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Portable System and User Interface for ECG and EMG Acquisition, Conditioning, and Parameters Extraction

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Abstract

Electrical signals from the human body are constantly the focus of research, searching for a better understanding of physiological events, discovering early signs of disease, and improving life quality. Developing devices that allow research beyond the usual requirements and allow easy adaptation regarding the system's acquisition, conditioning, and processing parts could be a step toward better understanding some behaviours. Therefore, this work focused on designing a system that goes from the discrete components to a graphical interface, allowing user control of parameters to set the acquisition in a way that favours the specific signal of interest. The resulting system allows the user to change parameters regarding the analogue and digital filtering, sampling frequency and events detection, namely R-peaks, in the electrocardiogram, to estimate heart rate and its frequency fluctuation, and muscle

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contraction in electromyogram, to analyse contraction strength and muscle fatigue. The system also allows the data to be stored, aiming to generate datasets to further process the data in AI-based algorithms.

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Keywords: Graphical User Interface; Biosignals; Printed Circuit Board; EMG processing; ECG processing.

1. Introduction

The study of electrical signals produced in humans' daily routine provides a large set of data that can be used from the earlier detection of diseases to increase the effectiveness of treatment to optimising athletes' muscular gain and recovery, allowing physitians a better follow-up in cardiovascular and muscular rehabilitation.

The electrocardiogram (ECG) graphically represents the heart's movements through measurements of its electrical potential during cardiac cycles. Even under normal heart behaviour, the maximum peak voltage levels are not constant, changing in regard to conditions such as sex and age [1], reaching up to 5 mV, while the signal's frequency band typically ranges from 0.5 Hz to 150 Hz [2].

Electrodes, such as Silver/Silver Chloride electrodes, are employed to acquire human electric potentials. The standard medical ECG acquisition system typically utilises ten electrodes. However, this configuration can be uncomfortable. Therefore, alternative configurations with only three electrodes have been designed [3,4], with electrodes placed equidistant from the heart forming an Einthoven triangle [3,5]. One electrode is positioned on the right rib as reference, while the other two are at heart height and spread towards the shoulders.

The electromyogram (EMG) is an electrical measurement used to analyse muscle contractions [6]. Its applications include medical diagnosis, muscle rehabilitation and the control of electric prostheses [7]. Surface electromyogram (sEMG) is a non-intrusive way of acquiring EMG signals using typically three surface electrodes [7] placed on the skin above the target muscle [8]. The maximum amplitude varies with the contraction intensity, the chosen muscle and the user strength. The frequency bandwidth normally stays within 10 to 500 Hz [6,7,9].

As both signals are acquired with bipotential electrical signals, when developed systems enable ECG and EMG acquisition, normally multipurpose channels are delivered where the signal type must be previously selected.

This work then aims at developing an acquisition board capable of acquiring both ECG and EMG simultaneously with modular and replicable circuits that transmit the acquired data wireless to a computer using Bluetooth® v4.2 with a Graphical User Interface (GUI) developed using MATLAB® R2021a App Designer that allows the user to see and analyse the data in real-time as it gets acquired, including processed parameters. The system also allows the user to save the acquired data in an 'xlsx' file, easing the creation of datasets to aid AI-based algorithms.

Therefore, the work is divided into the introduction, followed by a section that shows related work compared to the one proposed here. Then, the following two sections explain the hardware and GUI that were developed. The results are shown in acquisition examples, followed by the conclusion and future works.

2. Related Work

Studies have been published on the development of graphical interfaces for the presentation of biosignals, such as [10], where an ECG generated on a simulator was presented, with the possibility of detecting R peaks, or [11], where the acquisition board was developed, but the electrode signal came from a potential simulator. Studies on this subject have developed an interface for interpreting data from pre-existing datasets, such as [12], where certain frequency bands may have already been processed, restricting some studies beyond the standard frequency bands.

Meanwhile, some developments focus on developing the acquisition hardware without delving into the interface for presenting this data, as in [13]. There are also studies with the development of systems that include hardware and GUI, as in [14], where the ECG acquisition is sent via USB to a mobile device, which then transmits it to a server where the signals are presented graphically, but without autonomous parameterisation of the signals. In [15], the acquisition hardware and graphical interface are developed, but as it is aimed at education, it uses frequency bands that prioritise the clear visual recognition of ECG points instead of a complete signal's frequency spectrum.

Similarly, there are EMG-focused systems that start from a pre-existing database, as in [7] or [16], use pre-existing acquisition systems, as in [9], or without a focus on processing the signal parameters, as in [6].

