Wireless DSP architecture for biosignals recording

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Abstract— **The paper describes a ARM-based Bluetooth wireless system for biosignal recording and monitoring. The architecture is composed of two functional blocks: an ECG pre-processing board to acquire differential signals and a 8-channel DSP system. The acquisition, the digital processing and the transmission control are performed by an ARM7 chip. The transmission is carried out using a Bluetooth chip interfaced to a computer or a PDA This device addresses the new concepts of ubiquitous sensing and computing applied to health care: in particular it was validated in a wearable and environmental ECG setup. With these device new frontiers of applications in ambient intelligence and home care are going to be explored to expand the diffusion of a similar approach on ARM-based products.**

I. Introduction

Today, safety, comfort and wellbeing are key words in design of home, workplaces and products. Technology miniaturization allows for new concepts in healthcare and ambient intelligence as the emerging need and possibility to continuously monitor the patient's vital signs in his own natural daily life. This is going to implicate a spreading of computing devices everywhere - clothes, home, cars, office - [1] [2] [3] [4]. This paradigm called "ubiquitous sensing and computing" implies a new meaning of *"smart"* objects able to dynamically reconfigure their performances according to the user's need and to the environmental situations. Adaptivity becomes a key specification for these objects. Sensing interface to be worn without any discomfort for the user or special environmetal rubbers or devices embedded in everyday space and objects (car wheel, armchair, shirts etc.) are addressed as typical applications. Moreover cardiovascular diseases are the first death cause in the industrialized countries. Bad habits, unhealthy lifestyle and stress are the main reasons for such a huge incidence of deaths. Different biosignals and the correspondant extracted features are correlated and can monitor quantitatively the pathological risk. Their recording and on-line monitoring could offer to clinician and the user himself the possibility to prevent or treat more efficiently all these illnesses. For instance a real time continuous monitoring of the Heart Rate Variability (HRV) can be a good indicator of stress condition [5] [6]. A continuous bio-feedback of the heart activity can help the user to control his/her stress status. Wearable systems are totally unobtrusive devices that allow physicians to overcome the limitations of ambulatory technology and provide a response to the need for monitoring individuals over weeks or even months [7]. They take advantage of hand-held units to temporarily store physiological data and then periodically upload that data to a database server via a wireless connection. On the opposite, in wearable systems the sensor works in difficult and unusual conditions, far from the clinical standard, where sensors are firmly attached to the patient. The system we implemented is made robust for overcome this unfair condition. In this context, it has been developed a solution that integrates hardware and software in an ARM-based Bluetooth^{TM}(BT) wireless system, to implement an unobtrusive bio-signal acquisition and interpretation system. The main advantages of our solutions are:

- ARM is widely present in electronic devices
- Bluetooth provides a safe and efficient transmission
- Possible usage in wearable and environmental monitoring

This solution has been thought to be used in cooperation with sensors systems for the unobtrusive bio-electrical monitoring of the users by everyday objects. Troughout a learning phase of few seconds, the system sets its parameters in order to detect the QRS peak in the electrocardiographic (ECG) signal and to improve the S/N ratio

II. Description of the System

The architecture is composed of two functional blocks. An ECG preprocessing board to acquire a single lead signal and a DSP system. More in detail, the acquisition, the digital processing and the transmission control are performed by an ARM7 chip (ARM Ltd., Cambridge UK). The transmission uses a class III BT radio to transmit data to a computer or a PDA.

A. ECG analogue board

To realize an unobtrusive, wearable and environmental acquisition and analysis system the most important signal to start with is the heart rate. In our paradigm is important to adopt non-standard sensors which are really more critical than the standard Ag-AgCl electrodes from the quality point of view. The system has been designed to use our patented environmental sensors, which approximate polarizable electrodes [8]. Such sensors increase the effects related to the instability of the contact which can introduce high frequency noise. Moreover the skin-motion artifacts [9] [10] caused by the subject's movement might, in turn, affect the low frequency components of the ECG signal and produce saturation in the amplification circuit [10]. The high input impedance of the first stage of the biopotential amplifiers when accompanied with the polarizable electrodes and with unstable contact make the

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circuit prone to collect the 50Hz external interferences and thus to reach saturation in the output. The integration of a notch filter after the first stage would be the straightforward solution to the problem, but this approach bears several disadvantages: integrated notch filters are really demanding in terms of power consumption and space, moreover they introduce nonlinearities in the phases of the signal in the pass-band. For these reasons we prefer to reduce the gain of the complete circuit and to perform a digital filtering after the acquisition of the ECG signal. After the instrumentation amplifier we placed a three-pole Butterworth low-pass filter with a tunable cut-off frequency between 75Hz and 120Hz to reduce the artifacts produced by muscle activity and other high-frequency noise. These values are not all compliant with clinical standard ECG specifications but suite the specification for monitoring and is still possible to obtain clinical information, altough our new paradigm is completely out of the standard setup where all, either the subject, is controlled. The ECG processing circuit can use single power supply down to +2.7V, compatible with many actual digital systems.

