BITalino: A Novel Hardware Framework for Physiological Computing

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Abstract: Physical computing has spun a true global revolution in the way in which the digital interfaces with the real world. From bicycle jackets with turn signal lights to twitter-controlled christmas trees, the Do-it-Yourself (DiY) hardware movement has been driving endless innovations and stimulating an age of creative engineering. This ongoing (r)evolution has been led by popular electronics platforms such as the Arduino, the Lilypad, or the Raspberry Pi, however, these are not designed taking into account the specific requirements of biosignal acquisition. To date, the physiological computing community has been severely lacking a parallel to that found in the DiY electronics realm, especially in what concerns suitable hardware frameworks. In this paper, we build on previous work developed within our group, focusing on an all-in-one, low-cost, and modular biosignal acquisition hardware platform, that makes it quicker and easier to build biomedical devices. We describe the main design considerations, experimental evaluation and circuit characterization results, together with the results from a usability study performed with volunteers from multiple target user groups, namely health sciences and electrical, biomedical, and computer engineering.

1 INTRODUCTION

Nowadays, low-cost hardware is driving innovation in ways never before seen; in his book "The Medici Effect", Frans Johansson states that *"When you step into an intersection of fields, disciplines, or cultures, you can combine existing concepts into a large number of extraordinary ideas"* (Johansson, 2006), which is partially the secret behind this ongoing revolution. Physical computing has grown as a field in its own right (O'Sullivan and Igoe, 2004), and so far it has mostly been characterized by the use of hardware designed to deal with requirements that are not completely compatible with the needs of biosignal acquisition, such as relatively high tolerance to noise, low sampling rates, no need for galvanic isolation, among others.

While physical computing has the Arduino and its successors and predecessors as stepping stones, the physiological computing community has been mostly lacking a comparable tool. Biosignals have very specific requirements, and many projects end up heavily bounded by the high cost and limited access to suitable hardware materials. Building on the guiding principles of existing Do-it-Yourself (DiY) hardware platforms, in this paper we focus on BITalino; a low-cost and highly versatile hardware framework designed to allow anyone, from students to professional app developers, to create projects and applications with physiological sensors (Figure 1).

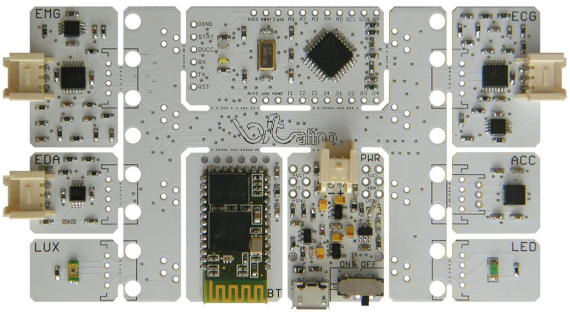

Figure 1: BITalino biosignal acquisition board.

The rest of the paper is organized as follows: Section 2 describes the background and related work; Section 3 details the overall architecture of BITalino; Section 4 presents the analog biosignal acquisition blocks and their benchmarking; Section 5 highlights the results of a usability study performed with multiple potential target user groups; and finally Section 6 summarizes the main conclusions and future work.

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2 BACKGROUND

Several authors have delved into the problem of making biosignal acquisition hardware tools accessible to anyone. One of the most comprehensive work known to date is the Open EEG Project[1]. This is a community driven effort to make affordable hardware and software tools available for anyone with interest in working with Electroencephalography (EEG), however it has been mostly focused on EEG data and is supported by technologies currently outdated.

With the advent of open source hardware platforms such as the Arduino (Banzi, 2009; Buechley and Eisenberg, 2008) or Raspberry Pi, efforts have been made to extend their capabilities to biosignal data acquisition. OLIMEX[2] created a low-cost sensor shield for Electrocardiography (ECG) and Electromyography (EMG), Advancer Technologies has devised the MuscleSensor[3] for EMG; the Pulse Sensor[4] for Blood Volume Pulse (BVP) data acquisition is yet another example. All of these are focused on very specific modalities and limited to the actual analog front-end for the sensors.

The main advantage of the Arduino-based approaches is the extremely low cost, given that from $25 anyone can buy an Arduino board. Nonetheless, they are designed to deal with very simple requirements for example in terms of sampling rate accuracy and tolerance to noise. Previous work from our group has actually attempted to use an Arduino Pro Mini board for ECG data acquisition, however, experimental results clearly demonstrated several of these shortcomings (Alves et al., 2013).

