Removing Power Line Interference from ECG Signal Using Adaptive Filter and Notch Filter

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Abstract— **Comparison of a typical Notch filter with three adaptive filters Normalized Least-Mean-Square (NLMS), Recursive-Least-Square- (RLS) and Kalman filter for the removal of power line interference in ECG signals in both time and frequency domains. Power spectral density and spectrogram analysis are also performed. Performance parameters such as SNR, %PRD, and MSE are calculated. Real-time data from the benchmark MIT-BIH arrhythmia database was used. It has been observed that adaptive NLMS filters are more effective in power line interference reduction than adaptive RLS and notch filters.**

Index Terms— **Electrocardiogram (ECG) , Normalized Least Mean Square Adaptive Filter(NLMS), Recursive-Least-Square- (RLS), Notch Filter PSD; spectrogram, Kalman filter and Colab.**

I. Introduction

Colab, the abbreviation for "Collaboratory," is very useful tool for collaborative programming and data analysis. It gives users a cloud-based environment wherein they can write and execute code in Python directly from a web browser. Colab has become popular with data scientists and machine learning practitioners due to its ease of use and the free availability of high-end hardware like GPUs and TPUs that enable the running of compute-intensive applications.

Because Colab integrates Jupyter Notebooks, it allows for the easy sharing of code, visualizations, and explanatory text; hence, it is a very good tool to use for collaboration and reproducible research. Besides, compatibility with standard Python libraries for data science, such as NumPy and Pandas, extends its usefulness for various purposes.

A. The structure of the tool in Figure

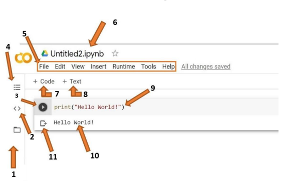

Fig.1: Colab structure.

II. Electrocardiogram (ECG) and Adaptive Filters

Electrocardiography-ECG: A graphical representation of the electrical activity of the heart is utilized to diagnose cardiac problems. The ECG electrodes are applied on the skin to monitor the electrical activity of the heart of a patient with time.

These are the signals that arise from sensors, susceptible to various distortions: baseline drift, body movement noise, and electrode movement [1].

The main interfering source is the 50 Hz power line interference contaminating the ST segment of the ECG signal within the frequency range of 0.05-100 Hz. Diagnosis of arrhythmia cannot be effectively carried out due to impairment in the ST segment. Hence, 50 Hz power line interference should be eliminated from the recordings of ECG for the diagnosis of arrhythmia [1].

Recently, adaptive filtering has become one of the effective and popular techniques for processing and analysing of ECG signal.

Different types of adaptive filters (e.g., NLMS, RLS and Kalman filters) and Notch Filter have been used to solve this problem.

A. NLMS(Adaptive-Filter):

NLMS is an adaptive filter which has a linear filter whose filter coefficients are varied according to the optimization algorithm i.e. NLMS algorithm. Firstly, the input signal (x[n]) is given to the linear filter which gives the output as y[n]. Then the error (e[n]) in the signal is calculated by finding the difference in the desired signal and the output of the linear filter. This error is then fed back to the NLMS algorithm that varies the filter coefficient of the linear filter [2].

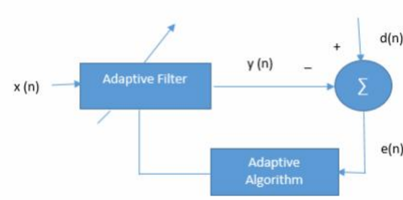

Fig.2: Block diagram of adaptive filter.

B. RLS(Adaptive-Filter):

The RLS algorithm is the fastest of all conventional adaptive algorithms, whose convergence does not depend on the input signal. However, the major drawback of the RLS algorithm is its large computational cost. Fast (small computational cost) RLS algorithms have been studied recently. In this paper we aim to obtain a faster algorithm by incorporating knowledge of the room impulse response into the RLS algorithm. Unlike the NLMS and projection algorithms, the RLS algorithm does not have scalar step-size. Thus, the variation characteristics of a ECG signal cannot be reflected in the RLS algorithm directly. In the following we study RLS algorithm from the view point of adaptive filter since (a) RLS algorithm can be regarded as one special version of adaptive filter and (b) each parameter in the adaptive filter has a physical meaning [3].

