Real-time Heart Monitoring and ECG Signal Processing

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Executive Summary

The real-time heart monitoring project involves the development of a stand-alone embedded system that is capable of performing signal processing on heart data and alerting a patient's doctor wirelessly of any dangerous arrhythmias, or irregular heartbeats. As healthcare monitors are quickly becoming automated and able to access the Internet, patients' diagnostic equipment must also be upgraded. In particular, the diagnosis of patients' arrhythmias is currently performed by Holter and event monitors. Standard Holter monitors are capable of storing patients' heart data, but this data can only be analyzed at the physician's office after the recording has completed. Event monitors are able to transmit a patient's heart data to a remote server using wireless technology. However, this process also has its limitations; signal processing of the heart data must be performed at the server end to confirm any arrhythmias detected on the monitor itself. Therefore, physicians are currently unable to address a patient's arrhythmic events as they are occurring.

For the purposes of this project, the team will focus on the detection of PVCs, or premature ventricular contractions, and transmit a wireless message to the patient's doctor in the case of VT, or ventricular tachycardia, a potentially life-threatening condition. The embedded device must perform all signal processing on-board and in real time. Also, the device must be battery-powered to allow for greater patient mobility. Lastly, the device should be compatible with all patient data, inexpensive, portable, and low-power.

Functionally, the real-time heart monitoring system must store heart data within the device, perform preprocessing on the heart signal, and detect the QRS complexes (or ventricular contractions) within the heart signal. Then the system must identify any PVCs, utilize PVC information to recognize VT, and transmit a wireless message to the patient's physician in the event of VT. The Pan-Tompkins algorithm will be used for preprocessing and R-peak detection, and a template-matching algorithm will be used for PVC detection. The criteria for VT will be three or more consecutive PVC beats.

The system will be implemented on the CC3200 LaunchPad, a Wi-Fi development board from Texas Instruments. The purchase of this inexpensive platform will be the only cost in the development of this system. The device features a wireless subsystem (for transmitting the message to the doctor) and an application subsystem (for QRS, PVC, and VT algorithm implementation). For testing purposes, the team will use anonymous heart data from the MIT-BIH arrhythmia database, and the WFDB toolbox will be used to confirm the accuracy of the different algorithms.

For implementation, the remaining tasks for the project have been divided into three phases: PVC algorithm development in MATLAB, PVC algorithm implementation in C, and wireless development. Shannon and Fatima are currently developing the PVC algorithm in MATLAB, and Claire and Shannon will code this algorithm in C. Lastly, Fatima and Claire will work on wireless communication. The PVC algorithm phase (both MATLAB and C) is scheduled for completion in the fall semester, and wireless development will be completed in the spring semester.

Finally, the project will have several impacts on both society and the environment. The design will change the way diagnostic care is performed and promote patients' privacy and independence. Also, the low-power design will reduce battery usage.

Abstract

Arrhythmias are a form of heart disease involving irregular heartbeats. The types of arrhythmias include premature ventricular contractions (PVCs). Three or more consecutive PVCs may signal ventricular tachycardia (VT), a potentially life-threatening condition. To facilitate real-time arrhythmia detection, a stand-alone embedded device has been proposed that will perform ECG signal processing and wirelessly alert the patient's doctor of VT. Requirements for the device include real-time ECG signal processing, on-board signal processing computations, and battery-powered functionality. Additionally, the device should be low-power, compatible with all patient data, reasonably priced, and portable. Lastly, the signal processing algorithm must detect PVCs with high accuracy, sensitivity, and specificity. The team selected a Wi-Fi microcontroller for system implementation. The design will use the Pan-Tompkins QRS detection algorithm and a template-matching algorithm for PVC detection. MATLAB, Code Composer Studio, and packet-sniffing software will be used to evaluate the solution with heart data from the MIT-BIH arrhythmia database. The sole cost for the project will be the inexpensive CC3200 LaunchPad. The project is divided into MATLAB simulation, C implementation, and wireless communication phases. Lastly, the design will impact society by reducing battery usage through low-power design, protecting patients' privacy and security, and promoting independence for senior citizens.

