ECG-BASED PROCESSOR FOR PREDICTING VENTRICULAR ARRHYTHMIA

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***Abstract*—*This project presents the design of a fully integrated electrocardiogram (ECG) signal processor (ESP) for the prediction of ventricular arrhythmia using a unique set of ECG features and a naive Bayes classifier. Real-time and adaptive techniques for the detection and the delineation of the P-QRS-T waves were investigated to extract the fiducial points. Those techniques are robust to any variations in the ECG signal with high sensitivity and precision. Two databases of the heart signal recordings from the MIT PhysioNet and the American Heart Association were used as a validation set to evaluate the performance of the processor. Based on application-specified integrated circuit (ASIC) simulation results, the overall classification accuracy was found to be 86% on the out-of-sample validation data with 3-s window size. The architecture of the proposed ESP was implemented using 65-nm CMOS process. It occupied 0.112-mm2 area and consumed 2.78-µW power at an operating frequency of 10 kHz and from an operating voltage of 1 V. It is worth mentioning that the proposed ESP is the first ASIC implementation of an ECG-based processor that is used for the prediction of ventricular arrhythmia up to 3 h before the onset.*

Keywords—Adaptive Techniques, Application-Specified Integrated Circuit (ASIC); Classification; Electrocardiograph (ECG); Feature Extraction; Low Power; Ventricular Arrhythmia

1. INTRODUCTION

Sudden cardiac death accounts for approximately 300 000 deaths in the United States per year, and, in most cases, is the final result of ventricular arrhythmias, including ventricular tachycardia (VT) or ventricular fibrillation (VF) [1]. Ventricular arrhythmia is an abnormal ECG rhythm and is responsible for 75%–85% of sudden deaths in persons with heart problems unless treated within seconds [1]. Most ventricular arrhythmias are caused by coronary heart disease, hypertension, or cardiomyopathy, and if not accurately diagnosed nor treated, immediate death occurs. VT is a fast rhythm of more than three consecutive beats originating from the ventricles at a rate more than 100 beats/min.

2. LITERATURE REVIEW

Recently, due to the remarkable advancement in technology, the development of dedicated hardware for accurate ECG analysis and classification in real time has become possible. The main requirements are low-power consumption and low-energy operation in order to have longer battery lifetime along with the small area for wearability. Many attempts succeeded to implement ECG signal processing and classification systems in hardware. Shiuet al. implemented an integrated electrocardiogram signal processor (ESP) for the identification of heart diseases using the 90-nm CMOS technology. The system employed an instrumentation amplifier and a low-pass filter (LPF) to remove the baseline wander and the power line interference form the ECG and employed.

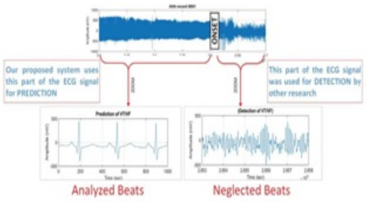


Figure 1: Prediction versus detection of the onset of VT/VF from the ECG heartbeat analysis.

The system was carried out in a field-programmable gate array and consumed a total of 40.3-µW power and achieved an accuracy of 96.6%. The main disadvantage of the system is that it uses fixed search window with predefined size to locate S and T fiducial points, which is not suitable for real-time scenarios.

Another ESP was proposed. The system was fabricated on the 0.18-µm CMOS technology and executed different functions for the three stages of pre-processing, feature extraction, and classification.

The second chip, the receiving end, had the receiver and the digital signal processing (DSP) unit. The last chip was the classifier. Discrete wavelet transform was adopted by the DSP unit for the ECG feature extraction and classification. The chip was fabricated on the 0.18-µm CMOS technology and consumed a total power of 5.967 µW at 1.2 V for the DSP unit only. The accuracy of the beat detection and the ECG classification was 99.44% and 97.25%, respectively.