There are also developments focused on specific applications, such as [17], with EMG acquisition as feedback to an electrical stimulation system for rehabilitation. The data is sent to a mobile phone using BLE (Bluetooth® low-energy), calculating electrical stimulation parameters based on the patient, pathology and EMG reading.

Furthermore, [18] presents a wearable acquisition system for EMG, ECG, body position and temperature data sent to a mobile phone using BLE. This system creates a platform to predict fall occurrences and electrical stimulation routines to prevent falls. On the other hand, some systems that seek both ECG and EMG acquisition normally trade off their signal-specific analogue conditioning blocks to make the system versatile, requiring the user to select the wanted signal before the acquisition, as in [19].

This work aims to develop multipurpose hardware and software with processed data presentation that goes beyond displaying signals. It is intended to support both ECG and EMG, with modular channels that allow replication, enabling the development of systems for more than one channel per signal.

3. Developed Hardware

The development of the system begins with creating the hardware block for signal acquisition, amplification, analogue conditioning, analogue-digital conversion and wireless transmission. The aim was to develop the system modular, low-consumption, and portable, first using discrete and readily accessible components.

3.1. Acquisition and Input

The system's contact with the user uses Ag/AgCl electrodes connected to a braided cable with a button-style connector on the input, compatible with the electrode, and a 3-pole audio jack style on the output, serving as a connector for the acquisition hardware. Both signals' potential channels (positive and negative) at the PCB go through an RC high-pass filter with a cut-off frequency of 0.19 Hz to remove the DC component and avoid saturating the amplifier. This filter uses low-tolerance components to maintain the common mode rejection ratio.

After this initial filtering, the signals are applied to an instrumentation amplifier, resulting in the amplified difference. The component selected was the INA128 from Texas Instruments due to its high CMRR (Common mode rejection ratio) > 120 dB, low power consumption and extensive use in various applications [20]. For amplification, a gain of 501 V/V (R_G 100 ohm) was set for the EMG channel, while a gain of 251 V/V (R_G 200 ohm) was set for the ECG. Through the component reference, the signals were applied to a DC offset for them to oscillate around half the voltage of the digital analogue converter so that the negative voltage components would not be discarded, and from then on, this DC voltage would be the reference for all the following signal conditioning components.

As for the reference electrode, the EMG is connected to the GND of the entire system, while the ECG allows for two methodologies that the user can easily alternate. In the first, connecting the third electrode to the system reference is possible, as is done with the EMG. In contrast, the second option allows the use of the right-leg-drive (RLD) method, where the midpoint of the subtraction of the potential electrodes is obtained by dividing the amplifier gain resistance into two of the same value, inverted in voltage, amplified by an integrating amplifier (low-pass f_c = 8682 Hz and G = 19.5 V/V) and fed back to the user body [21].

3.2. Analog Filtering

The next blocks are the analogue filters. For both signals, three concatenated filters were chosen: a second-order Sallen-Key topology high-pass filter with a Butterworth frequency response quality factor (Q = 0.707) for linear response in the pre and post-transition band, followed by a Notch filter to attenuate the induced power-line noise frequency (50 Hz), and finally a low-pass filter with the same topology, order and quality factor as the first. The low-pass filter was kept at the end to attenuate high frequencies that occur when using the operational amplifiers of the previous filters [22]. The cut-off frequencies for the high-pass and low-pass filters were set for each signal's frequency of interest, with 0.49 Hz to 151 Hz for the ECG and 20 Hz to 512 Hz for the EMG.

3.3. Power Circuit

The proposed acquisition system requires a symmetrical power supply, as the input signals before offset have negative components. Therefore, the power circuit is powered by a LiPo battery with a nominal voltage of 3.7 V, followed by a DC-DC boost converter with an output of 10 V, and a virtual reference regulated with a -5 V LDO (LM7905) fed with its ground input at the converter's positive output and its main input at the converter's negative output. Thus resulting in +5 V at the converter's Vout+, -5 V at the converter's Vout- and GND at LDO's Vout.