Table of Contents

1. INTRODUCTION 1

   A. Problem Background 1

   B. Problem Statement 2

   C. Constraints 2

   D. Scope 2

2. STATEMENT OF WORK 3

   A. System Description 3

      1) System Block Diagram 3

      2) High-level Flowchart 3

      3) Nonfunctional Requirements 3

      4) Functional Requirements 5

   B. Design Approach and Method of Solution 6

   C. Economic Analysis 7

   D. Project Timeline 8

   E. Division of Labor 8

   F. Societal and Environmental Impacts 9

3. SUMMARY/CONCLUSIONS 10

4. REFERENCES 11

5. APPENDIX 12

   A. Glossary 12

   B. Web Links 12

   C. Design Alternatives 12

   D. Detailed Gantt Charts 13

   E. Detailed Division of Labor 14

1. INTRODUCTION

A. Problem Background

Heart disease is the number one cause of death in the United States, with someone dying from a heart-related condition every 90 seconds and about 735,000 people in the United States having heart attacks each year [1]. Arrhythmias (or heart rhythm issues) are some of the most common heart disorders. These irregular heartbeats occur when the electrical signals in the heart do not work properly to coordinate the heartbeats.

Premature ventricular contractions (PVCs) are one of the most widespread forms of arrhythmia. Up to 40-75% of people have occasional PVC beats, but most of them are not considered clinically significant [2]. In rare cases, three or more PVC beats in quick succession can lead to ventricular tachycardia, where a patient's resting heart rate is above 100 beats per minute. In this condition, the hearts' ventricles (lower chambers) contract before they have completely filled with blood, and this can limit the amount of blood being delivered to the body [3].

An electrocardiogram (ECG) records the heart's activity, including the strength and timing of electrical signals. One of the key characteristics of an ECG is the R-peak, which is part of the QRS complex (see Fig. 1, page 2). This area of the ECG relates to the ventricular depolarization (contraction) and is important in the diagnosis of PVCs [4].

Holter and event monitors are commonly used to diagnose and monitor patients with arrhythmias. In the case of Holter monitors, patients are connected to the device through a series of wires and must carry the device at all times. In some cases, high activity levels can generate false positives. Therefore, these patients are requested to keep an activity log to assist medical diagnosis. Holter monitors commonly collect heart data for 24- or 48-hour periods [5].

Physicians may also use event monitors to capture a patient's ECG. Several types of event monitors include wireless functionality, which allows the devices to continuously transmit a patient's heart data to a server. Unlike Holter monitors, event monitors may be worn for several weeks at a time. Another benefit of event monitors is their ability to detect abnormal heart signals automatically [6]. Although event monitors are capable of performing some ECG signal processing, some of the arrhythmia-detection computations must be performed at the server level.

Although the current preventative measures serve the medical purpose of monitoring arrhythmias, these measures are often inconvenient for patients and medical staff. For example, these devices cannot collect data continuously. Also, some wearable devices, such as Holter monitors, are not always easily portable. Perhaps most importantly, these devices are unable to perform ECG signal processing completely on-board. For both Holter and event monitors, the recorded ECG must be analyzed offline by a physician or processed by a web server, respectively. Thus, the physician is unable to address a patient's arrhythmia as the event is occurring.

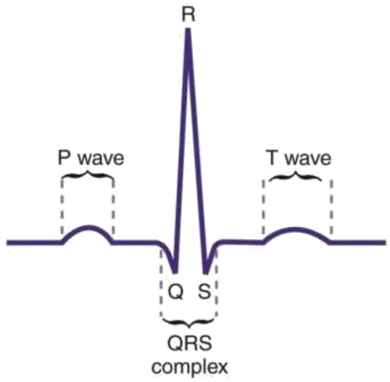

Figure 1. Features of a normal ECG [4].

B. Problem Statement

The client would like to develop a stand-alone embedded system that will be used for continuous heart monitoring. The unit will be able to process ECG data in real time and detect PVCs with high accuracy, sensitivity, and specificity. The device will also use wireless communication to alert the patient's doctor of any dangerous arrhythmias. Because the patient will use the unit continuously, the platform should be low power. Lastly, the system should be portable to allow the patient to have greater mobility.

