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Yedukondalu Kamatham and Nasreen Sultana

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DENOISING OF ECG SIGNALS USING SAVITZKY-GOLAY LEAST SQUARES POLYNOMIALS AND DISCRETE WAVELET TRANSFORM

Yedukondalu Kamatham[1]* and Nasreen Sultana[2]

[1,2]Department of ECE, Bhoj Reddy Engineering College, Vinay Nagar, Santhosh Nagar, Saidabad, Hyderabad-500059, India

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ABSTRACT

ECG signal is mostly used in biomedical research and for clinical diagnosis. Recorded ECG signal often contains a noise and interference with non-stationery properties. Electrode noise, electronic noise and motion artifacts are most common type of random noises which are recorded in the ECG signal. One of the major problem in biomedical signal acquisition is to separate small input signal from noise and disturbance caused by 50 Hz power supply. The main objective of this paper is the performance analysis of two adaptive filters namely Savitzky-Golay (SG) filter with and without smoothening and Discrete Wavelet Transform (DWT) for noisy ECG stimulus. Results are encouraging. The Mean Square Error (MSE) reduced to 5.07, 3.72, and 1.101 with Discrete Wavelet Transform (DWT), Savitzky-Golay (SG) Filter and Savitzky-Golay (SG) Smoothing Filter respectively. Hence SG Filter with smoothing is very useful for denoising ECG signals in medical diagnosis applications.

INTRODUCTION

A medical test that detects cardiac (heart) abnormalities by measuring electrical activity generated by heart as it contracts is an Electrocardiogram (ECG) [1]. The performance of the heart activities over the human body surface is represented in ECG. It is used to measure the heart rate. The heart is a muscular organ that beats in rhythm to pump the blood through the body. ECG's are often performed to monitor the health of patients who have been diagnosed with heart malfunction. ECG can help to diagnose a range of diseases including heart arrhythmias, heart enlargement, heart inflammation (Pericarditis or myocarditis) and coronary heart disease. ECG consists of noise which is non-stationary with obvious characteristics of micro energy and relatively small SNR. ECG is often accomplished by noises in the course of amplification and transmission as it is highly vulnerable to environmental impacts. These noises affect the reliability of ECG waveforms and results in wrong diagnosis. Therefore effective denoising methods are essential to process before ECG diagnosis.

ECG tracing consists of waveform components which indicate electrical events during one heartbeat. The ECG signal is characterized by six peaks labeled with successive letters P, Q, R, S, T, and U as shown in Fig.1. The front end of ECG must be able to deal with extremely weak signals ranging from 0.5 mv to 5.0 mv [1]. The P wave represents the initiation of depolarization in atrial contraction. The next part of tracing is called the QRS complex which represents the conductance and sequential depolarization of ventricles. An initial downward (negative) deflection in the QRS is termed as Q wave and upright (positive) deflection is termed as R wave. The S wave follows R wave and is a downward (negative) deflection. The ST segment follows the QRS complex which represents period of time in which ventricles are iso-electric. Evaluation of the ST segment is particularly important in considering cardiac ischemia (restriction of blood supply to tissue) and myocardial infarction (heart attack). The T wave is the last portion of PQRST complex. The T wave represents the re-polarization of the ventricles.

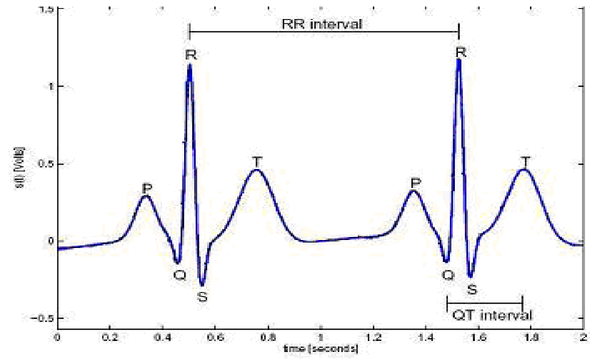

Fig. 1 A Typical ECG Waveform [4].

*Corresponding author: **Yedukondalu Kamatham**
Department of ECE, Bhoj Reddy Engineering College, Vinay Nagar, Santhosh Nagar, Saidabad, Hyderabad-500059, India

The morphology and the direction of T wave can provide critical information about cardiac ischemia and electrolyte abnormalities (imbalance of ionized salts like Ca, K, and Mg in blood).

