UNIVERSITY OF CALIFORNIA,
IRVINE

# Title of the Thesis

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Computer Science

by

Your name

Dissertation Committee:
Professor A, Chair
Professor B
Professor C

2012

# DEDICATION

(Optional dedication page)
To ...

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# ACKNOWLEDGMENTS

I would like to thank...

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**Awesome paper** **Jun 2011**
Conference name

**Another awesome paper** **Aug 2012**
Conference name

## SOFTWARE

**Magical tool** `http://your.url.here/`
*C++ algorithm that solves TSP in polynomial time.*

# ABSTRACT OF THE DISSERTATION


Title of the Thesis

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Doctor of Philosophy in Computer Science

University of California, Irvine, 2012

Professor A, Chair



The abstract of your contribution goes here.

# Chapter 1

# Introduction

# Chapter 2

# BlueBox

The previous chapter described the motivation for a emergency care device. This chapter will discuss the design consideration for implementing such a system. Section 2.1 Gives a short overview about the BlueBox system and the signal requirements that the system is designed to monitor and acquire. Relevant design decision and background is also described. Section 2.2. Elaborates more on the functional requirements of the system. Section 2.3 Explains some of the design considerations, requirements, and constraints encountered in the design of BlueBox.

## 2.1 Overview

BlueBox project is very much concerned with providing a very efficient and easy way to use the device on the patient in a short time at the same time providing the functionality to record all the required vitals and data . (It is easy to use for para medics and saves a lot of their time which they can invest in providing care for patients at the same time it provides all the functionality as needed).BlueBox is a wearable, low-power and low cost device that is supposed to be of size 4 cm X 6cm size . It can record a set of data which is considered as the most important and essential for emergency care as recommended by LABIOMED and physicians with whom we collaborated for this project.

BlueBox records ECG, Body temperature , chest rise(using IMU sensors), environment temperature and has two microphones where one is a contact microphone to record the patient's breathing pattern and other is used by paramedics to log the patients condition.The functionality of BlueBox is to record all the data into a persistent storage in the device to be retrieved later for analysis and can be a good indicator understanding patients medical condition and patient's response to emergency treatments before providing further care.Bluebox is placed on the patients when they are in transit to the hospital. It essentially records the patients vitals mentioned above and also records the paramedic log about the patients condition. The logs and the vital signs are synchronized and these synchronized information can provide a really good information about the patients initially condition during the emergency .

## 2.2 Signal requirements

### 2.2.1 The Electrocardiogram

The ECG has become a routine part of any complete medical evaluation and has been used as a diagnostic test since its discovery over 70 years ago [2]. Because electricity is conducted through the heart muscle (known as the myocardium), many (but not all) types of damage to the heart tissue can be detected with an ECG. The ECG waveform allows one to infer information about electrical activity associated with different aspects of a heart beat and is therefore of particular value for assessing an individual's health. BlueBox must perform at least as well as commercially available ECG monitoring devices, but with a small

| *Specification* | *Minimum* | *Target* |
|---|---|---|
| Leads | 4 | 4 |
| Channel | 1 | 1 |
| Sampling rate | 250 Hz | 500 Hz |
| Resolution | 8 bits/sample | 16 bits/sample |

Table 2.1: ECG signal requirements.

and comfortable form factor.A summary of the electrical specifications relating to ECG quality is presented in 2.1

### 2.2.2 Accelerometer

Signal requirements for the accelerometer are not as constrained as that of the ECG.The most important considerations are the acceleration range, resolution, and sample rate. Acceleration values for acceleration generated by individuals were usually within 4g [1], so that should be sufficient for obtaining the full range of accelerations. A summary of the specification relating to accelerometer is presented in Table 2.2.

| *Specification* | *Minimum* | *Target* |
|---|---|---|
| Range | $\pm 4g$ | $\pm 8g$ |
| Resolution | 8 bits | 16 bits |
| Sampling rate | 4 Hz | 12 Hz |

Table 2.2: Accelerometer signal requirements.

### 2.2.3 Temperature

The continuous monitoring of patients body temperature is often necessary during induced-hypothermia and general anesthesia, or when employed in the care of infants and premature babies. Intensive care units along with emergency rooms have also adopted patient temperature as a part of vital sign monitoring procedures.There are two different temperature, body temperature and the environment temperature, to be measured and their requirement is driven by its use case. They still share some common considerations like range being measured, resolution and accuracy / reliability. Table 2.3 summarizes the specification relating to the temperature .

| $Specification$ | $Bodytemperature$ | $Environmenttemperature$ |
|---|---|---|
| Range | $0 - 50°C$ | $-40 - 125°C$ |
| Resolution | $\pm0.1$ | $\pm0.1$ |
| Sampling rate | 2 Hz | 2 Hz |

Table 2.3: Temperature signal requirements.

