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A portable ECG monitoring device with Bluetooth and Holter capabilities for telemedicine applications

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Abstract—**A prototype of a portable ECG-monitoring device has been developed for clinical and non-clinical environments as part of a telemedicine system to provide remote and continuous surveillance of patients. The device can acquire, store and/or transmit ECG signals to computer-based platforms or specially configured access points (AP) with Intranet/Internet capabilities in order to reach remote monitoring stations. Acquired data can be stored in a flash memory card in FAT16 format for later recovery, or transmitted via Bluetooth or USB to a local station or AP. This data acquisition module (DAM) operates in two modes: Holter and on-line transmission.**

I. Introduction

In recent years, computer-based systems have become a *de facto* standard for a variety of applications and have made systems for remote vital-signs monitoring possible [1]. This is important to provide expert assistance for people living in far away locations and people requiring continuous monitoring in non-clinical environments (*i.e.* home, work) [2]. Specifically, ECG and blood-pressure signals can be monitored remotely in patients during cardiac rehabilitation, in order to detect risk situations. Telemedicine systems recently reported in the literature include a real-time ECG transmission system via telephone network [3] and mobile phone system [4], and a physiological signal monitoring system integrating Bluetooth and WiFi technologies [5].

In this project, a telemedicine application based on ECG signals is described with emphasis on the design and testing of the data acquisition module (DAM) with wireless transmission and storage capabilities.

Since the primary target of the project is to provide mobility and comfort to the patient, it is necessary to use wireless communication when continuous data transmission is required. Bluetooth technology was chosen because it can be easily connected to computer-based systems and it implements Frequency Hopping in order to provide noise and interference rejection. Therefore, this technology exhibits a very low packet drop when a device is in range (10 to 100 mts).

When there is no Intranet/Internet available or in Holter mode, the DAM must have the ability to store data for later evaluation. Therefore, there must be a high capacity non-volatile memory in the DAM. For easier data download to computer-based systems, a removable memory (*i.e.* Secure Digital Card) is available. Also, the DAM must store data with a standard file format, such as FAT16, in order to make information compatible with computer-based systems.

This work aims to describe the DAM prototype as part of a complete telemedicine system for vital signs. The structure of this paper is as follows. In section 2, an overview of the general telemedicine system is introduced followed by a description of the ECG DAM. In section 3, the most relevant results obtained with this device are given, followed by section 4 with concluding remarks.

II. Methodology

A. System Overview

The proposed ECG telemedicine system is divided in three functional blocks: a DAM, an Access Point and local or remote stations supporting telemedicine software applications (Figure 1).

Firstly, the DAM is the device in charge of the acquisition, digitalization and processing of a patient's ECG signals. Once the data is processed, it can be stored in a memory card for posterior inspection (Holter), or it can be wirelessly transmitted via Bluetooth to an AP or via USB to a local monitoring station (on-line transmission).

Secondly, the AP is a device located in a place near the patient which maintains connection between the DAM and the remote station via Intranet/Internet using TCP/IP. This connection could be continuous or event driven, *i.e.* when a risk situation is detected. However, this last capability has not yet been implemented.

Finally, the local and remote stations run applications to visualize, analyze and store the information received from each patient.

B. DAM

The main function of the DAM is to acquire, store and transmit the ECG signals and provide mobility to the patient in two operation modes. First, in on-line transmission mobility is subject to a limited space, determined by the Bluetooth device class. Second, off-line acquisition is available through Holter operation mode. Therefore, it is

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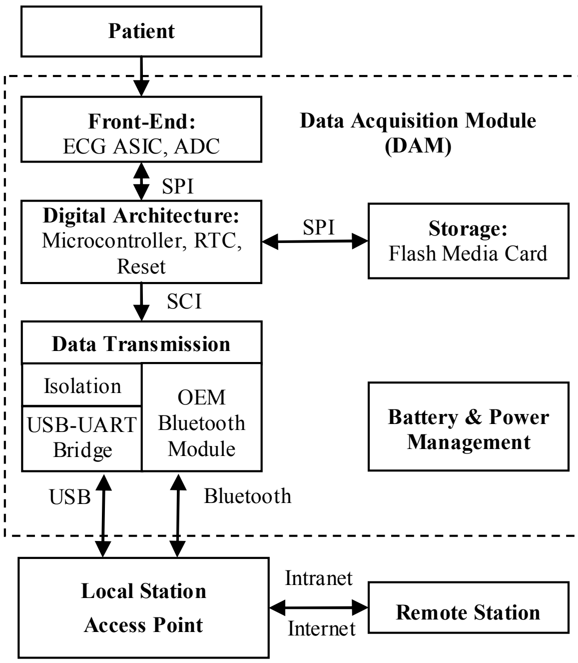

Fig. 1. ECG Telemedicine System Block Diagram

primarily designed for long-term usage in both modes.