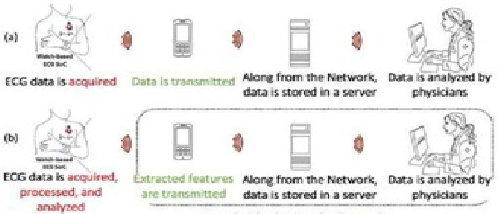


Figure 2: Comparison between (a) commonly implemented systems and (b) proposed one

Project Contribution: Prediction over Detection

This paper proposes a fully integrated low-powered ESP for the prediction of ventricular arrhythmia up to 3 h before the onset, and to the best of our knowledge, this is the first solution that performs prediction instead of detection. Previous VT-/VF-related research was mainly concerned with the detection of the VT/VF condition on and after it occurs, while our proposed solution performs prediction of it. This is achieved by analysing the ECG segment that precedes the onset of VT/VF condition. Furthermore, the databases used for this paper enabled us to process ECG signals up to 3 h before the onset of VT/VF and attain the earliest prediction interval ever reported. The remaining part of this paper is organized as follows.

3. SYSTEM OVERVIEW

The proposed system is a life saver for patients who are susceptible to ventricular arrhythmia by alerting them for immediate attention to their medical condition. Unlike other systems that acquire the ECG signal and transmit it for further analysis, the proposed system aims to design and develop an integrated biomedical processor that is capable of acquiring the ECG signal from the heart along with processing and analyzing it on the same chip without any external interaction, as shown in Fig. 2. Thus, the patient would have immediate alert to his situation and that is very important, especially in critical situations.

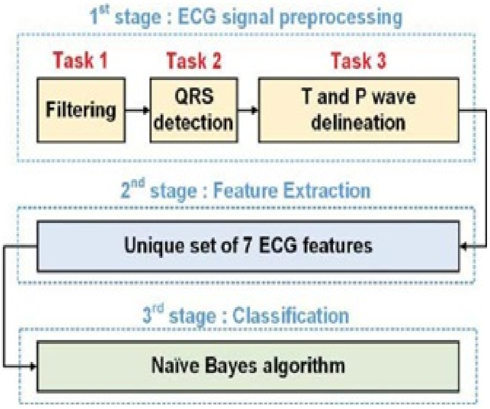


Figure 3: Schematic representation of the proposed ventricular arrhythmia prediction system.

In the first stage, the ECG preprocessing is responsible for three tasks: 1) ECG filtering; 2) QRS complex detection; and 3) T and P wave delineation. The ECG filtering removes the noise coupled with the ECG signal and prepares it for further analysis. After that, the QRS complex is detected using thePan and Tompkins (PAT) algorithm.

In the second stage, seven features are extracted from the ECG signal and grouped together to construct a unique set. All the features represent different intervals from the ECG signal, and they are RR, PQ, QP, RT, TR, PS, and SP intervals. Usually, the reported systems in the literature build their systems depending on one feature only, such as the heart rate interval, the variability of the timing delay of the ECG segments, or the QT interval variability. The combination of these features has never been used in any published detection or prediction method, yet it was proved to be the most significant combination.

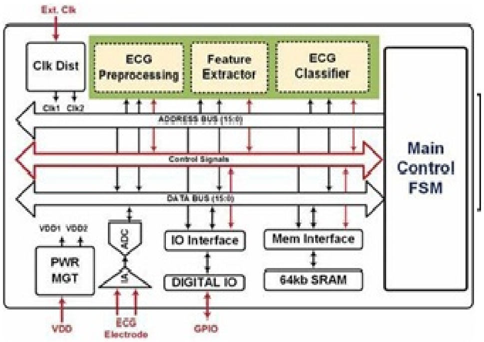


Figure 4: Architecture of the proposed ESP.

In the final stage, naive Bayes algorithm is used to identify the signals that are susceptible to ventricular arrhythmia. There are many reasons for choosing the naive Bayes.

4. HARDWARE DESIGN

The architecture of the proposed ESP is shown in Fig. 4. The architecture includes the modules of the three stages along with a main FSM that controls the flow of the data between the different stages, as shown in Fig. 5. The processing of the data is done using fixed point representation. The digitized ECG data are applied in series at the input to the preprocessing stage with a resolution of 8 bit, while a variable number of bits were utilized in the different stages to enhance the accuracy and avoid truncations errors.

