INTELLIGENT HOLTER: A NEW WEARABLE DEVICE FOR ECG MONITORING USING BLUETOOTH TECHNOLOGY

Santiago Led Ramos, Luis Serrano and Miguel Galarraga

Department of Electrical and Electronic Engineering
Public University of Navarra
Campus Arrosadia s/n, E-31006 Pamplona, Spain

santiago.led@unavarra.es

Abstract: This project focuses on the design and implementation of an intelligent wearable Holter device for cardiac events monitoring using Bluetooth wireless technology. The device is based on a former ECG monitoring system, and it has been designed to achieve two main goals: minimal size and very low power consumption. The paper shows the main blocks that make up the Holter with special attention to the aspects that have made possible the improvements.

Introduction

Nowadays the number of patients that require a continuous control of their health state is increasing more and more. This is the situation of elderly people, patients with chronic diseases or health abnormalities whose symptoms appear in a sporadic way, or even healthy people whose daily activities require some type of monitoring (called *wellness*). This has made the remote monitoring applications to be one of the Telemedicine fields with more interest in the last years.

The remote monitoring systems allow the control of the patient's health state through the acquisition, processing and transmission of information with medical interest (vital signals, biomedical parameters and even environmental conditions as temperature, fall detection, etc) to some faraway health centre, independently of the place where the patient is. Generally, these systems are made up of several sensors, which acquire and send the patient's data to a near receiver (gateway or access point) where it can be processed and retransmitted later to the health centre.

At present the remote monitoring systems are focusing on the development and use of intelligent "wearable" and "environmental" acquisition sensors. This type of sensors is characterized by having reduced size and weight, low power consumption and wireless communication ability [1,2]. The use of these acquisition devices allows the system to carry out the monitoring process while the patient remains at his regular environment (home, work place, walking the street, etc) and with minimal influence on his daily activities, by improving the patient's quality of life [3].

Among all the wearable and environmental sensors that can make up a remote monitoring system, the Holter device is one of the most interesting. A device of this type is able to acquire the ECG signal continuously, detect a possible cardiac event suffered by the patient and store it temporally for a later analysis by a health specialist.

In this paper the design of a new wearable Holter device is shown. This sensor is based on a previous design [4] and achieves the acquisition of up to three ECG signal leads for the detection, storage and transmission through Bluetooth wireless technology of cardiac events. The new device improves some basic aspects of the previous design as the size and power consumption, besides having more intelligence and additional functionalities (automatic detection of cardiac events, search of near receivers for the transmission of the stored cardiac events, etc).

The next section describes the main blocks that make up the Holter device with emphasis in those aspects that have made possible the size and power consumption reduction. The elements of each block, their features and functions are explained as follows. An overview of the power consumption is given too, and finally the obtained conclusions are shown.

Device description

The Holter device is composed of several analogue and digital blocks as it is shown in figure 1. All these blocks have been designed with small packaging electronic components in order to reduce the device size and weight. Figure 2 shows the real size PCB of the Holter device.

Some changes and improvements have been made to these blocks which provide the device with reduce size, power consumption and additional functionalities as ECG signal processing or automatic cardiac event detection.

Following the blocks are described including all the improvements carried out.

