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Development of a Patch Type Embedded Cardiac Function Monitoring System Using Dual Microprocessor for Arrhythmia Detection in Heart Disease Patient*

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Abstract— **A patch type embedded cardiac function monitoring system was developed to detect arrhythmias such as PVC (Premature Ventricular Contraction), pause, ventricular fibrillation, and tachy/bradycardia. The overall system is composed of a main module including a dual processor and a Bluetooth telecommunication module. The dual microprocessor strategy minimizes power consumption and size, and guarantees the resources of embedded software programs. The developed software was verified with standard DB, and showed good performance.**

I. Introduction

The heart beats 100,000 times and pumps about 2,000 gallons of blood each day. It adaptively maintains its rhythm depending on the physical situation and its function is relatively robust. However, a condition can occur in which the heart loses its rhythm. This condition is called arrhythmia, and may occur even in normal people. The term "arrhythmia" refers to any change from the normal sequence of electrical impulses that makes heart beats. If the electrical impulses are generated too fast, too slowly, or erratically, various types of arrhythmia may occur such as atrial fibrillation, tachycardia, bradycardia, ventricular fibrillation, conduction disorders, other rhythm disorders, premature contraction, and types of arrhythmia in children [1].

It is very important to note that some arrhythmias are life-threatening medical emergencies that can result in cardiac arrest. Not all arrhythmia causes death but the degree of risk that can cause sudden death is much higher for arrhythmia patients relative to normal healthy people. The fact that AED (Automated external defibrillator) equipment are nowadays prevalent in many public places such as train stations, shopping centers, and office buildings shows that arrhythmia can cause very urgent emergency situation in which anyone can provide help to the afflicted using the device, and at the same time shows that life-threatening crisis situations from arrhythmia can be managed with the device. In this context, we feel that there is a need of heart monitoring for arrhythmia, and in fact, many groups have been exerting their efforts on this theme [2], [3].

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There are many types of cardiac monitoring devices such as holter type, patch type, and wearable type devices, but the purpose of these devices are the same, that is, to monitor cardiac functions effectively while allowing portability for a long period of time. Till now, however, there have been no embedded ECG monitoring devices which can detect arrhythmias with embedded software. Almost all existing devices analyze arrhythmia in separate equipment such as a smartphones, PDAs, PCs, or dedicated terminals. Thus embedded cardiac function monitoring system would be very useful. Moreover, if it is compact, portable, and available for a long time, it would be much better to use. This research began from these motives, and we have achieved some successful results.

II. Materials and Methods

A. Backgrounds

Our group has researched the cardiac monitoring system for many years. The first prototype of this system was part of a bio-signal monitoring vest which aggregated various bio-signal monitoring devices in a vest in 2003. In the next version, we focused on the function of ECG monitoring and the revised form was the Bio-shirt in 2005, which was a wearable device for exercises. The Bio-shirt was able to detect ECG and acceleration signals in exercise situations such as marathon, and the signal was stored in the memory of the device or transferred wirelessly to the analysis terminal such as PDA or PC. There were many other garment type wearable devises like outdoor jacket, dress, and patient gown, etc. Similarly, we developed a patch-type device, that is, the Bio-patch, which has the same functionality as the Bio-shirt module. However, those devices were only able to provide a single channel ECG signal, lead II, because we concentrated on robustness in sports utility rather than more information. After that, we developed another device to expand the usage of the Bio-patch to detect a wider range of arrhythmia situations in clinical tests, which was the patch-type multi-channel ECG monitoring device in 2010 [4]. These devices wirelessly transmitted all ECG and acceleration signals as raw data to the analysis terminal device. In these cases, the wireless transmission consumed so much power that the battery did not last so long. To extend the operational time of the system, we concluded that the wireless transmission should be reduced dramatically. One of the best solutions could be the change to the embedded system type in which the processing module includes the ECG analysis algorithm. This change eliminated the raw data transmission and the system only sends processed results. We tried to integrate the arrhythmia detectable software algorithm to the processor's flash memory for single channel ECG data analysis in this study.

