

Wearable ECG Module for Long-term Recordings using a Smartphone Processor

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ABSTRACT

Life-threatening cardiovascular diseases require early detection or diagnosis. A standard procedure, long-term ECG monitoring of cardiac patients is currently the best way to reduce the number of heart failures. Dry and washable textile electrodes embedded in comfortable garment or in a wearable chest belt have been proven very effective for a long-term ECG monitoring in comparison to the conventional Ag/AgCl electrodes. Hereby, we present a wearable ECG chest belt, which contains stitched textile electrodes for ECG detection and analog preprocessing circuits embedded in tiny cell-phone plugs. With them we achieve on-site ECG processing, display and transmission using a dual-core OMAP3-based embedded system. Our experiments have shown promising results of textile electrodes along with our hardware and embedded system in conveying a better ECG signal quality having a clinical significance and hence enabled long-term ECG recording in a daily life.

Author Keywords

Textile electrode, long-term ECG, smartphone processor, OMAP3530, BeagleBoard.

ACM Classification Keywords

J.3 Computer Applications: Life and medical sciences.

General Terms

Design, Experimentation, Measurement.

INTRODUCTION

Cardiovascular diseases are the main cause of death in the middle-to-old aged people globally. According to WHO estimates, 16.7 million people around the globe die of cardiovascular diseases each year [4]. Early detection of symptoms in the risk group (patients with recent bypass surgery or angioplasty) can significantly reduce the number of heart failures or sudden deaths [1, 2, 3].

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Long-term ECG recording is a standard procedure in monitoring cardiac patients. In case of ECG recording during daily life activity, washable and comfortable textile electrodes can be woven at a precise target location in the daily wearable garments and hence make the ECG recording less cumbersome concerning electrode handling and adjustments on the body unlike conventional gelled electrodes.

During the past few years, a number of wearable physiological monitoring systems have been in practice for health monitoring of the patient in hospital and real life situations and their performances have been reported [5]. Some prerequisites for such wearable systems are their small size, low-power consumption, low weight, real-time signal processing and most importantly wireless connectivity [6]. Processors like the OMAP family from Texas instruments have a dual-core functionality (ARM+DSP) and are suitable for wearable health monitoring applications [7].

In this context, we present an Active Belt, which is a wearable single channel long-term ECG recording module developed in our laboratory (Fig. 1). Textile electrodes (TITV Greiz, elitex) are stitched on the skin-contact side of the belt. The electrodes are wired to analog processing circuits confined into two small cell-phone plugs. At the end, the digital ECG signal enters into a dual-core OMAP3-based embedded system for ECG processing, display and wireless transmission to a remote computer.



Figure 1: The Active Belt concept

MATERIALS & METHODS

Active Belt & Textile Electrodes

A stretchable and breathable chest belt (34.5cm x 84.5cm) was fabricated from neoprene material (SEDO Chemicals Neoprene GmbH, Germany) with velcro on the closing ends. Three Textile electrodes, two of them elliptical (---6.5cm and : 3.5cm) for ECG were stitched on two sides of the torso on the belt and a circular electrode for ground (Ø2.5cm) next to the navel as shown in Fig 2.

The washable textile electrodes (TITV Greiz, Germany) are made of polyamide threads (ELITEX[®]) coated with pure silver with a thickness of 1-2 μ m and a resistivity of 20 Ω /m [8]. Each thread can be stretched up to 7% of the original length without compromising the conductivity [8].

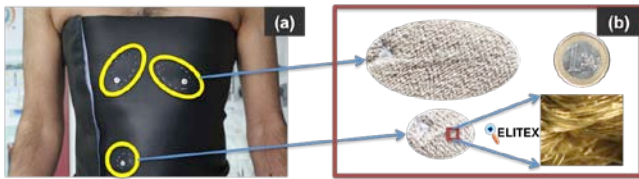


Figure 2: (A) The Active Belt with The textile electrodes (marked yellow) stitched and (b) the textile electrodes with microscopic (40x) view.

ECG Analog Circuits in Cell-phone Plugs

As shown in Fig. 3, the ECG analog circuits are embedded inside two 1.6cm x 2cm cell-phone plugs (AXR72161, Matsushita Electric Works, Ltd), amplifier and ADC plugs. Both plugs are mounted on the Active Belt in vicinity to the electrodes.

