Development of an acquisition circuit of multiple biological signals for integration into a wearable bracelet

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by
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of the requirements for the degree in
Electronics System’s Engineering

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Abstract

This project deals with the design, validation and prototyping of a circuit for the acquisition of biological signal. These signals are electrocardiogram and pulse through photoplethysmography and are measured on the subject's hands and on one finger.

The tests carried out have demonstrated that the design prototype is able to capture both, electrocardiogram and pulse by means of photoplethysmography, and to measure the PAT from these two signals.
**Resum**

Aquest projecte tracta sobre el disseny, validació i prototipatge d'un circuit per a l'adquisició de senyals biològiques. Aquests senyals són l'electrocardiograma i el pols a través de la fotopletismografia i està previst que es mesurin al canell del pacient i a la mà oposada.

Les proves realitzades han demostrat que el prototip dissenyat es capaç de mesurar tant l'electrocardiograma com el pols mitjançant fotopletismografia i mesurar el PAT fent servir ambdues senyals anteriors.
Resumen

Este proyecto trata sobre el diseño, validación y prototipado de un circuito para la adquisición de señales biológicas. Estas señales son el electrocardiograma y el pulso a través de la fotopletismografía y son medidas en las palmas del paciente y en un dedo de la mano.

Las pruebas realizadas han demostrado que el prototipo diseñado es capaz de medir tanto el electrocardiograma como el pulso a través de fotopletismografía y, a partir de estas, medir el PAT.
I would like to dedicate this thesis to my family, friends and especially my girlfriend, who has been by my side through all the way here, supporting me every day.
Acknowledgements

I would like to thank Victor Mileo for all the support while developing the boards and for the driver that he facilitated since without that the project would have been much long. Also, I would like to thank all the people that has lost a bit of its time to take measures with the device to ensure its correct behaviour.
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1. **Introduction**

The purpose of this project is to design a prototype for electrocardiogram (ECG) signal acquisition by means of electrodes and pulse acquisition by means of photoplethysmography (PPG) using different photodiodes. With this signals and further processing, the pulse arrival time (PAT) can be obtained.

Pulse arrival time is determined as time interval from QRS apex in ECG to a point of pulse signal, acquired by photoplethysmography in our case in a fingertip (or in the wrist), beat-by-beat.

Previous work done in another project [1] was mainly focused on the acquisition of electrocardiogram and pulse signals and then send that information through RS232 to a computer, where it should be visualized. With this new project, the target is to improve modularity of the system by means of a standard platform like Arduino, finish the design and to build a prototype for testing purposes. This design has a clear advantage since it can nourish from the huge community behind Arduino to keep enhancing the prototype with new features at low cost and with relative easiness.

The system that is intended to be build consist on a basic front-end for electrocardiogram and pulse acquisition. Two dry electrodes for the ECG and an assortment of different LEDs with a detector for light readings are the basic sensors for the acquisition of this signals. Next, ADS1294 takes care of sampling the input signals and to send those samples through SPI to a ATSAMD21 Cortex M0 (integrated on a Adafruit Feather M0 board). The Cortex M0 is the brain of the board and the one who makes the link either towards PC or to any other device like and smartphone. For simplicity and reach of the project, a link between Feather M0 and PC through USB will be created, where the data received will be evaluated and PAT measured.

1.1. **Electrocardiograph**

Physiology of the hearth is really complex, but keeping it simple, a heart is formed by four chambers. The upper two chambers (left/right atria) are entry-points into the heart, while the lower two chambers (left/right ventricles) are contraction chambers sending blood through circulation. The circulation is split in two loops, one through the lungs (pulmonary) where blood obtains $O_2$ and release $CO_2$ and one through the body(systemic) where $O_2$ is distributed and $CO_2$ gathered.

The cardiac cycle refers to a complete heartbeat from its generation to the beginning of the next beat, comprising several stages of filling and emptying of the heart chambers. The frequency of the cardiac cycle is referred to as heart rate, measured in beats per minute (BPM).

The heart operates automatically since it contains self-exiting cells. The rhythmic contractions of the heart occur spontaneously, but are sensitive to nervous or hormonal influences, particularly to sympathetic and parasympathetic activity.

Electrocardiography is the process of recording the electrical activity of the heart over time using electrodes placed on the skin. These electrodes record small electrical variations on the skin due to the heart electrophysiologic pattern during each heartbeat. The graph of voltage versus time obtained through these electrodes is referred to as electrocardiogram or ECG.
ECG records the electrical activity generated by heart muscle depolarizations and repolarizations, which propagate in pulsation electrical waves towards the skin.

