Design and Optimization of an ECG / Holter Hybrid System for Mobile Systems Based on DSPic

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Abstract

This paper presents the architecture of a portable system enabling the acquisition, processing, storage, and transmission in real-time, both as a 12-lead standard ECG and as long-term Holter. The prototype has been designed using a DSPic 33FJ256GP710 module, which allows an efficient local signal processing, potentially including morphological analysis and compression techniques. Our ECG data acquisition uses the new integrated circuit ADS1198 (low-power, 8-channel, 16-bit analog front-end for biopotential measurements), and is designed for memory management and local storage. The system is connected to a Smartphone through a Bluetooth module, which, on the one hand, allows to display and store the ECG signal in the Smartphone, and on the other hand, also displays and transmits he ECG signal for remote diagnosis and patient history storage. The preliminary analysis of the system was carried out with data taken from the Physionet dataset, in order to test its performance, in three different modalities. First, in the local mode, a recording time of over 120 hours has been achieved. Second, in the cellular mode, up to10 days of data could be stored in the phone. And third, in the remote server mode, practically unlimited time can be stored. For remote signal visualization, the average delay of the packets was less than 1.73ms, with a mean power consumption of 0.48 w/h, using a battery of 2 A/h (similar to a cellular phone one).

1. Introduction

Cardiovascular diseases are the principal cause of death in the world [1]. The possibility of acquiring ECG signals from institutions of primary attention can be very helpful and supportive to attend on time the cardiac emergencies, and it allows transmitting these signals for their remote review by specialists. The last systematic reviews of scientific literature show that few studies, and with limited scientific evidence, can be found which have addressed the efficacy of the acquisition, the processing and the transmission of ECG signals via Smartphones [2]. Several studies have used Smartphone for capturing and sending the cardiac rhythm, others only acquire ECG signals of one or up to 3 leads, and some others are able to take the 12 standard leads, but their consumption precludes them from being used also as Holter recorders in long-lasting mode [3,4]. Communications between the acquisition unit and the Smartphone, are usually provided by using NFC, Zigbee, WiFi, or Bluetooth [5,6,7,8]. Whereas a number of past projects have used GPRS to communicate with the storage system on the Internet, most of the nowadays studies use 3G or 4G [9,10]. It can be seen that previously proposed systems exhibit some limitations in the number of biosignal inputs, which precludes them from using the 12 leads required for a complete electrocardiographic clinical examination. More, the microprocessors in previous systems are also limited in terms of their processing capabilities for on-board high-precision analysis, which is usually required for the ECG signals.

In this work, we have proposed and implemented a new system overcoming those limitations [8,9,10].The developed prototype can monitor up to 10 entries from limb and precordial positions in order to generate the12 leads as usual in clinical electrocardiography. A DSPic integrated controller has been used in order to provide with advanced capabilities for digital signal processing, hence yielding a system which can also operates autonomously as a long-term Holter, which can store the information in a mini Storage Digital (SD) card even without any compression stage.

Therefore, the developed system is a hybrid ECG of 12 leads and long-lasting Holter, including an acquisition stage with low consumption, small size, and local storage capacity up to 120 hours. The acquisition stage is connected via Bluetooth to a Smartphone, allowing the verification of the correct positioning of each of the electrodes by visualization of the 12 signals. The set can also function as long-lasting Holter with uninterrupted phone storage up to 10 days. The system allows either real time or delayed transmission of the signals to a web server, for remote diagnosing, or for their entry into the patient record.

The rest of the paper is organized as follows. In Section 2, a general description of the system is presented. Then, the hardware and software architectures are presented in Sections 3 and 4, respectively, for the signal acquisition, the cellphone, and the web server. Preliminary results of performance tests are included in Section 5. Conclusions are given in Section 6.

2. General description of the system

The hybrid ECG/Holter system developed in this work captures ECG signals from 10 electrodes by means of an acquisition board of ECG signals, and it generates the 12 electrocardiographic leads from them. It has a Bluetooth unit for wirelessly transmitting the ECG biological signals to a cell phone, which has a Human Machine Interface (HMI) to capture these signals form the prototype, and subsequently visualizing and storing them.

The system has another HMI in a web server, allowing us to receive, display and store the ECG signals sent from the cell phone to the Internet cloud, and supporting the remote monitoring by accessing to the server. The system battery autonomy is of 12 hours, it is portable, of reduced dimensions and weight, so that it can be comfortably carried by any patient. In Fig. 1 we can see the system general diagram, whose modules are described next.

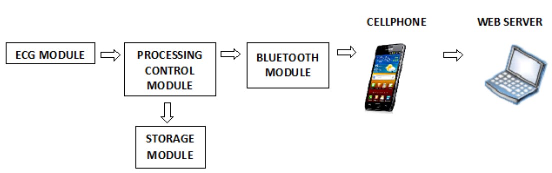


Figure 1. General diagram of system.

