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A New Method of Saccadic Eye Movement Detection for Optokinetic Nystagmus Analysis*

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Abstract— **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 as velocity, amplitude and duration. This paper concerns an accurate saccade detection method that is based on pre-processing signal and then the proposed non-linear detection function can be applied. The described method characterizes less sensitivity for any kind of noise due to an application of the robust myriad filter which is used to eliminate baseline drifts and impulsive artifacts. The congenital nystagmus is one of the field where our method can be applied to detect saccades. The proposed detection function is computationally efficient and precisely determines the time position of saccadic eye movements even when the signal-to-noise ratio is low. The presented method may have potential application in automatic ENG signal processing systems for determining visual acuity.**

I. INTRODUCTION

Eyes are photosensitive sensory organ whose primary functions as part of human visual system 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 simply talking information towards the brain [4]. Different technique and methods can be used to record or/and observe eye movements like electrooculography (EOG), electromyography (EMG), infrared-oculography (IR-OG) and image based methods [3].

Eyes movements generate biopotentials around eyes and they can be divided into two groups: forced eye movement (elecktrooculography - EOG) and voluntary eye movement (electronystagmography - ENG). In medicine the eye movements can be used to investigate and diagnose many different diseases or can be useful in sleep study.

The ENG signal can be applied for research of nystagmus. Electrical properties of ENG signal are very similar to EOG signal [1], [4]. Nystagmus is a type of eye movement produced as a response to stimuli which activate the vestibular and/or the optokinetic systems [6]. There exists two types of nystagmus. Congenital nystagmus (CN) is an ocular motor oscillation that usually appears in early infancy. The pathogenesis of the CN is still unknown [5], [7]. 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 [5]. The second type of nystagmus is optokinetic nystagmus (OKN) which is characterized as involuntary eye movement response when moving stimulus in a large visual field is presented [8].

The typical waveform of each type of nystagmus is characterized as a saw tooth waveform with longer lasting slow phase and shorter lasting fast phase, which is also called saccade movement [9]. An example of real OKN nystagmus waveform is presented in the Fig. 1.

It should be pointed out here that the variables measured in the human body (any biopotentials) are almost always recorded with a noise and often have a non-stationary features. Their magnitude varies with time, even when all possible variables are under control. This means that the variability of the ENG signals depend on many factors that are difficult to determine [1], [2], [4]. The main problem of nystagmus detection and quantitative analysis is the noise, artifacts and eye blinks associated with the eyes movements.

The detection of saccades and estimation of related saccade parameters are usually performed during the analysis of EOG, ENG signals. Several methods have been described for saccade detection. Traditionally saccades are detected by comparing the rectified velocity waveform of an recorded signal to a given threshold. Crossing the threshold level indicates saccade occurrence. In this paper it is the reference method. The number of false positives can be minimized

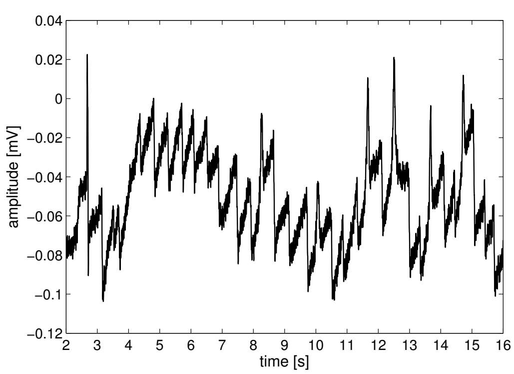

Fig. 1. An example of horizontal ENG signal for nystagmus cycles corrupted with spontaneous blinks and baseline drift.

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by satisfying certain additional requirements like execution some test statistics, adaptive filters and thresholds and synctatic methods [4], [5]. The other methods use adaptive filtering and adaptive threshold (e.g. the constant false alarm rate CFAR method) [4].

The main aim of this study is to present a new method of accurate detection of the fast phases (saccades) in OKN signal by application of the detection function. The rest of this paper is organized as follows: Section 2 describes the proposed method of the detection function and our recording system. The Section 3 presents some results and finally Section 4 is devoted to final conclusions.

