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Denoising EOG Signal using Stationary Wavelet Transform

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Eye movements are critical signs of the neurological disorders and they can be acquired by EOG. The EOG signal is electrical signal generated due to eye ball movements and is contaminated with brain signals and power line while recording. As the EOG signal is a non-stationary signal, it can be denoised by wavelet transformation techniques. The present work covers denoising of noisy EOG signal using Stationary Wavelet Transform (SWT), which was done with all suitable wavelets that are morphologically similar to an EOG signal by applying both Soft and Hard Thresholding methods. An EOG signal was simulated and added with noise to obtain noisy EOG signal. The wavelet analysis of the simulated noisy EOG signal reveals that the Biorthogonal 3.3 wavelet is the best wavelet to denoise by using SWT technique, wherein the yield achieved was good with Signal to Noise Ratio of 36.5882 dB and minimum Mean Square Error of 0.383313 for quality diagnosis.

Keywords: EOG signal, Wavelet transform, denoising, thresholding, biorthogonal wavelet

1. INTRODUCTION

THE ELECTROOCULOGRAM (EOG) is a graphic record of the electric activity of eye ball movements. The electrical signal is generated due to the potential difference between retina and cornea of the eye. The voltage for the horizontal eye movement is up to 16µV whereas it is 14µV for the vertical movement of the eye per 1° [1]. It is very clear from the literature that brain signals and power line interferences are noted in the recorded EOG signal and elimination of such contaminations is important for quality diagnosis. Although many techniques were available to denoise these signals, much attention has been placed recently on wavelet transformation as it presents high efficacy and less complexity [2], [3]. Therefore, analysis was performed by Stationary Wavelet Transform (SWT) using all suitable wavelets that were found morphologically similar to an EOG signal. To our knowledge there are no published reports on denoising of EOG signals by the proposed technique and therefore we herein present the results of our investigative study.

2. WAVELET TRANSFORM

A tool for the analysis of transient, non-stationary or time-varying phenomena that has energy concentrated in time is a wavelet which is simply a small wave, as shown in Fig.1. Haar, Biorthogonal, Daubechies were some of the wavelet families used for analysis and synthesis of the signal [4]. In analyzing non-stationary signals like EEG, ECG etc., wavelet transform has emerged as one of the superior techniques. Taking cue, the technique was applied for EOG denoising. The technique has its efficiency to understand the behavior of a signal by transforming a time domain signal into frequency localization. The wavelet transformation techniques were applied to identify ocular artifacts in EEG signal, wherein Haar wavelet was used for the decomposition [5]. The wavelet transformation technique has been applied to denoise other physiological signals, like ECG [6]. The present paper is significant in denoising the EOG signal, normally comprising of eye blinks, and eye movements in horizontal and vertical directions.

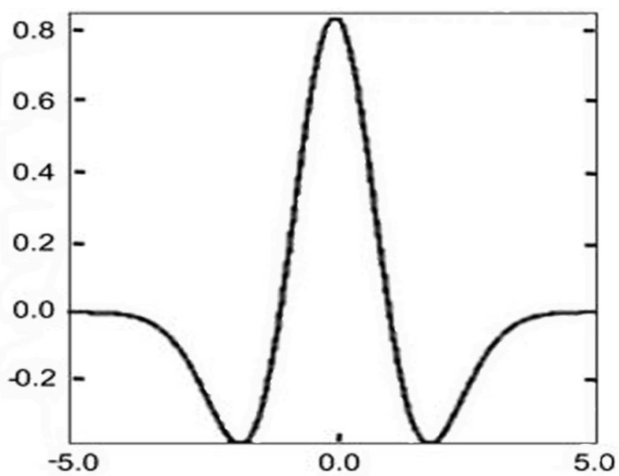

Fig.1. Wavelet Function

The Discrete Wavelet Transform (DWT) means choosing subsets of the scales 'a' and positions 'b' of the mother wavelet *Ψ(t)* .

$$\psi_{a,b}(t) = 2^{a/2}\psi(2^a t - b) \tag{1}$$

Dyadic scales and positions (a and b are integers) are based on powers of two. The translated resulting function interval on a grid is proportional to 2^{-a} when the wavelet for any function is built by dilating a function *Ψ (t)* with a coefficient 2^a (from equation (1)) [7]. The high frequency and low frequency components match the contracted and dilated versions of the wavelet function, respectively. The details of the signal are obtained at several scales by correlating the original signal with wavelet functions of different sizes. The hierarchical scheme of arrangement of these correlations with different wavelet functions is called multi-resolution decomposition. The multi-resolution decomposition algorithm separates the signals into “approximation” and “details” at different scales [8].

