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Eye Movement Analysis in Simple Visual Tasks

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Abstract. The small eye movements in the process of fixation on an image element give us knowledge about the human visual information perception. An in-depth analysis of these movements can reveal the influence of personality, mood and mental state of the examined subject on the process of perception. The modern eye tracking technology provides us with the necessary technical means to study these movements. Nevertheless, still a lot of problems remains open. In the present paper two approaches for noise cancellation in the eye-tracker signal and two approaches for microsaccade detection are proposed. The analysis of the obtained results can be a good starting point for interpretation by neurobiologists about the causes of different types of movement and their dependence on the individuality of the observed person and the specific mental and physical condition.

Keywords: fixation eye movements, eye tracker, microsaccade detection.

1. Introduction

The eye movements have long attracted the attention of specialists. They can be used to diagnose a person's mental state, his ability to concentrate, the speed of perception of visual information and much more. In the performance of various visual tasks the eye movement is influenced by external stimuli (the observed scenario), complex cognitive processes and by some unconditional fine sensorimotor mechanism. The so-called eye-trackers (ET) are used to study the eye movement, with the help of which the parameters of the eye movement are obtained. The latest generation of ETs are "non-obtrusive" (can not interfere with a person's freedom of movement) and can provide information with sufficient accuracy even for rapid eye movements. When a subject scans a visual scene two types of the state of his eyes occur: fast movements or saccades and periods of eyes fixations, when only a small amplitude movements are registered. This article discusses the fixational movements only. The fact of existence of fixation of the gaze on certain objects in the scene has been known for a long time. As early as 1879, the French ophthalmologist Emile Javal reported two main conditions of the eyes when a person is reading - rapid jumps (saccades, in fact, the term saccades was first used by Javal, which is in French and it is analogous to the English word jerk) and pauses [31]. Latter, it was discovered that even in pauses (the process of fixation), the eyes continue to move constantly and the described trajectories look chaotic and wandering. The instantaneous speed of these movements is not low, particularly when the head is not specially fixed. It was estimated to a value of about 1degree per second [4,23,30]. However, due to the ever-changing velocity vector, the average velocity of eye movement is low [10].

Fixational eye movements are subdivided into microtremor, drift and microsaccades [17,9]. It is assumed that these movements lead to small displacements of the image on the fovea when observing a still scene. These movements have not been clearly defined so far and their separation is still a scientific challenge [27]. There is also no well-proven theory about the visual functions of each of these micro movements.

ET is an appropriate measurement equipment for eye movement registration and it is assumed also the presence of Gaussian additive noise in the received signal.

The role of different eye movements in performing fixation has been intensively studied and analyzed for decades, but there are many difficulties in elucidating their physiological and perceptual functions. To this day, there is no consensus on these issues [27,19,26]. While for the larger saccades it has been established with high reliability that they move the image of the observed object in the area of the fovea with the highest resolution, the purpose of the microsaccades, tremor and drift is still a debatable issue.

The **fixation** of the gaze on a specific stationary object is characterized by a relatively stationary projection of the image of this object on the most sensitive part of the fovea. Usually, the fixation is associated with the time between two major saccades, when there are no other big eye movements and there only eye tremor and drift exist. Some scientists claim that the duration of fixation is about $250ms$ [14].

Saccades are relatively large eye movements in the range of $5^0 - 40^0$ [25].The saccade rate is approximately 2-3 times per second [27]. They serve to focus on the observed object by moving it to the most sensitive area of the fovea. Some of them can be considered volitional/conscious. For example, while performing large search saccades, we perform mostly unconscious eye movements during natural vision. We are also able to move to the conscious performance of saccades when performing a specific visual task. Their duration is estimated in the range of 30-80ms (112ms in [25]). In the problem of volitional fixation for a long period of time on a stationary object, considered in the present work, it turned out that the saccades cannot be suppressed all the time and they appear periodically.

Microsaccades are relatively fast eye movements (have the same dynamic characteristics as saccades), but with a smaller amplitude (up to 12 angular minutes usually) [9,13] and a frequency of $1 - 2$ times per second [27]. The purpose of the micro-saccades has not yet been definitively clarified and is a moot point. While it was initially thought to be ”noise” in the system, in recent years there has been a growing perception that microsaccades have a function of repositioning within the fovea during periods of fixation [27]. Other scientists consider microsaccades as compensatory eye movements for stabilization against head and body movements, which are guided by both visual and vestibular inputs [17]. Microsaccades are thought to be irregular and rare with a frequency of about 1 microsaccade per second [11,17] and their statistics reflect both perceived visual information and changes in a person’s cognitive state. The relationship between microsaccades and visual concentration has recently been confirmed by some researchers and they believe that microsaccades have been used to fine-tune the gaze [16]. There are also articles that provide evidence of reducing the number of microsaccades when performing work with high precision - threading or aiming, for example. In the specific experiments conducted in the present work, we assume that the microsaccades are involuntary/unconscious and the observed person does not even know about their existence.

Ocular microtremor is a small (up to one angular minute [27]) high-frequency eye tremor caused by extra-muscular activity stimulated by impulses emitted from the oculomotor area of the brainstem. It is inherent to all people. Several studies have shown that the incidence of this tremor is reduced in patients whose consciousness is decreased by anesthesia or head injury [6]. Ocular tremor is a non-periodic oscillation in the range of 70 - 103 Hz and the average frequency is 83.68 Hz [7].

