A Wireless EEG Acquisition Platform based on Embedded Systems

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Abstract: This paper proposes a wireless EEG acquisition platform based on Open Multimedia Architecture Platform (OMAP) embedded system. A high-impedance active dry electrode was tested for improving the scalp-electrode interface. It was used the sigma-delta ADS1298 analog-to-digital converter, and developed a "kernelspace" character driver to manage the communications between the converter unit and the OMAP's ARM core. The acquired EEG signal data is processed by a "userspace" application, which accesses the driver's memory, saves the data to a SD-card and transmits them through a wireless TCP/IP-socket to a PC. The electrodes were tested through the alpha wave replacement phenomenon. The experimental results presented the expected alpha rhythm (8-13 Hz) reactiveness to the eyes opening task. The driver spends about 725 µs to acquire and store the data samples. The application takes about 244 µs to get the data from the driver and 1.4 ms to save it in the SD-card. A WiFi throughput of 12.8Mbps was measured which results in a transmission time of 5 ms for 512 kb of data. The embedded system consumes about 200 mAh when wireless off and 400 mAh when it is on. The system exhibits a reliable performance to record EEG signals and transmit them wirelessly. Besides the microcontroller-based architectures, the proposed platform demonstrates that powerful ARM processors running embedded operating systems can be programmed with real-time constrains at the kernel level in order to control hardware, while maintaining their parallel processing abilities in high level software applications.

1 INTRODUCTION

Electroencephalography (EEG) signals have been used in numerous clinical applications, ranging from sleep studies, epilepsy, to brain function monitoring in intensive care units, and in several research applications used alone or in conjunction with other neuroimaging techniques (Niedermeyer and da Silva 2004); (Hung-Yi et al., 2006); (Campbell et al., 2010); (Lin et al., 2010); (Castellaro et al., 2011); (Pichiorri et al., 2011). Ambulatory EEG recordings with high-electrode density are often challenging. In applications such as epilepsy studies, which require long-term recordings, the electrolyte gel starts to dry, and the electrode's impedance increases causing the reduction of the signal-to-noise ratio.

The high-cable density that usually connects the patient to the acquisition platform also limits EEG applicability. Due to the large number of channels (32 channels or above) needed to record EEG signals with high spatial resolution, the setup comprises a minimum of 34 cables (considering reference and ground) connecting the EEG channels to the acquisition platform. These cables should remain stable in order to avoid artifact contamination into the EEG signals. Thus, all the applications are extremely limited to "non-movement paradigms", and so, the signals are recorded in abnormal environment for the patients.

Wireless technology applied to the EEG recording has been developed in the past few years (Modarreszadeh and Schmidt, 1997); (Hsieh et al., 2006); (Matthews et al., 2007); (Lin et al., 2008); (Penhaker et al., 2010); (Usakli, 2010); (Park et al., 2011). There are some interesting platforms that can fulfill some applications, such as drowsiness detection and epilepsy monitoring (Modarreszadeh and Schmidt, 1997); (Hsieh et al. 2006). The already reported EEG wireless platforms, present

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communication platforms based on Zig-Bee (Shao-Yen et al., 2009) and Bluetooth (Hsieh et al., 2006) protocols, channel density ranging from 2 to 14 channels, sampling frequencies below 256 SPS, resolutions usually below 12 bits (Hsieh et al., 2006); (Penhaker et al., 2010), wet or dry electrodes (Matthews, McDonald et al. 2007; Sellers, Turner et al. 2009).

Despite all of these developments, the ambulatory monitoring of epilepsy or sleeping disorders requires a new technology paradigm: long-term monitoring with a large number of channels and online data selection.

With the development of embedded systems and real-time signal processing techniques, there is a growing interest in applying them to these novel platforms (Chin-Teng et al., 2006); (Hsieh et al., 2006); (Penhaker et al., 2010). Features like low-power consumption, small size and high-speed performance, the embedded devices can produce signal-acquisition based applications that may be easy to migrate to other platforms with smaller and more powerful devices.

