

Throb: System-on-Chip based Arrhythmia Screener with Self Interpretation

Huey Woan Lim, Mohd Syafiq Affendi bin Mohd Sani, Amin Hashim, Yuan Wen Hau

Abstract—This paper presents an in-house design of System-on-Chip (SoC) based arrhythmia screener, so-called *Throb*, with self-arrhythmia classification using electrocardiograms (ECG) as the input signal. It is a light-weight, cost effective and equips with intuitive touch screen graphical user interfaces (GUI) design. It is able to provide early screening of arrhythmias for the public, especially for the small clinics and general hospital in rural area where the specialists or cardiologists are not sufficient to the population. *Throb* applies knowledge-based classification to identify Premature Ventricular Contraction (PVC), Ventricular Fibrillation (VF), Second Degree Heart Block, and Atrial Fibrillation (AF). The verification input is based on offline ECG dataset obtained from MIT BIH online arrhythmia database. The complete system is implemented on Terasic Video Embedded Evaluation Kit with Multitouch (VEEK-MT) which utilizes the Altera Cyclone IV FPGA chip and capacitive touch screen. This system is also equipped with the ECG acquisition unit to obtain the ECG from the patient as input signal. Result shows that this system is user friendly, and the arrhythmia classification accuracy of PVC is 88.56%, VF is 96.30%, 2nd degree heart block is 85.71% and AF is 86.17%, respectively.

Index Terms— Arrhythmia, Electrocardiogram (ECG), Field Programmable Gate Array (FPGA), Knowledge-based Classification, System-on-Chip (SoC).

I. INTRODUCTION

BASED on World Health Organization (WHO), approximately 36% of the Malaysian population died in cardiovascular disease [1]. However, 50% to 70% of the victims are not aware of their heart condition. There was a phase said: “Prevention is better than cure”, hence frequent monitoring of cardiac condition plays a vital role in saving people life. The most effective way to save the potential cardiovascular victims is monitoring their heart condition in house regularly.

Among the cardiovascular diseases, sudden cardiac arrest is the most fatal and the stroke is the most severe cardiovascular disease [2], which mainly caused by ventricular fibrillation and

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atrial fibrillation, respectively. Other than that, 2nd degree heart block also could cause the heart attack, whereas the premature ventricular contraction is the most common arrhythmia among the public.

Normally, most of the arrhythmia could be diagnosed by monitoring the electrocardiogram (ECG), which is a non-invasive method to detect the heart rhythm by acquires heart electrical signal through ECG sensor. Usually patients could only monitor their ECG in the hospital due to the fact that ECG device is expensive, bulky, and lack of self-classification and interpretation system. As a result, the public suffers from long distance travelling and long time queuing for frequent cardiac monitoring. Hence, a light-weight and cost effective ECG device with self-arrhythmia interpretation is desired, not only to enable outpatients to perform home monitoring for frequent cardiac condition checking, but also small clinic and general hospital in rural area to provide arrhythmia screening.

This paper presents a design of arrhythmia screener, so-called *Throb*, with the features of intuitive front-end touch screen graphical user interfacing (GUI) and back-end ECG signal processing and arrhythmias classification, as well as the ECG acquisition unit. It is able to detect four types of arrhythmias, AF, VF, PVC and 2nd degree block which are the most common and severe arrhythmias. Other than that, the user friendly touch screen GUI allows the user to understand the operation of the device in no time. ECG acquisition unit allows the user to obtain their ECG signal instantly by attaching the electrodes to their limbs.

The paper follows the content structure of introduction, types of arrhythmia, proposed design, result and discussion, and finally conclusion.

II. TYPES OF ARRHYTHMIA

Sudden Cardiac Arrest (SCA) is the unexpected pulseless condition of the heart which might cause the brain damage if the emergency rescue does not reach immediately [2]. The main cause of SCA is the ventricular fibrillation (VF) in cases of myocardial infarction and acute coronary insufficiency [3]. VF is the ventricular heart chambers that cannot function normally and fail to pump the blood to whole body including the brain. Within minutes, if the victim does not obtain any rescue, such as cardiopulmonary resuscitation (CPR) and defibrillator or Automated External Defibrillator (AED), the person will die due to the lack of oxygen reaching to the brain. According to Mina, the most effective way to decrease the SCA is to find the basic mechanism of VF onset [3].

