Real-Time ECG Beat Detection by using Adaptive Threshold with MATLAB HDL Coder

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***Abstract*—** The ECG beat detection is the essential process in the ECG analysis. By detecting its position, we can learn the physiological information of the subjects, e.g. heart rate. In this paper, we propose an FPGA oriented real-time ECG beat detection with MATLAB HDL Coder/Verifier. The detection algorithm is based on Pan-Tompkins algorithm. MATLAB HDL Coder/Verifier is used to convert floating point algorithm to fixed point algorithm and generate Verilog Hardware Description Language (Verilog HDL). The testing results show that the proposed architecture can achieve an efficient detection performance where the average detection accuracy exceeds 98.57%. The performance of algorithm tested against MATLAB routine and validated results based on the MIT-BIH arrhythmia database.

Keywords*—*ECG, QRS Complex, Pan-Tompkins, HDL Coder, MIT-BIH

I. INTRODUCTION

Electrocardiogram is one of the famous diagnosing tools which measure the electrical activities of the heart and record the details. The signals are used for early diagnosis of heart abnormalities and record changes in the heart. A typical ECG wave of a normal heartbeat consists of a P wave, R peak (QRS complex), and a T wave [1] as shown in Fig. 1. In ECG processing it is very important to accurately detect heartbeats, because it is the base for further analysis and can also be used to get information about heart rate. The energy of heartbeats is mainly located in the QRS complex, so an accurate QRS detector is the most important part of ECG analysis [2]. The QRS complex is the most extreme waveform, caused by ventricular depolarization of the human heart.

Thus, ECG is an effective tool for diagnosis of the heart abnormalities. On the other hand, it is a very time-consuming job for doctors to analyze long ECG records. Therefore, many computer-based methods have been proposed for automatically diagnosis of the ECG beat abnormalities. Thus, an accurate QRS detector is an important part of many ECG analysis tools. QRS detection is difficult, not only because of the physiological variability of the QRS complexes, but also because of the various types of noise that can be present in the ECG signal.

During the past decades, there have been many preprocessing and feature extraction algorithms applied to ECG signals and many of these algorithms have been further developed and implemented. However, most of them deal with signal processing techniques that use software applications. The complete signal processing of recognition is aimed to be implemented in FPGA (field programmable gate array).

FPGA is a programmed logic component which contains a matrix of reprogrammable logic blocks. The logic blocks are linked to each other by an interconnection network and can be controlled to be configured so that the FPGA can perform complex combinational functions. FPGA has many advantages, such as low price, inherent parallelism and fully customized design and configuration. Therefore, the FPGA is now widely used in the biomedical signal processing.

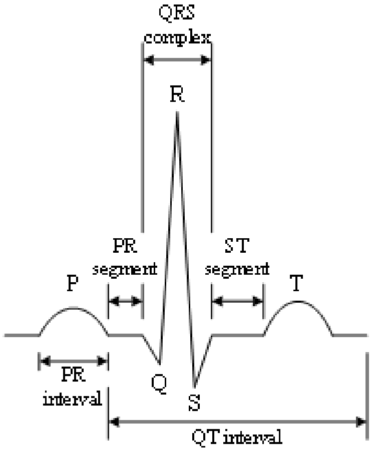

Fig. 1. Typical ECG waveform

II. RELATED WORK

In the literature, many methods, for example, Pan-Tompkins algorithm [3], have been proposed to detect the QRS complex from the ECG signal. However, these widely used algorithms are always implemented in the software on the personal computer and cannot be directly implemented in FPGA.

Bo Zhang et al. [4] presented an FPGA implementation of the QRS detection algorithm using integer Haar wavelet. The implementation was described in VHDL (Hardware Design Language) and was tested on an FPGA Cyclone EP3C5F256C6. In [5] and [6], the Pan-Tompkins algorithm was embedded in the FPGA-Based embedded system for the QRS complex detection as a processing stage of the automated ECG analysis system.

Stojanovi'c et al. [7], the authors presented a novel FPGA system for QRS complex detection using the Integer Haar Transform (IHT). The system was implemented in FPGA Cyclone EP1C12Q240 chip and an on-chip detection accuracy of about 95% was obtained. Similarly, in [8], the authors used the same strategy to detect the QRS complex from the ECG signal and presented an FPGA based telemonitoring system to detect cardiac Arrhythmia for high-risk cardiac patients.

