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A Novel Wavelet Based Technique for Detection and De-Noising of Ocular Artifact in Normal and Epileptic Electroencephalogram

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Abstract— The Electroencephalogram (EEG) is a biological signal that represents the electrical activity of the brain. Typical EEG instrumentation settings used are low pass filtering at 75Hz and paper recording at $100\,\mu V/cm$ and 30mm/s for 10 to 20 minutes over 8 to 16 simultaneous channels. A commonly encountered problem in clinical practice during EEG recording is the 'blanking' of the EEG signal due to blinking of the user's eyes. Eye-blinks and movements of the eyeballs produce electrical signals that are collectively known as Ocular Artifacts and these are 10 to 100 times stronger than the EEG signal which is being recorded. The effective filtering of these Ocular artifacts is extremely difficult owing to the fact that their frequency spread (1Hz-50Hz) is observed to be overlapping with that of the EEG. Another major drawback of the existing frequency based de-noising techniques is that they require continuous recording of the Electrooculargram (EOG) signals as well. In this paper, we present a novel and simple technique for the detection and subsequent de-noising of these ocular artifacts using Haar wavelets of high orders. A comprehensive error analysis has been carried out, both in the time domain based artifact detection as well as the frequency domain based de-noising of EEG. This procedure has also got the advantage of being highly artifact selective and so we have applied it to detect and de-noise Epileptic EEG signals.

Index Terms— Artifact De-noising, Electroencephalogram (EEG) Signal, Electrooculargram (EOG) Signal, Epileptic EEG Signal, Haar Wavelet Decomposition, Ocular Artifacts (OA).

I. Introduction

Electroencephalogram (EEG) serves as an extremely valuable tool for clinicians and researchers to study the activity of the brain in a non-invasive manner. The frequency content of the EEG is between DC and 75Hz and its amplitude is generally in the order of $10 - 45\,\mu V$. Extracting the EEG in an environment where the Signal-to-Noise Ratio (SNR) can be as low as 10dB forces us to ensure that the artifacts caused by sources internal to the human body like EOG and neck muscle movements are detected and filtered out accurately. The Cornea-Retinal Potential (CRP) developed as a result of the movement of the eye-ball also causes 'blanking' of the EEG Signal due to the spikes that occur [1]. This along with the blink related artifacts, which are often $10 - 100$ times stronger than the EEG signal which is being recorded, are often dominant over the other electrophysiological contaminating signals. The existing de-noising techniques that are based on frequency selective filtering lead to a substantial loss of the EEG data [2]. Prohibiting the subjects from blinking or moving their eyeballs is not a plausible solution and in-fact the effort of the subject in ensuring that he does not do the aforementioned actions can have a significant impact on the recorded EEG [3]. Stationary Wavelet Transform (SWT) has recently been used to de-noise the EEG data, but owing to the ocular artifacts being significantly uncorrelated with the recorded EEG data, the reconstructed signal is not a very good approximation of the original EEG. Wavelet based filtering is an attractive alternative owing to its ability to study the time-frequency maps simultaneously [4]. So basically, the problem with existing methods is that they are unable to detect the moment the eye-blink occurs accurately. The Haar basis $\Phi_H(t)$ is given by

$$\Phi_H(t) = \begin{cases} 1 & \text{for } 0 <= t < 1 \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

In this paper, we have shown how these Haar wavelets can be used to detect and de-noise the ocular artifacts in EEG.

II. Haar Wavelet Based Detection of Change in the State of the Eyes

The need to continuously monitor the EOG while recording the EEG signal and its corruption due to concentration on the part of the user so as not to move or blink his eyes forces us to device an alternate method for detecting and removing the ocular artifacts. The EEG signal which is picked up by non-invasive methods over the scalp of the subject is corrupted by a multitude of artifacts of which those caused by the EOG cause maximum distortion [5]. In this section we give a brief description of the effect that the ocular artifacts have in the amplitude and frequency spectrum of the EEG data that is recorded. We also describe a novel and elegant technique using the sharply varying Haar wavelets to accurately detect changes in the state of the eye and this shall be extended in the subsequent section to detect eye-blinks and Iris movements.

