35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Design and Tests of a Smartphones-based Multi-lead ECG Monitoring System

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***Abstract*—With the rapid development of wireless communications and sensor technologies, multi-lead electrocardiogram (ECG) monitoring systems can be implemented for real-time Cardiovascular Disease (CVD) tracking and prevention services by using mobile terminals. To meet this objective, we designed a 7-lead ECG monitoring system enabled by smartphones, which is a combination of user mobility requirement and clinical intelligent function. In the system, an application-layer protocol is conceived and tested for guaranteeing data transmission reliability between smartphones and portable sensors. In addition, the smartphone in the system can be customized as a personal health manager, which can control system function modes and device states, and also perform information management and deeper data analysis. Most significantly, we developed a health risk alarm algorithm to detect ECG signal abnormities, which could help professionals pick out the data with key clinical information. To test our system performance and validity, we carried out simulation tests and system experiments. The results show our system is helpful in CVD prevention services.**

***Keywords*—ECG monitoring system, Real-time monitoring, Anomaly detection, Smartphone**

I. INTRODUCTION

Cardiovascular Disease (CVD) is the leading cause of death in the world so far [1]. However, the limited medical resources are not enough to meet the rising demand of healthcare services. Meanwhile, with the rapid development of the information technology, smartphone-based healthcare system is becoming more and more popular, which helps to collect real-time health data anywhere for patients and medical professionals.

Wireless electrocardiogram (ECG) monitoring system is able to obtain the ECG from a person and transmit the real-time data wirelessly to the caregiver. The system can give the doctor a timely warning due to its continuous monitoring feature, so it offers strong support for detecting heart attacks. Therefore the development of a reliable system is of great significance. There have been some monitoring systems in research or even in use, but a more stable, more accurate and more intelligent system is still in need. In [2], [3], wireless monitoring systems based on GPRS or Zigbee were designed, but the communication method used in these systems was not trustable. In [4], a similar system based on smartphone was implemented. However, due to the limitations of the phone's computing power, real-time ECG collection was not supported. In [5], the author developed an android-based application to analyze the ECG signal, which raised another challenge: if all the ECG data was processed by the phone, the phone should be connected to the sensor all the time and it would quickly run out of battery.

To solve these problems, we designed and implemented an ECG monitoring system using Android-based phones. A smart 7-lead ECG device was developed to capture the ECG signals. Real-time abnormal ECG detection was implemented on the mobile device using feature point extraction method. Besides, we designed a reliable communication protocol, providing the functions of device controlling and data transmission. With the accurate signal collection, the real-time ECG analysis and the reliable data transmission, the system is able to work well under alarm mode. That is, only when abnormal events happen will the portable sensors send ECG data to the phone. This working mode reduces much network cost in monitoring services and is more power-saving. To make it convenient for the users to get detailed ECG information, other working modes are also supported in our system, such as real-time mode and history mode.

The paper is organized as follows. In Section II, we have an overview of the system and its working platform. In Section III, we present the details of the hardware and software design of the system. In Section IV, simulation and application test results are given. Conclusion is made in Section V.

II. SYSTEM OVERVIEW

Our ECG data collecting and analyzing system works on the telemedicine cloud platform, which is already being used for clinical trials in Peking University (PKU) People's Hospital [6].

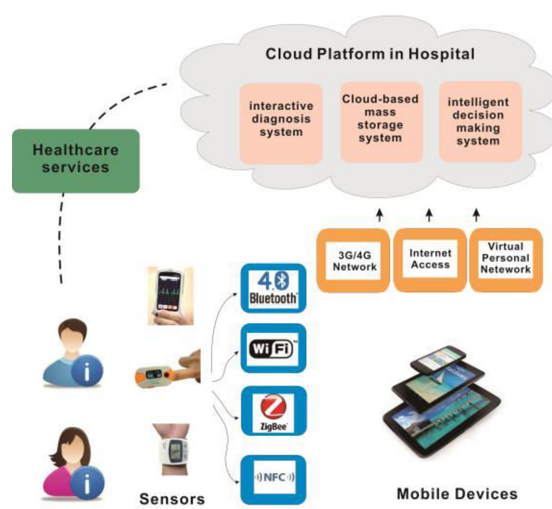

Figure 1. System Structure

Our system is mainly composed of three parts: a portable sensor as an agent, an android phone as a manager, and data transport protocol to connect the agent and the manager. Figure 1 illustrates how the system works. The ECG data collected by the sensor is transmitted to the phone via robust wireless channels. Then the android application on the phone takes a further analysis of the received data, and the results can be immediately uploaded to the monitoring center. In the cloud platform, the remote doctors can keep a closer watch over the users' health condition and are able to make quick responses whenever an abnormal event happens.