III. METHODOLOGY

In general, the ECG analysis and the ECG beat detection algorithms share the same architecture which is represented in two stages. The first stage is preprocessing stage and the second stage is QRS detection as shown in Fig. 2. In this section, the general structure of the QRS detection algorithm and its key functionalities are described.

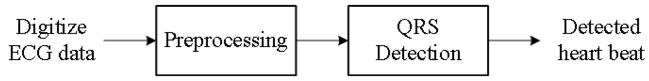

Figure 2. Block diagram of real-time ECG beat detection algorithm

A. Preprocessing Stage

ECG signal contains noises due to baseline drift, high-frequency interference, muscle noise, internal amplifier noise. The common problem in ECG signal processing is base line drift removal and noise suppression. The preprocessing stage involves four steps such as bandpass filter, derivative filter, Squaring Function and moving window integration as shown in Fig. 3.

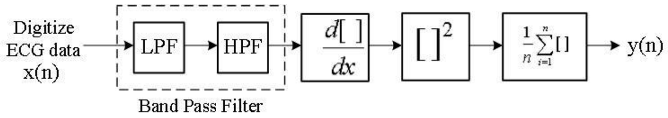

Fig. 3. Block diagram of preprocessing stage

1) Band-pass Filter: The band-pass filter reduces baseline drift, high-frequency interference, muscle noise, internal amplifier noise. The filter consists of cascaded low-pass and high-pass filters [3].

The low-pass filter is characterized by:

$$H(z) = \frac{(1-z^{-6})^2}{(1-z^{-1})^2} \tag{1}$$

The high-pass filter is implemented by subtracting a low-pass filter from all-pass filter

$$H(z) = z^{-16} - \frac{1}{32}\frac{(1-z^{-32})}{(1-z^{-1})} \tag{2}$$

2) Derivative Filter: The differentiator is used to provide the QRS complex slope information. This filter is widely used among the ECG analysis algorithms to find the slope information because the slope of the QRS complex is generally larger than the other features in the ECG waveform [9]. The difference equation for the derivative filter is shown in below.

$$H(z) = \frac{1}{8}[-z^{-2} - 2z^{-1} + 2z^{1} + z^{2}] \tag{3}$$

3) Squaring Function: Squaring the ECG signal means that the high frequencies will be emphasized and the entire data signal will be positive. The equation of this operation is

$$y(n) = [x(n)]^2 \tag{4}$$

4) Moving Window Integration: The moving window integration is a type of FIR filter that adds the N previous samples from the previous stage and then divides the sum by N.

$$y(n) = \frac{1}{N}\sum_{k=1}^{N} x(n-k) \tag{5}$$

B. QRS Detection Stage

The QRS Detection Stage consists of two phases, local peak detection and R-peak detection, using comparison with adaptive thresholds as shown in Fig. 4.

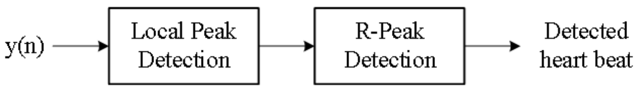

Fig. 4. Block diagram of QRS detection stage

1) Local Peak Detection: Local maximum is identified when the signal is to half its peak height, or it has been 200 ms since the peak height was detected. There can only be one QRS complex in any 200 ms window.

2) R-Peak Detection: The thresholding procedure in the original Pan-Tompkins algorithm adapts to changes in the ECG signal by computing running-estimates of signal and noise peaks. The signal peak is defined as the effective QRS complex, while noise peak represents the T wave.

In this algorithm, the thresholds are adapted with the latest signal peak or noise peak mean of previously detected eight peaks. In this way, the algorithm adapts dynamically to changes in the ECG signal from a particular person, improving by this manner once again the accuracy.

