Design of an Ultra-Portable Wearable Electrocardiograph

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Abstract

The diagnosis of several diseases can be improved by monitoring patients for long time periods. Wearable electrocardiographs (ECG) are devices that record the heart electrical activity of patients in their daily-life environment, enabling freedom of movement. The number of leads is limited, and noise removal becomes a very important parameter as the artefacts increase with movement. This project shows an approach of the design and implementation of an ECG Front End. The implemented system aims to work as a wearable when combined with wireless technologies. This is the reason why special attention has been given to size (3.3x2.9mm^2), weight, and power supply independence (coin battery, 3V). Experimental results demonstrate that the apparatus can amplify properly the signal acquired from the body, however more effort should be made to remove noise.

1. Motivation

Since 1786 the instrumentation of the Electrocardiogram is being improved and there are still reasons to continue innovating in this field. On the one side, investing in electrocardiography means investing in preventive medicine. ECG is the most important part of the initial evaluation for patients presenting cardiac complaints, specially to evaluate arrhythmias and ischemic heart disease. The goal is to detect factors that indicate the possibility to present diseases in the future or detect diseases that are already present, but at a stage where they are still curable [1]. In the other hand, empowering wearables as educational tools increases the patient safety. Technology has become a part of the day to day of the doctors, however, learning how to use it and how to interpret the results is not easy for students. The process of learning has care implications. Providing wearable devices to the potential doctors could be a way to give them independence to practice their skills [2].

2. Introduction

The ECG is one of the most common tools used for patient monitoring. It is an essential clinical device for evaluating cardiac electrical events, offering information on rate, rhythm and electrical conduction at a global and regional level [3].

The heart is the main responsibility of the blood distribution to all tissues. This is done, thanks to its electrical activity which triggers the cardiac contraction. The electrocardiograph is the graphic obtained during the continuous acquisition of the heart electrical signal, which has different deflections (P, Q, R, S, T, U). Each of them corresponds to a specific part of the heart contraction process. This signal must be recorded through electrodes placed at specific sites of the body surface. For a portable ECG, three electrodes are needed: right arm (RA, negative), left arm (LA, positive) and right leg (RL, reference). With three electrodes, the more common pathologies can be observed [4].

3. State of the art

Electrocardiographs have been, for many years, high-volume devices connected to patients through wires and limiting their mobility. However, in the last years, the possibility to transmit data wireless and the new advancements in low power circuitry have made the market to grow towards miniaturization, portability and communication between the device and the medical staff.

Many companies in the healthcare sector are investing in manufacturing portable electrocardiographs and other wearable diagnostic devices. Advancements in this field, make it possible to early diagnose and treat various diseases.

Currently there are several devices similar to what is intended in this project. Most of them have a single lead and a similar structure: two electrodes and over it, all the electronics. The price varies between 150$ and 750$. They send the data via Bluetooth to a mobile/tablet and there is also the option to take the data with a microSD or an USB connection which is also used to recharge the battery. Each of them has its own app [5, 6].

4. Materials and methods

The process of the design, implementation and evaluation of the device has been done in a sequential way. First studying the acquisition of the signal, then the pre-amplification of the signal, the feedback circuit to reduce the noise coming from common mode signals. Then, the filtering stage to attenuate or remove frequency components from the input data. And finally, the post-amplifier to amplify the resulting ECG signal without noise. Each stage has been designed and simulated individually and combined with the others. Also, first prototypes have been implemented. But at the end, a prefabricated Front-End has been used to be able to construct a small device, configured and tested as a single block.

During the stages of design and simulation the software NI Multisim has been used. For the implementation of the prototypes NI Ultiboard has been used along with the Weller WD2 Soldering Station to weld the components.

For the testing, three electrodes were attached to the skin of a volunteer. They were located, one on the right arm, another on the left arm, and the last one on the right leg. Such electrodes were connected to the device through a jack connector. The output signal was studied on the screen of the MSO-X-2002A Oscilloscope.

5. Results of the design

The design of this device is centred around the Front End AD8232. This integrated block of 4mm x 4mm in size, is specially designed to extract, amplify and filter ECG signals in the presence of noisy conditions, such as those created by motion or remote electrode placement. It works with a single supply operation between 2 and 3.5V together with a low current consumption (170µA typical).

