Pre-processing of ECG signal based on multistage filters

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Abstract—In this paper, a new approach was adopted in order to remove the artifacts present in the raw ECG signal. To realize this process, a multiple types of filters for a variety of types of noises have been applied to obtain the lowest possible noise. Initially, the ECG signal was filtered from the electromyography signal, and then the filtered signal was passed again on another filter for the purpose of removing its drift from the baseline. The effectiveness of the suggested approach has been assessed in comparison to the conventional ECG signal. Results of this study showed significantly less signaling noise than was present in the conventional signal. Overall, the signal to noise ratio and the mean square error of the filtered ECG reached 15.72 and 0.006, respectively, in the filtered signal of one of the ECG recordings.

Index Terms—electrocardiogram signal, baseline wander noise, electromyogram noise.

I. INTRODUCTION

Currently, one of the main causes of death worldwide is heart disease and heart failure. The World Health Organization (WHO) estimates that complications and heart disease account for 17.9 million annual fatalities [1-3]. As a result, an appropriate and clear measurement or examination method is required for the analyst to diagnose the human heart. Electrocardiogram (ECG) signals are an interpretation of the electrical activity of the heart over a specific time period and are widely used to diagnose and understand heart conditions [4]. The ECG signal is considered a relatively weak signal because its voltage typically ranges from 0.1 mV to 2.5 mV [5]. The weakness of this signal inevitably leads to distortion and immersion of its features, which has a significant impact on the results of the diagnosis. In addition, such applications are widely used in 5G networks [6, 7]. Therefore, processing the ECG signal by eliminating the noise associated with the original signal is necessary to preserve its characteristics from fading and loss.

The P wave, the QRS complex, and the T wave make up the ECG signal, which is depicted in Figure 1, and are used to check for various heart problems [8]. The ECG signal is a visual depiction of cardiac activity used to check for heart problems. As illustrated in Figure 1, this signal consists of the P wave, the QRS complex, and the T wave. Each portion of this wave contains information that is critical for the treating physician to make an accurate diagnosis. The faint and low frequency of the ECG signal, which spans from 0.5 Hz to 200 Hz, makes it very susceptible to interference from outside sources [9].

Abnormalities in the raw ECG signal include baseline wander noise, power line interference, and Electromyogram (EMG) noise. Body movement, respiration, and incorrect electrode connections are among the most common causes of signal deviation from the baseline [10]. The frequency of the baseline wander noise ranges from 0.1 to 0.5 Hz. However, this noise complicates peak detection because, due to wander, the T peak is higher than the R peak, resulting in peak detection errors [11]. Furthermore, the ECG signal is heavily influenced by EMG noise due to direct interference with the QRS complex [12]. It is possible that this interference extends to higher frequencies and is not just restricted to the QRS complex because the EMG frequency ranges from 100 to 500 Hz [13]. This form of noise is primarily caused by contractions of muscles other than the heart muscle, brought on by the patient’s movement.

In order for the physician to accurately and correctly assess and interpret the ECG signal, it is vital to reduce this kind of noise. This paper thus presents a cascaded filter capable of filtering the ECG signal from the baseline wander noise and the EMG signal to reach the minimum noise while ensuring that no information is lost from the original signal. To achieve this, the first step of the processing involves filtering the raw signal from EMG noise and then using a zero phase shift filter to eliminate the ECG signal from the baseline drift noise. The performance of the suggested cascaded filter can then be examined, and a number of evaluation metrics, including the Signal to Noise Ratio (SNR), Mean Square Error (MSE), and Power Spectral Density (PSD), can be examined to determine the effectiveness of the suggested method in terms of reducing signaling noise.

II. LITERATURE REVIEW

In recent years, various signaling noises on ECG signals have prompted several researchers to attempt to develop methods to reduce this noise. Thus, signal processing is essential for reducing noise on pertinent ECG signals and enhancing their effectiveness and quality [14]. In light of this,
in 2017, R. Qureshi et al. [15] adopted a multistage adaptive filter for the ECG signal that at each stage eliminated a specific type of noise. The filter has two stages: the first stage eliminates baseline drift and the EMG signal, while the second stage does the same for power line interference. The SNR, convergence rate, and temporal complexity were calculated in order to evaluate the performance of the suggested technique. Based on the findings, it was determined that the proposed technique enhanced the ECG signal's quality.

