Comparative study of several Fir Median Hybrid Filters for blink noise removal in Electrooculograms

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Abstract: - The presence of a kind of impulsive noise due to eye blinks is typical during the acquisition of electrooculograms. This paper describes a comparative study of several algorithms used to remove the blink noise in the electroculogram preserving the sharp edges in the signal produced by the so-called saccadic eye movements. Median filters (MF) and several types of Fir Median Hybrid Filters (FMH) have been analyzed. Two types of real electrooculogram register with saccadic movements in controlled position were used to test the performance of the pre-processing filters (sampling rate 20Hz). The filtered signals were later processed with a saccadic eye movement detector algorithm in order to detect changes in the sensitivity and positive predictive value. The results show that neither FMH filters nor WFMH filters produce better results than median filters, in this particular study. The highest averaged values of sensitivity and positive predictive value are obtained by using a median filter of length I=6 samples (S=96.22 %, V++=95.42%) and the variant SWFMH of the same length (S=96.27 %, V++=91.91%). Although the differences in detection rates are not meaningful between these filters, median filters obtain slightly higher rates of saccades detection than SWFMH, but a reduction in computational burden is obtained by using FHM variants.

Key-Words: - electrooculogram, median filter, fir median hybrid filter, blink, saccadic, eye movement, eye tracking

1 Introduction

The ability to operate a computer has become more and more important for everybody. This is true especially for quadriplegics. Because of their disablement, their interaction with the outside world becomes more and more difficult. With the assistance of computers, they can interact with the environment. Many bioelectrical signals have been used in order to build human computer interfaces (HCI): electroencephalogram (EEG), electromiogram (EMG), and electrooculogram (EOG) [1][2]

In basal conditions, the retina has a bioelectrical potential that is negative with respect to the cornea. Using surface electrodes placed around the eye can do the registering of this potential, called electrooculogram. It is a non-invasive technique and can be used as a marker of eye movements. The analysis of this bioelectrical signal has been extensively used in many applications, such as measurement the human eye blinking frequency during computer tasks [3], schizophrenia research [4].

Eyes control their movements by the use of six muscles that enable them to perform different kinds of movements. The rapid eye movements from one position to another position are called *saccades*. The small random movements when the gaze is fixed on an object are called *fixations*, and the when the gaze moves smoothly from one point to another generates *smooth pursuits* movements[5]. Among them, many authors have used saccades and fixations as switch signals for building HCI [6],[7].

There are some problems associated with EOG measurement. Eye blinks and eye-muscle electrical activity contaminate the signal; moreover, there is a considerable wandering of basal line due to electrode drift. All these factors are considered as noise overlapping to the target signal and must be eliminated using digital processing techniques as a previous step before signal interpretation.

It is important to be able to separate horizontal eye movements from vertical, and eye movements from blinks. By using electrode placement showed in Figure 1, horizontal and vertical recordings are obtained.

An eye blink is defined as when the upper and the lower lids are touching each other and the eye is temporally hidden. A typical blink has amplitude of 400 μV and lasts for about 200 - 400 ms. A blink can be recognized in the EOG by its sharp rise and fall (see Figure 2). It is very important to distinguish eye blinks from vertical eye movements because, although in this work eye blinks are considered as noise, some works have shown that a change in the form of the blink artefact can be used for hypovigilance detection. According to [8], a relaxed person blinks about 15-20 times per minute, but when performing cognitive tasks the blink frequency drops to as little as 3 blinks per minute, whereas an increase in blink frequency indicates reduced vigilance.

If we are interested in detecting fast eye movements (saccades), false detections can be produced in vertical movements due to the presence of blinks, because they tend to be misconstrued as looking up [9].

The purpose of this work is studying the behaviour of several non-linear digital filters for blinks removal in electrooculograms. The final purpose is to build an easy-to-use HCI, based on real-time interpretation of the EOG that uses saccadic movements and fixations to control the interface.

The outline of the paper is: in section 2, we introduce the registers used in this study and the blink filtering algorithms analyzed. In section 3 we propose a method for performance evaluation of the filters based on a saccadic eye movement detection algorithm. The parameters for optimum performance, for each type of registers, are shown. Finally, in section 4, we conclude with a discussion of the implications and limitations of the study.

