Real-time Heart Monitoring and ECG Signal Processing

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October 1, 2015
Contents

• Introduction and Overview
• Design Approach and Method of Solution
• Economic Analysis
• Schedule
• Division of Labor
• Societal and Environmental Impacts
• Summary and Conclusions
Introduction and Overview

• Problem Background
• Problem Statement
• Constraints
Problem Background

• Arrhythmias
  • Are irregular heartbeats caused by defective electrical signals in the heart [1]
  • Include premature ventricular contractions (PVCs)
Problem Background

- Premature ventricular contractions (PVCs)
  - Up to 40-75% of people have occasional PVC beats [2]
  - May lead to ventricular tachycardia (VT)

Figure 1. Electrocardiogram with “V” labels for PVCs [3]
Problem Background

• Ventricular tachycardia (VT)
  • Involves the ventricles contracting before they have filled completely with blood
  • Limits blood flow to the body

Figure 2. ECGs for normal heart rhythm and ventricular tachycardia [1]
Problem Background

• An electrocardiogram (ECG) describes the heart’s electrical activity

• An ECG can be recorded using a Holter monitor or event monitor

Figure 3. Features of a normal ECG [4]
Problem Background

- Holter monitor

Figure 4. Holter monitor with ECG reading [5]
Problem Background

• Event monitor

Figure 5. Wireless event monitor system [6]
Problem Background

• Holter and event monitors are limited in functionality
  • Utilize some in-platform signal processing for diagnostic assistance
  • Must perform some signal processing offline
  • Are unable to address medical issues in real time
Problem Statement

• Develop a low-power, stand-alone embedded system for continuous heart monitoring that will
  • Process ECG data in real time
  • Detect PVCs accurately and consistently
  • Alert the patient’s doctor wirelessly of ventricular tachycardia
Constraints

• Real-time ECG signal processing
• On-board signal processing computations
• Battery-powered functionality
### TABLE I. SCOPE OF HEART MONITORING SYSTEM

<table>
<thead>
<tr>
<th>In Scope</th>
<th>Out of Scope</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECG signal processing</td>
<td>Electrode interfacing, battery circuit</td>
</tr>
<tr>
<td>PVC and VT detection</td>
<td>Detection of other types of cardiac arrhythmias</td>
</tr>
<tr>
<td>High-level wireless communication</td>
<td>Security issues (encryption, data integrity, etc.)</td>
</tr>
</tbody>
</table>

**Scope**

**TABLE I. SCOPE OF HEART MONITORING SYSTEM**
Contents

• Introduction and Overview
• **Design Approach and Method of Solution**
• Economic Analysis
• Schedule
• Division of Labor
• Societal and Environmental Impacts
• Summary and Conclusions
Design Approach and Method of Solution

- System Block Diagram
- State Diagram
- Nonfunctional Requirements
- Functional Requirements
- Description of Solution
- Solution Testing
System Block Diagram

Unprocessed Heart Data → Real-time Heart Monitor System → Wireless Message

Figure 6. Overall heart monitoring system diagram
State Diagram

Figure 7. State diagram for heart monitoring system

Start

Store heart data into memory

Transmit a message to the doctor (for VT)

Perform preprocessing

Classify each beat as PVC or non-PVC

Determine if VT is present

Start
Nonfunctional Requirements

• Compatible with all patient data in the MIT-BIH database [3]
• Reasonably priced
• Portable
• Low-power
Functional Requirements

• Storing heart data input into memory
  • The embedded device must have an internal memory of at least 25 kB
Functional Requirements

• Performing preprocessing on the heart signal
  • Filtering/normalization must prepare the heart data for the QRS, PVC, and VT detection functions
  • QRS detection must have at least 90% sensitivity and 90% specificity [8]
  • QRS detection must be tested using heart data from the MIT-BIH arrhythmia database [3]
Functional Requirements

• Classifying each QRS complex as PVC or non-PVC
  • Must have at least 90% accuracy [9]
Functional Requirements

• Determining whether ventricular tachycardia is present using PVC detection results
  • Must have at least 90% accuracy
Description of Solution