More recently, Libelium[5] has proposed a multimodal sensor platform for e-Health, which includes sensors for BVP, Blood Oxygenation (SpO2), respiration, temperature, ECG, glucose, Accelerometry (ACC), Electrodermal Activity (EDA), and blood pressure. The advantage of this platform is the fact that it integrates multiple sensors with embedded processing algorithms. Still, most of the sensors do not provide access to raw data, all the sensors are bundled as a single unit (providing low flexibility for custom hardware configurations), and at ≈$500 it is not affordable for everyone.

Despite the work developed so far, the physiological computing community is still lacking adequate hardware frameworks, leading our group to develop preliminary work on hardware for multimodal biosignal acquisition (Guerreiro et al., 2013). As highlighted in our previous work, further research on the analog front-end of the voltage differential sensors, namely the ECG and EMG, was needed, and several usability issues related with the form factor ultimately limited the scope of application of our initial proposal.

In this paper we address the main problems found in the state-of-the-art, and present a completely revised approach to BITalino, which has resulted in the first low-cost, all-in-one, flexible and easy-to-use hardware framework for physiological computing.

[1]http://openeeg.sourceforge.net/doc/

[2]http://www.olimex.com/SHIELD-EKG-EMG.html

[3]http://www.advancertechnologies.com/

[4]http://pulsesensor.com/

[5]http://www.libelium.com/130220224710/

3 ANATOMY OF A BITALINO

3.1 Design Principles

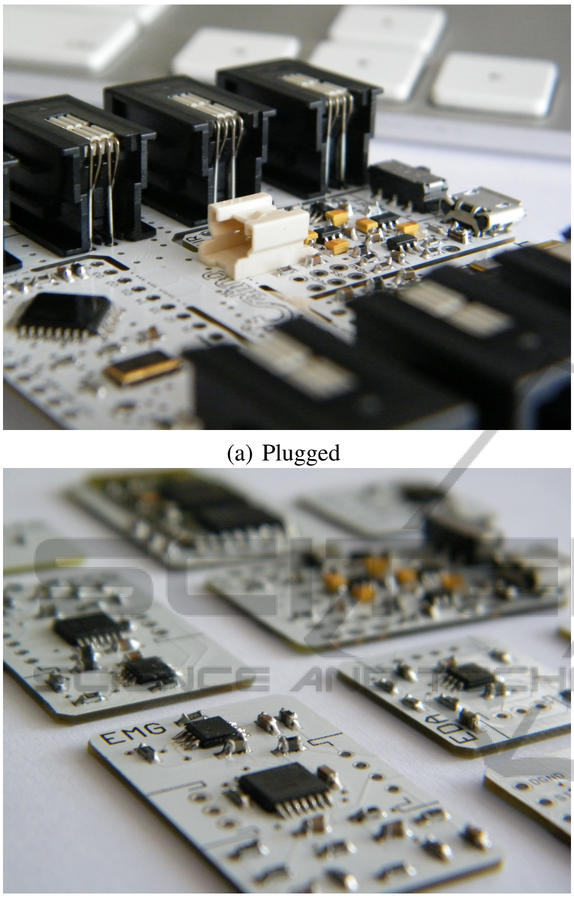
We devised BITalino as an all-in-one ”Credit Card” form factor that integrates multiple measurement sensors for bioelectrical and biomechanical data acquisition. The digital back-end is supported by a control block based on the ATmega328P microcontroller, a power management block, and a communication block that uses a Class II Bluetooth v2.0 module for wireless data transfer to a base station (e.g. computer, mobile phone, etc.). Two auxiliary connectivity blocks introduced in the board enable RJ22 plugs to be added to the device. The main specifications are summarized in Table 1.

Table 1: BITalino specifications.