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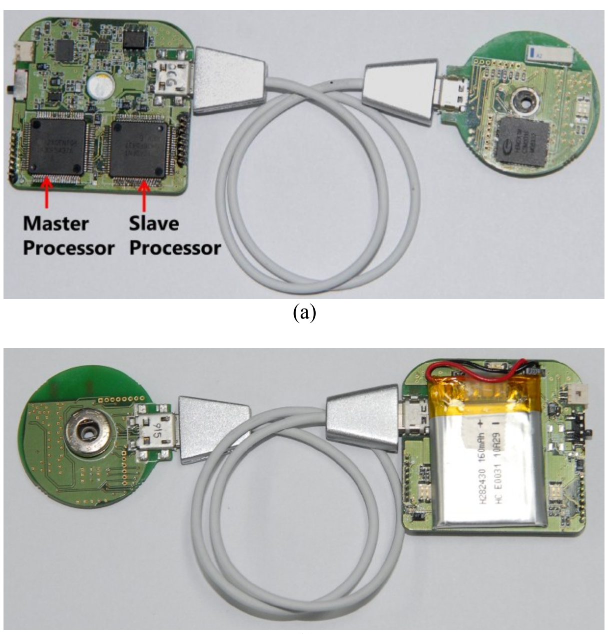
B. Materials

The developed system comprises two major parts, the main module and the Bluetooth telecommunication module (Fig.1). The processing module has two 16-bit microprocessors which communicates with each other through SPI (Serial Peripheral Interface). The reason why we adopted the dual processor concept is that this could increase the processing capacity and minimize power consumption. If we use a higher level processor, like ARM or DSP which is 32-bit processor, power consumption would greatly increase and there would be redundant functions not used. This could limit the portability because of the system size including the battery. On the other hand, if we use just one 16-bit processor, the resource of processor would not be able to properly perform its analysis function. Thus, we traded off and agreed to develop dual a 16-bit processor system. In this study, we chose MSP430F5437A (Texas Instruments, USA) as 16-bit microprocessor.

The two processors are designated as master and slave, and share five pins for communication. Three pins are assigned to 3-pin SPI communication, and two pins are assigned to port interrupt between the two microprocessors. The function of the overall system can be seen in the block diagram of Fig.2. When the ECG signal is gathered at electrode (Ag/AgCl disposable electrode), it goes through filters and is amplified in the analog circuit. The master microprocessor stores this temporarily and processes the signal to detect beat, etc. The slave microprocessor gets this signal from the master through SPI and run a classification algorithm and notifies to the master if the beat is arrhythmic or not. When the system



(a)

(b)

Fig.1. The appearance of developed 'embedded cardiac function monitoring system'.

(a) The square shape board on the left side is main module, the circular one on the right side is BT communication module. The main module has two processors, master and slave processor. Two modules are connected electrically with cable.

(b) This shows the backside of whole system. The battery is rechargeable Li-polymer type with 160mAh capacity.