2 Material al Methods

The study design has been deeply reported in detail in an earlier work [10]

2.1 Electrooculogram recording

A set of five electrodes Ag/AgCl has been used in the acquisition of the signal, located at the positions shown in Figure 1. Each register consists of a horizontal channel (channel H) and a vertical channel (channel V), which should enable the detection of changes in both directions. A 12 bits data acquisition card with 20 Hz sampling rate has been used to record the electrooculograms. A 2nd order analogue Butterworth filter with a cut-off frequency of about 4 Hertz was used to limit bandwidth.

Participants sat in front of a 17-inches screen monitor that displayed the visual stimuli. The visual stimuli are yellow circles on a black background. Each stimulus lasts 2 seconds. The distance of the subject to the monitor has been fixed to 50 cm. Additionally, the patients are asked not to move their heads during the acquisition.

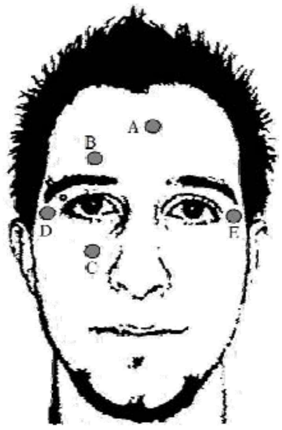

Figure 1. Layout of electrodes used in the acquisition of EOG registers. A. Reference electrode. Vertical variations are measured between B(+) and C(-) electrodes and horizontal variations are measured between D(+) and E(-) electrodes.

Type I registers. In this type of register, there are transitions that only affect one channel. They are composed of repeated patterns up-down or left-right. Thus, the EOG signal only reflects changes in one channel. Figure 2 shows an example of a type I register.

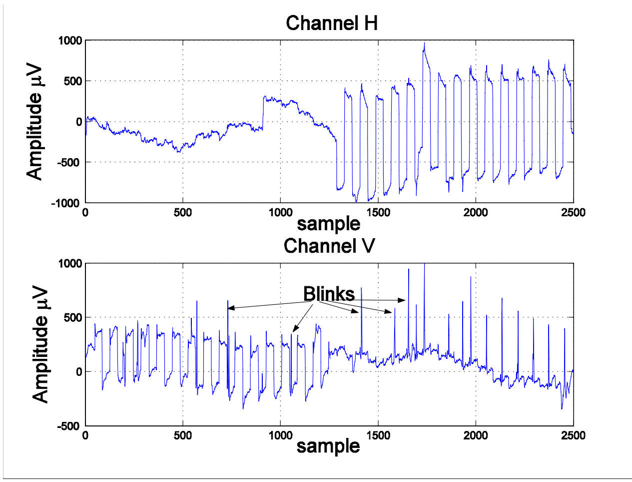

Figure 2. Example of a type I register which shows the effect of eye blinks, mainly in channel V

Type II registers. In this case, the registers are generated using a sequence with simultaneous vertical and horizontal transitions. Figure 3 shows an example of a type II register.

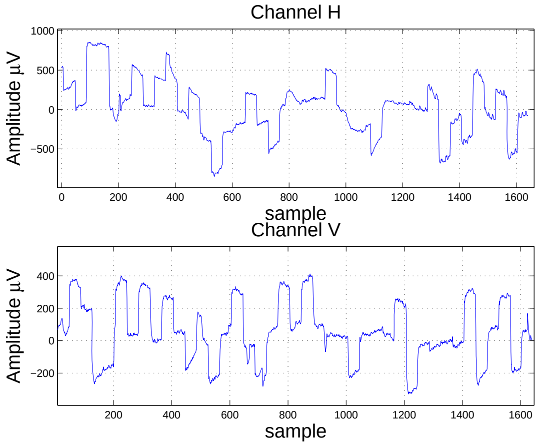

Figure 3. Example of a type II register. In this case, there are simultaneous transitions in both directions.

2.2 Blink filtering algorithms.

Figure 2 clearly shows the presence of blinks in channel V, which we can consider to be impulsive noise. This type of noise can be cancelled by using median filters. Median filters have been used in biological signal processing, mainly when the mean value of the signal changes abruptly. Other authors have used median filters applied to preprocessing EOG signals [11], [12].

