Chapter 5: ECG feature extraction using FPGA based standalone embedded system

5.1 Introduction

In this chapter an ECG feature extraction algorithm and its FPGA implementation is discussed. The algorithm was implemented on Xilinx Spartan XC 3s1500fg320-4. Single lead ECG data from Physionet database (ptbdb and mitdb data files) were used for validation of the algorithm. ECG samples were digitized with 8 bit resolution before being fed to the FPGA. A total of 180 single lead data, each containing 60000 samples were tested in FPGA. According to the organization of the chapter, at first, the real time ECG feature extraction algorithm is described. Thereafter validation of the algorithm in Xilinx simulation platform is described. Finally the implementation of the algorithm on Xilinx Software development kit (SDK) has been described.

5.2 An FPGA based real time ECG feature extraction algorithm

To simulate the real time computing environment, a PC based digital ECG simulator was developed to deliver digitized (8 bit) ECG samples at 1 kHz sampling frequency ($f_s$) to the FPGA board. At first ECG data samples were filtered using 50 Hz notch filter and final LPF, as described in chapter 4. Filtered data were then used for detecting ECG features.

At first R peaks were detected. With respect to detected R-peak positions, other wave peak (T and P) positions were detected in appropriate window search. Local baseline magnitudes were determined from the TP segment. With respect to detected local baseline magnitude, different component (P, T and QRS) wave peak’s onset and offset positions and their respective magnitudes (heights) and durations were determined.
QRS, P and T morphology of an ECG may widely vary among different age groups, genders, patients, demographic and geographical population. Hence, the algorithm for detecting each individual wave peaks was divided into two phases of operation. During training period, a reference slope and polarity characteristics (template) were extracted for the concerned wave peaks. In the detection phase template or signatures were matched with incoming ECG samples. A logic flow diagram of the ECG feature extraction algorithm is given below (figure 5.1).

![Logic flow diagram of ECG feature extraction algorithm](image)

The extracted features can be used to diagnose different kinds of heart diseases based on some rule base formed. The developed algorithm was tested with normal and abnormal ECG data from mitdb and ptb diagnostic ECG database under Physionet. The algorithm yielded comparable results with other reported works. An FPGA based QRS detection approach as described in [68-69], consumes much higher resources of FPGA, compared to the present implementation. Latency of R peak detection is also much higher compared to presented work.

The algorithm stages were divided into 3 parts, viz, noise removal, template generation from first 6-7 beats and feature detection.
For real time operations, the FPGA maintain a first in first out (FIFO) stack of 200 last samples at any point of time. \( m_{i-199} \) and \( m_i \) being the first in and last in element of the FIFO stack. R peak detection uses only latest 40 samples of the FIFO stack. For T and P peak detection last 100 elements of FIFO stack were utilized. For determining offset points of T and P wave peaks, 200 stack elements were utilized.

Different symbols used for describing ECG feature extraction algorithms are described below in tabular form.

Table 5.1: Notations and symbols used for algorithm

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Description</th>
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<tbody>
<tr>
<td>( m_i )</td>
<td>ECG amplitude of ( i^{th} ) sample or current sample value (quantized)</td>
</tr>
<tr>
<td>( m_{i-20} )</td>
<td>ECG amplitude of ((i-20)^{th}) sample or 20 sample before the current sample value</td>
</tr>
<tr>
<td>( Slp_{20-}) ( i-20) ( = m_{i-20} - m_{i-40} )</td>
<td>left side (towards beginning of ECG data array) 20 point slope w.r.t. ((i-20)^{th}) sample value</td>
</tr>
<tr>
<td>( Slp_{20+} ) ( = m_{i-20} - m_i )</td>
<td>right side (towards end of ECG data array) 20 point slope w.r.t. ((i-20)^{th}) sample value</td>
</tr>
<tr>
<td>( gr1 )</td>
<td>only those samples (basically ((i-20)^{th}) samples for R peak detection and ((i-50)^{th}) samples for T and P peak detection) are analyzed which has a positive peak</td>
</tr>
<tr>
<td>( gr2 )</td>
<td>only those samples (basically ((i-20)^{th}) samples for R peak detection and ((i-50)^{th}) samples for T and P peak detection) are analyzed which has a negative peak</td>
</tr>
<tr>
<td>( (\sum_{\text{Slp}<em>{L,R}^{20x,20y}})</em>{gr1} )</td>
<td>maximum of summation of absolute value of left and right side 20 point slope for ( gr1 ), as obtained for the training period of R peak detection</td>
</tr>
<tr>
<td>( (\sum_{\text{Slp}<em>{L,R}^{20x,20y}})</em>{gr1}, (\sum_{\text{Slp}<em>{L,R}^{20x,20y}})</em>{gr2} )</td>
<td>corresponding left and right side 20 point slope, where summation of both side slope is maximum for ( gr1 ), as obtained for the training period of R peak detection.</td>
</tr>
<tr>
<td>( (\sum_{\text{Slp}<em>{L,R}^{20x,20y}})</em>{gr2} )</td>
<td>maximum of summation of left and right side 20 point slope for ( gr2 ),</td>
</tr>
</tbody>
</table>
as obtained for the training period of R peak detection

\((\text{max}_\text{sum} \text{Slp}^{0.1_2})_{\text{gr} 1}, (\text{max}_\text{sum} \text{Slp}^{0.1_2})_{\text{gr} 2}\)

left and right side slope threshold value of an R peak, as determined at the end of R peak detection training period as a percentage of either of the sets \((\text{max}_\text{Slp}^{0.2_1})_{\text{gr} 1}, (\text{max}_\text{Slp}^{0.2_1})_{\text{gr} 2}\)

or \((\text{max}_\text{Slp}^{0.2_2})_{\text{gr} 1}, (\text{max}_\text{Slp}^{0.2_2})_{\text{gr} 2}\), based on dominance of gr1 or gr2.

