A Multimodal Low-cost Platform for Acquisition of Electrophysiological Signals Interfacing with Portable Devices

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Abstract: Advances in low-voltage integrated circuits have enabled the development of low-cost, low-power, and downsized portable instrumentation. In the biomedical field, mobile sensing platforms provide an efficient way to monitor the physical condition of a subject. Moreover, these platforms provide an input for human-computer interaction. We developed a low-cost platform that can be adapted to acquire different electrophysiological signals, and interface with portable devices for storing, processing, and displaying of data. The developed platform was used to acquire electrocardiography (ECG), electromyography (EMG), electroencephalography (EEG), and electrooculography (EOG) signals, and the results were compared with signals obtained with the benchmark BIOPAC system. For the same frequency bands, results show that our portable platform was able to acquire electrophysiological signals with similar accuracy as those acquired with the BIOPAC system. Due to its simplicity, low-cost design, and easy implementation, the developed platform suits researchers, developers, and hobbyists, in the fields of physiological monitoring, human-computer interaction, and perceptual computing.

1 INTRODUCTION

Recent advances in the miniaturization and availability of portable biomedical devices have shown to improve healthcare quality (West, 2012). The application of mobile health monitoring systems in ambulatory, emergency, home, and point-of-care settings provide a greater access to physiological data, leading to improved therapeutic decision-support, and decision-making. Similarly, rehabilitation procedures (Bin Ambar, 2012)(Roy, 2009), physiology-driven robotics (Yin et al., 2012), and human-computer interaction (Zheng, 2009)(Kim, 2004)(Andreoni et al., 2007) should benefit from the use of portable biomedical devices. The wide range of applications promotes further research in the area of system design and control for increased reliability, multimodality integration, and easy implementation and dissemination.

Most of commercially available biomedical portable devices are dedicated systems and usually focus on only one kind of electrophysiological signal (e.g. (Emotiv, 2013)(Alive Technologies, 2013)). Although beneficial, the use of such devices is confined to specific tasks and applications. On the other hand, multimodal acquisition systems on the market (e.g. (PLUX wireless biosignals, 2013)(Shimmer, 2013)) are designed based on two components: (1) a main unit for data storage, transmission, and processing, and (2) dedicated sensors for the acquisition of specific electrophysiological signals. Either single or multimodal approaches lead to unnecessary costs, as in the first case a completely different platform is needed for each electrophysiological signal to be acquired, and in the second case, different sensors are required. However most electrophysiological signals require the same acquisition steps: differential amplification, filtering, and additional amplification, depending on the target signal (Webster, 2010). Therefore, a single customizable platform for the acquisition of the different electrophysiological signals would be desirable and more cost-effective.

This work illustrates the development and imple-

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mentation steps of a low-cost multimodal acquisition platform, which interfaces with portable devices, such as laptops, tablets or smartphones to collect, record, process, and display electrophysiological data.

2 MATERIAL AND METHODS

The developed platform is comprised of three main blocks: an analogue circuit, an Arduino MEGA ADK board, and a mobile platform.

The analogue circuit was simulated in a general-purpose circuit simulation program (B^2Spice, Beige Bag Software), and implemented in a printed circuit board (PCB) using CadSoft EAGLE PCB design software. This platform was then connected to the Arduino MEGA ADK board, which was programmed to collect the signal, and connect to the mobile platform for data processing.

In this section, we will discuss in detail the stages of circuit development and implementation, and the interface with the Arduino and mobile platforms.

2.1 Analogue Circuit

The main analogue circuit is comprised of 8 sub-circuits, Figure 1: electrical protection circuit; differential (1st stage) amplification with a Driven Right Leg circuit (DRL); low-pass filter; 2nd stage amplification; notch filter; high-pass filter; 3rd stage amplification; and voltage offset circuit.

