Design and implementation of IIR Notch filter for removal of power line interference from noisy ECG signal

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Abstract
In Digital signal processing , IIR notch filter used to remove an unknown noise component in ECG signal lying within a 60 Hz frequency range. This paper gives the design appropriate signal processing algorithms for the refinement of ECG signals so that their characteristics may be extracted: this involves the design of a digital filter for the elimination of the power line interference and determines the waveform characteristics (PR, QRS and ST intervals and PR and ST segments) of the available ECG recording. Comparison of these characteristics with those of normal ECG recordings provides a way of identifying problems with the human cardiovascular system.

Keywords
ECG signals, Infinite Impulse Response (IIR) Notch Filter.

1. INTRODUCTION

electrocardiogram (ECG) signal is some index of the functionality of the heart. For example, a physician can detect arrhythmia by studying abnormalities in the ECG signal. Since very fine features present in an ECG signal may convey important information, it is important to have the signal as clean as possible [1]. Figure 1 shows a clean ECG signal. Power line interference is easily recognizable by interfering voltage in the ECG may have frequency 50/60 Hz [2].

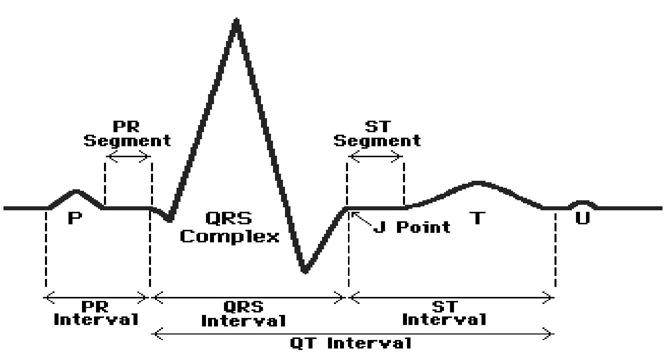

Figure 1: ECG Signal.

In this graph Q is the bottom starting point, R the top point, and S the bottom end point of the QRS Complex. Atrial contraction starts in the P-wave and continues throughout the PR interval. The blood is pumped into the ventricles and the ventricular pressure rises. Ventricular contraction begins at R which corresponds to the peak of the QRS complex, and continues during the ST segment and T-wave [14].
The mitral and bicuspid valves close due to increase in ventricular pressure. At R, the closing valves produce the heart sound. Between point R and S ventricular pressure increases greatly since the semi lunar valves are still closed and there is no blood flow. The semi lunar valves open at S when the ventricular pressure equals the aortic pressure. The ventricular contraction forces blood into the aorta and there is an increase in both aortic and ventricular pressure. The blood is pumped from the ventricles and is carried away in the aorta. Ventricular pressure drops. When the pressure drops below aortic pressure, the semi lunar valve shuts. After the T-wave the ventricular pressure falls below atrial pressure and the mitral and bicuspid valves open up [14].
The interference may be due to stray effect of the alternating current fields due to loops in the patient's cables. Other causes are loose contacts on the patient's cable as well as dirty electrodes. When the machine or the patient is not properly grounded, power line interference may occur. Figure 2 shows such a polluted ECG signal [1].

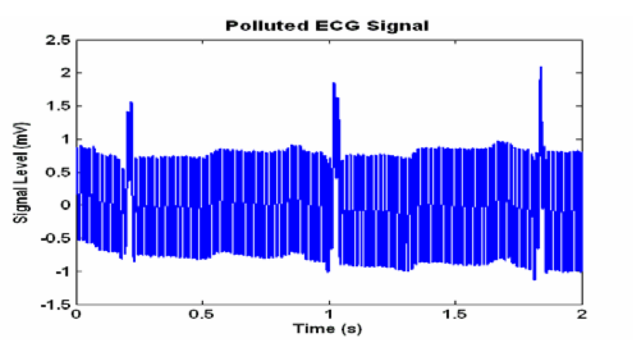

Figure 2: ECG Signal polluted by power line interference noise.

In this paper, the processed ECG waveforms were taken from the MIT-BIH Arrhythmias Database and Mat lab help from the math work to design [12] and write code for design IIR notch filter to remove power line noise from ECG. The ECG signal we used is real clinical data and has been sampled at fs = 360Hz for a period of just over 10 seconds. The ECG signal we began with is plotted in the time domain with correct time

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axis along with the signal's FFT with correct axis as well [13]. The results are seen in Figure 3.