LastR

last detected R peak index

\(K_B\)

index of Bth ECG sample

\(I_{R\text{R}}\)

latest average R-R interval

\((\text{max}_\text{sum} \text{Slp}^{0.5_1})_{\text{gr} 1}, (\text{max}_\text{sum} \text{Slp}^{0.5_1})_{\text{gr} 2}\)

maximum of summation of absolute value of left and right side 50 point slope for gr1 and gr2 respectively, as obtained for the training period of T peak detection.

\((\text{max}_\text{Slp}^{0.5_1})_{\text{gr} 1}, (\text{max}_\text{Slp}^{0.5_1})_{\text{gr} 2}\),

\((\text{max}_\text{Slp}^{0.5_2})_{\text{gr} 1}, (\text{max}_\text{Slp}^{0.5_2})_{\text{gr} 2}\)

corresponding left and right side 50 point slope, where summation of both side slope is maximum for gr1 and gr2 respectively, as obtained for the training period of T peak detection.

\(T_{\text{thk}}^{0.1_1}, T_{\text{thk}}^{0.1_2}\)

left and right side slope threshold value of a T peak, as determined at the end of R peak detection training period as a percentage of either of the sets \((\text{max}_\text{Slp}^{0.5_1})_{\text{gr} 1}, (\text{max}_\text{Slp}^{0.5_1})_{\text{gr} 2}\)

or \((\text{max}_\text{Slp}^{0.5_2})_{\text{gr} 1}, (\text{max}_\text{Slp}^{0.5_2})_{\text{gr} 2}\)

based on dominance of gr1 or gr2.

\(P_{\text{thk}}^{0.1_1}, P_{\text{thk}}^{0.1_2}\)

left and right side slope threshold value of a P peak, determined in a similar approach
5.2.1 QRS detection algorithm

For QRS detection, a similar approach as described in chapter 3 was adopted here. But in previous approach Q or S or QS peak was detected, in case of insignificant positive R wave, for the purpose of detection of heart rate. But in this approach an effort was made to determine the hidden positive R wave even in the presence of positive but insignificant R wave.

In R peak detection, slope has been used as the principal feature to characterize R wave. QRS wave polarization can be positive (R wave) or negative (QS wave). T and P peak can be positive (+ve, upright) or negative (-ve, inverted) as shown in figure 2.8 of chapter 2. Q and S peak is always -ve. If (+ve) qRS polarization (R peak) exists in the concerned ECG signal, it can be significant (qRs) or insignificant (Qr or rS), as shown in the Figure 3.4. In case of significant (+ve QRS polarization) R wave, both side (left and right) slopes are well dominated. Insignificant R wave is associated with either of Q or S wave, not both. For insignificant R wave, either of the two side slopes are dominated. In case of negative QRS polarization, coincided Q and S wave gives rise to QS wave. Hence in the training period of R peak detection, it needs to be identified that whether R peak or QS peak exists. Presence of Qr or rS peak was also determined.

Around 10 past samples were used to get the filtered data. At first 40 filtered samples were inputted into the FIFO stack. Thereafter for each successive i\textsuperscript{th} incoming samples (filtered), \( \text{Slp}_{-20}^{20-} \) and \( \text{Slp}_{-20}^{20+} \) were computed continuously throughout the rest of the incoming ECG samples. It was assumed that at least one R peak will be encountered in 1450 ms (i.e. within 1450 samples with 1 kHz \( f_s \)). R peak detection initiated after 50 (10+40) ms. A total of 1500 (1450 + 50) ms. period was used to estimate the slope and characteristics of R wave, to generate a slope and polarity based reference template. This period was considered as the training period for the detection of R wave. A brief flow chart of R peak detection algorithm is indicated in figure 5.3, which is detailed in Figure 5.4.

\[
\text{Slp}_{-20}^{20-} = m_{i-20} - m_{i-40} \quad \text{(5.1a)}
\]

\[
\text{Slp}_{-20}^{20+} = m_{i-20} - m_{i} \quad \text{(5.1b)}
\]
With each incoming samples (i\textsuperscript{th}) to the FPGA module, both side slope was computed continuously using equation (5.1a) and (5.1b) in two separate groups.

The first group (gr1), considered only those samples, for which a positive peaking occurs around (i-20)\textsuperscript{th} sample and both side slope is positive going towards (i-20)\textsuperscript{th} sample. That means conditions 1 hold. Similarly only those samples were considered in the second group (gr2), for which a negative peaking occurs around (i-20)\textsuperscript{th} sample. That means condition 2 holds.

\textbf{Condition 1 (gr1):}
\[
S_{\text{Sp}}^{i-20} > 0 \quad \text{and} \quad S_{\text{Sp}}^{i-20} > 0 \quad \text{and} \quad m_{i-20} = \max\{m_{i-17}, m_{i-18}, \ldots, m_{i-22}, m_{i-23}\} \quad (5.2a)
\]

\textbf{Condition 2 (gr2):}
\[
S_{\text{Sp}}^{i-20} < 0 \quad \text{and} \quad S_{\text{Sp}}^{i-20} < 0 \quad \text{and} \quad m_{i-20} = \min\{m_{i-17}, m_{i-18}, \ldots, m_{i-22}, m_{i-23}\} \quad (5.2b)
\]
5.2.1.1 Training phase: Generation of “Template”

Both side 20 point slope calculation was performed in two separate groups for QRS signature extraction during the training period. But now each group maintains a maximum sum of left and right side 20 sample slope abbreviated as \( \text{sumSlp}_{QRS}^{20pt}_{i-20} \) and \( \text{sumSlp}_{QRS}^{20pt}_{i+20} \) respectively. Each group also maintains corresponding left and right side 20 sample slope abbreviated as \( \text{leftSlp}_{QRS}^{20pt}_{i-20} \) and \( \text{rightSlp}_{QRS}^{20pt}_{i+20} \) respectively. On capturing \( i \)th sample, if it was found that \((i-20)\)th sample belongs to group1, then \( \text{sumSlp}_{QRS}^{20pt}_{i-20} \), \( \text{leftSlp}_{QRS}^{20pt}_{i-20} \) and \( \text{rightSlp}_{QRS}^{20pt}_{i+20} \) were maintained in the following way.

\[
\text{if } \left| \text{Slp}_{QRS}^{i-20} - \text{Slp}_{QRS}^{i-20} \right| > \text{sumSlp}_{QRS}^{20pt}_{i-20} \text{ or } \left| \text{Slp}_{QRS}^{i+20} - \text{Slp}_{QRS}^{i+20} \right| > \text{sumSlp}_{QRS}^{20pt}_{i+20} \text{ then } (5.3a)
\]

After 1510 samples, compute Equation (5.4) to characterize R-peak (qRs, QS, Qr or rS) and template generation using Equation (5.5).

