Low-Power Wireless Wearable ECG Monitoring Chestbelt Based on Ferroelectric Microprocessor

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Abstract: Since cardiovascular disease (CVD) poses a heavy threat to people’s health, long-term electrocardiogram (ECG) monitoring is of great value for the improvement of treatment. To realize remote long-term ECG monitoring, a low-power wearable ECG monitoring device is proposed in this paper. The ECG monitoring device, abbreviated as ECGM, is designed based on ferroelectric microprocessor which provides ultra-low power consumption and contains four parts—MCU, BLE, Sensors and Power. The MCU part means circuit of MSP430FR2433, the core of ECGM. The BLE part is the CC2640R2F module applied for wireless transmission of the collected bio-signal data. And the sensors part includes several sensors like BMD101 used for monitoring bio-signals and motion of the wearer, while the Power part consists of battery circuit, charging circuit and 3.3V/1.8V/4.4V power supply circuit. The ECGM first collects ECG signals from the fabric electrodes adhered to wearers’ chest, preprocesses the signals to eliminate the injected noise, and then transmit the output data to wearers’ hand-held mobile phones through Bluetooth low energy (BLE). The wearers are enabled to acquire ECGs and other physiological parameters on their phones as well as some corresponding suggestions. The novelty of the system lies in the combination of low-power ECG sensor chip with ferroelectric microprocessor, thus achieving ultra-low power consumption and high signal quality.

Key Words: ECG, Wearable device, Telemetry monitoring, Ferroelectric Microprocessor

1 Introduction

Cardiovascular disease (CVD) has posed a threat to human’s health caused about 17.7 million deaths worldwide in 2015, accounting for 31.5% of the total 56 million deaths. Besides, the cardiovascular mortality rates in low-income and middle-income nations is much higher than that in high-income countries [1]. Therefore, full-day electrocardiogram (ECG) signals are badly needed for treatment of CVD patients. However, it is too expensive and impractical for patients to lie still in the hospital for 24-hour ECG monitoring, thus making quite important the design of suitable long-time ECG monitoring device.

The holter, which is a type of mobile ECG monitoring device for CVD patients nowadays, works but not good enough. The CVD patients need to paste the electrodes on their skin and live with at least three leads, sometimes the amount of leads can be even twelve. There are many other defects wearing the holter for ECG monitoring. The holter is usually as large as an old radio and doesn’t look easy to moving for wearers which means CVD patients in this article. By the way, the wet Ag-AgCl electrodes the holter uses are not comfortable and likely suffer from allergy for wearers.

Is there an alternation which owns smaller volume, less bondage and more soothing? Wearable ECG monitoring device in truly sense may satisfy the CVD patients’ expectation. Nowadays there are several forms of wearable ECG monitoring device including watch shape, chestbelt shape, underwear shape and so on. A watch shape device seems not a great idea for continuously ECG monitoring because ECG measuring needs at least two leads. The underwear shape may be an ideal choice if the technique of flexible fabric electrode matures enough. It looks like that the chestbelt is the he most appropriate shape, relatively speaking, for long-time 2-leads or 3-leads ECG monitoring. And how to design a nice product like that is still worthy of discussion and research.

Teo et al. [2] proposed wireless sensor nodes based on the low-power system on chip (SoC) which enables the combination between conventional electrodes and continuous ECG monitoring in real time, thus presenting a solution for wearable wireless sensor nodes properly. With the help of planar fashionable circuit board (P-FCB), Yoo et al. [3] embedded the wireless system into breast band and integrated a dry P-FCB electrode and signal acquisition circuit on the basis of body sensor networks (BSN) to monitor ECGs in real time. Fensli et al. [4] developed a prototype of wireless cardiac monitoring system which makes into practical the transmission of electrode signal to handheld devices wirelessly. Lee et al. [5] designed such a bio-signal acquisition and classification system with wireless telemetry for BSN, that composed of three chips including a body-end chip, a receiving-end chip, and a classification chip, can correctly diagnose cardiac diseases based on MIT-BIH arrhythmia database and assist the cardiologists in diagnosing their patients. Deepu et al. [6] introduced a design for wearable wireless ECG sensors based on a low power 3-lead ECG-on-chip with integrated real-time QRS detection and lossless data compression technology. Satija et al. [7] implemented IoT-enabled real-time ECG monitoring framework using ECG sensors, Arduino, android phone, Bluetooth, and cloud server. An innovative light-weight ECG signal quality-aware (SQA) method was applied to classify the obtained signal into acceptable or unacceptable categories.