If P_k is signal peak,

$$SPK = \frac{1}{N}\sum_{k=1}^{N} P_k \tag{6}$$

If P_k is noise peak,

$$NPK = \frac{1}{N}\sum_{k=1}^{N} P_k \tag{7}$$

The threshold is calculated by using the following equation.

$$THR = NPK + 0.25(SPK - NPK) \tag{8}$$

IV. Implementation and Results

We used the MATLAB HDL Coder/Verifier to simulate and implement the ECG beat detection algorithm on FPGA platform [10]. Firstly, the ECG beat detection algorithm is simulated in MATLAB using floating point arithmetic and then converted to fixed-point arithmetic. Next process is to generate Verilog Hardware Description Language (Verilog HDL) code and co-simulate with test bench. The data records used to test the design were obtained from the MIT-BIH arrhythmia database from the Physionet website [11]. We used mainly first 61 seconds of 19 records of the MIT-BIH arrhythmia database: 100 to 109 and 111 to 119. The preprocessing and the ECG beat detection results are shown in Fig. 5 and Fig. 6. The floating point and fixed-point arithmetic comparison and errors are shown in Fig. 7.

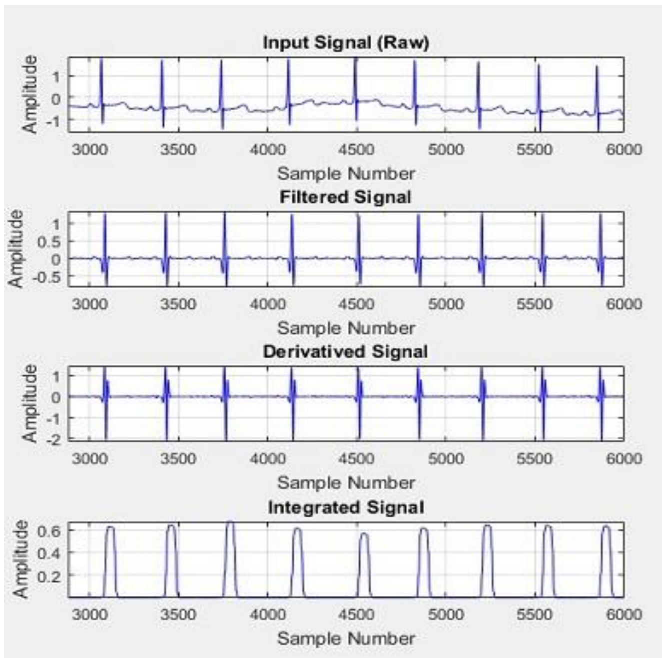

Fig. 5. Preprocessing result

Generic FPGA hardware resource utilization during MATLAB HDL code generation process is shown in Table I. These hardware resource utilization is generated with resource sharing factor of 1. If this factor is changed, the number of multipliers, adders, registers and multiplexers will be changed to optimize resource area.

