A Portable, High Density EEG Acquisition System

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***Abstract*—The search for simple yet precise electroencephalogram (EEG) recording systems has been long desired by researchers in the psychophysiology field. During the last two decades, the advancement of instrumentation amplifiers and microcontrollers has provided the adequate tools for the task. In this paper the design of a portable embedded system capable of recording up to 128 EEG electrodes simultaneously is presented. EEG records are stored in a standard SD flash card and can be transmitted to a host PC with a Bluetooth module. The main features of this device are portability, low power consumption, scalability, and low noise among others. The implemented device may allow psychophysiology researchers to perform non-invasive experiments, where individuals are not tied with an uncomfortable group of cables to amplifiers and test equipment.**

***Index Terms*— electrode, EEG, embedded systems, ERP**

I. Introduction

EEG is the temporal recording of electric potentials, generated by neural activity, over some points of the scalp. This technique has been used for several decades in research because of its temporal resolution and the low cost of the equipment needed. A German physiologist named Hans Berger recorded the first human EEG in 1924 [1]. Even though recording of cerebral activity with few electrodes (less than 16) is widely used in clinical neurology and psychiatry to diagnose seizures or to identify levels of consciousness, research in psychology is frequently carried out using the evoked-related-potentials method (ERP) requiring a much larger number of electrodes (for example 32 to 256). The idea behind this method is to present different stimuli to the subject being studied and to identify the potentials related to the psychological processes that take place during the experiment. In Fig.1 [2] a typical experimental set-up is shown including a helmet with electrodes connected to one (in some cases there can be more than one) multi-channel desktop amplifiers, the data is recorded and then different features are extracted in the digital domain.

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With the increasing interest in high quality multichannel EEG registers, few manufacturers appear to provide the necessary amplifiers, proper AD cards, and specific signal processing software. Some include BioSemi, Gtec, Braintronics, Compumedics. EEG signals have very low amplitude, ranging from 0.5µV to 100µV [1], low frequency from 0 to 30Hz [3], and are sometimes immerse in large common-mode signals coming from external sources like electronic devices, radio stations, and internal sources such as muscular movements.

Fig. 1. Typical EEG set-up by AD instruments.

In a regular multichannel EEG system, there is a single common electrode and the remaining electrodes are considered as a differential signal referred to the first one. An EEG amplifier shall be thus a differential instrumentation amplifier, with very low noise, a large CMRR, and capable of removing large DC component from incoming signals.

Traditional EEG amplifiers include a high performance instrumentation amplifier with high gain, a band-pass filter, and AD. State of the art desktop amplifiers in some cases utilize a 24-bits sigma-delta AD and DC component is digitally removed, this technique is used by BioSemi on their Active Two system. This approach results in very clean EEG registers but on the other hand in the case of 128 channels, 128-24 bits AD running at sampling rate of a few hundred Hz are expensive and consume too much power which does not make them usable in a portable device. The Active Two system, mentioned earlier uses a 24 bit AD on each EEG channel. The approach to be presented in this work resembles the classic topology of EEG systems, using high-gain DC-decoupled amplifiers, taking advantage of modern autozero off the shelve instrumentation amplifiers [4], having only tens µV offset, few µW power consumption, and a reduced footprint. Miniature, low power electronics enable to place a single amplifier on each electrode to obtain also very clean EEG records [4], [5], [6]. Also because of the low power consumption, the records can be stored with a portable unit broadening the experimental possibilities, not restricted to the laboratory [7], [8], [9].

II. The Proposed Acquisition System

A block diagram of the proposed EEG logger is shown on Fig. 2.

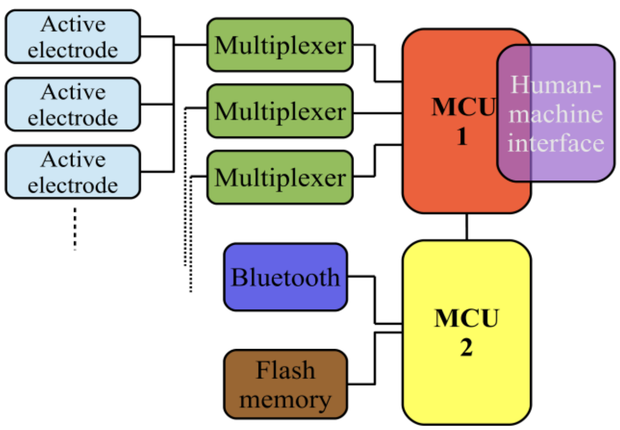

Fig. 2. General block diagram of the system.

