Design and Packaging of a Custom Single-lead Electrocardiogram (ECG) Sensor Embedded with Wireless Transmission

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Abstract—An embedded device is developed to acquire an electrocardiogram (ECG) signal by using only a single lead. The device is capable to capture the ECG signal of a human from the wrist or heart region and transmit data through Bluetooth low energy (BLE). The device includes a custom printed circuit board (PCB) for ECG acquisition. The custom PCB implements the AD 8232 chip for ECG calculation. The PCB is embedded with a commercial nRF52840 development board. Analog data from custom PCB is converted to the digital domain by using a 10-bit analog to digital converter (ADC) and transmitted through Bluetooth 5.3 both supplied by the development board. nRF52840 is 32 bit ARM^{\odot} $Cortex^{\text{TM}}$ processing unit. The BLE data is transmitted by a baud rate of 115.2 kbps. The PCB is 2-layer (32 mm X 50 mm X 4 mm). The device is powered by a 350 mA-hr LiPo battery and consumes approximately 0.58 mA of current. With this current consumption, the battery would last around 603 hours. Finally, all parts are packaged in a box to make it compact and functional for body-worn uses. The device is a low-cost, low-weight design suitable for mobile health (mHealth) applications.

Index Terms—electrocardiogram, printed circuit board, bodyworn, mobile health

I. INTRODUCTION

Wearable medical devices are growing exponentially with the help of embedded sensors. Uses of body-worn medical devices have become common in our daily life [1]. Electrocardiogram (ECG) is one of the important physiological signals required to observe human cardiac health. ECG captures the electrical activity of a heart and represents them in a voltage versus time graph. Abnormal ECG can indicate one or more serious health conditions including arrhythmia, valve disease, and early signs to stroke and heart failure [2-3]. Monitoring the heart condition regularly can help reduce the chances of getting different heart diseases. Different techniques are available for capturing the electrical activities from the heart, ranging from rigid metal electrodes to flexible inkjet-printed (IJP) electrodes [4].

Mobile health (mHealth) applications can provide a good user-device interaction and convey important health information to both users and medical professionals. mHealth applications are gaining popularity because of their flexibility

and user-friendliness [5-6]. A body-worn device embedded with wireless transmission capability can exploit the benefit of mHealth applications. This paper proposes a low-cost, low-power, and lightweight wearable device with wireless transmission capability.

We have designed a single lead ECG device that transmits data using BLE. Captured data are transmitted periodically to a BLE-compatible mobile application. The commercial gel electrodes are used to acquire the ECG signals. After proper conditioning of the data by the analog front end (AFE), they are sent to the processing unit for further processing. Like other embedded system technology, our device is designed and developed with modern hardware and software co-design approach. The device weighs around 75 g and costs approximately \$70 for a single unit at this prototyping phase.

II. OVERALL SYSTEM

As shown in Fig. 1, the device captures ECG by using electrodes and then sends data to the mobile device. Although gel electrodes are used, the device is portable with other forms of electrodes e.g., metal and IJP electrodes. As shown in the

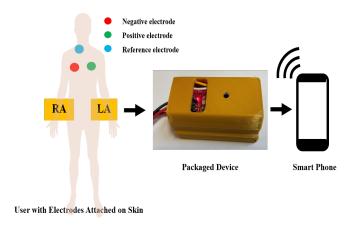


Fig. 1. Acquisition of Lead I (circles indicate the placement of electrodes) ECG data using the proposed device.

figure, the reference electrode is placed near the throat area.

The device can be used to capture ECG for 12-lead positions by changing the location of electrodes.

III. EMBEDDED HARDWARE SYSTEM DESIGN

Hardware components are divided into three main parts: power unit, AFE, and processing unit. The schematic and printed circuit board (PCB) is designed and developed in the KiCad EDA suite and fabricated by OSHPARK. Finally, the surface mount and a few through-hole components are populated on the PCB in a lab setting. Fig. 2 gives an overview of interfacing among three main hardware blocks.

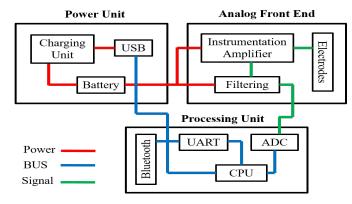


Fig. 2. A block diagram of the single-lead ECG device.