A. ECG Pre-processing Stage

1.ECG Filtering: The block diagram of the pre-processingstage is shown in Fig. 6.Bandpass filtering of the raw ECG signal is the first step in which the filter isolates the difference equations of the cascaded LPF and high-pass filter (HPF) are given respectively. The cutoff frequency of the LPF filter is 11 Hz, and it introduces a delay of six samples, whereas the HPF has a cutoff frequency anddelay of 5 Hz and 16 samples, respectively. The coefficients of the filters are all integers and of power-of-two, which make them suitable for hardware implementation

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

$$y[nT]=x(nT-16T)-\overline{32}\,[y(nT-T)+x(nT) \\ -x(nT-32T)]. \tag{2}$$

2.QRS Detection: To detect the QRS complex, thePAT method was used. The PAT is a widely used method, which is based on the amplitude threshold technique exploiting the fact that R peaks have higher amplitudes compared with other ECG wave peaks. With proper filtering of the signal, the method is highly capable of detecting the R peaks in every heartbeat using two threshold levels.

3.T and P Wave Delineation: The delineation ofT and P waves is based on a novel technique proposed. The method is based on adaptive search windows along with adaptive thresholds to accurately distinguish T and P peaks from noise peak. In each heartbeat, the QRS complex is used as a reference for the detection of T and P waves in which two regions are demarcated with respect to R peaks. These regions are then used to form the forward and backward search windows of the T and P waves, respectively.

A. *Onset and Offset Point Delineation:*

The method traces the onset and offset values of the P-QRS-T waves by finding the sample corresponding to the zero slope of the entitled ECG signal. The sample point that has a zero slope and former to the peak is identified as the onset point. Similarly, the offset point is determined at other side of the peak. Sometimes, however, a derivative sign change occurs, which reflects a false indicator.

B. *Feature Extraction Stage:*

The two main parameters that must be considered while developing a detection (or prediction) system are the complexity and the accuracy of the feature extraction technique in providing the best results. For example, if the technique that is used for the feature extraction requires complex transformation or data analysis of the ECG signal, this would increase the overall cost and complexity of the system, and thus, it will not be suitable for wearable biomedical devices.

Due to the fact that calculating the product of the above probabilities will lead to flot point underflow, the product operation is converted into summation by using log. Thus, instead of choosing the class with the highest probability, we choose the one with the highest log score. Given that the logarithm function is monotonic, the decision remains the same.

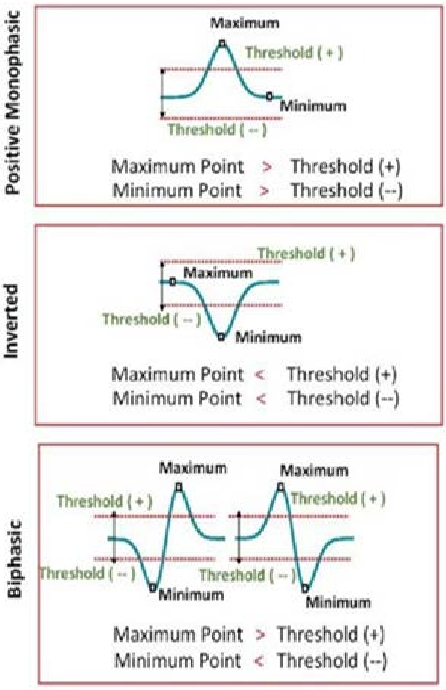


Figure 5: T and P peaks detection. Comparing the local maximum and minimum points in each designated wave with the threshold.

C. *Classification Stage:*

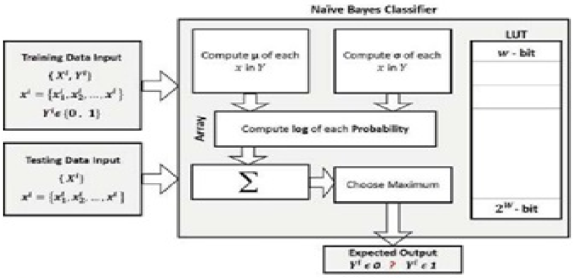


Figure 6: Architecture of naive Bayes classifier.

The choice of classifier in this paper was the native Bayes. The native Bayes classifier is easy to build with no complicate iterative parameter estimation, which makes it particularly useful for hardware implementation. The architecture of the classifier is implemented, as shown in Figure 7.

