INSTRUMENTATION AND SIGNAL ACQUISITION IN BIOENGINEERING
FINAL PROJECT
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Portable Electrocardiograph (ECG)

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Abstract

As a result of ageing population and a progressively greedy will of better healthcare, new devices have arisen. Some focus on prevention, others in treating. The prototype developed here focus in the acquisition of the heart's electrical activity with a simple electrical circuit embedded in an Arduino microcontroller, with the possibility of early heart diseases detection. An effective and cost contained solution was proposed and dozens of trials were performed with the device. These pointed to a high rate of detection of R, S and T peaks (~100%, 78,3% and 72,5%) with an accurate heart rate measure. Despite of the good results obtained, this device, for now, must not be used for other purposes than monitoring.

Introduction

Big efforts to provide good health care at affordable prices have become a central issue in the last decades. Along with wide technological developments, it has been possible to more efficient devices and with new available features. Wearables are a class of devices with an exponential growth in the last years, as problems with battery life get overpassed.

The developed electrocardiograph achieved by joining some Arduino capabilities with an analog circuit, which acquires, amplifies and filters a very weak signal obtained from the chest.

A set of algorithms were then proposed to detect arrhythmias, heart muscle necrosis, hypertrophic ventricles, variations in the heart rate depending on the position (lying down, seated or standing) of the person.

A set of trials were then carried out to evaluate the sensibility and reliability of the obtained measurements. Although we were only able to test our device in healthy people (thus, no pathologic recordings were obtained), different and representative results were obtained among all the candidates.

Given the results obtained versus the simplicity of the circuit, great improvements are expected to be achieved in a reduced time scale. Observing the world's tendency, in a near future, it is expected to have ECG (wearable) devices at home, automatically detecting many pathologies without clinician intervention.

Physiological Basis

A. Cardiac cycle and electrical activity

The cardiac cycle is controlled by the Sinoatrial node (SA node) via electrical stimulation. The node consists on a group of very peculiar cells with the ability to spontaneously produce an electrical impulse that propagates through a network of specialized fibers (Atrioventricular node, His bundle, Purkinje fibers), regulating heart muscle's contraction. Because it is responsible for setting the heart's rhythm, the SA node is often called the natural pacemaker.

This electrical activity of the heart is the biological fundament behind the electrocardiogram (ECG) register. In fact, each feature of the ECG is related to some phase of the cardiac cycle.

At the beginning of the cardiac cycle, both the atria and ventricles are relaxed (diastole), and the blood is flowing into the right and left atria from venae cavae and the four pulmonary veins, respectively. Since both the tricuspid and mitral valves are open, blood flows unimpeded from the atria to the ventricles.

Following atrial depolarization, represented by the P wave of the ECG, the atrial muscles contract from the superior portion of the atria toward the atrioventricular septum, pumping the blood into the ventricles through the open atrioventricular valves. At the start of atrial systole, the ventricles are usually filled with approximately 70–80 percent of their capacity, during the atrial systole the ventricles are completely filled. Atrial systole lasts approximately 100 ms and ends before the ventricular systole.

Ventricular systole follows the depolarization of the ventricles and is represented by the QRS complex in the ECG. Initially, the pressure generated in the ventricles isn't sufficient to eject the blood from the heart, the blood flows back and closes the atrioventricular valves, it's the isovolumetric contraction phase since blood's volume remains constant. When the contraction of the ventricular muscle counterbalances the pressures in the pulmonary trunk and aorta, the ejection phase of the ventricular systole begins and the blood is pumped from the heart.

Ventricular relaxation, or diastole, follows repolarization of the ventricles and is represented by the T wave of the ECG.

