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A Reconfigurable, Wearable, Wireless ECG System

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***Abstract*—New emerging concepts as "wireless hospital", "mobile healthcare" or "wearable telemonitoring" require the development of bio-signal acquisition devices to be easily integrated into the clinical routine.**

In this work, we present a new system for Electrocardiogram (ECG) acquisition and its processing, with wireless transmission on demand (either the complete ECG or only one alarm message, just in case a pathological heart rate detected). Size and power consumption are optimized in order to provide mobility and comfort to the patient. We have designed a modular hardware system and an autonomous platform based on a Field-Programmable Gate Array (FPGA) for developing and debugging. The modular approach allows to redesign the system in an easy way. Its adaptation to a new biomedical signal would only need small changes on it.

The hardware system is composed of three layers that can be plugged/unplugged: communication layer, processing layer and sensor layer. In addition, we also present a general purpose end-user application developed for mobile phones or Personal Digital Assistant devices (PDAs).

I. Introduction

Personal sensor networks are increasingly adopted in clinical applications due to several reasons: the need of continuous monitoring, their link to hospital area networks and the use of mobile phones and PDAs as clinical data terminals.

A wearable device requires small size, low-power consumption, low weight and interoperability with the different mobile devices and communication networks in the environment. Also, an important feature is the possibility of real-time signal processing.

SMD (Surface-Mount Devices) modules and the miniaturization of wireless communication electronics allow us to carry out new wearable designs with the interoperability required. Actually, the major limitation for mobility is the power consumption. A heavy long lasting battery is not convenient for wearable purposes.

Applying strategies such as ECG data transmission on demand, sending alarm messages after detecting a pathological heart rate or data compression algorithms, low consumption can be reached

For that purpose, real-time processing is necessary. Furthermore, a processing component allows to increase the functionality and the different operation modes.

Several solutions have been proposed recently [1]-[7]. Some of them are focused on the interoperability [8]-[10]. As part of the CodeBlue initiative at Harvard University [11] a similar ECG system has been developed. The system is not reconfigurable and it is based on the Mica2, MicaZ, platforms [12] with Zigbee as wireless protocol.

We propose a novel design yielding a trade-off solution for the set of requirements mentioned above. It includes the capability of providing different operation ways (alarms, data sending on demand, etc), signal processing (detecting heart rate and pathological conditions), interoperability (mobile phones and PDA's) and, low-power consumption.

The noteworthy portions of the design are (1) an FPGA-based processing module that allows flexibility in how the data are process prior to upload and (2) a Bluetooth interface that allows these data to be uploaded to a mobile device. We have chosen Bluetooth as wireless protocol, used by most commercial mobile devices.

The highlight of our design is its capability to be flexible reprogrammed or reconfigured on the needs of the monitoring scenario.

II. System Description

The system comprises two parts: the hardware system (the patient's acquisition and processing board), and a monitoring application for the mobile phone or PDA.

The overall scheme is shown in Fig. 1:

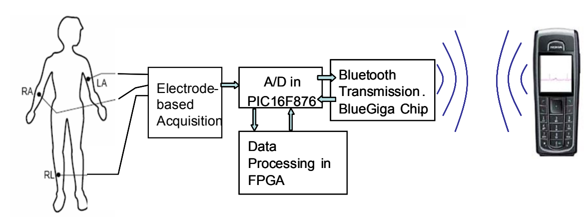

Fig. 1. System Description

The hardware system developed is composed of three layers that will be described independently.

The sensor layer consists of a bioamplifier, and a bandpass filter. The communication layer includes a Bluetooth module. The processing layer incorporates a microcontroller (PIC 16F876, [13]) and a FPGA (Xilinx Spartan3E-100, [14]). The microcontroller performs the following functions: captures and digitizes the ECG signal, establishes the connection to the Bluetooth device and sends the data accordingly with the operation mode. Algorithms to process de ECG signal, e.g. detect cardiopathies or heart

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rates [15], can be implemented in the FPGA. This powerful processing capability of FPGA makes the hardware system adaptable to many different applications. We outline its design and implementation in the next section.

The monitoring application runs on any mobile terminal equipped with Bluetooth and Java virtual machine. The user interface permits: the communication with other devices, as well as the reception of ECG and real-time data signal visualization. J2ME (Java Platform, Micro Edition or "Java ME") have been used for developing the application in the mobile device [16]. J2ME is a Java platform oriented to embedded devices with restricted graphical and computational resources.

III. HARDWARE SYSTEM

In the former section, we have presented the modular hardware system developed. According to the functionality of those layers mentioned above, this section is divided in three major parts: Signal Acquisition, Signal Processing and Bluetooth Data Transmission.

A. Signal Acquisition

In our ECG we use a simple three-lead system. The circuitry design chosen leads to robustness, low cost, low power consumption and small footprint as it is required in a wearable device [8].

