ENG signal,
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Tomasz PANDER[1], Robert CZABAŃSKI[1], Tomasz PRZYBYŁA[1],
Dorota POJDA-WILCZEK[2]

SACCADES DETECTION IN OPTOKINETIC NYSTAGMUS - A FUZZY APPROACH

The analysis of eye movements is valuable in both clinical work and research. One of the characteristic type of eye movements is saccade. The accurate detection of saccadic eye movements is the base for further processing of saccade parameters such velocity, amplitude and duration. This paper presents an accurate saccade detection method which is supported by the fuzzy clustering. The proposed detection function is computationally efficient and precisely determines the time position of the saccadic eye movement event. The described method is characterized by low sensitivity for any kind of noise and can be applied in the analysis of the congenital nystagmus.

1. INTRODUCTION

Eyes are the photosensitive sensory organs being an essential part of human visual system. The primary functions of eyes are: focusing of the light entering the eye from the visual field onto the retina, conversion of the incident light into nerve impulses, and transmission of the nerve impulses (information) towards the brain [8]. For that reasons eyes can be monitored in order to detect the weariness or diseases of a person based on the results of observation of eyelids, pupils or the character of gazes. Also the analysis of eyes movements can be used to investigate and diagnose different disorders. Different techniques and methods can be used to record or/and analyze the eye movements [8]. They generate biopotentials around eyes which can be divided into two groups, being the result of: forced eye movement (electrooculography, EOG) and voluntary eye movement (electronystagmography, ENG).

The EOG signal is based on electrical measurement of the potential difference between the cornea and the retina. The cornea-retinal potential creates an electrical field in the front of a head [15]. This field changes in orientation as the eyeballs rotate due to the capability of fixating on the target of interest in the visual field. The electrical signals EOG/ENG also come from the musculature of an eye. Its variability can be measured using electrodes placed near eyes. It is possible to obtain independent signal measurements from each eye. The amplitude of EOG signal varies from 50 μV to 3500 μV with a frequency range of about DC to 100 Hz. The movement velocities may reach the level of 700 ^{o}/s [8]. Its behavior is practically linear for gaze angles of $\pm 30^o$ [1]. However, EOG signals are usually recorded with a noise having a non-stationary features and its variability depend on many factors that are difficult to determine [1, 8, 15].

The ENG signal can be applied for investigation of nystagmus. Nystagmus is a type of eye movement produced as a response to stimuli which activate the vestibular and/or the optokinetic systems [14]. There exists two types of nystagmus: congenital (CN) and optokinetic (ON). Congenital nystagmus is an ocular motor oscillation that usually appears in early infancy. It is characterized by involuntary, conjugated, bilateral to and from ocular oscillations. CN is predominantly horizontal, with some torsional and, rarely, vertical motion. In CN patients, a clear and stable vision of the world is corrupted by rhythmical oscillations, which result in rapid movements of the target image onto the retina [13]. Unfortunately, the pathogenesis of the CN is still unknown [3, 13]. The optokinetic nystagmus (OKN) is characterized as involuntary eye movement response when moving stimulus in a large visual field is presented [16].

[1] Silesian University of Technology, Institute of Electronics, Akademicka Str. 16, 44 100 Gliwice, Poland.
[2] Department of Ophthalmology, Medical University Of Silesia, Ceglana Str. 35, 40-952 Katowice, Poland.

The typical waveform of each type of nystagmus is characterized as a saw tooth waveform. The slope on one side of each peak is smaller (slow component) that on the other side (fast component). These fast components are called saccades [7]. The slow component of nystagmus is related to the stimulus while the saccade refers to a rapid reset of eye position by the oculomotor systems [5]. Figure 1 presents an example of nystagmus signal corrupted with spontaneous blinks and baseline drift.