<table>
<thead>
<tr>
<th>Functions</th>
<th>Means</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storing heart data</td>
<td>RAM</td>
</tr>
<tr>
<td>Preprocessing (Filtering/QRS detection)</td>
<td>Pan-Tompkins</td>
</tr>
<tr>
<td>PVC detection</td>
<td>Template matching</td>
</tr>
<tr>
<td>Ventricular tachycardia detection</td>
<td>Three or more consecutive PVCs</td>
</tr>
<tr>
<td>Wireless functionality</td>
<td>CC3200 LaunchPad</td>
</tr>
</tbody>
</table>
Description of Solution: Hardware

• SimpleLink Wi-Fi CC3200 Launchpad
  • Inexpensive: $30.00
  • Simplifies data transmission
  • 256 kB RAM

Figure 8. CC3200 Launchpad [10]
Description of Solution: QRS Detection

• Pan-Tompkins algorithm [11]

Figure 9. Preliminary QRS detection using the Pan-Tompkins algorithm and MATLAB
Description of Solution: PVC Detection

• Correlation with normal QRS-complex and RR-interval templates

• Low correlation signals PVC

Figure 10. QRS and RR-interval templates and correlation [9]
Description of Solution: Ventricular Tachycardia

- Three or more consecutive PVC beats
- Wireless message transmitted to medical authorities

Figure 11. ECG demonstrating ventricular tachycardia [3]
Solution Testing

• MATLAB simulation of QRS, PVC, and VT detection
  • Use MIT-BIH arrhythmia database for testing data
  • Ensure that accuracy, sensitivity, and specificity are at least 90% using the WFDB toolbox
  • Estimate the execution time
Solution Testing

• C implementation of QRS, PVC, and VT detection
  • Store the heart data in the board’s memory and export the detection results to a file
  • Evaluate number of clock cycles required and quantization error propagation
  • Test the amount of time needed to send heart data from a PC to the board
Solution Testing

• Wireless communication
  • Use a packet sniffer to verify wireless communication
  • Verify that testing data sent from the board matches the data that the doctor would receive
Solution Testing

• System integration (C implementation and wireless communication)
  • Evaluate the delay between uploading the heart data and the doctor’s access to the data
  • Verify that heart data input with three or more consecutive PVCs correctly transmits a message to the doctor
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Economic Analysis

TABLE III. PROJECT COSTS FOR HEART MONITORING SYSTEM

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC3200 LaunchPad</td>
<td>$30.00</td>
</tr>
</tbody>
</table>
Contents

• Introduction and Overview
• Design Approach and Method of Solution
• Economic Analysis
• Schedule
• Division of Labor
• Societal and Environmental Impacts
• Summary and Conclusions
# Schedule

<table>
<thead>
<tr>
<th>Task</th>
<th>Duration (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC Algorithm (MATLAB)</td>
<td>65</td>
</tr>
<tr>
<td>PVC Algorithm (C)</td>
<td>100</td>
</tr>
<tr>
<td>Wi-Fi Communication</td>
<td>150</td>
</tr>
<tr>
<td>Progress Report I</td>
<td>80</td>
</tr>
<tr>
<td>Progress Report II</td>
<td>80</td>
</tr>
<tr>
<td>Final Presentation</td>
<td>80</td>
</tr>
<tr>
<td>Final Report</td>
<td>80</td>
</tr>
</tbody>
</table>

**TABLE IV. PROJECT SCHEDULE**
Figure 12. Gantt chart for the fall semester
Figure 13. Gantt chart for the spring semester
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• Introduction and Overview
• Design Approach and Method of Solution
• Economic Analysis
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• Division of Labor
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• Summary and Conclusions
Division of Labor

• MATLAB Simulation (PVC detection)
  • Shannon/Fatima

• C Programming (PVC detection)
  • Claire/Shannon

• Wi-Fi Communication
  • Fatima/Claire
Contents

- Introduction and Overview
- Design Approach and Method of Solution
- Economic Analysis
- Schedule
- Division of Labor
- **Societal and Environmental Impacts**
- Summary and Conclusions
Societal and Environmental Impacts

• Low-power modes minimize battery consumption
• Testing data contains no personally identifiable information
• Wi-Fi technology allows for additional security [10]
Contents

• Introduction and Overview
• Design Approach and Method of Solution
• Economic Analysis
• Schedule
• Division of Labor
• Societal and Environmental Impacts
• **Summary and Conclusions**
Summary and Conclusions

• PVCs are irregular heartbeats that may lead to VT
• An embedded device is proposed that will detect PVCs in real time and wirelessly alert the patient’s doctor of VT
Summary and Conclusions

• Design should be compatible with all patient data in the MIT-BIH database, reasonably priced, portable, and low-power.