5.1. Schematic Design

Surface mount resistors and capacitors have been used to configure the selected Front End. They occupy less space, can be placed in both parts of the PCB and have a good mechanical performance under shake and vibration conditions. The selected size of capacitors and resistors has been 0805 and 0603.

The schematic shown in Figure 1 has been conceived from the Cardiac Monitor Configuration proposed in the Front-End datasheet [7]. AD8232 includes a reference buffer to create a virtual ground between the supply voltage and the system ground. The reference voltage level is set at the REFIN pin with R10, R14 (forming a voltage divider) and C7 (for noise filtering). R10 and R14 are of high value to limit the power consumption of the voltage divider. The virtual ground is taken from the REFOUT pin and is used for any point in the circuit that needs a signal reference: the instrumentation amplifier output, the filtering circuits or the post-amplifier.

To obtain an ECG waveform with minimal distortion, the AD8232 is configured with a 0.5 Hz two-pole high-pass filter followed by a two-pole, 40 Hz, low-pass filter. R12 controls the Q of the band-pass filter, is recommended to be 0.14 times the value of R11 to optimize the filter for a maximally flat pass band. Lower values of R12 increase the Q but also the system instability. The cutoff frequencies of the filters are calculated with the following expressions.

$$fc_{HP} = \frac{10}{2\pi\sqrt{R_{11}R_{13}C_4C_6}} = 48mH \quad (1)$$

$$fc_{LP} = \frac{1}{2\pi\sqrt{R_6R_7C_1C_3}} = 41.09Hz \quad (2)$$

The gain of the instrumentation amplifier is set to 100V/V and it cannot be modified. However, there is an op amp between pins 7, 9 and 10 that acts as the post-amplifier. It is configured with a gain of 11V/V, resulting in a total system gain of 1100V/V. High value resistors had been used to not increase power consumption.

Resistors placed are of a high value to minimize additional supply current. R3, R4 and R6 are placed in series with the input and output electrodes as an input protection, limiting the current to be always less than 10µA.

The right leg drive (RLD) amplifier inverts the common-mode signal that is present at the instrumentation amplifier inputs. Then, is injected into the subject, improving the