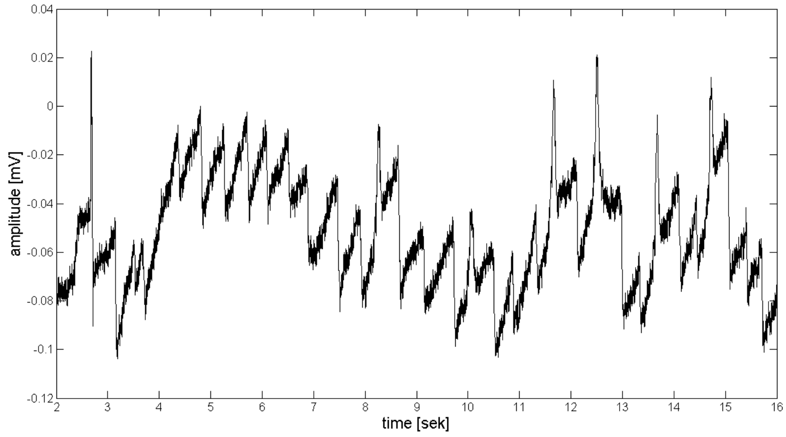

Fig. 1. Example of horizontal ENG signal for nystagmus cycles corrupted with spontaneous blinks and baseline drift.

The main aim of this paper is to present a new method of saccade detection which is supported by the fuzzy clustering in order to determine an amplitude threshold for accurate saccade localization.

2. SACCADE DETECTION METHOD

The main source of noise in ENG signal is an electrical activity of face's muscles. A movement of a head or muscle contraction while speaking can also disturb the ENG signal. Moreover, there are spikes in the ENG signal that represent eye's blinks. An idea of the application of the detection function in the process of saccade localization comes from ECG signal processing [6, 10]. The procedure consists of four main steps which are presented in Figure 2.

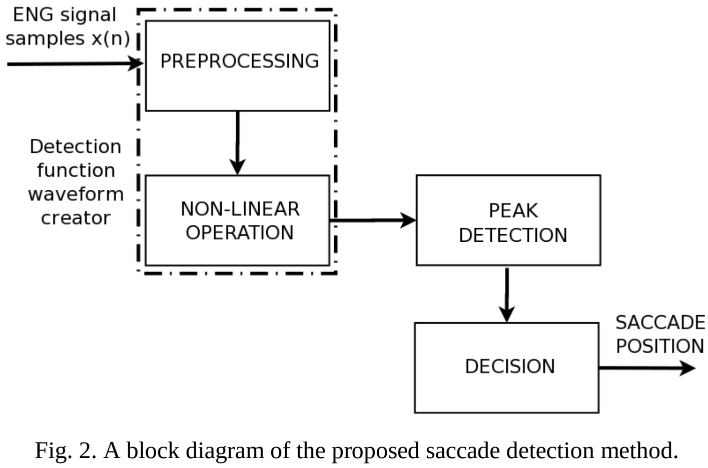

Fig. 2. A block diagram of the proposed saccade detection method.

In the preprocessing stage the DC component and baseline drift are removed from signal using a robust nonlinear and linear filtering. Because ENG signal contains signal components from DC-100 Hz, a cascade of digital filters is used:

- the IIR notch filter to remove power line components (50/60 Hz),
- the myriad filter to remove the baseline drift (with long window length),
- another myriad filter to remove outliners (short window length),

- the pass-band FIR filter (f_1=1.5Hz, f_2=25Hz) to form desired frequency characteristic of the processed signal.

The purpose of the signal filtering is to attenuate noise and enhance those features of the signal that are essential for the correct saccade detection. An example of the procedure of removing the baseline drift from the ENG signal using the myriad filter is presented in Figure 3.