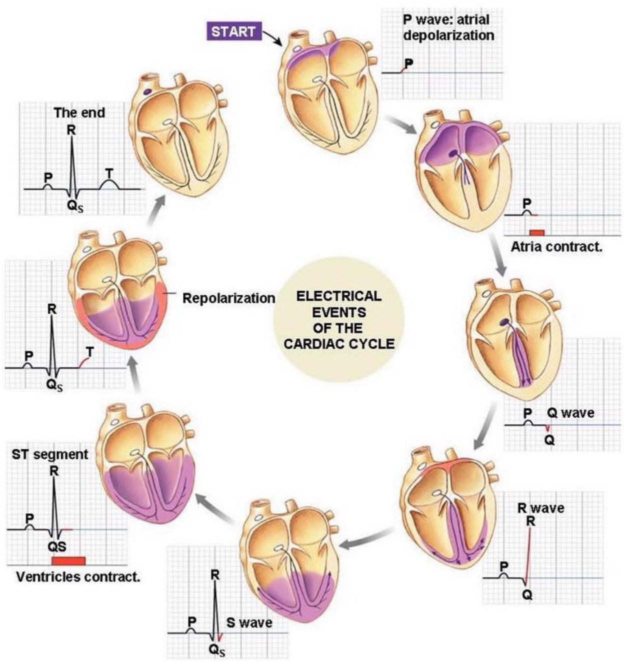


Figure 1 - Cardiac cycle events and corresponding ECG feature

B. ECG features and anomalies detection

P wave – Represents atrial depolarization during atrial systole, with a usual duration smaller than 120 ms. An increased or decreased P wave can indicate hypo or hyperkalemia, respectively. Right and left atrial hypertrophy can also be detected by observing P wave morphology.

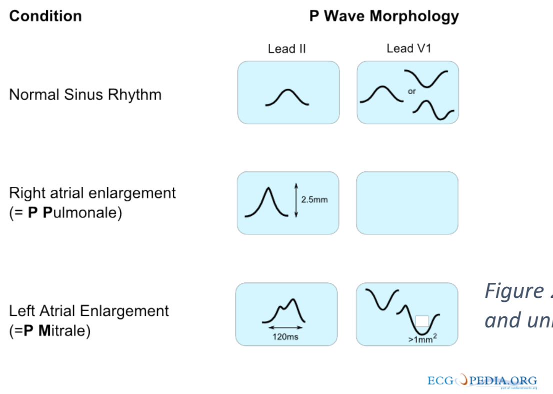


Figure 2 - P wave healthy and unhealthy morphology

QRS complex – Indicates ventricular depolarization and contraction during ventricular systole, with a usual duration between 60 and 100 ms. Prolonged duration indicates hyperkalemia or bundle branch block and increased amplitude indicates cardiac hypertrophy, which is a common condition in athletes. Other anomalies reveal the presence of infarction.

The time between R-R peaks may be used to compute the heart rate.

S-T segment – Refers to the gap between the S wave and the T wave, represents the time between ventricular depolarization and repolarization and has a usual duration between 80 and 120 ms. Flat, down sloping, or depressed ST segments may indicate coronary ischemia. ST elevation is the classical indicator for myocardial infarction.

T wave – Represents ventricular repolarization. T wave inversion (negative curvature) can be an indicator for several heart disorders.

U wave – Represents repolarization of the Purkinje fibers. It is not always visible on an ECG because it is a very small wave in comparison to the others.

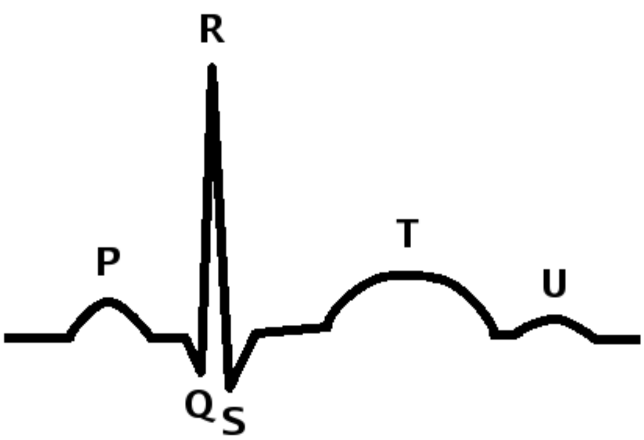


Figure 3 - Schematic representation of a standard ECG feature

Arduino

Arduino is an open-source electronic platform based on flexible and simple hardware and software. It was created in 2003 by a group of students from Interaction Design Institute Ivrea, in Ivrea, Italy. The name Arduino comes from a bar's name located in its native city where the creators used to meet. Its purpose is to create objects or environments. Arduino can sense the environment by receiving input from a variety of sensors and can affect its surroundings by controlling lights, motors and other actuators. The microcontroller on the board is programmed using the Arduino programming language, which is based on C++, and the Arduino integrated development environment (IDE), based on Processing. Most boards consist of an Atmel 8-bit AVR microcontroller with different number of pins, rom and ram memory (among others…). These pins use rows of female headers, in order to easily connect and integrate it with external circuits. The Arduino microcontroller also an integrated timer based on an oscillating crystal at 16 MHz. Arduino projects can be stand-alone or they can communicate with software running on a computer, such as MATLAB.