The prominent noise sources in ECG include [2]: Power Line Interference (PLI) caused by power system constituted by 50 Hz harmonics, in addition to Electromagnetic Interference (EMI). Electromyography (EMG) interference is an interference caused by human activities muscle tension. The nervous Clod stimulus or certain diseases etc. will also generate high frequency EMG noise. Base Line drift (BLD) caused by low frequency interference like movement of electrode or human breathing. This interference is lower than 1 Hz. There are different techniques available for use in de-noising ECG signals, such as adaptive filtering [3], LMS, NLMS, RLS, wavelet, and Savitzky-Golay filtering. The aim of this paper is to investigate and compare the performance of adaptive filters in detail from ECG signal processing aspect. Signal processing toolbox built in MATLAB is used for Simulation.

METHODOLOGY

In this paper artificial ECG signals from PTB database (s0010_rem) are used whose sampling number is 1000 and amplitude is 1mV [5]. Random noise generated by using MATLAB and is added to this ECG signal to get the desired mixed signal. Various researchers have done extensive work on this database. Savitzky- Golay (SG) filters and Discrete Wavelet transform (DWT) are performed on this noisy artificial ECG records sampled at 1000 Hz, with 11 bit resolution. Self-modifying frequency response to change behavior of the signal in time is the main property of an adaptive filter [6]. This property allows the filter to adapt the response to change the input signal characteristics. Therefore the adaptive filters have been employed in various applications such as biomedical-signal processing, telephonic echo cancellation, navigation system, communications channel equalization, and radar signal processing [6]. The block diagram of an adaptive filter is shown in Fig.2, with *x(n)* is input signal to a linear filter at time n, y(n) is response of the filter, *s(n)* is desired signal to the adaptive filter, and *e(n)* is the error signal that denotes the difference between *s(n)* and *y(n)* and *w(n)* is the filter coefficients. By subtracting *n(n)* from mixed signal *x(n)*, the desired signal *s(n)* is obtained.

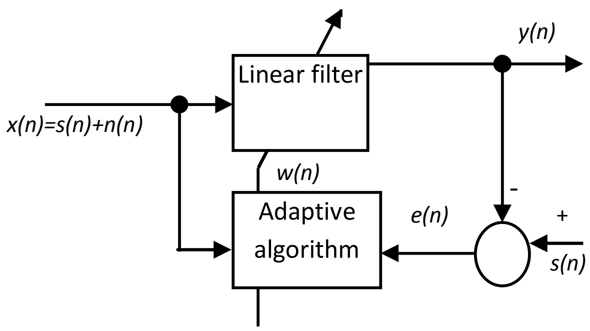

Fig. 2 Block diagram of an adaptive filter

In Savitzky-Golay filter least square polynomial algorithm *s(n)* is obtained by sampling *x(n)* for N=2M+1 samples centered at i=0, which is additively corrupted by noise of degree P polynomial. At i=0, the least square polynomial and its derivative is estimated in Savitzky-Golay (SG) filtering method. By applying a convolution with constant coefficient the SG filters performs the derivative to obtain SG smoothing. Whereas in DWT a wavelet oscillating function is used for better representation of transient and non-stationary signals, and such a function has its energy concentrated in time. It is used to convert signals to frequency domain from time domain i.e. discrete time signals are transformed to discrete wavelet domain signals.

Savitzky-Golay filters

Many publications present wavelets in denoising ECG signals, such as [7-10]. Savitzky-Golay is used in smoothing ECG Signals [8,9]. Before evaluating the resulting polynomial at a single point within the approximation interval, fitting a polynomial to a set of input samples is equivalent to discrete convolution with fixed impulse response. Savitzky-Golay filters are equivalent to digital Low pass filters. SG filters were first investigated in time domain, since those filters have been derived from the field of numerical analysis. Let *x(n)* be a signal composed of ECG signal of interest *s(n)* corrupted by noise *n(n)*.

i.e. $x(n) = s(n) + n(n)$ (1)

The problem is estimation of *s(n)* from *x(n)* which minimizes noise in *s(n)*, using smoothing technique. Let N=2M+1 samples of *x(n)* centered at i=0, which can be approximated by a degree M polynomial in least square sense. An estimate of $s(n_0)$ is given by $p(n_0)$, where *p(n)* is the degree *P* polynomial that minimizes to Eq. (2)[11].The polynomial used here is 30 with degree 5.

$$\sum_{k=-M}^{M}\left(p\left(n_0+k\right)-x\left(n_0+k\right)\right)^2 \quad (2)$$