• Design must include real-time ECG signal processing, on-board signal processing computations, and battery-powered functionality.
Summary and Conclusions

• Proposed Design
  • CC3200 LaunchPad (Texas Instruments)
  • Pan-Tompkins algorithm for QRS detection
  • Template matching for PVC detection
  • Three consecutive PVC beats for VT detection
  • Tested using MIT-BIH arrhythmia database and MATLAB
Real-time Heart Monitoring and ECG Signal Processing

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References


References


Figure 14. Gantt chart for the MATLAB simulation (PVC algorithm) phase of the project.
Detailed Gantt Chart (2)

Figure 15. Gantt chart for the C implementation (PVC algorithm) phase of the project
Figure 16. Gantt chart for the wireless development phase of the project
Specificity and Sensitivity [8]

\[
SP = \frac{TN}{TN + FP} \quad SE = \frac{TP}{TP + FN}
\]

- TP (True Positive): detected QRS complex that is present in the signal
- TN (True Negative): data point between QRS complexes that does not contain a QRS peak
- FP (False Positive): incorrect identification of QRS peak
- FN (False Negative): QRS peak that was not detected by the algorithm
Memory Requirements

• Sampling rate for ECG signal (MIT-BIH arrhythmia database): 360 Hz

• Number of samples required for 30 seconds of ECG data: 10,800

• Amount of memory required: 21 kB
Problem Background

• Heart disease is the number one cause of death in the United States

![Chart of the three leading causes of death in the United States](source)

Figure 17. Chart of the three leading causes of death in the United States

Source: Centers for Disease Control and Prevention [17]
Nonfunctional Requirements: Metrics

Objective: The device should be compatible with all patient data in the MIT-BIH database. [3]

Metric:

• Highly compatible: 10 points
• Very compatible: 7.5 points
• Compatible: 5.0 points
• Somewhat compatible: 2.5 points
• Not compatible: 0 points
Nonfunctional Requirements: Metrics

Objective: The device should be portable.

Metric:
• Very easy to carry around: 10 points
• Easy to carry around: 7.5 points
• Portable: 5.0 points
• Uncomfortable to carry around: 2.5 points
• Difficult to carry around: 0 points
Nonfunctional Requirements: Metrics

TABLE VI. QUANTITATIVE PERFORMANCE LEVELS FOR REAL-TIME HEART MONITORING [8, 9]

<table>
<thead>
<tr>
<th>Power Consumption in 24 Hours of Continuous Use (W)</th>
<th>Price ($)</th>
<th>Value Scaled</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50</td>
<td>500</td>
<td>10</td>
</tr>
<tr>
<td>2.50</td>
<td>600</td>
<td>7.5</td>
</tr>
<tr>
<td>3.25</td>
<td>700</td>
<td>5</td>
</tr>
<tr>
<td>4.00</td>
<td>800</td>
<td>2.5</td>
</tr>
<tr>
<td>4.75</td>
<td>900</td>
<td>0</td>
</tr>
</tbody>
</table>
### TABLE V. MORPHOLOGICAL CHART FOR HEART MONITORING SYSTEM [10,11,12,13,14,15,16]