A tree-like architecture was chosen. The signal processing chain starts on each of the 128 active electrodes where it is amplified, and each 8 electrodes are connected to a multiplexer-amplifier, then the signal is AD converted using 12bits by a microcontroller (MCU) to finally be stored inside a SD flash memory. The EEG records are also filtered along the signal path. Two low power MCUs are utilized, MCU1 essentially converts the EEG vector using its built-in 12 bit AD and MCU2 controls the flash memory and Bluetooth (user interface).

The system is composed of individual circuits, made on separate printed-circuit-boards (PCB) interconnected through ribbon wires. It is designed to be capable of handling up to 128 active electrodes [4] but the system can be built with fewer if desired. The active electrodes are connected to the multiplexers and the multiplexers are connected to MCU1, the MUX gain as well as the desired channel is selected using the standard Serial Peripheral Interface (SPI). The multiplexers are interconnected using the Daisy chaining configuration. MCU1 and MCU2, which process the information, are located in the same PCB. MCU1 makes 250 analog-digital conversions per electrode each second poling the 128 electrodes. The data is transmitted to MCU2, a few times per second via SPI. MCU2 stores the data in a text file located in the flash memory. A micro Secure Digital (SD) card was chosen for this purpose. Part of the EEG can also be sent via Bluetooth to an external device such us a PC [10].

A brief description of each circuit section follows.

A. *Active electrode*

The active electrodes can be separated in three parts: the electrode itself, and two amplification stages.

Plastic Al/AlCl plated disc electrodes were chosen. These electrodes generate a low half-cell potential, are disposable and inexpensive. A picture of the electrode is shown in Fig. 3. For mechanical robustness the electrodes were attached to a fabric-made cap.

The schematic of the circuit is presented on Fig. 4, the power supplies are not shown.

The first amplification stage is solely implemented with an INA333 instrumentation amplifier manufactured by Texas Instruments, labeled U1 in Fig. 4. R1 and R2 provide a return path for the bias current. The gain is set by properly choosing the RG resistor according to equation 1.

$$G = \;+\; \frac{100k\Omega}{RG}) \qquad (1)$$

This amplifier offers very low noise ($50\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ 1-100Hz), at low frequencies, where EEG components are present. Due to the autozero technique it exhibits a negligible flicker noise [11], and a very low offset of only 20µV. The noise spectral density is almost flat in the range of operation. The high CMRR, above 100dB, is also very helpful because high common mode voltages are frequent due for example to muscle potentials.

The current in the body and conducting gel is due to the flow of ions whereas in the electrode it is due to the flow of electrons, nonlinear phenomenon takes place in the interface. A potential, known as half-cell potential, arises in this interface. The gain was set to 11 in order to be able to handle a half-cell potential of up to ±150mV when powered by a source of 3.3V. This amplifier is cased in an 8MSOP package which is, because of its small size, ideal for our application. The amplifier consumes only 50µA current, resulting an ideal choice for a portable unit in contact with a patient (note 128 amplifiers are used).

The second amplification stage of the active electrodes consists of a dual pole band pass filter-amplifier. The poles were set to 0.5 and 30Hz. The band-pass gain is 100. For this stage, an operational amplifier (OPA171 by Texas Instruments labeled as U2 in Fig. 4) and two RC networks on an inverter configuration were used. The first RC (C1 and R3 in Fig. 4) imposes a zero at, s=0, which blocks the DC components (half-cell potential). The second RC (C2 and R4 in Fig. 4) provides the low-pass characteristic which removes undesired noise and also serves as an anti-aliasing filter. The OPA 171 consumes 475uA, which result a total of 525uA of quiescent current each active electrode.

The input noise of the OPA 171 is lower than $200\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$

within the band of interest (1-100Hz), this yields a total input noise lower than $54\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$ for the active electrode in the band of interest. The total gain of the active electrode is 1100. A picture of the miniaturized electrode's amplifier can be seen in Fig. 5.

Fig. 3. Al/AlCl plated plastic disposable electrode.

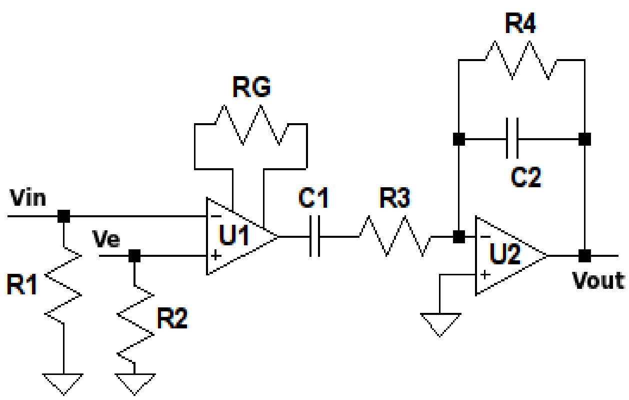

Fig. 4. Schematic of the active electrode's amplifier.