Sampling Rate	1, 10, 100 or 1000 Hz
Analog Ports	4 input (10-bit) + 2 input (6-bit)
Digital Ports	4 input (1-bit) + 4 output (1-bit)
Data Link	Bluetooth (range up to 10m)
Actuators	LED
Sensors	EMG; ECG; EDA; ACC; LUX
Battery	3.7 V Lithium Ion
Weight	30 g / 1.06 oz
Size	105x60 mm / 4.13x2.36 in

By default, the system comes as a single board, with its onboard sensors pre-connected to analog and digital ports on the control block. Nonetheless, the control, power, and communication blocks, as well as the firmware are completely general purpose, enabling people to use only the digital back-end of the BITalino with their own custom sensor and actuator designs. Furthermore, each individual block can be physically detached from the main board, allowing people to use it in many different ways; in essence, this architecture enables three configurations:

- *Board:* BITalino is used with no modifications, enabling people to simply experiment with the



(a) Plugged

(b) Freestyle

Figure 2: Possible BITalino configurations.

onboard sensors for prototyping activities or real time observation of multiple physiological phenomena (Figure 1);

- *Plugged:* plugs are added to the BITalino and the individual sensor blocks are separated from the BITalino main board, leaving only the control, power, communication and auxiliary connectivity blocks, and enabling people to interchangeably use different sensor combinations (Figure 2(a));
- *Freestyle:* all the individual blocks are detached from the BITalino main board, enabling people to combine them in any way that best suits their project ideas and applications (Figure 2(b)).

All the input channels selected by the user are sampled by the MCU on the control block, and formatted into data packets of variable size (the extreme cases are 8 bytes when all analog channels are selected, and 3 bytes when no analog channel is selected); a Cyclic Redundancy Check (CRC) code is computed to identify and recover from data packet inconsistency (e.g. due to loss of bytes in the communication), and a packet sequence number is also added to help on the detection of loss of data packets. Figure 3 shows the structure of the data packets sent by the device. The configurable settings on BITalino can be changed by sending 1 byte commands from the base station to the device; Figure 4 summarizes the command set that is interpreted by the device.

Bytes \ Bits	7	6	5	4	3	2	1	0
7	S	S	S	S	CRC	CRC	CRC	CRC
6	D0	D1	D2	D3	A0	A0	A0	A0
5	A0	A0	A0	A0	A0	A0	A1	A1
4	A1	A1	A1	A1	A1	A1	A1	A1
3	A2	A2	A2	A2	A2	A2	A2	A2
2	A2	A2	A3	A3	A3	A3	A3	A3
1	A3	A3	A3	A3	A4	A4	A4	A4
0	A4	A4	A5	A5	A5	A5	A5	A5

Figure 3: Data packets structure. The bit labels mark the positions corresponding to: the sequence number *S*; the *CRC* code; each digital input channel *D0* to *D3*, and each analog channel *A0* to *A5*.

3.2 Performance Evaluation

We tested the BITalino to evaluate the performance during real-time acquisition, namely the sampling rate accuracy (or temporal uncertainty) and the dynamic specifications of the Analog-to-Digital Converter (ADC) in what concerns the Effective Number of Bits (ENOB), and the quality of the analog front-end in terms of Signal-to-Noise Ratio (SNR), SNR plus Distortion (SINAD) and Total Harmonic Distortion (THD). In all of the tests we used an Agilent 33220A Function Waveform Generator.

To characterize the temporal uncertainty of each version of the BITalino, a synthesized ramp wave with a frequency of 1 kHz, 3 V_{pp} and offset of $V_{cc}/2$ was acquired and its slope ($\frac{\Delta V}{\Delta t}$) was analysed and compared with what was really injected. Table 2 summarizes the temporal uncertainty results; only the sampling rate Fs =1 kHz was tested as it is the most demanding.

Table 2: Sampling rate accuracy for each version of the BITalino (Board, Plugged and Freestyle).

BITalino	Fs (real) [Hz]	Skew [%]	Jitter [%]
Board	999.99 ± 0.025	0.00086	0.0025
Plugged	999.99 ± 0.025	0.00043	0.0025
Freestyle	999.99 ± 0.018	0.00129	0.0018

The ATmega328P features a 10-bit successive approximation ADC, which runs with input clock frequency of 200 kHz ensuring maximum resolution, and is connected to a 6-channel Analog Multiplexer