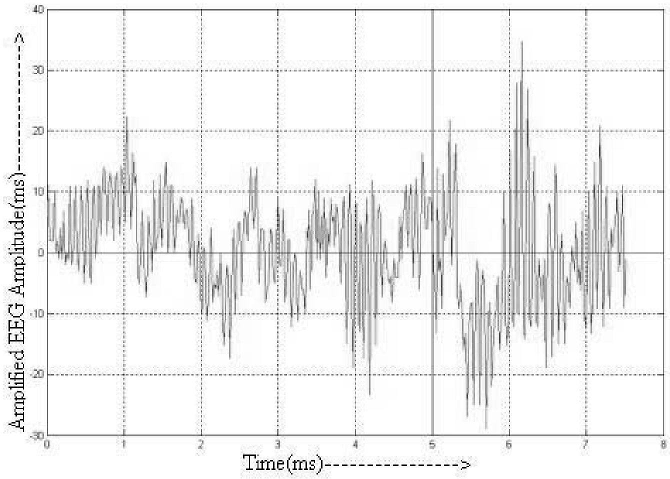

Fig. 1. EEG Signal with eyes closed at t = 5s.

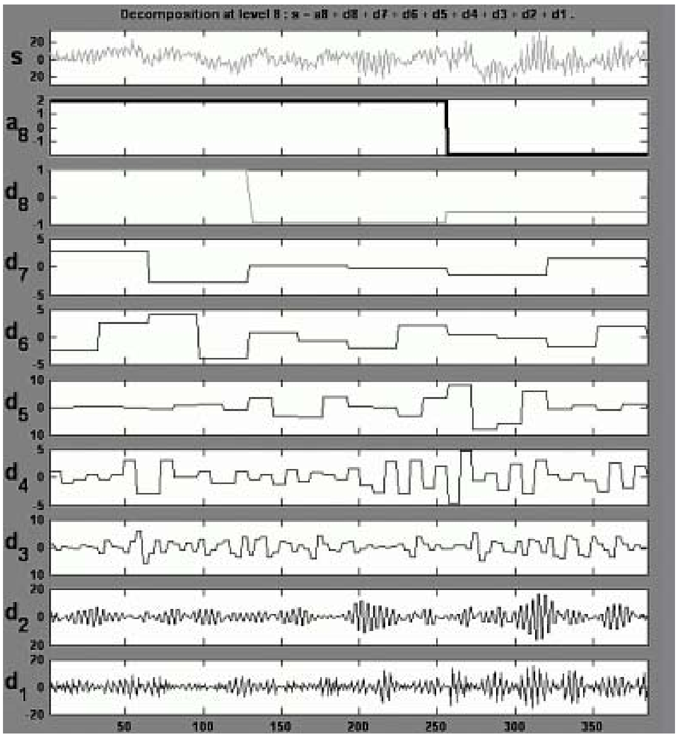

Fig. 2. Decomposition with Haar wavelet of 8th Order.

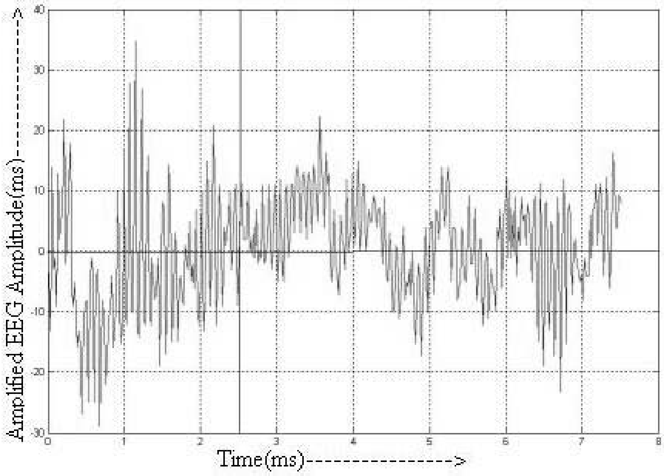

Fig. 3. EEG Signal with eyes opened at t = 2.5s.