S. O. Gilani et al. employed the notch filter, band stop filter, and Least-Mean-Square (LMS) filter in order to de-noise the ECG signal [16]. To evaluate the effectiveness of the filters employed for noise reduction, various metrics, such as settling time and inaccuracy relative to the pure ECG signal, have been used. Their results demonstrated that the LMS filter outperforms other filters at removing noise from ECG signals.

M. C. Saxena et al. presented a comparative analysis between Finite Impulse Response (FIR) filters and Infinite Impulse Response (IIR) filters with the aim of accurately showing the ECG signal [17]. The effectiveness of the employed filters has been evaluated in terms of removing high noise frequencies and low noise frequencies from the ECG signal. Moreover, the FIR and IIR standard deviations were examined. The findings show that the IIR filter output is less than the needed output, whereas the FIR filter output is extremely near to the required value and has a minor removal of high-frequency and low-frequency noise. Additionally, it was shown that the output standard deviation of the FIR filter with high frequency noise has a lower value than that of the IIR filter and that the output standard deviation of the IIR filter is significantly closer to the desired output.

R. Q. Zia-ul Haque et al. looked into a number of techniques for eliminating high frequency noise from the ECG signal [18]. Several adaptive filtering algorithms have been evaluated, including least mean square, Normalized LMS (NLMS), Log LMS, and Sign LMS. In addition, the SNR, convergence rate, and computation time were calculated to assess the performance of the filters used. The obtained results demonstrate that the NLMS algorithm can achieve higher SNR at a higher computational complexity cost than the Sign LMS algorithm, which is computationally efficient.

D. Zhang et al. proposed a sub-band smoothing filter that selects the wavelet coefficients that require noise removal based on wavelet energy while leaving the other coefficients unchanged [19]. The proposed approach's performance was assessed using the Signal-to-Noise Ratio (SNR), Mean Squared Error (MSE), and percent root mean square difference. This proposal showed an improvement in noise removal from the electrocardiogram signals.

Y. A. Altay et al. developed a polynomial filter of low- and high-frequency noise to improve the accuracy of signal informative parameter selection [20]. The efficiency of the proposed method was evaluated using reference samples of the ECG signal, and on the basis of quantitative indicators, it was compared with other known methods. In addition, some parts of the low-frequency and high-frequency noise were selected to evaluate the noise characteristics. It was concluded that the accuracy and the noise reduction of the ECG signal were significantly increased by using this method.

A. Mishra adopted automatic noise reduction technology by filtering the ECG signal based on the frequency and time filtering approach [21]. Several types of noise were added to many ECG signals during the evaluation of the method. The extracted results showed that this method is able to reduce the mean square error and improve the signal-to-noise ratio compared to the wavelet-based method.

M. Sraithe et al. studied a hybrid system consisting of a decomposition method followed by local means (LM) filtering in order to deal with different types of noise [22]. The effectiveness of this method was evaluated by adding different types of noise to ECG recordings with different levels of SNR for the purpose of numerical analysis of the method. In addition, several metrics such as SNR optimization, approximate entropy, fuzzy entropy, etc. were used for the purpose of this evaluation. The results show that after conducting an evaluation of the system by calculating the SNR and other parameters, it performs well in reducing noise compared to the rest of the methods used.

M. M. U. Faiz proposed eliminating the noise in the ECG signal using a four-stage cascade adaptive filter [23]. For the purpose of evaluating this method, the SNR improvement ratio was analyzed in several adaptive algorithms. The results showed an improvement in the signal-to-noise ratio by 12.7319 dB compared to other methods that use the same algorithm in the four stages.

S. Tahir proposed the use of an extended Kalman filter for the purpose of canceling out the noise associated with an ECG signal [24]. The evaluation was performed for four cases of power line interference (PLI). The proposed method was evaluated by calculating the mean squared error, frequency spectrum, and noise reduction. The findings demonstrated that in all four of the situations looked at, the suggested strategy efficiently eliminated the noise from the ECG signal.

In this paper, the raw ECG signal was processed in such a way that excessive noise on its parts was muffled. To achieve this, a multistage filter was used for the noisy ECG signal, at each stage eliminating a specific type of noise. The filtered signal was assessed and contrasted with the noisy signal and several other techniques as a first step in the feasibility analysis to see if this delivers better filtering for the ECG data. So, the remaining portions of this work are structured as follows: section III presents the suggested procedure, and section IV examines the outcomes of testing the suggested method. Some initial conclusions are drawn in Section V's conclusion.