The SWT (independent on the choice of origin) can be obtained by modifying the basic DWT algorithm. The DWT does not preserve translation invariance due to sub-sampling operations in the pyramidal algorithm. The SWT has been introduced because it preserves the property that a translation of the original signal does not necessarily imply a translation of the corresponding wavelet coefficients. To halve the bandwidth from one level to another level, the SWT utilizes recursively dilated filters instead of sub-sampling. The decomposition scheme is shown in Fig.2 [7]. The next step in wavelet based denoising is Thresholding. Two kinds of Thresholding were applied in the analysis, namely Soft and Hard Thresholding.

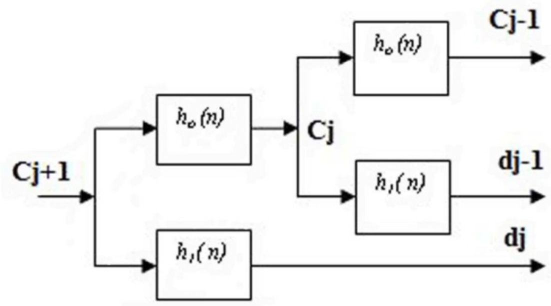

Fig.2. Wavelet Decomposition Scheme

3. SOFT AND HARD THRESHOLDING

Linear and non-linear methods are the two forms of denoising algorithms. The coefficient size by itself is not taken into account as the linear method is independent of the size of empirical wavelet coefficients. Fine scale coefficients contain signal noise and coarse scale ones do not, namely,

$$d_{j,k} = \begin{cases} 0, j \geq \lambda \\ d_{j,k}, j < \lambda \end{cases} \tag{2}$$

As the white noise is found in every coefficient distributed over all scales, non-linear method can be applied in two ways, Soft Thresholding and Hard Thresholding. The latter cuts off coefficients below a certain threshold λ, while the former reduces all coefficients by this threshold. The Soft and Hard Thresholds are respectively given by

$$S(x) = \begin{cases} Sign(x)(|x| - \lambda), |x| > \lambda \\ 0, |x| \leq \lambda \end{cases} \tag{3}$$

$$S(x) = \begin{cases} S(x), |x| > \lambda \\ 0, |x| \leq \lambda \end{cases} \tag{4}$$

where S(x) is the analyzed signal and λ is the chosen threshold [9], [10].

4. METHODOLOGY

An EOG signal comprising of eye movements in horizontal, vertical directions and eye blinks was simulated as shown in Fig.3 and also its details are given in Table 1. The power of the EOG signal is 43.2835 dB. The noisy EOG signal (Fig.4) was simulated by adding controlled noise and its power was found to be 43.2855 dB. Then this noisy EOG signal was denoised using the SWT technique with different wavelets (which are morphologically similar to it) namely Haar, Biorthogonal and Daubechies. The method proposed in this paper involves the following steps.

a. Application of SWT to the contaminated EOG with a specific wavelet as basis function and decomposition up to 6 levels.
b. Application of Soft or Hard Threshold.
c. Reconstruction of decomposed signal to obtain denoised EOG signal.

The Soft Thresholding includes Fixed Form Threshold, Rigorous SURE, Heuristic SURE, Minimax, whereas Penalize High, Penalize Medium, Penalize Low is Hard Thresholding. Both kinds of Thresholding were applied before reconstruction to obtain respective denoised EOG signals. Then the SWT technique was applied to the real time EOG signal (Fig.7).

Table 1. Details of reference EOG signal

Reference EOG signal details	Samples range
Eye movements in horizontal direction	1 to 5000
Eye blinks	5001 to 7000
Eye movements in vertical direction	7001 to 10,944

Estimation of Mean Square Error (MSE) and Signal to Noise Ratio (SNR):

The MSE value is estimated between the denoised EOG signal and the reference EOG signal.