Although linear digital filters could be suitable for saccadic eye movements, they cannot entirely reject impulsive noise. Moreover, in our problem, it is essential to preserve sharp edges, which is difficult, or impossible, for linear filters. A good alternative is a nonlinear median filter or any of its variants. Although a deep study of the theory of median filters can be found in [13], a brief explanation of the filters used is included.

2.2.1 Median filters (MF)

The median filter of a sampled signal x(n) with length 2*I*+1 can be computed as:

$$\hat{x}_k = median\{x_{k-I}, x_{k-I+1}, \ldots, x_{k+I-1}, x_{k+I}\} \quad (1)$$

This filter can attenuate impulsive noise when the duration of the noise peak is at most k sampling intervals [13]. This filter can perform poorly at noise reduction, but it will do a good job at edge preservation.

2.2.2 Fir Median Hybrid filters (FMH).

These filters combine the properties of the FIR filters for noise removal and the capability of median filters of preserving edges. Such a filter consists of M subfilters. When $\Phi_1, \Phi_2, \ldots\Phi_M$ are their outputs the output of the filter is obtained as:

$$\hat{x}_k = median\{\Phi_1(x(k)), \Phi_2(x(k)), \ldots\Phi_M(x(k))\} \quad (2)$$

The length k, and the number M of FIR subfilters are selected to allow an acceptable trade-off between noise reduction and edge preservation [14]. Usual values for M are three or five. Subfilters are usually of moving average type, but other more complex filters with better performance have also been proposed [13].

2.2.3 Weighted FMH filters (WFMH)

By weighting the different FIR filters, the resulting FMH filter can be tailored for different problems. The general expression has the form:

$$\hat{x}_k = median\{w_1 \circ \Phi_1(x(k)), w_2 \circ \Phi_2(x(k)), \ldots, w_M \circ \Phi_M(x(k))\} \quad (3)$$

where $\circ$ denotes duplication, $w_i \geq 0, \sum_i w_i \text{ is odd}$. A popular choice of the number of subfilter is five with the centre of the filter being the point itself. The two types of subfilters mainly used as substructures are the average and the ramp predictors that are zero and first order FIR filters.

The weighted FMH filter with length 2*I*+1 and 5 FIR substructures can be written as [14]:

$$\hat{x}_k = median\{w_1 \circ y_1, w_2 \circ y_2, w_3 \circ y_3, w_4 \circ y_4, w_5 \circ y_5\} \quad (4)$$

where

$$\begin{aligned} y_1 &= \frac{1}{I}(x_{k-1} + x_{k-2} + \ldots + x_{k-I+1} + x_{k-I}) \\ y_2 &= h_1 x_{k-1} + h_2 x_{k-2} + \ldots + h_{I-1} x_{k-I+1} + h_I x_{k-I} \\ y_3 &= x_k \\ y_4 &= h_I x_{k+1} + h_{I-1} x_{k+2} + \ldots + h_2 x_{k+I-1} + h_1 x_{k+I} \\ y_5 &= \frac{1}{I}(x_{k+1} + x_{k+2} + \ldots + x_{k+I-1} + x_{k+I}) \end{aligned} \quad (5)$$

When determining the output, the signal is analyzed from both sides of the currently analyzed sample, x_k. By averaging (y_1 and y_4 outputs) the mean of the signal is estimated. The first order predictors are used from an estimate of a ramp. The predictive filters designed are optimal predictors for an ith-order polynomial signal corrupted by Gaussian noise. The weights for the ramp predictor filter of length *I* are calculated according to the formula [15]:

$$h_i = \frac{4I - 6i + 2}{I(I-1)} \qquad (6)$$

where i is the distance of the sample to the centre of the filter.