The raw ECG signal detected by the textile electrodes on the body is fed to the amplifier plug, which contains the biopotential amplifier array RHA1016 (Intan Technologies...) with few additional components. The low-power RHA1016 contains 16 differential amplifiers (gain = 200), thus in principle suited for multichannel ECG [7]. Two external resistors R_1 and R_2 are board-mounted to set the cut-off frequency of 100Hz for a built-in programmable 3rd order butterworth low pass filter.

The amplifier's output connects to the ADC plug, which contains a single channel ADC (ADS1271, Texas Instruments Inc., USA) with a data rate up to 105kSps following an instrumentation amplifier (IA) with a gain of 20 [5]. The

ADC is controlled by an industry standard serial peripheral interface (SPI) from an external source, which in our case is the dual-core embedded system.

Dual-core OMAP3-based Embedded System

OMAP3530 (OMAP3) (Texas Instruments Inc., USA) found in new generation smart-phones is a dual-core (ARM+DSP) application processor, which is an ARM-based SoC with laptop-like performance. The OMAP3 has the following prominent features [10]:

- 720 MHz ARM Cortex-A8 core provides 1400 Dhrystone million instructions per second (MIPS) and runs fully-featured operating systems e.g., embedded Linux, Android, WindowsCE.
- 520 MHz C64x+[™] DSP furnishes excellent signal processing and computing.
- Display subsystem provides the advanced display.
- Comprehensive power and clock-management scheme enable high-performance and low-power.

The USB-powered BeagleBoard (beagleboard.org, USA) shown in Fig. 3 is an OMAP3530 based development board and comprises of all needed components in order to access the peripherals such as mouse, keyboard, monitor, speakers, mic, memory cards/sticks, internet, ADC, USB WLAN adaptor etc [11]. We chose a user-friendly linux distribution "Ångström" for the BeagleBoard [9]. The Ångström is a distribution with a highly portable and reconfigurable core, built using the OpenEmbedded build system with special attention to embedded devices [9].

Enabling SPI Bus on OMAP3

BeagleBoard provides access to various serial ports (SPI, I2C, GPIO, MMC, McBSP) at its expansion header [11]. Each pin of the expansion header has multi-functionality. In our application (see Table 1), multichannel serial port interface (McSPI3) furnishes four-wire SPI communication and