Test for condition (1) and (2) (Equation 5.2(a, b))

Condition (1) satisfied (gr.1)
Condition (2) satisfied (gr.2)
Compute Equation (5.3a)
Compute Equation (5.3b)

After Training phase

FIFO stack of 40 samples

Compute \( \text{slp}_{QRS}^{i-20} \) and \( \text{slp}_{QRS}^{i+20} \). (Equation 5.1(a, b))

Test for R-peak based on Equation (5.6)

R-peak index storage

Detection phase

Both for Training & Detection Phase (i.e. for all samples)

Figure 5.3: Logic flow diagram of R-peak characterization and detection
[i.e. if (i-20)th sample belongs to group1, and summation of both side 20 point slope is greater than the current maximum slope (summation of both left and right side slope) of group1, then current maximum slope of group1 is updated, so as to compute the maximum slope of group1, during training period. The left and right side 20 point slope are also captured for the sample for which summation of both side slopes are maximum for group1]

Group2 parameters were also determined in a similar way.

\[
\text{if } (\sum_{i-20}^{i+20} S_i)_{\text{group1}} > (\sum_{i-20}^{i+20} S_i)_{\text{group2}},
\]

\[
(\text{max} \quad \text{Slp}_{\text{QRS},20pt})_{\text{group2}} = (\sum_{i-20}^{i+20} S_i)_{\text{group2}},
\]

\[
(\text{left Slp}_{\text{QRS},20pt})_{\text{group2}},
\]

\[
(\text{right Slp}_{\text{QRS},20pt})_{\text{group2}}
\]  

(5.3b)

The objective of the operation is to capture maximum slope (summation of both side slope) of group2 during training phase, and corresponding left and right side slope, so that after the training period ends, a comparison can be made between the two groups.

After processing 1500 samples both groups were having with parameters \((\text{sumSlp}_{\text{QRS},20pt})_{\text{group1}}, (\text{leftSlp}_{\text{QRS},20pt})_{\text{group1}}, (\text{rightSlp}_{\text{QRS},20pt})_{\text{group1}}\) and \((\text{sumSlp}_{\text{QRS},20pt})_{\text{group2}}, (\text{leftSlp}_{\text{QRS},20pt})_{\text{group2}}, (\text{rightSlp}_{\text{QRS},20pt})_{\text{group2}}\) respectively. At 1500 sample, to discriminate between three type of peaks ((qRs), (QS wave) or (Qr or rS)), following criteria were applied

i) \(0.1 \times (\text{left Slp}_{\text{QRS},20pt})_{\text{group1}} > (\text{right Slp}_{\text{QRS},20pt})_{\text{group1}}\) OR \(0.1 \times (\text{right Slp}_{\text{QRS},20pt})_{\text{group1}} > (\text{left Slp}_{\text{QRS},20pt})_{\text{group1}}\)

\[\Rightarrow \text{QS peak}\]  

(5.4a)

That means if one side 20 sample slope is less than 10% of other side 20 sample slope of group1 then it was concluded that concerned ECG signal contains QS type peak.

ii) \(0.4 \times (\text{left Slp}_{\text{QRS},20pt})_{\text{group1}} > (\text{right Slp}_{\text{QRS},20pt})_{\text{group1}}\) OR \(0.4 \times (\text{right Slp}_{\text{QRS},20pt})_{\text{group1}} > (\text{left Slp}_{\text{QRS},20pt})_{\text{group1}}\)

\[\Rightarrow \text{rS or Qr}\]  

(5.4b)

Otherwise if one side 20 sample slope is less than 40% of other side 20 sample slope for group1, then it was concluded that concerned ECG signal contains Qr or rS type peak.

iii) Otherwise qRs peak exists.
If QS peak exists, group2 was considered dominant, otherwise group1 was considered dominant. Both side R slope threshold value ($R_{slpth_{left}}$ and $R_{slpth_{right}}$) was calculated, which was 75% of the left and right side 20-sample slope respectively of the dominant group.

$$R_{slpth_{left}} = 0.75 \times (\text{Slp}_{left}^{20})_{grR} \quad , \quad R_{slpth_{right}} = 0.75 \times (\text{Slp}_{right}^{20})_{grR} \quad \text{if +R peak exists , Gr.1 dominant} \quad (5.5a)$$

$$R_{slpth_{left}} = 0.75 \times (\text{Slp}_{left}^{20})_{grR} \quad , \quad R_{slpth_{right}} = 0.75 \times (\text{Slp}_{right}^{20})_{grR} \quad \text{if QS peak exists , Gr.2 dominant} \quad (5.5b)$$

If Gr. 1 was found to be dominant, R peaks were detected, otherwise QS peak search was initiated in the detection phase. Hence during this training period, QRS template was defined in terms of both side 20 sample slope threshold value and polarity of the wave peak. The presence of qRs, Qr, rS or QS peak was indicated by flag bits.