The number of possibilities of the filter is very large depending on the values of the weights. The weights amplify the importance of some of the subfilters in the median operation. Two filter structures are interesting: centre weighted FMH filter (CWFMH) and the subfilter weighted FMH filter (SWFMH) filter. Both filters have been analyzed in detail in [13]. Two examples of using WFMH filters with biomedical signals are given in this paper, but the authors note that the results are preliminary and a more profound evaluation must be done. CWFMH ($w_1 = 1, w_2 = 1, w_3 = 3, w_4 = 1, w_5 = 1$) leaves edges intact and preserves sinusoidal signals. SWFMH ($w_1 = 2, w_2 = 1, w_3 = 1, w_4 = 1, w_5 = 2$) preserves edges while removing high frequency noise. It works as a non-linear high-pass filter.

When the length of the filter is dimensioned in such a way that it covers the most part of the half way of the blink, the blinks are removed from the output [12]. Knowing the duration of the blinks (200-400 ms) and the sampling rate (20 Hz) an adequate length of the filter can be selected.

3 Problem Solution

Due to the fact that the final purpose of this work is the detection of saccadic movements, the evaluation of the pre-processing filters described in section 2.2 will not be done by visual inspection of the filtered signals. The evaluation of the filters will be done in an indirect way. The sensibility and the positive predictive value of the saccades detection algorithm will be the marker of quality. The method of measuring the performance of the algorithm is described by authors in [10].

3.1 Saccadic eye movement detection

We have used a variation of the algorithm based on the point-to-point derivative of the signal in order to determine the position of the gaze, among the different techniques described in [5]. The algorithm operation is the same for both H and V channels. The main difference with the originally proposed algorithm is that a pre-processing *filter* is applied to the signal. In [10], a median filter was used but no other options were studied. The saccadic eye movement detection algorithm is based on applying thresholds on the derivative of the pre-processed signal.

3.2 Pre-processing stage

As we have already noted the core of this work is the evaluation of several median filters for blink cancellation in EOG. The filters used in this study have been: median filter (MF), 3 subfilters FHM filter ($\hat{x}_k = median\{y_1, y_3, y_5\}$), 5 subfilter FHM filter ($\hat{x}_k = median\{y_1, y_2, y_3, y_4, y_5\}$), CWFMH and SWFMH filters. Next step is to select the values of the free parameters, the filter length I[1], and the slope threshold used by the detection algorithm ($slope_{th}$).

The values given to the free parameters were $slope_{th}$=0.2:0.05:0.9, and I=2:1:20, where MATLAB™ notation was used (InitialValue:Step:FinalValue).

3.3 Results

Many tests were performed on the free parameters and useful information about the optimal values was obtained.

The parameters that were used for optimal value selection were the sensitivity and positive predictive value of the saccadic eye movement detector. The optimum values for each pre-processing filter algorithm are shown in Table I:

	Type I		Type II	
Filter	I	$slope_{th}$	I	$slope_{th}$
MF	5	0.75	6	0.50
3-FHM	4	0.85	5	0.45
5-FHM	4	0.8	6	0.45
CWFHM	6	0.8	6	0.5
SWFHM	4	0.9	6	0.45

Table I. Optimum values for the free parameters I and $slope_{th}$, for type I and type II registers

The results obtained for I parameters agree the length used in [12] where a length 22 was used for a sampling rate of 100Hz. The reason is clear because when the length of the filter covers the most part of the half wave of the blink, the blinks are removed from the output leaving the saccades.

[1] For MF the length of the window is 2I+1

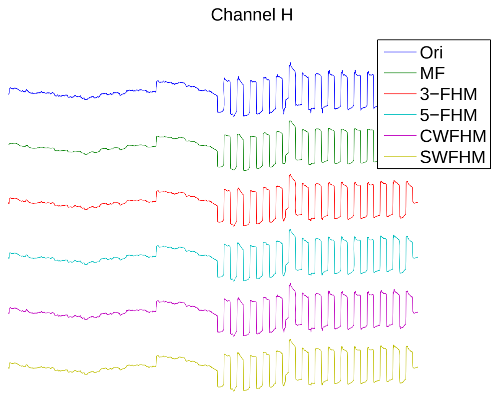

Figure 4. Filtered signal of a horizontal channel of a *type I* register with optimum length (*I*).

