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Filtering Frameworks for Removing Noise and Baseline Wander in ECG Signal

S. M. Walke [1*], Dr. R. S. Deshpande [2]

[1,2]Department of Electronics and Telecommunication, VishwakarmaInstitute of Information Technology, Pune, Maharashtra, India

Abstract:Electrocardiogram (ECG)is the most basic biosignal tool in automated wireless patient monitoring system to diagnose and measure the electrical activity of the heart. Automated wireless patient monitoring system demands wireless and noise-free ECG signal transmission foraccurate diagnosis of cardiovascular diseases (CVDs). Noise is evidently present in wireless systems and eliminating noise from the original signal becomes essential for effective and accurate detection of ECG signal. Several techniques have been developed for effective filtering of ECG signal. In this article, we present different filtering frameworks for removing noise of ECG signal. Here, four filters, namely: Butterworth, Chebyshev, Elliptical and Savitzky-Golay have been implemented for noise extraction using MATLAB simulation software on ECG signals from various databases for their performance analysis. Further, detrends in the ECG signal generated due to baseline wander has been removed using a low order fit polynomial. Average SNR values of Savitzky-Golay filtered ECG signals shows best performance in noise removal as compared to other filters.

Keywords- Noise, baseline wander, Savitzky- Golay filter, MATLAB

I. Introduction

Advances in wireless technology have shown that wearable devices for patient monitoring will be the next revolution. With revolutionary and miniaturized sensors, wireless patient monitoring will provide a new dimension in health care services. In fact, existing sensors/transducer in patient monitoring systems are able to collect various physical real-time parameters such as temperature, heart rate, respiration rate or blood pressure and transmit them over a wireless medium [1]. An Electrocardiogram (ECG) is one such most vital and useful bio-signal that determines the state of cardiovascular system.ECG signal represents the time domain surface potentials of human body obtained by placing electrodes originating from heart of a cardiac patient [2].

Transmitting an ECG over a wireless transmission medium can be subjected to various noise interference's and artefacts' such as flat line (FL) causedby the electrode disconnection, abrupt changes (AC) occurring from the physical activities, muscle artefact's raised from the muscle contraction, power line interference (PLI) and recording instrument noise (RIN) which can corrupt the signal, which can alter the fundamental information of the signal thereby compromising accurate analysis and correct diagnosis of the patient [3]. Baseline wander (noise) is one such example of noise in ECG which can result from various factors such as inhalation and exhalation, variation in impedance of the measuring electrode and excessive physical activities or movements [4]. Unless we effectively remove these noise(s) from the ECG signal the accuracy of extracted features from ECG will be never be guaranteed.

Accurate analysis of cardiovascular disease demands rapid recognition of various fiducial points – namely the P-wave, the QRS complex and the T- waves (as shown in Fig. 1).Any change in amplitude, duration or shape of these fiducial points can indicate an arrhythmia. An arrhythmia if not treated in its early stage can result in a cardiac arrest.

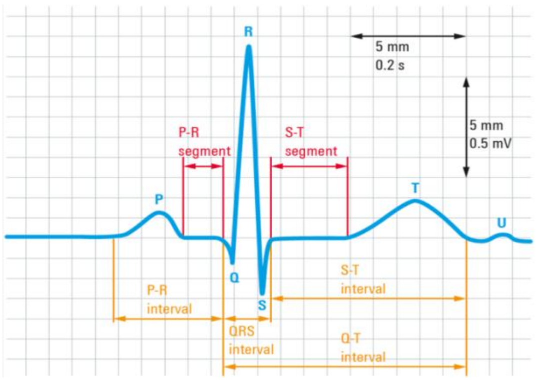

Fig. 1 ECG signal and its fiducial points

Noise in wireless systems can alter the amplitude/ duration or shape of the ECG signal resulting in false detection of an arrhythmia. This can result in improper treatment due to improper diagnosis of ECG signal compromising patient's health. Hence, effective extraction of noise is needed in wireless patient monitoring system.

