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DEDICATED SYSTEM FOR ECG COMPRESSION AND STORAGE BASED ON COMPRESSED SENSING

BY

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Abstract. This paper presents a system capable of ECG signal compression and storage based on the theoretical principles of compressed sensing. The main characteristics that stood behind the design were low size, low power consumption and good performance in terms of data compression.

Key words: biomedical signal processing; compressed sensing; ECG compression.

1. Introduction

In recent years there has been an ever-increasing interest for the application of signal processing techniques in biological signal processing (Fulford-Jones *et al.*, 2004; Marchesi & Paoletti, 2004; Bozomitu, 2012) and new signal processing techniques like compressed sensing have been proven to be of high applicability when it comes to biomedical signal processing.

Positive results regarding the possibility of ECG signals compression using compressed sensing (Fira *et al.*, 2010, 2011), as well as previous experience in the development of biological signal processing systems, have lead to the development of an implementation capable of compressing and storing ECG signals, with high performance.

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The main characteristics that stood behind the design were low size, low power consumption and good performance in terms of data compression.

The proposed system is based on the theory of compressed sensing, that has been widely presented by Fira *et al.* (2010, 2011). ECG signals are first sampled and segmented into separate cardiac patterns (beats) with the aid of an *R*-wave detector. Then the patterns are resampled to a fixed length and the compressed form on the ECG pattern is obtained by calculating a linear projection vector with the use of a projection matrix.

2. Method

The proposed system was developed using a development platform based on the Texas Instruments' transceiver IC CC1010. This is a system on chip family IC that contains an UHF transceiver and a high performance 8051 architecture microcontroller.

Among its main features we can emphasize the programmable output power of up to +10 dBm, a maximum data transfer rate of 76.8 kbps, low current consumption, RSSI output, 3 channel 10 bit ADC, 32 kB Flash memory, PWM, UART, RTC, SPI and DES encryption.

In addition to the development platform the design of an analog module was necessary, for ECG signal preprocessing. This module consisted of an instrumentation amplifier, necessary for ECG amplification and an *R*-wave detector.

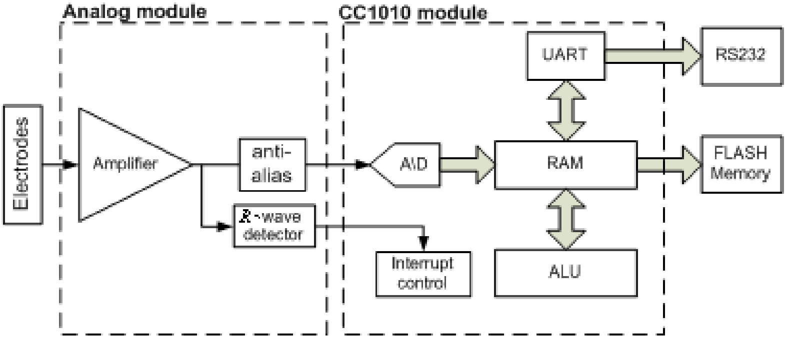

Fig. 1 – Block diagram of the proposed system.

The block diagram presented in Fig. 1 shows how the system is divided into functional blocks. We can observe the analog module, which contains the amplifier, the low pass filter and the *R*-wave detector, and also the functional blocks contained within the CC1010 IC: the ADC, the RAM, the processing unit (ALU), the input data ports and the UART communication interface. The RS232 interface and Flash memory are auxiliary peripherals that are attached to the development board and are not contained within the CC1010 IC.