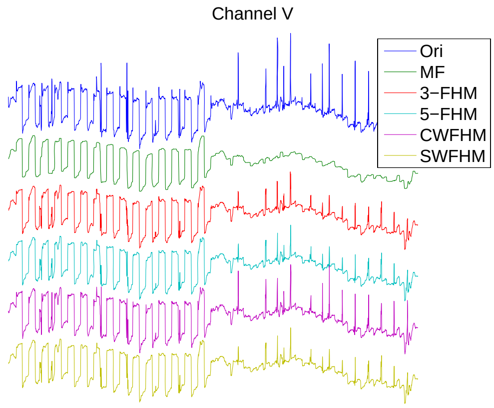

Figure 5. Filtered signal of a vertical of a *type I* register channel with optimum length (*I*).

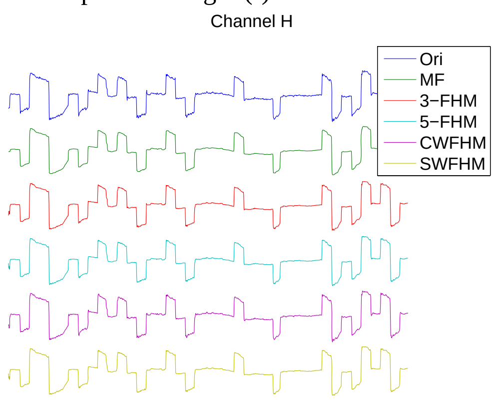

Figure 6. Filtered signal of a horizontal channel of a *type II* register with optimum length (*I*).

Figure 4 and Figure 5 show the filtered signal of a horizontal and a vertical channel of a *type I* register by using each of the proposed algorithms. The first signal, labelled as Ori, is the original data. Figure 6 and Figure 7 show the results of filtering a type II register with the set of filters analyzed. The values of the *I* parameter used in the filtering process are the ones that appear in Table I.

Table II shows the sensitivity (S) and positive predictive value (+PV) results of the saccadic eye detection algorithm when applied to *type I* registers. Table III contains the same information when the algorithm is applied to *type II* registers We have separated H and V channels, and positive (Hp, Vp) and negative (Hn,Vn) transitions. Taking into account sensitivity and positive predictive value, the best detection rates are obtained pre-processing with MF filter and SWFHM filter.

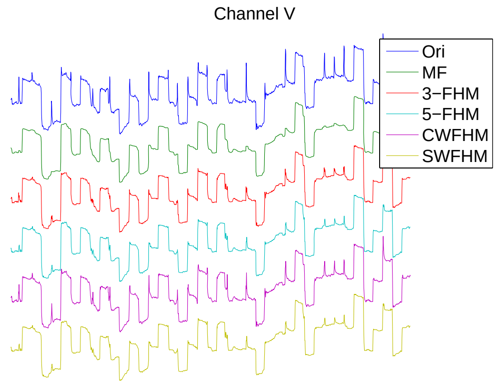

Figure 7. Filtered signal of a vertical of a *type II* register channel with optimum length (*I*).

Filter		**Hp**	**Hn**	**Vp**	**Vn**
MF	**Sensitivity**	100	98.43	93.75	97.50
	+PV	99.22	99.22	94.97	97.61
3-FHM	**Sensitivity**	98.33	97.66	93.75	95.0
	+PV	97.55	98.33	88.05	84.78
5-FHM	**Sensitivity**	98.33	97.66	94.53	95.83
	+PV	97.55	98.33	88.89	87.08
CFHM	**Sensitivity**	98.33	98.44	88.28	94.17
	+PV	97.55	99.21	90.29	89.28
SWFH	**Sensitivity**	98.33	97.66	94.53	95.0
	+PV	98.33	98.33	90.36	87.27

Table II. Results of the saccadic eye movement detection algorithm for each pre-processing filter, for *type I* registers. The optimum values for the free parameters *I* and $slope_{th}$ shown in Table I have been used. S: sensitivity(%). +PV: Positive Predictive Value.

