ECG Classification using Dynamic High Pass Filtering and Statistical Framework (HRV)

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Abstract

This paper presents a technique for detection of R peak from ECG using statistics of the input signal. In this method, high pass filter is derived from the statistics of given signal. Using Minimum Mean Square Error (MMSE) approach, filter parameters are estimated. For estimation of filter parameters, autocorrelation is used. Then further processing is done on the output of high pass filter to detect R peaks and analysis is carried out from the series of R-R intervals to estimate the time domain and frequency domain parameters. From these parameters, ECG classification is done as Normal Sinus Rhythm and Supraventricular tachycardia (SVT).

Keywords: MMSE, Normal Sinus Rhythm (NSR), Supraventricular Tachycardia (SVT).

1. INTRODUCTION

Automatic detection of R wave is important for efficient finding of R-R interval from ECG. R-R series is important for HRV analysis. Detecting R peak is the crucial task, which is significant for further processing of ECG. Various signal processing algorithms have been suggested and developed for detection of fiducial points of ECG to process it [1-8]. Beat detection algorithm typically incorporates preprocessing filters, which maximizes S/N ratio. For detection of peaks, a threshold is used to differentiate between a true peak and a false peak [1-2]. This algorithm operates at the same rate as that of ECG. Using filter bank theory, beat detection is done by decomposing the signal into different sub bands. With this type of algorithm, processing is done at a rate lower than input ECG (sub band rate) [3]. Extensive work is done with wavelet transform especially Db4, Haar, Cubic spline for Detection of R peaks [4-7]. Using squared double difference signal of ECG, peaks are detected with three stage of logic [8]. Most of the methods presented are quite complex and require more stages to detect R peaks.

This paper deals with the issue of estimating high pass filter matched to a signal in a statistical sense. The idea here is to use autocorrelation of the signal for estimating the coefficients of high pass filter, using MMSE approach. After passing the signal through this filter, it is further analyzed to detect the R peaks. ECG signal is classified as NSR and SVT by means of HRV analysis.

1.1 Heart Rate Variability

A healthy human heart does not beat at a precisely regular rate, but rather slightly irregularly in terms of the length of time between beats. Change in heart rate is a universal reaction of entire body to any impact from environment. This variation from beat to beat is known as the heart rate variability (HRV). HRV is very useful to understand sympathetic and parasympathetic autonomic balance and also gives information regarding the risk of sudden cardiac death in patients. Heart rate is controlled by the balancing action of the sympathetic nervous system (SNS) and parasympathetic nervous system (PNS) which are the branches of the Autonomic Nervous System (ANS). SNS stimulates organ's functioning, and PNS inhibits functioning of those organs. HRV analysis is a powerful tool in assessment of autonomic function [9-10].

1.2 Time Domain Parameters for HRV Analysis

Variations in the heart rate can be evaluated by finding time domain and frequency domain parameters.

Following are the time domain parameters which are evaluated for this work and are derived from the differences between RR intervals. RR intervals are the intervals between adjacent R peaks resulting from SA node depolarization.

SD ratio: It is a ratio of short term variability to long term variability which is calculated using Poincare plot. Poincare HRV plot is a graph in which each RR interval is plotted against next RR interval (a type of delay map) [11].

Kurtosis: It is a fourth moment of random variable. Kurtosis gives information whether the data has sharp peak or flat peak relative to a normal distribution. High Kurtosis signifies sharp peak where as low values of Kurtosis indicates flat peak near the mean value of data set.

1.3 Frequency Domain Parameter for HRV Analysis

LF/HF ratio: The LF/HF Ratio is defined as the ratio of low frequency to high frequency which is derived from power spectral density of tachogram (instantaneous heart rate). It is used to indicate balance between sympathetic and parasympathetic nervous system. Low value of this ratio indicates either increase in parasympathetic or decrease in sympathetic nervous system [9-10].

2. METHODOLOGY

Here a two stage method is used for automatic detection of R peaks.

2.1 First stage: Estimation of high pass filter from autocorrelation of the signal

Let $x(n)$ be a signal of length N and let $h(n)$ be a signal adopted high pass filter of length P.