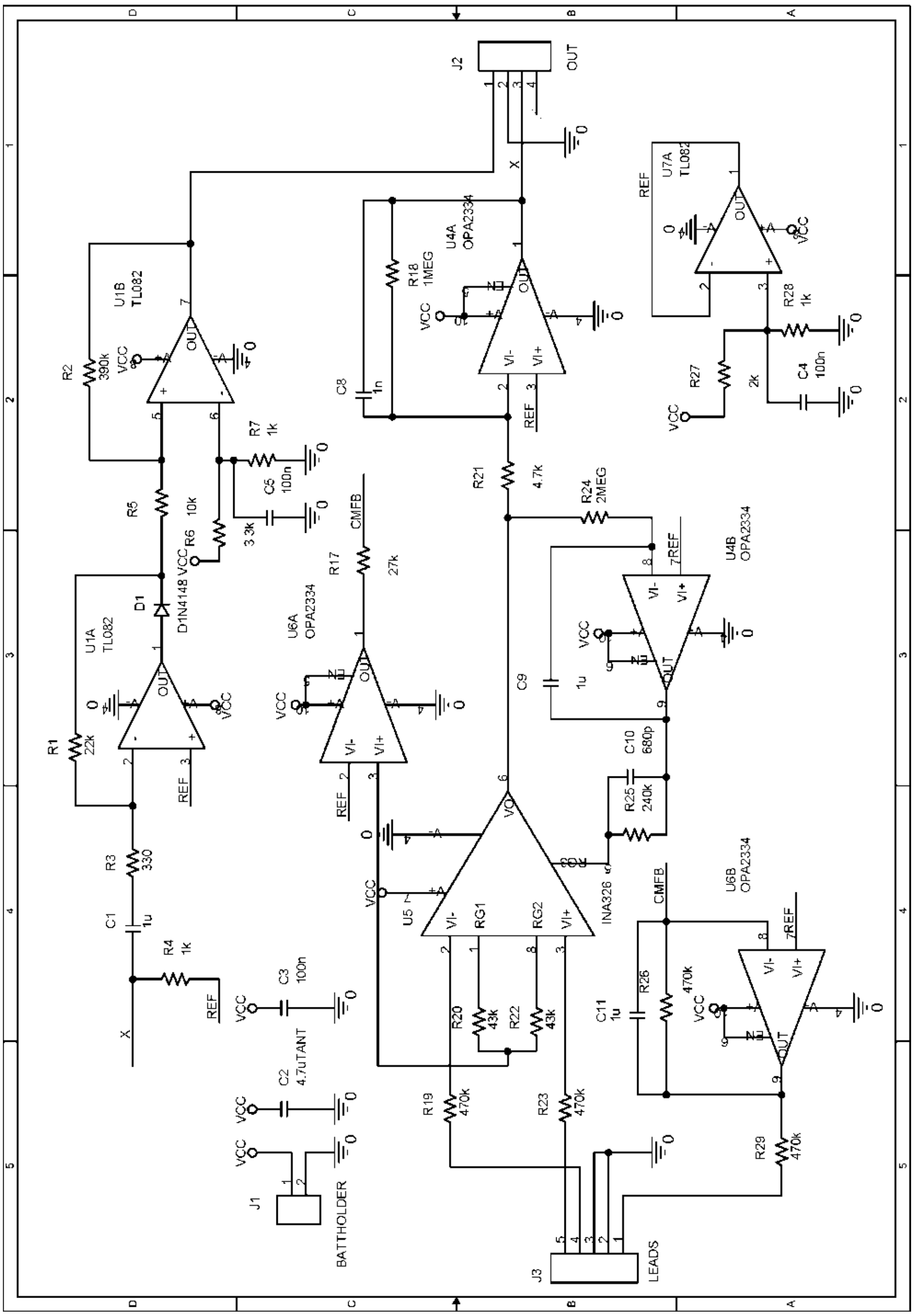

Fig. 2 – Schematic diagram of the analog module.

The ECG signal is picked up by the electrodes from the skin surface and is applied to the analog module where it is amplified and filtered, and where also the *R*-wave is detected. Fig. 2 presents the schematic diagram of the analog module.