B. DSP system and transmission

To realize a fully portable and miniaturized DSP system on chip we chooses an ARM processor, the core processor used in many electronic devices. This CPU is an ARM7TDMI microprocessor unit with 64kBytes RAM with all the most common peripherals and controllers. On the CPU there are three main layers in a logical stack. The lower layer is a STM custom operating system (OS) which allows the full control and management of the ARM and the BT radio. The second layer is the BT stack embedded on chip and the last one controls the bluetooth connections and the acquisition (Fig. 1). We implemented the third layer to suit our requirements, basically for the real time acquisition purpose and not only for single lead ECG signal, but also with the possibility to acquire up to eight different biosignals. Using an internal ADC will affects the signal quality in terms of resolutions and introduced noise, so we used an external 12bits, eight channel ADC with SPI transmission protocol (MCP3208, Microchip Inc., Chandler, AZ USA) (Tab. I). This ADC could be configured also as four differential channel mode to reject common mode noise and offset within $\pm 100mV$ respect the power supplies rails. In wearable wireless systems one of the

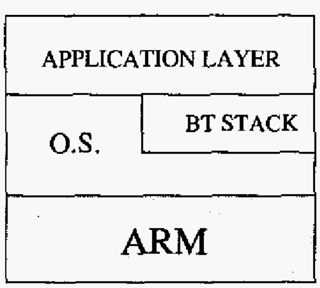

Fig. 1. Macro layers of the stack

Parameter	Value
Resolution	12bits
max THD	-75dB
max SFDR	80dB
DNL	$\pm$0.5LSB

TABLE I

ADC PERFORMANCES @1KHZ INPUT FREQUENCY AND 2.7V VREF

main problem is to reduce power consumption in order to use low dimensions and low weight batteries. For this purposes the CPU clock was set at 13MHz, the lowest compatible with the BT radio operation, although there is the possibility to use clock frequencies up to 24MHz. Running at the slowest clock frequencies the main problem is the need to obtain real-time acquisition and processing with a stable sampling frequency that faces with the BT stack threads operations. Moreover the OS provides only timers with 1ms of granularity which implies a maximum sampling frequency of 1ksps. We choose a tradeoff and trimmed a sample rate of 250sps for each channel with a time delay between every channel less than 25μs @1Mhz SPI clock and a resulting input throughput of 24kbps. It is worth nothing that all the eight data channels can be processed to extract the features required and these ones have to be transmitted themselves. In this application for example we identify the R peak, its position and the noise level of the signal, so also using one of the remaining 4 bit of the ECG signal as a flag for the R peak, we need to add one channel (the noise level one) for every lead acquired. For these reasons is possible to argue about the necessity to transmit at least eight additional data at the same rate of the acquired ones in the worst case. Our system has been designed and tested to provide up to sixteen data channels transmission of integer size (12 data bits, 3 bits for the channel identification and one for general purposes) which requires at least 64kbps for the BT transceiver, which is capable of 700kbps of data transmission rate. We took care of avoiding continuous data transmission which increases the power consumption, the average load for the BT controller and waste the BT band, so we used 128bytes buffers which have to be filled prior every BT transmission call. Through the use of Serial Port Profile (SPP) we can acquire the signals with a PC or a PDA.

C. ECG processing

In this specific application we used a standard and well known ECG processing algorithm [11] to extract the R peak (Fig. 2, Fig. 3). This algorithm has been adapted to grant a more reliable identification in our applications adopting an improved model of the ECG signal and noise variability from the statistical point of view, introducing also the use of an adaptive control of estimated peak to peak interval. More in detail, the system itself save a short history of the thresholds and other parameters that can change only after a correct identification of a R waves and only if the new values are

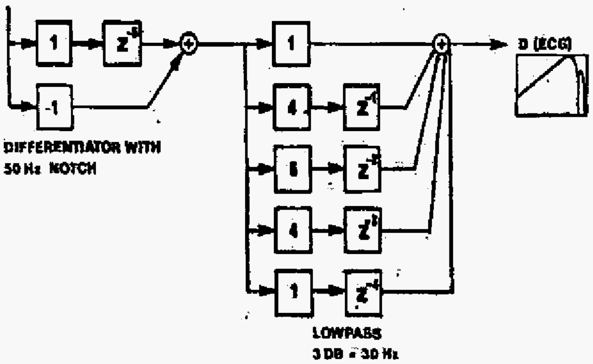

Fig. 2. The digital filter

compatible with the statistical variation of the signal. This adaptive algorithm requires a training session to choose the best working point to start the processing of the ECG signal. The learning phasehas to be executed during a controlled condition with a good signal received. The system can use a 5 seconds signal starting buffer to trimmer itself to reach the best performances.