C. Kalman Filter(Adaptive-Filter):

The Kalman filter is based on a state space formulation of a continuous or discrete time system. We will limit our discussion to discrete time. The system must be linear but may be time variant. The Kalman filter gives an estimate of the state of the system given a set of outputs. For the case of Gaussian signals, and given the assumed linear model, the state estimate is optimum in the sense that it minimizes the norm of the difference between the estimate and the actual state [6].

D. Notch Filter:

Notch filters and anti-notch filters are basically notch/ bandpass filters with a very narrow stopband/ stopband and two passbands /stopbands respectively, used to block or pass specific notches of any signal wave or peak frequency. Notch filters are used to remove various types of noise such as power variation, poor grounding electrode noise, noise due to the muscle movements and other noise associated with electrodes [4].

Notch filters are designed using active components for eliminating traces of 50Hz due to their enormous advantages over passive filters and because they provide excellent low frequency filtering, which is the prime requirement in ECG signal analysis. Active filters eliminate bulky inductors so require less space, are cheap, and provide good isolation between source and load with suitable gain. In designing these filters care needs to be taken in deciding the centre frequency tuning, stability, and repeatability as selectivity and centre frequency depends on the gain.

Fig.3: Notch Filter.

III. Noise Cancellation

Noise cancellation is a process of eliminating the background noise from the actual speech stream and prevents its deterioration. The deterioration of the voice signal has many challenges in certain applications like speech recognition. Clarity and pleasantness are the aspects of measurement for the quality of a spoken signal [7].

Adaptive filters can also be used for noise cancellation. An adaptive filter can, in effect, subtract noise from the signal in real-time. The desired signal d(n) consists of noise n(n) and desired information. In Figure.4 the adaptive filter is fed a noise signal n'(n), which is not related with the original speech signal but is related to the noise signal n(n)[7].

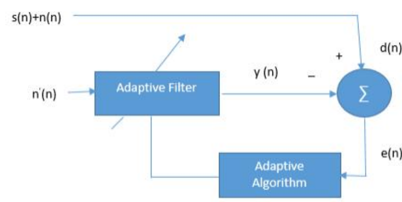

Fig.4: Block Diagram for Noise Cancellation.

The adaptive filter is a filter which adjusts the filter parameters according to some adaptive algorithm, thereby reducing the error function which is calculated as the difference between the desired signal and the output of the adaptive filter, resulting in a clean signal obtained as e(n)[7].

IV. Simulation And Results

We have analysed actual data from four patients from the benchmark MIT-BIH arrhythmia database [10], using one patient (record # 105) as a reference for the simulation results. Similarly, the same applies to other patients. In Fig. 5 shows real ECG signals without noise [8].

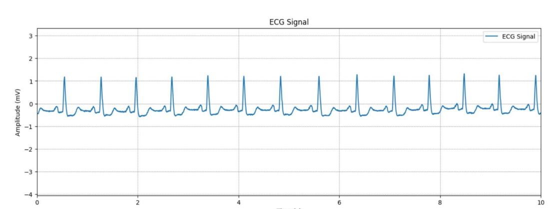

Fig.5: Real ECG Signal.

In Figure 6, you could find three modes of ECG signal after applying Notch filter, the black line shows the original ECG signal before make it noisy around 50 Hz which is shown in red line and the blue line shows the filtered ECG signal.

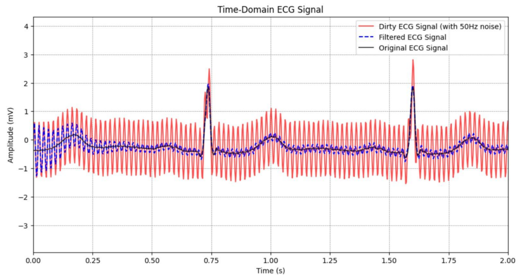

Fig.6:Notch Filter.

Figure 6 shows how a Notch Filter can be used to remove 50 Hz powerline interference from an ECG signal.

The red curve is the "Dirty ECG Signal"-that is, the raw ECG contaminated with 50 Hz noise. This noise appears as high-frequency oscillations superimposed on the ECG waveform, masking many of the critical features, such as the P-wave, QRS complex, and T-wave.