III. SYSTEM DESIGN AND IMPLEMENTATION

A. ECG Sensors

The design of the personal healthcare device should focus on two requirements: firstly, it collects the ECG signal with high sampling rate and supports real-time data analysis. Secondly, its sensing terminals are portable and have long-battery life.

1) Hardware Architecture

Considering the clinical significance of multi-lead dynamic electrocardiogram in cardiovascular diagnosis and treatment, we designed a seven lead real-time ECG signal collection system with sampling rate up to 500 Hz. As shown in Figure 2, the original ECG signals first pass through an amplifier array, then low-pass filters and high-pass filters. Right leg driven circuit is supported to eliminate the 50 Hz power-line interference. After that, the Analog Digital Converter (ADC) module converts the signals to digital data and inputs it to the microprocessor. Since a relative high processing performance is required, we use the STM32 chip as the system controller, which has a low-power ARM Cortex-M3 core. In our system, Bluetooth 2.1 is chosen to transfer the data, for its lower power consumption compared with WIFI. Furthermore, Trans Flash (TF) card supporting circuit was designed for long period ECG data recording.

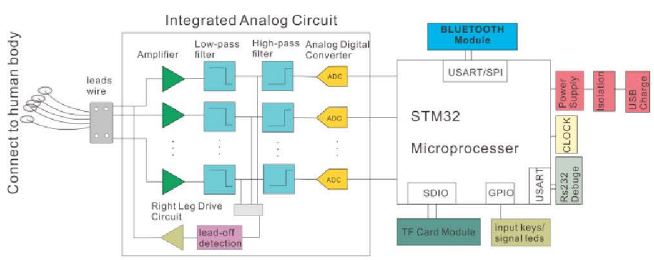

Figure 2. Hardware diagram of the ECG sensor

2) Alarm Subsystem

The software framework of the portable ECG device is based on uC/OS-II system, which is a small real-time embedded operating system written in C language. At the application layer, there are several tasks responsible for task managing, signal processing, wireless communications, data recording and alarming, respectively.

Traditional health monitoring devices, e.g. Holter, can record ECG continuously for 24 hours. However, there will be too much ECG information for the doctors to analyze without automatic diagnostic support. So we add the automatic alarm mechanism, which uses the feature point extraction method to detect ECG abnormalities. We use dynamic differential threshold algorithm to extract the R point, S point, J point and T point of the ECG waveform. The principle of this algorithm is consistent with the traditional ones, and the key difference is our method is optimized for real-time analysis.

Figure 3 illustrates the detection procedure of the QRS complexes, ST segments and T waves in ECG waveform. The first step is to remove the baseline of the raw ECG signal using Moving Average Method [7]. Then the amplitude and the slope of the signal are checked. If both of them outrange given thresholds, a peak detection sub process will be triggered. After the preliminary detection of the R wave, there will be a validation process, which yields a 30 ms time delay. Once the RR-interval is extracted, the heart beat can be calculated easily.

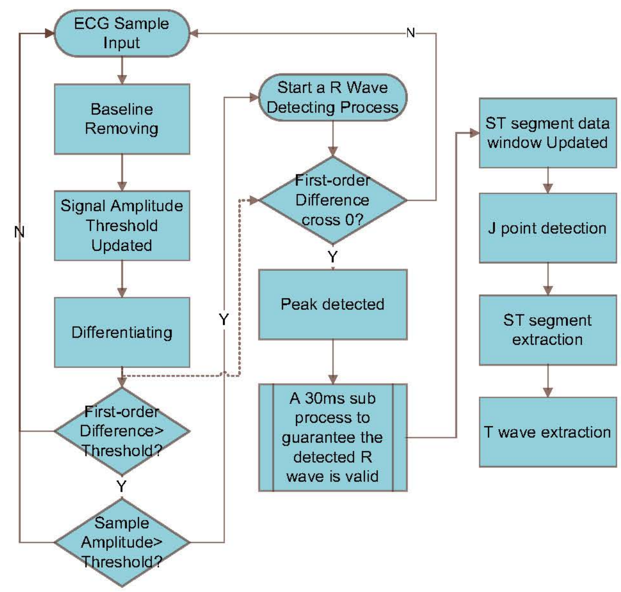

Figure 3. Feature point extraction procedure of ECG waveform

The data between two R waves is used for subsequent ST analysis. Starting from S point, J point is firstly detected as the first inflection point. Then a traditional J+X method is used to extract the amplitude of the ST segment. As the length of the ST wave varies with the heart rate, every time R wave is detected, the threshold parameter for the ST wave detection is updated. The last step is to isolate the T wave followed and get its maximum value.