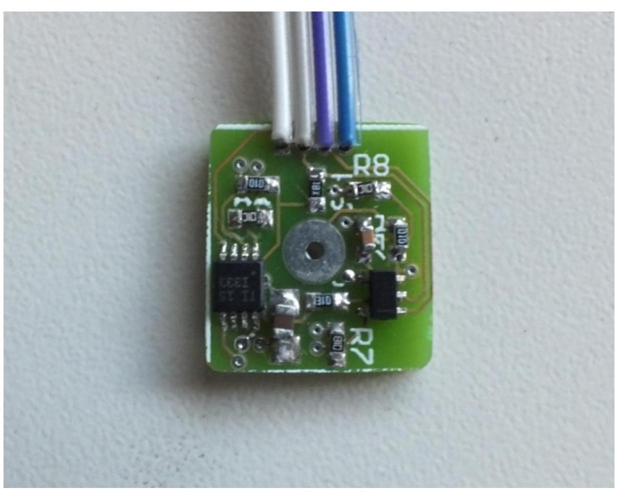

Fig. 5. Active electrode PCB.

B. Multiplexer

The multiplexer is a Microchip MCP6S28. It switches between eight input electrodes and also amplifies the signal. The gain and the channel selections are digitally controlled via SPI. The gain can be set to 1, 2, 4, 5, 8, 10, 16, or 32. Combined with the active electrode a total gain of 35200 is achievable. A picture of the multiplexer can be seen in Fig. 6.

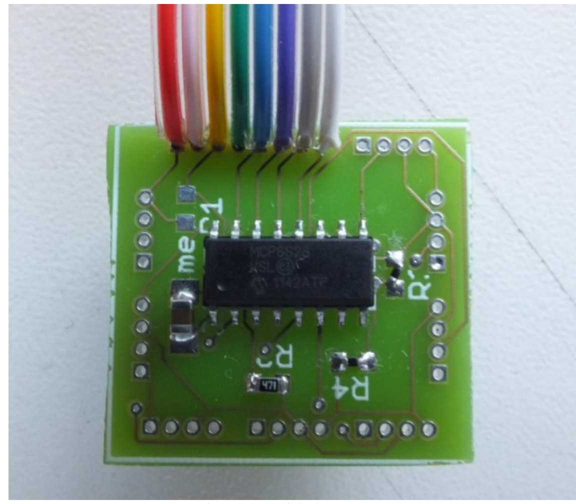

Fig. 6. Multiplexer PCB.

C. Microcontrollers

This circuit section contains the two MCUs labeled as MCU1 and MCU2 in Fig. 1. Both are Microchip PICs 24FJ128GA306, and are placed in the same PCB. This MCU model belongs to the Extreme Low Power (XLP) series well known for their low current consumption.

MCU1 is utilized for various purposes, it switches between the electrodes in a periodical sweep. Each electrode is read 250 times per second. It performs the AD conversion of each sample using the built-in 16-channel - 12 bit analog-digital converter. The AD has a maximum speed of 200k samples per second and has 11.3 effective bits. Six LEDs are connected to this MCU. These LEDs together with three buttons serve as the human-machine interface (HMI) shown in Fig. 1. The LEDs indicate the gain, the system state, and the Bluetooth state.

The samples are sent from MCU1 to MCU2 via SPI. MCU2 saves the data in a text file located in the micro SD card. The micro SD card is placed on another PCB, see Fig. 7. MCU2 also sends some samples of the signals to the Bluetooth unit if the unit is active.

Both MCU's run with an external crystal oscillator at 32MHz. A picture of the upper side of the MCU PCB can be seen in Fig. 7 and a picture of the bottom side in Fig. 8.

D. Storage and communication

The EEG data is stored in the micro SD card to be later processed with a specific software package, at the present custom Scilab sripts are being employed. On the other hand, the purpose of the Bluetooth module is to monitor the channels while recording [12] to check the proper installation of the electrodes. Sometimes the electrode does not make good contact with the scalp and in this case, more conductive gel should be applied or the skin should be cleaned.

To save power and bandwidth, not every sample is sent via Bluetooth. One out of every five samples is sent, which equals to fifty samples per second per channel allowing the visualization of up to 25Hz signals according to Nyquist rate.