In the next step of ENG signal processing a nonlinear operation (square or absolute value function) is performed. On that basis the description (detection) function is constructed. At first signal is differentiated in order to extract the velocity of ENG waveform. The numerical estimates of ENG signal derivatives give the approximate rate of the change of the eye rotation angle [8]. To form the detection function the absolute values of the differences are calculated:

$$y(n) = \left| x_p(n) - x_p(n-1) \right| , \tag{1}$$

where: $x_p(n)$ is the signal after pre-processing stage. Then the smooth filter with the length of N=61 and the square operation are applied:

$$y_{ave}(n) = \left(\frac{1}{2M+1} \sum_{i=-M}^{M} y(n+i) \right)^2 , \tag{2}$$

where N=2M+1. The Figure 4 presents the ENG signal and the corresponding detection function waveform.

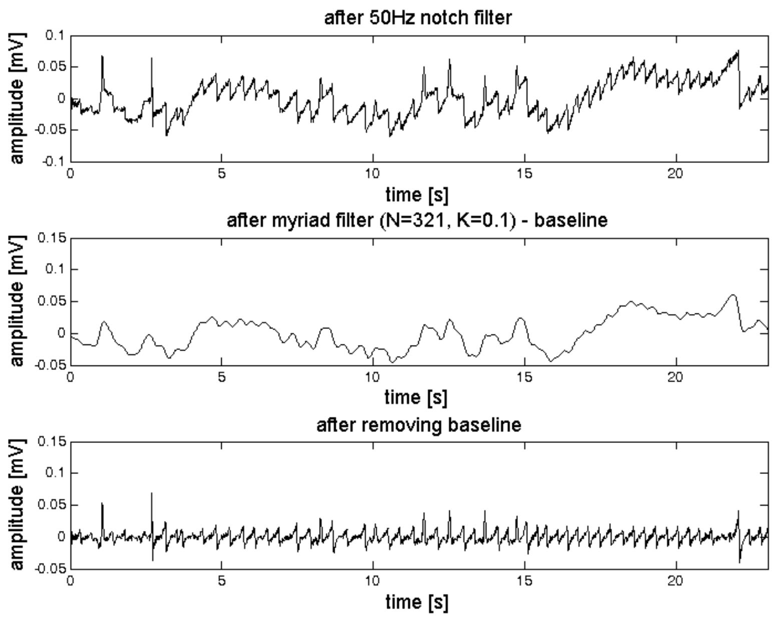

Fig. 3. The process of baseline drift removing from the ENG signal. The upper plot presents original ENG signal, a plot in the middle shows the baseline of ENG signal, while the lower plot shows ENG signal after removing the baseline drift.

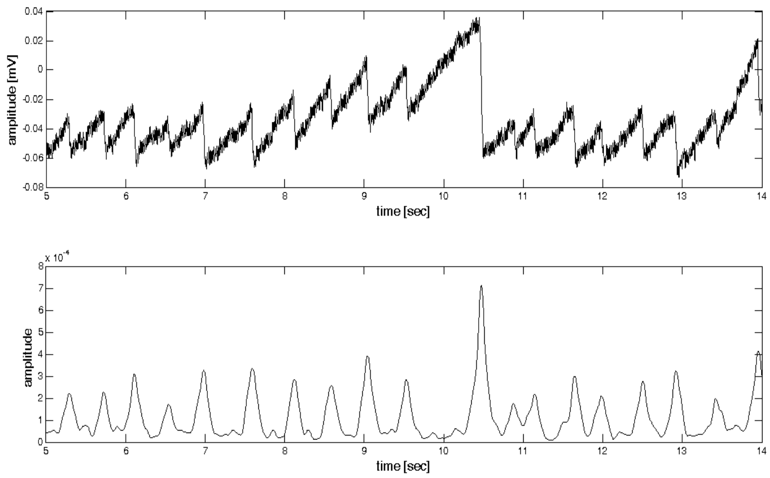

Fig. 4. An example of ENG signal and the corresponding detection function waveform.