### 2.2.4 Audio

The system is primarily required to record two audio signals. One Paramedic's log recording feature requires system to record the human voice whose typical range can lie between 300 to 3400 Hz. Another audio to record is record the patient's respiration/breathing pattern. Table 2.5 depicts the specification applicable for both of the audio signals.

| $Specification$ | $Minimum$ | $Target$ |
|---:|---:|---:|
| Sampling rate | 8 KHz | 12 KHz |
| Resolution | 16 bits/sample | 16 bits/sample |

Table 2.4: Audio signal requirements.

## 2.3 System Requirements

### 2.3.1 Hardware Requirement

A summary of the desired system specifications are listed in **??**. Both minimum and desired specifications are listed. Further details of each specification are provided below .

| *Specification* | *Minimum* | *Target* |
|---:|---:|---:|
| Usability duration | 2 Hours | 4 hours |
| Memory | 1 GB | 2 GB |
| Power Dissipation | 9.7 mW | 9.7 mW |

Table 2.5: Audio signal requirements.

The signal requirements and the use case provides the system level electrical requirements. To meet the requirement ECG is sampled at 500Hz, two audio channels are sampled at 12000 Hz, Accelerometer is sampled at 12 Hz and two temperatures are sampled at 2Hz. From the target sampling frequency and the resolution of all the signals, audio accounts for 48000 bytes/second , ECG accounts for 2000 bytes of data every second. Accelerometer and temperature data together sums up to 84 bytes per second. Approximatery 50 kilobytes of data is produces every second. For 4 hours 720 MB of data is generated. The system should have enough storage to save the data and also needs have enough processing bandwidth.

To record for 4 hours , over 720 MB of space is required(not including file system overhead). The data can either be transmitted to a base station / cell phone or be saved on board. Wirelessly transmitting the data to the base station is power intensive to do continuously and also require the user to have an additional device located nearby all the time. All the data needs to be stored on board, so a high density memory must be used. A micro SD card is well suited to this application. However, writing data to a micro SD card is a power hungry operation and latency of write operations are in hundreds of millisecond. Most low power Digital signal processors have low on-chip memory, so the system used for the application should have enough memory for buffering data. For a test duration of 4 hours, system should have a battery capacity of several hundreds of milliamp hours is required. A 300 mAH battery, for example, could support an average current of 75 mA for upto 4 hours at a supply voltage of 3.7V.

### 2.3.2 Firmware Requirement

The firmware requirements for BlueBox must be able to sample the signals with the required frequency as mentioned in the previous sections. Data must sampled, processes and saved continuously for atleast 4 hours. Additionally, the bare metal firmware must be able to manage the resource to control the system and to keep the power consumption as low as possible. A low power Digital Signal Processor is well suited for this task. The hardware system has to be designed in such a way that they has to expose enough control to the DSP and firmware inorder to extensive resource and power management. The low-power DSP must have enough communication resource for all the peripheral devices (Accelerometer, sd card, audio codec,etc) , built-in capability for power management(example: configurable power domain,clock gating, power gating, dynamic voltage and frequency scaling), enough debugging opportunities and sufficient onchip memory for buffering data.

### 2.3.3 Build-Quality requirements

The most important requirement is that the device be small in size(20 mm X 40 mm) ,robust, comfortable and comply with the medical guidelines. The device should have defibrillation protection feature.Additionally the device must be water and sweat proof. These requirements for the device must be achieved while maintaining the signal quality requirements discussed in section 2.2.

## 2.4 Design requirement and Constraint

In general, the requirements associated with a wearable devices places severe restrictions on size and power consumption. Even though battery technology is improving continuously and processors are rapidly improving in terms of power consumption,battery life and battery weight are issues that will have a marked influence on how Wearable medical devices can be used. These devices often require real-time processing capabilities, and thus demand high throughput. Power consumption is becoming the limiting factor in the amount of functionality that can be placed in these devices.