The "Filtered ECG Signal," represented by the blue dashed curve after applying the Notch Filter, is very similar to the "Original ECG Signal".

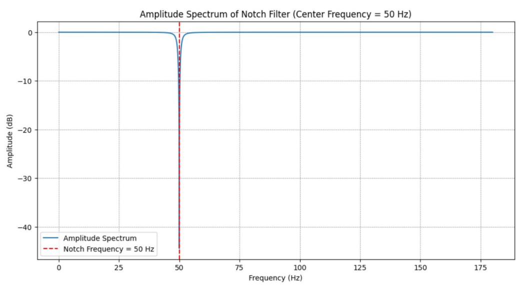

Fig.7: Amplitude Spectrum of Notch-Filter.

As shown in Figure 7, the noise was applied at 50 Hz. To be able to test the Notch filter and other filters effectively a random noise that ranges from (49.5 to 50.5)Hz was applied to the ECG signals.

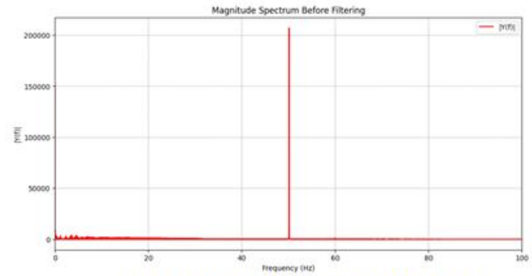

Fig.8: Magnitude Spectrum before filtering.

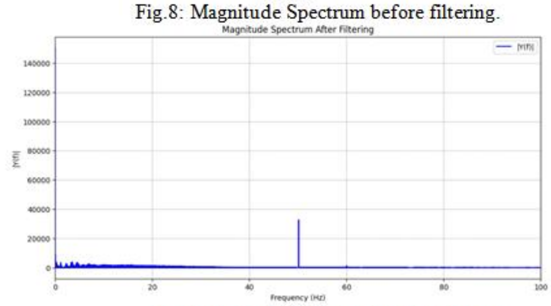

Fig.9: Magnitude Spectrum after filtering.

The two figures above illustrate the magnitude spectrum of an ECG signal before and after the application of a Notch Filter.

Figure 8 is the magnitude spectrum before filtering, with a dominant peak at 50 Hz due to the presence of powerline interference. This peak is actually noise distorting the ECG waveform and obscuring the important diagnostic features.

Figure 9 shows the magnitude spectrum after filtering. The peak at 50 Hz is significantly attenuated, meaning that the notch filter is effective in removing interference. Still, there is some noise because the filter's error margin is at ±0.5 Hz, allowing it to precisely reach just about 50 Hz. That would ensure the noise at the targeted frequency is at a minimum but can leave traces of those frequencies.

While the filter is quite effective at eliminating noise at 50 Hz, careful application of the filter must be made to prevent removal of vital ECG signal components around that frequency. Over-suppression might compromise the diagnostic integrity of the signal.

Another filter was tried but this time it was Adaptive filter-NLMS.

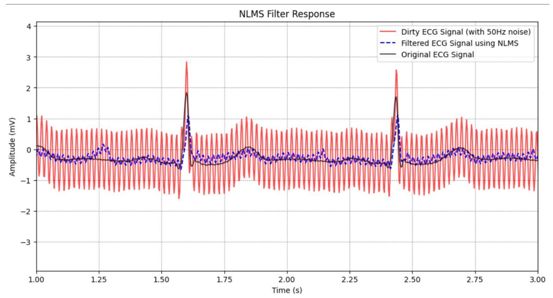

Fig.10: NLMS Filter Response.

Figure 10 presents the response of an ECG signal that has been processed using the NLMS adaptive filter. The red curve represents the "Dirty ECG Signal," which is contaminated with 50 Hz powerline interference. This noise causes significant distortion in the ECG signal, obscuring critical features such as QRS complexes and other waveform components.

The blue dashed curve plots the "Filtered ECG Signal using NLMS." The signal, after filtration through NLMS adaptive filter, suppresses the 50 Hz noise and restores a signal much like its original waveform. The adaptive nature of NLMS ensures continuous adjustment to keep up with characteristics of noise and signal.