The smooth peaks of the detection function correspond to moments when saccades appear. Any other signal components are removed, however there are also signal peaks being the result of the eye blinks. The peaks localization in the time domain can be realized using the simple method described in [9]. In [10] this method was successfully applied for blink detection in EOG signal. It is based on looking for downward zero-crossings in the smoothed first derivative (which is now obtained on the basis of the detection function) that exceeds a given slope threshold (S_{th}) and peak amplitudes that exceed given amplitude threshold (A_{th}). These two adjustable parameters allow to discriminate peaks being the result of the saccadic eye movements from blinks signal peaks. The slope threshold that allows for the recognition of narrow peaks corresponding to the saccade movement was defined as $S_{th}=0.7w^{-2}$, where w is the acceptable width of peak of detection function waveform. However, the most difficult is the proper calculation the amplitude threshold. In this work we proposed a fuzzy clustering based method to solve this problem.

2.1. AN APPLICATION OF FUZZY CLUSTERING TO AMPLITUDE THRESHOLD ADJUSTMENT

The fuzzy method of peaks detection is based on the fuzzy clustering procedure. The task of clustering is to divide a set of objects into groups (subsets, categories) whose elements will be characterized by a certain similarity. Similarity criterion is usually based on some properties of the object, which are represented by the so-called feature vector. Many clustering algorithms are based on minimization of the scalar index and among them methods of fuzzy clustering can be distinguished, which assume the possibility of partial membership of an object to the given group. In our approach we used the Fuzzy c-Means (FCM) [2] algorithm, however, any other (also more robust) clustering methods could be applied.

The groups (clusters) in FCM procedure are represented by so-called prototypes $\mathbf{v}_i$ ($\forall i=1,2,\ldots,c$) that are defined as weighted mean of the group elements:

$$\underset{1\le i\le c}{\forall} \mathbf{v}_i = \frac{\sum_{k=1}^{N} (u_{ik})^r \mathbf{x}_k}{\sum_{k=1}^{N} (u_{ik})^r}, \tag{3}$$

where $\mathbf{x}_k$ is a feature vector representing k-th object, r is a parameter (usually r = 2) and $u_{ik} \in [0, 1]$ is a element of the partition matrix $\mathbf{U}$, defining the degree of membership of the objects to the clusters. A zero value of u_{ik} indicates that the element $\mathbf{x}_k$ is not a member of i-th cluster, while u_{ik} =1 defines the full membership. The task of the FCM algorithm is to collect in one group the elements for which the distance from the group prototype is smaller than the distances from the prototypes of other groups.

When estimating A_{th} value two sets of samples of the detection function can be distinguished: with "low" (i = 1) and "high" amplitude (i = 2). Hence, values of $y_{ave}(n)$ can be used as a feature vectors (scalars) directly. However, our experiments showed that such approach provides incorrect (too small) values of A_{th}. Therefore, the feature vectors were defined as:

$$x_k = y_{ave}(n)\Big|_{y_{ave}(n)>\tau} \tag{4}$$

where τ is the threshold level. We defined τ as a median of detection function samples. The minimum of elements which belong to a group of samples having the "high" amplitude with a degree of $u_{2k} > 0.5$ was used as A_{th}. An example of threshold determination using the proposed method is shown in Figure 5.