The coefficients of $h(n)$ are obtained in the following fashion:

Let $e(n)$ be an error signal and $\hat{x}$(n) is the estimate of $x(n)$ obtained by considering the past N samples, then $e(n)$ can be written as

$$e(n) = x(n) - \sum_{k=1}^{P} h(k)x(n-k) \qquad \text{.......... (2.1)}$$

$$e(n) = x(n) - \hat{x}(n) \qquad \text{........... (2.2)}$$

where

$$\hat{x}(n) = \sum_{k=1}^{P} h(k)x(n-k)$$

By assuming error is orthogonal to observations i.e. $E\{e(n)x(n-l)\} = 0$ for $l = 1, 2, 3, \cdots, P$

We can write

$$E\{e(n)x(n-l)\} = E\{x(n)x(n-l)\} - E\left\{\sum_{k=1}^{P} h(k)x(n-k)x(n-l)\right\} \qquad \text{........ (2.3)}$$

$$0 = R_x(l) - \sum_{k=1}^{P} h(k) R_x(l-k) \; \forall l = 1,2,3,\cdots,P$$

These equations can be written in matrix form in the following manner.

$$\begin{bmatrix} R_x(1) \\ R_x(2) \\ R_x(3) \\ R_x(4) \\ \vdots \\ R_x(P) \end{bmatrix} = \begin{bmatrix} R_x(0) & R_x(-1) & R_x(-2) & \cdots & R_x(1-P) \\ R_x(1) & R_x(0) & R_x(-1) & \cdots & R_x(2-P) \\ R_x(2) & R_x(1) & R_x(0) & \cdots & R_x(3-P) \\ R_x(3) & R_x(2) & R_x(1) & \cdots & R_x(4-P) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ R_x(P-1) & R_x(P-2) & R_x(P-3) & \cdots & R_x(0) \end{bmatrix} \begin{bmatrix} h(1) \\ h(2) \\ h(3) \\ h(4) \\ \vdots \\ h(P) \end{bmatrix}$$

where

$$\underline{r} = \begin{bmatrix} R_x(1) \\ R_x(2) \\ R_x(3) \\ R_x(4) \\ \vdots \\ R_x(P) \end{bmatrix} \quad R = \begin{bmatrix} R_x(0) & R_x(-1) & R_x(-2) & \cdots & R_x(1-P) \\ R_x(1) & R_x(0) & R_x(-1) & \cdots & R_x(2-P) \\ R_x(2) & R_x(1) & R_x(0) & \cdots & R_x(3-P) \\ R_x(3) & R_x(2) & R_x(1) & \cdots & R_x(4-P) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ R_x(P-1) & R_x(P-2) & R_x(P-3) & \cdots & R_x(0) \end{bmatrix} \quad \underline{h} = \begin{bmatrix} h(1) \\ h(2) \\ h(3) \\ h(4) \\ \vdots \\ h(P) \end{bmatrix}$$

$\underline{r}$ and $\underline{h}$ are $P \times 1$ vectors and R is $P \times P$ matrix

$\underline{r} = R \cdot \underline{h}$

The coefficients of filter can be obtained by inverting R and multiplying this by vector $\underline{r}$

$$\underline{h} = R^{-1} \cdot \underline{r} \qquad \text{...... (2.4)}$$

As we have minimized the error, the corresponding filter will definitely behave like high pass filter. Therefore, corresponding impulse response would be

$$h_{HP}(n) = \left\{1, -h_{1,} - h_2, \cdots, -h_P\right\}$$

For given data case, again consider equation (2.1), which can be written for different values of n ranging from 0 to $N-1$ as follows:

$$\begin{bmatrix} e(0) \\ e(1) \\ e(2) \\ e(3) \\ \vdots \\ e(N-1) \end{bmatrix} = \begin{bmatrix} x(0) \\ x(1) \\ x(2) \\ x(3) \\ \vdots \\ x(N-1) \end{bmatrix} - \begin{bmatrix} x(-1) & x(-2) & x(-3) & \cdots & x(-P) \\ x(0) & x(-1) & x(-2) & \cdots & x(1-P) \\ x(1) & x(0) & x(-1) & \cdots & x(2-P) \\ x(2) & x(1) & x(0) & \cdots & x(3-P) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x(N-2) & x(N-3) & x(N-4) & \cdots & x(N-1-P) \end{bmatrix} \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ \vdots \\ h_P \end{bmatrix}$$

