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A two-stage framework for denoising electrooculography signals

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ABSTRACT

Denoising of electrooculography (EOG) signals is a challenging task as the noise and signal share the same frequency band. This paper proposes a two-stage framework for denoising EOG signals. The first stage approach is based on preserving the nature of eye movements while the second stage is based on the nature of noise (Gaussian or not). In the first stage, denoising is carried out using one out of four filtering methods, each filter being optimal for a particular EOG pattern. The four methods used in the first stage are linear bandpass filtering, stationary wavelet transform (SWT), empirical mode decomposition (EMD) and median filtering. The Stage I framework selects the output that provides the highest estimated signal to noise ratio (SNR). In case, the Stage I filtering does not provide a significant SNR, the system uses Stage II filtering. In the second stage, we use two recursive state estimators, i.e. a Kalman filter and a particle filter for further denoising. The two-stage method is found to provide a better SNR as compared to a single stage method.

1. Introduction

Electrooculography (EOG) refers to the standing potential difference between the cornea and the retina [1]. This potential is an indication of an eye movement. Typically, the retina has a negative bio-electric potential w.r.t. the cornea [2]. The potential for the horizontal eye movement is up to 16 μV whereas it is 14 μV for the vertical movement of the eye per 1°. The amplitude of EOG ranges between 50 μV and 3500 μV [2]. EOG signals are mainly used to analyze different types of eye movements such as saccades, vergence, and fixational movements [4]. EOG signals also find a role in the diagnosis of eye diseases such as unilateral vestibular neuritis [5], epileptic nystagmus [6], degenerative myopia [7], oguchi disease [8], choroideremia [9], retinal disorders [10], etc. EOG signals also have been utilized for rehabilitation purposes as reported in [11,12]. EOG signals have also been used for eye tracking purposes [13] and drowsiness detection [14]. These applications make EOG signals, a remarkable aspect of bio-medical engineering.

EOG signals are usually contaminated with noise. This phenomenon poses a major concern in its processing and information extraction [15]. The article in [16] reports the major interference in EOG signals to be sensor noise, power-line noise, interference due to head movements, speech, blinks, etc. Denoising of EOG is challenging because of the inherent unsupervised structure of noise [17]. The works in [18,19] describe the significance of denoising bio-medical signals. The prominent importance of denoising as reported in their work are

- to obtain accurate parameter estimation;
- increasing the accuracy of medical diagnosis and prognosis; and
- better interpretation of information from signals.

The works reported in [20,21] rely on band-pass and notch filtering for denoising EOG signals. These methods, however, are not efficient in removing all kinds of interference. Barea et al. [22] have made an attempt to eliminate the shifting of EOG potential using a band-pass filter of 0.05 Hz and 35 Hz cut-off frequencies. Merino et al. [1] have employed a band-pass filter having a bandwidth of 0.1–30 Hz on the derivative EOG signal instead of the raw signal. The major limitation of band-pass filtering is that signal and noise bear overlapping frequency bands.

Naga et al. [23] have proposed the use of stationary wavelet transform (SWT) for denoising EOG. They have employed biorthogonal 3.3 wavelet for the purpose. They have found that SWT preserves saccadic patterns to a significant extent. Bulling et al. [24] have compared three methods of denoising – low-pass filtering, wavelet-based denoising, and a median filter. Their results have revealed that the median filter had the best performance as it preserves edge steepness of saccadic eye movements and do not introduce any artificial signal changes. Reddy et al. [25] have

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employed empirical mode decomposition (EMD) for denoising EOG to classify the different eye movements. They have found that EMD is effective in separating blinks from EOG data.

From the review, the popular denoising methods are found to be band-pass filtering, EMD, SWT and median filtering. The issues which need attention while denoising EOG signals are as follows:

- preserving the eye movement patterns in the filtered EOG;
- preventing drifting of the resting potential due to filtering;
- removal of unusual noise and artifacts due to occasional loose contact of the electrodes because of physical activity; and
- the introduction of additional artifacts due to filtering that may be misinterpreted as saccades or blinks.

In this paper, we introduce a two-stage framework for denoising EOG signals thereby addressing some of these issues. In the first stage, the framework denoises the online EOG signal using one of the following methods, whichever gives a better SNR estimate:

- band-pass filter;
- median filter;
- EMD; and
- SWT.

In case, the denoised EOG has a lower SNR as compared to a predefined threshold of 20 dB, the algorithm switches to the second stage, which further improves the SNR using recursive state estimation. The threshold has been obtained empirically.

In the first stage, each filter has an advantage over the others for a given type of noise and eye movement pattern in the EOG. EMD is efficient in removing blinks as the blinks occupy the lowest intrinsic mode functions (IMF) [25]. Similarly, band-pass filtering removes a majority of the high-frequency sensor noise and power line interference, as the information content in EOG is band-limited to 1–15 Hz [19]. SWT helps in preserving the saccadic signature [23] whereas median filtering removes spiky noise while retaining the edge steepness of saccadic signature. The above argument justifies that a single denoising method is ineffective for denoising the whole EOG signal. This fact led us to use context-specific filtering in Stage-I.