Atrial fibrillation (AF) is another type of the cardiovascular disease, in which the main risk factor is ischemic stroke [4]. The stroke caused by AF will lead to more severe and greater mortality and disability compared to the stroke that cause by

other factors. According to the Chee [5], 10.6% of the stroke patients in Malaysia are having AF and most of them do not aware of their heart conditions. Consequently, early detection of AF is very important for early prevention of stroke attack. The ECG sample of AF arrhythmia is as shown in Fig. 1.

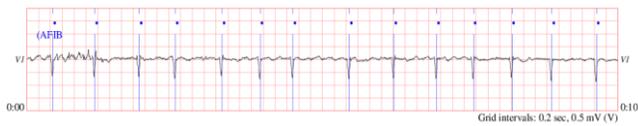


Fig. 1. ECG with Atrial Fibrillation (AF) from MIT-BIH online database

Premature ventricular contraction (PVC) is one of the most common arrhythmia in normal children and teenagers [6]. It is caused by an extra heart beat before the normal beat. This happens when the ventricular activation reaches the threshold early and the ventricular contracted.

Second degree heart block is a condition when an impulse from the Sinoatrial node is delayed longer than the previous impulse and this pattern of progressive prolongation the PR interval continuously. Lastly, the impulse fails to conducted to the ventricular and the ventricular unable to contract [7].

Many research works have been proposed in arrhythmia screening device design. For example, Jatmiko [8] implements an arrhythmia classification using wavelet techniques on an FPGA platform. However this system is designed without user friendly interfaces. Leutheuser [9] also implements arrhythmia detection on Android-based mobile devices, but it only could detect the existence of arrhythmia symptom without the detail arrhythmia type classification.

III. THROB – PROPOSED SYSTEM ARCHITECTURE DESIGN

Fig. 2 shows the top level of *Throb* system architecture, whereas Fig. 3 shows the overall system functionality behavioural flow. This work is implemented on Altera DE2-115 Video and Embedded Evaluation Kit-Multitouch (VEEK-MT) development board which utilize Cyclone IV FPGA chip and capacitive touch screen. Basically, the *Throb* can be divided into four subsystem which is ECG acquisition unit, offline ECG data management, front-end GUI design, and back-end ECG signal processing and arrhythmia classification.

ECG acquisition unit will acquire patient's ECG signal and it will store the offline ECG data at the external SD card and slots into VEEK-MT board. Based on the user option on from front-end touch screen GUI, the ECG signal processing and arrhythmia classification can be further break down into pre-processing part, R peaks detection and arrhythmia classification. After the classification, the user could view the result in terms of ECG signal, R-R interval as textual classification result. Currently, all the functionality is implemented as embedded software using C programming and executed by the ALTERA NIOS II processor.