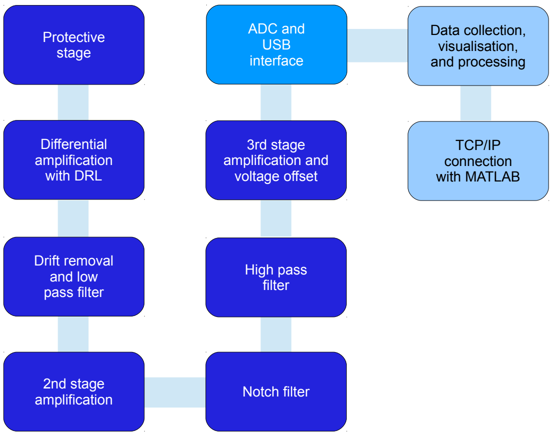

Figure 1: Pipeline of the developed multimodal acquisition platform. Dark blue stages correspond to the analogue circuit, medium blue stages to the Arduino Mega ADK board, and light blue stages to the mobile platform.

2.1.1 Circuit Development

The first sub-circuit (Figure 2) attenuates high frequencies present in the acquired signal, using a passive low-pass filter. Such circuit aims to reduce the radio-frequency (RF) noise induced in the cables, and its propagation from the electrodes to the analogue circuit. Additionally, this sub-circuit protects the user against electrical shock (high voltage) by means of two inverted diodes. Diodes are analogue components that only allow the passage of signal if the signal goes in the diode forward direction and if there is a differential potential over 0.7V at the diode terminals. Using this configuration, signals over +0.7V and under -0.7V flow directly to ground, while signals within these limits are not affected. Note that this is a redundant protective stage, and that the user should not be at any time connected directly to the main power supply. For example, if the computer is connected to the main power supply, and the acquisition platform is connected to the computer, the user is also connected to the main power supply. Thus there would be a high risk of electrical shock in the presence of an electrical discharge followed by failure of the protective circuit. In this case, the main protective stage is therefore the use of batteries in the acquisition device.

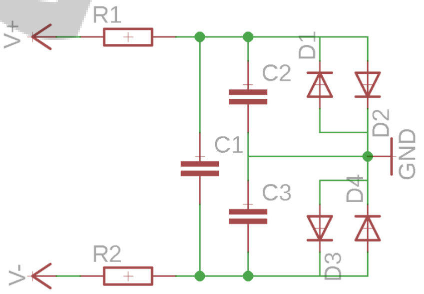

Figure 2: Protective sub-circuit and RF removal.

The sub-circuit following the protective stage circuit is responsible for the acquisition and amplification of the low amplitude electrophysiological signals, which range from microvolts to millivolts (Figure 3). The typical design approach is to use an instrumentation amplifier (IA) that multiplies the difference between the two inputs, typically between 10 and 100, reducing the common-mode noise. For this type of application, a low-noise, low-drift and low-power consumption IA is required, such as the INA114, which is widely applied in medical instrumentation (Burr-Brown Corporation, 1998). To improve the common-mode noise rejection a driven-right-leg (DRL) circuit may be used. In this system, the ground electrode is connected through a feedback loop to the IA, instead of directly to the reference input of the IA. This circuit feeds the user with a small current that is the inverse of the common-mode noise (obtained from the IA), therefore reducing the overall noise.

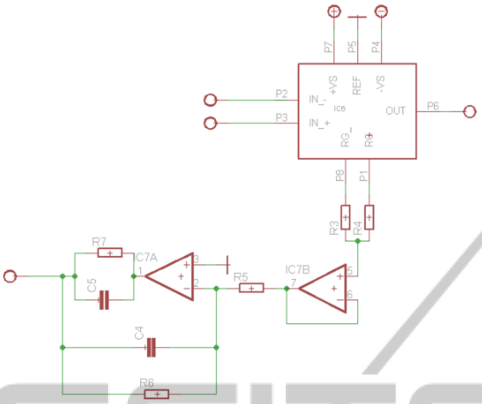

Figure 3: Differential amplifier sub-circuit with DRL feedback.

Although the chosen IA has low drift voltage ($50\mu V$ maximum for the INA114), this offset may still lead to the circuit malfunction after the amplification blocks. For example, in a typical EEG board, an amplification between 1000 and 100000 is required, therefore the offset is amplified from $50\mu V$ to $5V$. To account for this effect, a passive high-pass filter (HPF) with a very low cut-off frequency can be used, blocking continuous current while allowing variable current to pass. Next to this circuit, a low-pass filter (LPF) transparent to the frequencies below the frequencies of interest is used (Figure 4).