In addition, the signals' DC offsets are made using a voltage divider stabilised with a capacitor at the input of a buffer. To avoid fluctuations between the channels, an offset reference was made for each circuit

3.4. Microcontroller

The ESP32-32E microcontroller in its DevKit v4 was used for analogue-digital conversion, grouping the data and sending it wirelessly. The conversion is done in 12 bits, and the sampling rate is set by the clock's counting value necessary to activate the interrupt. Initially, the sampling rate is set to 1 kHz. Every time the interrupt is activated, the system acquires an ECG, a sEMG and a microsecond-scale time sample. Each sample packet then consists of 2 bytes of ECG, 2 bytes of EMG and 4 bytes of time. These samples are then concatenated into packets/buffers of 40 samples (320 bytes) to be sent via Bluetooth® v4.2 to the interface.

With the system planned, a 2-layer printed circuit board (PCB) was designed and assembled to validate the circuit. The resulting block diagram is shown in Fig. 1. (a), and the assembled, turned-on PCB in Fig. 1. (b).

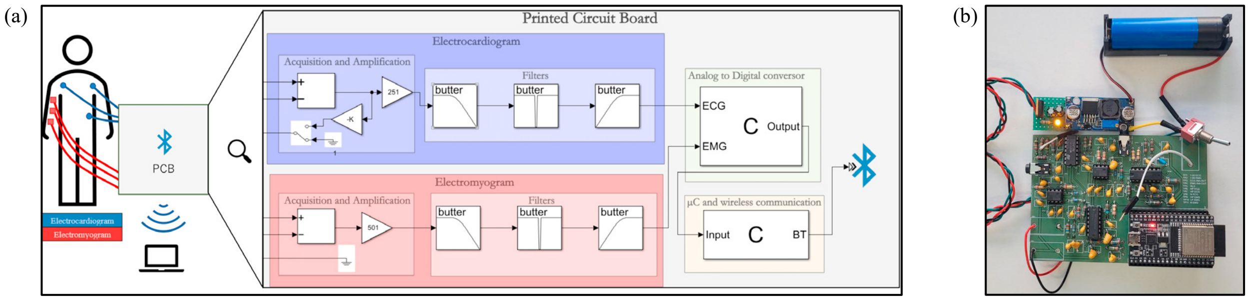

Fig. 1. (a) Hardware's block diagram; (b) Assembled PCB with power circuitry.

4. Graphical User Interface

A standalone application was developed using the App Designer platform of the MATLAB® R2021a software because of its worldly use dissemination and vector optimisation. The GUI is used to analyse the signal acquired with the acquisition board presented. Besides showing the signals, the objective included calculating processed parameters, allowing users to configure the application as intended and save the final result.

4.1. Receiving the signal

To begin the use, the interface requires the user to enter the Bluetooth® device's name to connect, alerting the user in case of a name error and displaying a list of available devices. Once the connection is correct, the system starts a data reception loop triggered by a callback linked to the number of bytes available for reading (320 bytes, 8 bytes per packet times 40 packets). When all the message's bytes are received, the algorithm first separates them into 8-byte vectors (separation by sample). Then it separates them into 2-2-4 bytes (ECG, EMG and Time), then casts the byte type to double (variable optimised on the MATLAB® platform), concatenating these final reading values into the corresponding vectors for each signal and time.

4.2. Fixed Panel

The first GUI panel, fixed to the interface's left size, as seen in Fig. 2, Fig. 3. and Fig. 4., connects the application to the acquisition system. It has communication buttons for connecting to the selected device, disconnecting or pausing data reception. There are also switches to independently turn one of the signals on or off. A sampling frequency selector also sends the new value the user selects to the microcontroller, changing the counting number needed to activate the acquisition interrupt. In addition, as the visualisation is continuous with the acquisition, the user can select how many seconds of signals the moving window should show. The user can also clear the stored signals to restart the acquisition. Finally, the user can save the data presented in an ‘xlsx’ file and, if there is new data, can append what has been received since the data was downloaded.

4.3. Signals Panel

The first panel switchable is available for the user to monitor the received signals, called the ‘acquisition’ panel and shown in Fig. 4.. At the ECG graph, in addition to visualising the signal and interacting with the graph, the user can activate R-peak detection. When peak detection is activated, the algorithm marks the amplitude and time of each R peak received based on the evaluated methods presented by [23]. The system also calculates the patient's heart rate by up to ten R-peak intervals. This operation occurs by default the first time after 3 s of signal and in successive iterations continuously every 5 s, with an overlap of 2 s to mitigate errors that may arise in each detection's first and last peak. Nevertheless, it is open to the user to change these operating times.

The electromyogram graph offers interactions with the user by recognising contractions from the acquired signal. To this end, the system has two functions. The first is to detect variations in the signal amplitude, which defines a contraction, and the second is to validate the recognised contractions, mitigating incongruences in the detection.