![ECG waveforms](image)

**Figure 1. ECG of a heart in normal sinus rhythm.**

ECG interpretation is that of a pattern recognition. These patterns are produced due depolarization and repolarization of the heart with each contraction. Normal rhythm produces four different waves: P wave, QRS complex, T wave and U wave.

- The P wave represents atrial depolarization (contraction).
- The QRS complex represents ventricular depolarization (contraction).
- The T wave represents ventricular repolarization (distention).
- The U wave represents papillary muscle repolarization (distention).

Voltage generated by those contractions is small, but can be picked up reliably with electrodes attached to the skin. There are different ways of placing electrodes around the body in order to acquire the ECG signal.

![Limb leads and augmented limb leads](image)

**Figure 2. Limb leads and augmented limb leads**

 Leads I, II and III are called the limb leads. The electrodes that form these signals are located on the limbs. The limb leads form the points of what is known as Einthoven’s triangle. In this project, lead I is used to acquire the ECG signal. This lead references the voltage between the left arm (positive – LA electrode) and the right arm (negative – RA electrode). Electrodes used will be dry type since previous evaluation [1] made clear that they give a good response for the purpose of this project.
1.2. **Photoplethysmography**

Photoplethysmography is an optical technique used to detect volumetric changes of an organ. It is a low cost and non-invasive method that can be used to make measurements at the surface of the skin. Since light is differently absorbed by blood than the surrounding tissues, the changes in blood flow can be detected by PPG sensors as changes in the intensity of light. The voltage signal from PPG is proportional to the quantity of blood flowing through the blood vessels. Even small changes can be detected using this method.

![Figure 3 a. PPG waveform](image1)

**Figure 3. Pulse wave shape and generation**

Pulse wave obtained by photoplethysmography can be separated in two phases: the anacrotic phase where the signal rises (related with systole) and the catacrotic phase where the signal descends (related with diastole).

1.3. **Uses of electrocardiogram and pulse signal**

1.3.1. **Pulse Arrival Time**

Pulse arrival time (PAT) is the time interval which is needed for pulse wave to travel the distance from the heart to some distal place of the body (e.g. finger, earlobe, toe). Measurements of PAT have several applications as estimation of the arterial blood pressure or baroreflex sensitivity.

One of electrocardiogram (ECG) and photoplethysmogram (PPG) applications is the estimation of PAT. There are several definitions of PAT since the end point of measured time interval could not be defined perfectly.

![Figure 4. Different PAT definitions](image2)
In this project, PAT will be measured from the apex of QRS complex of ECG (R wave) to the pulse maximum derivate of the PPG signal.

1.3.2. Heart Rate Variability
Heart rate variability (HRV) is the variation of the time intervals between heartbeats. It is measured by the difference between beats.

Methods used to detect beats include ECG and the pulse wave derived from PPG. With these signals we can obtain the RR series (temporal series between R peaks). HRV oscillations can be studied in both temporal and frequential domains.

1.4. State of the art
Nowadays, the market is being flooded with devices for monitoring our physical activity all day long. Many of these devices make use of PPG to obtain the pulse of the subject but a few ones are starting to incorporate also ECG measurement methods like the ones proposed in this project. A quick overview of the most known devices will be done to have an idea of the current market status.

- Polar A370

Polar wrist-based heart rate measurement integrates heart rate into a device that can be worn on the wrist. It enables to quickly and easily check the heart rate by activating the training mode. It measures heart rate accurately and easily, and gives training guidance on how to train at the right intensity. Polar wrist-based heart rate measurement is based on Polar’s proprietary optical heart rate algorithm to give the best possible results, with an emphasis on both design and functionality.

- Garmin Vivoactive HR

Same concept that Polar device, with Garmin Elevate proprietary technology, it measures the heart rate using tow LED on the wrist side. This wristband is able to compute how many calories are burned along the day and quantify the intensity of the activities performed.
– Zucoor RB77
This device comes from the Chinese market. It allows pulse measures by photoplethysmography and also electrocardiogram acquisition using two electrodes in the wrist plus one in the display to place a finger. They use the PWTT (pulse wave transit time) to measure the blood pressure of the subject. For the data acquisition this wristband uses one of the chips of the ADS129X family from Texas Instruments.

![Figure 7. Zucoor RB77 device](image)

– Binyeae G20:
Like the Zucoor RB77, the Binyeae G20 features the acquisition of electrocardiogram and pulse by photoplethysmography in the same device. It uses the same principle to acquire PWTT, one LED and electrode on the wrist and another electrode in the display region.