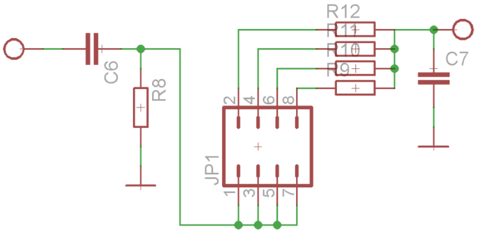

Figure 4: Offset removal and LPF with variable cut-off frequency sub-circuits.

As the frequencies of interest vary with the target electrophysiological signal (Table 1), a four-input one-output switch was used for the purpose of achieving multimodality. Hence either electrocardiography (ECG), electromyography (EMG), electroencephalography (EEG) or electrooculography (EOG) signals can be recorded adjusting the values of the resistors, in order to change the value of the LPF cut-off frequencies.

As the filtered signal still has a very low amplitude, a second amplification stage is needed (Figure 5). For the same reasoning used for the LPF, a four-input one-output switch was used to increase differently the amplitude of the signal according to the electrophysiological signal of interest. For example, the EEG signal has a very low amplitude and will need higher amplification when compared to an ECG signal, which can have an amplitude 1000 times higher (Table 1).

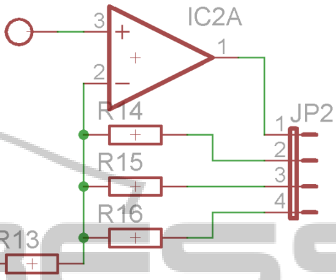

Figure 5: Variable second stage amplification sub-circuit.

The next circuit module is an active notch-filter (NF), designed to attenuate the electric grid noise at 50/60 Hz[1]. For this purpose, a band-stop filter centred at 50Hz was implemented according to the schematic in Figure 6. As the main hub noise has frequencies in the range of those of electrophysiological signals, a switch was implemented to turn on and off the notch filter, depending on the application.

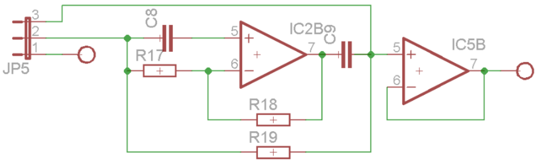

Figure 6: Main hub (50Hz) notch filter sub-circuit.

At this stage, the acquired signal has already been filtered for low-frequencies and main hub noise, as well as amplified. Yet, an HPF is required to reduce the noise which has frequencies above the frequencies of interest. For the purpose of generalization and customization, the HPF was also adapted for different inputs (Figure 7).

Although the analogue signal could already be passed to a microprocessor for analog-to-digital conversion (ADC), and passed to a mobile device or laptop via USB or Bluetooth connection, programming a microprocessor is not straightforward. An easy way to do it is to use an Arduino platform, which is our purpose. Therefore two final analogue steps are required to use the Arduino board (Figure 8). Firstly,

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[1] EU and US mains frequency, respectively.

Table 1: Frequency and amplitude ranges for ECG, EMG, EEG, and EOG(National Instruments, 2013).

Signal	Frequency range (Hz)	Amplitude range (mV)
ECG	0.01 – 300	0.05 – 3
EMG	50 – 3000	0.001 – 100
EEG	0.1 – 100	0.001 – 1
EOG	0.1 – 10	0.001 – 0.3

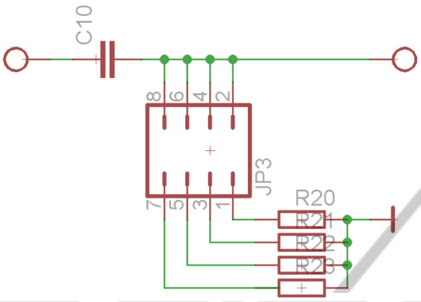

Figure 7: High-pass filter with variable cut-off frequency sub-circuit.

a third amplification stage is required to increase the signal amplitude of the acquired signals to the 0-5V interval, specially for the EEG signal. Secondly, a voltage offset circuit is required to translate the signal to positive voltages only.