II. Related Work

ECG signals when transmitted over wireless medium demand error-free transmission of the signals. Noise in the wireless channel can alter the signal (change the amplitude, duration or shape) thereby causing inaccurate feature extraction of the ECG signals resulting in improper diagnosis.Sensitivity and prediction accuracy depends on effective noise removal from the ECG signal. Over the decade significant research efforts have been devotedto increasing sensitivity and prediction accuracyfor the analysis of ECG signal and arrhythmia detection. Several algorithms have been developed for ECG signal filtering using wavelets have been reported in [5]-[7], using linear filtering in [8]-[10] and using modifications on methods of empirical mode decomposition in [10], [11]. More effective filtering methods use adaptive filters have been reported in [12]-[14].

In this paper, performance analysis of four filters namely- Butterworth, Chebyshev, Elliptic and Savitzky-Golay is computed in terms of average SNR. Further, baseline wander is removed by implementing a fit a low order polynomial technique. The simulation is carried out simulation software MATLAB and performance analysis is evaluated by testing 128 ECG signals across three databases.

III. Filters For Ecg Signal Denoising

Digital FIR filters are commonly deployed to remove the baseline wander and noise in the ECG signal. The cut of frequency and phase response characteristics are two main design factors to be considered while designing FIR filters. FIR filters can be easily implemented using appropriate hardware making them popular for denoising ECG signals. However, the main limitation of the FIR filter is that they require high order filters for achieving a given level of performance. IIR filters, on the other hand, are complex when hardware implementation is considered. However, they can be implemented using very low order filters to achieve the same level of performance as achieved by FIR filers. Here, we have discussed different IIR filters commonly used for ECG signal filtering:

a) Butterworth filter: Butterworth filters have been used because of excellent flat (smooth) magnitude response in the passband and overallmonotonic response. However, thisflat response comes at the price of decreased roll-off in steepness [15]. The magnitude response of Butterworth low pass filter is given by:

$$|H(j\Omega)| = \frac{A_v}{\left[1+\left(\frac{\Omega}{\Omega_c}\right)^{2N}\right]^{0.5}} \quad \text{...(1)}$$

Where Av is the filter gain

Ω_c is the 3dB cut off frequency

N is the filter order

In the factorized form the transfer function of the Butterworth filter is given by:

$$H(s) = \prod_{K=1}^{N/2} \frac{b_k\Omega_c^{\ 2}}{s^2 + b_k\Omega_c s + c_k\Omega_c^{\ 2}} \quad \text{...(2)}$$

For N = even

$$H(s) = \frac{b_0\Omega_c}{s + c_0\Omega_c} \prod_{K=1}^{N-1/2} \frac{b_k\Omega_c^{\ 2}}{s^2 + b_k\Omega_c s + c_k\Omega_c^2} \quad \text{...(3)}$$

For N = odd

Where the coefficientsb_k and c_k are given by:

$$b_k = 2\sin[(2k-1)\pi/2N] \quad \text{...(4)}$$

And $c_k = 1$ ...(5)

b) Chebyshev filter:Chebyshev filters, on the other hand,haveequi-ripple characteristics in the passband and monotonic in the stopband. Chebyshev Type 1 filters offer faster roll-off than Type 2 filters, however can cause greater deviation from unity in the passband [16].

The magnitude response of Chebyshev low pass filter is given by:

$$|H(j\Omega)| = \frac{A_v}{\left[1+\xi^2 C_N^2\left(\frac{\Omega}{\Omega_c}\right)\right]^{0.5}} \quad \text{...(6)}$$

Where Av is the filter gain, ξ is constant and Ω_c is the 3dB cut off frequency.

In the factorized form the transfer function of the Chebyshev filter is given by:

$$H(s)=\prod_{K=1}^{N/2}\frac{b_k\Omega_c^2}{s^2+b_k\Omega_c s+c_k\Omega_c^2} \quad ...(7)$$

For N = even

$$H(s)=\frac{b_0\Omega_0}{s+c_0\Omega_c}\prod_{K=1}^{(N-1)/2}\frac{b_k\Omega_c^2}{s^2+b_k\Omega_c s+c_k\Omega_c^2}$$

...(8)

For N = odd

The coefficients of b_k and c_k are given by:

$$b_k = 2Y_N \sin[(2K-1)\pi/2N] \quad ...(9)$$

$$c_k = Y_N^2+\cos^2\frac{(2K-1)\pi}{2N} \quad ...(10)$$

$$C_0 = Y_N \quad ...(11)$$

Where

$$Y_N=\frac{1}{2}\left\{\left[\left(\frac{1}{\xi^2}+1\right)^{0.5}+\frac{1}{\xi}\right]^{1/N}-\left[\left(\frac{1}{\xi^2}+1\right)+\frac{1}{\xi}\right]^{-1/N}\right\}$$

...(12)

c)Elliptic filters: Elliptic filters, on the contrary, offer steeper roll-off responseas compared to Butterworth or Chebyshev filters. However, these filters have equiripple characteristics both in the passband and the stopband. In general, elliptic filters meet given performance specifications with the lowest order of any filter type [17].