After the extraction of the wave's feature points, we set up several thresholds to implement the alarm function. For example, if ST segment drops by 0.1 mV, which happens over 20 times in less than 30 seconds, a warning of myocardial ischemia will be raised. These thresholds can be set through the smartphones by caregivers according to the patient's physical condition.

B. Transport Protocol

As mentioned above, the communication system in ECG monitoring system should be fully automated and reliable. Considering the scalability of the system, we implemented a transport protocol in application layer, which allows incorporation of various communication platforms to facilitate efficient exchange of care device data.

We selected Bluetooth as the access technology in communication physical layer. The Bluetooth module on the ECG device works under the slave mode, while the android phone under the master mode, in which the phone can connect several devices simultaneously. After the link is established, the two sides can start data exchanging.

The application protocol allows device associating, remote controlling and data transferring. Figure 4 shows the state machine of the ECG device. Associating procedure is entered automatically right after the device is connected. Firstly, the phone sends an association request, and then the device responds with its unique device ID and sensor type. According to the device ID, the phone can tell whether the device has ever associated with it before. If the sensor is new to the phone, it will be requested to report its configuration details, such as ECG sampling rate, alarm threshold and user information, or else the sensor just reports its current status briefly. At last the phone acknowledges the device and the two sides get associated.

ECG device will get into standby state by default, at which it responds to the control command of the phone. If the terminal completes the requested task, it will give its operation result as response, otherwise there will be an ERROR response.

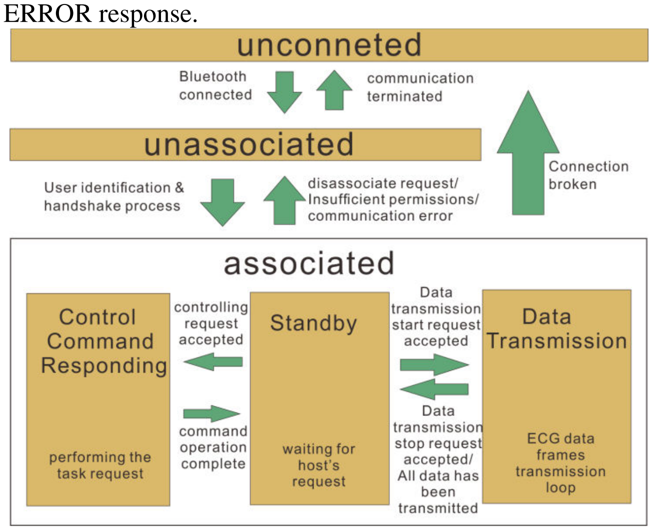

Figure 4. State machine of the ECG device's communication system

We designed our protocol to support different data transmission modes. We found that people didn't keep an eye on the phones' screens all the time when using phone-based healthcare systems. What they usually care about is whether there's an abnormal event happening to them. So we let the system work under the alarm mode by default. That is, the sensor terminal's network module is on standby state most of the time and only sends ECG data frames when abnormalities happen. Even though the calculation burden brought to the terminal increases, the network costs are reduced and the working time gets longer. When the system works under real-time mode, the terminal sends ECG data frames continuously. When under history mode, the data stored previously in the portable device is transferred.

We designed a dedicated ECG data frame, which provides the remote manager with all the information required to reshape the signal. The specific of the frame structure is shown in Figure 5. The whole frame is composed of a header and multi-lead ECG data. This kind of structure garantees the real-time data transmission, even if there are packet losses. With the presence of the alarm bytes, our system can easily detect abnormanities such as ECG leads off or ST segment changes.

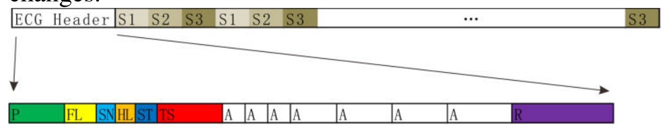

Figure 5. ECG data frame structure

TABLE I. ECG DATA FRAME FIELDS DISCRIPTION

Frame type	Length	Description
S1,S2,S3	1 byte	ECG sample data,S1-S3 represents data of different channels
P	4 bytes	Protocol identity
FL	2 bytes	Frame length, used for frame extraction
SN	1 byte	Sequence Number, help check frame loss
HL	1 byte	Header length, used for header extraction
ST	1 byte	Sensor type
TS	4 bytes	Time stamp, used to record the time of the first sample in the frame
A	1-3 bytes	Alarm status, including relative alarming time and alarm extent(optional)
R	4 bytes	Reserved bytes

C. Android Application

We select android as the smartphone platform because it is open source and widely used. The software consists of three parts: (1) Data Stream Parsing Module (2) Device Information Manager (3) Graphic User Interface (GUI).