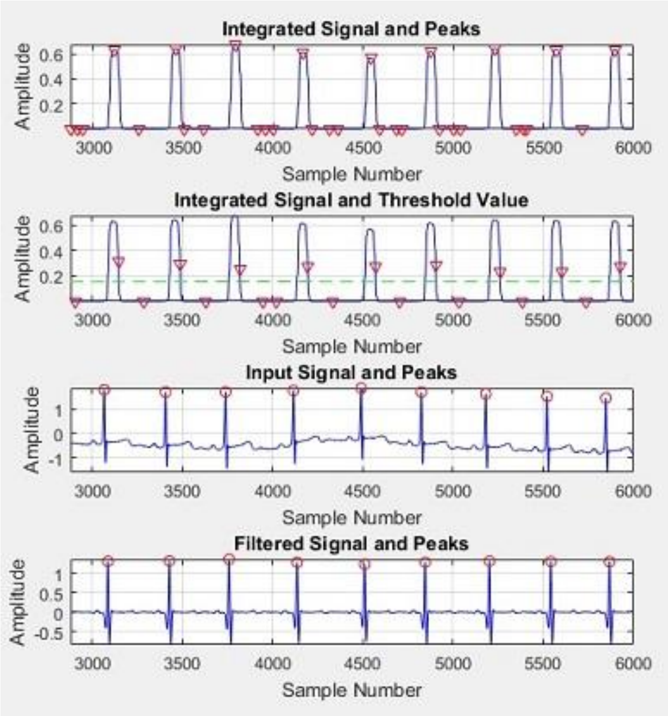

Fig. 6. R-Peak detection

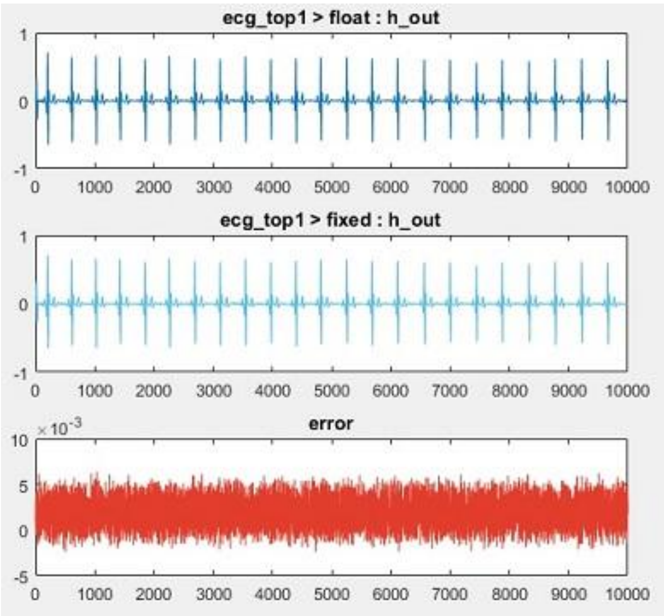

Fig. 7. Floating-point and fixed-point comparison

The Table II illustrates errors and accuracies of 19 records in the MIT-BIH arrhythmia database. The accuracy of the QRS complex detection is calculated as

$$\text{accuracy} = \left(1 - \frac{\text{error}}{\text{actual value}}\right) \times 100\% . \quad (9)$$

Overall, the accuracies of records are high above 95%, except for record 119 which has only 90.63% accuracy. The 100% accuracy is achieved for 8 records and other 8 records has above 97% accuracy. The testing results show that the proposed architecture can achieve an efficient detection performance where the average detection accuracy is 98.57%. The performance of algorithm is tested against MATLAB routine and validated the results based on the MIT-BIH arrhythmia database.

Table 1: Hardware Resource Utilization

Resource	Utilization
Multipliers	54
Adders/Subtractors	75
Registers	352
Total 1-Bit Registers	4454
Multiplexers	373
I/O Bits	220
Shifters	0

Table 2: QRS Detection Accuracy

No	File Name	Original Beat	Detected Beat	Absolute Error	Accuracy
1	100.dat	65	65	0	100.00%
2	101.dat	63	63	0	100.00%
3	102.dat	64	64	0	100.00%
4	103.dat	62	63	1	98.39%
5	104.dat	68	65	3	95.59%
6	105.dat	73	74	1	98.63%
7	106.dat	62	61	1	98.39%
8	107.dat	62	62	0	100.00%
9	108.dat	55	55	0	100.00%
10	109.dat	81	80	1	98.77%
11	111.dat	62	61	1	98.39%
12	112.dat	75	75	0	100.00%
13	113.dat	51	52	1	98.04%
14	114.dat	48	49	1	97.92%
15	115.dat	56	56	0	100.00%
16	116.dat	70	69	1	98.57%
17	117.dat	44	43	1	97.73%
18	118.dat	64	64	0	100.00%
19	119.dat	64	58	6	90.63%
	Total	1189	1179	17	
	Average				98.57%

CONCLUSION

In this paper, we present an FPGA oriented ECG beat detection in MATLAB environment with HDL Coder and Verifier plus-in that implements the most popular algorithm and widely adopted by the patient monitoring industry, that is, the Pan and Tompkins QRS detector algorithm, which is based on slope, amplitude and width information. The information about the R Peak and QRS complex obtained is very useful for ECG classification, analysis, diagnosis authentication and identification performance. The QRS complex is also used for beat detection and the determination of heart rate through R-R interval estimation. The main advantage of this research is less time-consuming for FPGA development with the best accuracy, but little more resource utilization. As our research is still in progress, our future work is the FPGA implementation of ECG beat classification with artificial neural network using MATLAB HDL coder. Thus, in the end, the complete ECG signal processing will be implemented in FPGA.

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