II. THE DETECTION FUNCTION FOR SACCADES DETECTION

The ENG signal can be very noisy and is non-stationary in its nature. In this work the ENG signal is not converted from [mV] to degrees [^{o}], in order to maintain the primary processing domain. Such operation is just a scaling and has no impacts on the performance of the presented method.

The main source of noise in ENG signal is a signal of electrical activity of face's muscles. A movement of a head or speaking can also disturb ENG signal. Some spikes which appeared in signal represent eye's blinks.

An idea of the detection function comes from ECG signal processing [11]. The concept of such device consists of two steps [10]. The first step is a preprocessing stage (including removing the DC component and baseline drift, a robust nonlinear and linear filtering) and the second step is nonlinear operation (square or absolute value function). Then the detection function waveform is made. On the base of this function the algorithm decides of saccade occurrence.

A. Preprocessing stage

The preprocessing step is very important because it determines the effectiveness of subsequent processing steps. Because ENG signal contains signal components from DC-100 Hz, it is possible to construct a cascade of digital filters to detect saccades. The purpose of the signal filtering is to attenuate noise and enhance those features of the signal used for detection as this leads to an increased probability for correct detection of saccades.

At first interference of power-line noise 50 Hz is suppressed. In this work the second-order IIR notch digital filter is used. The second step of preprocessing stage is removing the baseline drift which can occur. This type of noise contains low or very low frequency components. The high-pass filter with $f_{\text{cut-off}} = 0.05$ Hz is usually applied to suppress such type of noise. In this study the non-linear myriad filter is used to realize this task. The myriad filter belongs to the family of maximum likelihood estimator of location (M-estimator) [12], [13], [14]. This filter is defined in the following way. Given a set of observations (input samples) x_i such as $x_i = \beta + \nu_i$ ($i = 1, \dots, N$; β is a location parameter and $\{\nu_i\}_{i=1}^{N}$ is a sequence of i.i.d. zero-mean noise components) an M-estimate of their common location is given by [12], [13]:

$$\hat{\beta}_K = \arg\min_{\beta} \sum_{i=1}^{N} \log\left[K^2 + w_i\left(x_i - \beta\right)^2\right] \quad (1)$$

where: K is the scale parameter, $\{w_i\}_{i=1}^{N}$ are assigned weights and N is the filter window length. In this work weights equal the Chebyshev weights. The myriad filter is defined as a running window filter outputting the $\hat{\beta}_K$ value on the base of N elements in the window. For more details of myriad filter see [12], [13]. In this study $N = 321$ and $K = 0.1$. The Fig. 2 presents removing the baseline from the ENG signal. The next operation of pre-processing step is rejection of any outliers from signal by an application the myriad filter with the window length $N = 41$ and the weights $w_i = 1$. The second stage of pre-processing step is linear filtering of the obtained signal after baseline drift removing. This part consists of the bandpass filtering realized by serial joined of three FIR filters (applying Matlab procedures) [10]:

- The low-pass filtering with $f_{\text{cut-off}} = 30$ Hz realized as the 32$^{\text{th}}$ order low-pass FIR filter.
- The high-pass filtering with $f_{\text{cut-off}} = 1.5$ Hz applying the Chebyshev window with 20 dB of relative sidelobe attenuation is also used. The order of the filter is 62.
- The low-pass FIR filtering with $f_{\text{cut-off}} = 25$ Hz realized as the 60$^{\text{th}}$ order low-pass FIR filter and the Chebyshev window with 20 dB of relative sidelobe attenuation is also used.

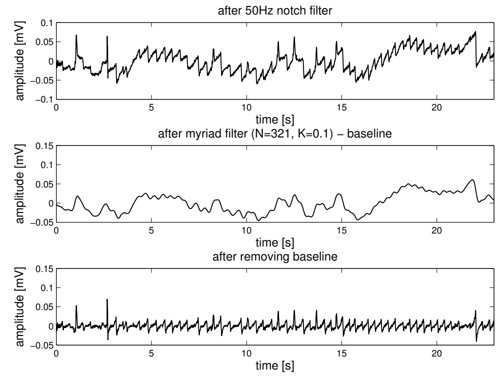

Fig. 2. Removing the baseline from ENG signal (upper plot presents original ENG signal, plot in the middle shows the baseline of ENG signal, lower plot shows ENG signal after removing the baseline drift).