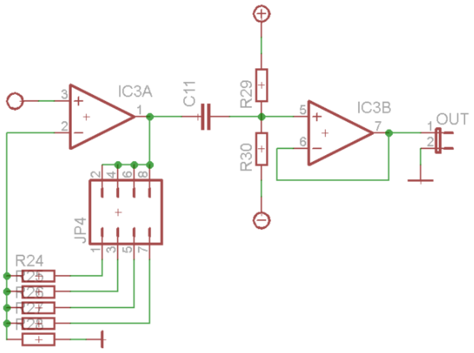

Figure 8: Third stage amplifier and voltage offset sub-circuits.

2.1.2 PCB Implementation

After having the circuit design completed, tested, and simulated, it was implemented in a printed circuit board (PCB). The main issue in this stage is to occupy the least possible space and avoid acute angles - to reduce induced noise -, whilst trying to have few crossing connections. Therefore the components are placed in the board and organised in a way such that connections between components have the shortest length possible. Ground connections were performed with a polygon instead of lines, such as to reduce the overall noise (by increasing the ground area). The final manufactured board has 52mm height and 92mm width.

In the developed board (Figure 9) a two-layer PCB was implemented. This configuration was chosen because it is the standard used by many PCB manufactures, and therefore reduces costs of production.

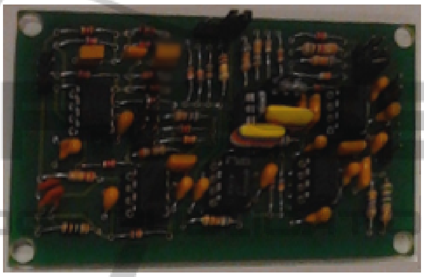

Figure 9: Multimodal electrophysiological signal acquisition PCB board (with components). The board has 52mm height and 92mm width, and two layers.

2.2 Arduino Platform

The analogue board was connected to an Arduino MEGA ADK platform in order to use its ADC. The Arduino MEGA ADK board has 54 digital input/output pins, of which 15 can be used as Pulse Width Modulation (PWM) outputs, 16 analogue inputs, 4 UARTs (hardware serial ports), a 16MHz crystal oscillator, and a USB connection. It has a 10-bit resolution, and is able to acquire analogue signals at a maximum sampling frequency of 10kHz, therefore suitable for handling biomedical data.

Due to the high number of analogue inputs, the Arduino platform can be easily set up for additional acquisition boards, i.e. channels; this improves the customization of the device, and facilitates the integration of different platforms.

The USB host interface given by MAX3421E IC allows the connection, and subsequent interaction, of the Arduino board with any type of device that has a USB port. For example, it may be used to interact with many types of phones, control Canon cameras, or interface with keyboards, mouses and games controllers as the Wii remote and PS3 controller.

The Arduino programming language is an implementation of Wiring, a similar physical computing platform, which is based on the Processing multimedia programming environment. Arduino programs are written in C/C++. The Arduino IDE comes with the software library **Wiring** from the original Wiring project (Wiring, 2013), which makes many common input/output operations easier. To make a runnable cyclic executive program developers only need define two functions: `setup()` - a function run once at the start of a program that can initialize settings; and `loop()` - a function called repeatedly until the board powers off.

2.3 Mobile Platform

To communicate with the Arduino board, a desktop computer or mobile platform can be used. The interface is programmed such as to receive the digital signal from the Arduino via microUSB connection, and to store the data either in a desktop hard disk, or in a mobile internal disk or SDcard. In a typical laptop-Arduino connection, high level programming languages (e.g. MATLAB) can be used to decrease programming hassle. This becomes even more important as more complex applications are needed, such as real-time processing or visualization.

The ability to interface with mobile platforms brings full portability to the acquisition device, yet usually at the expense of more complex programming software. On the other hand, high level programming languages, e.g. Octave and MATLAB, and typical desktop operating systems (OS), e.g. Linux, are also being implemented in mobile platforms due to their increased processing capabilities. These advances open new possibilities of mobile communication for users with low programming skills, and for the development of general applications, opposed to OS-specific applications.