ISSN: 1727-1983 © 2005 IFMBE

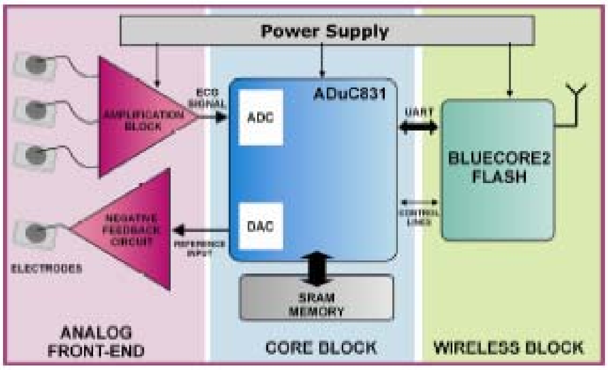

Figure 1: Block diagram of the Holter device

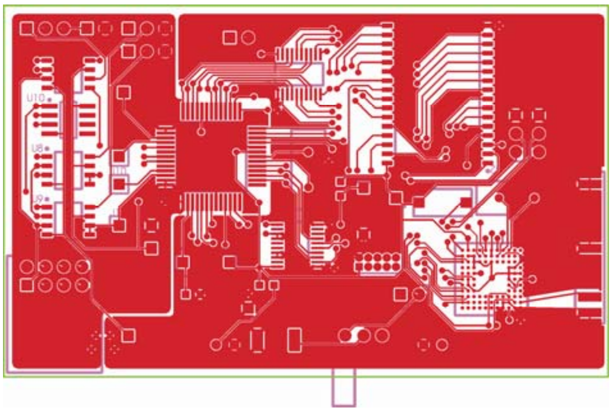

Figure 2: Real size PCB of the Holter device

Analogue Front-End

The analogue front-end is based on a former very low power analogue system designed for achieving the acquisition and conditioning of the ECG signal through several amplification and filtering stages [5]. An important feature of this analogue system is the use of high order filters (eight order high pass filter with a cut-off frequency of 0.05Hz and a Notch filter with a narrow rejection band at power lines interference frequency) which require a great amount of electronic components when they are implemented physically. This makes the filtering stages to require a significant area in the Holter device.

For this reason, and with the goal of reducing the device size, all these filtering stages have been eliminated and implemented as digital filters in a microcontroller (see Core block section). This reduces the device dimensions considerably, but also forces to take into consideration others aspects as the control of slow offset variations in the ECG signal or an efficient software implementation of the digital filters.

Two basic blocks make up the analogue front-end: amplification stage and negative feedback circuit.

The amplification stage consists of three instrumentation amplifiers, which perform the ECG signal conditioning for a later analogue to digital conversion. These amplifiers allow the device to acquire up to three ECG signal leads which can be selected through several hardware jumpers according to the application requirements.

Two models of very low power and low noise instrumentation amplifier are used in this stage: MAX4196 and MAX4194 from Maxim IC [6]. These two models have similar features and the only difference between them is the ability (or not) to select the gain factor among several available values. A gain factor of 10V/V has been used in all the amplifiers of the device.

These precision instrumentation amplifiers have several additional features which must be mentioned since they have been used in the device:

- Low power shutdown mode that reduces the power consumption of the amplifier when it is activated.
- Adjustable output offset level that is changed through the voltage applied to a reference input.

The shutdown mode allows the device to reduce the total power consumption when not all the ECG signal leads are acquired. If the application doesn't require the acquisition of a concrete ECG lead, the instrumentation amplifier that performs its conditioning can be put in shutdown mode. In this way, the power consumption of the device is optimized. Actually, the low power mode of each amplifier is activated through a hardware jumper.

As it will be explained later, the ECG signal has an offset voltage with slow time variations at the output of the instrumentation amplifiers. These variations are a clear problem when the device is designed because a high value of them can make the ECG signal to be out of the amplifier output range or even out of the analogue to digital converter input range. In any case, the information of the ECG signal is lost and the system can not operate correctly.

The adjustable output offset feature of the instrumentation amplifiers allows the elimination, or at least the reduction, of these time variations. This output offset is modified (increased or decreased) according to the ECG signal offset, by keeping the signal in the analogue to digital converter input range. This adjustment of the output offset is achieved by a microcontroller that controls the ECG signal offset continuously and modifies the voltage applied to the reference input of the amplifiers through a digital to analogue converter output. In this way, the analogue output of the microcontroller changes the voltage applied to the reference input and, consequently, the offset that the ECG signal has at the output of the amplifiers.

The second block that can be distinguished in the analogue front-end is a "right leg driven circuit" stage. This circuit performs a negative feedback with the human body to reduce the common mode voltage of the ECG signal. This stage provides a high reduction of this voltage but not a total elimination, and the ECG signal shows a time variable DC offset at the output of the instrumentation amplifiers. An additional conditioning stage is needed in order to eliminate this signal offset. The previous design made use of a high pass filter with a cut-off frequency of 0.05Hz, but a different conditioning mechanism must be used in the new Holter device because this analogue filter has been eliminated. In this case, the control of the variable DC offset is performed through the modification of the offset output voltage in the instrumentation amplifiers as it was explained before.