The magnitude squared response of Elliptic low pass filter is given by:

$$|H(j\Omega)|^2=\frac{1}{1+\xi^2U_N\left(\frac{\Omega}{\Omega_c}\right)} \quad ...(14)$$

Where $U_N(x)$ is the jawbain elliptic function of order N

And ξ is the constant related to the passband ripple.

d)Savitzky-Golay filters:Savitzky-Golay smoothing filters are typically used to smooth out the noise from signals that have relatively higher frequency spans. This type of filter is particularly best suited in these application scenarios as ECG signals have a relatively higher frequency span. Also, Savitzky-Golay filters provide much better smoothing as compared to standard averaging FIR filters, which have a tendency to filter out a substantial portion of the signal's high-frequency content along with the noise [18]. Savitzky-Golay hence effectively preserve high frequency components of the ECG signal however are less effective in noise rejection as compared to standard averaging filters. Savitzky - Golay filters can minimize the least-squares error by fitting a polynomial to frames of noisy data [19]. Here, we have used a finite impulse response (FIR) SavitzkyGolay filter of order = 7 and frame length= 21.

Iv. Baseline Wander Removal Using Fit A Low Order Polynomial

As stated earlier, in practice, baseline wanders in an ECG signal can result from various factors resulting in inaccurate analysis of ECG signal due to ECG signal degradation and PQRST complexities [3]-[4]. Unless we effectively remove the baseline wander from the ECG signal the accuracy of extracted features from ECG will be compromised and in return will provide inaccurate diagnosis. Several researchers have proposed various techniques to remove detrends from the ECG signals [11]. However a common technique consists of using a low order fit polynomial function to remove detrends from the signals.

Algorithm I: Fit low order polynomial for removing baseline wander in ECG signal

I. **Read** the ECG signal

II. Calculate least-square fit polynomial coefficient (p), error estimation structure (s) and centering and scaling values (μ)

III. Calculate the polynomial (y) p at each point on the ECG signal using the scaling values (μ)

IV. Remove the detrend by subtracting the polynomial (y) from the original ECG signal

V. **Methodology**

a) ***ECG signal Database:***

The ECG data sets are downloaded from Physionet.org. PhysioNet offers free web access to large collections of recorded physiologic signals (PhysioBank). PhysioNet is supported by the National Institute of General Medical Sciences (NIGMS) and the National Institute of Biomedical Imaging and Bioengineering (NIBIB).We have downloaded three datasets the details of which are listed in Table I:

TABLE I: ECG signal dataset

Sr. No.	ECG Dataset	ECG ID	No. recc
1	CU Ventricular Tachyarrhythmia Database(CUDB)	cuo1 to cu35	35
2	MIT – BIH Arrhythmia Database (MITDB)	100, 101, 102, 103, 104, 105, 106, 107, 108,109, 111, 112, 113, 114, 115, 116, 117, 118, 119, 121, 122, 123, 124, 200, 201, 202, 203, 205, 207, 208, 209, 210, 213, 214, 215, 217, 219, 220, 221, 222, 223, 228, 230, 231, 232, 233, 234	47
3	MIT – BIH Malignant Ventricular Ectopy Database (VFDB)	418,419, 420, 421, 422, 423, 424, 425, 426, 427, 428, 429, 430, 602, 605, 67, 609, 610, 611, 612, 614, 615	22

b) Signal filtering: The ECG signals are pre-processed by filtering them using all the four filters described earlier to remove or extract any noise present in them. The filtered signals are further applied to a fit low order polynomial to remove baseline wander present in the signal. For testing the performance of the filters and baseline wander filter we have used 128 ECG signals from various databases mentioned in Table I. Choosing ECG signals from various databases ensures that the obtained results are valid and applicable along with all databases. The performance of different filters is measured in terms of average SNR before and after filtering.