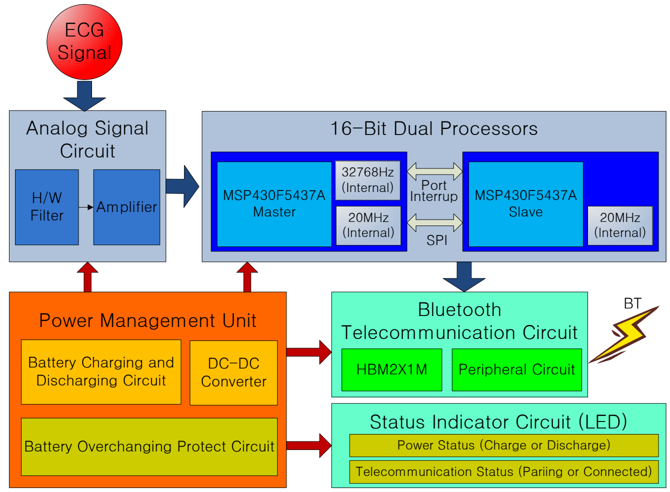


Fig.2. Block diagram of developed 'embedded cardiac function monitoring system'. This figure shows the whole hardware components at a glance. The input stage of ECG signal is composed of analog circuit such as filter and amplifier. The signal after analog circuit goes to master microprocessor and is treated to detect beat. The slave processor receives the beat data from master through SPI communication and classifies the beat to investigate the arrhythmia. When arrhythmia is detected, slave returns the alarm code to master and master alarms abnormal sign to smartphone through Bluetooth connection.

judges that arrhythmia occurs, the system sends an alarm sign to the user's terminal device (i.e. smartphone) through Bluetooth connection. The user's device, smartphone, can show the monitoring status and result through its display, and can send this situation to the caregiver's device or system through 3G network.

C. Methods

The gathered ECG signal is processed in the main module. The master and slave microprocessors in the main module communicate and cooperate interactively to find arrhythmias. The role of each processor is described in Table I. The two processors communicate with a 3-Pin SPI protocol, and they need another two port interrupt pins for stable SPI communication. The master processor undertakes tasks such as ADC, beat detection, fibrillation detection, beat data transmission to the slave processor, and alarming the arrhythmia detection, etc. The slave's main function is beat classification and it returns the result to the master.

TABLE I. FUNCTIONAL IDENTITY OF EACH PROCESSOR

Processor Name	Functional Description
Master	Total control of the system Analog to Digital Conversion Beat Detection Ventricular Fibrillation Detection Master in SPI communication Alarm signal generation to Smartphone
Slave	Beat classification Return the classification result Slave in SPI communication

The detailed workflow of monitoring arrhythmia and alarming process is described in Fig.3. The developed software algorithm is available for these arrhythmias such as PVC (Premature Ventricular Contraction), pause, ventricular fibrillation, and tachy/bradycardia. The developed algorithm is tested with standard DB, such as AHA, MIT/BIT, NST and CU to verify their performance.

III. Results

The algorithms which are prepared for this embedded system are pretested with the standard DBs in PC. There are three main algorithms in this system, which are beat detection algorithm, ventricular fibrillation algorithm, and beat classification algorithm. At first, the beat detection algorithm shows 99% performance in sensitivity. This algorithm is based on the published papers [5], [6]. This was verified with standard DB, and also used in pre-described Bio-Shirt and multi-channel ECG system. Besides, we verified this clinically with reference systems equipped in hospitals and the result was 99.9% correlation with the system. The second tested algorithm is for ventricular fibrillation. We tested this with standard DB and compared with other algorithms. Though our algorithm is revised to fit the embedded system, which was much reduced in process and program size, the performance is close to the compared algorithms. Table II shows the performance of fibrillation detection algorithm. Third algorithm of which the performance we are presenting is the beat classification algorithm. This is verified by the calculation of sensitivity and positive predictivity of VEB (Ventricular Ectopic Beat). The VEB sensitivity is 91.56 %, and the VEB positive predictivity is 96.59 %. The criteria used in performance tests over all algorithms are defined and required in standard documentations [8], [9].