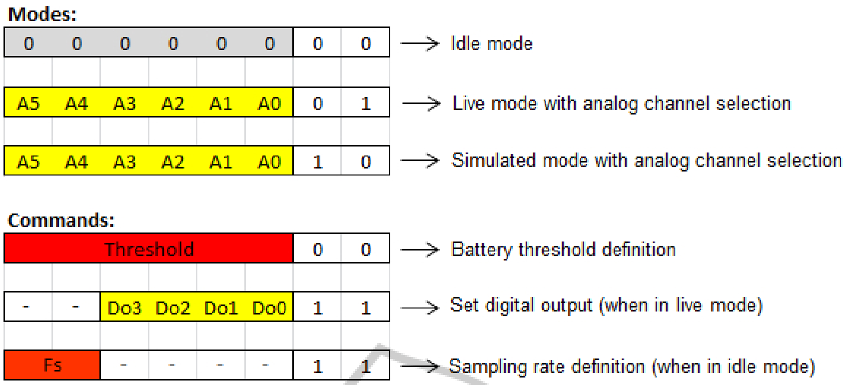


Figure 4: Firmware commands.

with single-ended voltage inputs ($0-3.3$ V). As previously described, to evaluate the performance of the ADC we used the SNR, THD, SINAD, and ENOB.

The SNR was computed as the ratio of AC signal power to noise power below half of the sampling frequency (Equation 1); it is important to note that the noise power excludes harmonic signals and DC. The THD was determined as the sum of the powers of the harmonic components (spurs) divided by the input signal power (Equation 2). We computed the SINAD as the ratio of the amplitude of the fundamental input signal to the sum of all other spectral components below half of the sampling frequency excluding DC (Equation 3); it is important to note that the theoretical minimum for the SINAD is equal to the ideal SNR (Equation 4). Finally, the ENOB was computed as shown in Equation 5; a higher ENOB means that voltage levels recorded in an analog to digital conversion are more accurate.

The crosstalk between each channel was also tested, and it is less than the ideal SNR (-61.96[dB]) for 10-bits resolution.

$$SNR(\text{dB}) = 10\log_{10}\frac{\text{P}_\text{s}}{\text{P}_\text{n}} \tag{1}$$

where P_s is the signal power and P_n is the noise power (exclude harmonic signals and DC).

$$THD(\text{dBc}) = 10\log_{10}\frac{\text{P}_\text{s}}{\text{P}_\text{d}} \tag{2}$$

where P_d is the power of all the specified spectral components (harmonics).

$$SINAD(\text{dBc}) = 10\log_{10}\frac{\text{P}_\text{s}}{\text{P}_\text{n}+\text{P}_\text{d}} \tag{3}$$

$$SNR(\text{dB})_{ideal} = 6.02n + 1.76 = 61.96[\text{dB}] \tag{4}$$

where n is the number of bits.

$$ENOB = \frac{SINAD - 1.76}{6.02} \tag{5}$$

Table 3 shows the results of the ADC dynamic specifications. Tests were performed by applying a synthesized sine wave with a frequency of 15 Hz and voltage range of 95% ADC full-scale range.

Table 3: Dynamic specifications of the ADC (15 Hz sine wave; $Fs = 1$ kHz).

SNR [dB]	SINAD [dBc]	THD [dBc]	ENOB [bit]
55.72	54.29	-59.80	8.73

We also evaluated the power consumption of BITalino; tests with a LiPo battery of 850 mAh showed the autonomy to be $\approx$ 17 hours in real-time acquisition over Bluetooth with all sensors connected. This enabled us to conclude that the system typically has a $\approx$ 50 mAh load current.

4 ANALOG FRONT-END

4.1 Overview

The analog front-end integrates individual sensor blocks for Electromyography (EMG), Electrocardiography (ECG), Electrodermal Activity (EDA) and Accelerometry (ACC); the board is also fitted with light sensor (LUX) and LED analog blocks, to enable synchronization with third-party equipment (e.g. a computer screen or video camera).

The ECG sensor can be used for 1-lead measurement of the *bioelectrical activity* of the heart and derived parameters (e.g. heart rate, heart rate variability, etc.), works both with gelled and non-gelled electrodes, and can be applied in any standard location (e.g. chest, left/right hand palms, left/right fingers) (Silva et al., 2011).

Table 4: Onboard sensor specifications.