A. Power Unit

The device is powered by a Lipo battery (Pkcell LP552530). The battery capacity is 350 mA-hr with nominal voltage of 3.7V. The battery (30 mm X 25 mm X 5.5 mm) is light weight with ultra-thin characteristics. A charging unit is provided by the commercial development board which uses MCP 73831 IC (Microchip Technology, USA). MCP 73831 is a linear charge management controller which can charge at 500 mA. The power consumption for the device is 0.58 mA. With this current consumption, the battery would last 603 hours approximately.

B. Analog Front End (AFE)

As depicted in Fig. 2, the AFE part is responsible for collecting analog ECG data with the help of electrodes. Electrodes can be placed at different ECG lead positions at different time to capture all 12 lead data. Signals from electrodes are processed through an instrumentation amplifier to measure the bio-potential for ECG. AD8232 (Analog Devices, USA) [7] chip provides the instrumentation amplifier and corresponding circuitry. Additional circuit is added to the design to remove noises due to motion artifacts. Moreover, the fast restore is enabled to reduce the effect of long settling time. Fig. 3 presents a top view of the custom PCB.

C. Processing Unit

The processing unit incorporates a commercial nRF 52840 mini development board (Sparkfun, USA). The board features a Raytac MDBT50Q-P1M module which combines a 32 bit

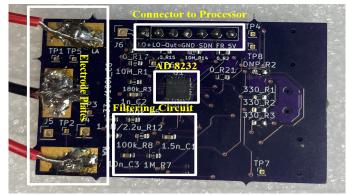


Fig. 3. Top view of the custom PCB.

ARM[®] Cortex[™] CPU and 2.4 GHz Bluetooth radio [8]. The BLE is programmed to run with maximum of 75 ms intervals with a baud rate of 115.2 kbps. The BLE module remains on for a very short time and send the data within that time. Each BLE transmission cycle consumes an average of 2.5 mA of current before going back to sleep mode. Moreover, hardware for timer interrupt and direct memory access (DMA) is implemented for efficient operation and power conservation.

IV. EMBEDDED FIRMWARE DESIGN

The firmware block diagram shown in Fig. 4 gives an overview of the system functionality in terms of software implementation. Initially, the ADC is in idle state. As soon as

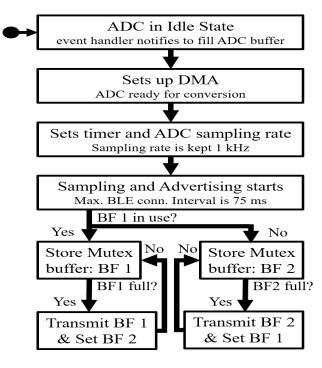


Fig. 4. Firmware block diagram of the single-lead ECG device.

an ADC task event is generated, an event handler notifies the processor to fill the ADC buffer (48 samples per ADC buffer). Following this notification, the ADC is initialized with a gain

factor of 25 and resolution of 10 bit. The DMA module is also set up for efficient read and write operation. At this stage, the ADC module is ready for conversion at a sampling rate of 1 kHz. A timer module set with a clock frequency of 31.25 kHz is implemented to set the sampling rate. With this sampling rate, the ADC unit is expected to consume an average of 11.98 μ A. The average current consumption for ADC unit is calculated by the following equation,

$$I_{Avg} = \frac{t_{Conv} + t_{Acq}}{SIn} \times I_{ADC,Conv} + \frac{SIn - (t_{Conv} + t_{Acq})}{SIn} \times I_{ADC,Idle}$$

Where, I_{Avg} is the average current consumed by the ADC unit, t_{Conv} and t_{Acq} is the conversion time and acquisition time respectively. SIn represents the sampling interval in μs . For 1kHz sampling rate, SIn is 1000 μs . Also, $I_{ADC,Conv}$ and $I_{ADC,Idle}$ represents current during conversion state and idle state of the ADC respectively. All measurement data is taken from data-sheet to calculate the average current.

As soon as ADC is ready for conversion, the sampling and BLE advertising starts. Sampled data is saved in 2 mutex buffer of 96 bytes each. When buffer 1 (BF1) becomes full, BLE is notified and data are transmitted. At the end of data transmission of BF 1, it sets the control to buffer 2 (BF2) and vice versa. For power optimization, the BLE advertising is activated for 3 minutes to connect to the mobile device. The custom device needs to refresh if advertising is needed after 3 minutes period. Upon successful connection to mobile device, the custom device can transmit data following BLE universal asynchronous receiver-transmitter (UART) protocol. BLE is programmed to send data within every 75 ms with a band rate of 115.2 kbps which makes the system more power efficient. The firmware code requires 39.3 kB of memory space and takes approximately 2.9 s for processing. A Visual Studio Code[®] environment is used to program the custom device with the help of USB serial interface.