Eye drift is another smoother and slower movement of the eyes when fixed. The similarity of the movement as a result of eye drift with the brown movement of the particles is often pointed out - randomly and arbitrarily. The frequency of ocular deviations is significantly lower than that of microtremor and is in the range 0 - 40 Hz, and the amplitude of change - about 1.5' - 4' with an average speed of about 4'/s [10]. One of the hypotheses for this eye movement pointed out that the eye drift helps to be obtained higher resolution information for the observed stationary objects [18,2]. In another paper a suggestion was proposed that eye drift is related to the coding and processing of visual information in space and time [1]. All of these fixational eye movements were considered vital for the observation of stationary scenes that were thought to fade over time without movement [24]. Although this remains a controversial topic to this day [27], it is clear that these movements play a very important role in the perception of information by the brain and their analysis can reveal basic properties of the visual system. The correct classification of one or another type of fixational eye movements is a challenge [27], to which this article is devoted.

The small eye movements during fixation is the main object of research in this article. Several algorithms for different fixational eye movement segmentation are proposed. The block diagram of the proposed algorithms for eye tracker data processing is shown on Fig. 1. The obtained results are discussed.

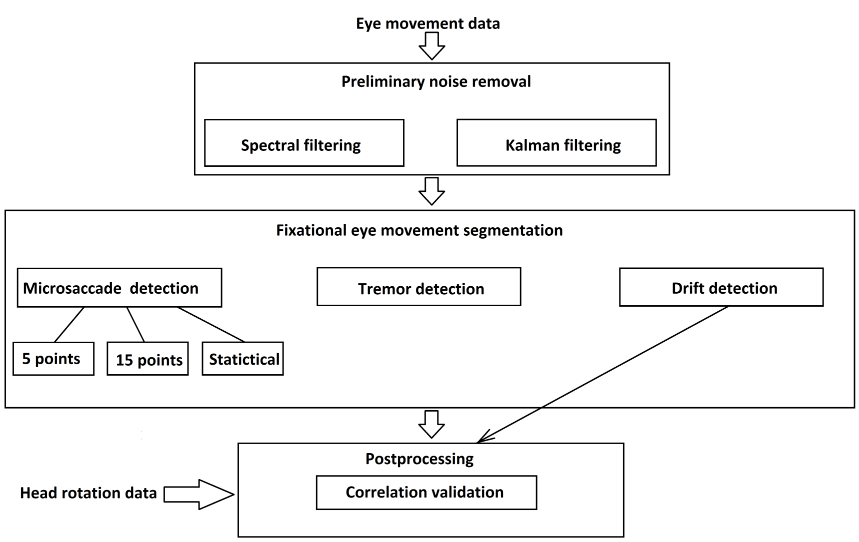

Fig. 1. The block diagram of the proposed algorithms for eye tracking data processing

The paper is organized as follows. After short review of state of the art in the field of fixational eye movement research a mathematical model of fixational eye movement is proposed in Chapter II. Then a description of experimental setup is given. Two noise filtering techniques are proposed in Chapter IV. The first one considers spectral filtering, the second one - Kalman filtering. Chapter V gives description of two methods for microsaccade detection. One of them is based on eye movement velocity, the other analyses the statistical characteristics of ET signal. In Chapter VI microtremor and eye drift are detected and separated. The analysis of results is discussed in Chapter VII and finally the authors contributions are summarized in Conclusion.

2. Eye Movement Description

In this article the fixational eye movements will be commented only. From the brief description in the previous chapter it is clear that there are several types of fixational eye movements with insufficiently clear origin and purpose. Due to the significant differences in frequency and amplitude values of the three types of movements during fixation (microsaccades, microtremor and drift) we will accept the hypothesis that they are additive. Let us denote the movement of the eyes in the process of fixation by m. The movement of the eyes is carried out by rotating the eyes in horizontal and vertical directions. Therefore, the movement of the eyes in the process of fixation will be described by the two-dimensional vector $m = \begin{bmatrix} m^{(h)} \\ m^{(v)} \end{bmatrix}$ and will be measured by the degrees of rotation [deg] on each of its components (h - horizontal and v - vertical). In clinically healthy observed individuals, we will assume that $m = \frac{m_l + m_r}{2}$, where m_l is the rotation magnitude vector of the left eye and m_r is the rotation magnitude vector of the right eye. In fixation mode, according to our hypothesis:

$$m = m_s + m_t + m_d \,, \tag{1}$$

i.e. the total eye movement is equal to the sum of the rotations caused by microsaccades, microtremor, and eye drift. The eye tracker, eye rotation measuring instrument, used in the experiments, measures the values of the components of the vector m every $0.001s$. Like any measuring device, eye tracker measures the rotation of the eyes with an error that with high plausibility could be considered as Gaussian distributed and additive to the measured values:

$$m^{(ET)} = \begin{bmatrix} m^{(ET_h)} \\ m^{(ET_v)} \end{bmatrix} = \begin{bmatrix} m^{(h)} \\ m^{(v)} \end{bmatrix} + \begin{bmatrix} \epsilon^{(h)} \\ \epsilon^{(v)} \end{bmatrix} = \begin{bmatrix} m_s^{(h)} + m_t^{(h)} + m_d^{(h)} + \epsilon^{(h)} \\ m_s^{(v)} + m_t^{(v)} + m_d^{(v)} + \epsilon^{(v)} \end{bmatrix} \,, \tag{2}$$

Eliminating noise and separating the different types of movements in the scan path is a mandatory step in the analysis of eye movement. The quality of the subsequent analysis also depends on the quality of noise reduction and fixational eye movement detection and separation. In the following chapters several algorithms for noise removal and eye movement separation are proposed and analyzed.