Core block

The main block of the Holter device is the ADuC831 MicroConverter. This microcontroller is a fully integrated data acquisition system with several basic features: multi-channel 12-bit ADC, 8052 programmable 8-bit MCU, programmable I/O ports, external interruptions, UART port, etc. The chip is specified for 3V operation and it has some power saving modes to get the lowest power consumption in the device [7]. Table 1 shows some ideal power consumption values of the microcontroller.

Table 1: Power consumption of the ADuC831 chip

State	Power consumption
Normal mode	8mA
Idle mode	3.5mA
Full power-down mode	15µA

This microcontroller is the intelligent core of the device and achieves several tasks. On one hand, it carries out the analogue to digital conversion of the ECG signal from the instrumentation amplifiers. A sampling rate of 500samples/sec. is used for the conversion of each ECG lead. In this way, the acquired signal has enough resolution for a correct medical analysis of the ECG information.

On the other hand, the microcontroller accesses to an external SRAM memory in order to store the ECG signal when a cardiac event occurs. The BS62LV4006 model of memory with a storage capacity of 4Mbit has been used in the design [8]. The ECG signal is stored in the memory continuously until a cardiac event is detected. When this happens, the acquisition process continues for a specific time and stops finally. This storage mechanism allows the device to have in memory a significant period of ECG signal about the event.

The core block also communicates with the wireless block through the UART serial port and two I/O control lines. The UART port is used for the exchange of information (by means of a customized application communication protocol) with the remote receiver when a Bluetooth connection has been established. The I/O control lines are used for the notification of specific events between the microcontroller and the wireless block as the establishment or loss of Bluetooth connection or the necessity of searching a remote receiver because a cardiac event is stored in memory and must be transmitted.

In addition to the basic tasks mentioned previously, the ADuC831 microcontroller also performs several processing tasks which have been added to the new Holter device. As it has been explained in the analogue front-end section, several digital filters are implemented in the microcontroller: a four order Butterworth high pass filter with a cut-off frequency of 0.05Hz and a Notch filter with the rejection band at the power lines interference frequency (50Hz). The reduced order of the implemented filters shows an outstanding feature: the reduction of the total power consumption due to the filters can be implemented with short code routines and the microcontroller can stay more time in some power saving mode. Moreover, the conditioning process is not modified in a considerable way because of using low order filters.

The core block is also able to obtain the patient's heart rate from the ECG signal and use it for achieving an automatic detection of cardiac events. According to the value of the heart rate, the Holter device considers if a cardiac event has occurred or not.

Finally, as it has been mentioned in the analogue front-end section, the microcontroller also controls the output offset of the instrumentation amplifiers in order to keep the ECG signal in the analogue to digital converter input range. This output offset is modified through an analogue output of the microcontroller that is connected to the reference input of the instrumentation amplifiers. In this way, when the ECG signal offset decreases, the microcontroller increases the voltage applied to the reference input and consequently the output offset of the amplifiers. And vice versa, when the ECG signal offset increases, the voltage applied to the reference input is decreased. This makes the ECG signal to have a constant and no time variable offset voltage at the input of the analogue to digital converter.

An outstanding feature of all the tasks performed by the microcontroller is that they are implemented in assembler code. This provides a high efficiency and low power consumption when the code is executed.

Wireless block

The wireless block performs the Bluetooth communication between the Holter device and a remote receiver, and it is based on the BlueCore2-Flash single chip from CSR [9]. This device has a 16-bit RISC processor with an internal FLASH. The chip also includes several digital peripherals as programmable I/O lines and serial communication interfaces (SPI, USB and UART). The BlueCore2-Flash chip has a reduced power consumption that depends on several factors: chip state, transmission bit rate, etc. Moreover, a very low power state (called Deep Sleep) is activated when the chip has not any process to execute. This makes possible the reduction of the total power consumption.

The BlueCore2-Flash chip uses several interfaces for the communication with the ADuC831 microcontroller (see core block section). On one hand, the UART port allows the exchange of information between the microcontroller and the remote device. On the other hand, two programmable I/O lines are used as control

ISSN: 1727-1983 © 2005 IFMBE

lines with the microcontroller for the notification of specific events.

