} = \arg\max_m \lvert h_2(m,m) \rvert$ |
| **21** | $x_{21}$ | $x_{21} = \arg\max_m \lvert h_3(m,m,m) \rvert$ |

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