3. Experimental Setup

The eye movements of the participants in the experiment were recorded by a specialized hardware - ”Jazz novo” eye tracking system (Ober Consuting Sp. Z o.o.). The recordings from all the sensors of the device for one session per person were collected with 1 kHz frequency rate and the information is saved in files for analysis. The obtained sensor data include: the calibration information; records of horizontal and vertical eye positions in degrees of visual angle; information received from device accelerometers (vertical and horizontal accelerations) and gyroscopes (rotation rate in vertical and horizontal planes); information about tested subjects and type of the experimental trial for each particular record.

The eye tracker ”Jazz novo” is a mobile nonobtrusive device, which consists of several sensors:

– Monocular eye tracking sensor which measures the rotations of both eyes and gives as an output an averaged rotation. The sensor is located above the person’s nose;
– 2-axial gyroscope, which measures the speed of rotation rate of the head in Y and Z (yaw) axes;
– 2-axial accelerometer, which tracks the acceleration of the head in Y (pitch) and Z (yaw) axes.

The stimuli were presented on a gray screen with mean luminance $50cd/m^2$ using $20.1''$ NEC MultiSync LCD monitor with Nvidia Quadro 900XGL graphic board at a refresh rate of 60 Hz and screen resolution 1280×1024 pixels.

The stimulus, which the test subjects were exposed to, consists of PowerPoint animation, shown on a dark background, displayed on a 41x31 cm screen. The test subject is sitting at a distance 58 cm from display. Scenario consists of several tasks: eye fixation on a dot; tracking a moving dot on the screen (dynamical task); several search tasks on a complex scenario. The first part of experiment is discussed in this article.

The especially designed scenario includes five consecutively appearing dots, located in the middle of the left display edge, in the middle of the right display edge, in the middle of the upper display edge, in the middle of the lower display edge and in the middle of the screen, respectively. Every of these points remains stationary $15s$ and then disappears.

Eight persons were examined. Six of them were of age between 20 and 30 years. One participant was 40 years old and the last one was 60 years old. The results from one of them are presented in the article, the results from others were used to tune and validate algorithms for eye tracker data processing.

4. Eye Tracker Signal Filtering

Signal noise filtering aims to cut or to attenuate the noise and its effect on the useful signal. The ET signal for horizontal eye movement and 2D eye movement in fixational state are displayed on Fig. 2 and Fig. 3 correspondingly. Two approaches to noise filtration have been implemented.

The first of these is based on our a priori knowledge of the frequency properties of eye movement during fixation on an object. It has been found that the highest frequency component of these movements is of the order of 104 Hz. The first noise suppression algorithm converts the ET signals $m^{(ET_h)}$ and $m^{(ET_v)}$ from time domain into frequency domain and reset the frequency coefficients higher than 104 Hz to zero. Then the signal is converted from the spectral to the time domain back. The results of each of the filtration steps are shown on Fig. 4 and Fig. 5:

Additionally several peaks were found in the regions around 50 Hz, 100 Hz and 150 Hz. We consider that there are harmonics of power supply with standard frequency of 50 Hz. The region around 50 Hz (± 0.01 Hz) has been zeroed in order to remove the power supply influence.

Clearing certain frequencies gives more realistic picture of the real eye movement. Most of the predictable factors have been cleared. Some random body movement and unpredictable sensor disturbances still remain uncleaned.

The second filtering approach uses a two-dimensional Kalman filter [5]. We choose the window size of 11 measurements ($10 * 0.001s = 0.01ms$ - the window size corresponds to a frequency of 100 Hz). In this window the statistical characteristics of the signal are calculated. It is assumed that these are the statistical characteristics of the additive noise (frequencies are 100 Hz and higher).

The state equation is defined as:

$$s_{k+1} = Fs_k + \omega_k \tag{3}$$

In this equation s_{k+1} is the state vector at the $k+1$ -st moment and $s_{k+1} = \begin{bmatrix} x \\ \dot{x} \\ y \\ \dot{y} \end{bmatrix}$, where $x, \dot{x}$ are the horizontal location of the eye and its rotation speed in degrees and degrees per second, respectively, and $y, \dot{y}$ are the vertical location of the eye and its rotation speed. The matrix $F = \begin{bmatrix} 1 & \Delta t & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & \Delta t \\ 0 & 0 & 0 & 1 \end{bmatrix}$ is a matrix of the transition from state in k-th moment to state in k+1-th moment.The vector $\omega_k = \begin{bmatrix} \sigma_x^2 \\ \sigma_{\dot{x}}^2 \\ \sigma_y^2 \\ \sigma_{\dot{y}}^2 \end{bmatrix}$ sets the uncertainty in the change of the state vector (the uncertainty in the model of the observed system). It is assumed the uncertainty to have multivariate normal distribution with zero mean and covariance Q_k: $\omega_k \sim N(0, Q_k)$. The covariance matrix of the error of the state vector at the k-th moment is expressed by:

$$Q_k = \begin{bmatrix} \sigma_{xp}^2 1/3\Delta t^3 & \sigma_{xp}^2 1/2\Delta t^2 & 0 & 0 \\ \sigma_{xp}^2 1/2\Delta t^2 & \sigma_{xp}^2 \Delta t & 0 & 0 \\ 0 & 0 & \sigma_{yp}^2 1/3\Delta t^3 & \sigma_{yp}^2 1/2\Delta t^2 \\ 0 & 0 & \sigma_{yp}^2 1/2\Delta t^2 & \sigma_{yp}^2 \Delta t \end{bmatrix}$$