C. Constraints

- The ECG signal processing must occur in real time. The maximum amount of time available for the system to classify each R-peak is the time interval between two peaks.
- The embedded system must be able to operate independently and perform all necessary signal processing computations on-board.
- The device must be battery-powered.

D. Scope

For the project's scope, the team will be creating the software for a real-time heart monitoring system. Because the project focuses on the software aspect of a heart monitor, hardware issues (such as electrode interfacing and the construction of a battery circuit) will not be addressed in this project. The software will be able to detect PVCs and VT, but the detection of other types of cardiac arrhythmias is outside the scope of the project. Lastly, the team will be using high-level functions to implement wireless communication. Because of this, lower-level security issues, such as encryption and data integrity, will not be addressed.

TABLE I. SCOPE OF THE HEART MONITORING SYSTEM

In Scope	Out of Scope
ECG signal processing	Electrode interfacing, battery circuit
PVC and VT detection	Detection of other types of cardiac arrhythmias
High-level wireless communication	Security issues (encryption, data integrity, etc.)

2. STATEMENT OF WORK

A. System Description

1) System Block Diagram

The system in Fig. 2 will accept heart data as input, which may be from a sensor or from the MIT-BIH arrhythmia database [7]. After the system processes the data, a wireless message will be sent to the patient's doctor if ventricular tachycardia is detected.

2) High-level Flowchart

When the embedded device is powered on (Fig. 3 on page 4), it will first accept heart data as input and store the data into its internal memory. Next, preprocessing (which includes filtering and normalization) will be performed to prepare the signal for the R-peak (or QRS), PVC, and VT detection phases. Then the system will detect the R-peaks in the resulting heart signal, and a classification algorithm will be used to distinguish PVC and non-PVC beats. The amount and frequency of PVC beats will then be used to determine if the patient has ventricular tachycardia. If so, the doctor will be notified of the event via a wireless message. In either case, the process will then begin again by accepting new heart data, and the software will execute continuously.

3) Nonfunctional Requirements

To evaluate the proposed designs, the team generated a list of non-functional requirements, or characteristics that the heart monitoring system should have. Table II is organized with the objectives listed in descending order of importance.

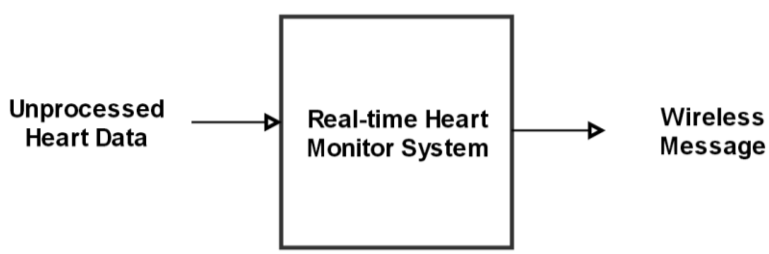

Figure 2. Block diagram of the overall heart monitoring system.

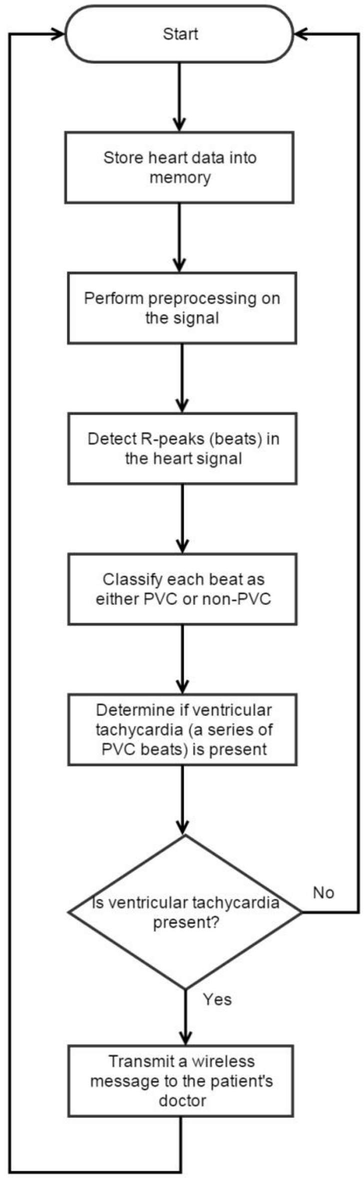

Figure 3. High-level flowchart.