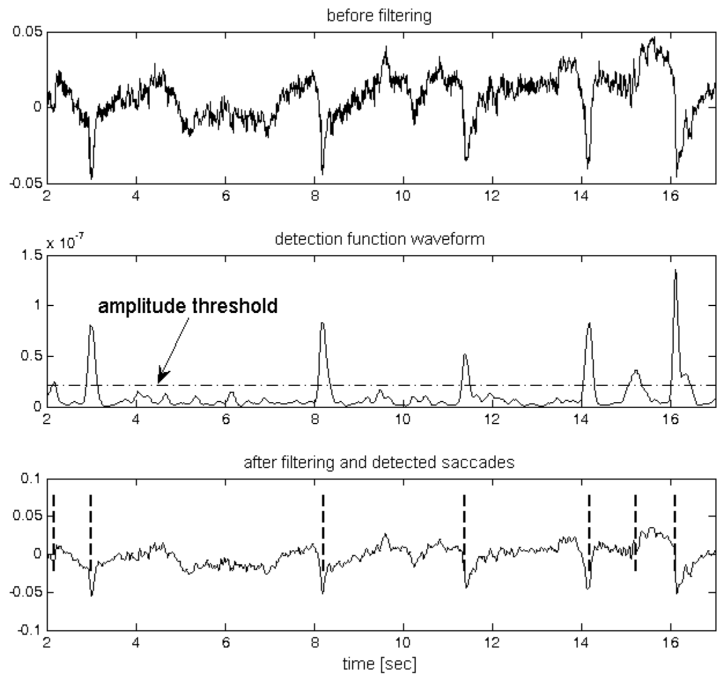

Fig. 5. An example of noisy ENG signal (the upper plot), the corresponding detection function waveform with amplitude threshold level calculated with the fuzzy clustering (the middle plot) and the detected saccades (the lower plot). The saccade localization is marked with dashed lines.

3. RESULTS AND DISSCUSIONS

To investigate the performance of the presented method of automated saccade detection, the artificial ENG optokinetic nystagmus cycles were generated on the basis of the real ENG signal. Such approach allows for controlling the exact saccade localization as well as the noise level. Optokinetic nystagmus was elicited by a black-and-white stripe pattern stimulation using a rotary cylinder. The ENG signal was recorded using the measurement system based on the Biopac MP-36 unit. The six Ag/AgCl electrodes were placed around the eyes providing the measurements of individual movements of each eye in the horizontal direction. The frequency sampling was 500 Hz.

To construct a single OKN cycle we use a triangle model of real OKN cycles. In our experiments we used the following parameters of the model:

- a directional factor a_{up}= 0.07509 [mV/s] and time duration t_{up}= 0.56 [s] for the slow phase of OKN,
- a directional factor a_{dwn}= –0.92969 [mV/s] and time duration t_{dwn}= 0.04694 [s] for the saccade (fast phase).

For simplicity we assumed a constant period of OKN cycles in ENG signal. The accurate saccade position is located in the middle of the saccade slope. Such signal has an infinite SNR. In order to simulate the real conditions of acquisition of ENG signal we added a noise with known value of generalized SNR [11] which was modeled with the symmetric α-stable (SαS) distribution [4, 11]. As the main source of disturbances in ENG signal is the face's muscles activity, which has an impulsive nature, we used the characteristic exponent (α) of SαS equal to 1.8 [12]. Moreover, we added a baseline drift to the considered signal as well. The baseline drift was modeled with sinusoidal wave of 0.05 Hz frequency. As a reference we used a method of saccade detection based on differentiating the ENG signal after Savitzky-Golay filtering. It provides the localization of the saccade by seeking the maximum change of the signal speed [8].