The equation of the relationship between the measurement vector and the state vector looks like this:

$$z_k = Hs_k + v_k, \tag{4}$$

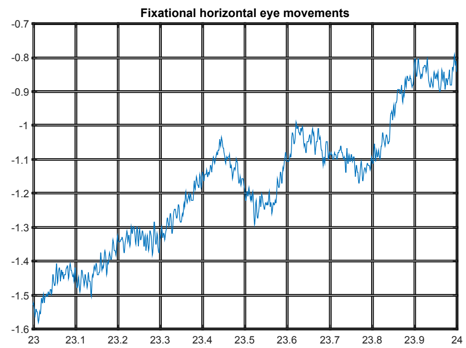

Fig. 2. ET noisy signal for horizontal eye movement

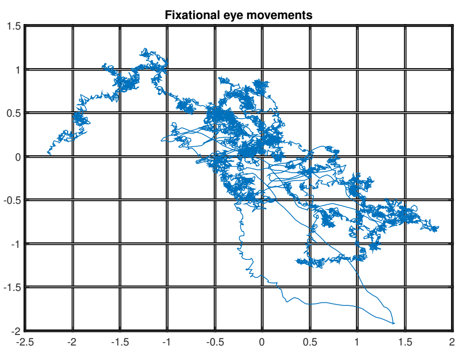

Fig. 3. 2D ET signal (for 2D eye movement)

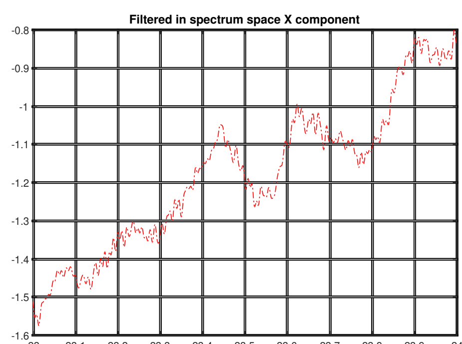

Fig. 4. Filtered in frequency domain ET measurements (horizontal only movement)

where $z_k = \begin{bmatrix} z_x(k) \\ z_y(k) \end{bmatrix}$ is a vector of measurements obtained by ET for eye movements in the horizontal and vertical directions, respectively; $H = \begin{bmatrix} 1\,0\,0\,0 \\ 0\,0\,1\,0 \end{bmatrix}$ is the correspondence

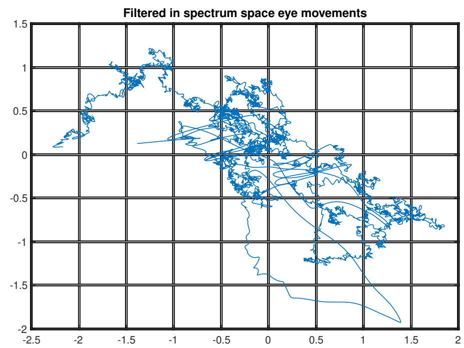

Fig. 5. Filtered in frequency domain ET measurements (2D movement)

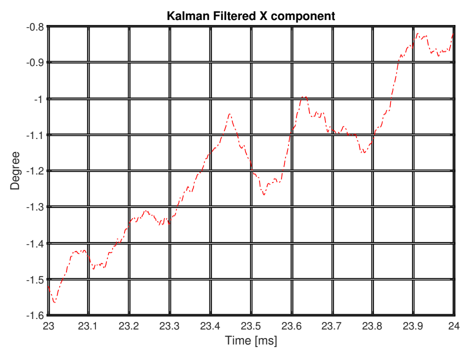

Fig. 6. Kalman filtered measurements (horizontal eye movement)

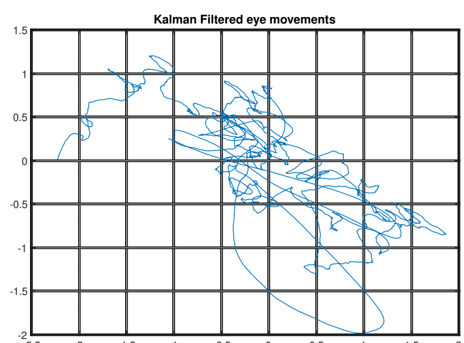

Fig. 7. Kalman filtered measurements (2D eye movement)

matrix between the state vector and the vector of the measurements and $R_k = \begin{bmatrix} \sigma_x^2 & 0 \\ 0 & \sigma_y^2 \end{bmatrix}$ is the covariance matrix of the errors of the used ET $(v_k \sim N(0, R_k))$.