This paper proposes a new design of wearable ECG monitoring device (ECGM) which features ultra-low power consumption and high signal quality, on the basis of previous research work. It is a important part of a complete telemetry healthcare system proposed in our previous work. And the detailed in-
Introduction of the designed ECG monitoring device is placed at the following sections.

Apart from this section (Section 1) which introduces the significance of ECG monitoring, why design the chestbelt ECG monitoring device and some researchs on ECG monitoring, the following sections expound the design of the ECG monitoring device. Section 2 states the design scheme of the proposed ECG monitoring device. Section 3 describes the main hardware design, including the parts selection and the circuit design. Section 4 expounds main software design during the implement of the device. Section 5 concludes the paper and points out the future research direction.

2 Design Scheme

The significance and reason of designing a wearable ECG monitoring device chestbelt are stated in the last section. As for this section, the overall design scheme is introduced. There are lots of aspects to take into account for designing a wearable ECG monitoring device and the key one is the signal’s quality. The collected ECG signals, which output as electrode voltage generally ranging from 0.1 mV to 2.5 mV [8], are easy to be disturbed by noise and how to eliminate the signal noise is the first problem to design a wearable ECG monitoring device. The technique to filter the noise in ECG signals can be summed up as two ways: hardware filtering and software filtering. Compared to hardware filtering, Software filtering shows several apparent advantages, such as low cost, low circuit complexity, high accuracy, and high flexibility. There are four main types of noise in ECG acquisition, namely low-frequency baseline drift, power frequency interference, muscles movement interference, contact interference [8], and the efforts put into finding out excellent algorithm to reduce the damage brought by these noise sources are particularly important when design a ECG monitoring device.

Another big problem that can’t be ignored is the battery life of the designed ECG device. With no great technique breakthrough in battery energy storage density, an ultra-low energy consumption feature is crucial for a qualified wearable ECG monitoring device because users hope the device keep working for a relatively long time, e.g. a week. The major source of power consumption in a wearable ECG monitoring device is the wireless transceiver [10]. On the basis of using ultra-low power components as far as possible, therefore, minimizing the use of transceiver and compressing data flow can effectively reduce the overall power consumption of the device.

Based on the above analysis, the ECGM should implement the basic work that collects the wearers’ bio-signals and sends them to the mobile phone or any other available monitor-end device. At the same time, it is nonnegligible to ensure the accuracy and low-power character of the designed ECGM. A new type of ECG monitor device with wireless data transmission, high resolution, low power consumption and small volume is preliminarily designed and tested. The proposed ECG monitoring device, which named ECGM, contains four main parts, including MCU part for event dealing, BLE part for wireless transmission, Sensors part for bio-signal acquisition and Power part for different voltage supplies. Fig. 1 shows the scheme of the ECGM. The MCU part is actually based on MSP430FR2433, which is one TI microcontroller with low power and cost, as well as outstanding performance. The BLE part is designed for wireless communication and the main device applied is CC2640R2F, one new Bluetooth Low Energy chip fabricated by TI. The sensor part, which contains ECG sensor and some other sensors which are used to monitor physiological parameters such as temperature, oxyhemoglobin saturation and blood pressure. In addition to the mentioned three parts, the power parts supply several kinds of voltage to the whole device. The working process of the ECGM can be simply described as: the sensor part collects the wearer’s body information and then send them back to the MCU part. The MCU part send the wearer’s data to the BLE part after the data were received. The BLE convert the data from UART protocol to BLE protocol and transmit them to the receiver, for example, a phone with Bluetooth module. The wearer can view their physiological parameters in the form of number or charts on their mobile phones.

3 Hardware Design

The hardware design in this section mainly introduces the four part selection and design of the proposed ECGM. Limited to limited length, only important components are expounded and the others are briefly mentioned.

3.1 MCU Circuit

The choice of the MCU is quite significant. There are many factors to consider in MCU selection: performance, power, stability, cost, compatibility and so on. Compared to the other serial MCUs like STM32, the MSP430 serial MCU from TI win a not bad score on the above-mentioned factors.