B. Non-linear operation

This stage of the detection function consists of two operations. At first signal is differentiated in order to extract the velocity of ENG waveform. Practical differentiators compute numerical estimates of derivatives, which, in case of ENG signals, give the approximate rate of change of the eye rotation angle [4]. Additionally the derivative operation is connected with the calculation of the absolute value and raising a whole to the square. This operation can be written as:

$$y(n) = |x_p(n) - x_p(n-1)|^2 \quad (2)$$

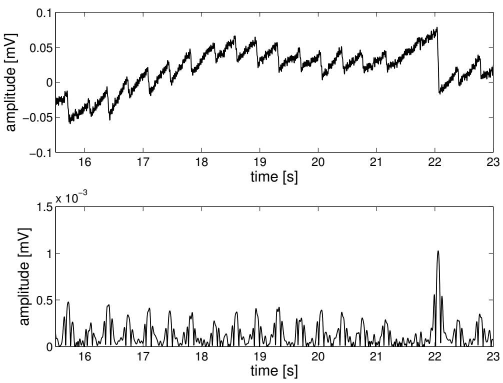

Fig. 3. An example of ENG signal and corresponding detection function waveform.

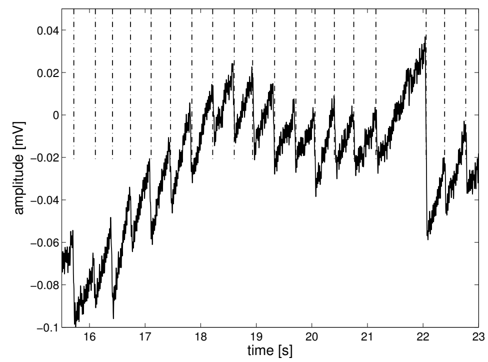

Fig. 4. The part of ENG signal with detected and precisely located saccades.

where: $x_p(n)$ is the signal after pre-processing stage. The Fig. 3 presents ENG signal and its corresponding detection function waveform. Peaks which occur in the shape of detection function correspond to that time moments when saccades appear. All peaks of the resulting detection function waveform are smoothed and are responsible for appropriate saccades. Any other signal components are eliminated, however eye blinks may cause some problems.

C. Peak detection

The third stage of the saccade detection function is a localization in time domain on the base of the shape of the detection function waveform. This can be realized using the simple method described in [15]. In [10] this method was successfully applied for blinks detection in EOG signal. The method of peak detection and localization is based on looking for downward zero-crossings in the smoothed first derivative that exceeds some a slope threshold and peak amplitudes that exceed given amplitude threshold, and determines the position. Adjustable parameters allow to discriminate of blinks signal peaks from a noise or saccadic eye movements which can appear in a detection function. The pseudo code of the applied algorithm is the following [10]:

```
for i=1:length(y)
 if sign(d(i)) > sign(d(i+1))
  if (d(i)-d(i+1)) > SlopeThreshold*y(i)
    if y(i) > AmpThreshold
      begin
        gather points around peak
        find maximum of points
      end
    endif
  endif
 endif
```

where **y** is the vector variable which represents the detection function waveform from eq. (2), **d** is the vector variable which denotes the first derivative of the detection function waveform, $sign(\cdot)$ is the sign function, **SlopeThreshold** and **AmpThreshold** are adjustable parameters which values depends on the values of the detection function. When the sampling frequency equals 500 Hz, the average width of peaks in the detection function waveform 100, then

$$\text{SlopeThreshold} = 0.5 \cdot \text{width}^{(-2)} \qquad (3)$$

The **AmpThreshold** is chosen on the base of the obtained detection function waveform and usually **AmpThreshold** equals ca. 0.15-0.25 maximum value of $y(n)$.

The additional step in the algorithm of peak detector is smoothing the first derivative of the detection function waveform because it has many local fluctuations. This step is necessary to be able to get a smooth waveform of this first derivative. The length of smoothing moving average filter equals the half of average width of peaks in the detection function. Positions of located peaks correspond to the largest angular velocity of eye movements during saccades.

The presented new detection function of saccades can be used for each channel separately. The Fig. 4 presents detected saccades in recorded signal.