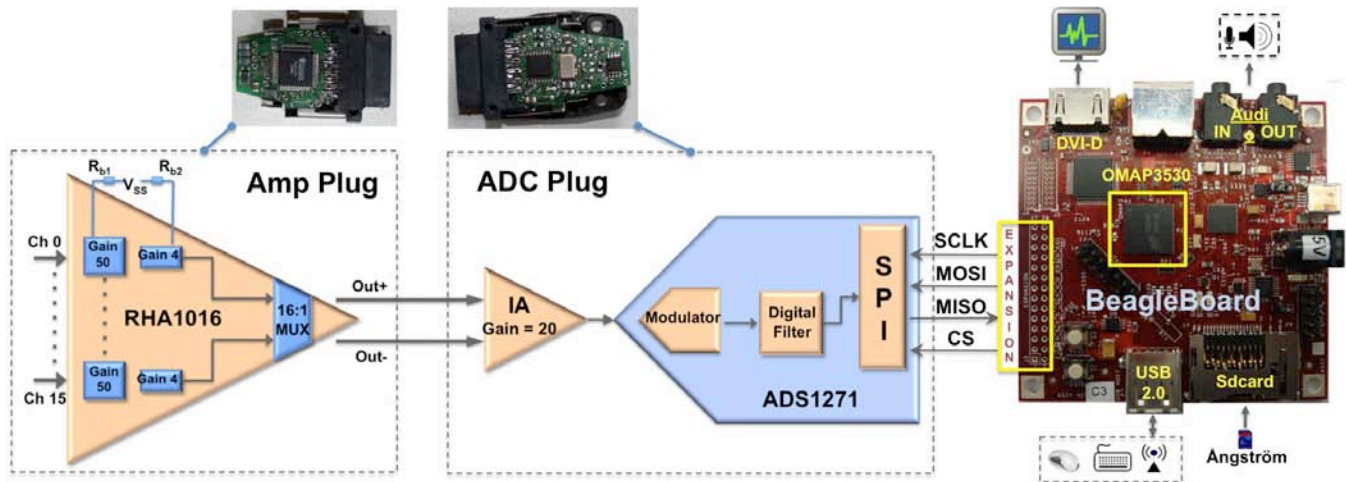


Figure 3: The amplifier plug amplifies and filters the raw ECG signal. The ADC plug provides high resolution (24-bit) digital conversion. The digital data is then fed to the BeagleBoard via SPI port at expansion header. The BeagleBoard running on Ångström facilitates various functions such as user interface devices, ECG data visualization, audible alarms and wireless data transfer to a remote computer.

is available on the expansion pins. The four pins also provide other functionalities e.g., MMC and GPIO (default). It requires thus a boot procedure to enable SPI communication on OMAP3 with external hardware (in our case, the ADC). On-chip pin multiplexer (PINMUX) controlling the pin function can be configured by selecting the mode 1 in the bootloader and linux kernel settings. Hence, the McSPI3 functionality was made available on the expansion header of the BeagleBoard.

Table 1: The McSPI3 expansion pins on the BeagleBoard and their other functions [11]

Pin No.	MUX			
	Mode: 0	Mode: 1	Mode: 2	Mode: 3
11	MMC2_DAT3	McSPI3_CS0	-	GPIO_135
17	MMC2_DAT0	McSPI3_MISO	-	GPIO_132
19	MMC2_CMD	McSPI3_MOSI	-	GPIO_131
21	MMC2_CLKO	McSPI3_CLK	-	GPIO_130

ECG Processing, Display and Transmission

Our C++ embedded application running on the ARM side of the OMAP3 fetches a single channel digital ECG signals from the ADC and prepares them for display and transmission. First, the digital to analog conversion takes place and yields decimal values of the signal. The application also plots the converted data in real-time on the Ångström desktop environment utilizing the SDL library. Simultaneously, the application sends the decimal values to the remote PC over wireless LAN using the TCP/IP server-client protocol.

RESULTS & DISCUSSIONS

Textile Electrode under Test

In long-term surface biopotential recordings, the skin-electrode impedance plays a major role in the quality of signals. Experiments were conducted to measure the skin-electrode impedance of the textile electrodes in comparison with commercial gelled disposable ECG electrodes with the help of an USB amplifier (g.USBamp, Guger Technologies,

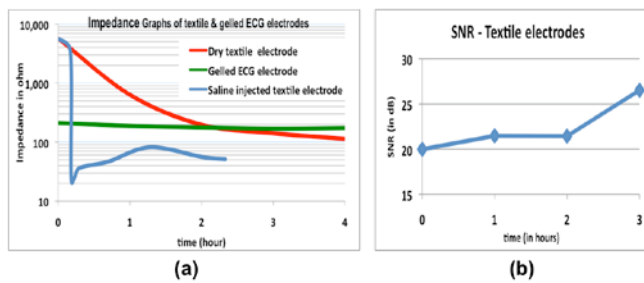


Figure 4: (a) Impedance graph of the textile and conventional ECG electrodes and (b) SNR over time for the textile electrodes

Austria). As shown in Fig. 3 a, the conventional electrode has a flat response over time. The impedance measured from the textile electrodes on the Active Belt shows a gradual decrease during the beginning hours. Our hypothesis behind such exponential decline in impedance is that created sweat under the textile electrode location improves the contact. To corroborate our theory, we injected a sweat phantom (saline-0.9% NaCl) into one of the textile electrodes. At the same moment, we observed the impedance of textile to plummet.

To evaluate the performance of the textile electrodes for long-term ECG recording, the signal-to-noise ratio (SNR) was calculated for ECG signals captured by the textile electrodes. For this, the commercial USB amplifier was used to measure impedance at intervals of 1 hour. Fig. 3 b depicts a n increase in SNR after some hours as the textile electrodes improve their skin contact and hence enhance ECG signal quality.

Features resulting from the textile electrode experiments strongly lead to the conclusion that the textile electrode is an appropriate candidate for the long-term ECG recording . However more research is needed to improve mechanical skin-electrode contact not the least to remove motion artifact.