The first function, analyse the signal by default in windows of 0.1 s. As the EMG signal is characterised by a high-frequency signal modulated into a low-frequency signal representing the contraction amplitude, the algorithm starts by taking the power’s moving average of a portion of the signal in a window of 100 samples, obtaining the low-frequency curve of the contraction. With this, the rising and falling edges of the contraction can be set to define the period in which the muscle was contracted. However, a contraction can fluctuate between the defined limit, which the algorithm would interpret as multiple contractions [24]. To avoid this problem, the contraction correction function is activated for every three (or user-selected value) falling edges recognised by the system.

This second function analyses the total contraction time and the time between two contractions, which must be within the limit the user sets. A research-accepted threshold of 30 ms is considered the time limit of a contraction to result in an actual muscular movement [24]. Therefore, the minimum value a user can set for considerable contraction is 30 ms. By default, two contractions must be spaced 0.5 s apart; if not, they will be merged into a single contraction; similarly, by default, a contraction must be at least 0.1 s long; if not, it will be eliminated. These higher initial thresholds make the detection more rigorous. Checking compliance with these requirements is done by prioritising joining contractions rather than eliminating them.

The user can access a slider and three buttons when the contraction detector is active. The button switches between ‘Sensitivity’, ‘Minimum Contraction Time’ and ‘Minimum Time Between Contractions’. The cursor changes the value of the selected parameter, allowing changes while acquiring data. This customisation allows configuring the system with regard to what kind of muscle contraction intensity it must consider and how much time the contraction should have in active and rest events.

The user can also switch the ECG or EMG-specific digital and analogue filter on or off, allowing the effect of each component on the final signal to be analysed. This allows an in-depth understanding of the effect of each filter or even to test combinations of digital filters without the analogue components.

4.4. Contractions Panel

To display specific EMG parameters, there is an interface that statically displays each recognised contraction and its respective frequency spectrum, shown in Fig. 2. (a) calculating parameters of interest for studying the signal, such as the maximum amplitude and the RMS amplitude, in mV, to assess the intensity of the contraction, and also the median frequency, a parameter widely used to estimate muscle fatigue, as it classifies the types of muscle fibres that predominate in the execution of the movement [25,26]. A decrement in the frequency median means a change in fast-twitch (type 2) fibres to slow-twitch (type 1) fibres, therefore indicating muscle fatigue [27].

In addition to the graphics, there is a contraction selector for the user to change the contraction being displayed, a button to delete the contraction, one to split the selected contraction in two and another to create a contraction from the original signal. In these last two functions, when the split is started, a horizontal cursor is shown to the user, just below the graph that the contraction is on, as well as a line on the graph that follows the position of the cursor, allowing the user to select where they want the new falling and rising edge between the two contractions. The interaction is similar to creating a new contraction, except the complete signal will be displayed for the user to select where the contraction should be, as shown in Fig. 2. (b). All these interactions are protected if the user tries to overlap two contractions, which should not happen.

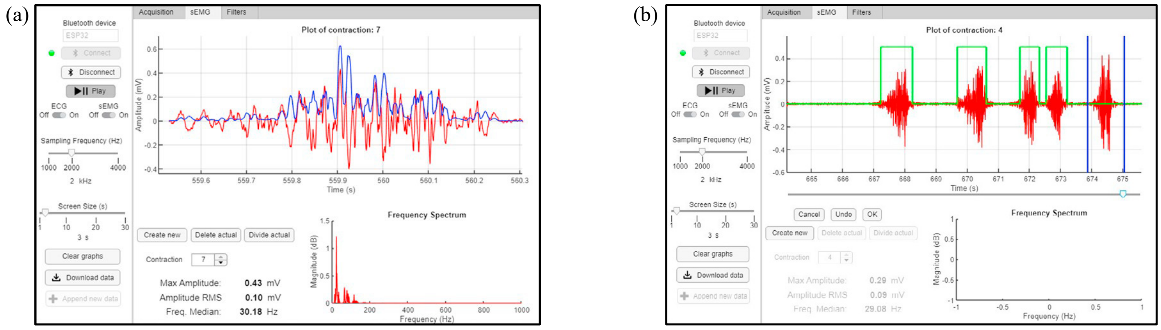

Fig. 2. Contraction panel (a) with the first contraction selected; (b) creating a deleted contraction.