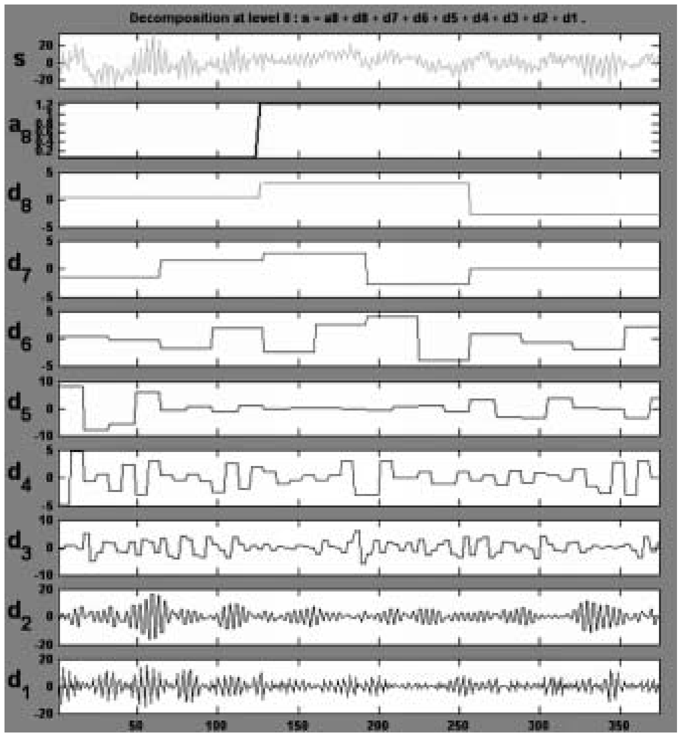

Fig. 4. Decomposition with Haar wavelet of 8th Order.

A. EEG Amplitude dependence on the State of the Eye

It has been known for quite some time now that the alpha rhythm of the EEG, which is the principal resting rhythm of the brain in adults while they are awake, is directly influenced by visual stimuli. Auditory and mental arithmetic tasks with the eyes closed leads to strong alpha waves, which are suppressed when the eyes are opened [6]. A suitable processing of these EEG signals gives two diferent levels coresspond to the two different states of the eye. This property of alpha EEG was used for a long period of time to detect eye blinks and movements. Though it is suitable for Bio-control schemes, the slow response of thresholding, its failure to detect fast eye blinks and the lack of an effective de-noising technique forced researchers to study the frequency and phase characteristics of the EEG signal as well.

B. Detection of Change in State of the Eyes: Need for a Wavelet based Approach

On analysis of the frequency spread of the EEG data that contained the ocular artifacts, researchers found that the difference in the frequency of the spikes caused due to eye blinks and the EEG signal could be used along with a simultaneous recording of the EOG to detect and remove these artifacts. But correlation of the EEG and EOG is futile, especially because

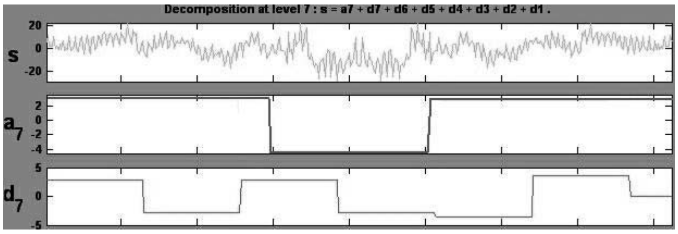

Fig. 5. Detection of Eye-blink with Haar wavelet of 7th Order.

TABLE I

NORMAL EEG: DEVIATION OF DETECTION TIMES FROM ACTUAL

Action Done	Min.(ms)	Max.(ms)	Mean(ms)
Eyes Opened	0	12	0.92
Eyes Closed	0	18	3.01
Eyes Blink	0	19	3.87
Eyes Movement(Vertical)	2	24	7.11
Eyes Movement(Horizontal)	3	20	7.14

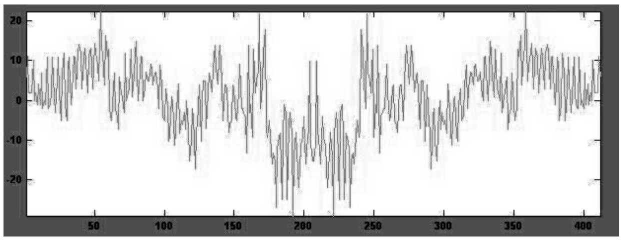

Fig. 6. Re-constructed EEG at output of Haar Wavelet

TABLE II

EPILEPTIC EEG: DEVIATION OF DETECTION TIMES FROM ACTUAL

Action Done	Min.(ms)	Max.(ms)	Mean(ms)
Eyes Opened	0	28	3.73
Eyes Closed	1	32	4.07
Eyes Blink	4	35	6.70
Eyes Movement(Vertical)	6	43	13.00
Eyes Movement(Horizontal)	6	40	12.89

of the inherent corruption of EEG data by the restraint on the users eye movements and blinks [7]. The failure of accurate detection of these artifacts by singular observation of the time or frequency domains forces us to use wavelets to study time-frequency maps. In this section, we describe how Haar wavelets of high orders are used to decompose the recorded EEG signal in-order to detect the exact moment when the state of the eye changes and its subsequent de-noising for arriving at extremely good reconstructions of the original EEG data. This technique has been extended in the subsequent section to detect eye-blinks and movement of the eyeballs as well.