Let $\underline{e} = \left[e(0), e(1), e(2), \cdots e(N-1)\right]^t$

$$\underline{x} = \left[x(0), x(1), x(2), \cdots x(N-1) \right]^t$$

$$\underline{h} = \left[h_1, h_2, h_3, \cdots h_P \right]^t$$

$$X = \begin{bmatrix} x(-1) & x(-2) & x(-3) & \cdots & x(-P) \\ x(0) & x(-1) & x(-2) & \cdots & x(1-P) \\ x(1) & x(0) & x(-1) & \cdots & x(2-P) \\ x(2) & x(1) & x(0) & \cdots & x(3-P) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x(N-2) & x(N-3) & x(N-4) & \cdots & x(N-1-P) \end{bmatrix}$$

In vector notation, we can write

$$\underline{e} = \underline{x} - X \cdot \underline{h} \qquad \text{……….. (2.5)}$$

By using least approach, h can be obtained as follows:

In least square approach, $\underline{e}$ is $\perp$ to column vector of matrix

$X = \left[\underline{x}_1, \underline{x}_2, \underline{x}_3, \ldots, \underline{x}_P \right]$ where $\underline{x}_1, \underline{x}_2, \underline{x}_3, \ldots \underline{x}_P$ are $N \times 1$ vectors.

$$X^t \cdot \underline{e} = \begin{bmatrix} x_1^t \\ x_2^t \\ x_3^t \\ \vdots \\ x_P^t \end{bmatrix} \cdot \underline{e} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \qquad \text{……….. (2.6)}$$

Therefore by multiplying equation (2.5) by X^t and using condition of orthogonality given in equation (2.6), we get

$$X^t \cdot \underline{e} = X^t \cdot \underline{x} - X^t \cdot X \cdot \underline{h}$$

$$\Rightarrow X^t \underline{x} = X^t \cdot X \cdot \underline{h}$$

$$\underline{h} = Inv\left(X^t \cdot X \right) X^t \cdot \underline{x} \qquad \text{………. (2.7)}$$

Therefore corresponding P^{th} order high pass filter would be

$$h_{HP}(n) = \left\{ 1, -h(1), -h(2), \cdots - h(P) \right\}$$

Thus from autocorrelation of the signal, high pass filter is derived. As the filter is statistically matched with the input signal, the frequency range of the estimated filter will lie within the range of input signal. As high pass filter is used for edge detection, the same is used here for detecting R peaks, which are more prominent in ECG. By further processing the output of high pass filter, R peaks are detected and analysis is carried out to estimate the time domain and frequency domain parameters and thereafter classifying Normal Sinus Rhythm (NSR) and Supra ventricular tachycardia (SVT) using these parameters.

2.2 Second stage: Algorithm for detecting R peaks of ECG signal using the estimated high pass filter

1. Estimate high pass filter using the above method. Here filter coefficient length (P) is considered as 5.
2. Apply moving window averaging of size 2 to the output of high pass filter.
3. Find the mean of positive values obtained from moving window averaged output.
4. Now to detect all R peaks

A. Draw a line by using threshold =1.15*mean and find the indexes where this line cuts the signal.
B. Find the maxima between two index values and store them as peaks which include both TP and FP (TP- R peak correctly detected and FP-Noise spike detected as R peak).
C. Find the interval between consecutive peaks. If interval is >0.8*mean interval, then store these peaks as a true peak otherwise discard it.(By taking into account the absolute refractory period, interval is decided)

5. Find the R-R interval series from true peaks.
6. Calculate statistical parameters: kurtosis & LF/HF ratio.
7. Classify the signal using above parameters.

3. RESULTS AND DISCUSSION

The ECG data set is derived from Physionet database (http://www.physionet.org). The data for Normal Sinus Rhythm (NSR) subjects is taken from MIT BIH Normal Sinus Rhythm database, where the ECG data is sampled at 128Hz, which is fully annotated [12].

Supraventricular tachycardia (SVT) data set is taken from MIT-BIH Supraventricular tachycardia (SVT) database, where the ECG data is sampled at 128 Hz which is fully annotated. For implementation of the proposed algorithm, MATLAB version 7.11.0.584(R2010b) is used. For determining the coefficients of high pass filter, 5000 samples of ECG signal are considered. The average processing time is less than 30 seconds on 30 minutes of data on I7 processor.