The relevance of this hardware is its ability to convert a physiological signal into a mathematical signal, which can be saved, modified and analyzed in a computer, using specific biomedical software. This data processing could be essential in a medical diagnostic center, where the least variation in the physiological signal could be crucial for the correct diagnosis of certain pathology.

Any program written in Arduino is commonly called a sketch and is saved under the extension ".ino". In order to be executed, it only requires 2 basic functions: setup and a loop. The 1st one is only executed once (after powering up the or resetting the board). Information like setting output/input pins; bit rate (baud); variables (…) can be given in this section of the program. Libraries can also be initialized in this section. These play an important role in Arduino programming, since a limited number of functions are available to be promptly used. On the other side, the loop will be executed cyclically with/without interruptions depending on the existence of interrupts or functions that deliberately pause the execution (delay, delayMicroseconds).

Many projects prototype can be performed, robots, automatized dispensers, games, printers and, of course, ECGs, EMGs, EEGs, Pletismography devices are some examples.

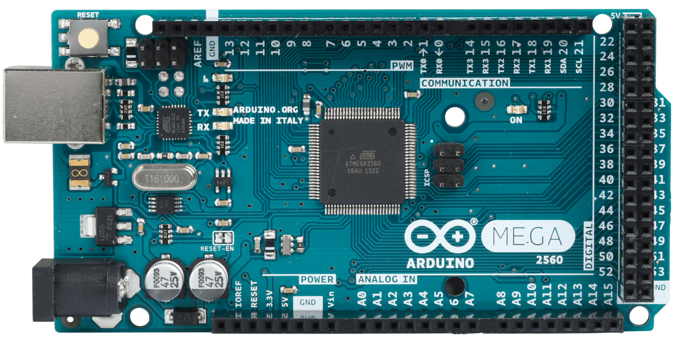


Figure 4 – Arduino Mega 2560 microcontroller board

Prototype Development & Design

The circuit used to measure heart's electric activity can divided in several blocks. Signal acquisition, amplification, filtration and offsetting were the 4 main procedures used to extract a very weak signal from ones' chest. All the connections were performed in a breadboard and then an Arduino Mega 2560 was chose to achieve all the digital processing.

A. Acquisition

The circuit proposed in this paper was based on a standard circuit of ECG acquisition. The input electrodes are connected directly to the ampop's positive terminals. Therefore, it was possible to amplify a very weak signal without disturbing the body voltage (due to high input impedances). To do so, ECG specific electrodes (*Tiga-Med Gold*) were used to gather the signal and transmit it through a set of 3 coaxial cables created to better insulate the circuit from external electromagnetic interferences. Along with this, another big advantage of these cables is the electromagnetic fields carrying the signal exist only in the space between the inner and outer conductors. This allows coaxial cable runs to be installed next to other metallic objects (e.g. other cables).

The position of each electrode greatly influences the polarity and the shape of the electric heart activity registered. Different positions empower one to study different specific ECG curve parameters. This is why in a clinical environment, it's expected to perform these tests with more than 3 electrodes.

B. Amplification

Taking into consideration that biosignals tend to have small and weak amplitudes, ranging from micro to mili volts, it is essential to amplify the signal before processing and display it. In order to achieve that, it was used an Instrumentation Amplifier INA126, which was supplied with ±9 V. Since it is intended to get a signal ranging Volts (able to be read by the Arduino, after passing through the analog filters), it is necessary to dimension the gain in the order of magnitude of 1000, to do so we used 2 amplification stages. At the end, the amplification in our targeted frequencies (1 to 5 Hz), was 2010 ×, which we verified experimentally by amplifying a signal generated with a known amplitude.

One way of improving our circuit would be to purchase the INA126 in a chip, in order to get a better amplification with the lowest noise (the right ampops would allow a higher CMRR). Due to cost containment criteria, this wasn't done.

The energy supplied to each ampop was provided by a set of two 9 V batteries (maximum voltage at the output of each one). To amplify the difference between the signal from each electrode (V3 and V4) we had to remove the DC component, which was done adding a capacitor in series (C1 and C2).