III. PROPOSED METHOD

The proposed implementation method has been illustrated in this section in order to separate the ECG signal from the background noise. As a result, a new filtering method was put forth that uses cascading filters in both design and application. The evolution of the proposed cascade filtering
technique has been depicted in Figure 2.

![Block diagram of the proposed multistage filters.](image)

In order to proceed, the raw ECG signal must first be purified of EMG interference. In general, the frequency of the EMG signal is greater than 100 Hz, whereas the frequency of the ECG signal is primarily concentrated between 0.01 and 100 Hz. Therefore, in this analysis, a low-pass filter with the Butterworth approximation was used to remove EMG interference. This filter is distinguished by the fact that, despite its simplicity, it exhibits a flat response in the pass band with no fluctuation as shown in Figure 3. Furthermore, at the stop band, the pass range of this type of filter gradually decreases to zero. The filter order directly affects how much amplitude attenuation occurs in the stop band; the greater the filter order, the faster the amplitude attenuation.

![Amplitude and frequency response of the proposed low-pass filter.](image)

The proposed low pass filter with Butterworth approximation has been built with a cut-off frequency of 100 Hz and 1.2 dB of attenuation in the passband because the ECG signal's critical information is located in frequencies lower than 100 Hz. In addition, a zero phase shift filter was applied to the signal to prevent it from deviating from the baseline. This type of filter was used to prevent the phase of the signal from being changed after being filtered. Moreover, this filter eliminates phase distortion by utilizing the pre-and post-information of the current signal point. The efficiency of the employed filters should be assessed in terms of removing noise from the ECG signal in order to guarantee the viability of the proposed approach. Therefore, the mean squared error between the original and filtered ECG signals, as well as the signal-to-noise ratio and other quantitative characteristics, were calculated in this work.

The SNR is the ratio of the filtered signal produced by the proposed cascade filters to the noise components present in the raw ECG signal. The performance of the proposed method improves with increasing SNR. The SNR can be calculated as:

$$\text{SNR}_{\text{out}} = \frac{\sum_{n=1}^{N} (S(i))^2}{\sum_{n=1}^{N} (\text{noise}(i))^2}$$  \hspace{1cm} (1)

where,

- $\text{SNR}_{\text{out}}$: SNR of the de-noised ECG signal.
- $N$: size of the signal.
- $S(i)$: Input ECG signal.
- $\text{noise}(i) = S(i) - \hat{S}(i)$

$$\text{where,}$$

- $\hat{S}(i)$: Filtered ECG signal.

$$\text{SNR}_{\text{out}} \text{ } \text{dB} = 10 \log_{10} \text{SNR}_{\text{out}}$$ \hspace{1cm} (3)

The mean square error (MSE) describes the difference in the power of the ECG signal before and after filtering. Filter quality improves as MSE value declines. The MSE is thus calculated as:

$$\text{MSE}_{\text{out}} = \frac{\sum_{n=1}^{N} (S(i)-\hat{S}(i))^2}{N}$$ \hspace{1cm} (4)

### IV. RESULTS AND DISCUSSION

The aim of this research is to develop a method that successfully removes noise from the ECG signal. As a consequence, cascading filters with different cut-off frequencies were designed and implemented to remove the EMG signal and baseline drift from the raw ECG signal. In order to compare the proposed method with the method proposed in [25], the noisy ECG signals of records 100m, 101m, 103m, 104m, 105m and 106m come from the MIT-BIH database. Each signal of these records was then passed through a low-pass filter to remove the associated EMG noise before being passed through yet another filter, a zero-phase-shift filter, to eliminate baseline drift.

The MATLAB 2018 software package was employed in order to assess the performance of the suggested method with regard to noise removal. Furthermore, several performance parameters such as SNR and MSE, as well as Power Spectral Density (PSD), were used in this evaluation to visualize the filter's performance. The findings for this methodology were compared with the Chebyshev low pass filter method proposed by S. Basu et al. [26] in 2020 and the Cooperative filtering method proposed by B. Liu et al. [25] in 2021. Figure 4 depicts a noisy ECG signal of recordings 104m with different noise levels. As shown in the figure, the ECG signal contains clear noise from the EMG signal as well as a clear drift of the signal from the baseline.
To accurately and clearly filter this signal, the spectral distribution of power must first be studied because the power of the signal in the frequency domain appears through the spectral density of that signal. It is feasible to determine what frequency can be discarded by looking at the PSD distribution of the signal depicted in Figure 5. The EMG signal, which is noise and needs to be removed in order to clean up the raw ECG data, turns out to be frequency dependent, with all frequencies above 100 Hz being the frequencies of the EMG signal.