5.2.1.2 Detection phase: Template matching for wave detection

From 1501 samples onwards for each sample again both side (left and right) 20 sample average slope was computed with respect to current sample of reference ($i^{th}$ sample) and was checked for following conditions, to be considered as a valid R peak, according to the type of R peak determined during training phase :

$$\begin{align*}
\text{if peak type = qRs} & ; \quad \text{Slp}_{i-20}^{j-20} > R_{slpth_{left}} \quad \text{and} \quad \text{Slp}_{i-20}^{j-20} > R_{slpth_{left}} \quad \text{and Condition 1} \\
\text{if peak type = Qr or rS} & ; \quad \text{Slp}_{i-20}^{j-20} > R_{slpth_{left}} \quad \text{or} \quad \text{Slp}_{i-20}^{j-20} > R_{slpth_{left}} \quad \text{and Condition 1} \\
\text{if peak type = QS} & ; \quad \text{Slp}_{i-20}^{j-20} > R_{slpth_{left}} \quad \text{and} \quad \text{Slp}_{i-20}^{j-20} > R_{slpth_{left}} \quad \text{and Condition 2}
\end{align*}$$

(5.6)

That means both side 20 sample slope is greater than respective R slope threshold for QS or qRs type peak and the dominant side (as learned in training period ) slope is greater than respective R slope threshold for Qr or rS type peak. Both side 20 sample slope is positive (or negative) going towards the current sample of
reference for qRs (or QS) type peak. And either side 20 sample slope (which side satisfied criteria ‘a’) is positive going towards the current sample of reference for Qr or rS type. Sample magnitude of current sample of reference (i.e. \( m_{i-20} \)) should have maximum value in surrounding region for qRs or Qr or rS type peak and have minimum value in surrounding region for QS type peak.

If either of the conditions were satisfied for a particular instant with respect to current sample of reference, for the type of peak determined in training phase, then the index of current sample of reference (i.e. \((i-20)\)th sample) was considered as concerned peak. QRS polarization was already determined in the training period. To confirm its candidature as a valid R-peak, then it was checked whether the last detected R-peak is 400 samples apart from the current index. If this condition was satisfied, the current R-peak index was taken as a valid R-peak and the corresponding index was stored in a memory cell. If this index difference is less than 30, this may be a case of RR’ peak. In such a case, the index of the preceding R-peak was replaced by the current R peak index. Staying at \( i^{th} \) sample (i.e. on capturing \( i^{th} \) sample), \((i-20)\)th sample can be claimed as R peak, hence the algorithm has a latency of 20 ms for R peak detection. That means when an R peak occurs, after 20 more samples, it can be detected.
Figure 5.4: Flow chart of R peak detection algorithm
5.2.2 S wave peak detection

S peak detection was performed, if the type of QRS for the concerned ECG signal was ‘significant positive R wave type’ or ‘rS type insignificant R wave’. Otherwise S peak detection was not performed. S and Q peak detection was also initiated after an initial training period of first 1500 samples. It was assumed that an S wave peak exists after the occurrence of R wave peak and within next 10 to 50 samples (in case samples are taken at 1 ms interval). Hence for the determination of S wave peak a search was initiated in that region after determination of each successive R-wave peak. Again staying at i\textsuperscript{th} sample, (i-20)\textsuperscript{th} sample was checked for a valid S peak or not. The position of i\textsuperscript{th}, (i-20)\textsuperscript{th} sample is shown in Figure 5.5. For an (i-20)\textsuperscript{th}, sample to be considered as S-wave peak, have to satisfy the following criteria.

a. $\frac{\text{Slp}_{(i-20)}}{20} < 0$

That means left hand side 20 sample slope is negative going towards the (i-20)\textsuperscript{th}, sample value. Left hand side 20 sample slope means 20 sample slope towards the beginning of the data array, (i.e. towards the last detected R peak).

b. $|\frac{\text{Slp}_{(i-20)}}{20}| > \text{R}_{\text{S/Q peak}}$

After determination of at least one R-wave peak, attempt was made to determine all successive S peak. In Figure 5.5, it may appear that in case of prominent Q wave peak, where the left hand side 20 sample slope satisfies the 3 conditions, for the ‘W’ point (which is actually Q-wave peak point) to be determined as S wave peak point. But the ‘W’ point does not remain within the searching zone of S wave, as mentioned earlier. Hence ‘W’ point’s candidature, to be considered as a valid S-peak was nullified at the first stage. Similarly ‘Y’ point’s candidature as a valid Q peak was also nullified at the first stage. This was because while considering ‘Y’ point as a Q-peak, the just previous R-wave peak was already determined. And ‘Y’ point was not apart from last detected R-wave peak by 350 sample.

In the presented scheme, accurate determination of Q, S wave peak positions depend upon online accurate determination of R wave peaks with a small latency at most by the statistically observed minimum interval between adjacent R and Q or S wave peak positions plus 20 sampling interval. But the presented work is capable of online detection of R-wave peaks with sufficient accuracy and with a latency of 20 ms (it is twenty sampling interval), which is far less than the worst case required one.

Magnitude of the slope should exceed R slope threshold, so as to be considered as QRS region slope.
c. \((LastR+10) < K_{i-20} < (LastR+50)\)

--where \(K_i\) represent \(i^{th}\) samples index value and LastR represent last detected R peak index value

d. \((i-20)^{th}\) sample value must have minimum value in that region--

--amongst other samples which also satisfies above two conditions.

In criteria a and b, only left hand side that means R-wave side slope was considered for satisfying certain conditions, but T-wave side slope was not considered. This is because for insignificant type S wave, only the left hand side or the R-wave side slope is prominent. Right hand side or T-wave side slope is less prominent or last for very small duration.