The Kalman filter is described by the following two main steps:

Prediction step:

$$s_{k+1/k} = F\hat{s_k}, \tag{5}$$

Here $s_{k+1/k}$ is the predicted state of the system at $k+1$-st moment based on the estimated state vector s_k at the previous k-th moment.

$$P_{k+1/k} = FP_{k/k}F^T + Q_k, \tag{6}$$

where $P_{k+1/k}$ is the predicted value of the covariance matrix of the error based on the specified covariance matrix of the error $P_{k/k}$ at the k-th moment and the covariance matrix of the error of the state vector Q_k.

Update step:

Finding the innovation for the predicted value:

$$\nu_k = z_k - Hs_{k/k-1} \tag{7}$$

Calculation of the gain:

$$K_k = P_{k/k-1}H^T(R + HP_{k/k-1}H^T)^{-1} \tag{8}$$

Finding the updated status vector:

$$s_{k/k} = s_{k/k-1} + K_k\nu_k \tag{9}$$

Finding the updated error covariance matrix:

$$P_{k/k} = (I - K_kH)P_{k/k-1} \tag{10}$$

Fig. 6 and Fig. 7 show the results of applying the Kalman filter on the measurements obtained from ET. The received results are for the following values of Kalman filter parameters: $\Delta t = 0.001s, \sigma_{xp}^2 = \sigma_{yp}^2 = 10000, \sigma_x = 3.35, \sigma_y = 2.67$ [3].

The proposed filters for noise rejection have some principal differences. The spectral filtering algorithm is based on the knowledge of the useful spectrum of data obtained from eye tracker and removes everything outside this spectrum. In the case of noise presence in the bandpass region, this noise is not removed and will continue to affect the useful signal. The electricity supply $(50Hz)$ should serve as an example of noise in the allowable spectrum range. Special measures have been taken to be eliminated.

The second method uses the analysis of the eye tracker data [3]. Applying Kalman filter with parameters, corresponding to the used apparathus the eye tracker measurement error will be minimized, but the part of the useful signal will be affected also and this leads to deviations in the results.

Due to the difficulty of making an accurate balance of which of the methods is better, both approaches are presented and depending on the problem to be solved and the equipment used, the more appropriate one can be chosen.

5. Microsaccade Detection

Microsaccades are relatively large movements of the eye in fixation mode. If we assume that the microsaccade detecting technique is similar to the technique of saccade detection, then the following methods could be applied [28]:

- Methods based on the speed of movement of the eye. These methods use the hypothesis of a higher velocity of the eye in saccade compared with other eye movements in fixation mode. The same hypothesis could be successfully applied to distinguish microsaccades from tremor and drift;
- Methods using dispersion. These methods are based on the dispersion, which in this case is a measure of the deviation of the gaze from the point of fixation. The method is also applicable to distinguish microsaccades from drift and ocular tremor, due to the different statistics of these movements;
- Methods using the fixation area. The article cited above also mentions so-called microfixations. Under microfixations the authors considered fixation points, which are closely located and the movements in them could be performed by the microsaccades we are looking for;
- Methods using the saccade duration. These methods use the predefined information that the fixation is seldom shorter than 100 ms, most often in the range between 200-400 ms;
- Locally adaptive methods. This type of method estimates the approximate duration of fixation of each observed person and uses it for subsequent signal analysis. Therefore, this method is adaptive to the specifically observed person.

In this article we implemented two algorithms for microsaccade detection. The microsaccade is defined as continuous eye movement, exceeding a certain velocity threshold.

The first of them is based on finding the highest speeds of eye movement during fixation (Fig. 8). To reduce the impact of outliers, eye movement velocities are calculated using windows with length of 5 or 15 points. This part of the algorithm can be regarded similar to the classical algorithm of Engbert and Kliegl ([12]), but with the use of other window sizes. Finding the maxima in the (average) 2D velocities of eye movement, the search for the starting and end points of each microsaccade begins. Unlike the Otero-Millan et al. ([22]) algorithm, where the starting points are determined by means of a constant threshold ($3^0/s$) in the proposed algorithm an adaptive threshold is chosen depending on the average speed of eye movement during fixation. A term of a reasonable distance for connecting neighboring microsaccades is also introduced. It serves to merge saccades if the distance between them is smaller than a threshold. The obtained results of saccade detection are shown on Fig. 8, Fig. 9, Fig. 10 and Fig. 11 for two cases of 5 and 15 points windows.

The second solution is based on statistical signal analysis. We assume that the statistical signal parameters change significantly during microsaccade motion. The algorithm for microsaccade detection looks for an event of a significant change in the dispersion of the signal received from ET in the fixation mode. In order to test this hypothesis a window signal processing is organized, considering 11 consecutive measurements. For the current window, the obtained measurements can be considered as a realization of 11 normally distributed random variables. They can also be normalized to the sum of their squares χ^2_{10}:

$$\chi^2_{10} = \Sigma_{i=1}^{11}((X_i - \mu_i)/\sigma_i)^2$$

which represents a chi-square distribution with 10 degrees of freedom. Here X_i denotes the i-th measurement in the window, $\mu_i = (\Sigma_{i=1}^{n} X_i)/n$ is the mean of the measurements