As can be observed, the signal is first amplified and brought to a level within the range of 1…1.5 V. The ECG amplifier, that represents a simplified version of the amplifier proposed in a previous paper (Bozomitu *et al.*, 2011), consists of a two stage amplifier, the first one being built around the high precision instrumentation amplifier INA326 (U5). Two feed-back loops can be identified: the first, implemented with U4B, has the role of establishing a fixed DC level at the ECG amplifier output, preset at one third of the supply voltage, and a second loop implemented with U6A and U6B, which creates an active reference topology, with the role of minimizing the common mode voltage at the instrumentation amplifier input. The second amplifier stage (U4A) established the final gain of the amplifier and also acts as an anti-aliasing filter, limiting the bandwidth at 150 Hz.

Although several methods of detecting the *R*-wave exist and have been extensively tested (Pan & Tompkins, 1985; Harris, 1971; Fraden & Neuman, 1980), a low complexity solution was preferred, that works by thresholding the first derivative of the ECG signal (U1A and U1B from Fig. 2), due to the benefit of low resource consumption and reasonable performance.

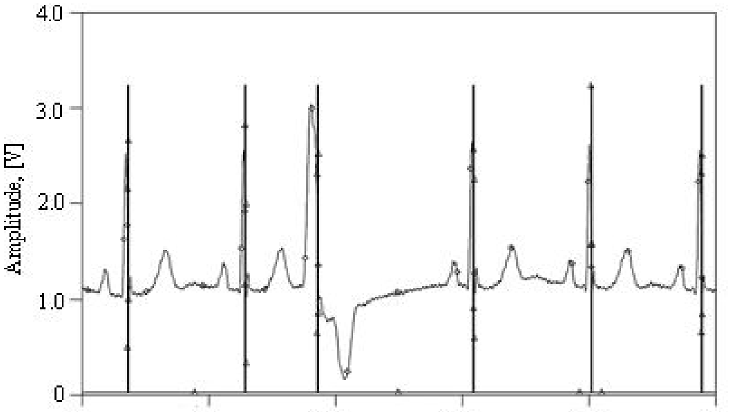

Fig. 3 – The two signals present at the analog module output: the amplified ECG signal and the *R*-wave detector output.

At the output of the analog module we will find two signals: the amplified and filtered ECG signal and logic pulses that will correspond to the *R*-waves. Fig. 3 displays the results of a SPICE simulation for the *R*-wave detector using an ECG sample waveform from the MIT-BIH arrhythmia database that shows several normal beats and one pathological beat.

The two signals provided by the analog module are fed to the development platform, the ECG is fed to the ADC input of the CC1010 and the *R*-wave pulses are fed to a digital data input port. The operation of the microcontroller from the CC1010 chip is divided in two threads that run in parallel.

The first thread, which has the highest priority and runs continuously, corresponds to the signal acquisition. At every 3 ms, or with a frequency of 333 Hz, a sample is read by the ADC, with an 8 bit precision, and stored in a buffer that stores the ECG signal in raw unprocessed format. In this same routine, verification is made to see if the current sample corresponds to an impulse given by the *R*-wave detector. If this is true, the location in the buffer where the sample is stored is marked as being an *R*-wave. Together with the stored location of the previous *R*-wave, the distance between them is calculated and the index located at one third of the distance is stored in a list called *segmentation list*. To avoid successive samples being marked as separate *R*-waves a protection measure was introduced by using a counter for stored samples since the last detection. Successive *R*-wave samples placed at less than 80 samples from each other will be discarded. The same counter ensures protection against missing *R*-wave detections and if there has been no detection for 500 samples, the system automatically marks the 501st sample as an *R*-wave.