### 5.2.3 Q wave peak detection

Q peak detection was performed, only for ‘significant positive R’ or ‘Qr’ type QRS complex. Similarly for determining a Q wave peak, from the incoming ECG signal \((i-20)^{th}\) sample was checked for a valid Q wave, staying at current sample \((i^{th})\). If for a particular current sample \((i^{th})\), the left hand side 20 sample slope is positive going towards current sample (i.e. \(\text{Slp}_{i-20}^i > 0\)) and satisfies the R slope threshold criteria (i.e. \(|\text{Slp}_{i-20}^i| > \text{Rslpth}_{left}\)), then it was checked that if 20 sample before the current sample have the minimum value in the region, amongst the others whose 20 sample previous point already satisfied the above conditions. If the criteria was satisfied, then 20 sample before the current sample (i.e. \((i-20)^{th}\) sample) was chosen as Q-wave peak. If at least one R wave peak is determined by the algorithm, then for determining all subsequent Q-wave peaks search was initiated for those samples which were at least 340 sample after the last detected R-wave peak. This reduces the searching time by reducing span of search zone. After an R-wave got detected, next 340 samples were not used for searching. Reduction of the span of searching in case of Q and S wave peak detection also reduces the chances of a high frequency noise signal to be considered as concerned peaks. Q wave detection scheme is shown in Figure 5.6. For Q wave detection also, R wave side slope was considered.
5.2.4 T and P wave peak detection

T and P wave detection was also performed in two phases (i.e. template generation and detection).

5.2.4.1 Training period duration for T and P wave detection

For detection of T and P wave peaks, initial training period was extended from 1500 to 6000 samples. T and P peak detection was initiated after 6000 samples but R peak detection was initiated after 1500 samples, because for determining T and P wave characteristics, at least two R peak positions needs to get determined. After determination of R wave characterization during an initial training period of 1500 samples, another 3000 samples were used for estimating R-R interval, which was used to estimate probable location of T and P wave peaks. During another next 1500 samples (i.e. from 4500 to 6000 samples) T and P peak characterizations (slope- magnitude and polarity based) were determined. T and P wave detection is shown in Figure 5.7. A flowchart of T and P wave detection is indicated in Figure 5.8.
5.2.4.2 T and P wave searching zone

T and P waves were determined in reference with last detected R-peak positions. As soon as successive R-peaks were determined, average R-R interval was calculated in a cumulative manner. The ECG wave-segment part between each successive pair of QRS-offset and the following QRS-onset constitute non-QRS region as shown in Figure 5.7, where T-wave of the current beat and P-wave of the following beat occur. Staying at an \( i^{th} \) point in non-QRS region, subsequent QRS-onset point was estimated with respect to last detected R-wave peak position and using average R-R interval. P and T waves were identified on the basis of their location, in non-QRS region, and respective searching zones for T and P wave were formed.

Figure 5.7: T and P peak detection
Figure 5.8: Q, S, T and P peak detection flow chart
5.2.4.3 Slope calculation

Since T and P waves are more blunt than Q, R, S waves and of larger duration, hence for determining T and P wave slope, both side 50 sample slope was considered, for determining slope and polarity based characteristics of P and T wave, during training and detection phase. That is why 100 sample FIFO stack was actually maintained to store the history of last 100 sample values. R, Q and S peak detection has utilized only last 40 samples of the stack. If i represent current captured sample’s absolute index, then (i-50)th sample was considered as current sample of reference-which was checked for a valid T or P wave peak. 50 sample slope was calculated with respect to current sample of reference for both sides (left and right) of it. Then following checking’s were made for each successive current sample of reference, corresponding to each captured sample, in respective searching zones.

5.2.4.4 Detection of T and P wave

The principle of T and P wave detection is illustrated in Figure 5.7. FPGA device maintains a first in first out (FIFO) stack to store past history of last 200 samples as shown in Figure 5.2. Point ‘A’ corresponds to current sample, point ‘B’ and ‘C’ corresponds to 50 and 100 sample before the current sample, as shown in figure 5.7. That means while capturing ith sample value, staying at point ‘A’, the middle element in the stack being the amplitude of (i-100)th sample, which corresponds to point ‘C’ and last element being amplitude of ith sample corresponding to point ‘A’ in Figure 5.7. The point ‘B’, which corresponds to (i-50)th sample was checked for a valid T or P wave peak after capturing ith sample. SlpB50 and SlpB50 represent 50-sample left side slope and right side slope w.r.t. point ‘B’, in the P and T wave detection and training period.
5.2.4.5 T wave characteristics extraction during training period

To determine T wave signature during a training period of 4500 to 6000 samples, following conditions were checked for each B points (Ref. Figure 5.7).

a) \( S_{Blp}\_50 > 0 \) and \( S_{Blp}\_50 > 0 \) and \( m_{r-50} > m_{r-40} \) and \( m_{r-50} > m_{r-51} \) or
\( S_{Blp}\_50 < 0 \) and \( S_{Blp}\_50 < 0 \) and \( m_{r-50} < m_{r-40} \) and \( m_{r-50} < m_{r-51} \)

b) \( K_p > (K_{last} + 80) \)

where \( k_{B} \) represent ‘B’ point index and \( k_{last} \) represent last detected R peak index. So that any Q or S wave or any point in that region cannot be wrongly interpreted as T or P wave.

c) \( K_p > (K_{last} + 0.5 \times t_{RR} - 10) \)

where \( t_{RR} \) represent latest average R-R interval.

Amongst those ‘B’ points that satisfy above given criteria, maximum of average of both side slopes (\( \left( |S_{Blp}\_50| + S_{Blp}\_50 \right) / 2 \)) was calculated in two separate groups based on whether both side slope is positive or negative going towards ‘B’ point. This was denoted as \( S_{T\_max}\_avg \). \( S_{Blp}\_50 \) and \( S_{Blp}\_50 \) were also noted separately for both the groups, for those points, for which average of both side slope is maximum. They were denoted respectively as \( S_{T\_max}\_left \) and \( S_{T\_max}\_right \). Hence at the end of training period both groups were having with their \( S_{T\_max}\_avg \), \( S_{T\_max}\_left \) and \( S_{T\_max}\_right \). The group having higher \( S_{T\_max}\_avg \), was considered dominant, and determined the polarity of T wave. Left and right side T wave slope threshold value (\( S_{T\_th}\_left \) and \( S_{T\_th}\_right \)) was denoted as 0.75 * \( S_{T\_max}\_left \) and 0.75 * \( S_{T\_max}\_right \) respectively, calculated from the dominant group.
5.2.4.6 P wave characteristics extraction during a training period

P wave was searched in a similar approach like T, during a training period of 4500 to 6000 samples, but the concerned searching zone was different. The criteria b and c imposed for T wave characterization was modified in the following way for detecting the signature of P-wave peak.

b) \( K_B > (K_{LastR} + 0.5 \times t_{RR} + 10) \)

c) \( K_B > (K_{LastR} + t_{RR} - 80) \)

P slope threshold and the polarity of P wave were determined in the same way as mentioned for T wave characterization.