A picture of the communications/power PCB can be seen in Fig. 9.

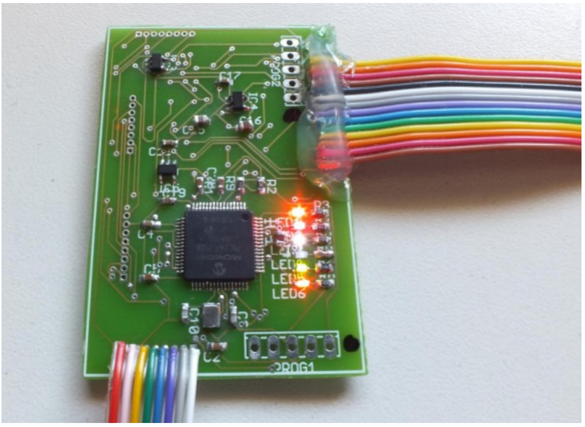

Fig. 7. Top view of the PCB containing the MCUs.

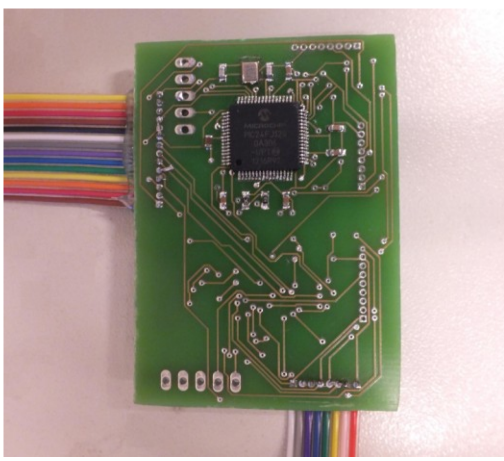

Fig. 8. Top view of the PCB containing the MCUs.

E. Power supply and voltage reference

Every active component of the circuit is powered by one of three LD2981 3.3V linear-low-dropout regulators (LDO). These LDOs can handle up to 100mA output current. One LDO is reserved for the Bluetooth module because it can consume up to 50mA. Two extra LDOs were used to separate digital and analog supply voltages, to avoid high frequency switching present on both MCUs inducing noise in sensible analog circuits. Each LDO is powered by 3 AA batteries. The system was designed to have a ten hour autonomy or longer. The system was tested to run for 15 hours with the Bluetooth module transmitting, using 2000mAh AA alkaline batteries.

A high precision voltage reference was chosen for the AD converter reference. The voltage reference used is the LM4132 which has a 3V output and approximately 1.5mV of tolerance. This guarantees that the accuracy of the least significant bit of the AD converter.

Table 1 shows the current consumed by each device as well as the total consumption. The Bluetooth module was considered to be transmitting.

TABLE 1
Total current consumption when the Bluetooth is transmitting.

Device (quantity)	Individual current	Current
INA333 (128)	50uA (quiescent)	6.4mA
OPA171 (128)	475uA (quiescent)	60.8mA
MCP6S8 (16)	1mA	16mA
24FJ128GA306 (2)	5mA	10mA
Voltage reference (1)	60uA	60uA
LED (7)	2ma	14ma
Bluetooth transmitting (1)	30mA	30mA
LDO (3)	800uA	1.6mA
Total		128.86mA

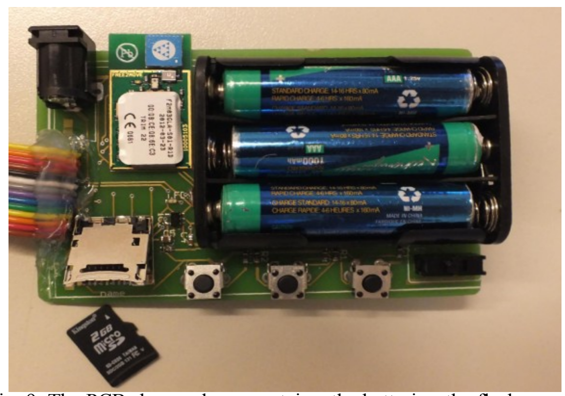

Fig. 9. The PCB shown above contains: the batteries, the flash memory, 3 buttons, 1 switch, one led and the Bluetooth module (not installed).

F. Monitoring software

To visualize the EEG signals while installing the electrodes on the subject to be studied, a PC software was developed. The programming language chosen was C#. The software is used to establish the wireless connection, change the serial communication parameters and display the signals. To make the communication simpler, a wireless UART connection was chosen. A picture of the graphical user interface can be seen in Fig. 10.