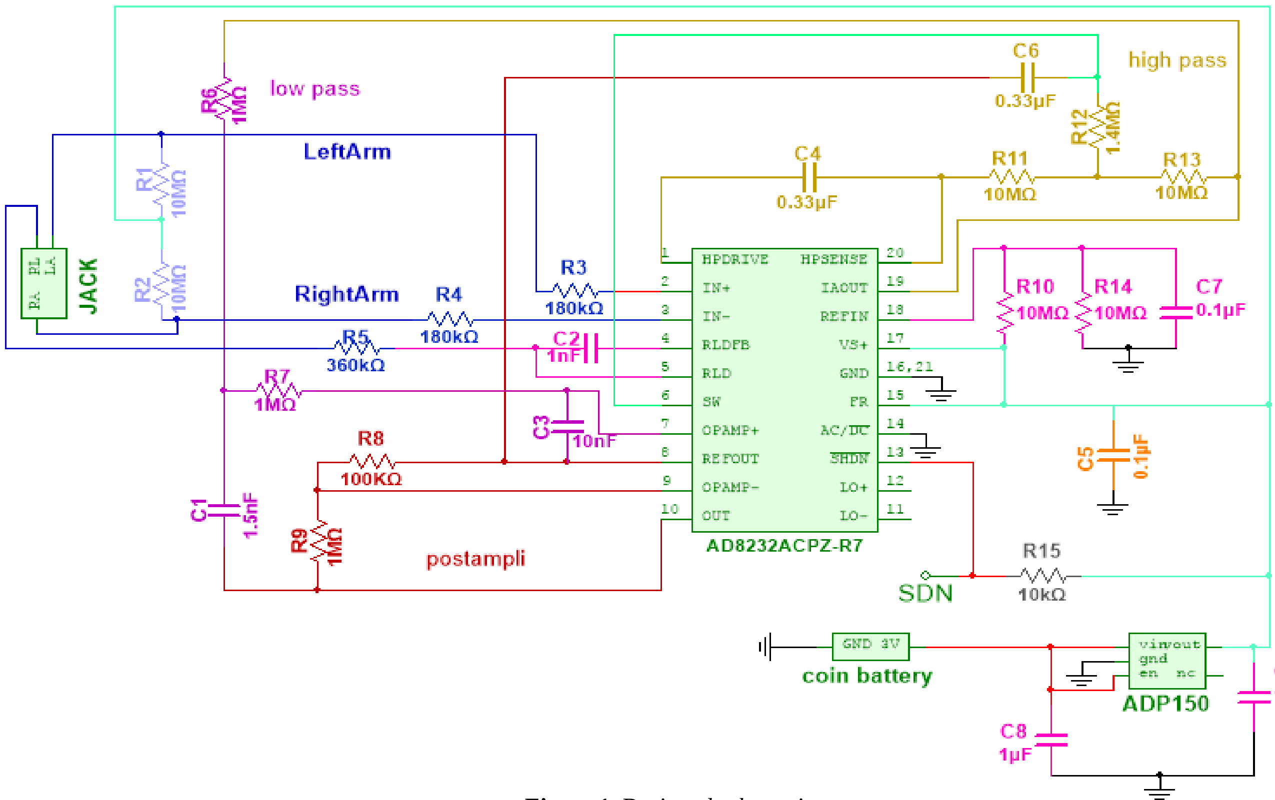

Figure 1. Designed schematic

common-mode rejection of the system [7]. Connecting a capacitor (C2) between RLD FB and RLD terminals an integrator is built. With a value of 1nF it is able to reduce the line noise in about 26dB.

Finally, the power supply is given by a 3V coin battery CR2032 type (lithium, 20 mm diameter, 3.2 mm height). On any device, supply voltage varies with load and regulators are needed to maintain a steady voltage and protect the load and the system in case of a component failure. Therefore, a linear regulator ADP150 is implemented to avoid damage to the part. It is configured in a 5-lead TSOT package. Basically, two bypass capacitors (C8 = C9 =1µF) are connected to VIN and VOUT pins, and for an automatic start-up, EN is connected to VIN [8].

5.2. Implementation

The prototype is less than 10cm^2 in size. On the one hand, the jack box and the battery holder are placed at the bottom side of the board. On the other hand, the passive components, the integrated Front End and the linear regulator are placed at the top face. All the components are SMD type, unless the battery holder that, together with the jack connector it defines the size of the PCB created.

During layout of the board, bypass capacitors are placed as close to the relevant pins as possible. All the connections made with high impedance nodes are as short as possible to avoid introducing additional noise and errors from corrupting the signal. Traces of the power supply are the widest ones to provide low impedance paths and reduce the effects of glitches on the power supply line. The ground plane is used to improve the noise rejection of the system. Finally, there is only one pin for testing it corresponds to the out, in order to take out the signal and visualize.

To be able to attach the PCB to the t-shirt and look as it was portable, a hole has been made to the PCB by which a needle will be inserted to be able to be hooked with a pin as it can be seen at Figure 2.

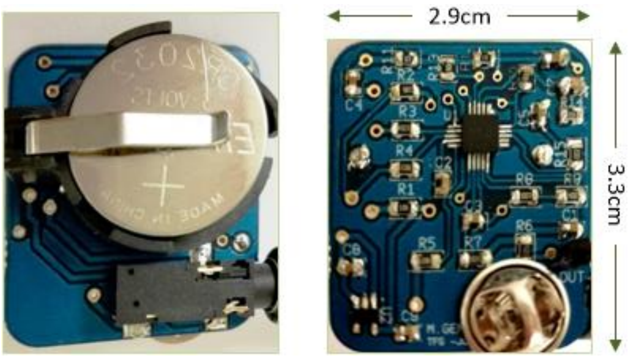

Figure 2. *Prototype of the Front End*

6. Testing Results and Discussion

After implementing the previous design, this small, and integrated Front-End is obtained. In Table 1 are shown the main specifications of the final device. As it can be seen in the oscilloscope's screenshot from Figure 3, the heart signal acquired at the output has an amplitude of 3.3V. However, it has not the typical shape of an ECG. The period of the found signal is of 2.6s. That would correspond to 156 beats per minute, above the normal pulsations of a person at rest.

This is the first version of the prototype and the first results obtained it has to be enhanced and make a detailed study of what is occurring. The problem seems to come from a bad welding and also noise coming from the GND and Output pins.