4.5. Filters Panel

The system allows signals to be digitally filtered, enabling the user to change the frequency response of three more filters per signal, a low-pass and a high-pass Butterworth IIR filter, where the user can change the filters' cut-off frequency and order, as well as a Notch filter, allowing changes in the filter's cut-off frequency and number of harmonics. It is also possible to switch the filters on or off independently. The configuration is made in the filter interface shown in Fig. 3, with the resulting frequency response being displayed below each selection frame.

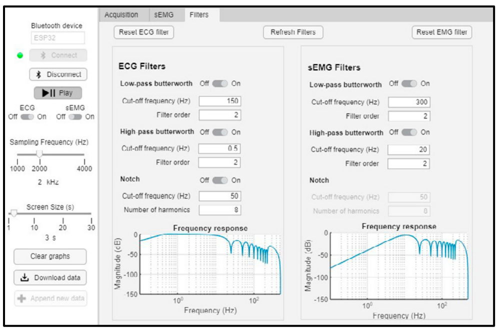

Fig. 3. Filters panel with initial parameters.

The user can also return to the initial pattern, with two second-order filters for the ECG, resulting in a passband between 0.5 Hz and 150 Hz and two second-order filters for the EMG, with a passband between 20 and 300 Hz. The notch filter is the same for both signals, with a cut-off frequency of 50 Hz and the following eight harmonics, i.e. starting at 100 Hz, every 50 Hz, up to 450 Hz. Considering IIR filters were chosen, the system also delivers an algorithm that protects the user from selecting an unstable set of filters.

5. Results

The acquisition circuit connected to the graphical interface has multiple variable options for displaying the signals. Fig. 4. (a) shows the ECG signal sampled at 2 kHz, in a 5-second window, with the analogue filter switched off and the digital filter switched on, and in Fig. 4. (b) the ECG and sEMG signal is shown sampled at 1 kHz in a 10-second window with the digital filter switched on in both signals and the analogue filter switched off at ECG and on at EMG graphs, where it is possible to see the disturbance caused by an arm contraction on the ECG.

These examples show peak and contraction detection, with the BPM estimation on the upper-right side. The contractions could then be analysed in the sEMG contracton panel shown in Fig. 2. (a). The performance of the GUI showed to be promising, detecting the points of interest and displaying the signal smoothly. Even with the number of customisable parameters, the panels and controls were grouped and described to simplify the user understanding. The ability to change filtering parameters during the acquisition enables the user to find the most useful combination in regard to what feature will be evaluated.

(a) (b)

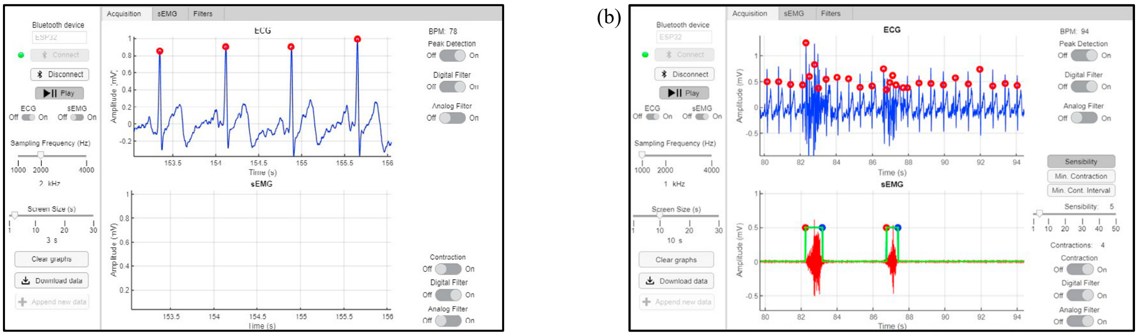

Fig. 4. Acquisition panel with (a) ECG sampling at 2 kHz and a 5-second screen; (b) ECG and EMG sampling at 1kHz and a 10-second screen.

6. Conclusion

The system developed features hardware, firmware and software for acquiring ECG and EMG, displaying the signals in real-time, detecting heartbeats and calculating heart rate, detecting contractions and gathering muscle parameters, as well as a range of alterable parameters that allow for greater versatility in terms of the positioning or material of the electrodes, as well as being a modular system allowing multiple channels of each signal. Promising data were obtained, easily detecting the points of interest for a more in-depth analysis of both signals.

Future work aims to extend the interface even further, looking for new parameters to be presented, especially concerning cardiac variations. Finally, upgrading the acquisition board, testing new methodologies and integrated components, and communicating with the Wi-Fi protocol will be developed.

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