The estimate of $s(n_0)$ provided by $p(n_0)$ can be written as $p(n_0)=(h*x)n_0$ .Where h(n) is the transfer function of SG filter of length N=2M+1 and smoothing parameter L. Therefore smoothing of noisy data by polynomials is equivalent to low pass finite impulse response (FIR) filter. Assuming L=2k+1, h(n) can be written as Eq.(3)

$$h(n)=\begin{cases} c_k \frac{1}{n} q_{2k+1}(n); n=(+1)....(+M),(-1).....(-M) \\ c_k q'_{2k+1}(0); \quad n=0 \end{cases} \quad (3)$$

Where K is the degree of h(n).

$$c_k = c_k = (-1)^k \frac{(2k+1)}{(k)^2} \prod_{k=-k}^{k} \frac{1}{2M+2k+1} \quad (4)$$

Where polynomials q_l are generated via recurrence $q_0(n)=1$, $q_1(1)=n$

$$q_{l+1}(n)=\frac{2l+1}{l+1} n q_1'(n)-\frac{l(2M+1+l)(2M+1-l)}{4(l+1)} q_{l-1}(n) \quad (5)$$

And $q_l{}'$ denotes derivative of $q_l(n)$.

Discrete Wavelet Transform

DWT is a wavelet transform for which the wavelets are discretely sampled. Unlike Fourier Transform, Discrete Wavelet Transform provides more information in its domain which includes both frequency and time representation. DWT is most popular in application because of the usage of computers. Wavelet is a process that choose an appropriate function of basic wavelet or mother wavelet and through translation, basic wavelet stretches out and draws back the form a series of small wavelet and constructs a signal space in which we will project on analysis-needed signal. The principle is to eliminate the wavelet coefficient caused by noise, reserve or even strengthen the wavelet coefficient caused by desired signals [2]. The wavelet is used to remove the 50/60 Hz power line interference from ECG signals in Gokhale [12],

The wavelet function "sym10" and soft thresholding is used to denoise ECG signal. There are two types of thresholdings in wavelet: soft and hard thresholding. In this paper soft thresholding is preferred as it is much stable than hard threshold and it tends to have a larger bias due to shrinkage of larger wavelet coefficient as described in Eq. (6) [13,14] .

$$w_{st} = \begin{cases} [sign(\omega)](Mod(\omega)-t); & Mod(\omega) \ge t \\ 0; & Mod(\omega) < t \end{cases} \qquad (6)$$

Where ω = wavelet coefficient, t=value of threshold applied on wavelet coefficient.

In this paper wavelet coefficient is "den" and threshold value is 795.68 with "soft" thresholding. For denoising, the threshold value should be calculated using the Eq. (7):

$$\partial = \sigma\sqrt{2 * \log M} \qquad (7)$$

Select "soft" threshold for quantization of wavelet coefficient where σ is standard deviation and M is coefficient vector length. Normally biomedical signals are non-stationary in nature, so the thresholding is performed to improve the signal characteristics like amplitude and signal similarities. From Eq. (1) to separate *s(n)* from *n(n)* the DWT denoising algorithm used is:

1. Decompose *x(n)* using DWT. Choose 'den' as a wavelet coefficient to determine decomposition level as 10 of wavelet transform, then implement 10 layers wavelet in decomposition of ECG signal.
2. Select threshold method for quantization of wavelet coefficient. Apply wavelet function "sym10" on each level of wavelet decomposition which removes wavelet coefficient above the threshold value. The threshold value is calculated as 795.68.
3. Finally the denoised ECG is reconstructed without affecting any features of the signal.

RESULTS AND DISCUSSION

The simulation results of three methods DWT, SG filter and SG smoothing filter are used to analyze the ECG signal quantitatively.

DWT is appropriate tool for analysis of ECG signal as it removes noise from ECG signal by using a single analysis window which is of fixed length i.e.10 in both time and frequency domains. The SNR of original ECG is calculated as 80.55 dB whereas it is 80.59 dB for denoised ECG using DWT, and MSE decreases from 5.1 to 5.07. An increase in SNR indicates it as a good filter. The key issues in DWT are ECG signal decomposition and reconstruction. The response of DWT filter is shown in Fig. 3.