Configuration of this device is achieved through serial communication, either USB or Bluetooth, with a local or remote station monitoring this device. The most relevant parameters to be configured are: sampling frequency (250, 500, 1000 Hz), leads used (3 or 5) and operation mode (Holter or on-line transmission).

The DAM is composed of several blocks as seen in figure 1:

1) Front-End: This block is for signal conditioning and digital conversion:

--ECG ASIC [6]: The function of this OEM Application Specific Integrated Circuit (ASIC) by Welch Allyn, is to condition ECG signals from the electrodes in two formats: 3 and 5 leads. This ASIC has 4 independent channels: two channels are used for a 3 lead ECG and three channels are used for a 5 lead ECG. The remaining channel can be used for respiration impedance pneumography, but this option was not implemented on this prototype. Each differential channel is amplified by 8. It also has the following characteristics: built-in pacer pulse detector, filtered lead-off for each electrode, programmable input offset for each channel, selectable reference electrode (5 choices), on-chip RF filtering on all inputs and built-in self-test capability. This ASIC is configured through serial peripheral interface (SPI).

--ADC: Digital conversion of the ECG differential channels is achieved through Analog Devices' analog to digital converter AD7716BS [7], with 4 independent and simultaneous delta-sigma sampling channels with 22 bits resolution. This ADC has 3 configurable sampling frequencies: 250, 500 and 1000 Hz. Samples from each channel, including channel and device address, are stored in 32-bit registers for later transmission. This device signals each end of conversion trough a pin connected to the microcontroller (μC). Finally, this data is requested by the μC and transmitted via a five line synchronous serial I/O.

2) Digital Architecture: This stage is constituted by three main components: a RISC 8 bit microcontroller, a real-time clock (RTC) circuit and a reset circuit.

--Microcontroller: An Atmel ATmega128 [8] is used for setting the configuration of peripheral devices (ECG ASIC, ADC and Memory Card), processing and storing digital data acquired by the front-end, and establishing communication with local stations or APs through Bluetooth or USB. When the flash memory card is used, most of the processing time of the μC is employed to update the FAT16 information in RAM and to communicate with the card. Therefore, the memory card and the front-end are connected to the μC through two different serial interfaces to ensure independence of the acquisition and storage process. Also, the end conversion pin of the ADC was connected to a high priority external interrupt to ensure that every set of samples was received with as little delay as possible. This set of samples is buffered awaiting its storage in the card.

The 22-bit samples provided by the ADC can be stored and/or transmitted in both a 22-bit or 16-bit format, that is, data can be pre-processed in the μC to reduce storage and data rate requirements.

--RTC: The Maxim DS1337 [9] serial real-time clock used is a low-power clock/calendar with I2C bus interface for data transfer. The clock/calendar provides seconds, minutes, hours, day, date, month, and year information for recording identification purposes.

--Reset: A Texas Instruments TPS3836K33 [10] is used as a supervisory circuit providing circuit initialization and timing supervision for the μC, to generate a power-on reset and power supply monitoring.

3) Storage: In this stage, collected data is stored in a flash memory card using FAT16 file format. Therefore, the memory card can be removed from the DAM for data retrieval in any computer-based platform. Each acquisition produces a new file with a simple protocol structure including sampling rate and lead configuration. Communication between the memory card and the μC is established through SPI bus.

In the prototype, three different memory cards were tested since they share a common communication protocol: Multimedia Memory Card (MMC), Secure Digital Card (SD) and TransFlash.

4) Data Transmission: Two independent serial communication protocols are proposed: USB and Bluetooth.

On the one hand, USB compatibility is accomplished using a CP2103 from Silicon Laboratories which is a complete USB 2.0 full-speed function controller, bridge control logic and a UART interface with transmit/receive buffers and modem handshake signals [11]. This chip supports baud rates up to 1 Mbps, which is the DAM's default baud rate for USB communication. Power supply to this circuit is provided by the USB host to which this device will be connected. Also, the CP2103 is electrically isolated from DAM to protect the patient. The four line SCI communication (RX, TX, RTS, CTS) go through a quad channel digital isolator, based on Analog Devices' iCoupler technology (ADuM1402) [12].

On the other hand, Bluetooth compatibility is attained with an OEM module from BlueRadios, the BR-C30 Class 1 [13]. This module is configured using AT commands and accepts or establishes connections with other devices using Serial Port Profile (SPP) conforming to Bluetooth V1.2. The default communication baud rate with this OEM module is 115.2 kbps.

5) Battery and Power Management: Two AA batteries provide power to the DAM. A 95% efficiency step-up switching converter is used to generate 3.3 V for system components. This converter also provides a battery supervisory circuit for low voltage detection, allowing the µC to shut-down properly when battery is low.

Since the ECG ASIC and the ADC requires 5 V to operate, two extra converters are implemented: a 5 V charge pump connected to the 3.3 V power supply and an inverter cascaded with the 5 V charge pump.