The MSP430FR2433 [10] microcontroller (MCU) is part of TI’s lowest-cost family of MCUs for sensing and measurement applications. The architecture, FRAM, and integrated peripherals, combined with extensive low-power modes, are optimized to achieve extended battery life in portable and battery-powered sensing applications in a small VQFN package (4 mm × 4 mm). What’s fantastic is that the MSP430FR2433 combines uniquely embedded FRAM and a holistic ultra-low-power system architecture, allowing system designers to increase performance while lowering energy consumption.
FRAM technology combines the low-energy fast writes, flexibility, and endurance of RAM with the nonvolatility of flash. A significant benefit is that some unchanging data can be stored in FRAM to lower the power of the MCU while speeding up the compute.

In the proposed ECGM, the MCU acts as a controller and data forwarding. All the used pins contain power pins, communication pins, LED pins and programming pins. The communication pins actually means the peripherals used for communication, containing UART and SPI. UART works for data transmission between BMD101 and MSP430FR2433, while SPI is used for the other sensors. Actually, two communication ways are implemented in one multiplexed enhanced universe serial communication interface (eUSCI). One kind of programming method that MSP430FR2433 support is flash through JTAG interface which is named MSP-FET in MSP430 serial. Fig. 2 shows the MSP430FR2433 circuit.

3.2 BLE Circuit

To transmit the data from MSP430FR2433, a wireless transmission technique is required. Nowadays there are several popular wireless techniques in internet of things (IoT), namely, WiFi, Bluetooth LE, GPRS, ZigBee, FSK, etc. Considering uses need ECG monitoring at home instead of hospital, ZigBee network is not a feasible solution. WiFi brings relatively high power consumption for mobile phone and ECGM, while GPRS brings additional communication cost. On the whole, Bluetooth low energy (BLE) seems the best choice for personal ECG monitoring at home.

CC2640R2F is a Bluetooth ultra-low energy wireless MCU with a main CPU, a radio frequency (RF) core, a sensor controller and other general peripherals/modules. The chip is designed mainly for Bluetooth 4.2 or Bluetooth 5 low-energy application. Very low active RF and MCU current and low-power mode current consumption provide excellent battery lifetime and allow for operation on small coin cell batteries and in energy-harvesting applications. It’s feasible to apply the CC2640R2F as the host MCU and BLE module at the same time, but in the proposed design, it acts a BLE module only for a better battery life. In order to smaller the volume of ECGM and speed up product development, a 4mm × 4mm CC2640R2F BLE module is chose in the design.

The interface circuit of the applied BLE module is showed in Fig. 3. RX and TX ports is responsible for data transmission through Bluetooth LE. Except VCC, GND, RX/TX, there are three important ports which are worthy of attention: EN, BCTS and BRTS. When the electrical level of EN port goes high, the whole MSP430FR2433 chip powers up. BCTS port need to set to be high before everytime the BLE module receive some data from the host MCU and send them out. By the way, once the BLE module transmit data successfully, the output of BRTS port will be high and become a flag of transfer success for the host MCU.

3.3 Sensors Circuit

The sensors parts contains several sensors to monitor wearer’s physiological parameters: BMD101, ADPD188GG, ADT7310 and ADXL362. Actually, because of the first aim of ECG monitoring, BMD101 is the main sensor introduced in this section.

3.3.1 BMD101 Circuit

The BMD101 circuit works as a bio-signal processor in this system. BMD101[9], with advanced analog front-end (AFE) circuitry and a flexible, powerful digital signal processing (DSP) structure, is the 3rd generation bio-signal SoC of NeuroSky.

For the AFE part, the main components are a low-noise-amplifier (LNA) and a 16-bit high resolution analog-to-digital converter (ADC). And for the DSP part, there are a configurable notch filter and a low-pass filter dealing with the ADC data. Once BMD101 starts working, the collected voltage signal from wearer by the sensor goes through a high-pass filter and a low-noise-amplifier which are both parts of the AFE. Then the amplified analog signal is converted to digital signal by the ADC in the AFE part. After data leaves the ADC, it goes through the digital filters for reducing the negative influence brought by kinds of noise. Finally, the row data with CRC checksum is sent out through universal asynchronous receiver/transmitter (UART).

Besides, there are several points to notice in the design of BMD101 circuit. The first one is the PI filter circuit and it help stable the supply to 3.3V for BMD101. The two capacitors are both 10µF while the inductor be selected to be 10µH. Another point is that the analog GND and the digital GND should be separated by an inductor. In the BMD101 circuit, a 10µH inductor is employed to reach the above target. In addition to the
above-mentioned tips, there are two TPD1E10B06s, one kind of single channel ESD protection device in a small 0402 package, are used to protect the BMD101 chip from damage when the voltage between the two electrodes varies suddenly.