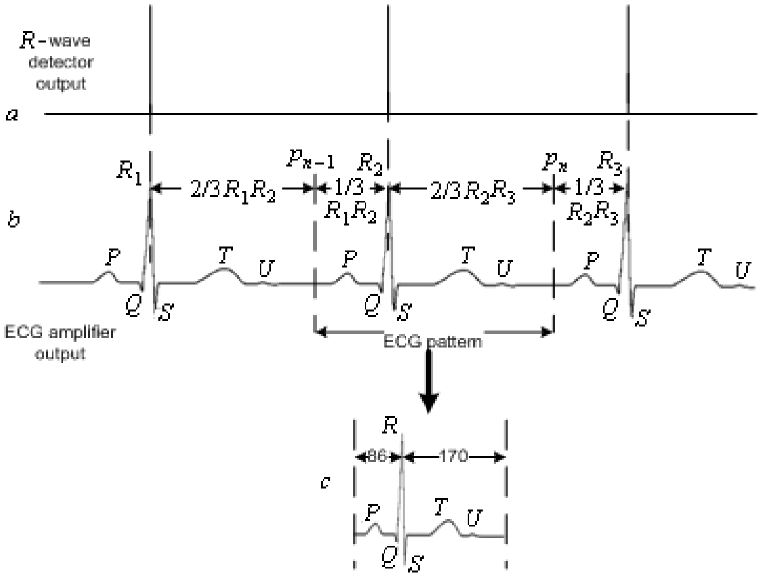

Fig. 4 – ECG segmentation: *a* – signal provided by the *R*-wave detector; *b* – ECG signal; *c* – extracted and resampled ECG pattern, with the *R*-wave placed at 1/3 of the pattern length.

The second thread becomes active only when the segmentation list contains at least two values and it will run only when the first thread is not active. The first operation performed is the segmentation of the ECG signal, illustrated in Fig. 4.

The first two indices (p_{n-1}, p_n), are extracted from the list and then using the indices values, an ECG pattern is extracted from the main ECG data buffer. This pattern will consist of the ECG signal samples starting at the first index and ending at the second index value. The pattern is then resampled to obtain a preset length of 256 samples, whilst keeping the *R*-wave position fixed related to its length, in two steps. First the portion up to the position of the *R*-wave is resampled to 86 samples and then the rest of the pattern length is resized to 170 samples. This will ensure the *R*-wave will be always placed on the 76th sample in all patterns.

The original pattern dimensions are stored and the ECG pattern is compressed using a 16 by 256 projection matrix, with uniformly distributed 0 and 1 values. By using a matrix with 0 and 1 values the calculations are much simplified, because when multiplying the pattern with the projection matrix instead of performing 256 multiplications and 256 summations, only 256 summations will be necessary.

Depending on how the system is configured, after calculating the ECG pattern projection, that in fact represents its compressed form, it will either be stored in a Flash memory, together with the original pattern dimensions, or transmitted using the RS232 interface. Once the compressed pattern is stored or transmitted, the thread becomes inactive.

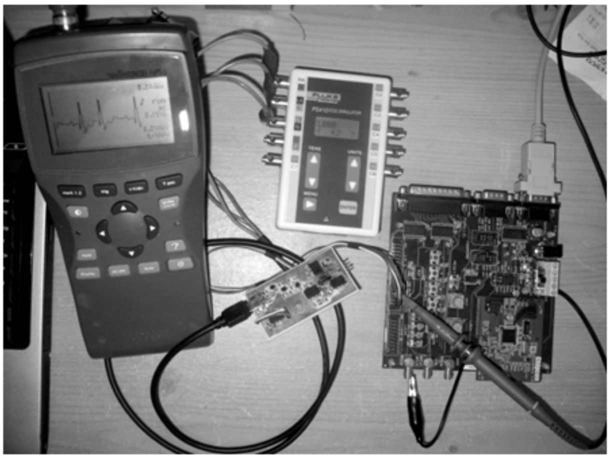

Fig. 5 – System test setup using the Fluke PS410 patient simulator.

3. Results and Discussions

A compressed pattern size will always be of 288 bits, where 256 bits represent the 16 projections represented using a 16 bit number format, and 32 bits represent the original dimensions of the pattern, 16 bits for each segment, that will be needed for a correct reconstruction.

The system was tested using ECG signals from a Fluke PS410 patient simulator, and also from a human subject. The PS410 simulator has been designed for testing medical devices and is able to simulate an array of 35 cardiac arrhythmias, pacemakers, normal adult and infant rhythm, noise and artifact simulations, for a maximum of 12 lead ECG. The ECG parameters that can be adjusted are cardiac frequency, amplitude, ECG type and many others.