The *ECG module* allows the bioelectrical signal acquisition as generated by the heart from all the four limbs and the six precordial leads, in order to digitizing them in eight channels for latter transmitting them to the processing and control module, in frames of 2 bytes per channel and using the Serial Interface Protocol (SPI).

The *Control and Processing module* has a microcontroller and an integrated Digital Signal Processing (DSP) module, commercially known as DSPic, which is responsible for controlling the ADS1198 chip and the management interfaces of the prototype, such as the SD card for storage and the Bluetooth module for communications. Note that an essential advantage of using the DSPic is that it provides powerful capabilities to run signal processing algorithms, which are extremely useful in ECG processing, such as morphological signal processing or signal compression [11]. Nevertheless development of on-board algorithms for these purposes is ongoing work and goes beyond the scope of the present work.

The *Bluetooth module* transmits the ECG signal to the cell phone for display, storage, and remote transmission to the web server. The web server module is responsible for online displaying of the patient's signals, storing them, and allowing the remote access by doctors.

The *Storage module* allows to save the ECG signal into a file with MIT16 standard format, which can be read from any computer with adequate reading interface.

The *Cellphone module* consists of a Smartphone that has been programmed with a graphical interface to handle communication with the prototype via Bluetooth, as well as to display and store the ECG signals, and to transmit them to the Internet cloud and the web server.

Finally, the *Web Server module* is connected to the Internet to display and store the ECG signals received from the cellphone by means of a graphical interface. It also provides access to remote users.

3. Hardware architecture and design

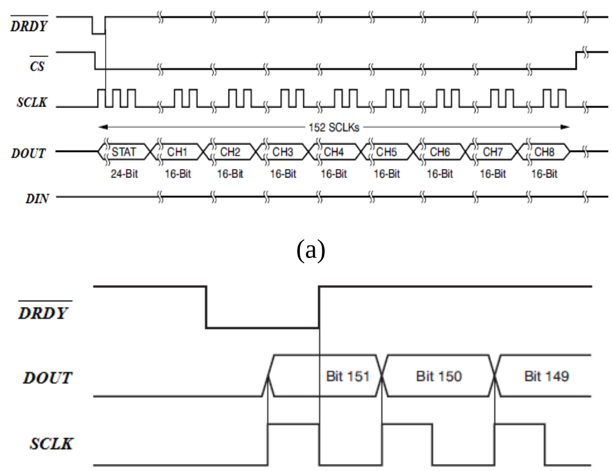
After the functional description given in the previous section, the design of the architecture of the hardware system modules is summarized below.

ECG module. One of the key contributions of the present work has been the control of the ADS1198 integrated circuit with the DSPic, which has involved a meticulous review of the manuals and the accurate interpretation of the timing diagrams for their translation into commands in the programming software of the DSPic.

In the acquisition module of ECG signals, the ADS1198 integrated circuit has been used to take the bioelectric signals of the four limbs and the six precordial leads, which have been conditioned and digitized in order to be processed by the DSPic. The ADS1198 integrated circuit has low noise specification, low energy consumption, multi-channel inputs, simultaneous sampling of 16-bit with 8 digital analog converters, and with a Programmable Gain Amplifier (PGA), which has been set to a gain of 2.

The serial interface compatible with the SPI consists of four signals, namely, CS, SCLK, DIN, and DOUT. The interface reads the data conversion, reads and writes in the registers, and controls the ADS1198 performance. The DRDY output is used as a status signal to indicate when data are ready. The DSPic generates these signals according to the timing diagrams in Fig. 2(a). When

DRDY is low, new conversion data are ready. DRDY behavior depends on whether the device is in RDATA or RDATAC mode. The START pin puts the device in normal mode for data captures. Figure 3 shows its behavior with respect to DRDY DOUT and SCLK.



(a)

(b)

Figure 2. Time signals in the DSPic. (a) SPI output data. (b) Time diagram for data recovery. (From [12]).

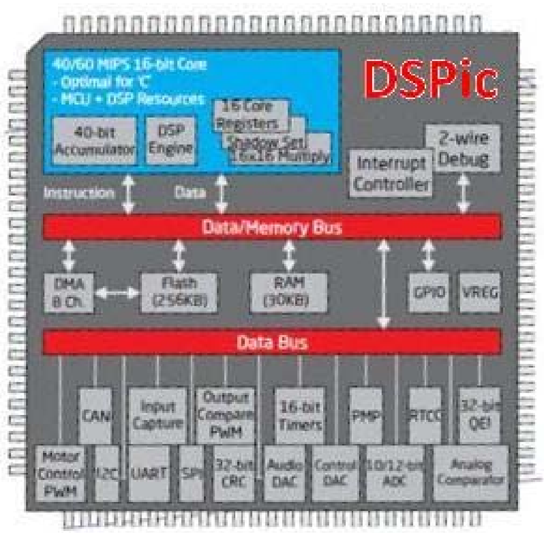


Figure 3. DSPic architecture (from [13]).