A problem follows the design of BMD101 circuit is to chose right electrodes which are important for the accuracy of the collected ECG signals. For BMD101, there are some limits in selection of electrodes. Electrodes suitable for ECG acquisition using BMD101 should be stainless steel, silver-silver chloride (Ag-AgCl), conductive cloth, etc. To ensure long-time monitoring and users’ comfort, thereby, fabric electrodes are used in this design. As for dimensions of sensors, an about 10mm-diameter electrode is recommended.

3.3.2 Other Sensors

It is worthy of explanation that there are other sensors applied in the design for test. Actually a feasible ECG monitoring design should be as lean as possible and that is why this article titled for ECG monitoring. The other sensors, including ADPD188GG, ADT7310, ADXL362, is used to acquire other bio-signals except ECG.

The ADPD188GG[12] is a complete photometric system designed to measure optical signals from ambient light and from synchronous reflected LED pulses. The module integrates a highly efficient photometric front end, two LEDs, and two photodiode (PD). The data output and functional configuration occur over a 1.8 V I^2C interface or a serial peripheral interface (SPI) port. The ADPD188GG applied in the ECGM is to measure the wearer’s heart rate and SpO2 through a optical way.

The ADT7310[12] is a high accuracy digital temperature sensor in a narrow SOIC package. It contains a band gap temperature reference and a 13-bit ADC to monitor and digitize the temperature to a 0.0625 °C resolution. The ADT7310 applied in the ECGM is to measure the wearer’s temperature.

The ADXL362[12] is an ultra-low power, 3-axis MEMS accelerometer that consumes less than 2 µA at a 100 Hz output data rate and 270 nA when in motion triggered wake-up mode. The ADXL362 is used mainly for motion identification. Once the wearer is in motion, the ECG signal or other bio-signals will be no longer the same as those acquired under state of rest. Thus it’s necessary to rectify the deviation for bio-signals under motion state according to the motion data of the wearer.

3.4 Power Supply

At the time the other three parts which mean MCU, BLE and sensors are selected and designed, the power of the ECGM need to be designed. Cause the 3V battery is very easy for consumers to reach and the most components used need an input voltage around 3V, a 3V battery is quite suitable in the proposed design.

The input voltage required by the components applied in the ECGM are listed in Table 1.

| Component     | Input Voltage   |
|---------------|-----------------|
| MSP430FR2433  | 1.8V - 3.6V     |
| CC2640R2F     | 1.8V - 3.8V     |
| BMD101        | 3.3V (+/-10%)   |
| ADPD188GG     | 1.7V - 1.9V; 4.0V - 5.0V |
| ADT7310       | 2.7V - 5.5V     |
| ADXL362       | 1.6V - 3.5V     |

It’s clear that a 3V DC power is suitable for the ECGM and, to reduce the volume of ECGM as much as possible, a rechargeable LIR3032 is applied. LIR3032 is one type of button-cell battery with output voltage range from 2.75V to 4.2V and capacity of about 120 mAh. In the charging circuit, a MCP73831 chip in charge of the charging of the LIR3032. The charging current of the LIR3032 should be no more than 0.5CmA and that means a good charging speed is two hours or longer for a full charge. Thus, a 16.7 kΩ or larger resistor is needed to meet the charging speed limit in the charging circuit.

Rechargeable feature makes it more convenient for users because they don’t have to buy a new battery from supermarket. What is worth noting is, the voltage will decrease continuously as the battery is used, proper voltage stabilizing circuit is necessary. A TPS63036 buck-boost converter capable of providing a regulated output voltage is applied to generate stable 3.3V output voltage.

In addition to 3.3V voltage, 1.8V and 4.4V is also needed for ADPD188GG. Taking account of that, a TLV70718 LDO voltage regulator and a TPS61099 booster converter is used for 1.8V and 4.4V voltage supply, respectively.

4 Software Design

The software introduced in this section mainly contains three aspects, the master control program (MCP) for the data receiving/transmitting through UART/BLE, the SPP program for protocol converting between UART and BLE, as well as ECG data parsing program. Limited to the article length, other software in the ECGM and the APP for ECG display are skipped in this section.

4.1 The master control program

For the MSP430FR2433, the most important task is receiving the sensing data and then send them out to the BLE module. The MSP430FR2433 MCU has one active mode and several software-selectable low-power modes of operation. An interrupt event can wake the MCU from low-power mode, service the request, and restore the MCU back to the low-power mode on return from the interrupt program.