Some aspects must be considered with regard to the Bluetooth communication. Security and privacy are essential features in the Holter device because personal information is being acquired and transmitted. For this reason, all the security and encryption mechanism provided by Bluetooth technology are used: device authentication through PIN code before the establishment of any connection with a remote receiver, and encryption of all the information transmitted. Apart from these security mechanisms an additional codification of the information exchanged at application level is carried out.

The communication between the Holter device and the remote receiver is performed through a customized communication protocol based on commands. These commands allow the configuration of the Holter operation, the control of the communication, the notification when a cardiac event is stored in memory and even the transmission of the cardiac event.

Power Supply

The power supply block provides to every component the required supply voltage. All the blocks that make up the device are specified for a 3V operation except the instrumentation amplifiers which require ±3V dual supply voltage.

Two regulated charge pump components make up the power supply block: MAX1759 and MAX868 from Maxim IC [6]. The first model is a regulated inverting charge pump that provides -3V supply voltage while the second one is a Buck/Boost regulating charge pump with +3V of output supply voltage.

The regulated supply voltages provided by the charge pumps are obtained from a 3.7V rechargeable battery with a capacity of 830mAh [10]. This allows the device to have great operation autonomy. The battery also has a reduced size and weight, which make it a suitable component for being used in the Holter device.

Power consumption

One of the most important aspects in the design of the Holter device is the power consumption. All blocks have been designed and selected in order to reduce the total power consumption. Moreover, the power saving modes of the ADuC831 microcontroller and BlueCore2-Flash chip have been used each time that it has been possible, getting an efficient use of the power supply. Average power consumption values are shown in table 2 according to the state of the Holter device.

The capacity of the battery used in the design provides operation autonomy of 160 hours approximately in a continuous monitoring state.

Table 2: Power consumption of the Holter device

State	Power consumption
Cardiac event monitoring	5mA
Cardiac event stored	0.5mA

Conclusions

A new wearable Holter device has been designed with the aim of improving some basic features of a previous ECG monitoring system as the size and power consumption.

The suitable selection of the components, the elimination of some analogue conditioning stages and an efficient code development have made possible to design a device with features of wearable sensor.

Moreover, additional features have been added to the Holter device as automatic cardiac event detection or patient's heart rate extraction. These features are added values which make the Holter to be a more intelligent and easy to use device. This allows the improvement of the patient's quality of life.

Acknowledgments

This work was supported by projects G03/117 from Fondo de Investigaciones Sanitarias (Spanish Government) and 41/2003 from Departamento de Salud (Navarra Regional Government) and a personal grant to Miguel Galarraga from Departamento de Salud (Navarra Regional Government).

References

[1] ALEX PENTLAND (2004): 'Healthwear: Medical Technology Becomes Wearable', *Computer Journal*, **37**, pp. 42-49
[2] K. DUCATEL, M. BOGDANOWICZ, F. SCAPOLO, J. LEIJTEN and J-C BURGELMAN (2001): 'Scenarios for ambient intelligence', *Final Report IPTS-Seville*
[3] SUNGMEE PARK, SUNDARESAN JAYARAMAN (2003): 'Enhancing the Quality of Life Through Wearable Technology', *Engineering in Medicine and Biology Magazine*, **22**, pp. 41-48
[4] S. LED, J. FERNÁNDEZ, L. SERRANO (2004), 'Design of a Wearable Device for ECG Continuous Monitoring Using Wireless Technology', Proc. of EMBC 2004 – Conf. of the IEEE Eng. in Med. and Biol. Society, San Francisco, California.
[5] J. FERNANDEZ, S. LED, L. SERRANO (2004): 'Design and Implementation of a Bluetooth Mobile System for ECG Monitoring', Proc. of MEDICON 2004 – Mediterranean Conf. on Med. and Biol. Eng. Island of Ischia, Naples, Italy.
[6] Maxim IC web site: http://www.maxim-ic.com
[7] Analog Devices web site: http://www.analog.com
[8] BSI web site: http://www.bsi.com.tw
[9] CSR web site: http://www.csr.com
[10] VARTA web site: http://www.varta.com

ISSN: 1727-1983 © 2005 IFMBE