TABLE II. OBJECTIVES FOR REAL-TIME HEART MONITORING SYSTEM

Objectives	
Compatible with all patient data	The device should be capable of accurately processing any patient data in the MIT-BIH arrhythmia database.
Low-power	The device's software should be energy efficient and able to operate continuously for long periods of time on a battery.
Portable	The device should be lightweight, easy to carry, and convenient in terms of battery capacity.
Reasonably priced	The device should be affordable for the average consumer.

4) Functional Requirements

Table III describes the functional requirements for each subsystem of the real-time heart monitoring system. Each function includes one or more specifications, which are criteria for evaluating the performance of each function.

TABLE III. FUNCTIONS/SPECIFICATIONS FOR REAL-TIME HEART MONITORING SYSTEM

Subsystem	Functions	Specifications
Preprocessing	Storing heart data input into memory	The internal memory of the device must be at least 25 kB.
	Filtering and/or normalizing the heart data	The filtering/normalization must ensure that the heart data is compatible with the QRS, PVC, and VT detection functionality.
QRS Detection	Identifying each QRS complex	The device must have at least 90% sensitivity (correctly identified QRS peaks divided by the total number of QRS peaks present in the original signal) and at least 90% specificity (correctly identified non-QRS peaks divided by the total number of non-QRS peaks in the original signal). The QRS detection algorithm must return the R-peak indices for use in the PVC detection subsystem.
PVC Detection	Classifying each QRS complex as PVC or non-PVC	The device must have at least 90% accuracy (correctly identified PVC and non-PVC beats divided by the total number of beats in the original signal). The PVC detection algorithm must return the PVC indices for use in the VT detection subsystem.
VT Detection	Determining whether ventricular tachycardia is present using the calculated PVC information	The VT detection algorithm must return a 30-second interval of heart data surrounding the VT event for use in the wireless communication subsystem.
Wireless Communication	Transmitting a wireless message to the patient's doctor in the event of ventricular tachycardia	The time delay between the device transmitting the message and the doctor receiving the message must be less than one second.

B. Design Approach and Method of Solution

From the initial design space (see Appendix C), the team selected a design with one mean for each function. For wireless functionality, the proposed design features the CC3200 LaunchPad, a Wi-Fi development tool manufactured by Texas Instruments [8]. The tool includes Wi-Fi Internet-on-a-Chip for network processing, an ARM Cortex-M4 for application development, two 20-pin connectors, LEDs, and push-buttons on a compact board. Also included in the kit is a USB cable to allow the board to be programmed using a PC.

The board can be powered either via USB or using two AA batteries. For storage, the LaunchPad includes 256 kB of RAM on the CC3200 chip, and the ARM Cortex-M4 microcontroller also features multiply-accumulate instructions for more efficient algorithm implementation. The microcontroller's UART can be used for simple communication with a PC. Lastly, the Wi-Fi Internet-on-a-Chip can be configured for Wi-Fi Direct, Station, and Access Point modes depending on application requirements.

For testing purposes, the ARM Cortex-M4 will be powered and programmed via USB (which is connected to a PC). Although the CC3200 board is capable of supporting battery-powered functionality, for ease of use, the team will not be constructing a battery circuit in this project (see Table I, page 2). The ARM microcontroller will be programmed with all of the algorithm code for QRS, PVC, and VT detection. The Wi-Fi Internet-on-a-Chip system on the board will handle the wireless communication phase of the system.

For QRS detection, the design features the Pan-Tompkins algorithm, which uses thresholds to find the R-peaks in bandpass-filtered and integrated signals. After peak detection, a template-matching algorithm will identify PVCs by using the correlation between a normal beat (the template) and successive beats. When three or more consecutive R-peaks are determined to be PVCs, a wireless message is transmitted to the doctor.

To complete this project, the team will need to program in MATLAB for the QRS, PVC, and VT algorithm simulation. For algorithm implementation, team members require C programming knowledge. For the wireless development phase, the team will need to perform additional research to determine the most appropriate wireless protocol to use in the design. This research will be integrated into the wireless development phase of the project.