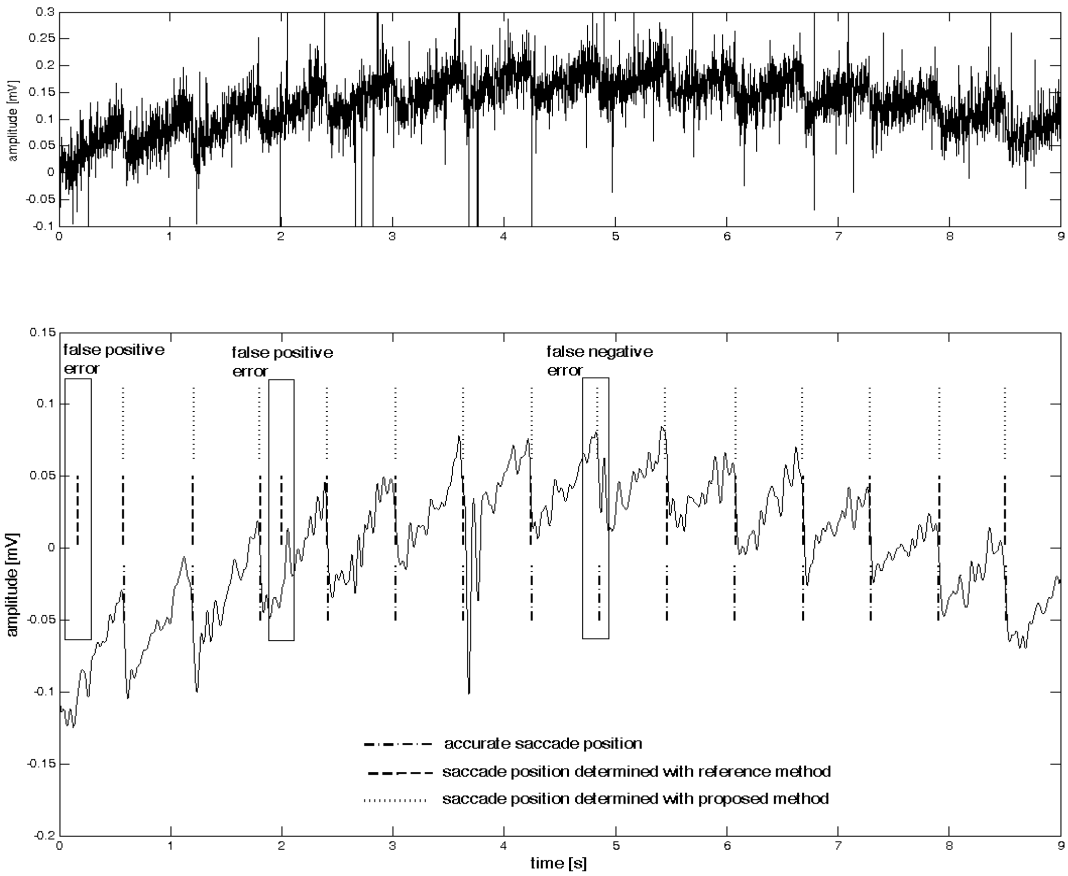

Fig. 7. An example of noisy OKN cycles (GSNR=35 dB, α=1.8) in ENG signal (upper plot) and the corresponding saccade positions detected with the proposed and the reference methods. Rectangles denote mistakes made by the reference method.

In the Figure 7 we presented an example of noisy OKN cycles and the corresponding location of detected saccades. The detailed results of saccades localization are presented in Table 1. It can be noticed that the worse results were obtained with the reference method. Two times the saccade was detected (0.17 s and 2.00 s) despite it did not appear in the ENG signal (false positive error). The reference method also failed to localize a saccade (false negative error) in 4.86 s of the signal.

Table 1. Position of saccades [s], P_{ac} – given location of saccades in OKN cycles ENG signal, P_{rm} position of saccades estimated with the reference method, P_{det} position of saccades estimated with the proposed method.

P_{ac}	–	0.58	1.20	1.81	–	2.42	3.03	3.64	4.25	4.86	5.47	6.08	6.69	7.30	7.91	8.52
P_{rm}	0.17	0.58	1.20	1.81	2.00	2.41	3.02	3.64	4.24	–	5.46	6.08	6.69	7.30	7.92	8.51
P_{det}	–	0.58	1.21	1.80	–	2.41	3.03	3.64	4.25	4.84	5.44	6.08	6.68	7.29	7.91	8.51

4. CONCLUSIONS

In this paper a new approach for saccade detection was presented. The proposed method was based on the detection function supported by the fuzzy clustering. The main task of the electronystagmography signal processing was to suppress noise and enhanced signal features allowing for the correct saccades detection. The composition of the detection function allowed for removing the baseline drift and the outliers from the ENG signal providing a single peak for each of saccade events. The main problem of the calculation of the amplitude threshold calculation that indicates the peaks corresponding to the saccades was solved by the fuzzy clustering method. The presented idea allows for investigating the optokinetic nystagmus. The accurate saccade positioning is necessary for the precise determination of the nystagmus parameters resulting in the accurate model of eyes movement.

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