The master control program in MSP430FR2433 is designed to wait for the UART interrupt and then do the interrupt program. A brief procedure of the master control program is showed in Fig. 4 and described as the following sentences. At the time the MSP430FR2433 powers up, the watchdog timer, which perform a controlled system restart after a software problem occurs, will be stopped first. Then the clock system module which supports low system cost and low power consumption should be initialized and the general purpose input and output (GPIO) ports used in the design need to be configured. After that, it is indispensable to disable the GPIO power-
on default high-impedance mode to activate previously configured port settings. The UART port used need to be initialized and configured containing selecting the clock source, setting the baudrate and deciding the UART mode etc. Of course the BLE module used for data transmission need to be initialized, too. After all the above steps are performed, the MSP430FR2433 enter hibernation mode (LPM0 in MSP430 serial) and enable the general interrupt.

![Fig. 4: Procedure of MCP](image)

When the BMD101 sends out ECG raw data to the UART RX interrupt pin of MSP430FR2433, the host MCU which means MSP430FR2433 awaked, enter the active mode (AM) and receive the continuous data according to the UART protocol. Namely the host MCU sends the data out through TX pin to the BLE module after the digital processing of the bio-signal data is done. The procedure described above is the most directly related to the target of ECG monitoring and some other procedure are skipped here.

### 4.2 The SPP Program

In this design, what the BLE module acts is a RF transceiver. The BLE module receives the data from the host MCU through UART and then converts them into data obeying the BLE protocol. Of course the BLE data is then transmitted to the wearer’s monitor such as mobile phones.

The application named spp_ble_server in the BLE module is simple and the main processing is implemented within the application task function. The application gets the UART data from the SDI layer and sends it over the air in notification packets. The application does not directly receive wireless data; the data goes to the profile layer and gets sent to the UART by the SDI layer. By the way it is feasible to implement queues to transfer the data to the application layer for further processing.

The initialization of spp_ble_server happens before running the main task and it configures parameters in the peripheral profile, the GAP, and the GAP bond manager. The initialization function sets up the serial port service with standard GATT and GAP services in the attribute server and set the parameters of UART. The registration for receiving UART messages can be set up from the SDI layer. Also during this phase, the initialization function of spp_ble_server calls the GAPRole_StartDevice function to set up the GAP functions then calls the GAPBondMgr_Register to register with the bond manager.

### 4.3 ECG data parsing

How to parse the ECG data is important for implement the ECGM and the data parsing program can run on MSP430FR2433 or on the monitor-end (mobile phones). BMD101 communicates through UART interface which deploys a 1 start bit, 8 data bits, and 1 stop bit format. A digital output packet of the UART interface is sent as an asynchronous serial stream of bytes. Each packet begins with its Header, followed by its Data Payload, and ends with its CRC checksum byte. The Data Payload itself consists of a continuous series of DataRows. Parsing a Data Payload involves parsing each DataRow until all the bytes of the Data Payload have been parsed. A DataRow consists of different bytes which are EXCODE, CODE, LENGTH and VALUE respectively. The process of parsing a ECG digital output packet is illustrated in Fig. 5 and only all the steps described above are executed correctly in sequence the packet can be parsed.

![Fig. 5: The process of parsing a data packet](image)

### 5 Conclusion

In this paper, a low-power wireless wearable ECG monitoring device in a chestbelt shape is proposed based on ferroelectric microprocessor MSP430FR2433 and the BMD101 bio-sensor. The ECG monitoring chestbelt includes four parts, namely, MCU part for event dealing, BLE part for wireless transmission, Sensors part for bio-signal acquisition and Power part for different voltage supplys. The main process is: ECG signals are collected, preprocessed, and digitalized by BMD101 sensor, which acts as a front-end in the ECGM; The digital output packets are received by MSP430FR2433 through UART, then sent to the BLE module through UART after necessary event handling. Then the CC2640R2F converts the UART data to BLE data and transmit them out for the wearer monitoring their bio-signals especially ECG signal. Because of the high resolution and low power consumption of BMD101, ultra-low power consumption and ferroelectric character of
MSP430FR2433, the proposed ECG monitoring device features low power consumption, high signal quality, comfort, etc. By the way, the main software consist of data parsing, master control program and the SPP program are briefly introduced. A preliminary design of the proposed ECG monitoring device is complete and furthermore, more details, such as improving the design and ECG classification algorithm, need to be studied in the near future.

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