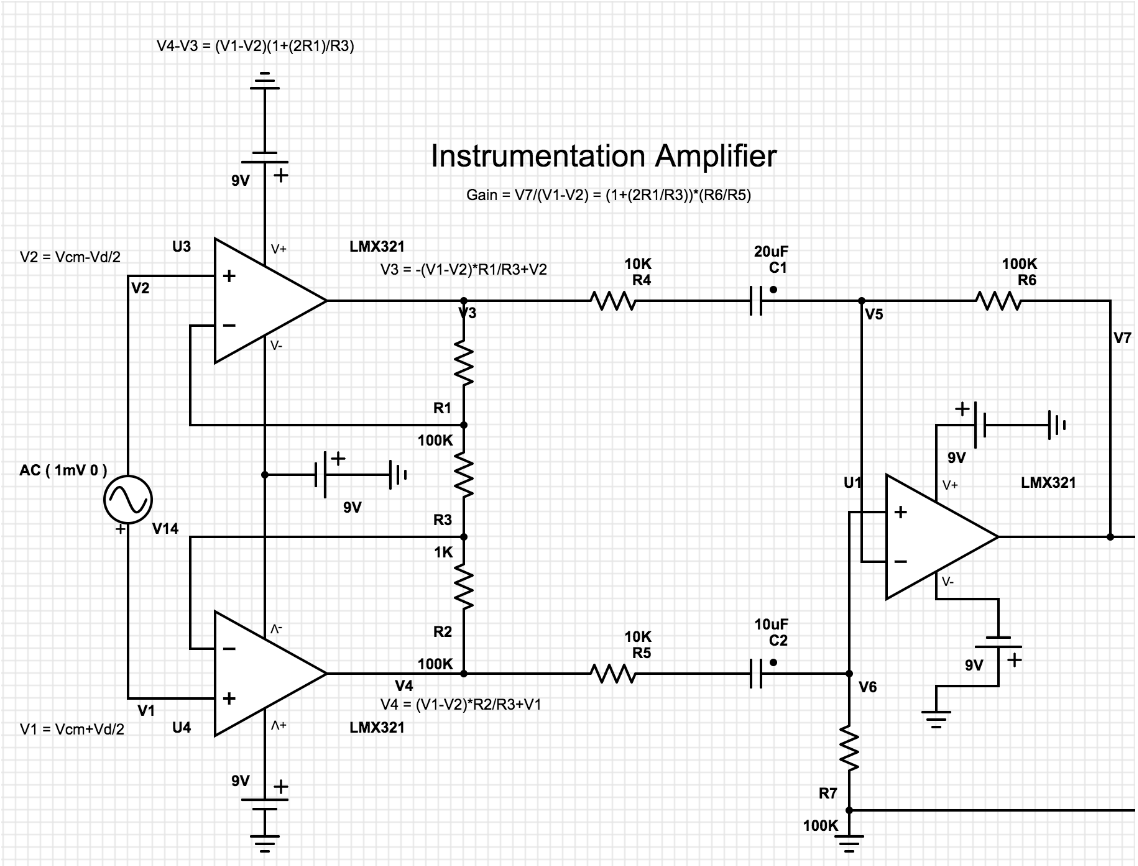


Figure 5 - Acquisition and 2 stage amplification circuitries

C. Filtration

The human body is a good conductor acting as an antenna which picks up electromagnetic radiation present in the environment. In the current project, the most common electromagnetic radiation, that was necessary to deal with, was the one coming from the power line, which has a fundamental frequency around 50Hz. To reduce its sources, both ampops and the Arduino were supplied with batteries. Other possible interference sources are muscular activity (apart the one from the heart), including respiration and movement. It is also important to refer the limitations of breadboards and the enormous number of connections which has interfered in the circuit stability and contributed to signal distortions. Moreover, the electrodes should also be as tighten as possible to the skin. To improve conductivity in the interface between the skin and the electrode, a conductor gel could be used (although we didn't use it for the sake of model simplicity and low cost). To remove all these distortions sources, we designed 2 analog low-pass filters and 1 analog high-pass.

Low-Pass Filters

2 low-pass filters with 2 different cutoff frequencies (24 Hz and 44 Hz) were used to eliminate power line frequency at a higher rate than 20 db/dec (Fig. 6). Since, we got an acceptable frequency response with these 2 passive filters, we avoid using active filtration (with ampops) to get a circuit as energetically efficient as possible, considering energy limitations present in portable devices.

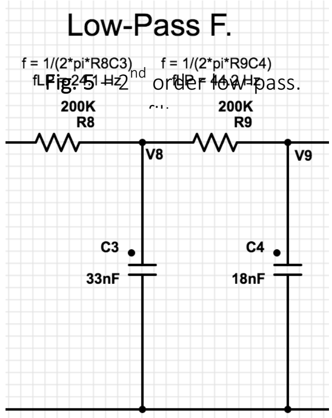


Figure 6 - Low-pass filter circuitry

High-Pass Filter

This high-pass passive (same reason as before) filter aimed to remove DC component and slow undesirable oscillations in the signal (Fig. 7).