IV. Results And Discussion

Fig2 shows the filtered signals for cu01.mat signal of the CU Ventricular Tachyarrhythmia Database (CUDB) database. As observed almost all the filters have efficiently eliminated noise from the ECG signal. A small variation in R-peak amplitudes and position in the filtered signal can be observed as shown in Fig2. Savitzky-Golay filter has efficiently filtered the noisy ECG signal without significant variation in R-peak amplitude and position.

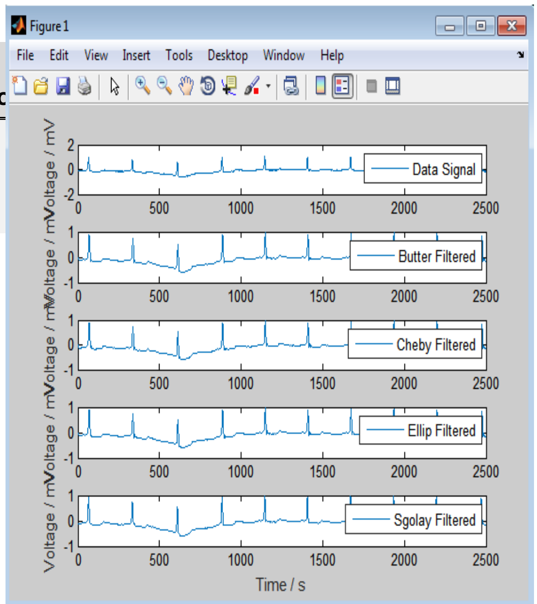

Fig. 2 Original Signal and All four filtered signal

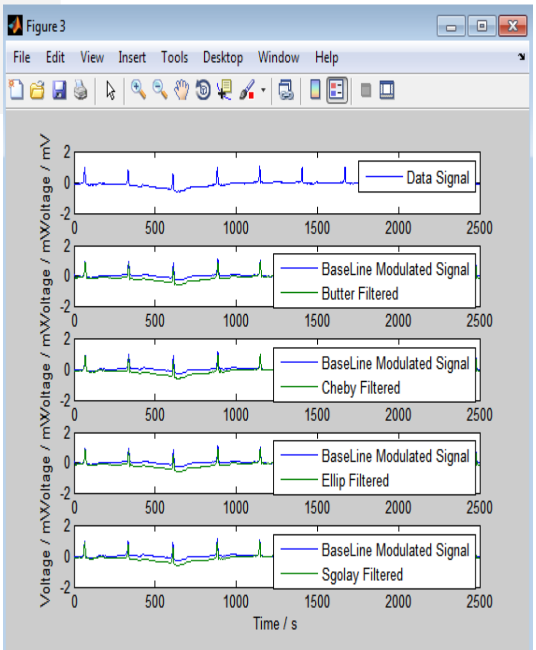

Fig. 3 Baseline wander removal using fit a low order polynomial detrends

As discussed earlier, a baseline wanders noise can cause a baseline shift in the original ECG signal and therefore does not represent the true amplitude. In order to remove the trend, fit a low order polynomial detrend is used to remove the baseline shift. Figure 3 shows the baseline drifting of the filtered signal. It can be seen that using the detrending method the filtered signal is shifting to the baseline signal. Table II shows the average SNR computed for various filters before and after filtering.

Table II: Average SNR values before filter application and after filter application

Sr. No	Data-base	ASNR before filter application	ASNR after filter application			
			Butterworth	Chebyshev	Elliptic	Savitzky-Golay
1	CUDB	0.199	0.20	0.21	0.19	0.22
2	MITDB	17.79	18.58	17.80	18.22	21.23
3	VFDB	0.174	0.174	0.176	0.174	0.19

V. Conclusions

In this paper, an efficient filtering framework using adaptive filtering for removing noise in an ECG signal has been investigated. Four different adaptive filters have been implemented for denoising the ECG signals. The investigation is carried out on signals from three different databases. The average SNR values for all four filtered signals are shown in Table II. As observed, Savitzky-Golay filtered signals provide better SNR values as compared to rest of the other filters. Furthermore, a low order fit polynomial was implemented to remove the baseline wander present in the ECG signal.

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