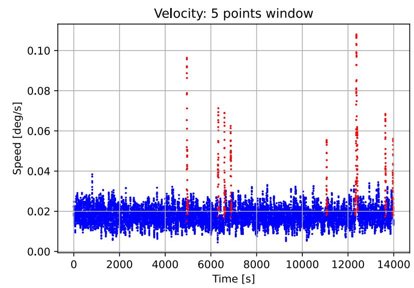

Fig. 8. Velocity microsaccade detection (5 points window; blue - horizontal fixational eye movement; red - microsaccades)

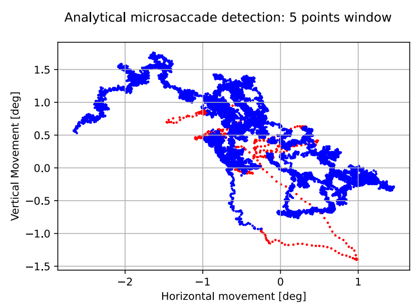

Fig. 9. Velocity microsaccade detection (5 points window; blue - 2D fixational eye movement; red - microsaccades)

in the window, and σ_i is the variance of the measurements in the window. The following hypothesis will be tested:

$$H_0 : \sigma^2 = \sigma_0^2$$
$$H_1 : \sigma^2 \neq \sigma_0^2$$

To test the hypotheses we use a significance level $\alpha = 0.01$. The obtained results are shown in Fig. 12. The statistical microsaccade detector finds more segments in comparison with velocity microsaccade detector (see Fig. 8, Fig. 10 and Fig. 12). Nevertheless the contours of the detected microsaccades often remain torn is several subsegments (Fig. 13). Summarizing the received results, it becomes obvious that the proposed microsaccade detectors complement each other, which leads to the conclusion that in the microsaccade detectors it should be applied a more complex criterion, and not just a single restriction.

6. Eye Tremor and Drift Detection and Segmentation

The eye tremor and drift segmentation could be fulfilled by frequency filtering. The source signal is ET Kalman filtered signal between second and third microsaccades (see Fig. 12). Applying bandpass filters for the frequencies bands 0-40 Hz and 70-104 Hz the corresponding eye drift (Fig. 14) and tremor (Fig. 15) are segmented .

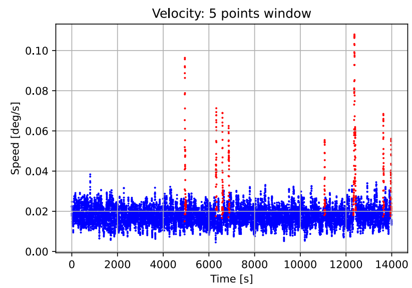

Fig. 10. Velocity microsaccade detection (15 points window; blue - horizontal fixational eye movement; red - microsaccades)

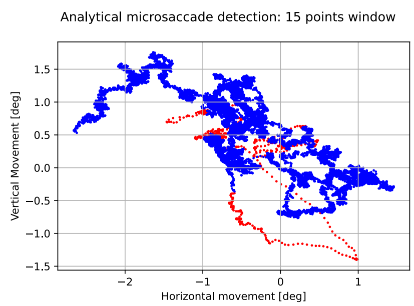

Fig. 11. Velocity microsaccade detection (15 points window; blue - 2D fixational eye movement; red - microsaccades)

7. Analysis of the Received Results

The obtained results demonstrate the abilities of the proposed algorithms to eliminate the influence of power supply on the readings of ET. Applying different filters minimizes the influence of additive high-frequency Gaussian noise. The optimal setting of the parameters of these filters is a prerequisite for obtaining a quality result achieving maximum noise reduction without loss of useful information. Both proposed noise rejection algorithms successfully reduced additive noise. Below we compare the characteristics of the Kalman filter with those of the ”classic” Engbert - Kliegl filter [12] (based on the five points average $\overrightarrow{v}_n = (\overrightarrow{x}_{n+2} + \overrightarrow{x}_{n+1} - \overrightarrow{x}_{n-1} - \overrightarrow{x}_{n-2}/6\Delta t)$ and its 11 - point modification in [29] (where $\overrightarrow{v}_n = [\sum_{i=1}^{5}(\overrightarrow{x}_{n+i} - \overrightarrow{x}_{n-i})]/30\Delta t$). The Engbert - Kliegl filter and its modification were realized by implementation of linear convolution filters with corresponding kernels.

To compare denoising algorithms one and same signal is passed through the three filters. The signal was taken from https://github.com/sheynikh/msdetect, quoted in [29]. The chosen segment (in the interval $48s - 58s$) from the whole signal is is very close to the signal, presented on fig. 2A of the same article. The signals after denoising filters are depicted on Fig. 16. Finally, the signal-to-noise ratio is calculated for the visualized segment of signal with microsacades, labeled in advance. For Kalman filtered signal

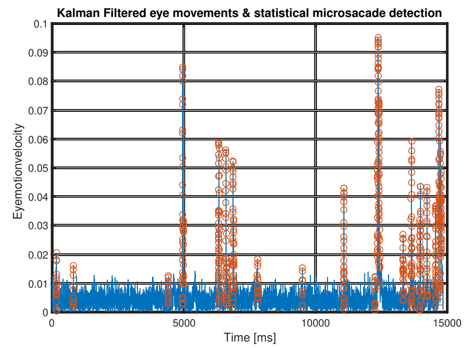

Fig. 12. Statistical microsaccade detection for Kalman filtered signal: blue - horizontal fixational eye movement; red - microsaccadic eye movement)