5.2.4.7 P and T wave detection phase

At the end of the training period T and P wave detection was initiated. For detection of T and P wave peaks after the training region, in addition to above mentioned three criteria a, b, c, one additional criteria d was imposed.

d) \( |Sp^{\phi}_{\omega B} > Sp^{\phi}_{\omega A} \ and \ |Sp^{p}_{\omega B} > Sp^{p}_{\omega A} \ for \ T \ wave \)

\( |Sp^{\phi}_{\omega B} > Sp^{\phi}_{\omega A} \ and \ |Sp^{p}_{\omega B} > Sp^{p}_{\omega A} \ for \ P \ wave \)

Left and right side absolute slopes with respect to the ‘B’ point should exceed respective thresholds for a wave to be considered as T wave or P wave.

Amongst the ‘B’ points that satisfy above mentioned four criteria, was chosen as the concerned T or P wave peak.
5.2.5 Baseline detection and wave peak height and duration detection

Individual wave peak heights were determined, by comparing wave peak temporal location magnitude w.r.t. the detected local baseline magnitude. Local baseline magnitude were determined in three different methods. In first method, average magnitude value of consecutive 30 sample value calculated at the midpoint of last two detected R peaks was considered as baseline magnitude. In second approach, 30 sample absolute slope was calculated in the middle one third region of an estimated next R-R interval, after detecting each successive R peaks. The point having minimum 30 sample absolute slope in that region, was used for estimating baseline voltage. But it was checked that w.r.t. middle point of that 30 point region, both side 50 sample slope should not exceed T slope threshold value. This was used to avoid any U wave, being miss-detected as baseline. If the criteria was satisfied, then average magnitude value of said 30 point region was considered as baseline voltage. In third approach, it was calculated that which of the quantized digital value (0-255), was assumed more frequently by the samples between last two detected R peaks. For this purpose a counter was maintained for each quantization levels. Most frequently used quantization level was assumed as baseline magnitude. Height of individual wave peaks determined, w.r.t. final baseline voltage calculated during last R-R interval. Wave peak duration (QRS duration, T and P wave duration) were calculated w.r.t. detected onset and offset points of respective wave peaks. Considering widest T wave from consultation with medical professionals, it was assumed that maximum duration of an ECG component wave can be maximally 300 ms. QRS duration was determined by calculating the difference of temporal location of Q wave onset and subsequent S wave offset for qRs type wave peak. Onset point search of a peak was initiated just after detection of the peak. Starting from that particular peak point, a backward search (i.e. towards previous sample values) was initiated until the value of an ECG sample remains within 0.8% tolerance of last baseline magnitude. If within previous 150 samples, no such onset point detected, some relaxation on percentage of tolerance was applied in a recursive manner, until a valid onset point detected. Figure 5.9 illustrates the use of 200 element FIFO stack for T or P peak onset point determination Offset point detection of a particular peak was initiated 150 samples after the peak occurrence. Here a forward search was initiated from peak point towards next 150 samples. For the detection of onset and offset point a FIFO stack to hold last 150 ECG samples around a peak was required. The 100 sample FIFO stack memory as used for T and P wave peak detection, can hold last 50 samples about T and P wave peak. Hence FIFO stack size was incremented, to hold last 200 samples.
(instead 100 samples) so as to hold last 150 samples around any peak point, for the purpose of detection of onset and offset points.

Figure 5.9: Use of 200 element FIFO stack for T or P peak onset point determination

5.3 Testing of the feature detection algorithm

5.3.1 Testing in Xilinx ISE 8.2i simulation environment

After successful validation in MATLAB, the algorithm was simulated using Xilinx ISE 8.2i. The block diagram of the system in simulation environment is shown in Figure 5.10. For simulating the developed algorithm two VHDL modules were designed. One module was named as ‘test bench module’. This module plays the role (or simulates the behavior/performance) of PC and the rest of SDK board other than FPGA kit. ‘Test bench module’ reads the digitized ECG data files and deliver the digitized ECG samples to main ‘design module’ in synchronization with 1 kHz trigger pulse. 1 kHz trigger pulse was also generated by test
bench module. The ‘design module’ was called from the ‘test bench module’. An instance of FPGA module was created within the test bench module to simulate its performance. Actually two control signals were used to synchronize the data transfer, as described in methodology section. The ‘test bench module’ is simulatable module and the ‘design module’ is FPGA synthesizable or implementable module. The ‘design module’ captures the digitized ECG samples at regular intervals and process the data. The ‘design module’, on detection of an Q, R, S, T or P wave peak, complements the logic levels of five output signals named Q10, R10, S10, T10 or P10 respectively. These Q10, R10, S10, T10 and P10 signals were captured by ‘test bench module’, while delivering ECG samples, and were stored in five separate files. These five newly generated files along with the concerned ECG data file was used for simultaneous plot of Q10, R10, S10, T10, P10 and ECG signal, to determine wave peak detection correctness. Figure 5.11 (a) and (b) shows the timing diagram of Q10, R10, S10, T10 and P10 signals, obtained with Xilinx ISE 8.2i simulation, for V6 lead of ptbdb ECG dataset record numbers s0072lre and s0143lre respectively. The Figure 5.11 also shows last detected Q, R, S, T and P wave peak index positions, on detection of successive wave peaks, in decimal notation with latency of 20 ms for R peak and 50 ms for T and P wave peaks.