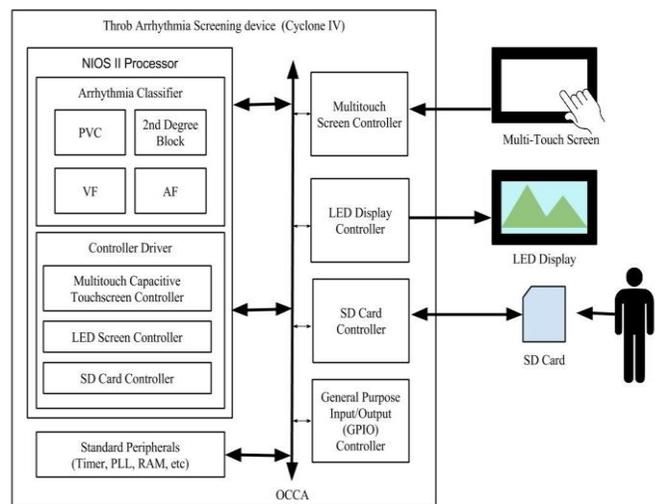


Fig. 2. The Top Level System Architecture

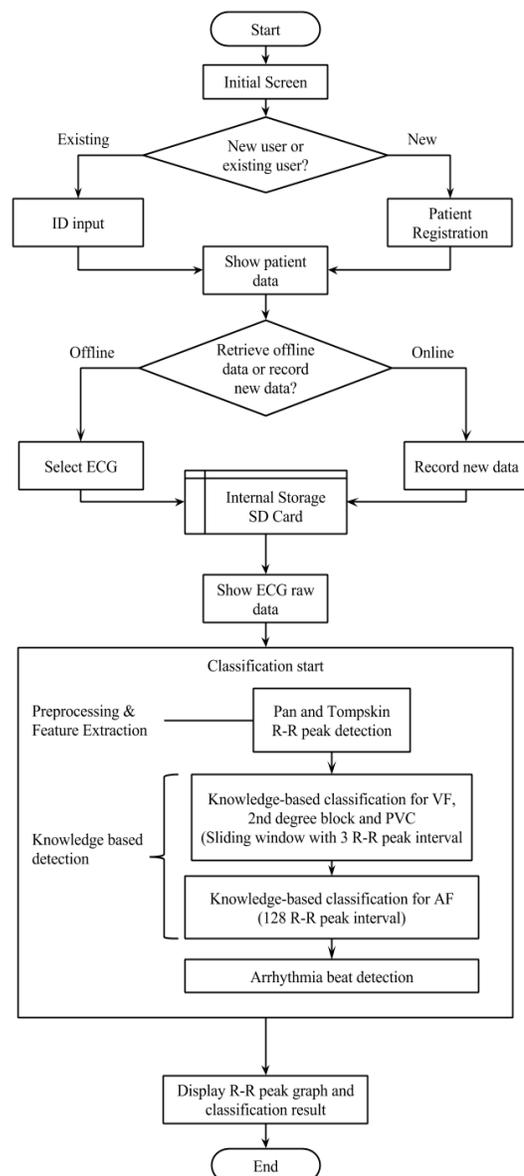


Fig. 3. The processing block diagram in *Throb*.

A. Touch-Screen Graphical User Interface

A user-friendly, easy to use graphical user interface (GUI) equipped with patient management features is included in the *Throb* system to assist and guide user through the system using the page mapping as shown in Fig. 4.

On the system start up, user will be greeted by the splash screen displaying a logo followed by the welcome screen that will ask the user whether the user is a new user or an existing user. If the user is a new user, they will be redirected to the registration where patient are required to key in their patient ID, name, age and gender. If the user is an existing user, they will be redirected to patient ID input page where they are required to key in their patient ID and then the system will search through the database for the patient previous data. Patient is then will see the information section where their information and list of recorded ECG data is displayed. To start the classification from existing records, patient need to select the data that will be processed from the ECG data list page. Before processing, the system will show the patient the ECG wave graph. After the classification, the patient will get into the result section where it will show the patient the R-R peak of the ECG data and the classification result.

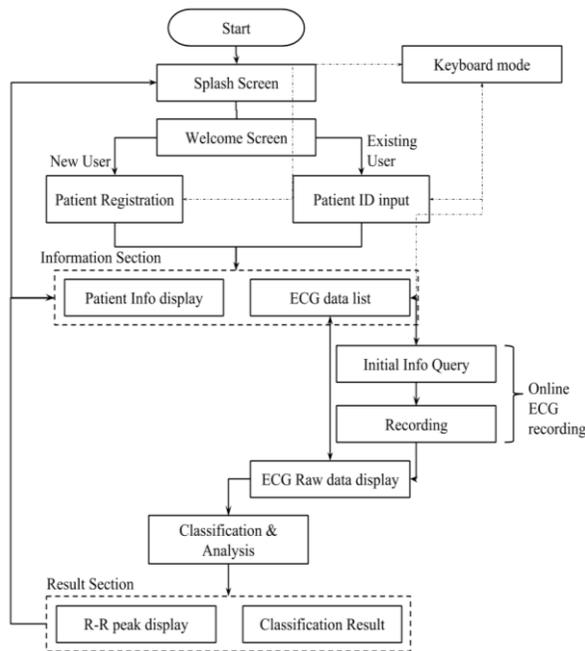


Fig. 4. GUI Page Mapping of *Throb*

B. ECG Acquisition Unit

The platform that we are using is equipped with an SD card slot. Offline ECG data consist of ECG data from SD card, which is stored in text file format and contains a number set. The ECG data might be obtained from ECG acquisition unit.