Based on these ideas, a mobile communication script was developed to store the data acquired with the Arduino platform in the mobile platform, to be further processed and visualized with the GNU Octave application, or with MATLAB via computer with a TCP/IP connection. It is important to note that currently there is no direct communication from the Arduino platform to the mobile Octave application, and the mobile MATLAB software only works through cloud computing. An example of communication from the Arduino platform to MATLAB is presented below.

```
unsigned long time;
int sensorValue;
int pos;

void establishContact() {
  while (Serial.available() <= 0){
    Serial.println('A');
    delay(300);
  }
}

void setup(){
  Serial.begin(115200);
  establishContact();
}

void loop(){
  time = millis();
  Serial.print(time);
  for (pos=0; pos<10;pos++){
    Serial.print(',');
    sensorValue = analogRead(A0);
    Serial.print(sensorValue);
  }
  Serial.println(',');
}
```

arduino_code.c

```
s1 = serial('COM#');
s1.BaudRate=115200;
set(s1, 'terminator', 'LF');
fopen(s1);

w='B';
while w~='A'
  w=fscanf(s1,'%s');
  fprintf(s1,'%s\n','A');
end

acq_time=zeros(1,1000000);
acq_data=zeros(1,1000000);
pos=1;
while 1
  siz=10;
  raw_data=fscanf(s1);
  delimiter=',';
  raw_data = textscan(raw_data, '%d
      ','delimiter',delimiter);
  raw_data=double(raw_data{1});
  acq_data((pos-1)*siz+1:pos*siz)=
      all_data(2:siz+1)*5/1024;
  acq_time(pos)=all_data(1);
  pos=pos+1;
end
fclose(s1);
```

matlab_code.m

2.4 Set-up

The developed platform was used to acquire: a lead I ECG; an EMG of the brachioradialis muscle contraction; an EEG of the occipital cortex; and an EOG of the horizontal direction for a reading task. Recorded signals were then compared to the corresponding signals obtained with the commercially available benchmark BIOPAC system to evaluate the performance of the developed platform. All acquisitions were performed with one channel - three electrodes: positive, negative and reference. The platform was supplied with a dual voltage source of 9V. In addition, the high-pass and low-pass filters' cut-off frequencies and amplification gains were adjusted to those of interest for acquiring ECG, EEG, EMG, and EOG signals (Webster, 2010).

3 RESULTS

The multimodal platform is shown in Figure 10. The communication of the analogue circuit with the Arduino Mega ADK platform was performed through jumper cables (not shown in Figure 10). Other interface options could have been implemented, such as adapting the analogue circuit into an Arduino shield. Such approaches are easily implemented as both platforms have roughly the same size. Further considerations have been made to implement the proposed platform through surface-mount technology to decrease size or to provide additional channels within the same size. Although such approach is highly recommended in commercial devices it may impair the implementation for researchers and hobbyists with low practice in soldering electronic circuits.

The communication of the Arduino with the mobile platform is performed through a microUSB cable. This approach leads to simpler hardware and software implementation. A wireless communication between the two could be implemented without having to re-design the analogue circuit: one could combine a Bluetooth shield with the Arduino platform.

The acquired ECG, EMG, EEG, and EOG signals obtained with the developed acquisition platform are shown in Figure 11 (left) as well as the corresponding signals obtained with the BIOPAC system (right). The cut-off frequencies of the low-pass (fcLP) and high-pass (fcHP) filters were adjusted, respectively, to fcLP = 116, 248, 116, 48 Hz and fcHP = 0.04, 16, 0.16, 0.05 Hz. For the BIOPAC platform the cut-off frequencies of the LPF and HPF were selected, respectively, to fcLP = 100, 250, 100, 30 Hz and fcHP = 0.05, 30, 0.5, 0.05 Hz. Results show that the different signals present similar traces for both acquisition platforms. Moreover a higher signal-to-noise ratio is observed for the ECG signal of the proposed system when compared to the BIOPAC platform, while for the EMG and EOG a lower signal-to-noise ratio is verified.