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(x(i) - \overline{x}(i))^2 \tag{5}$$

where N is the length of the EOG signal, $x(i)$ is the reference EOG signal (Fig.3) and $\overline{x}(i)$ is the denoised EOG signal (Fig.5) [4] and

$$SNR = 10\log\frac{\sum_{i=1}^{N}x(i)^2}{\sum_{i=1}^{N}(x(i) - \overline{x}(i))^2} \tag{6}$$

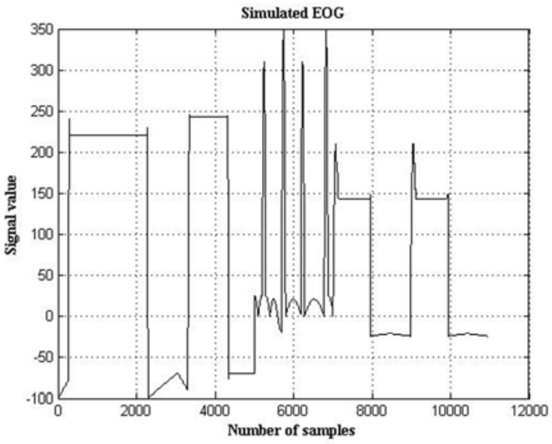

Fig.3. Reference EOG Signal

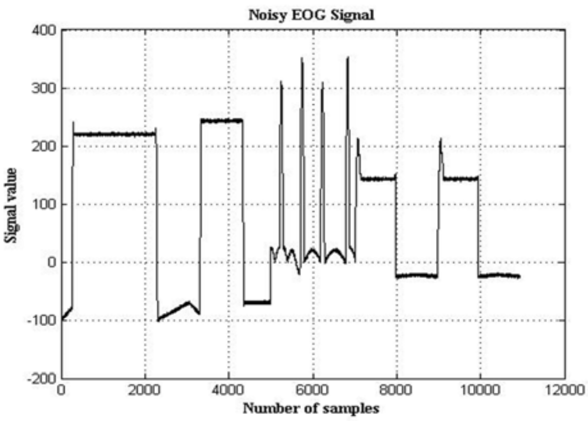

Fig.4. Noisy EOG Signal

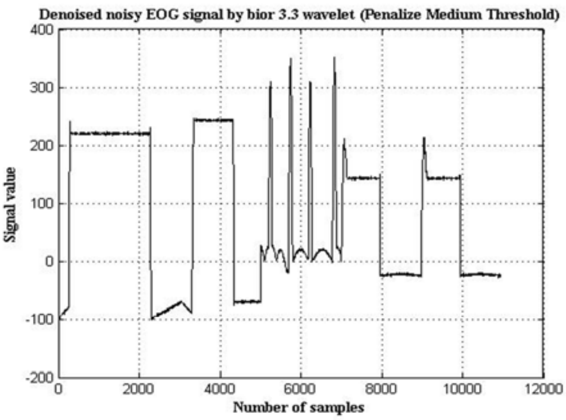

Fig.5. Denoised noisy EOG signal by bior 3.3 wavelet

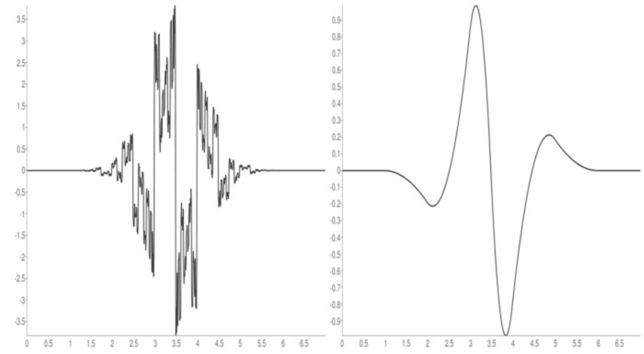

Fig.6. bior 3.3 wavelet

5. RESULTS AND DISCUSSION

The noisy EOG signal was decomposed with db7 and db9 wavelets of Daubechies wavelet family for the analysis. Subsequently SNR and MSE values were estimated and depicted in Table 2. As evident from Table2, high SNR and low MSE values were obtained for the penalize method of thresholding. Among the db wavelets tested, db7 was found to be satisfactory with SNR and MSE values of 36.4479 dB and 0.4466, respectively.

Similarly, denoising was performed with biorthogonal wavelets bior 1.3, bior 1.5, bior 3.3 and bior 3.5. The analysis with bior 3.3 wavelet (Fig.6) was found to be better than db7 wavelet with SNR and MSE values, respectively, 36.5882 dB and 0.383313 for penalize medium thresholding as shown in Table2. Further the proposed denoising technique was also applied for a real time EOG signal (Fig.7) obtained from PDS lab [11] as a pilot test. Fig.8 shows the denoised real time EOG signal.