![Figure 8. Binyeae G20 device](image)

1.5. **Requirements and Specifications**
This project is englobed in a bigger one that pretends to create a wristband able to obtain multiple biological signals and the board designed in this project will be responsible of acquiring the necessary signals to compute PAT.

Main goals are to design and validate the circuitry for electrocardiogram and photoplethysmography signal acquisition, to design a PCB able to accomplish those targets and to validate the PCB.

Having in mind those goals, some work packages has been defined to maintain a tracking of the work realized:

1. Design a circuit with different photodiodes to evaluate which wavelength and position is best for the acquisition of the signal.
2. Design a circuit for ECG acquisition, with hardware filtering of the signal to reduce noise.
3. Design a PCB with previous circuits integrated and validate the design
When developing the PCB, focus must be kept on two principal points:

- To have a modular design easily expansible with possibility to integrate other sensors.
- To acquire ECG and PPG signals with enough resolution regardless the user.

Specifications given for the project are just to design a PCB able to capture the electrocardiogram and the pulse signal.
1.6. **Time Plan**

The time plan has suffered changes since critical review. Due to the extra time required, it was not possible to deliver the project in the first deadline. Hence, final documentation has been displaced from where initially was intended to be written to where has been finally written. Some time was spent at the beginning understanding the signals and its implications. Later, design and acquisition of the electrocardiogram and pulse by photoplethysmography was started and, upon its finalization, design of the PCB began. PCB has been delayed and are still on its way to Barcelona. When they arrive, the components will be soldered and some measurements will be taken.

![Time plan of the project](image)

*Figure 9. Time plan of the project*
2. Circuit Design and Acquisition

2.1. Overview

This prototype acquires both electrocardiogram and pulse following a simple process: measure voltage on electrodes and photodiode, sample that voltage with ADS1294, send data through SPI to Feather M0 and use USB connection to collect the data in a computer with MATLAB.

For the pulse by photoplethysmography two points will be considered, finger and wrist. Several measurements will be made to decide where photodiodes will be placed. The objective is to illuminate the skin of the subject and capture the quantity of light reflected by the skin depending on how much blood is travelling.

The electrocardiogram will be obtained using a reference voltage and two electrodes, one against the skin of the arm and one placed on top of the prototype where a finger from opposite arm will be placed, following the Einthoven first deviation. Using both signals and a differential amplifier, the electrocardiogram is obtained from the subject.

The ADS1294 uses the channel one for electrocardiogram acquisition and the channel two for pulse acquisition. The third channel is also connected to the photoplethysmogram device with a different conditioning circuit for test purposes. Once signal arrives to ADS1294, it passes through a programmable gain amplifier, which will be configured to have a gain of 6x, and then is sampled on a delta-sigma analog-to-digital converter. Once signal has been converted it is sent through SPI to the next device.

To be able to manage all the information acquired by the front-end, a Commercial Off-The-Shelf product is used, the Adafruit Feather M0. The advantage of using a product like this one is notorious. For instance, since it uses an Arduino base platform for programming the device, the Arduino GUI can be used for developing, compile and debug the code for this component. This board also come with battery management circuitry integrated, which makes designing a portable prototype simpler. Using this device allow to improve and expand the prototype with relative easiness, making it more modular, since it has 20 GPIO pins, I2C and SPI protocol support, BLE integrated module and USB connection for data transmission but also for charging.

Signal in Feather M0 is received by SPI and then sent through USB to a computer, where MATLAB will evaluate and represent the information collected.

2.2. Signal conditioning

Three different blocks can be differentiated in the conditioning of the signals acquired:

- Photoplethysmogram conditioning
- Creation of reference level to leverage full range of ADS1294
- Electrocardiogram conditioning

For photoplethysmogram conditioning, the selected combination of LEDs must be driven by a MOSFET and then the voltage on the photodetector (OSRAM SFH 7050) has to be measured.

The OSRAM SFH 7050 is a fully integrated optoelectronic sensor, specifically designed and optimized for reflective photoplethysmography. This sensor features three different
emitters and one detector with a light barrier to minimize optical crosstalk between emitters and detector improving signal-to-noise ratio all in a small package (4.7 mm width, 2.5 mm depth, 0.9 mm high).