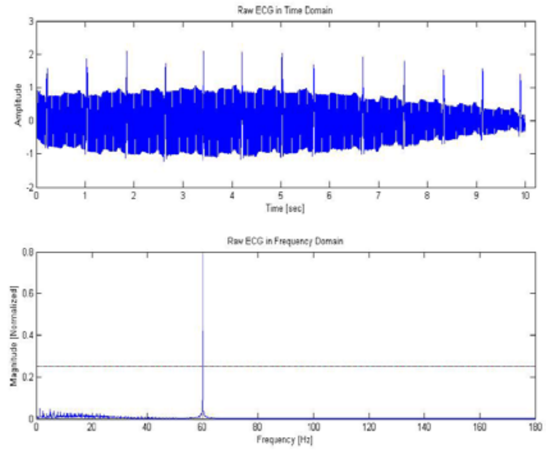

Figure 3: ECG signal in time domain and frequency-domain.

The average power spectrum of the ECG was computed as well and plotted on the same axis as the FFT of the ECG in Figure 3 as well. This gives a very clear picture of the nature of our interference; that of a simple 60Hz sinusoid [1, 2].

This design project is to leverage our knowledge of digital signal processing to remove an unknown noise component in a medical Electrocardiogram (ECG) signal. We begin by finding the Fast Fourier Transform (FFT) of our ECG signal. From the information gained by plotting the FFT of the ECG signal in the frequency-domain we proceed to design digital filters to remove this interference. The filter is an infinite impulse response (IIR) notch filter [3, 5]. We examine the filter's amplitude and phase response which is followed by a discussion of the filter's effectiveness and practical consideration. We then examine the ECG signal both in the time and frequency domain after the notch filter is applied. In the IIR notch filter effectiveness and practical considerations are discussed and the filtered data is examined in both the time and frequency domain. Upon having a clean ECG signal the quantative properties of the data are determined from the IIR filtered ECG signal. This includes the PR, QRS and ST intervals along with the PR and ST segments. Lastly we discuss a method for automating extraction of the aforementioned intervals [6].

2. PROCEDURE OF IIR NOTCH FILTER DESIGN

The first filter designed for the task of removing the noise from our signal is an IIR notch filter [12]. A notch filter lends itself quite well to this task considering that we are interested in removing a very specific, narrow band of frequencies. Equation 1 was the transfer function used to implement the filter where the filter coefficient, b_0 is given by Equation 2. The center frequency of the filter, F_0 was chosen to be at exactly 60Hz and the bandwidth, ΔF = 4Hz.

$$\text{Hnotch}(z) = \frac{b_0(z^2 - 2\cos(\theta)z^{-1} + z^{-2})}{1 - 2r\cos(\theta)z^{-1} + r^2 z^{-2}} \quad \ldots (1)$$

$$b_0 = \frac{|1 - 2r\cos(\theta) + r^2|}{2\,|1 - 2r\cos(\theta)|} \quad \ldots (2)$$

Where θ and r are given in Equation 3 and 4 respectively.

$$\theta = \frac{2\pi F_0}{f_s} \quad \ldots (3)$$

$$r \approx 1 - \frac{\Delta F_\pi}{f_s} \quad \ldots (4)$$

The magnitude and phase plot of this filter are shown in Figure 4. An IIR notch filter offers the very best of what IIR filters have to offer; very high attenuation with a low order. The notch filter presented is of order two and has only one coefficient. These properties lend themselves to being a light computational load. This high attention along with a narrow stop band can easily be seen in the magnitude plot of the notch filter [4]. IIR filters are not linear phase filters and this is shown by the severe phase shift primarily around the stop band of the filter as seen in phase plot of Figure 4.