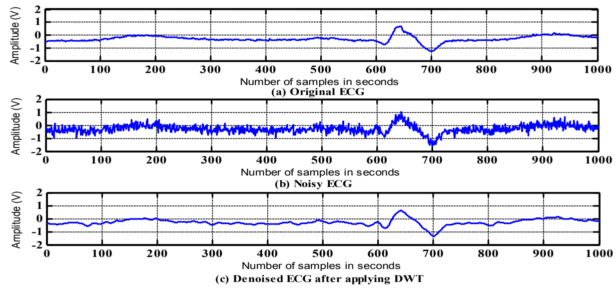

Fig. 3 Response of DWT

In SG filter if the polynomial 30 with degree 5 is decreased then more noise will be removed. Proper QRS diagnosis is done if the ECG signal is denoised properly, where QRS is combination of three signal deflections seen in a typical ECG signal. The SNR in this algorithm increases from 80.55 dB of original ECG to 81.65 dB of Denoised ECG using SG filter. The response of denoised ECG using SG filter is shown in Fig. 4.

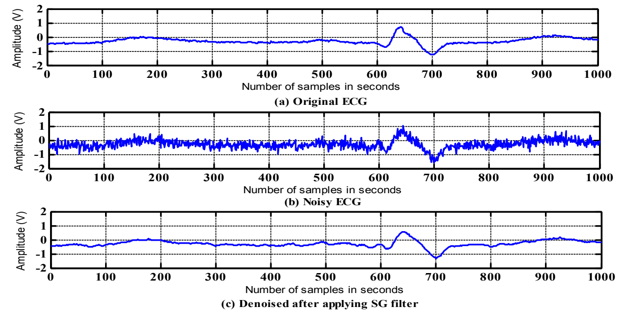

Fig. 4 Response of SG filter

SG smoothing of ECG signal is done to increase SNR without distorting the signal which is achieved by convolution. The response shows a very smooth ECG signal which helps in proper diagnosis, as there is progressive increase in QRS width. The SNR drastically increases from 80.55 dB of original ECG to 81.75 dB of denoised ECG and MSE decreases to 1.101 using SG smoothing filter. The response of SG smoothing filter is shown in Fig. 5

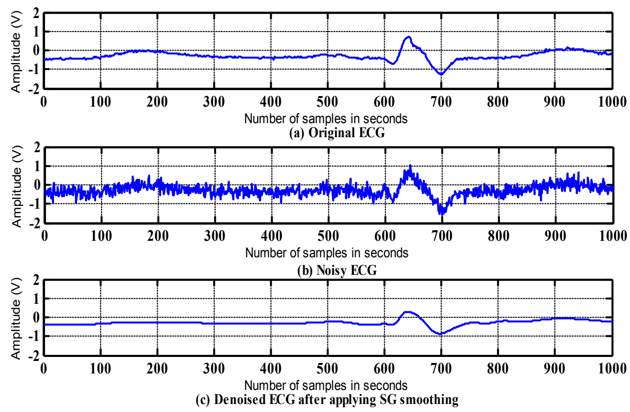

Fig. 5 Response of SG Smoothing filter

Frequency spectrum can be generated by applying Fourier transform on the signal. The frequency spectrum of 50 Hz noisy ECG signal with sampling number 1000 and amplitude 1 mV, DWT filter, SG filter and SG with smoothing is shown in Fig. 6 (a, b, c, d) respectively. Better denoising is performed by SG smoothing filter which converges at 20 Hz, whereas DWT and SG filter converges at 50 Hz and 40 Hz respectively. Therefore SG smoothing filters give significant reduction of noise in less processing time and retain ECG signal morphology effectively.

In this paper we have shown that the SG smoothing filter denoises ECG signal exceptionally better than other two i.e. DWT and SG filter in terms of SNR, PSNR, MSE, Entropy, Standard deviation and ratio of squared norms show in Table 1. The performance of each method is governed by these operation parameters. SNR is the measure of signal strength relative to background noise. The ratio is measure in decibels. SNR is calculated using Eq. (8). PSNR is the ratio of maximum possible power of original ECG signal to power of corrupted noise which affects the fidelity of the original ECG signal. It is calculated using Eq. (9).