The proposed solution can be broken into phases for testing. The data storage functionality can be tested by examining the total memory (both RAM and Flash) available on the device. The CC3200 LaunchPad contains 256 kB of RAM, so the memory specification is met for the team's device.

The preprocessing algorithms, QRS detection, and PVC detection will be simulated in MATLAB using data obtained from the MIT-BIH arrhythmia database, which contains heart data from patients with normal and PVC heartbeats. Many different types of heart signals, including those with noisy data and large voltage offsets, are included in the database. To verify the algorithms' accuracy in the simulation phase, the team will use the WFDB toolbox functions in MATLAB. Using the toolbox, the team can load database signals into MATLAB and write the annotations of the signal (classifying each beat as normal or PVC) into a file. The toolbox is then able to evaluate the team's annotations against the actual (doctor-evaluated) annotations stored in the database and generate a report of the algorithms' accuracy. Once the

QRS, PVC, and VT algorithms have at least 90% accuracy, sensitivity, and specificity for each of the records in the MIT-BIH database, the team's algorithms can be considered satisfactory for the MATLAB simulation phase. This will also verify that the preprocessing produced heart signals that were compatible with the QRS, PVC, and VT functionality.

Next, the algorithms will be coded in C and programmed onto the CC3200 LaunchPad using Code Composer Studio. For implementation, the board will also be loaded with testing data from the MIT database. Because only about fifty seconds of heart data can be directly loaded onto the board at a time due to memory constraints, a UART communication system between the board and a PC will be used to simulate continuous testing data. Every second, the PC will send a buffer containing one second (360 samples) of heart data to the board. The board will analyze the incoming data and save positive QRS and PVC detection results into an array. Once the data transfer from the PC has terminated, the board will save the QRS and PVC detection results to a .dat file. This .dat file can then be opened in MATLAB and analyzed using the WFDB toolbox (similar to the way the algorithms were tested in the MATLAB simulation phase). Again, once the QRS, PVC, and VT algorithms have at least 90% accuracy, sensitivity, and specificity in the reports generated in MATLAB, the C implementation phase can be considered satisfactory, and the preprocessing can also be considered adequate.

Lastly, the wireless communication subsystem can be tested by using packet sniffer software (such as Wireshark) on a PC. The PC will receive the wireless message transmitted by the CC3200 LaunchPad and simulate the role of the doctor's cell phone in the system. The message received at the PC end will be compared to the message sent from the board; if the messages are identical, then the wireless communication quality is satisfactory. Also, the time interval between the board's transmission of the data and the PC's receipt of the data will be measured. To be considered satisfactory, this time interval must be less than one second (or the number of seconds of heart data sent in the continuous testing data phase). This is to ensure that the wireless message corresponds to the correct segment of heart data.

C. Economic Analysis

The CC3200 LaunchPad, available for $30.00 from Texas Instruments, will be the sole hardware component used in the project. MATLAB, which is freely available on the lab computers at Bradley University, will be used for simulation purposes. For C implementation, the team will use Code Composer Studio, which can be used with a free license (for up to 16 kB of code) from Texas Instruments. To test the wireless communication, the team can use Wireshark, a free packet-sniffing program. Also, the team will utilize the complimentary software development kit (SDK) on TI's website, which features examples for both wireless and application development.

TABLE IV. PROJECT COSTS FOR HEART MONITORING SYSTEM [8].

Component	Cost
CC3200 LaunchPad	$30.00

D. Project Timeline

Figures 4 and 5 contain the abbreviated Gantt charts (for the fall and spring semesters) for the project. For the full Gantt charts, see Appendix D. The QRS detection simulation and implementation phases were completed prior to the publishing of this document. The critical path for the project will involve the simulation and implementation of the PVC detection code. This phase will provide the heart data necessary for the wireless development phase.

As described in Table V, the team anticipates that the Wi-Fi communication phase of the project will be the most time-consuming. Although the wireless communication phase is not on the critical path and not listed in the fall semester, preliminary research on different web technologies will be performed during the fall semester if time permits. This will ensure that work on the Wi-Fi phase of the project can begin more quickly in the spring semester.