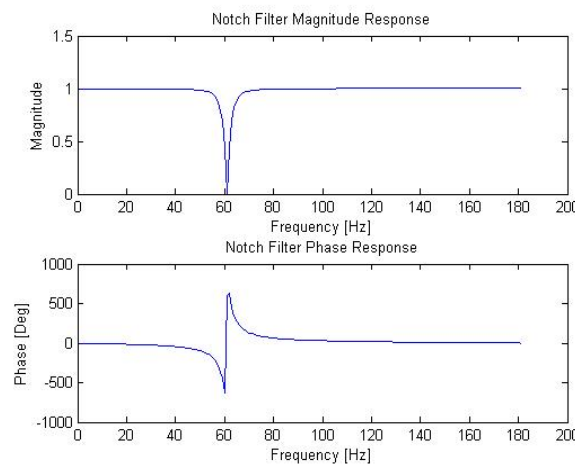

Figure 4: Notch filter magnitude and phase plots.

This could pose a problem for this application given the importance of maintaining meaningful timing data. After all, the physician is primarily concerned with the time at which different peaks and waves occur at within the ECG. Looking at the notch filtered ECG signal time domain and frequency domain plot in Figure 5.

We see that in the beginning there is some oscillation which settles in the first half second or so. All the noise seems to be removed quite effectively after the oscillation has settled. It's important to note that IIR filters are also not stable and so it is possible for our filter to begin oscillating indefinitely, luckily that is not the case. We must keep this in mind however. Looking at the plot of the filtered signal in the time domain we see that the noise has been brought to an extremely low level because the amplitude's scale is now from 0.00 to 0.05 whereas before it was from 0.00 to 0.80. This would all seem to indicate that IIR notch filter is quite a good choice for this application [8, 9].

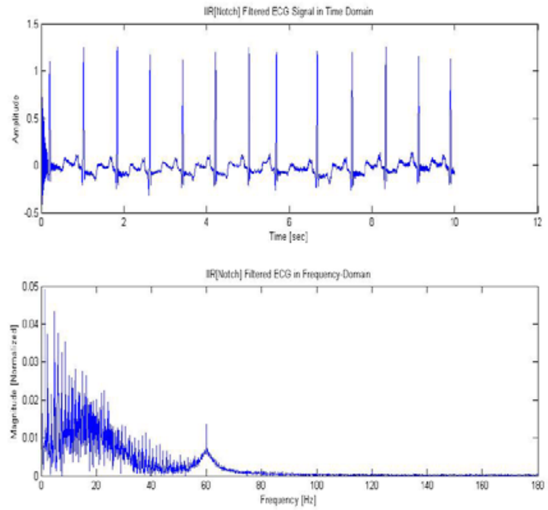

Figure 5: Time and frequency domain plots of ECG signal filtered with IIR notch filter.

3. RESULTS

After closely examining an IIR notch filter, we found the IIR to perform best overall. Although the IIR filter's phase response is non-linear, almost all of the non-linearity occurs within the stop-band. This would seem to indicate that it's shifting the phase of frequencies we're not interested in anyway. The IIR's low computation cost is also of importance especially if you're looking at implementing some sort of noise filter for an actual piece of medical equipment. This implies finite computational resources and keeping costs down [10]. The IIR filter achieves both of these goals while still delivering a high quality filtered signal. The analysis of filter in time domain and frequency domain you can see in Fig.5.

It is important to note though that upon closer inspection of the two signals in the time domain it appears that they do differ relatively significantly [7]. The biggest difference is the shift in time. Specifically the Q peak of the notch filter appears to be at ~1.85 seconds. It would seem like if anything the notch filtered ECG data should have extra noise because looking at its FFT the 60Hz interference is not as attenuated as that of the FIR filtered ECG. The noise extracted after subtracting the filtered signal from the original input in the time domain is also shown in Figure 6.

For the notch filter, signals look drastically different. The reason for this would seem to be the highly selective nature of the notch filter versus the band-stop's fidelity to our original specification that is our specifications called for a band stop filter with a stop band of four Hertz. Its result indicates clearly that this paper give very satisfactory result for removal of power line noise in dynamic ECG signal [8, 11].

Upon having a clean ECG signal the quantative properties of the data are determined from the IIR filtered ECG signal. This includes the PR, QRS and ST intervals along with the PR and ST segments [6, 10]. Lastly we discuss a method for automating extraction of the aforementioned intervals shown in Fig. 7.