ECG acquisition unit utilizes embedded systems including Arduino UNO, Olimex EKG-EMG shield, and its passive electrode. The passive electrode is a standard three lead ECG electrodes accompanied by amplifier circuit, and the Olimex EKG-EMG shield. Next, the analogue ECG signal will be converted into digital signal and store in the SD card using the

Arduino UNO.

This procedure is good enough for the classification as the processing only needs ECG data from a single channel. The recorded ECG data is then stored into the SD card for later analysis. All the ECG data stored is managed by GUI patient management.

C. Offline ECG Data Management Subsystem

The VEEK-MT platform is equipped with an SD card slot to store the offline ECG data which might be obtained from other ECG recording machine. All the patient information is kept in a file named “*index.csv*” in the SD card. The CSV format, also known as Comma Separated Value is a simple format that can be accessed on desktop with spreadsheet application such as Microsoft Office Excel. This simplifies the process of retrieving and adding patient information because everything is in single file. By using comma and semicolon as separator, the system can breakdown a line into tokens necessary information such as patient ID, patient name, gender and age as shown in Fig. 5.

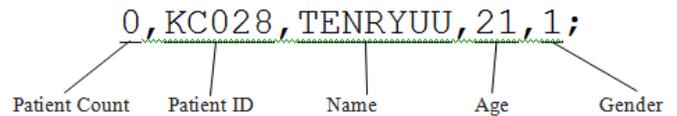


Fig. 5. Tokenization of CSV Syntax

For the management of multiple ECG files, a systematic file naming is used to identify the ECG wave files. The name of the file consist of patient ID, date and time ECG was recorded as shown in Fig. 6. A custom file extension named THW (Throb Wave) is created to avoid conflict with other files in the same folder.

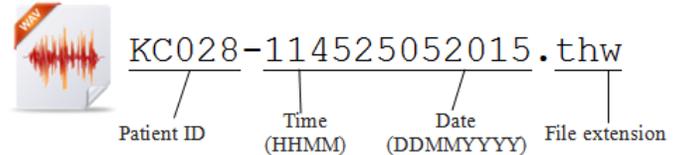


Fig. 6. Throb Wave File Naming Convention

D. ECG Signal Processing and Arrhythmia Classification

This subsection discusses the algorithm to perform the ECG pre-processing, features extraction and multiple arrhythmia classification in detail in following subsections. Fig.7 shows the behavioural flow of ECG signal processing and arrhythmia classification.

i. Pan and Tompkins with R peak detection

The function of the Pan and Tompkins algorithm [10] is used to filter out the noise from the raw ECG data. Other than that, it also serves as the R peaks detection algorithm which is very important stage for the further arrhythmia classification. Pan and Tompkins consists of four parts which are band pass filter, differentiator, squaring function and moving integrate window. The band pass filter consists of high pass and low pass filter in between the frequency 5 Hz to 15 Hz. The interest within this range of frequency is the QRS complex. The equation of low pass and high pass filter show in (1) and (2) respectively where $y(n)$ is the output signal of the low pass filters, $x(n)$ is the input

ECG signal, and $p(n)$ is the output signal of high pass filter.

$$y(n) = 2y(n - 1) - y(n - 2) + x(n) + 2x(n - 6) + x(n - 12) \tag{1}$$

$$p(n) = x(n - 16) - \frac{1}{32} [y(n - 1) + x(n) + x(n - 32)] \tag{2}$$

The differentiation stage is used to obtain the information on slope and overcome the baseline drift problem. Refer to (3), $x(n)$ is the input signal in differentiator which come from output of band pass filter and $y(n)$ is output signal of differentiator.

$$y(n) = \frac{1}{8} [2x(n) + x(n - 1) + x(n - 3) - 2x(n - 4)] \tag{3}$$

Squaring stages used to convert all negative value signals into positive value signals. It is also emphasizes the high frequency component but attenuates the low frequency component in ECG signal. Lastly, the moving window integral filter is used to smooth the signal for better R peaks detection algorithm. The squaring function shows in (4), where $y(n)$ is the output signal and $x(n)$ is the input signal of squaring function from the output of differentiator. The equation of moving integrate window shows in (5), where $y(n)$ is the output signal and the $x(n)$ is the input signal from the output of squaring function.