Figure 5.10: The block diagram of the system in simulation environment
Figure 5.11: (a) and (b) Simulation result of wave peak detection with V6 lead of pttd-db record no. (a) s0072lre (b) s0143lre
5.3.2 Implementation in Xilinx Spartan III

After simulating the algorithm in Xilinx ISE 8.2i, the algorithm was implemented in the Xilinx FPGA. The block diagram of the designed system is indicated in Figure 5.12. Interfaces of the design module is indicated in Figure 5.13. The main ‘design module’ was implemented on Xilinx Spartan XC 3s1500fg320-4. Figure 5.14 (a) shows the experimental setup used for FPGA based ECG feature Extraction. The Experimental setup used for FPGA based ECG filtering has been already described in section 4.3.3. Figure 5.14 (b, c) shows detection of R and T wave peak by FPGA using R10 and T10 signal, displayed within a DSO (Digital Storage Oscilloscope). The R10 and T10 signal, as described earlier, alternate their logic levels on detection of R and T wave with a latency of 20ms and 50 ms respectively. Apart from displaying different wave peak indicator signals within DSO, Q10, R10, S10, T10 and P10 binary signals, as outputted from FPGA, were captured through status port and serial port of PC. Q10, R10, S10, T10 and P10 signals, as captured by PC M1(described in section 4.3.3), were scaled to 50, 255, 100, 200, 150 values respectively, before storing them to five separate files. The simultaneous plot of scaled Q10, R10, S10, T10, P10 and quantized ECG signal, as shown in Figure 5.15 (a-d), shows Xilinx implemented wave peak detection results for some ptbdb (a, b) and mitdb (c, d) ECG data files respectively. For visual clarity only 6000 to14000 samples are shown. The Table 5.2 summarized the resource utilization within FPGA device Xilinx Spartan XC 3s1500fg320-4 for the said implementation of the algorithm.
Figure 5.12: Block diagram of FPGA based ECG wave peak detection and feature extraction

Figure 5.13: Interfaces of the designed module along with assigned pins of Xilinx xc3s50pq208
[20 ms after the occurrence of an Q or R or S peak, they are detected, according to the algorithm. Similarly the algorithm detects T and P peaks with 50 ms latency]
Figure 5.15: (a) and (b) Xilinx implemented wave peak detection with ptbdb ECG data files
Figure 5.15: (c) and (d) Xilinx implemented wave peak detection with mitdb ECG data files

Table 5.2. Device utilization summary using Xilinx Spartan III XC3S1500FG320-4

<table>
<thead>
<tr>
<th>Elements</th>
<th>Used</th>
<th>Available</th>
<th>% Of use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Slices</td>
<td>12872</td>
<td>13312</td>
<td>96%</td>
</tr>
<tr>
<td>Number of Slice Flip Flops</td>
<td>4679</td>
<td>26624</td>
<td>91%</td>
</tr>
<tr>
<td>Number of 4 input LUTs</td>
<td>24269</td>
<td>26624</td>
<td>91%</td>
</tr>
</tbody>
</table>
In the said feature detection algorithms, the evaluation criteria were Sensitivity ($S_e$) and Positive Predictivity ($P+$), as defined in chapter 1. A total of 180 single lead data, each containing 60000 samples was tested, with an average $S_e$ and $P+$ of 98.4% and 98.17% respectively for R peak detection. An average $S_e$ and $P+$ of 97.58% and 96.84% for P wave detection, and 97.78% and 98.04% for T wave detection were obtained respectively. Table 5.3 represents some of the sensitivity and predictivity values for R peak detection on single lead ECG using mitdb data with Xilinx implementation. Table 5.4 and 5.5 shows some test results for P and T wave detection respectively with ptbdb data. Table 5.6 and 5.7 represent a comparison of $\%$FN, $\%$FP and $\%+P$ obtained in Xilinx implementation of the of P and T wave detection in the presented algorithm with another reported work. The table shows an appreciable detection rate for current implementation. Table 5.8 and 5.9 shows the comparison of algorithmically measured relative duration and height values with actual values for P and T waves respectively. Relative duration and height were measured w.r.t. determined average R-R interval and total amplitude span of QRS wave.

Table 5.3: Sensitivity and Predictivity figures for R peak detection using mitdb data (with Xilinx implementation)

<table>
<thead>
<tr>
<th>Patient-ID in Physionet</th>
<th>Lead</th>
<th>$%R_e$</th>
<th>$%P+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>V5</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>102</td>
<td>V2</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>103</td>
<td>V2</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>104</td>
<td>V2</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>106</td>
<td>V1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>107</td>
<td>V1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>108</td>
<td>V1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>109</td>
<td>V1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>112</td>
<td>V1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>113</td>
<td>V1</td>
<td>100</td>
<td>85</td>
</tr>
</tbody>
</table>
### Table 5.4: Sensitivity and Predictivity figures for P peak detection using ptbdb data (with Xilinx implementation)

<table>
<thead>
<tr>
<th>Patient-ID and record number in Physionet</th>
<th>Lead I</th>
<th>Lead II</th>
<th>aVR</th>
<th>V2</th>
<th>V5</th>
</tr>
</thead>
<tbody>
<tr>
<td>P172/S0304LRE(N)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>P182/S0308LRE(N)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>P121/S0311LRE(N)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>P006/S0022LRE(MI)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>P046/S0168LRE(MI)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>P003/S0017LRE(MI)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>85</td>
<td>92</td>
</tr>
</tbody>
</table>

(Narration: N: Normal data; MI: Myocardial Infarction)