SPI Communication – OMAP3530 and ADC

After configuring the PINMUX for McSPI3 on Beagle-Board, the SPI driver test program running on the ARM side of OMAP3 enables the SPI master-slave communication with the ADC. As shown in Fig. 5, the master-OMAP3 initiates the communication by sending chip select (CS) signal to the slave-ADC. The OMAP3 sends the clock signal and simultaneously provides the control word. After interpreting the control word, the ADC executes the digital conversion and sends the data to the OMAP3. After that the



Figure 5: The SPI communication between OMAP3 and the ADC

cycle starts over again.

ECG Recordings

Fig. 6 a shows ECG signals captured by textile as well as by conventional Ag/AgCl electrodes in connection with a commercial monitor. It appears that the textile electrode possesses a sufficiently good quality for ECG recording.

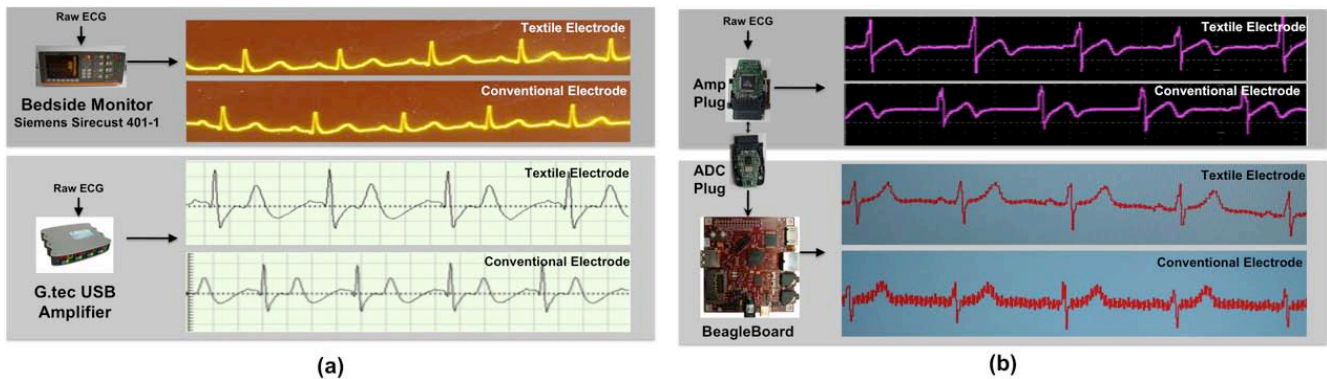


Figure 6: (a) The screenshots of the ECG recorded by the commercial monitors and (b) the screenshots of the ECG recorded by the amplifier plug and the complete Active Belt system

Fig. 6 b depicts ECG signals as output of the amplifier plug. These amplified signals are indistinguishable from the signals of the commercial amplifiers and hence validate the performance of the amplifier plug circuit. The processed ECG signals arriving at the BeagleBoard represented in Fig. 4 b show that the ECG signals from convention electrodes are even more contaminated by power-line noise than the textile electrode signals. Quantization resolution of the ECG signals out of the ADC plug is very high resolution with 24-bit at sampling frequency of 105 kSPS. Our C++ embedded application running on the ARM side of OMAP3 fetches digital ECG signals from the ADC and converts them into decimal values. The application also plots the signals in real-time on the Ångström desktop environment utilizing the SDL library.

CONCLUSIONS

We have presented a successful implementation of a wearable single channel ECG Active Belt for a long-term ECG recording with the potential of up to 16 channels. Initially, the textile electrode was compared with the conventional electrode in terms of their ability to perform long-term recording. The textile electrode has shown a promising outcome by exhibiting low skin-electrode impedance and a high SNR for long-term recording. We have mounted analog processing hardware in tiny cell-phone connectors, which are detachable and mounted in the vicinity to the ECG detection site. We have achieved ECG processing, and display on the Active belt utilizing the computing power of the dual-core processor OMAP3. The ECG data transmission from the Active Belt to a remote computer visa WLAN is currently under development. Thus, the Active Belt brings a long-term ECG recording in patient's daily life and helps in the future by on-site analysis and/or remote experts to diagnose cardiovascular problems earlier.

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