Bandwidth	0.05Hz - 41Hz
Channels	RA, LA and RL as a reference
Supply voltage	Single Supply = 3V
	Lithium-ion cell battery
Size	3.3mm x 2.9mm
Gain	1100 V/V
Consumption	0.222mA/666µW

Table 1. *Specifications*

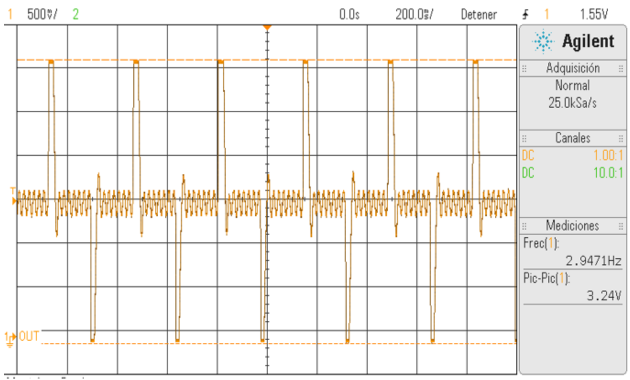

Figure 3. *Output Signal*

7. Conclusions and Future Works

In the present work a first approximation of a wearable ECG is shown. It consists on a low-cost device, with low consumption, battery powered and almost portable. The results point out that more effort must be made at the filtering stage. Once having improved the filter capabilities, extra functionalities should be included and total impedance achieved.

The fact is that final device is not independent, it needs to be connected to an oscilloscope to see the ECG signal. In a future project, with more time an analog to digital converter should be integrated together with a Bluetooth module to grant the autonomy of the system.

The constructed ECG does not make use of the lead-off detection circuitry included in AD8232. It could be useful to avoid recording disturbances. Also, it would be useful to include a system to detect when the electrodes have been placed in a wrong way. Reversal of the RA and LA cables is very frequent and is easily recognizable by the presence of negative P and QRS waves.

On further investigations, capacitive electrodes could be implemented. It is a technology that permits us to pick up potentials through clothing. They work with displacement currents instead of real charge currents, and the electrolytic electrode–skin interface is replaced by a dielectric film [9-11].

Finally, mention that from the integrated circuit to the discrete components the market product regulations have been followed. However, the device developed in this project is not comparable to the ones commercialized, since the highest multinational companies as Boston or MedTronics are investing in this type of products and the competitiveness is very high. For now, the main use of this ECG is for educational purposes.

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References

[1] Fye WB. A history of the origin, evolution, and impact of electrocardiography. *Am. J. Cardiol.*, vol 73, no 13, 1994, pp 937–49.

[2] Vallurupalli S, Paydak H, Agarwal SK, Agrawal M., Assad-Kottner C. Wearable technology to improve education and patient outcomes in a cardiology fellowship program - A feasibility study. *Health Technol*. vol 3, 2013, pp 267–270.

[3] Klabunde RE. Cardiac electrophysiology: normal and ischemic ionic currents and the ECG. *Adv. Physiol. Educ.*, vol 41, no 1, 2017.

[4] Wesley K. Huszar's ECG and 12-Lead Interpretation. 5th edition. Elsevier Health Sciences, 2016 (ISBN: 9780323355759).

[5] Engel JM, Mehta V, Fogoros R, Chavan A. Study of arrhythmia prevalence in NUVANT Mobile Cardiac Telemetry system patients. Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2012, pp 2440–2443.

[6] Perez L. New generation dynamic, wireless and remote cardiac monitorization platform: A feasibility study. *Int. J. Cardiol*., vol 144, 2010, pp 1–2.

[7] Single-Lead, Heart Rate Monitor Front End, AD8232. Analog Devices, Norwood, 2017.

[8] Ultralow Noise, 150 mA CMOS Linear Regulator. ADP150. Analog Devices, Norwood, 2015.

[9] Park C, Chou PH, Bai Y, Matthews R, Hibbs A. An ultra-wearable, wireless, low power ECG monitoring system. IEEE 2006 Biomedical Circuits and Systems Conference Healthcare Technology, BioCAS, 2006, pp 241–244.

[10] Spinelli E, Haberman M. Insulating electrodes: a review on biopotential front ends for dielectric skin–electrode interfaces. *Physiol. Meas.*, vol 31, no 10, 2010, pp. S183–S198.

[11] Matthews R, McDonald NJ, Hervieux P, Turner PJ, Steindorf MA. A Wearable Physiological Sensor Suite for Unobtrusive Monitoring of Physiological and Cognitive State. 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2007, pp 5276–5281.

[12] De Oliveira IH, Cene VH, Balbinot A. Portable electrocardiograph through Android application. Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS, 2015, pp 6780–6783.