6. CONCLUSION

The present study illustrates the application of bior 3.3 as a better wavelet for denoising the EOG signal using SWT. The results obtained are extremely encouraging and can be applied to denoise the EOG signal obtained in noisy environments for further use in biomedical quality diagnosis. Further work is underway to apply the technique for the real time EOG signal wherein, the information procured may provide a strong evidence for the bior 3.3 as a potential wavelet.

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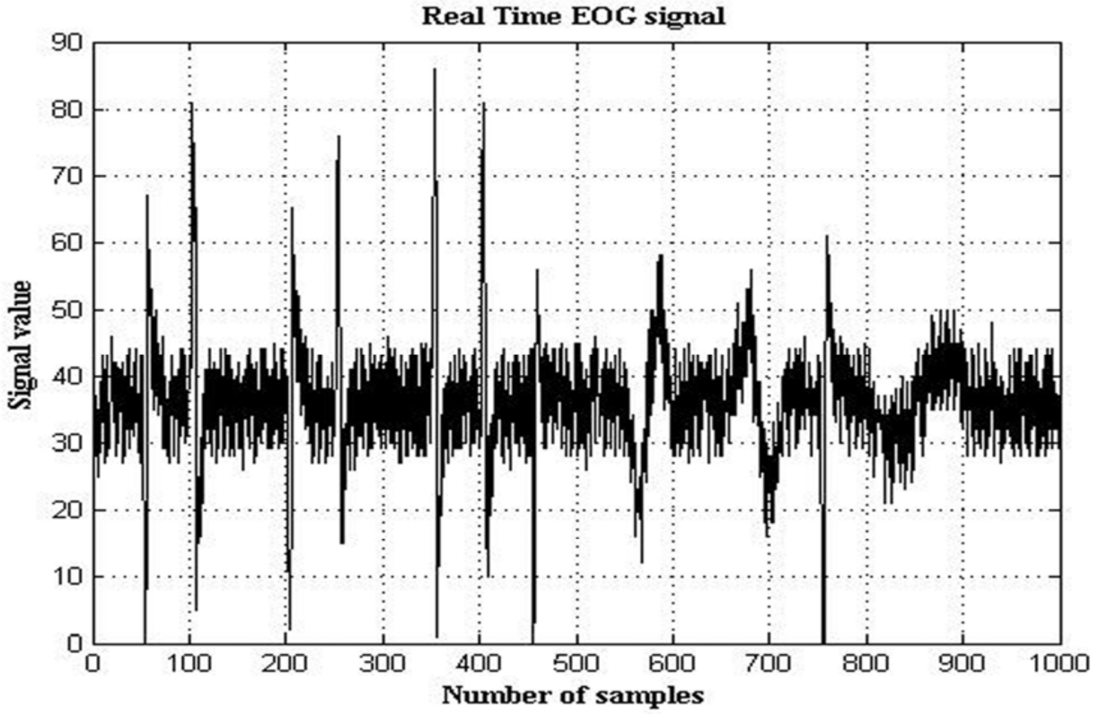