The black curve represents the "Original ECG Signal" and serves as the baseline for comparison. It can be seen that the filtered signal is closely following the original signal, which means the NLMS filter has been able to remove noise without losing the key features of the ECG waveform.

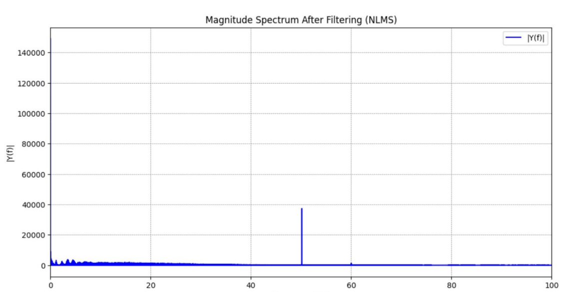

Fig.11: Magnitude Spectrum after NLMS filtering.

This figure illustrates the magnitude spectrum of the ECG signal after being filtered using the NLMS algorithm. A noticeable peak remains at 50 Hz, which indicates that the NLMS filter does not completely suppress the 50 Hz power line interference. However, the overall spectral content is smoother, and other noise components are reduced effectively.

RLS adaptive filter also have been used to solve the problem around 50Hz.

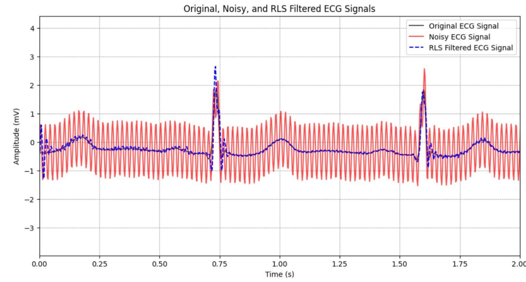

Fig.12: RLS Filter Response.

Figure depicts a sample output of an ECG signal which has been treated by the RLS adaptive filter. The red curve, that is, "Noisy ECG Signal" is infected with 50 Hz power line interference and also with a high frequency noise. The distortion brought into the ECG masks all the important features like the QRS-complexes and all other waveform morphologies.

The blue dashed curve represents the "Filtered ECG Signal using RLS." The RLS adaptive filter suppresses the 50 Hz noise and other high-frequency interferences quite effectively, thereby restoring the ECG signal to a form that is quite similar in appearance to its original waveform. This is because of the adaptive nature of the RLS filter in precisely tracking and removing the noise while preserving the key features of the signal.

The black curve represents the "Original ECG Signal" and serves as a baseline for comparison. It is seen that the filtered signal closely aligns with the original signal, proving the RLS filter has cleaned noise without losing essential characteristics of the ECG waveform.

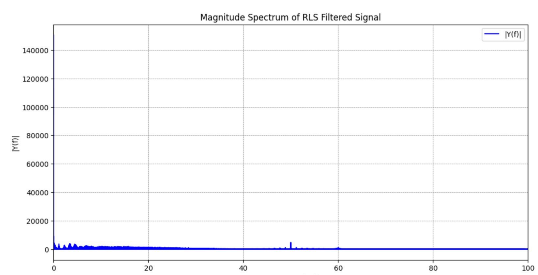

Fig.13: Magnitude Spectrum after RLS filtering.

This figure shows the magnitude spectrum of the ECG signal after filtering with the RLS algorithm. The spectrum indicates that the 50 Hz power line interference is significantly attenuated, as there is no prominent peak near 50 Hz. The RLS filter successfully reduces noise while preserving the low-frequency components critical for the ECG signal. However, some residual components are visible, indicating that the RLS filter may not completely eliminate interference at all frequencies.

The NLMS filter performs well in general noise reduction, though it may not be as effective as the RLS filter in removing specific frequency interference like 50 Hz.

The third adaptive filter we have used Kalman Filter as the following:

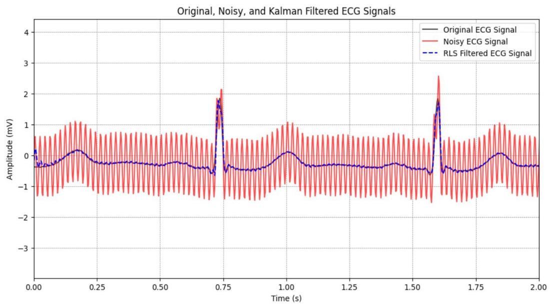

Fig.14: Kalman Filter Response.