In the event, Stage-I filtering is insufficient to provide a significant SNR of 20 dB, the algorithm switches to Stage-II. The second stage, being a model-based recursive filtering, helps to achieve a better SNR as compared to the Stage-I filtering. The two-stage approach marks the best use of time, memory and accuracy conjointly as is evident from the results.

The key contributions of this paper are as follows:

- Context-based filtering in Stage-I based on SNR estimate; and
- a finer stage of denoising using Kalman and particle filtering that can address the peaky nature of the EOG signals under saccades as well as smooth pursuits.

Fig. 1 outlines the proposed denoising framework. In its first stage, it attempts to improve the SNR of the EOG signal using one of the four methods which provides the maximum SNR. In the event, none of the algorithms provide a significant SNR, the algorithm uses recursive state estimation for obtaining a higher SNR.

A significant finding of this work is the improvement in SNR using the recursive state estimators in Stage II. However, owing to the computational burden of these estimators, as compared to the other prevailing denoising methods, they are used only if the SNR estimate in Stage I falls below a threshold.

The paper is organized as follows. Section 2 describes the methods and material, while Sections 3 and 4 discuss the Stage I and Stage II denoising respectively. A signal quality estimation is provided in Section 5. Section 6 shows the results of our work, with a conclusion in Section 7.

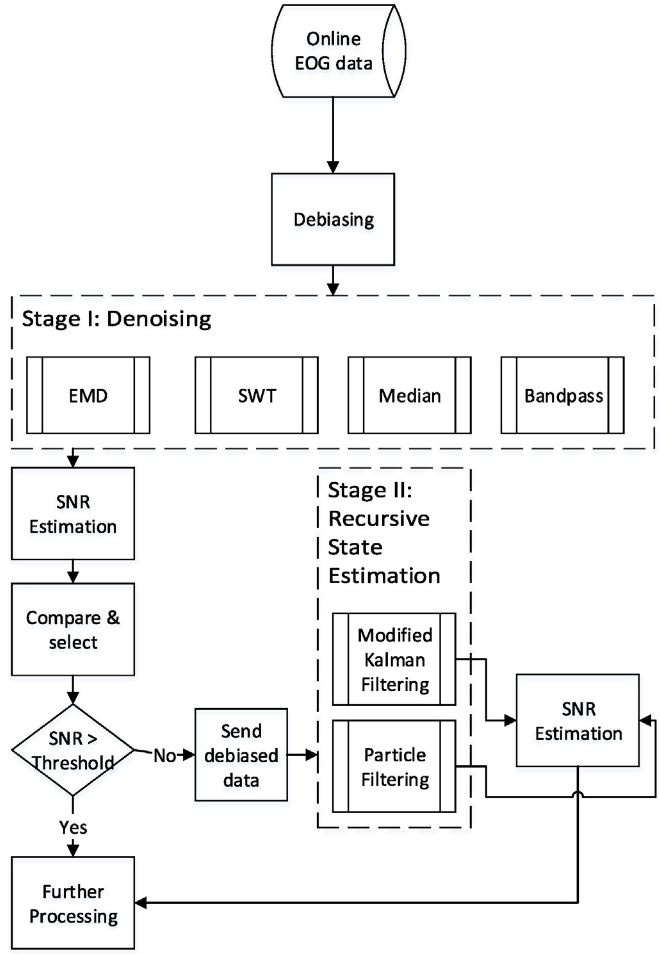

Fig. 1. The overall denoising framework: Stage I denoising contains either of EMD, SWT, median filtering, pandpass filtering while Stage II uses either of KF or PF; the switching to Stage II is done on the basis of SNR estimate.

2. Methods and material

2.1. Experiment design

An experiment is conducted on 30 subjects to create an EOG database to compare the denoising techniques. The EOG was recorded using RMS EEG Victa 64 machine, sampled at 256 Hz. The subjects were given verbal instructions regarding the reading task they had to perform. Informed consent and ethical approval were obtained from the concerned authorities respectively, prior to the experiment. The experiment was carried out following the International Society for Clinical Electrophysiology of Vision (ISCEV) Standard for Clinical EOG [26]. The bipolar EOG electrodes were placed near the canthus of both the eyes, with the reference electrode being placed in the middle of the forehead as shown in Fig. 2. A 13 × 13 array of English letters was displayed in a projector, and the subject was asked to find out the number of occurrences of the letter A from the list as shown in Fig. 3.

The acquired horizontal EOG data is stored for analysis in MATLAB. The offline analysis is just carried out for testing the framework. The final framework is designed for online EOG data processing.