The hardware of these platforms must face the best of two requirements, low-power consumption and enough speed to acquire, process and transmit the signals as close as possible to real-time. To accomplish these requirements, some platforms are based in ASIC (Application-Specific integrated circuit), but a low-cost COTS (Commercial off-the-shelf) EEG platform is becoming more feasible.

There have been made some advances in embedded systems multi-core processing (Chin-Teng et al., 2006); (Majoe et al., 2012). Because OMAP (Open Multimedia Architecture Platform) architecture has both an ARM and DSP cores, some studies have explored the parallel use of the ARM to interface and communicate with peripherals, with DSP to manage and to process signal data recordings.

This work proposes an EEG acquisition platform based on a OMAP embedded system, low-power COTS hardware components, with dry electrodes, signal resolution of 16 bits, sampling rate of 1000 samples per second, and wireless TCP/IP-Socket transmission.

2 SYSTEM ARCHITECTURE

The developed system can be divided into three major functionality blocks: the active dry electrodes, the analog-to-digital converter (ADC) and the central processing and transmission unit (CPTU). The diagram of the proposed system is given in the Fig. 1.

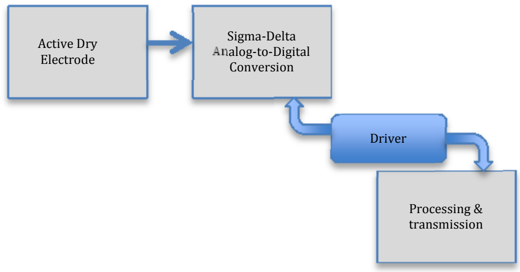

Figure 1: Diagram of the EEG acquisition platform.

The EEG electrodes are connected to the ADC ADS1298. The developed software driver establishes a bidirectional communication between the ADC ADS1298 and the CPTU both for ADC configuration and data acquisition. Once the acquired data arrives to the CPTU memory buffer, they are remotely transmitted to a PC by wireless TCP/IP (Fig.2).

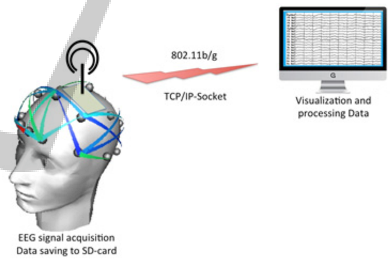

Figure 2: Diagram of the whole EEG acquisition platform and remote PC for signal visualization.

2.1 Processing and Communications Unit

The Processing and Communications unit is composed by Gumstix's Overo^{TM} Fire development platform that includes an OMAP3530-based computer-on-module that delivers ARM cortex-A8 running at 720 MHz, DSP (Digital Signal Processor), 3D graphics acceleration and 802.11b/g wireless communication on-board. Its software development is given by a high-level Open-source Linux operating system, the Angstrom Distribution.

The main functions of this unit are:

- Acquisition data samples from the ADS1298;
- Store data conversions in a SD-card for offline analyses and backup;
- Data wireless transmission by TCP/IP-socket to a PC or a mobile platform.

To accomplish these functions, we developed a linux character driver in the "kernelspace" environment that implements the following tasks: bi-directional communications with ADS1298 and access to the data conversion readings from a "userspace" application. To communicate with ADS1298 we used a SPI Bit-Bang technique to control the required sequence and GPIO (General Purpose Input Output) toggle timings. For synchronization purposes, we developed an interruption in a GPIO that manages the sampling frequency conversions. After programming the ADC's 25 registers, the driver synchronizes readings with an interrupt routine given by ADS1298's DRDY (Data Ready) signal (Fig.3).

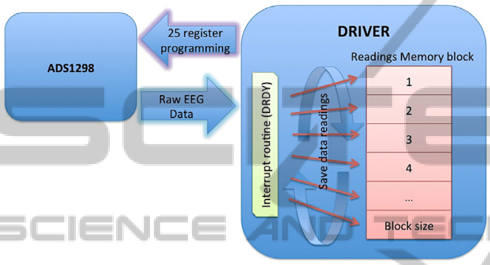

Figure 3: Diagram of the interaction between ADS1298 and communication driver.

The driver also allocates two equally sized blocks of memory: one is used to manage the data readings in every interruption; the other one is a mapped memory block to be used as a "shared memory buffer" with a flag to sign an event occurrence (Fig. 4).