The major milestones for the project will be the two progress reports, the final presentation, and the final report. According to the Gantt chart in Fig. 4, the team's goal is to complete the PVC algorithm in MATLAB and complete roughly half of the PVC algorithm implementation in C for the first progress presentation. For the second progress presentation, the team plans to complete roughly one-third of the wireless development phase.

E. Division of Labor

Shannon and Fatima will both work on the MATLAB simulation of the PVC algorithm, and Claire and Shannon will complete the C implementation of the PVC algorithm. Lastly, Fatima and Claire will work on the wireless development phase of the project. By having two team members work on each project phase, the team will ensure that each successive phase has at least one team member who worked on the previous phase. This will allow for smooth transitions between phases. For a detailed breakdown of division of labor, see Appendix E.

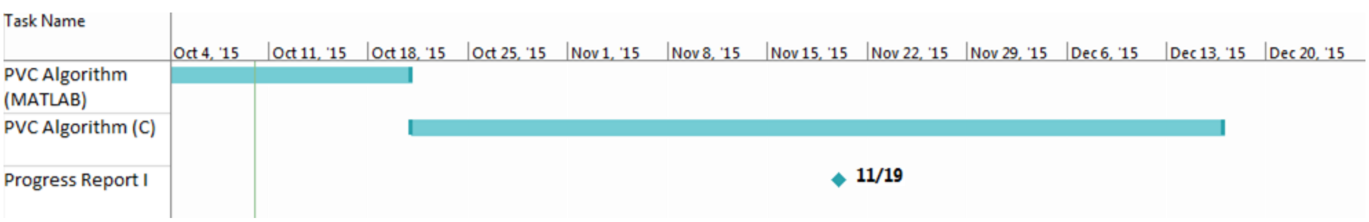

Figure 4. Abbreviated Gantt chart for the fall semester.

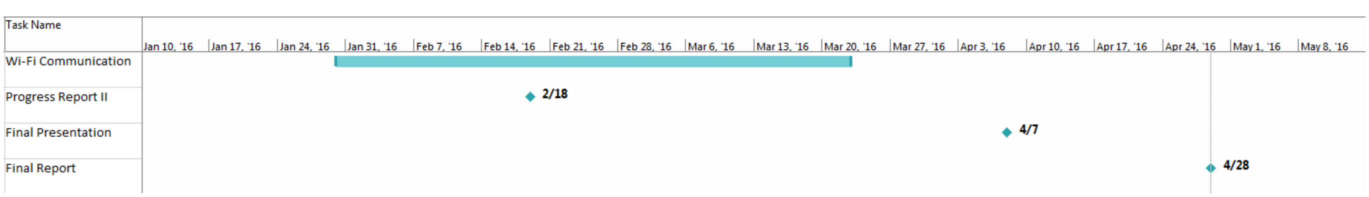

Figure 5. Abbreviated Gantt chart for the spring semester.

TABLE V. DEADLINES AND DURATIONS OF PROJECT TASKS

Task	Deadline	Duration (hours)
PVC Algorithm (MATLAB)	10/20/2015	65
PVC Algorithm (C)	12/16/2015	100
Wi-Fi Communication	3/22/2016	150
Progress Report I	11/19/2015	80
Progress Report II	2/18/2016	80
Final Presentation	4/7/2016	80
Final Report	4/28/2016	80

F. Societal and Environmental Impacts

The real-time heart monitoring system will assist in the rapid diagnosis of potentially life-threatening arrhythmias. In this way, the device will help to protect patients' well-being. By alerting doctors as soon as a patient is experiencing a medical emergency, the system can increase the possibility that the patient will receive medical attention as soon as possible. Also, the proposed product will give increased independence for patients suffering from chronic PVCs, as monitors that are currently in the market are sometimes obtrusive and inconvenient. Because the device could be lower cost, the device may also help patients who cannot currently afford an arrhythmia monitor. The system may also change the way doctors and patients interact; the device will allow a patient's status to be directly communicated to doctors.

In addition to impacting healthcare, the system also addresses privacy and environmental concerns. Because the team is using anonymous heart data from the MIT-BIH database, the project will be compliant with HIPAA laws to protect patient privacy. Also, because the proposed device can operate in a low-power mode when it is not transmitting data wirelessly, the battery life of the device is increased. This will make the team's product more affordable for consumers in the long-run, as they won't have to replace the batteries as often. Thus, the device will also reduce battery waste that may be sent into landfills.