<table>
<thead>
<tr>
<th>Functions</th>
<th>Means</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storing heart data</td>
<td>Flash memory</td>
</tr>
<tr>
<td></td>
<td>RAM</td>
</tr>
<tr>
<td>Preprocessing (Filtering/QRs detection)</td>
<td>Pan-Tompkins</td>
</tr>
<tr>
<td></td>
<td>Wavelet transform</td>
</tr>
<tr>
<td></td>
<td>Wavelet transform and Pan-Tompkins</td>
</tr>
<tr>
<td>PVC detection</td>
<td>Wavelet transform</td>
</tr>
<tr>
<td></td>
<td>Template matching</td>
</tr>
<tr>
<td></td>
<td>RR-interval</td>
</tr>
<tr>
<td>Ventricular tachycardia detection</td>
<td>Three or more consecutive PVCs</td>
</tr>
<tr>
<td></td>
<td>Three or more consecutive PVCs, heart rate greater than 100 beats per minute</td>
</tr>
<tr>
<td></td>
<td>Statistical analysis</td>
</tr>
<tr>
<td>Wireless functionality</td>
<td>eZ430-RF2500</td>
</tr>
<tr>
<td></td>
<td>CC2540 (Bluetooth)</td>
</tr>
<tr>
<td></td>
<td>CC3200</td>
</tr>
</tbody>
</table>
Design Evaluation: Design Alternatives

- Total design space: 162 designs
- Two designs analyzed in detail
TABLE VIII. FIRST DESIGN FOR HEART MONITORING SYSTEM

<table>
<thead>
<tr>
<th>Functions</th>
<th>Means</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storing heart data</td>
<td>Flash memory</td>
</tr>
<tr>
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<td>Pan-Tompkins</td>
</tr>
<tr>
<td>PVC detection</td>
<td>RR-interval</td>
</tr>
<tr>
<td>Ventricular tachycardia detection</td>
<td>Three or more consecutive PVCs and heart rate above 100 beats per minute</td>
</tr>
<tr>
<td>Wireless functionality</td>
<td>CC2540 (Bluetooth)</td>
</tr>
</tbody>
</table>
### Design Evaluation: Design 2

#### TABLE IX. SECOND DESIGN FOR HEART MONITORING SYSTEM

<table>
<thead>
<tr>
<th>Functions</th>
<th>Means</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storing heart data</td>
<td>Flash memory</td>
</tr>
<tr>
<td>Preprocessing (Filtering/QRs detection)</td>
<td>Wavelet transform and Pan-Tompkins</td>
</tr>
<tr>
<td>PVC detection</td>
<td>Wavelet transform</td>
</tr>
<tr>
<td>Ventricular tachycardia detection</td>
<td>Three or more consecutive PVCs</td>
</tr>
<tr>
<td>Wireless functionality</td>
<td>eZ430-RF2500</td>
</tr>
</tbody>
</table>
Design Evaluation: NEM

- The two designs were then evaluated against the constraints and objectives

**TABLE X. CONSTRAINTS AND OBJECTIVES FOR HEART MONITORING SYSTEM**

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real-time ECG signal processing</td>
<td>Compatible with all patient data in the MIT-BIH database [3]</td>
</tr>
<tr>
<td>On-board signal processing computations</td>
<td>Low-power</td>
</tr>
<tr>
<td>Battery-powered functionality</td>
<td>Reasonably priced</td>
</tr>
<tr>
<td></td>
<td>Portable</td>
</tr>
</tbody>
</table>
## Design Evaluation: NEM

### TABLE XI. NUMERAL EVALUATION MATRIX

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Design</th>
<th>Design 1</th>
<th>Design 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real-time ECG signal processing</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>On-board signal processing computations</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Battery-powered functionality</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

+ : Constraint met
## Design Evaluation: NEM

### TABLE XII. NUMERAL EVALUATION MATRIX

<table>
<thead>
<tr>
<th>Objectives</th>
<th>Design</th>
<th>Design 1</th>
<th>Design 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compatible with all patient data in the MIT-BIH database</td>
<td></td>
<td>7.5</td>
<td>10</td>
</tr>
<tr>
<td>Low-power</td>
<td></td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Reasonably priced</td>
<td></td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Portable</td>
<td></td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>
Alternative Solution: Hardware

- eZ430-RF2500 (Texas Instruments)
  - MSP430F2274 MCU
  - CC2500 wireless transceiver
  - 32 kB flash memory

Figure 18. eZ430-RF2500 Development Kit [12]
Alternative Solution: Software

• PVC detection
  • Wavelet transform algorithm [13]
  • RR-interval algorithm [14]