Filter		**Hp**	**Hn**	**Vp**	**Vn**
MF	**Sensitivity**	96.67	97.22	94.12	92.06
	+PV	92.71	94.40	94.42	90.77
3-FHM	**Sensitivity**	96.67	98.02	95.75	95.63
	+PV	88.73	92.92	88.51	85.64
5-FHM	**Sensitivity**	97.41	97.22	94.44	96.03
	+PV	89.57	92.87	90.76	86.80
CWFHM	**Sensitivity**	97.41	95.63	90.85	94.44
	+PV	89.88	91.02	89.82	88.94
SWFH	**Sensitivity**	97.41	97.22	94.44	95.63
	+PV	89.92	92.87	90.76	87.47

Table III. Results of the saccadic eye movement detection algorithm for each pre-processing filter, for *type II* registers. The optimum values for the free parameters *I* and $slope_{th}$ shown in Table I have been used. S : sensitivity(%). +PV: Positive Predictive Value.

Figure 8 shows the results of the saccadic movements detector when the signal is pre-processed with a MF filter (I=6). A dot marks the points with negative slope, and an asterisk marks the points with positive slope. The determination of the direction of the movement depends on the channel being considered.

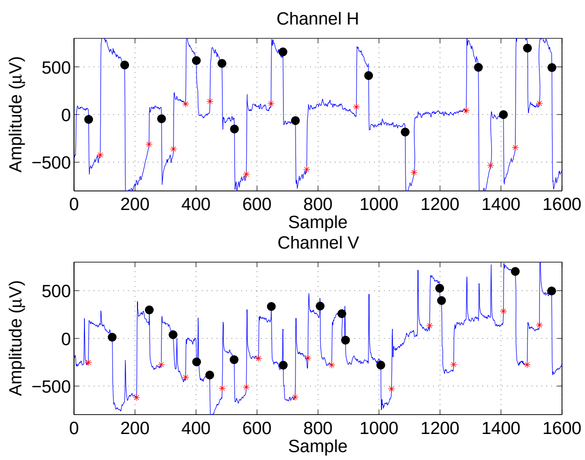

Figure 8. Results of the saccade detection algorithm in a type II register. Signals have been filtered with a MF filter.(I=6, $slope_{th}$=0.45)

. optimum length (*I*).

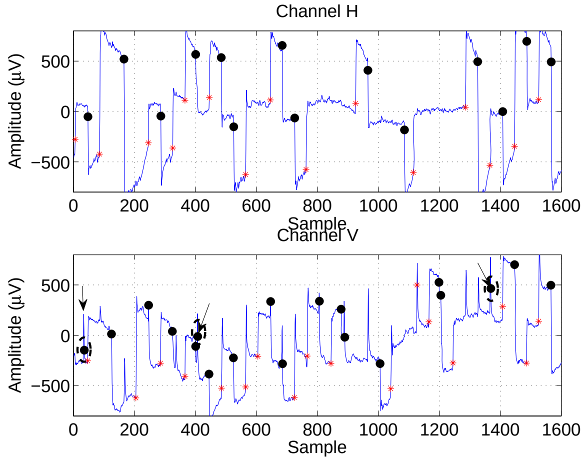

Figure 9. Results of the saccade detection algorithm in a type II register. Signals have been filtered with a SWFH filter (I=6, $slope_{th}$=0.45).

Figure 9 is similar to Figure 8 but pre-processing the signal with a SWFH filter (*I*=6). In both cases the slope threshold used by the saccadic eye movement detection algorithm is 0.45.
A comparison between Figure 8 and 9 shows identical results of the detection algorithm in channel H. The differences in detection marks appear in channel V. Those differences are marked with arrows in Figure 9. Pre-processing with SWFH increases the number of false positives of the detector due to a non complete blinks cancellation.

4 Conclusions

Even though the results are preliminary, neither FMH filters nor WFMH filters produce better results than median filters, already used by the authors. The highest values of sensitivity and positive predictive value are obtained by using a median filter. Although the differences are not important 3-FMH and SWFMH produce slightly higher rates of saccades' detection. It means that a zero order predictor is more appropriate for the kind of signals under test. Due to cut-off frequency (3dB) of the anti-aliasing analogue filter used; about 4 Hz, the amount of Gaussian noise present in the registers is very small. As a consequence no noticeable reduction of noise appears in the filtered signals. As regards the impulsive noise, although the biggest reduction is obtained with the median filter, the saccades' detection algorithm is robust enough to deal with the blink residuals already present in the signal after pre-processing. Despite of the fact that S, and V++ are very similar a reduction in computational burden is obtained by using FHM variants.

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