	ECG	EMG	EDA	ACC	LUX
Principle	V. Diff.	V. Diff.	Resist.	MEMS	Photo Trans.
Electrodes	2 or 3	3	2	-	-
Bandwidth	0.5-40 Hz	10-400 Hz	0-3 Hz	0-50 Hz	-
Input Imp.	100 GΩ @ 3 pF	100 GΩ @ 3 pF	-	-	-
CMRR	110 dB	110 dB	-	-	-
Range	0-3 mV	0-3.3 mV	0-1 MΩ	±3 G	360-970 nm
Gain	1100	1000	2	-	-

The EMG sensor can be used for measuring the *bioelectrical activity* of the muscles and derived parameters (e.g. onset, duration, etc.), and can be applied to any surface muscle; the standard recommendations are for the sensor to be applied with the differential electrodes centered mid-way along the muscle belly, with a 2 cm inter-electrode spacing, and aligned with the muscle fibers beam (Basmajian and De Luca, 1985).

The EDA sensor can be used for measuring *skin resistance*; a typical use of this sensor is to assess the sympathetic nervous system activity, in which case the two sensor leads are applied at the hand palms or feet, allowing the measurement of the variations in the skin impedance originated by sweat duct secretion activity (Boucsein, 2011).

Finally, the accelerometer can be used for measuring *biomechanical* events (e.g. tilt, step counting, fall detection, physical activity), and the light sensor can be used for measuring ambient light or for optical synchronization with external sources (a typical example being the synchronization of BITalino with content being presented in a computer screen).

Table 4 presents the specifications of the individual sensor blocks provided by default on the analog front-end, and through which the users are able to experiment with multiple biosignals.

4.2 Sensor Characterization

We characterized the dynamic specifications of the ECG and EMG voltage differential circuits using a synthesized sine wave with frequencies of 24 Hz and 55 Hz, respectively, 25 mV_{pp} and offset of $V_{cc}/2$. The gain of each sensor was reduced to 100 (IN-AMPs with unity Gain); this procedure ensured a desirable output signal without saturation and ranged between $0-3.3$ V.

Table 5 summarizes the results of the dynamic specifications of the the circuits of the three versions of the BITalino (Board, Plugged and Freestyle). Figure 5 shows the frequency response of each circuit. In the top plots, we show the time response of each circuit to a synthesized chirp wave with 1 second duration and frequencies ranging between $0-100$ Hz (for the ECG) and $0-500$ Hz (for the EMG), 25 mV_{pp} and offset of $V_{cc}/2$. As expected, the output signal is a chirp wave with attenuation at low and high frequencies. The bottom plots show the frequency response.

Table 5: Dynamic specifications (ECG and EMG, Fs = 1 kHz). For the BITalino Plugged results, * denotes a 10 cm cable length while ** denotes a 100 cm cable length.

BITalino	Sensor		SNR[dB]	SINAD[dBc]	THD[dBc]
Board	ECG		37.38	37.11	-49.39
	EMG		35.96	35.86	-52.03
Plugged	ECG	*	39.39	36.58	-39.80
		**	34.09	32.70	-38.34
	EMG	*	34.96	34.67	-46.61
		**	34.49	34.21	-46.17
Freestyle	ECG		39.72	36.71	-39.72
	EMG		32.03	31.95	-49.23

We also performed a transient analysis of the voltage differential circuits, which showed that the ECG circuit has 2.337 seconds time delay, while the EMG circuit has 0.146 seconds time delay. One should note that the time delay is bounded by the time constant ($\tau = RC$) of the integrator network at the first stage of the biosignal amplifier in both circuits.

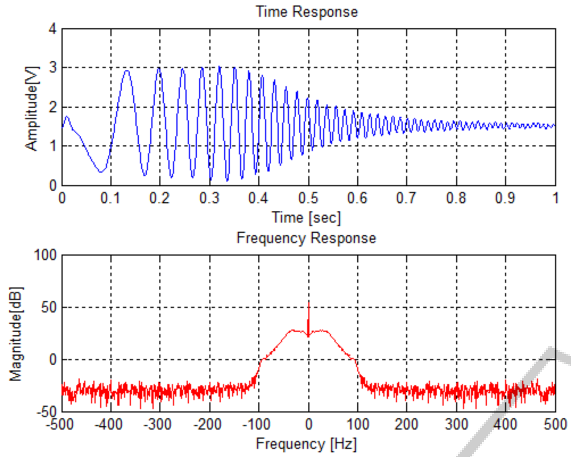
To further reinforce the performance of each circuit, Figure 6 shows real-world data. For the ECG, we used an off-the-person placement as described in (Silva et al., 2013), while for EMG measurement we placed pre-gelled electrodes fixed over a muscle.