Embedded wearable systems design has been a continuously developing research field. Its complexity actually lies on the fact that an engineer has to take many considerations into account, when designing the systems. There is no system with unlimited resource available, such that the system can perform extremely well without suffering from resource shortage. On the other hand, there is no system that does not follow the user requirements when it tries to accomplish its tasks. In the field of Embedded system designs, engineers are usually constrained by the trade-offs between resource availability and required performance. When it comes to wearable systems, engineers has to take size and power into consideration. Now the engineers are constrained by the trade-offs between resource availability, size, power and performance. This introduces lot of interesting challenges into the design. The characteristics and the potentials of a system are determined by the resources it has. system requirements are always to be fulfilled by the designers. These requirements are to be satisfied if the system is desired to function as it should. With a limited amount of resources provided by the system, an engineer has to think carefully about how to use the existing resources in such a way that they can suffice the need to carry out the required tasks.

In general wearable embedded systems design is a hardware-software codesign problem as the system optimization consist of scheduling and binding[12]. Scheduling has to be done to meet the deadline of each task that has to be accomplished by the system, while binding has to be done to meet the availability of resource on the system. In other words, scheduling is related to performance and binding is related to resource. For battery operated devices power management becomes the important aspect of functional requirement and software design and it heavily influences schedulability and binding. Functional requirements, including power management, and the way it is planned to be accomplished with the software provides the necessary information about schedulability and binding for the design optimization. Thus requiring a hardware-software codesign.

In a system, scheduling and binding parameters are determined to optimize the following objectives:

- **Area:** Area is related to the amount of resources, e.g. Arithmetic Logic Unit (ALU), DSP accelerators, memory, etc., available on the system.
- **Latency:** Latency is the number of cycles needed to accomplish the task
- **Battery capacity:** Energy required to accomplish the task for the required duration.
- **Clock Frequency:** Time interval of a cycle

The main problem of such design is to find the most efficient combination of resource usage, optimal performance and battery capacity. The basic rule is to use the available resources as efficient as possible, while trying to achieve, at least, the required performance, i.e. latency or execution time under the power budget. This means all deadlines have to be met with whatever resource existing on the system with minimum power consumption.

As mentioned in the previous section BlueBox has an size and weight constraint which is considered during the design to optimize the resources of the system to fulfill the constraints. BlueBox system is required to run for a minimum of two hours on battery. BlueBox is optimized to have the minimum required resources to acquire, process and store the large number of high frequency data sets, mentioned in the previous section, with the required performance. Coming to battery selection. Battery capacity is directly proportional to its area and weight[] .The battery consideration is primarily based on its size, weight and heat dissipation as BlueBox should be a medical grade wearable. So here the battery capacity is traded off to meet the size and medical guidelines. TODO: Calculation on battery power consumption

# Chapter 3

# Hardware Architecture

This chapter explains the systems architecture and the important features of all the components and peripherals that plays a vital role in the design of the system.Diagram and explanation of each of the important aspect of the system is provided. This section also talks about the sensors that are part of the BlueBox system. This chapter gives a foundational understanding of the architecture which helps in designing and architecting the firmware.

## 3.1 Final System overview

Final System overview: The final implementation of the BlueBox consists of a central board, along with electrode, microphone and body temperature sensor attachment. The additional electrodes attach to the central board via 9 pin RS232 interface. The contact microphone attached through a standard 2.5mm audio jack. The body temperature sensor is attached through solder pads in the board. All the other sensors are on bord. The figure 3.1 shows the overall system architecture for bluebox.