ECG signal got undeniably better, although it still had some noise due to the presence of a transition band in each frequency response. To complement these 3 filters, another 2 (digital) were added. Using 'iirnotch' and 'butter' functions in Matlab, we extracted the corresponding IIR coefficients and implemented the filters through the Arduino interface. In order to calculate each coefficient, sampling frequency had to be provided. We will explain in further detail, how we were able to sample an analog signal from the circuit with a constant and well-defined time step.

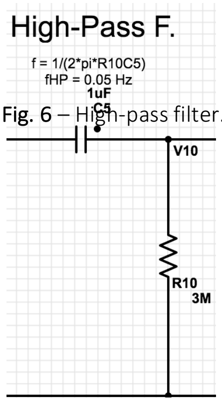


Figure 7 - High-pass filter circuitry

D. Offsetting

Arduino's analog input pins are only able to read frequencies between 0 and 5V. Since our output signal varied between positive and negative voltages, a voltage divider had to be added to ensure the total signal was detected. 1 resistance of 1.1 MΩ and another of 200 kΩ between V_{cc} and the ground, allowed us to sum 1.4 V (DC) to the body signal.

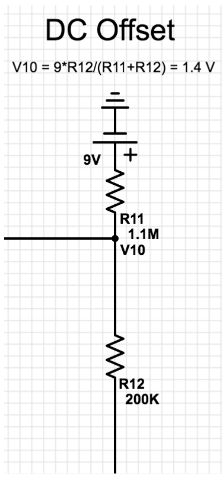


Figure 8 - DC offset addition circuitry

E. Arduino

To visualize the obtained signal, we connected the prototype's output to Arduino Mega 2560 microcontroller.

The output signal (amplified and filtered) from the circuit was then received by the analogic pin A0 and the ground reference of the circuit connected to GRD pin of the hardware.

In Arduino IDE the signal was filtered by an IIR notch filter (from 40 to 60 Hz) and another IIR low-pass Butterworth (cut-off frequency 100 Hz) of 3rd and 4th orders, respectively:

Notch Filter

$$y(t) = 0.2012\,x(t) - 0.3256\,x(t-1) + 0.2012\,x(t-2) + 0.3256\,y(t-1) + 0.5975\,y(t-2)$$

Low-Pass Filter

$$z(t) = 0.0495\,y(t) + 0.1486\,y(t-1) + 0.1486\,y(t-2) + 0.0495\,y(t-3) + 1.1619\,z(t-1) - 0.6959\,z(t-2) + 0.1378\,z(t-3);$$

These coefficients were obtained using the Matlab function iirnotch and butter, respectively (see Matlab script attached to this report to know exactly which parameters do these functions receive and the frequency response of each one).

An important criterion for the filters' parameter definition is the sampling frequency. To monitor this, an interrupt was set. Every time the interrupt is ON, it interrupts the loop cycle and some previously defined operations in the ISR function are performed, including the signal acquisition from pin A0. We chose a sampling period of 2 ms, or equivalently, a sampling frequency of 500 Hz. By the Nyquist theorem we should be able to acquire frequencies below 250 Hz without aliasing (we note the low-pass filters at 24 and 44 Hz plus the digital at 100 Hz). We tested the sampling frequency acquiring a 50 Hz generated signal and confirming we had 10 samples per period.

After collecting signal from the circuit and filtering it using 2 digital filters, some peak detection algorithms were applied to detect heart rate (4 digit 7 segment display showing it), QRS and ST time interval in the ISR function. Finally, based on this value, a simple algorithm to detect arrhythmias was proposed.