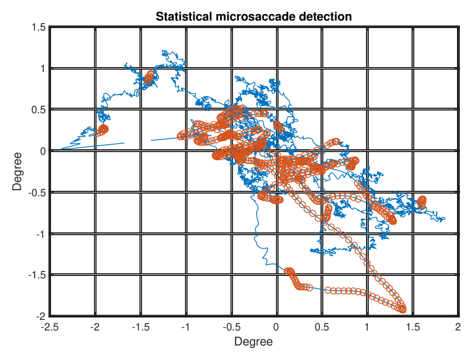

Fig. 13. Statistical microsaccade detection for Kalman filtered signal: blue - 2D fixational eye movement; red - microsaccadic eye movement)

$SNR_{Kalman} = 20.15dB$; for E&K filter $SNR_{E\&K} = 14.38dB$ and for modified (by Sheynikhovich et al.) filtered signal $SNR_{S\&etc} = 18.10dB$. The best results of Kalman filtering are received without any losses in microsaccades (Fig. 16).

The detection of microsaccades in a state of fixation, however, is burdensome. This is due to the uncertainty in the definition of microsaccades. Two different algorithms with window technique for detecting microsaccades were proposed in the article. In the first of these approaches we are looking for eye movements performed at a higher speed than normal in the fixation process. Two windows of 5 and 15 consecutive measurements were used. Microsaccade detector with longer window allows more precise segmentation of the fixational microsaccades. However, in the 2D image of fixational eye movement (see Fig. 9 and Fig. 11), some trajectories can be distinguished that strongly resemble saccades, but have a lower (close to normal) speed of eye movement. These examples prove that the criterion for detecting saccades by the speed of eye movement is not precise enough.

In the next experiment we examine the differences in the detection of microsaccades by four different algorithms: the newly proposed 5-point window, 15-point window and statistical algorithms, described in this paper, and the algorithm of Sheynikhovich at al.

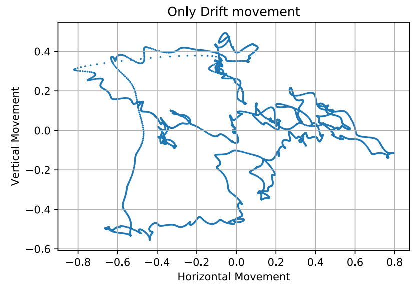

Fig. 14. Isolated eye drift

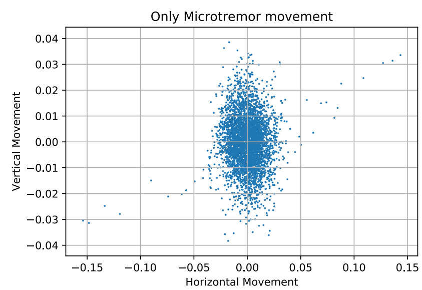

Fig. 15. Isolated eye tremor

in [29]. The microsaccade detectors were tested on the same segment of data from the previous experiment. The number of labeled saccades is 15 (according to the public data and software, cited in[29]). The summary of results are presented in the Table 1:

Table 1. Microsaccade detection

Algorithm	**Original signal**	**Noised signal** $\sigma = 0.005$	**Noised signal** $\sigma = 0.02$
Labeled microsaccades	15	15	15
Sheynikhovich et al.	15	15	15
5-points window	19 (4 additional)	17 (2 additional)	17 (2 additional)
15-points window	17/18 (3 additional; 1 merged)	16/17 (2 additional; 1 merged)	16/17 (2 additional; 1 merged)
Statistical	19 (4 additional)	19 (4 additional)	17 (2 additional)

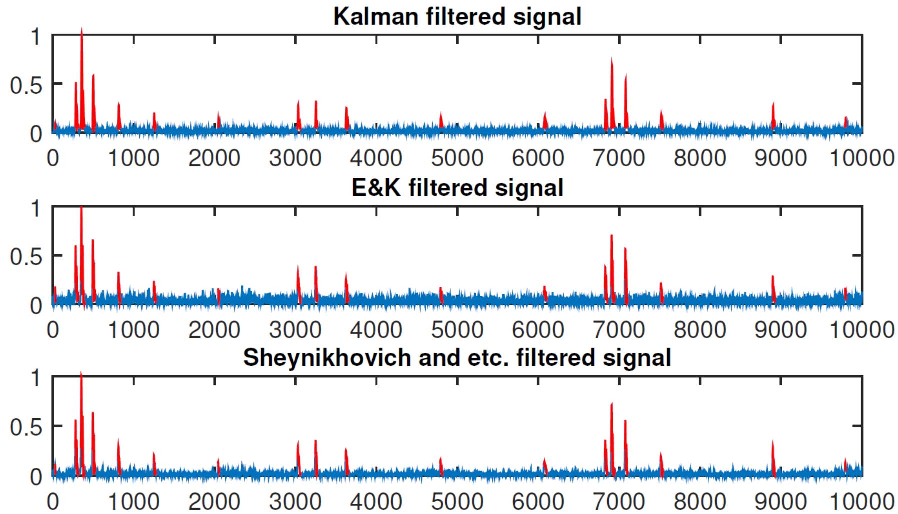

Fig. 16. Comparison between Kalman filter, Engbert - Kliegl filter and Sheynikhovich filter

All tested algorithms work well with denoised signals or signals with weak noise. They all detected the micro-saccades marked by experts. The algorithms working with a five point window and the statistical algorithm detected four additional microsaccades. The algorithm working with a 15 point window detected only three out of the four additional microsaccades. These (four) saccades are marked in red in the 2D representation of eye movement (see Fig. 17). There is no doubt, for at least two of them, that these eye movements are microsaccades. The non-registration of these movements by experts requires additional commentary. It is probably due to the velocities of eye movements close to the thresholds for detection of microsaccades (statistical characteristics are almost the same as those of non-saccade eye movements - this fact was also established by the statistical detector of microsaccades). It is also interesting to denote, that the 15-point algorithm also detected three of these eye movements as microsaccades, but its larger window inflicts on nearby microsaccades to be merged.