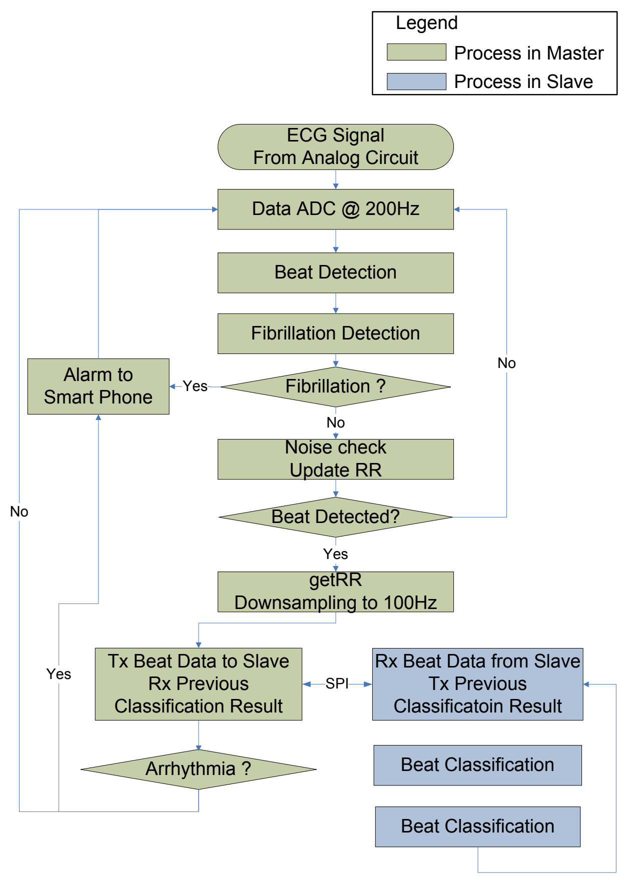


Fig.3. Flowchart of F/W in developed 'embedded cardiac function monitoring system'. This figure shows the whole F/W algorithm running process in each master and slave processor at a glance. The application program of smartphone is omitted.

TABLE II. Performance Comparison of Referred and Developed Algorithm

Algorithms	Sensitivity	Specificity	Pos. Pred.	Accuracy
MAV & EMD	91.1	99.4	90.7	99.2
Jekova Count	88.9	99.3	86.0	98.9
Our work	88.5	99.1	84.8	98.6

Algorithm MAV & EMD, Count are referred in [7]. (unit : %)

IV. Discussion and Future Work

The purpose of this study is to develop the portable ECG monitoring system which has embedded software so the power consumption of wireless transmission for ECG analysis could be reduced dramatically. However there were some limitations in implementing this purpose. First, almost currently commercialized android smartphones have Bluetooth adapter in them, but Bluetooth communication is basically electric power eater. If alternative wireless communication adapters such as Bluetooth Low Energy chip (TI, Texas, USA), or ANT+ profitable devices (Alberta, Canada) could be utilized more widely in smartphones, the power consumption for wireless communication could be reduced dramatically. In the future, we would try to apply ANT+ technology to this system. Besides, we would upgrade the application program in smartphones and server systems. The current application program operates stably, but we need fancier user interface, and more comfortable functions, and so on. Also, a service system which can provide network accessibility to users and caregivers is ~~needed~~ essential.

Moreover, we should increase the available ECG channels to be analyzed, increase the types of detectable arrhythmia, and enhance performances such as sensitivity, predictivity, etc. More research would be required on arrhythmia detection and classification.

Of course, we could use GPRS, GSM, or CDMA mobile phones and dedicated dongle instead of smartphone and Bluetooth. But the trend is heading for using smartphone and its application programs according to users preferences. Thus we considered the trend and applied it to this study.

This paper is somewhat focused on hardware design. Some software part material especially fibrillation detection algorithm is described in other paper of same conference, which is 'Sequential Algorithm for the Detection of the Shockable Rhythms in Electrocardiogram' by Ji-Wook Jung.

V. Conclusion

The patch type embedded cardiac function monitoring system was developed in this study. To reduce power consumption and hardware size, we chose a dual 16-bit microprocessor system. Two microprocessors are connected with five pins, two pins for port interrupt and three pins for SPI telecommunication, to interact with each other. The entire system is divided into two modules: the main module to process signals and Bluetooth module for wireless telecommunication with smartphone. When arrhythmia is detected by embedded algorithm in main module, an alarm signal is transmitted from the Bluetooth module to smartphone wirelessly. Now the system is available for single channel, but more channels could be used in this system after additional research. Further research may enable to reduce wireless telecommunication power consumption, increase the performance and convenience.

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