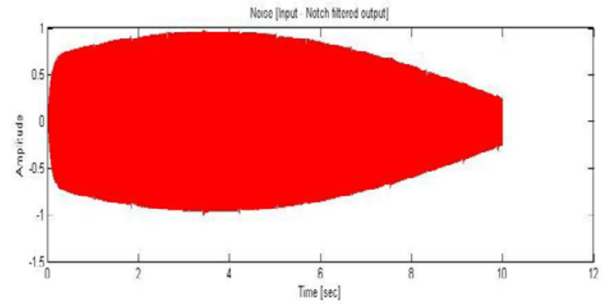

Figure 6: IIR Notch filter computed interferences.

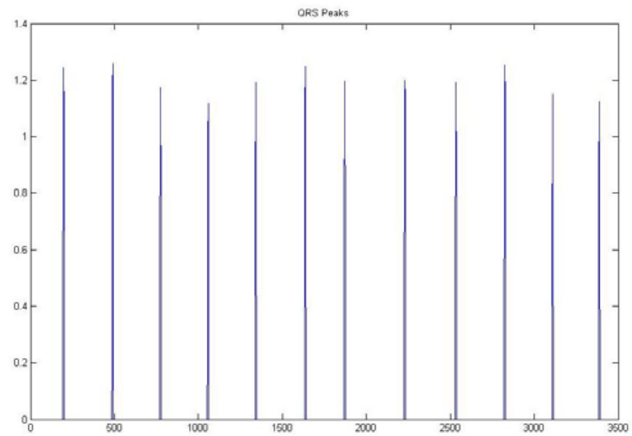

Figure 7(a). QRS Peaks

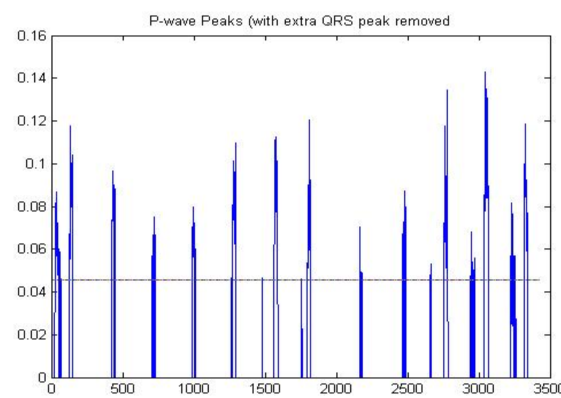

Figure 7(b). P-wave Peaks (with extra QRS peak removed)

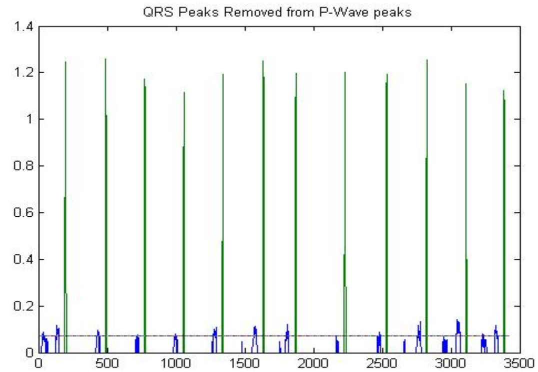

Figure 7(c). QRS Peaks Removed from P-wave Peak

Figure 7: Automating extraction of the aforementioned intervals using IIR notch filter.

Utilizing our IIR filtered ECG signal the following interval times were extracted as can be seen in Table-I.

Table-I: ECG Interval times.

Interval	Time [seconds]
PR Segment Start	0.9139
PR Segment Start	0.9861
PR Segment Start	0.0722
PR Segment Start	0.8167
PR Segment Start	0.9861
PR Segment Start	0.1694
ST Segment Start	1.0750
ST Segment Start	1.3333
ST Segment Start	0.2583
QRS Segment Start	0.9861
QRS Segment Start	1.0750
QRS Segment Start	0.0889
QT Segment Start	0.9139
QT Segment Start	1.5140
QT Segment Start	0.6001

4. CONCLUSION

This paper proposed analysis of the noise polluted signal in both the time and frequency domains we came to understand the nature of the noise. From this understanding we designed and implemented IIR classes of digital filter [7]. We compared the filtered signals produced by IIR and other filter's result and concluded that the IIR notch would be the best filter choice given the application and the likely DSP platform for actual implementation [9]. In the end much knowledge and understanding has been gained but there's always ways to improve things.

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