The Bayesian classifier uses Bayes theorem to find out the probability of a data belonging to a particular class given observations. For a set of feature vectors d and class ci , the Bayes theorem is given in

$$P(c_i \mid d) = \frac{P(d \mid c_i)\,P(c_i)}{P(d)} . \qquad (5)$$

$$c = \text{argmax } P(c_i \mid d) \qquad (6)$$

$$c = \text{argmax} P(c_i) P(x \mid c_i). \qquad (7)$$

And thus

$$c = \text{argmax } P(c_i) \qquad \underset{X}{P(x \mid c_i)}. \qquad (8)$$

Due to the fact that calculating the product of the above probabilities will lead to flot point underflow, the product operation is converted into summation by using log. Therefore, (9) can be calculated as follows:

$$c = \text{argmax} \quad \log(P(c_i)) + {}_{x} \log(P(x \mid c_i)) . \qquad (9)$$

5. ASIC IMPLEMENTATION

The ESP was designed using Verilog-HDL and implemented using an automatic synthesize, place, and route approach. A low-power industry standard 65-nm process was used for the implementation with standard cell library carefully designed for low-power applications. The routing was limited to metal layer-5. The design occupied a total core area of 0.112 mm^2 and consumed a total statistical power of 2.78 μW at 10-kHz frequency.

6. PERFORMANCE AND RESULTS

Apart from MATLAB simulations, extensive Verilog simulations were done using Modelsim and Synopsys tools to verify the working of the design

A. ECG Databases

ECG recordings from the PhysioNet and the American Heart Association databases were used to construct the study data sets of this paper. This paper included two groups; GROUP A included a set of five single-lead normal ECG records obtained from the NSRDB and sampled at 250 Hz. These records have no significant arrhythmias. Group B involved a total of six single-lead beat-by-beat annotated abnormal ECG records with significant ventricular arrhythmias.

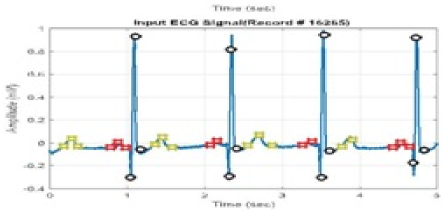
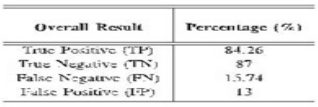


Figure 7: Verilog results of QRS detection and T and P wave delineation for different ECG records.

B. Results of Classification Stage

The classification results, which were obtained after simulating the ECG data in Modelsim, are presented.
PROCESSING TECHNIQUE: VERILOG

7. RESULTS



Overall Result	Percentage (%)
True Positive (TP)	84.26
True Negative (TN)	87
False Negative (FN)	15.74
False Positive (FP)	13

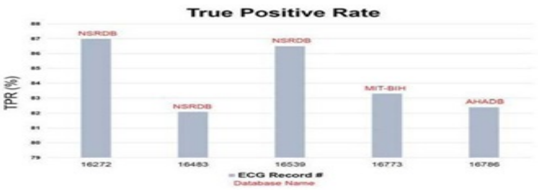


Figure 9:Percentage of TPR in GROUP A records.

These results are based on the classifier output on 3-s processing window. The classification accuracy is computed and found to be 86% (TN refers to the number of true negative detections).

A geometric representation of the classification output for some pair of feature vectors that are associated with two classes. The two classes are represented in red circles for normal ECG signals and blue triangles for ECG signals with VT/VF rhythms.

8. CONCLUSION

In this project, a fully integrated digital ESP for the prediction of ventricular arrhythmia that combines a unique set of ECG features with naive Bayes was proposed. Real-time and adaptive techniques for the detection and delineation of the P-QRS-T waves were investigated and employed to extract the fiducial points. The combination of these features has never been used in any previous detection or prediction system. The ESP was implemented using the state-of-the-art 65-nm technology, and based on the design constraints, it occupied an area of 0.112 mm2 and consumed a total power of 2.78 µW. Moreover, the proposed ESP achieved an outstanding capability of predicting the arrhythmia up to 3 h before the onset. A prediction accuracy of 86% was obtained on the out-of-sample validation data by tenfold cross validation with 3-s window size

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