Typical specifications for ECG bio-signals acquired by the sensors (low differential voltage from 1 to 3 mV, high common-mode rejection ratio level and low frequency range) require the use of a differential amplifier with a gain around 1000, CMRR (common-mode rejection ratio) greater than 110 dB and 0.05-200 Hz bandwidth. The bioamplifier has been implemented using commercial off-the-shelf, low-voltage and high precision instrumentation amplifiers. The topology of the bio-amplifier is described in [17] and is shown in Fig. 2. In order to reduce the common-mode noise, a right-leg driver is used. This amplifier injects common-mode signals back into the patient to cancel them out. Common-mode signals are "bootstrapped" to ground through the amplifier. The resulting common-mode rejection ratio improves significantly since electrodes do not reduce skin impedance.

The filtering stage is a band pass filter to eliminate the artefacts caused by muscle contractions, respirations, movement of the electrode cables, and by other electronic equipments or radio interferences.

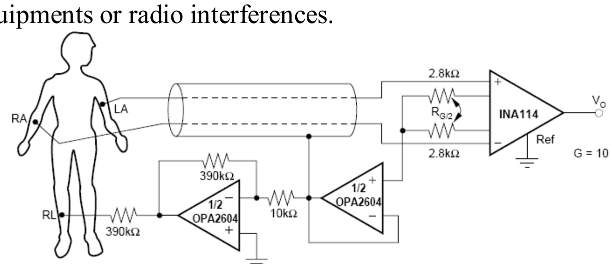

Fig. 2. Bioamplifier

B. Signal Processing

A PIC16F876 microcontroller [13] is used for analog to digital conversion. This device is a low cost 8-bit CMOS Flash Microcontroller based on RISC (Reduced Instruction Set Computer) technology with 10-bit multi-channel Analog to Digital converter. The signal frequency can reach 200 Hz, so we have selected a 500 Hz sampling frequency, with a resolution of 10 bits. Extension to 12 bits, to fulfill the requirements of telematic emergency services [10], is straight forward by choosing a microcontroller with a 12 bit converter.

After A/D conversion, the digital ECG is processed in order to increase the signal to noise ratio (S/N) and allow different operation modes.

To establish different operation modes and functionalities we have chosen a FPGA. The FPGAs allow reconfigurable systems which can efficiently implement real-time processing algorithms. Synthesis and reprogramming jobs are made automatically, shortening the time spent on it considerably.

We have used a Xilinx Spartan3E-100. The Spartan-3E family reduces system cost by offering the lowest cost-per-logic of any FPGA family, supporting the lowest-cost configuration solutions including SPI, parallel flash memories, and the functions integration of many chips into a single FPGA [14].

C. Bluetooth Data Transmission

The Bluetooth module used is the WRAP THOR 2022-1-B2B chip from BlueGiga [18]. It provides an API (Application Programming Interface) for communication through the AT commands. Since the PIC 16F876 establishes a RFCOMM channel with the BlueGiga Chip via AT commands.

We have optimized the internal parameters of Bluetooth module to get the lowest consumption mode.

In the typical operation mode, the duty cycle has periods of 6 seconds and a mean current consumption of 35mA (Fig. 3). Changing the value of some parameters (chip operation mode, discoverable option, etc), we can reduce the current consumption to 17mA for a duty cycle of 2.5 seconds

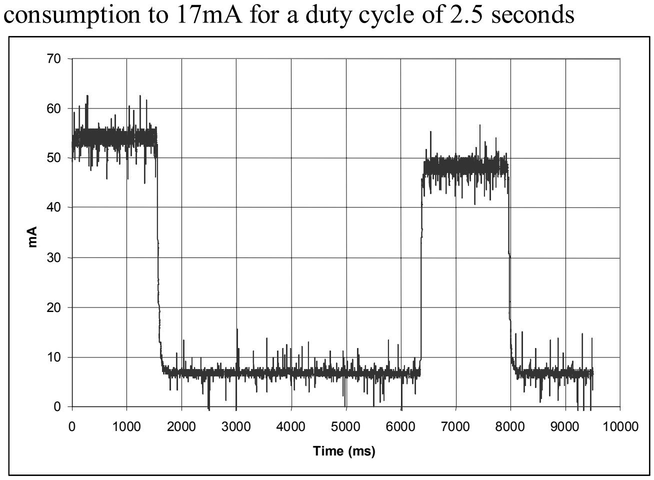

Fig. 3.Bluetooth Chip: Typical current consumption

Figure 4 shows the current consumption of the BlueGiga Chip with customized parameters. It can be observed a base line about 13.5 mA and peaks of consumptions, periodically spaced, about 62.5 mA,