It was developed also a "userspace" application that accesses the "shared memory buffer", saves the data readings in a SD-card and sends them wirelessly by TCP/IP-socket.

The diagram of the application and driver interaction is presented in Fig. 4.

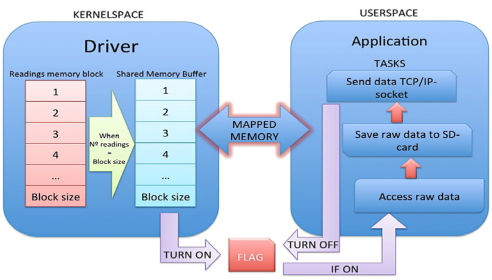

Figure 4: Diagram of application and driver's interaction.

When the number of readings reaches the size of the memory block, the driver locks that process, copies the data to the "shared memory buffer", turns the flag "on" and unlocks again the readings process, all just in time to not compromise the sampling frequency. At the same time, the application checks the flag's state and when it's turned "on", accesses the "shared memory buffer´s" data, saves it in the SD-card, sends it by a socket structure and turns the flag "off". The flag's double access from the application and driver allows them to be synchronized.

The memory blocks can be resized according to the transmission data rate, and restart the whole process.

2.2 Analog-to-Digital Conversion

Sigma-Delta Texas™ ADS1298 performed the analog-to-digital conversion. This component was chosen due to its low power and specific design for bio-signal application features. The ADC features 8 channels with 24 bits resolution, sampling frequencies from 250 SPS to 32 kSPS, instrumentation amplifier with CMRR of -115dB, Programmable Gain Amplifier (PGA) of 1 to 12, Driven-Right-Leg (DRL) input, input noise of 4µVpp (150Hz BW, G=6) and power consumption of 0.75 mW/Channel.

All ADS1298 configurations, sampling rate, PGA, reference, DRL properties, lead-off detection, and others, are accessible through its 25 registers. Through the SPI protocol, we managed to program the ADC with 1000 SPS sampling rate, PGA of 6, internal reference of about ½ of VCC, and DRL switched on.

In continuous reading mode, the ADS1298 provides an output signal timer interrupt (DRDY-Data Ready), which allows the synchronization with the processing unit.

2.3 Active Dry Electrodes

The active dry electrodes were assembled in two parts: the mechanical interface with the scalp and the signal conditioning circuit.

A set of 25 probes, each consisting of a head, a plunger, a spring and a barrel (Fig. 5), interfaces with the patient's scalp. The probes were soldered to a round copper plate of 1cm radius. On the copper plate's top, we soldered a spring clip that is attached to the electronic part of the electrode (Fig.5).

The proposed conditioning signal circuit (Fig. 6) uses a bootstrap technique based on a unity gain buffer (TLC272), first order low-pass filter at 160 kHz and high-input impedance at low frequency signals (<100 Hz) of 900 GΩ as shown in the impedance spectrogram in Figure 7.

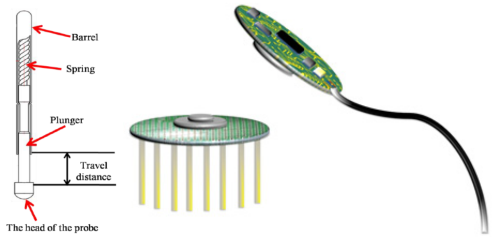

Figure 5: Active dry electrodes schematic.

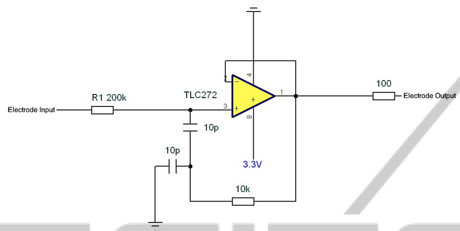

Figure 6: Electrode´s electronic schematic.