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

$$y(n) = \frac{1}{32} \sum_{k=1}^{32} x(n - k) \tag{5}$$

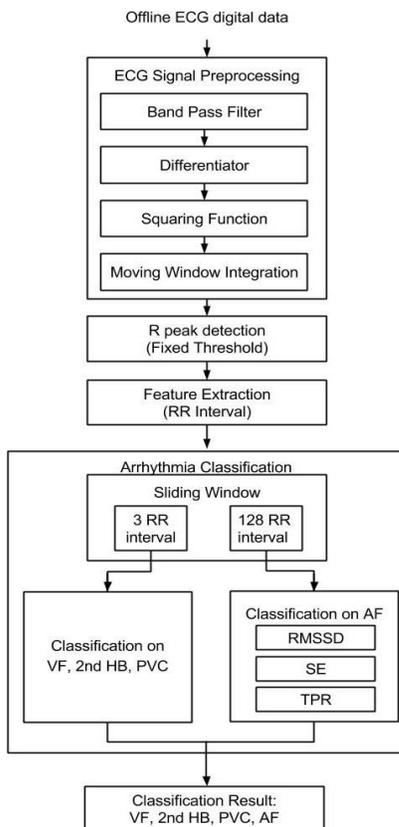


Fig. 7. ECG Signal Processing and Arrhythmia Classification

A threshold algorithm is being introduced to detect the R peaks. If the output from the moving window integration passing through the threshold, it will be detected as R peak. Next it will compare with the next eight peaks and the highest peak value. Lastly, it will only be confirmed that the peak detected have the highest value since the R peak is the highest amplitude compare to others.

ii. Arrhythmia Classification

The technique used for the detection of arrhythmia in this device is knowledge-based classification which is based on the past experience from medical experts and the doctors [9]. In this device, it can be divided into two parts, one is used for the detection of VF, 2nd degree heart block, PVC and normal beats with the function of three RR peaks interval sliding window. The other one is used for the detection of AF with 128 RR peaks interval sliding window.

The function of the sliding window algorithm is used to ensure all the R peaks able to be classified by the classifier. That is because the classifier only able to be processed in a certain number of R peaks. It is also able to circle the area of interest and determine the location of the arrhythmia. In addition, RR peaks interval data will be obtained while running the sliding window.

The classifier for VF, 2nd degree block, PVC and normal beat need three R-R peak intervals as the input data. If the sliding window has successfully being detected as arrhythmia, the middle RR peak interval will be detected as the arrhythmia beat out from the three RR peak intervals. There are six conditions (C1 to C6) in this algorithm for the detection of the arrhythmia which could be referred to [11]. The arrhythmia classification of VF, PVC and 2nd degree heart block are shown in figure 8.

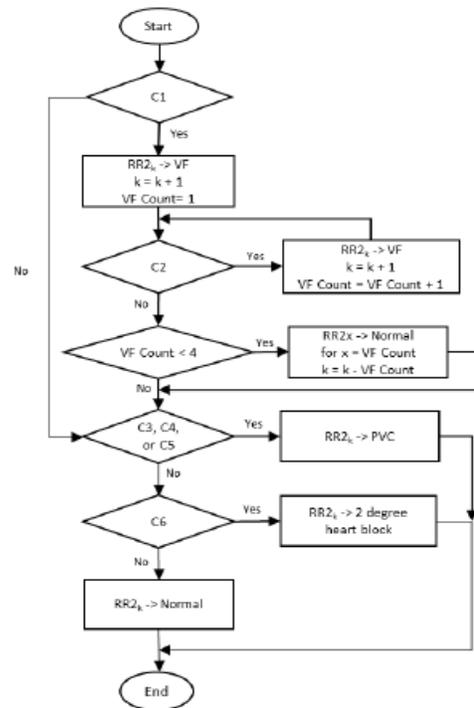


Fig. 8. Arrhythmia classification for VF, PVC, 2th heart degree block.

This AF detection algorithm have used a generally accepted hypotheses which is the AF will have a significant increase in variability and complexity of RR intervals series [12]. In this algorithm, the parametric test and non-parametric test was used to detect the AF. Foremost, the ECG data after signal pre-processing will be divided into 128 beat segments. Each of 128 beat segments will begin with 1 RR interval after the previous 128 beat segment. Next it will remove the longest 8 beat segments and shortest 8 beat segments of outliers from each 128 beat segment. This is used to ensure the accuracy of the next two statistical methods. This three statistical methods will analysis the heart rate variability (HRV) and to determine characteristics of AF. In the table below, it will discuss about each of the algorithm.