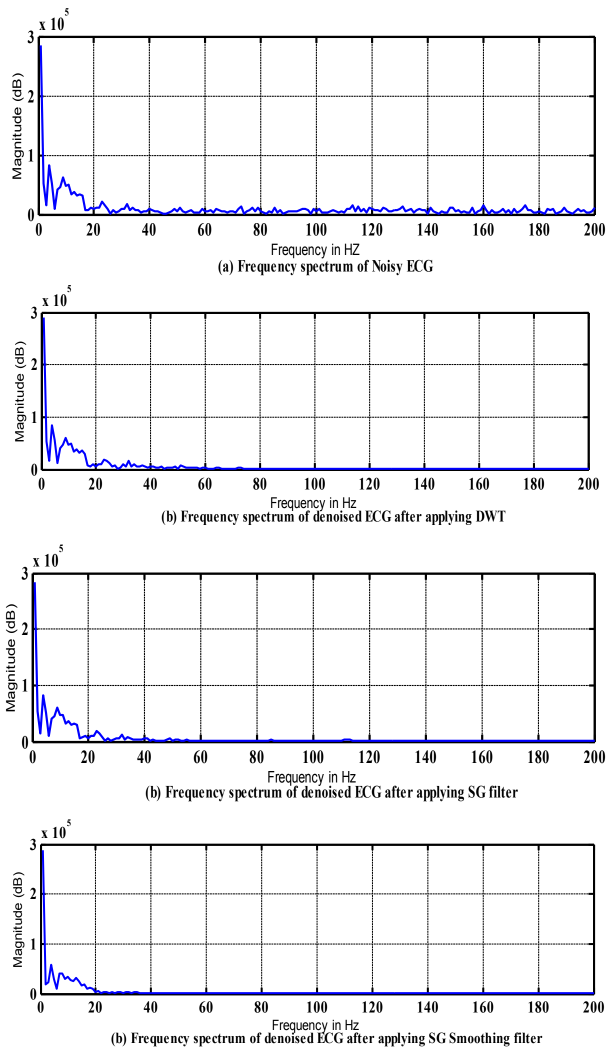

Fig. 6 Frequency response of noisy ECG and denoised ECG with DWT, SG filter, SG smoothing filter

In SNR we calculate how strong the signal is to how strong is the noise, whereas in case of PSNR we are interested in signal peak (R wave which detects the cardiac problem) because we can easily calculate bandwidth of signal, number of bits we need to represent. MSE measures the average of the squares of the errors which should be as low as possible for proper diagnosis of ECG signal. It is calculated using Eq. (10).

Entropy is the measure of randomness of the signal. Maximum is the entropy, maximum will be the randomness of the ECG signal which helps in proper diagnosis of ECG signal. Entropy measures the complexity from a relatively small amount of data. It is calculated using Eq. (11). Standard Deviation (SD) measures the amount of variation from the average. Low SD means the recovered signal is very close to the expected signal.

Table 1 Performance analysis of DWT, SG and SG smoothing

Type of algorithm	SNR (dB)	PSNR (dB)	MSE	SD	Entropy	Ratio of squared norms
Original ECG	80.55	1.05	5.1	251.02	0.18	0.604
DWT	80.59	1.07	5.07	251.21	0.199	0.6048
SG filter	81.65	2.415	3.72	260.05	0.39	0.7803
SG smoothing	81.75	3.63	1.101	170	0.45	0.8308

Ratio of squared norms is the ratio of squared norms of the recovered ECG signal to the input signal. The tabular analysis indicates that the reconstructed ECG signal obtained from SG smoothing has high SNR, high PSNR, minimum MSE, high entropy and minimum standard deviation.

$$SNR = 10\log\left\{\frac{\sum_i x_i^2}{\sum_i d_i^2}\right\} \tag{8}$$

where d_i = Root mean square amplitude of noise,
x_i =Root mean square amplitude of signal.

$$PSNR = 10\log_{10}\left(\frac{MAX^2}{MSE}\right) \tag{9}$$

where MAX= maximum possible value of the signal

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left[s(n) - n(n)\right]^2 \tag{10}$$

Where $s(n)$ is the original signal and n(n) is noisy signal.

$$ENT_{\log j,n} = \sum_{i=1}^{N} x_{j,n,i}^2 \tag{11}$$

Where j=beat number, n=decomposition level, N=sample size, i=sample number.

CONCLUSIONS

Analysis of noisy and filtered ECG signal reveals that Savitzky Golay filter with smoothing reduces white noise properly. The analysis of different performance parameters SNR, PSNR, Entropy, SD, MSE, frequency spectrum and convergence reveal that SG filter with smoothing is more appreciable for removing noise from ECG signal. Further application of the SG smoothing filter by reducing the polynomial degree can be done to increase the signal to noise ratio (SNR).

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