3. SUMMARY/CONCLUSIONS

The main goal of "Real-time Heart Monitoring and ECG Signal Processing" is to allow for rapid diagnosis of premature ventricular contractions (PVCs). These arrhythmic heartbeats are relatively common in the general population, but they may develop into ventricular tachycardia, a life-threatening condition.

Current diagnostic tools, such as Holter and event monitors, cannot track the heart's electrical signals continuously and cannot communicate directly with a physician. Also, some of the signal processing must be done offline, either by the doctor (for Holter monitors) or by a server (for event monitors). Because of these factors, the doctor is currently unable to address a patient's arrhythmic events as they are occurring.

The real-time heart monitor system will be able to perform preprocessing and PVC detection on-board and transmit wireless messages to the patient's doctor. In this way, the system will be able to diagnose ventricular tachycardia in real time and alert medical authorities of an emergency in a timely manner.

4. REFERENCES

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5. APPENDIX

A. *Glossary*

- arrhythmia: a type of irregular heartbeat caused by defective electrical signals in the heart
- ECG: electrocardiogram, a signal that describes the heart's electrical activity
- sampling rate: how often the value of an analog signal is taken
- ventricle: one of the two lower chambers of the heart

B. *Web Links*

- Visual demonstration of ventricular tachycardia: http://watchlearnlive.heart.org/CVML_Player.php?moduleSelect=arrhyt
- Image of a Holter monitor: http://www.nlm.nih.gov/medlineplus/ency/imagepages/8810.htm

C. *Design Alternatives*

To facilitate design development, a list of means for each of the heart monitor's functions was created. From Table VI, there are 162 possible combinations for different designs (with one mean chosen for each function).

TABLE VI. MORPHOLOGICAL CHART [9, 10, 11, 12, 13, 14, 15, 16].

Functions	**Means**		
Storing heart data	Flash memory	RAM	
Preprocessing (Filtering/QRS detection)	Pan-Tompkins	Wavelet transform	Wavelet transform and Pan-Tompkins
PVC detection	Wavelet transform	Template matching	RR-interval
Ventricular tachycardia detection	Three or more consecutive PVCs	Three or more consecutive PVCs and heart rate above 100 beats per minute	Statistical analysis
Wireless functionality	eZ430-RF2500	CC2540 (Bluetooth)	CC2530 (Zigbee)