In the next experiment a Gaussian noise with zero mean and standard deviation 0.005 was added to the signal. All the algorithms perform well microsaccade detection. The statistical microsaccade detection algorithm found the same number of microsaccades. The 5 point window algorithm found 17 microsaccades - the 15 labeled saccades and the two not labeled microsaccades. The 15 point window algorithm detected also 17 saccades, but one of them is merged to another. The statistical algorithm found again the same number of 19 saccades.

The high-noise regime was obtained with additive Gaussian noise with zero mean and standard deviation 0.02. In both of the experiments with additional noise was used a Kalman filter for noise reduction. The five and 15 points window algorithms found the same saccades as in the previous paragraph. The statistical algorithm found 17 saccades. Its quality was deteriorated because of high rate of the noise.

During all the experiments the Schenikhovich algorithm found exactly the 15 labeled saccades, showing good noise stability, but it missed to detect the additional (unlabeled) microsaccades.

The used experimental equipment did not contain high precision eye tracker like cited in [15,8,20,21]. There was no possibility to accurately assess the exact position of the image of the object under attention on the retina in time of microsaccades and local image movement. We had no enough information to find evidence of a direct relationship between the microsaccades and accurate fixation or image stabilization on retina.

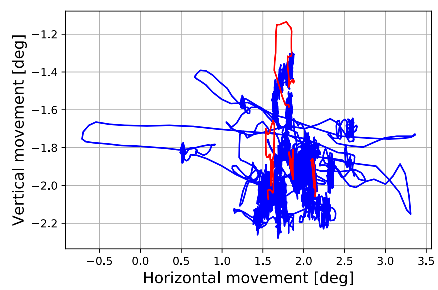

Fig. 17. Microsaccades additionally found

8. Analysis of Fixational Eye Drift

The corrective role of fixational eye drift on image locus was also verified. In the performed experiments the head rotations with respect to the eye movements were estimated. We compare the signals of ET gyros with those of segmented eye drift. The choice to use gyroscope readings is not accidental. Gyroscopes measure the speed of rotation of the head and even a slight rotation of the head leads to a large displacement of the image on the retina and requires correction by the oculomotor complex of the eyes for stabilization of the image on a specific retina area. The accelerometers measure accelerations in the horizontal and vertical directions, and approximately any shaking of the head in the horizontal or vertical direction imparts a corresponding displacement of the image on the retina. The gyroscopes measurements (pitch and yaw velocity of rotation) were processed to estimate exact head rotation. To do this the gyroscope measurements were integrated in order to obtain the angle position of the head. The horizontal drift eye movement and horizontal head movement are shown in Fig. 18 and Fig. 19. An inverse relation between these two movements could be observed. The correlation is estimated to -0.6251.

The given signal on Fig. 18 is disturbed with microsaccadic movements. No dependency between microsaccades and head movements was found. The clear drift signal was isolated by using the microsaccade detection algorithm. All microsaccades were replaced by smooth linear movement. The results are shown on Fig. 19 for the same horizontal drift movement of the eye without any saccades. The correlation is estimated to -0.6332.

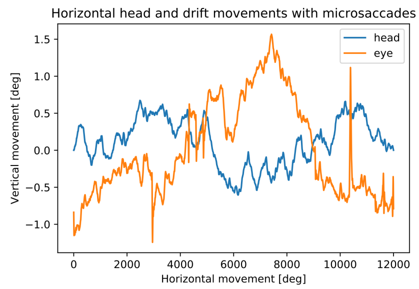

Fig. 18. Correlation between eye and head movements (with microsaccades)

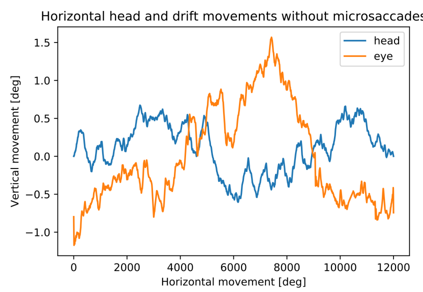

Fig. 19. Correlation between eye and head movements (without microsaccades)

The provided results prove the relation between the drift and the head movement. Something more, a time delay of eye reaction to the head movements is noticed and it can be estimated.

9. Conclusion

This article presents eye movement analysis in simple visual tasks. It considers small fixational eye movements only. A general additive mathematical model of these eye movements is proposed. Two approaches for elimination/reduction of noise in ET measurements and the influence of the power supply of the equipment have been implemented. Two options for detecting microsaccades have also been proposed. The results prove the role of eye drift in image stabilization on the retina of the eye. The analysis shows that new approaches and algorithms for detecting microsaccades should be sought.

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