Also, three MOSFETs are connected to the power supply of different stages of the device: Front-End, Bluetooth module and Memory Card. Therefore, when one stage is not required, it is completely disabled to optimize battery life-time.

Finally, exhaustive battery life-time measurement has not been carried out for all the operations modes. For a design estimate we considered the worst case for minimum battery life-time.

This condition occurs in two cases: Holter mode, witch includes the SD and real-time transmission, witch includes the Bluetooth module. In both cases, two 2500mAh AA batteries were assumed as power supply for the system.

In Holter mode, calculations were made using maximum current during memory writing and maximum and minimum writing times according to manufacturer's specifications for both MMC and SD cards. A preliminary estimate suggests that battery lifetime should be at least 25 hours for MMC and 20 hours for SD cards. Information for TransFlash was unavailable.

In real-time transmission, an estimate of at least 11 hours of battery life-time was obtained based on maximum power consumption under maximum data rate of the module and assuming continuous transmission (Bluetooth module constantly transmitting data).

III. Functional Description

Operation modes for the DAM are selected using serial commands sent through the USB serial interface. Each operation mode has a different function execution order.

In Holter mode, data acquisition can not be interrupted regardless of the time required to store each data block in the memory card, although it can be stopped when the memory card is found to be full or through a serial command. Interrupting or delaying the data acquisition process leads to unreliable and inaccurate sampling of the ECG data. Therefore, it is given a higher priority by using an interrupt to handle the communication with the ADC when it signals that new data is available. This data is introduced to a 2048-byte circular buffer waiting to be stored in the memory card. The main program is constantly waiting for the buffer to hold 512 bytes (minimum block size [14]) or more data to begin the process of writing a data block to the card. Also, to provide minimum data-loss in case of hot removal of the card or batteries, FAT tables are updated every two minutes. This ensures that data can be recovered by commercial readers up to the last update.

In real-time transmission, data acquisition is serviced in the main program storing data in a 256-bytes circular buffer. This buffer is emptied in an interrupt routine triggered every time a byte has been successfully sent to a communication module.

IV. Results

A prototype that implements all of the above capabilities has been developed. This prototype is constituted by a finished SMD printed circuit board (PCB) design for the Front-End (Figure 2) and a separate card for the rest of the system. The PCB final design for this second card is being implemented for future use in clinical testing.

The DAM was tested for data transmissions to Bluetooth-enabled local stations for all sampling frequencies and lead configuration via Bluetooth at different distances with no data loss. Also, it was tested using USB interface with a local station.

For evaluation purposes, each card was tested for a 30 min period acquisition with different sampling configurations, starting with the lowest demanding case, *i.e.* 3 leads sampled at 250 Hz with 16 bit precision. Table I states the maximum sampling rates achieved with each memory card. Therefore, the TransFlash memory card is selected because it is smaller than the others, reducing PCB space required, and it showed a better performance than a standard SD card.

V. Conclusions and Future Work

An ECG telemedicine device for non-clinical applications has been successfully developed and tested for two particular functions: Holter and on-line transmission.

Since, all memory cards tested exceed the usual sampling rate for Holter mode, the TransFlash was selected because it is smaller than the others.

Further study will be carried out to test transmission reliability in the presence of a variety of standard consumer electronics, e.g. cordless phones and WiFi devices operating in the same frequency band that may adversely affect data transmissions via Bluetooth at different distances.

Additionally, extensive testing will be carried out to determine the average battery life-time of the DAM under both real-time transmission and Holter mode.

In a near future, other vital-sign signals will be appended to this system, including non-invasive blood-pressure and respiratory impedance pneumography.

Furthermore, data compression algorithms will be studied to optimize memory card usage by reducing records size and power consumption due to data writing.

Also, the DAMs will be used to implement telemedicine systems in the area of cardiovascular monitoring services for non-clinical environments. For this application it is imperative to provide data privacy and integrity.

Finally, an agent-based Java application is being developed to provide analysis and detection of arrhythmia using several vital-sign signals.

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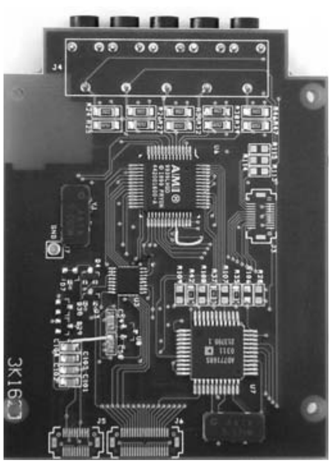

Fig. 2. Actual view of the DAM´s Front-End PCB card.

TABLE I
HOLTER OPERATION: MAXIMUM SAMPLING RATES.

Memory Card	Max. Sampling Rate
SD	500 Hz/3 leads/16 bits per sample
MMC	1000 Hz/5 leads/16 bits per sample
TransFlash	500 Hz/3 leads/24 bits per sample

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