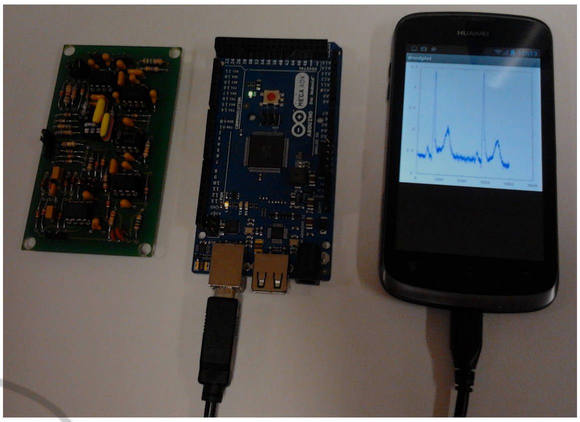

Figure 10: Developed multimodal acquisition platform. From left to right: Analogue board, Arduino MEGA ADK and mobile platform (connections between the Analogue board and the Arduino MEGA ADK, and battery power supply not shown for clarity).

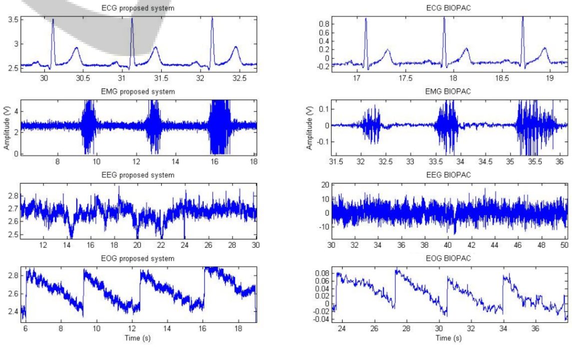

Figure 11: Acquired signals. ECG (first row), EMG (second row), EEG (third row) and EOG (fourth row) signals acquired by the developed platform (left) and the BIOPAC system (right).

An estimation of the cost of the proposed prototype is presented in Table 2, for a 1- and 4-channel acquisition platform. The predicted cost for both the single, and multichannel acquisition platform is $\leq$ 250€, thus presenting a low-cost approach to multimodal acquisition systems. Note that the price does not scale linearly with the number of channels, even for prototyping, because of the fact that one Arduino Mega ADK is able to simultaneously acquire up to 16 channels, requiring no additional boards, and a higher number of PCB boards is cheaper.

These results suggest that accurate and low-cost

Table 2: Approximated cost estimation for a 1- and 4-channel acquisition board in euros (€).

Component	1-channel acquisition board	4-channel acquisition board
Instrumentation amplifier (INA114AP)	10€	40€
Other through hole components	15€	60€
PCB Board	35€	100€
Arduino Mega ADK	50€	50€
Total	110€	250€

multimodal solutions can be developed for biomedical signal acquisition, without requiring expertise in both electronics and programming. As previously suggested, some enhancements of this platform can be performed to increase robustness, reliability, and portability, making this system useful for advanced biomedical applications at the expense of higher knowledge of electronics and programming.

4 CONCLUSIONS

A low-cost, simple and easy to implement portable multimodal acquisition platform was developed using an analogue circuit, an Arduino MEGA ADK and a mobile platform. The developed platform was able to acquire different electrophysiological signals, such as ECG, EMG, EEG, and EOG, by changing the low-pass and high pass filters' cut-off frequencies and amplification gain.

Two further developments to increase portability and usability of the acquisition platform were foreseen. Firstly, the modification of the design of the analogue platform in order to use it as an Arduino shield. This modification allows the user to add extra analogue acquisition platforms, up to 15 additional boards for the Arduino Mega ADK, such that different electrophysiological signals can be acquired simultaneously (e.g. 16 EEG channels, or 8 EEG channels + 8 EMG channels). Secondly, the replacement of manual switching to digital switching. Such conversion allows the user to digitally control the acquisition parameters without physical interaction, allowing for the abstraction of the electronics, and enhancing usability.

The developed platform is ideal for researchers, developers and hobbyists, as it is portable, low-cost, easily adaptable to acquire various physiological signals, and scalable/customizable in order to acquire a larger number of channels. Due to its characteristics, the developed platform is suitable for application development in the fields of physiological monitoring, human-computer interaction, and perceptual computing.

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