1) Haar wavelet based detection: Closing of the eyes: In order to detect closing of the eyes, we have used the EEG data samples like the one shown in fig. 1. Here the subject's eye is open for the first 5s and is then closed at $t = 5$s after which it remains closed. Let us denote the state prior to the ocurrence of the change in the state of the eye by the signal $s_{low}(t)$ and the signal after the change to be $s_{high}(t)$, then $s_{eeg}(t)$ the overall eeg signal may be represented by

$$s_{eeg}(t) = s_{low}(t) + s_{high}(t), \forall t \in [0, \infty]. \qquad (2)$$

On decomposing this EEG data sample with the discontinuous Haar wavelet of order 8, we obtain 8 successive approximations. The final stage of approximation yields a step function, whose falling edge accurately detects the moment when the user's eye goes from the open state to the closed state. This can be seen clearly from fig. 2 where at $t = 5$s and sample index $n = 256$, the Haar wavelet decomposition yields the falling edge of the step function. We have extensively tested this technique on various EEG data samples acquired from a spectrum of sources and even under extremely noisy conditions with multiple artifacts, we are able to successfully detect the closing of the subject's eye. The resulting time measurement is accurate to ± 18ms as we shall see in the next section.

2) Haar wavelet based detection: Opening of the eyes: In order to detect opening of the eyes, let us consider as an example, the EEG data shown in fig. 3. Here the subject's eyes are closed for the first 2.5s and are then opened at $t = 2.5$s after which they remain open. Let us denote the state prior to the ocurrence of the change in the state of the eye by the signal $p_{high}(t)$ and the signal after the change to be $p_{low}(t)$, then $p_{eeg}(t)$ the overall eeg signal may be represented by

$$p_{eeg}(t) = p_{high}(t) + p_{low}(t), \forall t \in [0, \infty]. \qquad (3)$$

Once again, the final stage of approximation yields a step function, whose raising edge accurately detects the moment when the user's eye goes from the closed state to the open state. This is depicted in fig. 4 where at $t = 2.5$s and sample index $n = 128$, the Haar wavelet decomposition yields the raising edge of the step function. As concluded previously, we are able to successfully detect the opening of the subject's eyes under a multitude of conditions, some of them with SNR as low as 10dB. The resulting time is accurate to ± 12ms as we shall see in the next section.

III. EXTENSION OF THE HAAR WAVELET BASED ANALYSIS TO DETECT AND FILTER EYE BLINKS

As we had seen in the previous section, on decomposing the EEG data with the Haar wavelets of high orders we obtain a step function with a falling edge for a change in the state of the eyes from open to closed and a step function with a rising edge for a change in state of the eyes from closed to open. In this section we shall extend the same technique to detect eye-blinks accurately. For this we shall consider as an example, the EEG data with a blink artifact between 0.3s and 0.5s. On decomposing this with a Haar wavelet of degree 7, the final approximation yielded the step function with the falling edge at 0.28s and the rising edge at 0.5s as shown in fig. 5. If $s_{eeg}(t)$ represents the EEG signal recorded and $\Phi_H(t)$ is the Haar basis defined by (1), then the output of the filter at the maximum level of decomposition [8], $s_{filt}(t)$ will be given by

$$s_{filt}(t) = \Phi_H(t) * s_{eeg}(t). \tag{4}$$

The reconstruction of the EEG signal at the output of the Haar wavelet and subsequent filter yields us the signal as shown in fig. 6. The main advantage of this technique over existing wavelet based EEG de-noising methods is the precise detection of the moments when the state of the eye changes which ensures the absence of remnant ocular artifact and the perfect reconstruction of the EEG data.

The values of minimum, maximum and mean deviations in detection times for the 157 normal EEG samples and the 114 Epileptic EEG samples recorded are summarized in *Table-1* and *Table-2* respectively.