Fig.7. Real time EOG signal

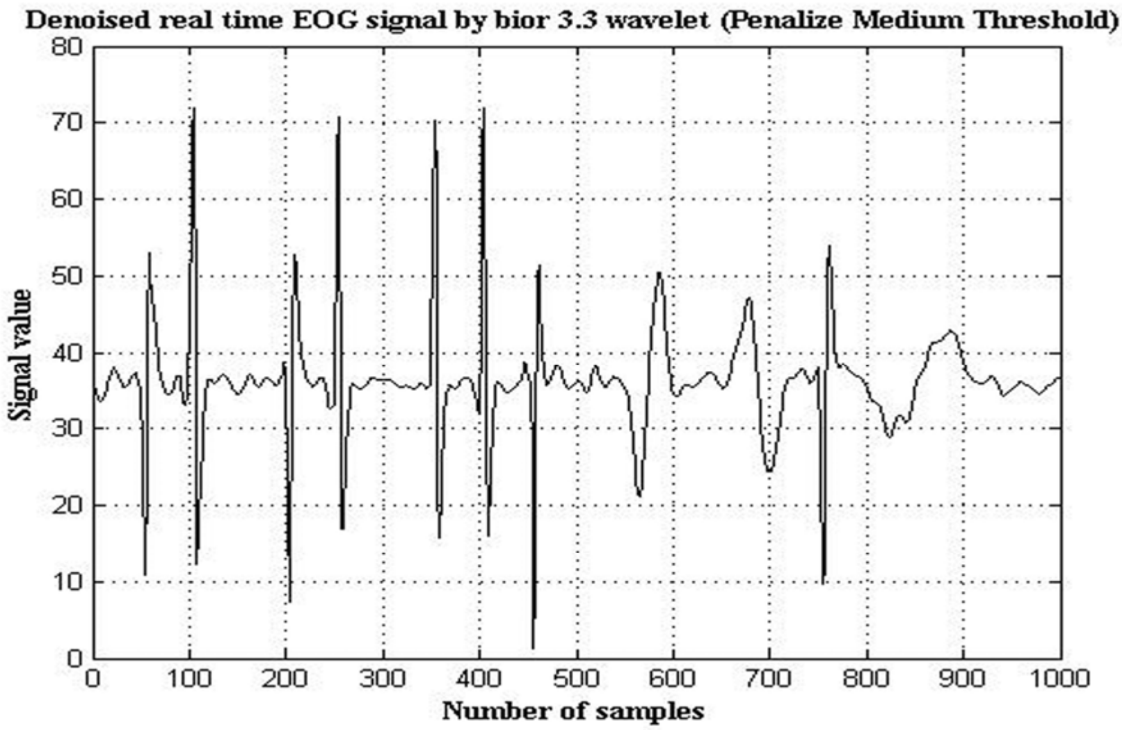

Fig.8. Denoised real time EOG signal by bior 3.3 wavelet

Table 2. Estimated SNR and MSE values when denoising the noisy EOG signal with different wavelets

Wavelet	Threshold		SNR (dB)	MSE
	Method	Value		
Haar	Fixed Form	23.181	28.0251	0.6356
	Rigorous Sure	4.378	35.4193	0.4123
	Heuristic Sure	4.378	35.4193	0.4123
	Minimax	15.297	30.3736	0.7116
	Penalize High	4.052	35.9181	0.4175
	Penalize Medium	2.411	35.6765	0.4997
	Penalize Low	2.069	35.6402	0.5217
bior 1.3	Fixed Form	23.181	32.2826	0.4259
	Rigorous Sure	4.378	33.2324	0.4081
	Heuristic Sure	4.378	33.2324	0.4081
	Minimax	15.297	34.838	0.3714
	Penalize High	4.052	34.6162	0.3879
	Penalize Medium	2.411	34.5594	0.3907
	Penalize Low	2.069	34.543	0.4383
bior 1.5	Fixed Form	23.181	33.3882	0.4546
	Rigorous Sure	4.378	34.5941	0.4142
	Heuristic Sure	4.378	34.5941	0.4142
	Minimax	15.297	35.7193	0.3964
	Penalize High	4.052	36.2201	0.3919
	Penalize Medium	2.411	36.2221	0.3512
	Penalize Low	2.069	36.1299	0.3916
bior 3.3	Fixed Form	23.181	27.7645	2.037324
	Rigorous Sure	4.378	32.4184	0.843024
	Heuristic Sure	4.378	32.4184	0.843024
	Minimax	15.297	29.9822	0.947362
	Penalize High	4.052	36.3775	0.436598
	Penalize Medium	**2.411**	**36.5882**	**0.383313**
	Penalize Low	2.069	36.3037	0.53313
bior 3.5	Fixed Form	23.181	29.7343	1.3238
	Rigorous Sure	4.378	33.2597	1.1991
	Heuristic Sure	4.378	33.2597	1.1991
	Minimax	15.297	32.4123	1.0315
	Penalize High	4.052	36.5472	0.45
	Penalize Medium	2.411	36.3852	0.4382
	Penalize Low	2.069	36.3151	0.4888
db 7	Fixed Form	23.181	26.2531	3.0683
	Rigorous Sure	4.378	28.0357	2.2363
	Heuristic Sure	4.378	28.0357	2.2363
	Minimax	15.297	28.3323	1.4517
	Penalize High	4.052	34.7512	0.4607
	Penalize Medium	2.411	36.4479	0.4466
	Penalize Low	2.069	36.4283	0.4633
db 9	Fixed Form	23.181	22.9422	11.1115
	Rigorous Sure	4.378	34.5728	0.387
	Heuristic Sure	4.378	34.5728	0.387
	Minimax	15.297	24.7163	5.2013
	Penalize High	4.052	35.7683	0.4856
	Penalize Medium	2.411	35.6475	0.4682
	Penalize Low	2.069	35.6228	0.4842

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