For evaluation of the method, the compressed ECG was sent to a PC using the RS232 interface, where it was reconstructed in MATLAB. A rigorous verification in terms of reconstruction errors was not possible because the signal picked up by the electrodes was not available in numerical format. However verification was made by qualitative analysis of the reconstructed ECG signal. Reconstructed signals can be observed in Fig.6.

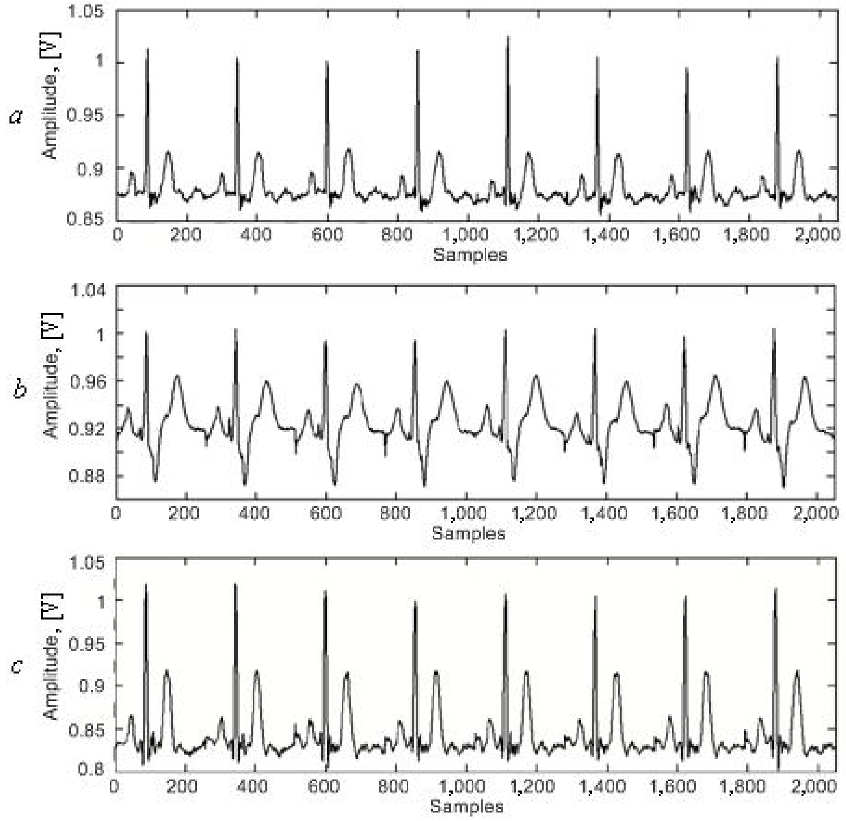

Fig. 6 – Reconstructed ECG signals: *a* – from Fluke PS410 – normal; *b* – from Fluke PS410 – right bundle branch block pathology; *c* – human subject – normal.

4. Conclusions

The ECG compression and storage system, based on the theory of compressed sensing that was presented, has been shown to have good results.

Considering an ECG with an average period of 80 bpm, a 7:1 compression ratio was obtained while keeping the reconstruction errors low enough for good signal reconstruction. Considering this ratio, if we take into account a common flash memory dimension of 8 Mbytes then it would be sufficient for 8 × 1,024 × × 1,024 × 8/288 (230,000) beats, or 48 h. The only sensitive issue that can affect the performance of the system is the correct operation of the *R*-wave detector, however under normal conditions it has proved to be reliable.

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SISTEM DEDICAT COMPRESIEI ȘI MEMORĂRII SEMNALULUI ECG BAZAT PE ACHIZIȚIA COMPRIMATĂ

(Rezumat)

Se propune un sistem capabil de compresie şi stocare a semnalului ECG, bazat pe principiile teoretice ale achiziției comprimate. Principalele caracteristici în baza cărora a fost construit sunt: dimensiunile reduse, consumul redus şi performanțele superioare din punctul de vedere al compresiei.