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</tr>
<tr>
<td>2</td>
<td>GA</td>
<td>Green LED Anode</td>
</tr>
<tr>
<td>3</td>
<td>RA</td>
<td>Red LED Anode</td>
</tr>
<tr>
<td>4</td>
<td>PA</td>
<td>Photodiode Anode</td>
</tr>
<tr>
<td>5</td>
<td>PC</td>
<td>Photodiode Cathode</td>
</tr>
<tr>
<td>6</td>
<td>RC</td>
<td>Red LED Cathode</td>
</tr>
<tr>
<td>7</td>
<td>IA</td>
<td>Infrared LED Anode</td>
</tr>
<tr>
<td>8</td>
<td>IC</td>
<td>Infrared LED Cathode</td>
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Table 1. Pinout of SFH 7050

In Figure 10, the basic structure of this sensor can be seen. It contains a green emitter (525 nm peak), a red emitter (660 nm peak) and an infrared emitter (950 nm peak). The photodiode contained in this chip can capture light in the spectre from 400 nm to 1100 nm, with its peak at 920 nm, making it more sensible to infrared lights.

One N-channel MOSFET for each light has been used to activate them separately. To control the amount of current through the LED, a 100 Ω resistor has been placed as well as a 1 kΩ resistor in series with gate transistor for protection.

The detector, has been conditioned in two different ways, by a resistor or by a transimpedance amplifier.

First method uses a 1 MΩ resistor in parallel with the photodiode. Since typical current values are around 0.4 µA, measured voltage on the resistor will be around $1.62 \pm 0.4$ V. The circuit is represented in figure 12 a, where design can be observed, with added jumpers to be able to select which type of acquisition is preferred.

Second way of measuring the photocurrent is using a transimpedance amplifier (TIA), a current-to-voltage converter implemented by an operational amplifier. Although a transimpedance amplifier is a good method to convert the linear response of the photodiode into a voltage measurement, a lot of care should be taken while designing this transimpedance amplifier since they are prone to oscillate. To design this transimpedance amplifier a Microchip MCP6024 has been used, a rail-to-rail input and output operational amplifier. Also, the recommendations from has been considered to avoid unwanted behaviours [6].
In figure 12 b, the circuit proposed for this transimpedance amplifier is represented. Also, taking advantage of the remaining operational amplifiers, one of them has been used to create a reference voltage value by means of a simple voltage divider and a voltage buffer to isolate from any loads that can affect the reference produced. No filtering for the photoplethysmography signal has been implemented in the final board since signal is later processed by software. However, a low-pass and high-pass filters could be implemented in order to reduce computational cost.

For electrocardiogram conditioning, the design has been refurbished from previous project [1] and small modifications has been done over that design. The focus has been to remove frequencies out of the region of interest by means of a couple of filters, a high-pass and a low-pass filter. For the low-pass filter, a passive RC is in charge of avoiding aliasing effects and signal filtering with a cut-off frequency $f_{c-l} = 40.81 \text{ Hz}$.

$$\text{Lowpass filter: } f_{c-l} = \frac{1}{2\pi R_1 C_{26}} = 40.81 \text{ Hz}$$

$$\text{Highpass filter: } f_{c-h} = \frac{1}{2\pi R_2 C_{25}} = 1.59 \text{ Hz}$$
2.3. **Signal Acquisition**

For the electrocardiogram and pulse signal acquisition, the past choice was the ADS1294, device compliant with ANSI/AAMI EC11, EC13, IEC 60601-2-1, IEC 60601-2-27 and IEC 60601-2-51 regulations.

In this project, this selection is maintained since it is the best overall device that can be find in the market and leave space for expansions.

This device features four channel with 24 bits depth each, delta-sigma analog-to-digital converters that offers data rates from 250 SPS to 32 kSPS, integrated programmable gain amplifiers with gains from 1 to 12 and a SPI compatible interface.

It has a highly-programmable multiplexer that allows for temperature, supply, input short and right-leg drive (RLD) measurements. Additionally, this multiplexer allows any of the input electrodes to be programmed as the subject reference drive. It also features a lead-off detection to ensure all leads have a suitable connection with different strategies for this detection.

Data retrieval from ADS1294 is accomplished in one of two methods:

- **RDATAC**: read data continuous command sets the device mode that reads data continuously.
- **RDATA**: the read data command reads just one data output from the device.

RDATAC mode will be used to have continuous data stream, this way the Feather M0 only concern is to get the data converted by ADS1294 and send it to a computer, speeding up the process and avoiding timing managements onto the microcontroller.