V. DEVICE PACKAGING

The device is packaged inside a 3-D printed box. The box is printed using ANYCUBIC S (Shenzhen ANYCUBIC Technology, China) 3-D printer. The printing is done at 210⁰ C by using a filament of 1.75 mm diameter. Fig. 5 provides 3-D view of the box from two different angles. A lid is used to enclose the box. The size of the box is approximately 62 mm X 35 mm X 28 mm. Following Fig. 5 a), the commercial board goes on top with LiPo battery in the middle and custom PCB board at the bottom. Necessary insulation is provided with the battery so that, there is no short circuit error. The box by itself contains all 3 major parts tightly. In addition, hot air glue is used to enhance the stickiness of the parts inside the 3-D box.

Fig. 6 shows a real time setup for the custom device where, a user is wearing the electrodes for Lead I ECG measurement. Three gel electrodes are placed accordingly with the reference electrode place near the throat. The custom device is placed in the pocket of the shirt. The device is powered by a LiPo

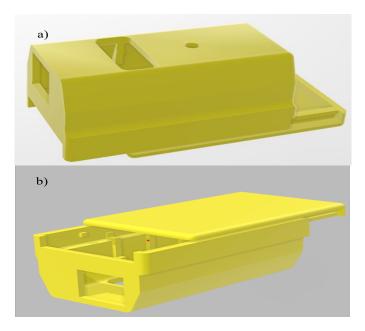


Fig. 5. 3D view of the package: a) cavities throughout the box as needed, b) a lid closing the box.

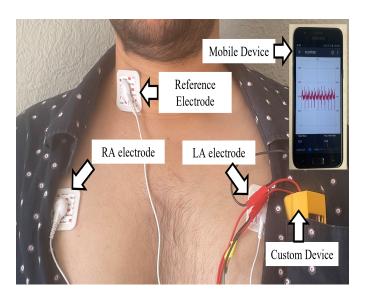


Fig. 6. Wearable setup of the custom device: (Inset) data captured in a mobile device

battery. A mobile device is connected to the custom device through BLE. Upon proper connection, the single lead ECG data is observed to the mobile app with UART capability. The firmware code needs to save once and does not require to reload every time the device is turned off. A single pole switch is available to turn on or off the device. Moreover, an option for USB cable is provided by the development board so that we can recharge the LiPo battery. The custom device has been tested in this setup up to 30 minutes of continuous observation. The device has been able to provide single lead ECG data for this observation period.

VI. RESULTS

This section presents the data acquisition from the custom device. Fig. 7 shows real time ECG data plotting by an oscilloscope (Model. Rigol MS05104). This data is taken from the output pin of AFE of the custom device. Fig. 8 presents the effect of filtering on the raw ECG signal. A smoothing filtering technique is applied on the 10 s raw ECG. The filtered signal has less noise and different ECG peaks are detectable. The filtering is executed in MATLAB® simulation environment. It is observed that R peak to R peak (R-R) interval is approximately 0.625 s.



Fig. 7. Lead I ECG captured in oscilloscope.

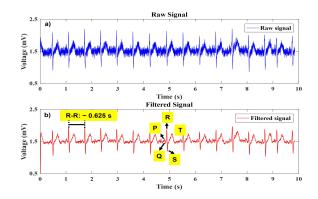


Fig. 8. ECG filtering: a) raw and, b) filtered ECG.

Fig. 9 depicts the ECG data acquisition to a mobile device. The data obtained contains prominent ECG peaks: P, Q, R, S, T. Availability of these features makes the custom device more appropriate for in-depth cardiac analysis.

VII. CONCLUSION

The proposed device is able to capture single lead ECG data and send the data to a mobile application. The device provides a fast restore feature so that it can come back to normal operation even if there is any disruption due to muscle movement. The firmware system is designed to be memory and time efficient. The device weighs around 75 g and costs approximately \$70 for a single unit at this prototyping phase. Finally, the device can be integrated to mHealth applications which can help the daily life users to keep track of their cardiac health.

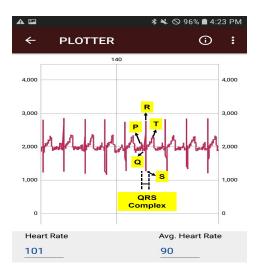


Fig. 9. Lead I ECG captured in mobile device.

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