D. Detailed Gantt Charts

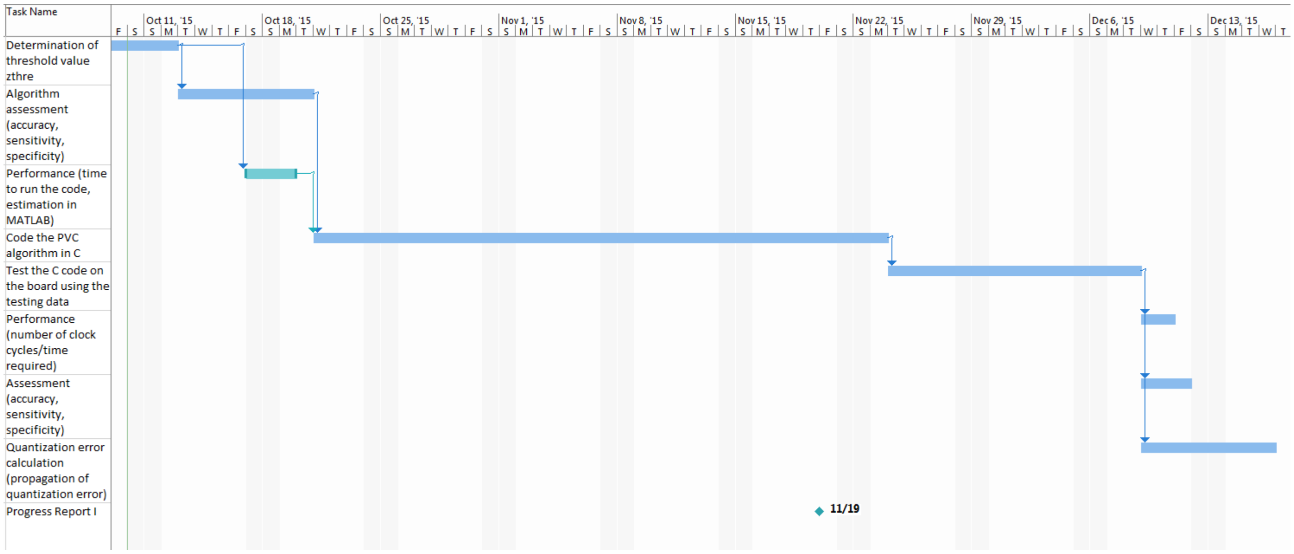

Figure 6. Detailed Gantt chart for the fall semester. The critical path is represented by a darker shade of blue.

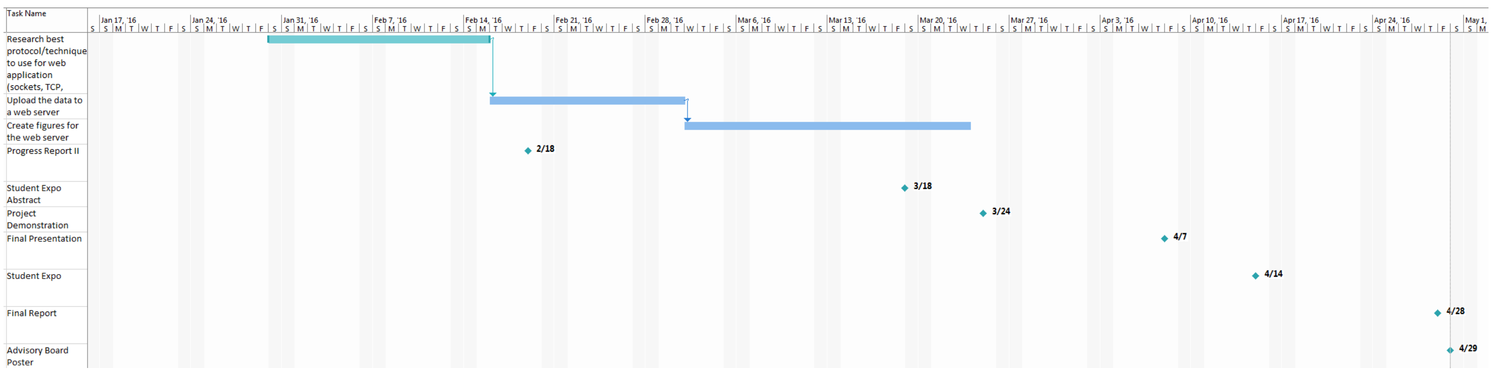

Figure 7. Detailed Gantt chart for the spring semester. The critical path is represented by a darker shade of blue.

E. *Detailed Division of Labor*

TABLE VII. DETAILED DIVISION OF LABOR WITH TASK DURATIONS

Task Name	Team Member(s)	Duration (hours)
Determination of threshold value zthre	Fatima/Shannon	40
Algorithm assessment (accuracy, sensitivity, specificity)	Fatima/Shannon	12
Performance (time to run the code, estimation in MATLAB)	Fatima/Shannon	12
Code the PVC algorithm in C	Claire/Shannon	40
Test the C code on the board using the testing data	Claire/Shannon	30
Performance (number of clock cycles/time required)	Claire/Shannon	10
Assessment (accuracy, sensitivity, specificity)	Claire/Shannon	10
Quantization error calculation (propagation of quantization error)	Claire/Shannon	10
Research best protocol/technique to use for web application (sockets, TCP, HTTP, etc.)	Fatima/Claire	50
Upload the data to a web server	Fatima/Claire	70
Create figures for the web server	Fatima/Claire	30
Progress Report I	Heart Team	80
Progress Report II	Heart Team	80
Student Expo Abstract	Heart Team	20
Project Demonstration	Heart Team	30
Final Presentation	Heart Team	80
Student Expo	Heart Team	30
Final Report	Heart Team	100
Advisory Board Poster Presentation	Heart Team	50