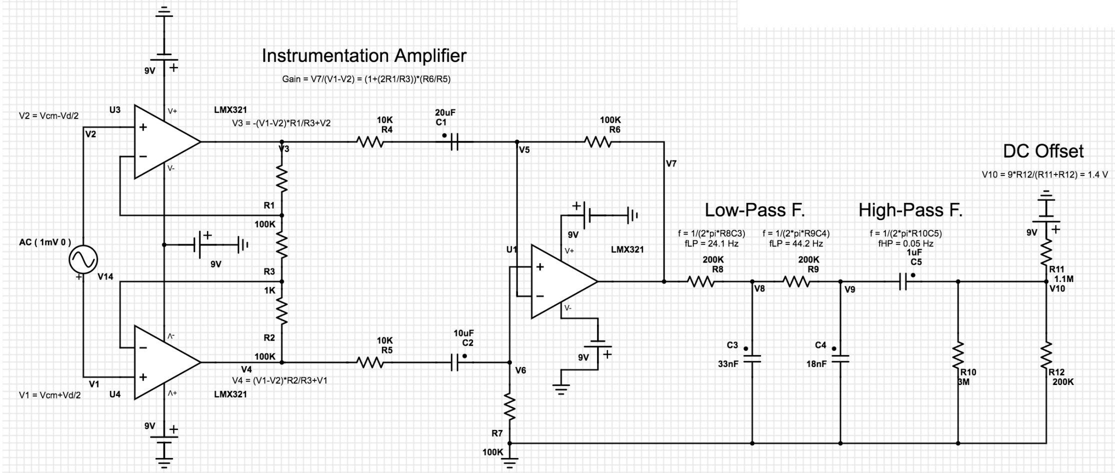
F. Complete Electric Circuit Scheme

After joining each block explained before, a final electric ECG circuit can be represented.

On the left side, the voltage source represents the expected signal from the body, 2 electrodes are connected to the chest of the person under clinical analysis. The 3rd reference electrode (left wrist) will be in contact with the circuit's ground.

The circuit output signal is in the node V10 and is connected to an Arduino analog port. Check PartSim reference [8], where all our ideas were brainstormed before implementation.

Figure 9 - Complete analogic circuitry



G. ECG Real & Schematic Prototype

Schematic Prototype

All the physical connections performed in the lab in a common breadboard are represented in Fig. 10. Due to the lack of some components in circuits.io (software used to design the circuit), assume functions generator as the electrodes connected to the body; the isolated 9 V battery is connected to a specific adapter, which is plugged to the Arduino and 4 yellow cables were connected to extra digital pins which are not present in the scheme (pretend the pins used are possible digital inputs).