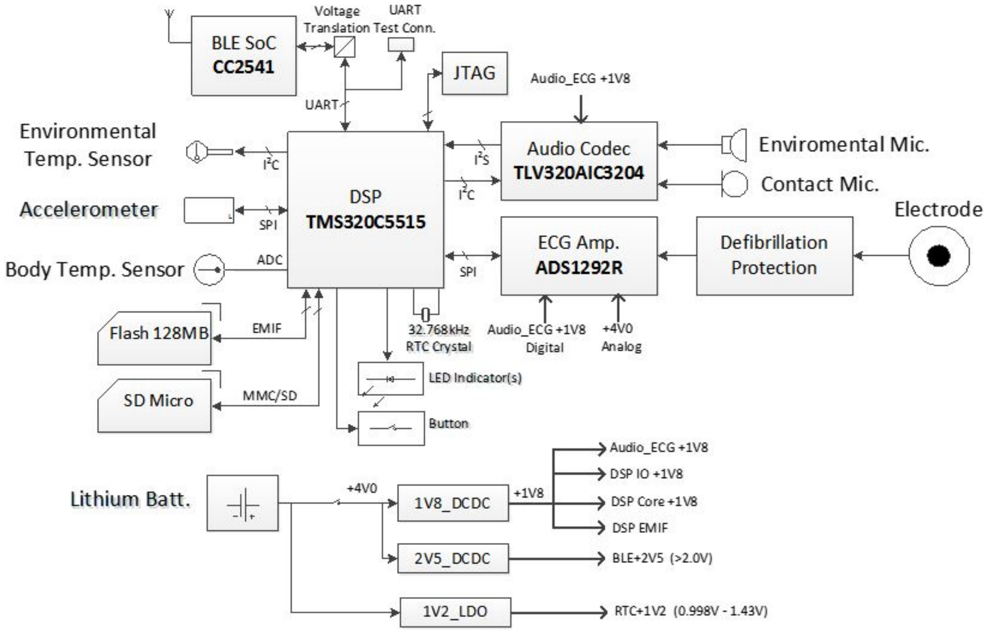


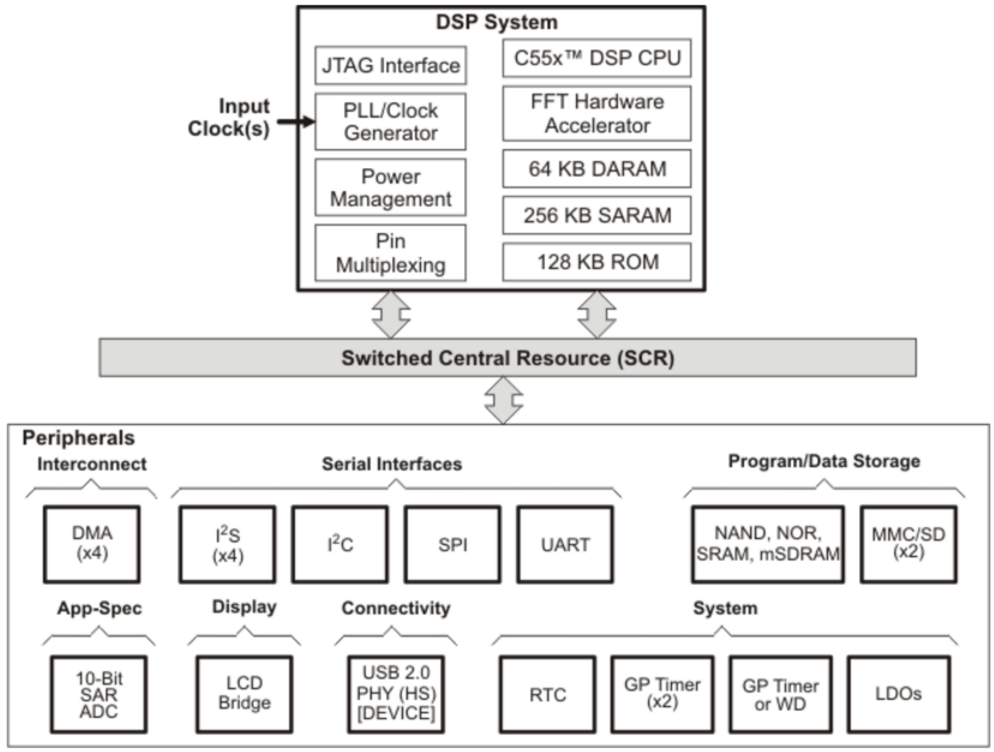

Figure 3.1: BlueBox Hardware System Architecture

## 3.2 Digital Signal Processor

TMS320C5515 is a fixed-point DSP is based on the TMS320C55x DSP generation CPU processor core. The C55x DSP architecture achieves high performance and low power through increased parallelism and total focus on power savings. Figure 3.2 shows the DSP architecture

### 3.2.1 Clock frequency

The DSP has a low power software programmable Phase Locked Loop(PLL) clock generator that supports 60-,75-,100-,120-MHz clock rate.




Architecture.PNG

Figure 3.2: DSP Architecture

### 3.2.2 On-Chip Memory

The DSP has 320K Bytes Zero-Wait state On-Chip RAM and 128K of On-Chip ROM

### 3.2.3 Peripherals

The general-purpose input and output functions along with the 10-bit SAR ADC provide sufficient pins for status, interrupts, and bit I/O for LCD displays, keyboards, and media interfaces. Serial media is supported through two Multimedia Card/Secure Digital (MMC/SD) peripherals, four Inter-IC Sound (I2S Bus) modules, one Serial-Port Interface (SPI) with up to 4 chip selects, one I2C multi-master and slave interface, and a Universal Asynchronous

Receiver/Transmitter (UART) interface.