Root Mean Squares of Successive Differences (RMSSD) is a parametric statistic and measured the variability of a data set. Hence, it is sensitive to outlier. Refer to (6), it is the formula for RMSSD and the threshold shows in (7), where a_j is the first RR interval and a_{j+1} is the consecutive of next RR interval.

$$RMSSD = \sqrt{\frac{1}{112-1} \times \sum_{1}^{112-1} (a_{j+1} + a_j)^2} \quad (6)$$

$$\frac{RMSSD}{Mean\ RR} > 0.1 \quad (7)$$

Turning Points Ratio (TPR) is a non-parametric statistic and measured the randomness of fluctuations within a data set. It will compare the amount of turning points in the data to the maximum number of possible turning points. The null hypothesis of the TPR ratio is the RR intervals are random, hence corresponds to AF. The alternate hypothesis is RR intervals are non-random, corresponding to normal sinus rhythm. The threshold for the TPR is in between the values of 0.54 and 0.77. The equation for TPR shows in (8) and (9) where l refer to arbitrary length of random data points.

$$\text{Expected number of turning points} = \frac{2l - 4}{3} \quad (8)$$

$$\text{Standard deviation} = \sqrt{\frac{16l - 29}{90}} \quad (9)$$

Shannon Entropy (SE) is a parametric statistic that measures the uncertainty of a random variable. Due to the high uncertainty of the AF, the value of SE will be higher than normal sinus rhythm. The bin is created to further divide the 128 beat segments into a 16 bin histogram. The threshold for AF is when SE greater than 0.7. The equation for SE shows in (10) and (11). N_i is the number of beat in that particular bin, l is the length of segment, $N_{outliers}$ is the number of outliers and $p(i)$ is the probability of each bin.

$$p(i) = \frac{N_i}{l - N_{outliers}} \quad (10)$$

$$SE = \sum_{i=1}^{16} p(i) \frac{\log(p(i))}{\log(\frac{1}{16})} \quad (11)$$

The AF will be detected if and only if all the non-parametric and parametric statistic are passing the threshold based on 128 RR peak intervals as shown in Fig. 9. Lastly, all the detection beats of the arrhythmia will be counted and displayed in the screen.

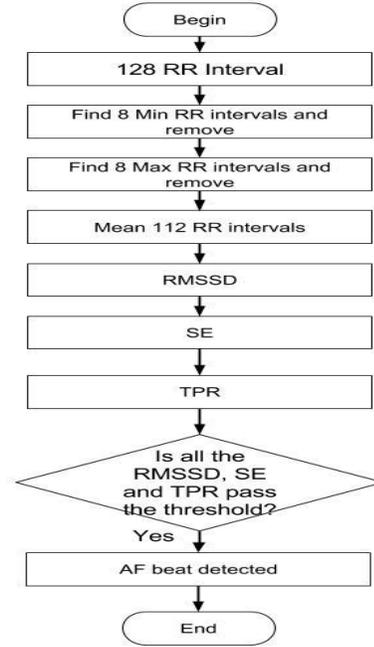


Fig. 9. Arrhythmia classification for AF

IV. RESULT AND DISCUSSION

The *Throb* complete system is prototyped on ALTERA VEEK-MT board with the FPGA Cyclone IV with the running frequency at 100MHz. In order to detect the AF, the minimum duration of raw ECG data is 5 minutes [13]. However the duration of ECG raw data for VF, PVC and second degree block is 1 minute will be sufficient. All the ECG raw data are taken from Lead I ECG electrode and source from the MIT-BIH with 360 sampling frequency. There are four sets of data for AF detection, 10 data sets for both PVC and normal beats, and 1 data set for VF and second degree heart block.

Based on the Table 1, it can be observed that the accuracy for the normal beat is 93.61%, PVC is 88.56%, VF is 96.30%, second degree heart block is 85.71% and AF is 86.17%. The calculation for the accuracy is using the true false table by comparing the annotation beat from the MIT-BIH online ECG database.