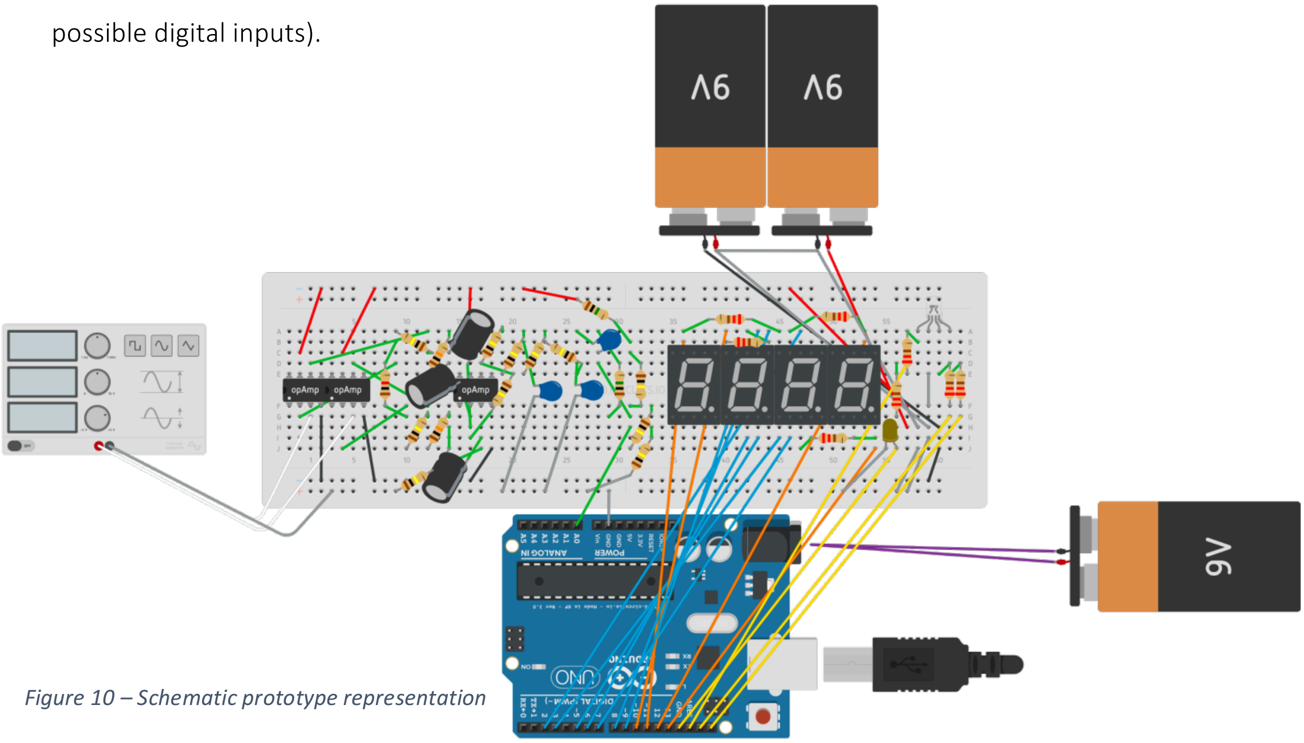


Figure 10 – Schematic prototype representation

Real Prototype

The actual board, with all the circuitry, is represented in Fig. 11. Because it is reasonably less perceivable, the previous scheme was added for a better understanding.

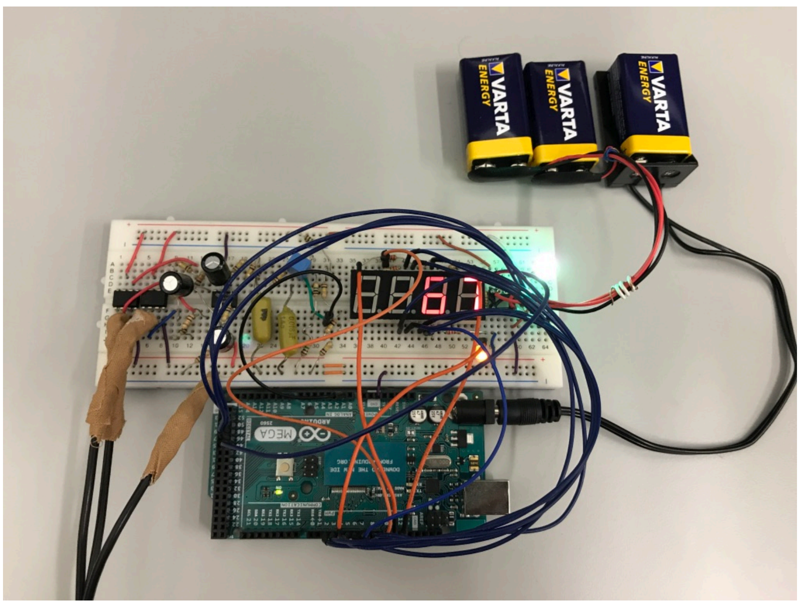


Figure 11 - Actual prototype aspect

Results

In the end, we were successful in obtaining a good-looking ECG signal (Fig. 12 and 13) and plot it in the computer.

Heart Rate (HR)

We were able to compute either the instantaneous heart rate (from the time between each R peak) as the average heart rate (from the time of a 5 sequence of R pulses). We chose to show in the 4 digits – 7 segments an average of both (so the displayed value wasn´t as volatile as the instantaneous HR nor as static as the 5 sample HR). We also compared our HR computed values with the ones obtained with the plethysmography smartphone app Instant Heart Rate©, from Azumio Inc., and found them to be similar.

It was also possible to note the HR increase with deep inhalation and decrease with exhalation.

Features Detection

In the Arduino, we implemented algorithms for R, S and T feature detection. After trying both derivative and threshold based algorithms we went for the latter due to the better results, for the T wave detection we experimented several empirical conditions.

In a still person, in the absence of artifacts, our algorithm detects practically 100% of the R peaks! (Thus, the very good results in HR calculation).

The results, however aren´t so good in S and T detection, in three 2 minute tests we missed 21,7% of the S and 27,5% of the T wave (S and T misses appear to be uncorrelated). As we can see from Fig. 12, ECG varies from person to person, in one of our tests there were also some false detection of Q peaks as S. We had already identified some systematic errors in our S detection algorithms and think that with more time we would be able to perform in S detection as good as in R. T wave detection is a more complicated challenge, a literature search revealed that T real-time detection is a hard problem, we think the solution would have to include derivatives (and even a conjugation of derivatives and thresholding).