TABLE 1

Normal Sinus Rhythm					Supraventricular tachycardia (SVT)				
Signal	Actual R peaks	Detected R peaks	LF/HF ratio	Kurtosis	Signal	Actual R peaks	Detected R peaks	LF/HF ratio	Kurtosis
16265	5264	5264	1.945	4.072	803	1924	1899	0.436	10.324
16273	4777	4782	2.243	2.284	804	2653	2667	0.516	7.909
19093	4113	4139	2.4	2.88	808	1746	1759	0.851	52.784
17453	4961	4961	2.306	4.561	810	1839	1895	0.759	28.065
17052	4465	4467	2.376	3.522	812	1758	1775	0.748	20.729
16773	4423	4422	1.085	3.489	826	2581	2526	0.646	14.793
16786	4405	4406	1.037	3.209	845	2828	2800	0.747	93.942
19090	4772	4817	2.796	4.556	870	1786	1826	0.515	27.632
Mean ±S.D.			2.023 ±0.638	3.572 ±0.799	Mean ±S.D.			0.652 ±0.148	32.02 ±28.727

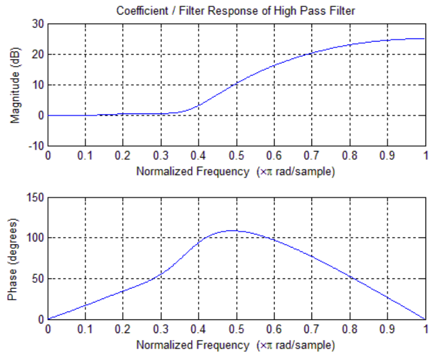

FIGURE 1: HP Filter response for NSR.

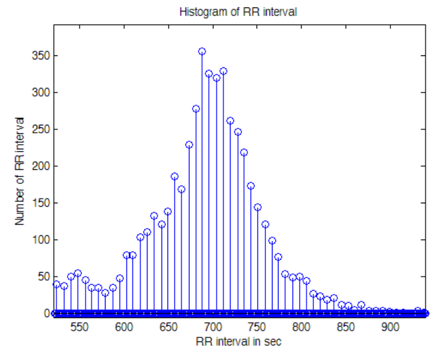

FIGURE 2: Histogram for NSR.

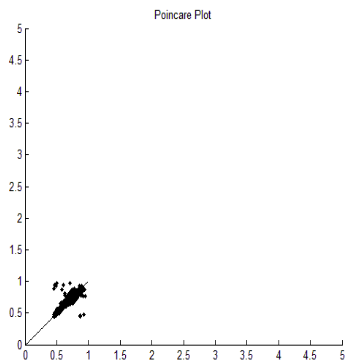

FIGURE 3: Poincare plot for NSR.

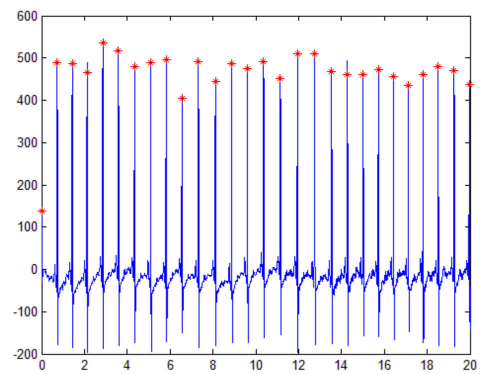

FIGURE 4: R Peak detection for NSR.

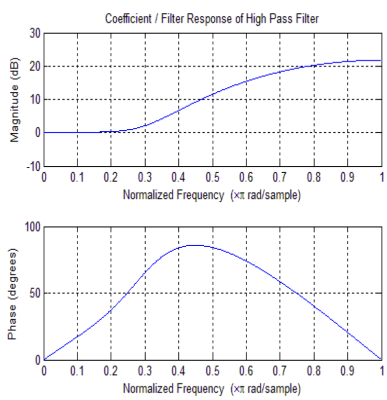

FIGURE 5: HP Filter response for SVT.