A low-pass filter with a Butterworth approximation and a cut-off frequency of 100 Hz has been applied to the noisy ECG signal in order to cancel the higher frequencies of the raw ECG signal (EMG noise). The filtered ECG signal of record 104, depicted in Figure 6, shows that the EMG noise has been canceled from its parts. Compared to the unprocessed ECG signal seen in Figure 4, this signal is unquestionably considerably purer. Because of that, the EMG signal's noise has already been taken out of the original ECG signal, which is why the filtered signal is clearer.

The SNR and MSE of the filtered ECG signal obtained from the Butterworth low-pass filter were calculated and compared to the primary ECG signal to assess its performance. The SNR and MSE of the ECG records from the first stage of the proposed technique have been listed in Table 1. The first stage of the proposed technique represents the signal after it has been filtered with a low-pass filter, while the second stage represents the signal after it has been filtered with a zero phase shift filter. These are acceptable results when compared to the other methods employed. Moreover, to further guarantee that the noise is effectively eliminated, the spectral distribution of the power of the filtered signal is shown in Figure 7. This distribution can be used to identify the frequencies that have been muted in various parts of the signal. When compared to the spectrum distribution of the power of the initial signal, the spectral distribution of the filtered signal reveals the level of power concentration at frequencies below 100 Hz.

The deviation of the signal from the baseline is still present in the filtered signal, which causes errors when reading the peaks by the physicist. In order to correct for this discrepancy, the filtered signal was once more passed through the zero phase shift filter. The signal handled by this filter is depicted in Figure 8.
The figure clearly shows that this drift from the baseline has been completely removed. In addition, the SNR and MSE values of the first stage (after the low-pass filter) and second stage (after the zero phase shift filter) have been verified in Table 1.

Table 1. The performance of multistage filters in term of SNR and MSE of different ECG records

<table>
<thead>
<tr>
<th>Proposed Method</th>
<th>SNR of 100m</th>
<th>MSE of 100m</th>
<th>SNR of 104m</th>
<th>MSE of 104m</th>
<th>SNR of 106m</th>
<th>MSE of 106m</th>
</tr>
</thead>
<tbody>
<tr>
<td>First stage</td>
<td>12.015</td>
<td>0.1017</td>
<td>12.32</td>
<td>0.049</td>
<td>8.282</td>
<td>0.055</td>
</tr>
<tr>
<td>Second stage</td>
<td>13</td>
<td>0.008</td>
<td>15.72</td>
<td>0.006</td>
<td>13.04</td>
<td>0.024</td>
</tr>
</tbody>
</table>

Table 2 presents the results of the proposed method compared to other methods in terms of SNR. As can be seen, the proposed method outperforms other methods in terms of SNR. The results that have been listed in this table are the best results for each method. Furthermore, Figure 9 shows how the proposed architecture performs well in comparison with cooperative filtering and without cooperative filtering proposed by B. Liu et al. [25].

Table 2. A comparison between the proposed technique and other techniques in terms of SNR

<table>
<thead>
<tr>
<th>Techniques</th>
<th>Signal to noise ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chebyshev Low Pass Filter</td>
<td>11.96</td>
</tr>
<tr>
<td>Without cooperative filtering [25]</td>
<td>8.5</td>
</tr>
<tr>
<td>Cooperative filtering [25]</td>
<td>12</td>
</tr>
<tr>
<td>Proposed multistage filters</td>
<td>15.72</td>
</tr>
</tbody>
</table>

In this work, a new ECG signal filtering method was proposed as a possible contender for expanding heart status screening systems. The adopted filtering method makes use of low-pass and zero phase shift filters as a design domain. Various parameters, including SNR, MSE, and power spectral density, were taken into account in order to test and assess the signaling noise. In comparison to the conventional signal, the suggested approach enhances the signal's purity and cancels its regression from the baseline according to the findings of these inquiries. The proposed method's testing indicates that it has the potential to lower the overall signaling noise in the ECG signal. It was also shown, using two separate filtering scenarios, that using a low-pass filter increased one ECG recording's SNR to 12.32 dB, while using a zero phase shift filter increased it to 15.72 dB. In light of these results, the presented cascaded filters likely perform well in respect of lowering total signaling noise on the ECG signal components and so give a fresh approach for the new heart status screening systems.

REFERENCES