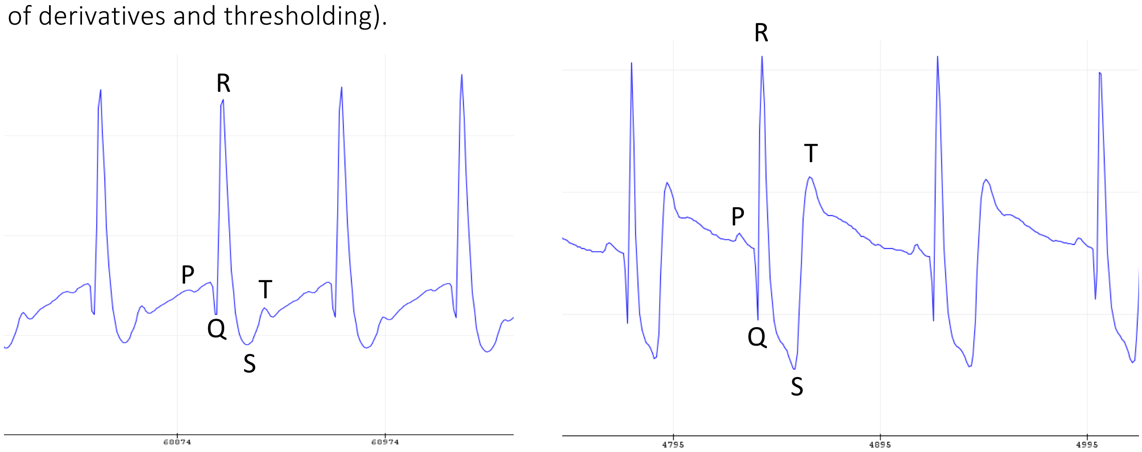


Figure 22 - ECG curves acquired from 2 different people and identified features

QRS Amplitude

We computed a naive algorithm for the detection of sinus arrhythmia, based on the variations of the QRS complex amplitude. However, we didn´t test it because all our tests were performed on healthy subjects. Nevertheless, arrhythmia detection seems easy to achieve with our ECG prototype.

Segment Duration

In the beginning of this paper we mentioned that segment duration was important to determine several heart disorders. With this in mind we also designed an algorithm to compute RS duration (and estimate QRS complex duration by duplicating this value) and also ST duration. However, in the latter, the obtained results are largely compromised due to the S and T missed detections. Also, we only had the possibility to test the prototype in healthy subjects and thus we don't know how helpful these could be in anomalies detection.

Figure 33 - ECG curve with less distinguishable features, electrodes location is a key factor for the signal quality

Discussion

The coaxial cables, the analogue & digital filters along with the reduction in the number & length of wires made possible the 50 Hz noise removal from the body's ECG signal. Nevertheless, the output signal slightly contains its information compromised due to the noise. Its attenuation was not entirely achieved since the design and the choice of certain compounds may not be the most correct:

- Different ampops have different common mode rejection ratios;
- Depending upon the diameter of the coaxial cables, they will better conduct low or high frequency signals.

These points were only slightly addressed due to time constraints.

Nevertheless, we were able to detect practically 100% of all R peaks, 78,3% of S and 72,5% T peaks, in real time, present in the signal. Last one with less accuracy due to the reduced dimensions and location in the signal, more difficult to threshold.

Relatively to the processing task, we were able to develop an algorithm to measure heartbeat, the time interval ST, as well as, the time across the complex QRS. The maximum amplitude of this complex was also determined.

Conclusion

Since the world's population is ageing and particular regions are becoming depopulated, the healthcare assistance with continuous monitoring of physiological parameters (allowing preventive care, which is more effective and less costly than treating) for patients who live in remote locations can be a crucial device. Moreover, it would allow teleconsulting, patient medication, diagnosis and the prevention of unnecessary specialist consultations or laboratory examinations.

In this project, an electrocardiograph was designed and developed. A small prototype which acquires, with three electrodes, one placed in the arm and 2 in the chest, the cardiac electrical activity.

Despite the tremendous difficulty in recognizing the cardiac activity from the input signal (acquired with the electrodes) we managed to greatly attenuate the noise and obtain a clean, feature recognizable, final signal.

The signal acquisition and instrumentation part of the prototype is working properly, we obtain a good-looking signal with a very simple circuit embedded in a highly portable system.

However, we fell short on the signal processing part, real-time feature detection algorithms needed more time to be refined, and more controlled tests had to be performed to validate those detections, this however was out of the scope of this course.

A future improvement, besides algorithm refinement, would be to attach a wireless emitter to the system to allow signal monitoring without being connected to a computer. With the acquired signal stored on a computer, harder algorithms for feature detection that can't be performed on real time, as Wavelet decomposition or Empirical Mode Detection, could also be used.

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