III. Results

Our system provides a complete and versatile DSP architecture for the acquisition and processing of biosignals. The biological signals requires high gain, low distorsion and good noise rejection but in turn the bandwidth is relatively small despite other signals. Moreover is worth nothing that is required a stable and accurate sample rate expecially for long term monitoring and data processing. For these reasons we give the highest priority to the timing compatible with the BT stack operation which of course is more critical and demanding. We realize a complete development system to test

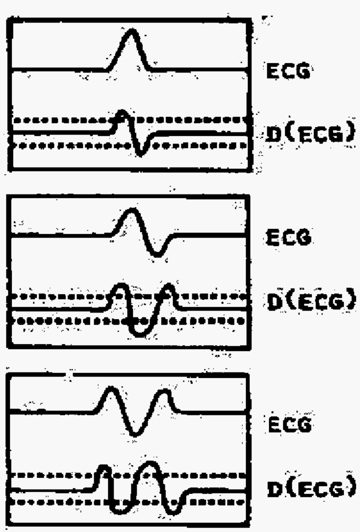

Fig. 3. ECG signal analysis and QRS detection

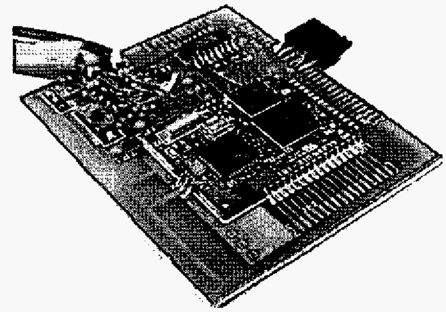

Fig. 4. The test board

our DSP architecture. This prototype is composed by two boards, a DSP BT board with integrated antenna and on the back side a single lead ECG board (Fig. 4). The device is a 4cm x 5cm and provides:

- power supply regulation;
- 8 analogue input channels;
- 1 SPI port;
- 1 UART port;

The typical range of transmission in a workplaces environment is about 10 meters, with a power consumption less than 50mA allows a long term monitoring with a standard cell of 750mAh. We tested also a parallel ECG processing of all the eight input channels without any loss of data or transmission interruption. The acquisition and processing of the data requires only 360μs with good performaces (Fig. 6. The operating mode of the board is on-line reconfigurable using our client software: is possible to choose the number of the channels, the ADC acquisition mode (single-ended or pseudo-differential) and also to set the parameters of the ECG processing algorithm.

IV. Conclusions

The use of ARM technology with an embedded OS make our architecture a full portable core solution that can be easily configured and embedded in every ARM-based system

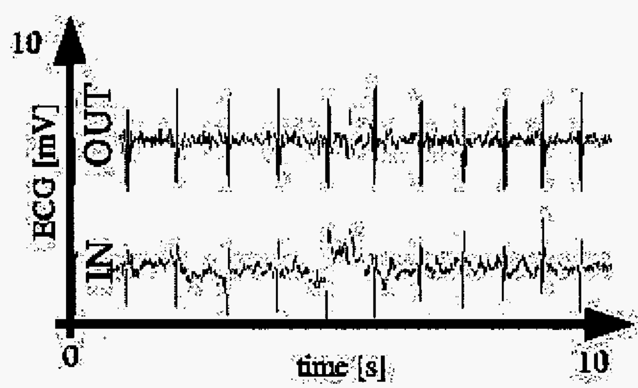

Fig. 5. Input (bottom) and filtered ECG (top)

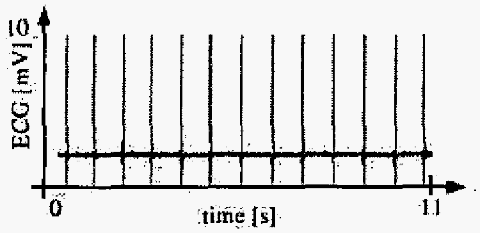

Fig. 6. Real-time R peak recognition

which has equal or greater resources. In our mind there is the possibility to reach a wide diffusion of such kind of monitoring paradigm to improve the quality of life and the safety. Aim of this work was also to understand the capabilities of the BT transmission system not only for signal recording purposes, but also for a DSP usage and the results showed there is a concrete possibility in this direction. The most critical point we can evidence is the problem related to the integration of the sensors and the biosignals pre-processing board, an integration that will involve many studies for the miniaturization of the circuitry and the design of the environmental and wearable sensors.

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