Only the voltage differential sensors were revised in the scope of our work, and as such, we refer the reader to the work by (Guerreiro et al., 2013) for the characterization of the remaining sensor blocks.

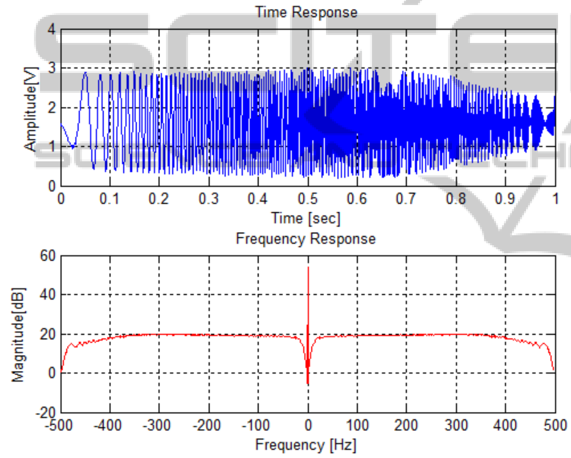
5 USABILITY ASSESSMENT

5.1 Methodology

A major concern in our work was the ease-of-use and adequacy of our hardware framework within potential target user groups, reason for which we have conducted a usability study. We adopted the approach

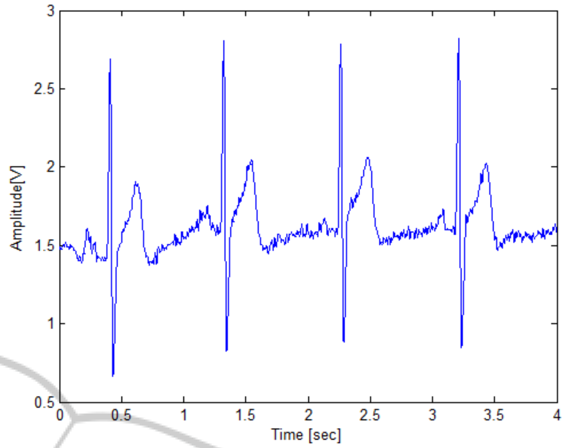


(a) Frequency response of the ECG sensor. Bandwidth between 0.5 – 40 Hz.

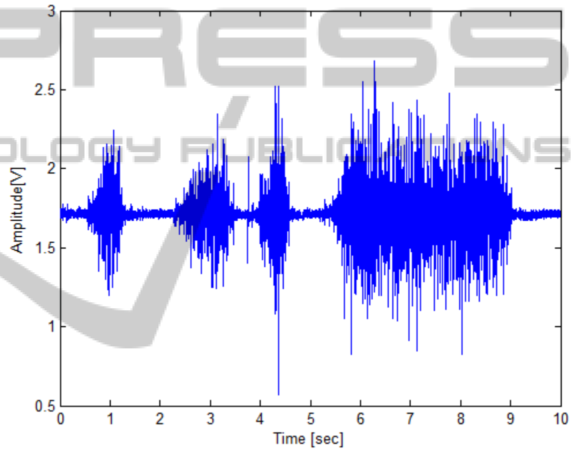


(b) Frequency response of the EMG sensor. Bandwidth between 10 – 400 Hz.

Figure 5: Time and frequency response of the voltage differential sensors.



(a) Example of an ECG signal acquired by the BITalino.



(b) Example of an EMG signal acquired by the BITalino.

Figure 6: Samples of real-world data collected with the voltage differential sensors.

proposed by Brooke (Brooke, 1996) around the System Usability Scale (SUS). The SUS is composed of a 10-item questionnaire, in which each question is a statement that the user needs to rate on a five-point scale that ranges from *"Strongly Disagree"* to *"Strongly Agree"*, and measures the subjective perception of interaction with a system. The SUS items have been developed in accordance with the *effectiveness*, *efficiency*, and *satisfaction* criteria as defined by the ISO 9241-11, and it has been widely adopted within the engineering and usability practitioners community.

As proposed by Brooke, the SUS assessment was performed after the volunteers had contact the system and before any debriefing or discussion. The participants were requested to respond to all items, and to mark the center of the scale for the items in which they felt they were not able to respond. Furthermore, instead of thinking about the items for a long time, the participants were asked to record their immediate response to each item.