The Data Stream Parsing Module allows interpreting the binary network data stream. It distinguishes different kinds of frames and dispatches them to different processes.

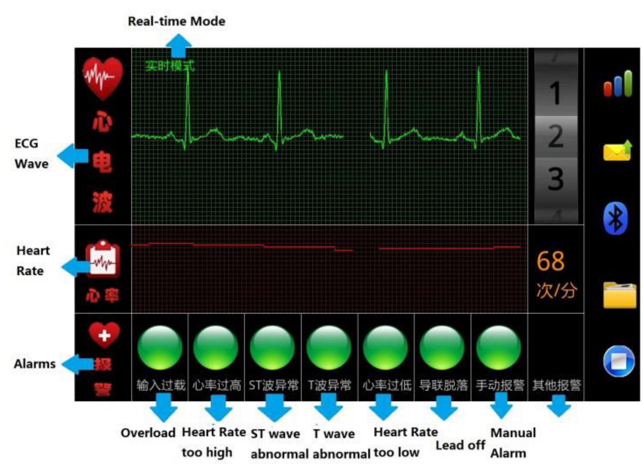

Figure 6. GUI of the android application

The Device Information Manager aims at offering an efficient way for controlling the device. It stores all the information of the sensor, which synchronizes with the real entity. By operating on the dummy device objects, the user can interact with the real sensor.

A user friendly GUI was implemented on the android phone. As Figure 6 shows, it shows the real-time dynamic ECG waveforms. Besides, it draws the heart rates curve, which makes it much clear to see how the heart rate changes in recent one minute. The seven round signs at the bottom of the screen indicate different kinds of alarms.

IV. EXPERIMENT RESULTS

The developed system was tested to validate its function and analyze its performance. Figure 7 shows the actual testing scenario. We used Samsung GT-N7000 as the testing android phone and all the functions worked well as expected. The ECG sensor was easily synchronized with the phone, and the waveform was accurately collected and smoothly displayed. When the sensor just worked under alarm mode, it could work up to 44 hours without charge, and when it was continuously transferring data to the phone, it could work 19 hours.

Figure 7. System test in real envirenment

1) Simulations of Abnormal ECG Detection

The MIT-BIH Arrhythmia databases were used for the test of our abnormal ECG detection algorithm. As the first step, we invited doctors to annotate all the abnormal waves of the sample data. Then we simulated our detection procedure. The test results were then compared with the existing valid ones.

TABLE II. RESULTS OF ABNORMAL ECG DETECTION ALGORITHM ON MIT-BIH DATABASES

Abnormal ECG type	**Accuracy rate**	**False negative rate**	**False positive rate**
Abnormal R Wave Detection	99.46%	0.54%	1.08%
Abnormal ST segment Detection	84.39%	15.61%	2.45%
Abnormal T Wave Detection	80.21%	19.79%	2.32%

Table II indicates that 99.46% of the abnormal R waves are detected, and only 1.08% of the detection results are false alarms. The performance of abnormal ST segment and T wave detection are slightly degraded, because the algorithm is based on empirical values and some abnormal waves may not be accurately captured when heart rate has a large fluctuation.

2) System Experiments in Real Environment

To have a comprehensive test of the system performance in real environment, we used TESTWIT MSG-300U ECG waveform simulator to generate different kinds of abnormal ECG signals as input, such as arrhythmia and ST–elevation. We recorded the analysis result and the warning delay time, which is shown in table III. It shows that the heart rate alarm has a high accuracy, and the alarm system also works well when there are significant ST segment changes. While when the changes are small, the error rate rises because of the noise effect, where there’s much room for the algorithm to improve.

TABLE III. STATISTICAL RESULT OF ALARM SYSTEMTEST

Abnormal ECG type	**Accuracy rate**	**Average alarm delay(second)**
Tachycardia	99.2%	7
Bradycardia	98.3%	6
ST +0.4	89.0%	13
ST +0.2	85.3%	13
ST +0.1	73.0%	20
ST -0.1	62.0%	20
ST -0.2	79.2%	14
ST -0.4	84.3%	14

V. CONCLUSION

In this paper, we proposed a 7-lead ECG monitoring system based on smartphones. An automatic real-time analysis of ECG along with an intelligent warning system was implemented in the ECG terminal. As the experiment results show, with a smartphone, a user can easily get his accurate ECG data collected by the portable device. Due to its effective performance, the system can provide strong support to cardiovascular patients and medical professionals.

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