IV. Results and Discussions

The effectiveness of the de-noising of ocular artifacts from EEG is dependent to a large extent on their accurate detection. Our experiments have shown conclusively that using discontinuous wavelets like Haar of high orders is the simplest way to determine the instant when ocular artifacts occur and as we have seen in the previous section, this leads to very accurate reconstruction of the EEG signal. The validity of the technique has also been verified with the EEG data samples obtained by invasive methods using the correlated output of multiple needle electrodes. In situations where the EEG signal strength is in the order of 50dB or more, we are able to detect the ocular artifacts with an average accuracy of ± 0.92ms for opening of the Eyes, ± 3.01ms for the closing of the eyes and ± 3.87ms for eye-blinks. For movements of the eyeballs in the horizontal and vertical directions the detection accuracy is found to be around ± 7ms on an average. In case of Epileptic EEG, where the seizure spikes and artifacts create a situation with SNR around 10dB, the detection accuracy decreases by about ± 1ms to ± 6ms on an average and these are certainly satisfactory. We are presently researching on the extremely artifact selective nature of our Haar wavelet filters as this could aid in the accurate detection of Alzheimers disease while eliminating the need for EOG recording and obtaining a very good reconstruction of the EEG signal as well. From the reconstructed approximation at the output of the wavelet filters and subsequent correlation with EEG obtained from invasive methods we can confidently declare that the use of Haar wavelets of high orders is a very viable solution to the problem of detection and de-noising of ocular artifacts in Electroencephalogram.

V. Conclusion

Mere frequency based ocular artifact de-noising from EEG and even those techniques based on wavelet analysis leads to loss of data and there is still remnant artifact in the collected samples. The main reason for this is incorrect detection of the artifacts and not the process of their separation using wavelets, which is the most efficient among the existing options. This paper presents a novel and efficient method for accurate detection and subsequent de-noising of these artifacts caused by eye blinks and eyeball movements, both of which generate signals that are $10 - 100$ times stronger than the EEG that is being recorded. By making use of the sharply varying Haar wavelets of high orders we are able to make precise detection of these ocular artifacts and this leads to their complete removal and accurate reconstruction of the EEG signal. The analysis on the error involved in our technique has produced encouraging results with the maximum deviations being as low as 18ms for Normal EEG and 24ms for Epileptic EEG. Another significant result, which we are presently doing further research on, is the extremely artifact-selective nature of these discontinuous Wavelets that can be designed to remove just the ocular artifacts while permitting the slow qEEG waves caused due to Alzheimers disease to appear in the observed EEG Signal and this could aid in its early detection in clinical EEG recording itself. Hence, our efforts are directed towards researching and designing Haar and other wavelets for highly artifact selective detection and de-noising.

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References

[1] R.J.Croft, and R.J.Barry, "Removal of ocular artifact from the EEG: a review", *Neurophysiol. Clin.*, 30(1), 5-19, 2000.

[2] Chiri Yamaguchi, "Fourier and Wavelet Analyses of Normal and Epileptic Electroencephalogram(EEG)", *Proceedings of the 1st International IEEE EMBS Conference on Neural Engineering*, Capri Island, Italy, March 20-22, 2003.

[3] B.W.Jervis, M.Thomlinson, C.Mair, J.M.L.Lopez and M.I.B.Garcia, "Residual ocular artifact subsequent to ocular artefact removal from the electroencephalogram", *IEE Proceedings- Sci. Meas. Technol.*, Vol 146, No. 6, 293-298, Novmeber 1999.

[4] Michael Unser, Akram Aldroubi, "A review of wavelet in biomedical applications",*IEEE Transactions on Biomedical Engineering*, vol. 84, pp.626-638, 1996.

[5] Zhouyan Feng, Zheng Xu, "Analysis of rat Electroencephalogram under Slow Wave Sleep using Wavelet Transform", *Proceedings of the Second Joint IEEE EMBS/BMES Conference*,Houstan,TX,USA,94-95,2002.

[6] N.V.Thakor et al., "Multiresolution Wavelet Analysis of Evoked Potentials", *IEEE Transactions on Biomedical Engineering*, Vol. 40, No 11, pp. 1085-1093, November 1993.

[7] Jitendran Muthuswamy and Rob J.Roy, "The Use of Fuzzy Integrals and Bispectral Analysis of the Electroencephalogram to Predict Movement Under Anesthesia", *IEEE Transactions on Biomedical Engineering*, Vol. 46, No. 3, 291-299, March 1999.

[8] C.K.Chui, "An Introduction to Wavelets", *Academic Press*, New York, USA(1992).

[9] The Mathworks Inc., *Matlab users guide. Wavelet toolbox*,1997.