The ***Bluetooth module*** uses the firefly-888A integrated card set as slave, with transmission speed 19200 bps with a 10 m coverage, supply source of 3.3V and 8-bit words for transmission.

The ***Storage module*** has a 4 GBs mini SD card for storing ECG signals in the MIT16 format. This module has been included for also supporting the subsequent system benchmarking with both measured and Physionet signals, hence making possible the detailed evaluation of advanced signal processing algorithms.

Finally the ***Processing and Control module*** is fully provided by the DSPic, which has an integration-optimized architecture with an integrated microcontroller with a DSP (see Fig. 3). This integration includes 40-bit accumulators, DSP engineering, and the ability to perform 40 Millions Instructions Per second (MIPS) with 16-bit registers, hence providing the system with the ability to perform complex signal processing.

4. Software architecture and design

The software in the system has been designed in three phases, as described below.

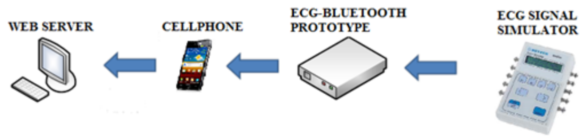
The ***DSPic Software*** has been developed in the Micro C platform, and it consists of several consecutive processes, as follows: (a) receiving the prototype configuration from the cellphone; (b) configuring the AD1198 integrated; (c) receiving the data using the SPI port of AD1198; (d) structuring the frames for storage in the mini SD Card; and (f) managing the information sent to the cellphone by the Bluetooth interface.

The ***Cellphone software*** that manages the cellphone has been developed on the Android platform by using the Eclipse software and it's *Android* for *Samsumg*^{TM} libraries. Object oriented programming has been used to handle the following items: the M*ySQL* database, the Bluetooth communications, the graphical interface for viewing the ECG signals, and the remote transmission by the Internet to the remote server.

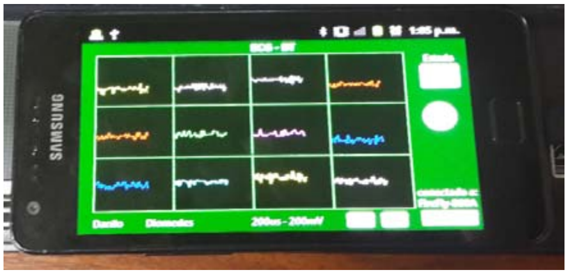
The ***Web Server software*** has been developed by using the *Matlab*^{TM} graphical interface, and it controls the following aspects: (a) the information reception via the 8080 port from the Internet cloud; (b) the ECG signal display; (c) the management of patient recording database; and (d) the data availability for remote users.

5. Testing and validation

A test and benchmarking scenario was created by using the *Netech MiniSim 300* simulator, which is shown in Fig. 4(a). An ECG signal of normal sinus rhythm (80 beats per minute) was injected from the simulator to the prototype, with an amplitude gain 1, which is subsequentl displayed in the cell phone, as shown in Fig. 4(b). Also, the remote transmission to the web was checked from the web server, and the resulting signal is visualized with the usual grid for clinical ECG recordings, as seen in Fig. 4(c).



(a)



(b)

(c)

Figure 4. System validation and experimental setup. (a) Test scenario. (b) Signals displayed on the cellphone. (c) ECG signals displayed on the remote Web server.

Several quantitative tests were made on the system performance. As an example, a packets delay lower than 1.73ms is obtained when they are sent in real time from the cellphone to the web server. Also for test purposes, a 2A-h battery was used for achieving a high autonomy for the system, and it could be verified that the local mode allowed a local data storage up to 120 hours, with a SD card memory of 4 GB.

6. Conclusions

A system has been proposed and implemented which allows the hybrid working modes for 12-leads electrocardiography and long-term Holter monitoring. The improved signal processing performance has been a key design criteria, aiming to provide with local analysis capabilities in order to support advanced ECG signal processing, such as morpohological processing or suitable signal compression.

On the one hand, the use of the ADS1198 integrated circuit has provided an efficient acquisition of the ECG signal of the ten usual locations to generate the 12 electrocardiographic leads, which are processed and transmitted to the web server, hence performs the functions for portable electrocardiography. On the other hand, the use of a 4 GB mini SD card in the system memory allows the storage of ECG signals during 120 hours, hence yielding the long-term Holter mode while allowing the storage of 12 leads. The system design using a DSPic, provides with high precision processing capabilities to the system, to be further exploited in the near future.

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