### 3.2.4 DMA

The device includes four Direct Memory Access(DMA) controllers, each with 4 channels, providing data movement for 16-independent channel contexts without CPU intervention. Each DMA controller can perform one 32-bit data transfer per cycle, in parallel and independent of the CPU activity.

### 3.2.5 Power

Furthermore, the device includes three integrated LDOs (DSP LDO, ANA LDO, and USB LDO) to power different sections of the device. The DSP LDO can provide 1.3 V or 1.05 V to the DSP core (CVDD), selectable on-the-fly by software as long as operating frequency ranges are observed.

## 3.3 AIC3204 : Audio Codec

TLV320AIC3204 is an analog interface chip (AIC) of TI company which is a flexible, low-power, low-voltage stereo audio codec with programmable inputs and outputs, PowerTune capabilities, fixed predefined and parameterizable signal-processing blocks, integrated PLL, integrated LDOs and flexible digital interfaces. It has both recording and playback capabilities. The record part of the TLV320AIC3204 covers operations from 8kHz mono to 192kHz stereo recording, and contains programmable input channel configurations covering single-ended and differential setups, as well as floating or mixing input signals. It also includes a digitally-controlled stereo microphone preamplifier and integrated microphone bias. It integrates A / D and D / A conversion functions, it achieved high-precision A / D and D / A converter in the low-cost using - technology. The size of the chip is very small and compact and its is available in 5 mm  5 mm 32-pin QFN Package. As it has capabilities of recording stereo audio signals, it has two channels that it can record. We use one channel for respiration recording and the other for paramedic's log recording.

## 3.4 ADS1292R : ECG Frontend

ADS1292R is the ECG analog front end chip to which the electrode output is connected to. ADS1292R is a two channel, simultaneous sampling, 24-bit, delta-sigma () analog-to-digital converters (ADCs) with a built-in programmable gain amplifier (PGA), internal reference, and an onboard oscillator. ADS1292R incorporate all features commonly required in portable, low-power medical electrocardiogram (ECG), sports, and fitness applications.With high levels of integration and exceptional performance, the ADS1292R enable the creation of scalable medical instrumentation systems at significantly reduced size, power, and overall cost. ADS1292R have a flexible input multiplexer per channel that can be independently connected to the internally-generated signals for test, temperature, and lead-off detection. Additionally, any configuration of input channels can be selected for derivation of the right leg drive (RLD) output signal. The ADS1292R operate at data rates from 500SPS up to 8 kSPS. The devices are packaged in a 5-mm  5-mm, 32-pin thin quad flat pack (TQFP). Operating temperature is specified from 40C to +85C. ADS1292R is interfaced with the DSP through SPI.

## 3.5 MPU9250 : Accelerometer sensor

MPU-9250 is a 9-axis MotionTracking device that combines a 3-axis gyroscope, 3-axis accelerometer, 3-axis magnetometer and a Digital Motion Processor (DMP).With its dedicated I2C sensor bus, the MPU-9250 directly provides complete 9-axis MotionFusion output.MPU-9250 features three dedicated 16-bit analog-to-digital converters (ADCs) for digitizing each of the gyroscope outputs, accelerometer outputs, and magnetometer outputs. For precision tracking of both fast and slow motions MPU-9250 provides a user-programmable accelerometer full-scale range of 2g, 4g, 8g, and 16g. The package size down to a footprint and thickness of 3x3x1mm, to provide a very small yet high performance low cost package.

## 3.6 Temperature sensor

### 3.6.1 STS21 : Environment temperature sensor

STS21 is a low power, fully self calibrated digital temperature sensor well suited for applications with high demand on temperature accuracy. With dedicated I2C bus it directly provides the temperature output. The sensor comes in a package sized 3 x 3mm footprint and 1.1 mm height.

### 3.6.2 MA100: Body temperature sensor

MA100 is a Biomedical Chip Thermistor assemblies that are designed for use in applications involving both intermittent and continuous patient temperature monitoring. Although low in cost and small in size, these are highly stable, precision thermochips provide reliability, tight interchangeable tolerances, geometries, and fast response time that are often required.