TABLE 1
ARRHYTHMIA DETECTION ACCURACY

Classification	Total Sample	Detection Accuracy
Normal Beat	10	93.61± 5.64
PVC	10	88.56 ± 9.04
VF	1	96.30
2° Heart Block	1	85.71
AF	4	86.17± 9.21

In terms of timing performance, Table 2 below shows the total computation time of all the signal processing blocks which included ECG data loading, low and high pass filter,

differentiator, squaring function, moving window integration, R peak detection and the arrhythmia classification. It can be observed that the complete processing totally consume approximately 74 seconds, which the most time consuming block was the arrhythmia classification of VF, 2nd HB, and PVC. This is because the arrhythmia classification block classified three types of arrhythmia by using 3 RR intervals only. While compare to the arrhythmia classification of AF, it uses 128 RR intervals in the sliding window. The ECG data loading takes around 21 seconds to read the ECG data from the SD card. This is the second most time consuming block because of the long transferring pathway from the SD card to the microprocessor through the Altera Avalon interconnect fabric as the on-chip communication architecture.

TABLE 2
COMPUTATION TIMING PERFORMANCE

Processing Tasks	Computation Time (Seconds)
ECG Data Loading	20.99
Low Pass Filter	1.33
High Pass Filter	2.71
Differentiator and Squaring Function	3.54
Moving Window Integration	0.50
R Peak Detection	0.34
Arrhythmia Classification: VF, PVC, 2° HB	35.26
Arrhythmia Classification: AF	9.48
Total	74.14

The complete *Throb* system could also display the arrhythmia classification on capacitive multi-touch screen in terms of raw ECG signal, R-R peak interval chart and textual classification result as shown in Fig. 10-12, which dedicated to different categories of the users.

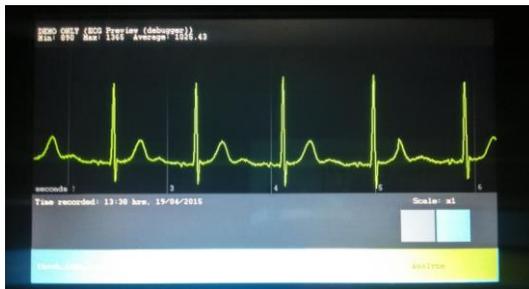


Fig. 10.Raw ECG signal display

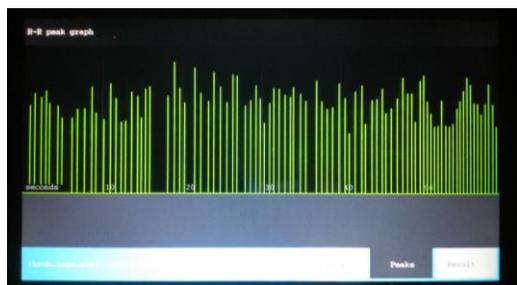


Fig. 11.R-R peak interval chart

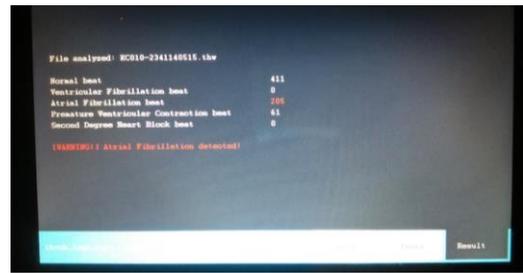


Fig. 12.Textual arrhythmia classification result

V. CONCLUSION

This paper has presented the SoC-based implementation of arrhythmia classifier named *Throb*. The *Throb* is equipped with user friendly touch screen GUI as front end user interfacing system, and the back-end processing system based on offline electrocardiograms (ECG) data using embedded software implementation. The complete system is prototyped on Terasic VEEK-MT platform which houses an Altera Cyclone IV FPGA chip and a capacitive multi-touch screen. It able to detect four types of arrhythmias, namely ventricular fibrillation, premature ventricular contraction, two degree heart block and atrial fibrillation which all four of them is significant indicator of various cardiovascular diseases. The usage of knowledge-based classification will ensure the accuracy of the classification result and resource efficiency for the system. The *Throb* could also display the result in various forms in terms of ECG raw signal, R-R peak interval chart, and laymen textual description which aim to different group of users according to their background. The future work should include the ECG acquisition unit to process the online ECG data, higher accuracy algorithm for arrhythmia detection, and extended classification for more types of arrhythmia detection.

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