We enrolled volunteers from multiple target user groups, namely: a) *Biomedical engineering (BME):* users that are familiar with electronics, computer programming and biosignals; b) *Electrical engineering (ECE):* users that are mostly familiar with electronics and computer programming; *Computer science (CS):* users that are mostly familiar with computer programming; and c) *Health sciences (HS):* users that are familiar with biosignals but non-proficient in computer programming nor electronics. Individual interviews were performed with each user, and none of the volunteers had previous experience with BITalino.

5.2 Experimental Results

A total of 100 volunteers were involved in the study (BME: 25; ECE: 25; CS: 25; and HS: 25), with ages rangin between 19 and 30 years old. Table 6 shows the results for each SUS item in terms of mean and standard deviation ($\mu \pm \sigma$), highlighting the best results in bold. The overall results suggest that our framework is very easy to use, and that it has a fast learning curve. Nevertheless, a few participants stated that they would appreciate a more comprehensive training before using the system.

Taking into account the SUS score interpretation guidelines, BITalino not only exhibited above average results, but it's also an A grade system given that the SUS scores across all groups stand above the 80.30 threshold (Brooke, 1996). As expected, BME users presented the highest SUS scores, since they are more familiar with the underlying principles and topics. Interestingly, CS users actually presented higher SUS scores for the BITalino than ECE users; this may be due to the fact that ECE users have a stronger background on hardware, leading their evaluation to be more meticulous. Another interesting finding were the high ratings of all users regarding the frequency and ease of use of the system, which we interpret as an indicator that a hardware framework such as the BITalino is indeed necessary.

6 CONCLUSIONS

Affordable instrumentation has been a fundamental problem in the field of physiological computing for many years, and while the state-of-the-art is rich in attempts to provide sensors and systems, no single work found to date has provided a comprehensive and reliable solution.

In this paper we presented the BITalino, a low-cost all-in-one hardware framework that has a basic set of multimodal sensors, enabling anyone to easily integrate biosignal acquisition in their projects and applications. Our work builds on previous research from our group to provide a novel purpose-built hardware framework for physiological computing. Experimental results related both with the benchmarking of the BITalino hardware blocks and usability assessment demonstrate its suitability for the intended application.

Future work will be mainly focused on the creation of a bootloader capable of enabling people to upload custom firmware to the control block and also on creating additional sensors for other modalities.

Table 6: Ranking for each SUS item in terms of mean (μ) and standard deviation (σ). The rating is on a five-point scale ranging from *"Strongly Disagree"* to *"Strongly Agree"*.

Item	**BITalino**			
	BME	**ECE**	**CS**	**HS**
I think that I would like to use this system frequently	**4.48 ± 0.65**	4.00 ± 0.75	4.12 ± 0.73	4.31 ± 0.68
I found the system unnecessarily complex	**1.32 ± 0.48**	1.73 ± 1.08	1.56 ± 0.96	1.42 ± 0.50
I thought that the system was easy to use	**4.84 ± 0.37**	4.73 ± 0.45	4.44 ± 0.71	4.62 ± 0.57
I think that I would need the support of a technical person to be able to use this system	**1.60 ± 0.76**	1.65 ± 0.85	**1.60 ± 0.87**	2.12 ± 1.03
I found the various functions in this system were well integrated	4.28 ± 0.68	4.19 ± 0.80	**4.40 ± 0.58**	4.08 ± 0.63
I thought there was too much inconsistency in this system	**1.28 ± 0.46**	1.54 ± 0.90	1.48 ± 0.71	1.46 ± 0.58
I would imagine that most people would learn to use this system very quickly	4.60 ± 0.50	4.69 ± 0.55	**4.72 ± 0.54**	4.15 ± 0.78
I found the system very cumbersome to use	**1.40 ± 0.58**	1.65 ± 0.75	1.48 ± 0.82	1.69 ± 1.01
I felt very confident while using the system	**4.32 ± 0.63**	4.19 ± 0.69	**4.32 ± 0.69**	3.85 ± 0.78
I needed to learn a lot of things before I could get going with this system	1.84 ± 0.94	1.65 ± 0.98	**1.52 ± 0.65**	1.92 ± 0.80
SUS Score:	**87.70 ± 9.87**	83.94 ± 11.67	85.90 ± 10.68	80.96 ± 12.19

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