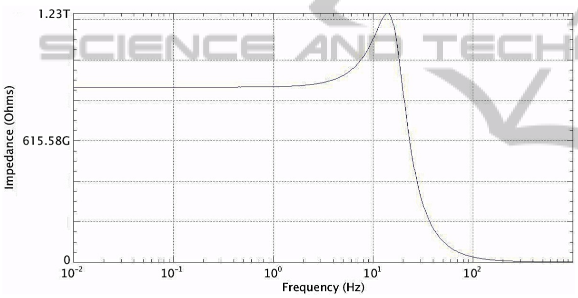

Figure 7: Impedance spectrogram simulated in TINA™ SPICE for the proposed circuit.

3 RESULTS AND DISCUSSION

The presented platform was tested in respect to driver and application performance, communication throughput, power consumption and overall system functionality.

3.1 Performance of Embedded System

The driver showed a SPI clock frequency of 2,5MHz, as a result of a bit-bang technique. The driver spends about 420 µs to read 512 kbits (32 Channels x 16 bits x 1000 samples) for each interruption. The time that the driver needs to copy a set of data from de "readings memory buffer" to the "shared memory buffer" is about 305 µs. In overall, for each interruption given by DRDY, the driver took about 725 µs to read the 512 kbits and copy them to the "shared memory buffer".

The time required for the "userspace" application to access the 512 kb in the "shared memory buffer" is about 244 µs. The read/write speed in the SD-card showed a 470 Mbps, and took respectively 1.4ms to save 64Kb.

Then, the synchronization flag was configured to be turned on after the acquisition of 250 samples (128 kb), 500 samples (256 kb) and 1000 samples (512 kb). For each configuration, we measured the time required for the application to access the "shared memory buffer" and send the data through wireless TCP/IP-Socket. It resulted respectively in 2, 3 and 5 ms, with an average throughput of 12.8 Mbps. In our case the sample block is 1000 samples so the total time of acquisition and transmission is 5 ms.

Other studies applied different wireless communication protocols, like Bluetooth and Zigbee. Usually, these systems provide less than 8 channels, less than 12 bits resolution per channel, and sampling frequencies of less than 256 SPS (Hsieh et al., 2006); (Shao-Yen et al., 2009); (Christoforou et al., 2010). In these cases, the bandwidth necessary to transmit wirelessly the signal data is quite small in comparison to our platform (12.8 Mbps). In studies of epilepsy or sleeping disorders, a higher number of channels, higher resolution (at least 16 bits) and higher sampling rates (at least1000 SPS) are often required.

The power consumption of the proposed platform was measured. As expected, the WiFi communication module is the most expensive part. Acquiring and saving data to a SD-card with WiFi turned off consumes about 200 mAh. When the wireless feature is turned on, the consumption increases up to 400 mAh. Therefore, a 6000 mAh lithium ion polymer battery will be able to power the proposed platform during 30 hours (WIFI off) or 15 hours (WIFI on). In comparison to other systems already reported (Parthasarathy et al., 2006); (Sullivan et al., 2007); (Yates and Rodriguez-Villegas, 2007); (Yazicioglu et al., 2009), our platform consumes more power, due to the usage of a more expensive communication protocol. Although the other platforms may consume less energy, they also provide fewer channels, less signal resolution and lower sampling rates, which renders in a data package a lot smaller than the data package transmitted by the proposed platform. The requirements of high channel density, signal resolution and sampling rate drove the decision of selecting an 802.11g communications infrastructure, even considering the power consumption limitations.

In applications such as long-term monitoring of epileptic patients, the EEG acquisition platform must read the EEG data for periods as long as 24 hours continuously. Because long-term monitoring produces large amounts of data, an event detection algorithm is mandatory. The transmission of selected EEG segments with identified epileptic-like activity allows the reduction of bandwidth and power consumption requirements.

3.2 EEG Data Acquisition Signals

A simple TCP server application that receives data from the platform and saves it in a file was developed. At the same time, KST2 software was configured to open the file and process the visualization in real-time as the data arrives. KST2 is an Open-source software platform for visualization and processing of large-dataset signals.

With the ADC inputs shorted to ground, an input noise of 5,7 µVpp was measured. According to (Usakli, 2010), EEG noise amplitude should be less than 2 µVpp. To overcome this limitation, a new version of the proposed platform will be developed based on an EEG-specific ADC (ADS1299 with 1 µVpp noise input feature) instead of the ADS1298, more suitable for electrocardiogram monitoring applications.