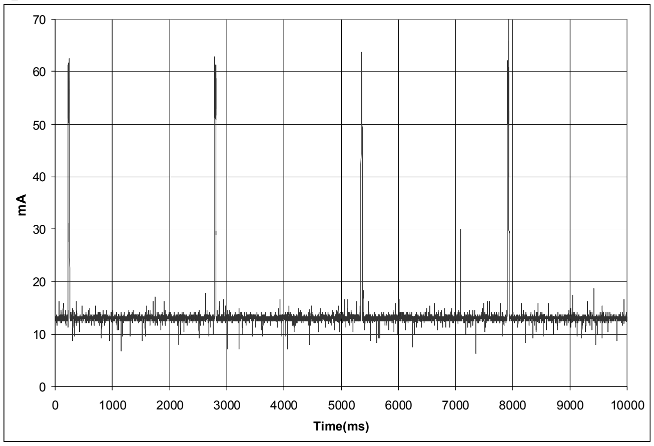

Fig. 4. Bluetooth Chip: Current consumption with customized parameters

IV. MONITORING APPLICATION FOR MOBILE DEVICE

The application for embedded devices, such as mobile phones or PDAs, offers a service in the SPP port via Bluetooth. It will allow us to monitor the patient's ECG in real-time.

The mobile device can be used as a client or as a server depending on the operation mode. When the medical staff requires ECG data on demand, the mobile device operates as a client. On the other hand, when alarm condition comes up, the wearable device can start the communication with the mobile terminal.

The application has been developed using the Java platform for embedded devices (J2ME). The Bluetooth communication was programmed using the Java Bluetooth API. Binaries were obtained using the J2ME Wireless Toolkit [19].

V. RESULTS

To evaluate our approach of a Reconfigurable, Wearable, Wireless ECG, the acquisition and communication modules were implemented in a small footprint PCB (Printed Circuit Board), with a size similar to a credit card, as can be observed in Fig. 5.

For developing and debugging algorithms a platform has been implemented. It consists of the acquisition and a communication modules, a Digilent Basys Board [20] (which includes a Spartan 3E FPGA), and, finally, a VGA interface (Fig. 6). This platform is autonomous. None other devices, such as PCs, are needed for designing and for testing algorithms. Furthermore, it allows to monitor and to compare the ECG signal and the processing results in real-time.

Fig. 5.ECG prototype

Filtering algorithms and heart rate computations have been implemented on the FPGA. The R waves of each cardiac cycle are detected, measuring the time between two consecutive waves, thus obtaining the patient's pulse. Should the patient show a value outside the limits for a given number of consecutive cardiac cycles whether by period excess (bradycardia) or defect (tachycardia), this condition is a cause for alarm, and is sent to the mobile device.

The R waves in the QRS complex and in the standard derivation used are characterized by their greater amplitude within the complex, rising sharply to a peak and falling away sharply afterwards. Use of amplitude only as an R-wave detection criterion could give rise to many problems since, as already pointed out, the baseline might undergo variations. One must also use the signal variation criterion, calculating its derivative and detecting the points at which the variation occurs in the derivatives. The presence of the R wave can be associated with the instant at which the derivative passes through zero. This simple procedure makes it possible to detect the R waves with sufficient precision to measure the interval between them, using a suitable timer.

Once the algorithms have been evaluated, they can be included in the processing layer of the proposed Reconfigurable, Wearable,Wireless ECG System.

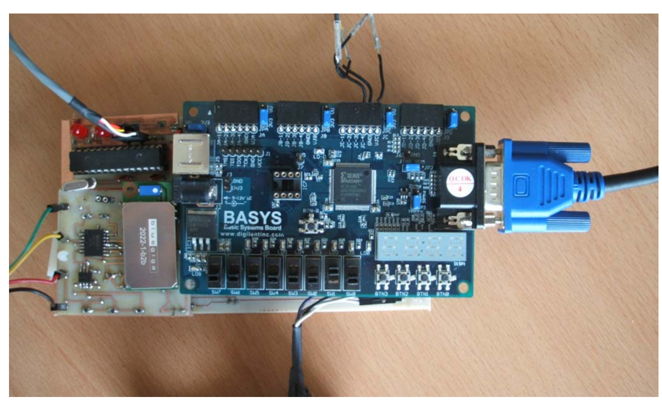

Fig. 6. Debugging and prototyping system

Finally, Fig. 7 shows the resulting ECG signal displayed in a mobile phone after acquisition and processing in the wearable system proposed.

Fig. 7. ECG visualization in the mobile phone

VI. CONCLUSIONS

We have developed a low cost system for ECG acquisition and visualization in mobile devices which can be easily used by any patient.

The modular hardware system developed allows technical updates to be done in an easy way and also provides intelligence to the system for automatic detection of pathologies. Furthermore, the inclusion of any other kind of biomedical signals as EMG (Electromyography), pulse oximeter, etc, is also possible. Simultaneously, we have developed a FPGA-based platform in order to provide quick assessment of new processing algorithms and functionalities.

We are optimized the Bluetooth parameters and operation modes to reduce the power consumption as much as possible. So, it is feasible to use low weight Lithium Polymer(LiPo) or NiMH batteries.

Further improvements would include connection to a hospital database adding GSM/GPRS or WIFI technologies. On the other hand, we are developing a set of algorithms to carry out the hardware processing of the ECG signals as well as other biological signals

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