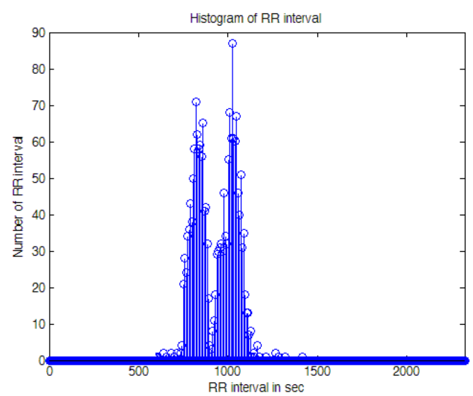

FIGURE 6: Histogram for SVT.

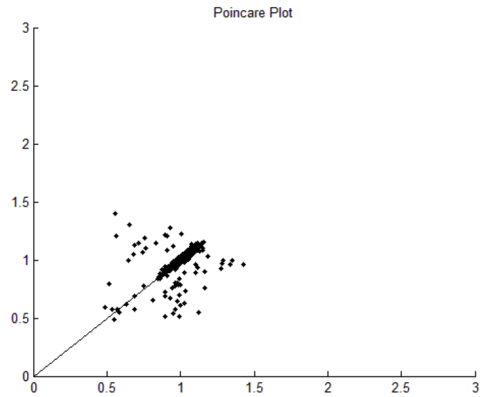

FIGURE 7: Poincare plot for SVT.

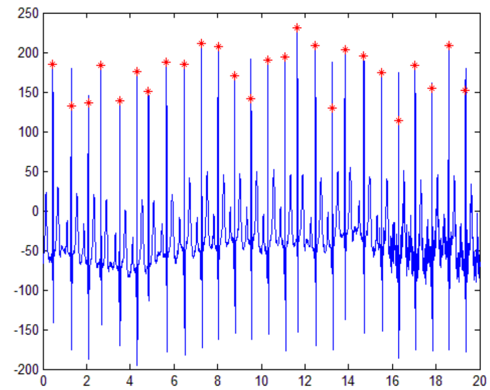

FIGURE 8: R Peak detection for SVT.

In proposed work, where estimation of high pass filter is made from the autocorrelation of the ECG signal, the accuracy for detecting normal R peaks is almost 99%. From detected R peaks, R-R intervals are measured and from the series of R-R intervals, Kurtosis and LF/HF ratio are calculated. For normal sinus rhythm, Kurtosis is 3.571± 0.799 (as for normal distribution of data set, this value is 3), which indicates that the data has fewer tendencies to produce unusually extreme values, which are true assessment of normal sinus rhythm. For Supraventricular tachycardia (SVT), Kurtosis is very high, indicating large deviation from mean R-R interval due to extreme differences between consecutive R-R peaks for small time periods which occur frequently. In case of Normal Sinus rhythm, most of the information is in low frequency region. Hence LF/HF ratio is more in case of Normal Sinus rhythm. In Supraventricular tachycardia (SVT), we get the information in high frequency region for recurrence of fast heart rate. Hence the ratio is small. From table 1, we can observe that the value of LF/HF ratio for normal sinus rhythm is high as compared to SVT, which shows the influence of sympathetic nervous system for NSR. SD1/SD2 ratio is also calculated from Poincare plot and this is more in case of SVT due to more variations in R-R intervals. Poincare plot is a delay plot, in which each R-R interval is plotted against next R-R interval and this Poincare plot is more scattered in case of SVT (fig 7) than NSR(fig 3). Histogram is the graphical representation of the distribution of R-R intervals. It is seen that in case of NSR (fig 2) it is more close to normal distribution. Hence with the help of parameters like Kurtosis and LF/HF ratio, we can classify Normal Sinus Rhythm with Supraventricular tachycardia (SVT), which can be validated with the help of Poincare plot and Histogram of R-R interval.

4. CONCLUSION

In this paper, a novel two stage methodology is discussed for the automated detection of R peaks in ECG signal. Here in the first stage, signal is passed through estimated high pass filter and stage two is a two level peak finding logic whereas in [1,2,3,7] more than three levels are used. The percentage accuracy of detecting R peaks in NSR rhythm is almost 99% and 97% for SVT. The key idea here is estimation of high pass filter from a given signal to detect the R peaks. It is clear that this approach found to be easier, more accurate, and computationally efficient as only two levels are used for automatic detection of R peaks.

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