## 3.7 Memory

The BlueBox system has on-chip memory and the persistent micro SD card storage. Because a micro SD card is power intensive and takes hundreds of milliseconds to write to, the on-chip memory is used as buffer. Once there is enough buffer the data is written to the micro SD card and can be accessed by a computer. All the heavy lifting data transfer are done with the help of Direct Memory access peripheral interconnect to take off load from DSP. SD card is interfaced to DSP using MMC/SD interface. The SD card used for the application is a high capacity card that can support a maximum clock frequency of 50 MHz. These high capacity cards are not byte addressable. These high capacity cards are organized in 512 Byte sector or block and they are block addressable. In this thesis, the testing was done on kingston 8 GB micro SDHC card.

## 3.8 Battery and Power management circuitry

A GMB 302547 Lithium ion polymer rechargable battery is used to power the system. It has a capacity of 300 mAH at 3.7 V. The following picture shows the battery. It is 4 cm long , 2cm wide and 0.2 mm thick. And it weighs 8 grams. The battery is place on top of the central board housing. The central board has a battery charging circuitry that can charge the battery completely in 2 hours. The power management circuitry provides a powertrain that powers up the different power domain in the DSP as shown in the system overview diagram above.

# Chapter 4

# Firmware Architecture

## 4.1 Overview

The firmware for the system is implemented on Texas Instrument's TMS320C5515 DSP in C and assembly using Code Composer Studio IDE. TI provides DSP/BIOS (in later versions called SYS/BIOS) a real time operating system for their DSPs. These operating systems provides a wide range of system services to an embedded application such as preemptive multitasking, memory management and real-time analysis. The RTOS is feature rich and helps in quicker development and testing of firmware. But the very important of drawback of using the RTOS is the trade off of performance and controllability of the DSP for quicker development. For a resource and power constrained application, it is required to squeeze out the performance from the system which requires the firmware to have complete control over the underlying hardware. Thus firmware for the system is implemented on baremetal using C and using the chip support library (CSL) for C5515 provided by TI.

The functions of Software could be categorized as the following:

- Initializing System and Sensors
- Data collection
- and storage Power management

//*TODO* The flow chart goes here

## 4.2 Initializing System

First thing the firmware does after boot-up is to initialize the clock by configuring the PLL registers. PLL is configured to generate a 100 MHz clock to tick the system. After the clocks have been set up, the multiplexed I/O pins are configured to function as a specific peripheral or a input/output pins. Then the clock and power to those I/O pins and peripherals are enabled. After the I/O pins are configured, the communication peripherals such as SPI,I2C and I2S are configured. Their mode of operation(master or slave) , frequency of operation etc are initialized and configured. DSP's I2S module is configured as the I2S master(who supply bit clock and word clock) and the Audio codec AIC3204 is configured as the I2S slave.

## 4.3 Initializing sensor

Audio Codec AIC3204 is configured, through the I2C interface , to sample the audio signal at 12Khz on each of the two channels and configured to amplify the signal with automatic gain correction feature enabled. The codec is also configured to filter the audio signal using first order IIR filter and 5 BiQuad filters to improve the audio quality.

The ECG analog front end ADS1292R is configured to sample ECG signal at 500 samples per second. ADS1292R is configured to generate a hardware interrupt to inform the DSP when the sample is ready so that DSP can read the data using SPI interface. The ECG data is again stored in a ping-pong buffer and the data is stored in the permanent storage with the same mechanism as mentioned earlier. The environment temperature sensor STS21 is configured to sample the temperature with a 11bit precision. This data is acquired by polling. For every 500 ECG interrupt the STS21 is polled once to collect the temperature data. The Analog to Digital converters on board are configured to sample the body temperature once for every 500 interrupt of ECG.

## 4.4 Data Collection and storage

# Chapter 5

# Low-Power Firmware Design techniques

# Chapter 6

# Clinical Test

# Chapter 7

# Conclusion

# Bibliography

[1] M. M. K. Delano. A Long Term Wearable Electrocardiogram (ECG) Measurement System , 2012.

[2] R. G. Mark. Clinical Electrocardiography and Arrhythmias, 2004.

# Appendix A

# Appendix Title

Supplementary material goes here. See for instance Figure A.1.

## A.1 Lorem Ipsum

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"I am glad I was up so late,
for that's the reason I was up so early."
*William Shakespeare (1564-1616), British dramatist, poet.*
*Cloten, in Cymbeline, act 2, sc. 3, l. 33-4.*

Figure A.1: A deep quote.