### Table 5.5: Sensitivity and Predictivity figures for T peak detection using ptbdb data (with Xilinx implementation)

<table>
<thead>
<tr>
<th>Patient-ID and record number in Physionet</th>
<th>Lead I</th>
<th>Lead II</th>
<th>AVR</th>
<th>V2</th>
<th>V5</th>
</tr>
</thead>
<tbody>
<tr>
<td>P185/S0336LRE(N)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>P184/S0363LRE(N)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>P121/S0311LRE(N)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>P005/S0021BRE(MI)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>P005/S0021ARE(MI)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>P014/S0071LRE(MI)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

(N: Normal data; MI: Myocardial Infarction)
Table 5.6: Comparison of P peak detection performance with other reported work

<table>
<thead>
<tr>
<th></th>
<th>Actual No. Of P waves</th>
<th>TP</th>
<th>FN</th>
<th>FP</th>
<th>TE</th>
<th>% FN</th>
<th>% FP</th>
<th>%+P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Presented work</td>
<td>12437</td>
<td>12043</td>
<td>394</td>
<td>308</td>
<td>702</td>
<td>3.17%</td>
<td>2.47%</td>
<td>97.51%</td>
</tr>
<tr>
<td>Threshold-based Detection of P and T-wave [43]</td>
<td>16301</td>
<td>15810</td>
<td>491</td>
<td>427</td>
<td>918</td>
<td>3.01%</td>
<td>2.62%</td>
<td>97.35%</td>
</tr>
</tbody>
</table>

Table 5.7: Comparison of T peak detection performance with other reported work

<table>
<thead>
<tr>
<th></th>
<th>Actual No. Of T-waves</th>
<th>TP</th>
<th>FN</th>
<th>FP</th>
<th>TE</th>
<th>% FN</th>
<th>% FP</th>
<th>%+P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Presented work</td>
<td>12705</td>
<td>12412</td>
<td>293</td>
<td>352</td>
<td>645</td>
<td>2.31%</td>
<td>2.77%</td>
<td>97.24%</td>
</tr>
<tr>
<td>Threshold-based Detection of P and T-wave [43]</td>
<td>17833</td>
<td>17479</td>
<td>354</td>
<td>549</td>
<td>903</td>
<td>1.93%</td>
<td>3.08%</td>
<td>96.98%</td>
</tr>
</tbody>
</table>

Table 5.8: T wave relative duration and relative height

<table>
<thead>
<tr>
<th>Lead, Patient ID, record No. and MI type from ptbdb database</th>
<th>duration</th>
<th>height</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured (algorithmic) mean</td>
<td>Actual mean</td>
</tr>
<tr>
<td>I 027/s0096lre (Anterio Lateral)</td>
<td>0.2107</td>
<td>0.2285</td>
</tr>
<tr>
<td>V4 027/s0096lre (Anterio Lateral)</td>
<td>0.1570</td>
<td>0.1863</td>
</tr>
<tr>
<td>aVL 293/s0557_re (Anterio Lateral)</td>
<td>0.3941</td>
<td>0.3619</td>
</tr>
<tr>
<td>II 004/s0020bre (Anterio Septal)</td>
<td>0.1748</td>
<td>0.1892</td>
</tr>
<tr>
<td>III 043/s0141lre (Lateral)</td>
<td>0.3566</td>
<td>0.3142</td>
</tr>
<tr>
<td>V6 105/s0303lre (Normal)</td>
<td>0.3248</td>
<td>0.2940</td>
</tr>
</tbody>
</table>
Table 5.9: P wave relative duration and relative height

<table>
<thead>
<tr>
<th>Lead, Patient ID, record No. and MI type from ptbdb database</th>
<th>duration</th>
<th>height</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured (algorithmic) mean</td>
<td>Actual mean</td>
</tr>
<tr>
<td>II 038/s0162lre (Anterio Lateral)</td>
<td>0.2225</td>
<td>0.1987</td>
</tr>
<tr>
<td>I 027/s0096lre (Anterio Lateral)</td>
<td>0.1438</td>
<td>0.1347</td>
</tr>
<tr>
<td>II 293/s0557_re (Anterio Lateral)</td>
<td>0.4551</td>
<td>0.3968</td>
</tr>
<tr>
<td>II 004/s0020bre (Anterio Septal)</td>
<td>0.2298</td>
<td>0.2378</td>
</tr>
<tr>
<td>V5 025/s0091lre (Anterio Septal)</td>
<td>0.1198</td>
<td>0.1134</td>
</tr>
<tr>
<td>aVF 122/s0312lre (Normal)</td>
<td>0.1407</td>
<td>0.1538</td>
</tr>
</tbody>
</table>

5.4 Conclusion

This chapter describes an approach for real time detection of ECG wave peaks, followed by measurement of clinical features using FPGA system. In the current implementation, only normal and a few MI variant data was used with the respective lead. The implementation of the proposed algorithm in FPGA device had a latency of 20 ms for Q, R and S-peak and 50 ms for T and P peak plus few nano-seconds (for actual implementation of the algorithm by the programmable hardware). T and P peak onset points were detected with a latency of 200 ms. Hence with this perspective, the algorithm can be claimed as a near real time algorithm, instead claiming it to be real time algorithm. An average sensitivity and predictivity of 97.58% and 96.84% for P wave detection, and 97.78% and 98.04% for T wave detection were obtained respectively. Different features, which include different ECG component wave peak heights and duration of different ECG characteristics wave segments were determined with an average 3% error. A comparison of P and T peak detection performance with other reported works was depicted in Table 5.6 and 5.7. Table 5.2 summarizes the resource utilization within FPGA device Xilinx Spartan XC 3s2000fg900-4, for the said implementation of the algorithm. As per resource utilization, design described in [68-69], consumes 76% resource of Xilinx Spartan xc3s400 for R wave peak detection only, which is much higher than present implementation. If Q, R, S, T and P wave peak detection algorithm (excluding height, duration detection and LCD interface) of the present implementation, is mapped to architecture of Xilinx xc3s400, it consumes
only 50% resources. Using extracted ECG features in FPGA hardware, a classification was performed between three category of heart patients (subjects), as described in chapter 6.

**Publication out of the work presented in this chapter:**