Then the active dry electrodes were plugged to the scalp of a normal subject for EEG signals acquisition. First the subject was asked to be relaxed and keep eyes closed. As a preliminary evaluation in EEG recordings (Webster, 2009), in awaken relaxed subjects, a paradigm of the visual alpha rhythm was employed. The alpha rhythm appears on occipital regions of the scalp when the eyes are closed, and disappears when the eyes are opened. In this experiment, two bipolar dry electrodes (both with and without the electronic active circuit) were placed on the scalp of the subject, on the Cz and O1 positions, forming one EEG channel. The signal was band-pass-filtered (fourth order FIR-Finite Impulse Response) at 0.5-40 Hz and the power spectrum amplitude was calculated. The Figure 8 presents three signals, eyes open (EO), eyes closed (EC) and the respective power spectra. As shown in Fig. 8, the data is comprised in an amplitude envelope of 40 µV.

In Fig. 8.c. we can observe the differences in power spectra of EO and EC signals, specifically in the 8-13 Hz frequencies (alpha rhythm). As expected, the spectrum from the EC segment shows higher power on alpha frequency range than the spectrum of the EO segment.

The time spent to mount the cap and electrodes was significantly less then the traditional wet electrodes.

Finally, the results showed that the proposed system seems to be feasible and satisfies the requirements established at first.

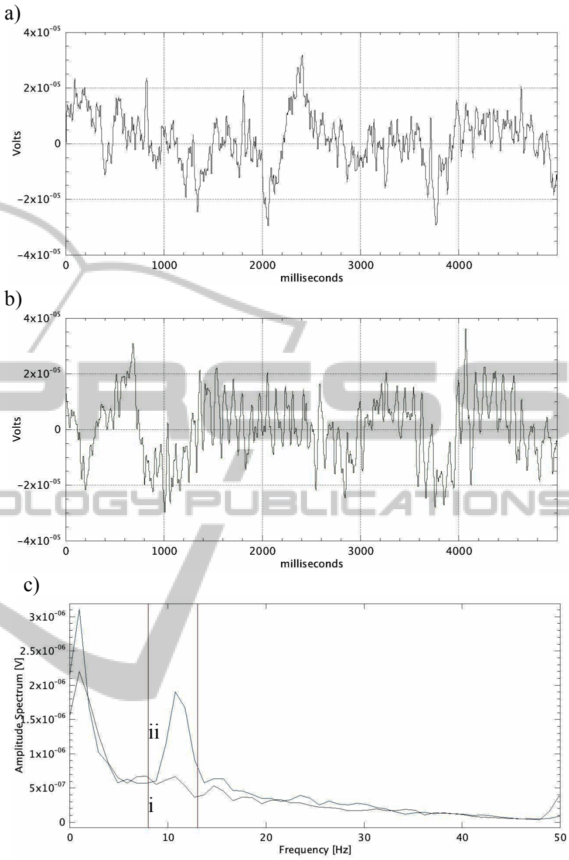

Figure 8: EEG data acquired with a) eyes open (EO), b) eyes closed (EC) and e) (i) EO versus (ii) EC power spectra.

4 CONCLUSIONS

The proposed system integrates the development of EEG dry electrodes, linux embedded system programming of “kernelspace/userspace” and wireless transmission techniques.

The proposed platform integrates an ARM core of OMAP embedded system and interfaces with a sigma-delta ADCs with 16 bits resolution and sampling rate of 1000 SPS. Once the data arrives in the processing unit, they are saved in SD-card and sent by 802.11g TCP/IP-socket protocols with minimum delay.

Although the proposed monitoring system presents higher power consumption than others already reported, it provides higher channel density with more signal resolution and state-of-the-art sampling rate, which establishes an interesting tradeoff between power consumption and system flexibility.

The development of monitoring platforms such as the one proposed challenges the traditional usage of microcontrollers to interface with the ADCs and implement low level hardware operations. Currently, the powerful ARM processors running embedded operating systems can be programmed with real-time constrains at the kernel level to control hardware, while maintaining their parallel processing abilities in high level software applications.

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