D. Acquisition of ENG signal

The ENG signal is recorded in a horizontal direction of eye's movements. This requires six electrodes which are placed in the front of a human face. In this work applied measurement system is based on the Biopac MP-36 unit.The six Ag/AgCl electrodes are placed around the eyes. This configuration allows to measure individual movements of each eye in a horizontal direction. In our work the frequency sampling is 500 Hz. Optokinetic nystagmus stimulation was generated by simple device equipped with electric motor which allows to rotate cylinder whose lateral surface were placed vertical black stripes of different widths (0.75mm, 1 mm, 6mm, 12mm). A volunteer sits in front of a cylinder approximately in distance of 55 cm and his head is stabilized by a chin rest in order to ensure repeatability and eliminate head movements. Subject is instructed to look at the centre of the visual field to produce stare nystagmus without following the stripes.

III. RESULTS

The mathematical analysis of a complex non-linear system, which is the eye control system, is a difficult task even if only one aspect of its operating is considered – saccades.

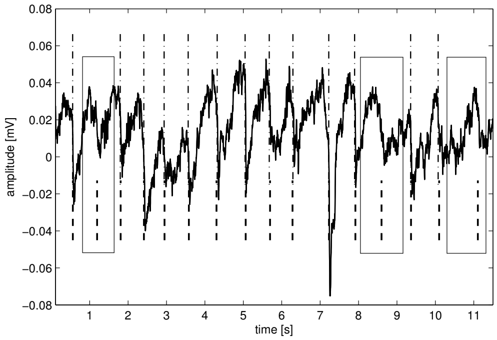

Fig. 5. An example of ENG signal with detected saccades with proposed method (dash-dot line) and other type of eye movements (marked with rectangle) in comparison to traditional method (dashed line below ENG signal).

TABLE I

COMPARISON OF TIME LOCATION OF SACCADES FOR THE PROPOSED METHOD (PM) AND THE REFERENCE METHOD (RF).

nr of saccade	T_{PM} [ms]	T_{RF} [ms]
1	0.558	0.562
2	x	1.194
3	1.796	1.808
4	2.41	2.412
5	2.938	2.948
6	3.564	3.582
7	4.32	4.302
8	5.048	5.062
9	5.676	5.696
10	6.292	6.282
11	7.226	7.230
12	7.898	7.918
	x	8.598
13	9.356	9.368
14	10.074	10.10
	x	11.106

Disadvantage of such approach is that the chosen signals cannot represent every possible ENG waveform, but different data are used in different investigations and straightforward comparison is difficult or impossible. The signal presented in Fig. 5 contains OKN cycles and other type of eye movements. The proposed method is able to distinguished OKN cycles and corresponding saccades, and other eye movements where properly rejected. In the case presented in the Fig. 5 the detection method based on threshold fails.

In the Table I we present an accurate positions of saccades in time domain for signal presented in the Fig. 5. Considered methods lead to obtain nearly the same results in time domain, although the reference method produces detections where saccades do not occur (velocity of such eye movement is slower than for saccadic one). Having the position of the saccade, other parameters can be estimated such as: its duration, velocity, the frequency of saccades per time unit. It carries a specific diagnostic information.

IV. CONCLUSIONS

In this paper a new method of saccade detection is presented. The proposed method is based on the detection function which the main task is to suppress noise and any other movements of eyes and enhanced saccades. The structure of the detection function consists of the baseline drift removing step, the step of removing outliers from processed signal, the band pass filter and the stage of nonlinear operation. The advantage of such structure is ability of obtaining a single peak when a saccade occurs. In this work a new application of the myriad filter is presented. This non-linear filter is used to estimate the baseline drift from the signal and then baseline drift can be effectively removed. In the last stage we are able obtain single peaks corresponding to saccades which are separated from any other components of ENG signal. All experiments were run in the MATLAB environment.

Presented in this paper the idea of application of the detection function for saccades detection and positioning allow to investigate optokinetic nystagmus. Knowledge of the exact saccade location allows us precise determination of the parameters of the slow phase and the fast phase of nystagmus, so that we can build more accurate a model of eyes movements. The use of such tools will allow us to carry out research on visual acuity and will also allow the automation of ENG signal processing.

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