The following figure presents the response of an ECG signal that has been processed using the Kalman filter. The red curve represents the "Noisy ECG Signal," which is contaminated with high-frequency noise, including a dominant 50 Hz powerline interference. This noise introduces distortion, masking important features of the ECG waveform, such as the QRS complexes and other significant components.

The blue dashed curve shows the "Filtered ECG Signal using the Kalman Filter." After being processed by the Kalman filter, the signal demonstrates a substantial reduction in noise, particularly the suppression of the 50 Hz interference. This enables the key features of the ECG waveform to become more discernible. The Kalman filter leverages its predictive and corrective capabilities to estimate the clean signal effectively.

The black curve represents the "Original ECG Signal," serving as a baseline for comparison. Observing the filtered signal closely following the original signal indicates that the Kalman filter successfully removes the 50 Hz powerline noise and other high-frequency distortions while preserving the integrity of the critical features in the ECG waveform. This highlights the effectiveness of the Kalman filter in recovering the signal without losing essential information.

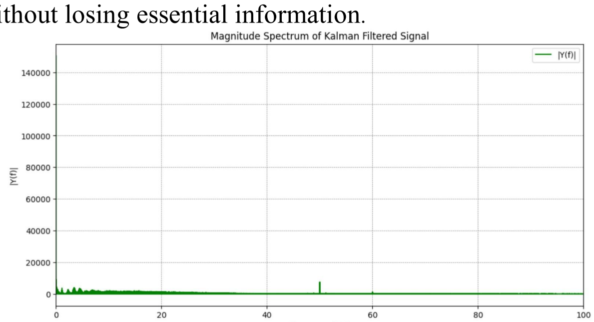

Fig.15: Magnitude Spectrum after filtering.

The performance parameters of the noisy, notch-filtered, NLMS-filtered, RLS-filtered, and Kalman-filtered ECG signals are summarized in table 1. Higher SNR and lower %PRD and MSE values indicate that the signal quality is much better. Overall, the best performance was achieved with the Kalman filter, since it has the highest average SNR = 21.53 dB and the smallest values of %PRD = 8.54% and MSE = 0.00357, indicating the best noise cancellation and signal reconstruction. RLS and NLMS filters also improve the quality of signals, though at a little improved %PRD and MSE of RLS compared to NLMS.

Notch filtering results in the least signal improvement among these filters with a minimum value of SNR and maximum %PRD and MSE. Hence, the Kalman filter will be the best to use to enhance an ECG signal.

Table.1: VALUES OF PERFORMANCE PARAMETERS (SNR, %PRD AND MSE)

Performance Parameter	Database Record No.[10]	Filter			
		Notch	NLMS	RLS	KALMAN
SNR	100	2.17 dB	11.95 dB	21.54 dB	21.54 dB
	103	1.39 dB	11.85 dB	15.53 dB	21.48 dB
	104	10.04 dB	11.93 dB	10.04 dB	21.50 dB
	105	10.99 dB	11.99 dB	8.06 dB	21.60 dB
	Average	6.1475	11.93	13.7925	21.53
%PRD	100	77.93	25.25	16.73	8.38
	103	85.22	25.75	16.22	8.43
	104	31.49	25.31	31.49	8.55
	105	28.22	25.14	28.17	8.82
	Average	55.715	25.3625	21.065	8.545
MSE	100	0.095431	0.010019	0.002263	0.001102
	103	0.114120	0.010273	0.011131	0.001010
	104	0.015578	0.010067	0.015578	0.001117
	105	0.012511	0.009935	0.100114	0.011051
	Average	0.05941	0.03242725	0.0322715	0.00357

V. Conclusion

Time and frequency domain analyses show that the Kalman filter is more powerful in suppressing the 50 Hz power line interference compared with the adaptive NLMS, adaptive RLS, and traditional notch filters. The performance of the Kalman filter is better in terms of the highest SNR, lowest %PRD, and lowest MSE compared to the other filters. The outcome of this will lead us to the conclusion that the Kalman filter-based denoising technique is most effectual and optimal compared to adaptive NLMS, adaptive RLS, and traditional notch filtering techniques for the elimination of 50 Hz power line interference from ECG signals.

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