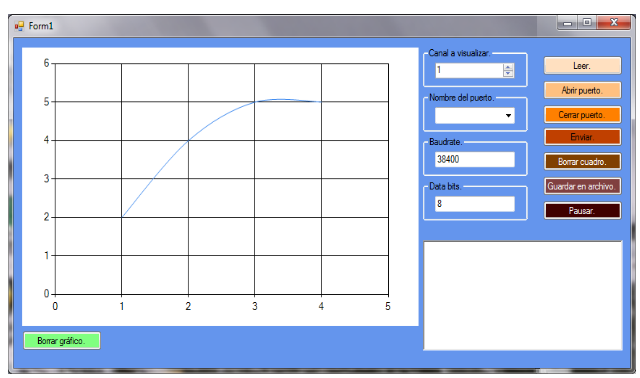

Fig. 10. PC graphical user interface.

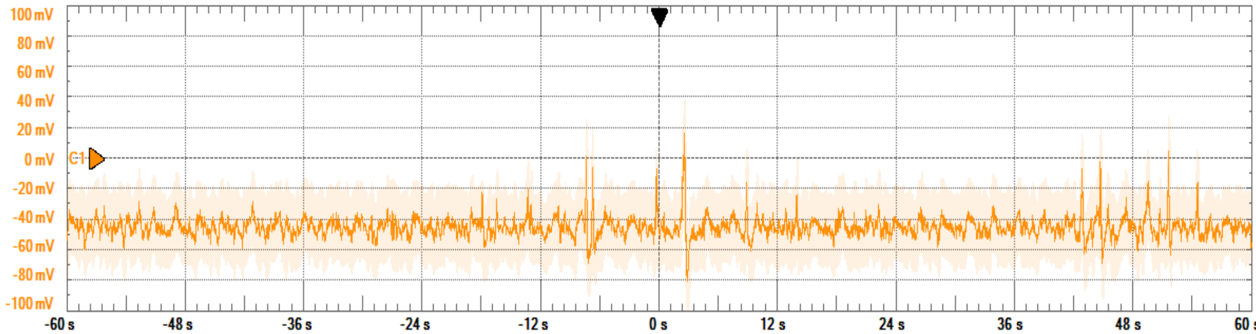

Fig. 11. Eye Artifacts.

III. Results

A recording made on a real person is shown in Fig. 11, the electrodes were placed over the frontal lobe which makes the eye artifacts easily recognizable because of their high magnitude compared to that of the EEG signals, later computer aided processing can reduce the noise produced by muscle movements. The gain was set to 1100 for this experiment. The eye artifacts seen on Fig. 12 have an amplitude between 50µV and 100µV.

The set-up used for the recording shown in Fig. 12 was a sine wave generator connected to the active electrode and what can be seen in the picture are the different amplification levels registered. Alpha waves, which are the most common waves registered in a relaxed person have a frequency in the range of 8 to 13Hz [1], this is why a sine wave with a frequency of 10 Hz was used. The amplitude of the signal was 45µV.

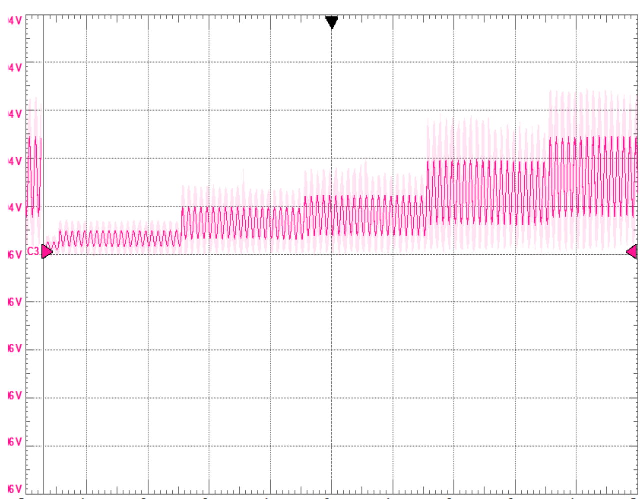

Fig. 12. Output of the multiplexer when placed a sine wave in the electrode and the gain swept form 1 up to 16.

IV. Conclusion

The design and architecture of a portable EEG system has been presented, including some preliminary results. The design was focused on portability, low power consumption and low noise. Other features like high frequency sampling, which is desirable for studies involving FFTs were not part of the objectives. State of the art electronic components such as the INA333 and the XLP MCUs were used. Modern communication technologies were also employed like a Bluetooth link and a high capacity flash storage. The results show that the proposed system is capable of recording small EEG signals in the range of microvolts and low frequencies (below 50Hz).

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