![Figure 14. ADS1294 Simplified Schematic](image-url)
The configuration that is used on the ADS1294 for the acquisition of data is the following:

- Low-power mode with a sampling frequency of 1kSPS.
- No internal reference and RLD disabled.
- Channel 1 and 2 in normal operation mode, with PGA of 6x and normal electrode input.
- Enable SPI communication and set RDATAC mode.

For the design of the acquisition circuit, it has to be taken into consideration that a 3.3 V power supply is been used, hence the full-scale range of our signal will depend on:

\[
\text{Full Scale Range} = \frac{2 \cdot V_{\text{REF}}}{\text{Gain}}
\]

where \(V_{\text{REF}}\) is 1.65 V, provided by an external circuit and gain is set to 6x. The ADS1294 output 24 bits of data per channel in binary two's complement format, MSB first. The LSB has a weight of \(V_{\text{REF}} / (2^{23} - 1)\). A positive full-scale input produces an output code of 7FFFFFFh and the negative full-scale input produces an output code of 800000h. Having this in mind, the maximum differential input that will not saturate the device with current configuration would be:

\[
2 \cdot V_{\text{REF}} \cdot \frac{6}{\text{Gain}} = 2 \cdot 1.65 \cdot \frac{6}{6} = 0.55 \text{ V}
\]

And a resolution of:

\[
\frac{V_{\text{REF}}}{(2^{23} - 1)} = \frac{1.65}{(2^{23} - 1)} = 0.197 \text{ μV}
\]

The reference can be also obtained from the same ADS1294 without need for an external bias by internal configuration, but this reference is limited to 2.4 V (with 3 V power supply) and 4 V (with 5 V power supply). To have more control over this reference level, it was decided to implement it with an external source at 1.65 V.

2.4. Data management

As stated in the overview of the system, once signals have been sampled, ADS1294 send the data through SPI to the Adafruit Feather M0 board. This board collects the data and send them to a computer to represent and process the results. In this case, a USB connection is used to send data to a computer, where MATLAB is in charge of collect, represent and evaluate measures.

2.4.1. Adafruit Feather M0

For the development of this prototype an Adafruit Feather M0 Bluefruit LE has been selected. The Feather M0’s comes with an ATSAMD21G18 ARM Cortex M0 processor, clocked at 48 MHz and at 3.3V logic. This chip has a 256K of FLASH and 32K of RAM. It also comes with mini-USB connector and driver, with USB-to-Serial program and debug capabilities already build-in. It is specially focused for portable projects, with an added connector for 3.7V Lithium polymer batteries and integrated battery charging through USB. The Feather M0 automatically switch over to USB power when its available. This version of the board comes with integrated Bluetooth Low Energy chip, the Nordic nRF51822. The communication with this device is over UART and Adafruit have built applications for iOS and Android that can be useful as starting point to send data over Bluetooth.
The prototype board will share the same shape of this Feather M0, making it easy to assemble and reducing total dimensions. Also, it will maintain the same pinout. This way other feather boards can be attached to the system without concerns about compatibility.

For the integration between the TI ADS1294 and the Feather M0 an already developed driver has been used. This driver has been provided by Victor Ferrer Mileo in order to focus the efforts into acquisition algorithm [7]. The code that allows the acquisition data can be consulted on Appendix II.

In figure 15, the flow diagram of the execution on Feather M0 can be observed. The basic workflow that it follows is:

- Configuration of Feather M0: pin Mode, serial speed, …
- Initiation of ADS1294: reset to default, configuration of sampling speed, gain of each channel and put device in “read data continuous” mode
- Start loop sequence
  - If there is available new data:
    ▪ Get data and print byte per byte into Serial
    ▪ Repeat loop
  - If there is no data:
    ▪ Repeat loop

![Flow diagram of Feather M0](image)

**Figure 15. Flow diagram of Feather M0**

### 2.4.2. MATLAB scripting

For the data representation, a MATLAB script has been written in order to acquire the data Feather M0 is sending through serial port, rearrange bits in correct order, filter signals and represent them altogether. Code can be consulted on Appendix III.

The script basic functionality is to understand the binary data that Feather M0 is sending and to generate a plot to observe the behaviour of the signals acquired, electrocardiogram and pulse. Different blocks can be defined for the implementation of the script, those are:

- Data acquisition
- Data arrangement
- Post-processing
Data acquisition
First variables from previous commands are wiped in order to avoid possible issues. Next, serial port were the Feather M0 is connected has to be opened and data coming from it is stored into a .txt file in case is needed later on. Finally, serial port and file are closed and variables for time, electrocardiogram and pulse are created and filled with the corresponding data.

Data arrangement
Data need to be recomposed into a sole value since it arrives as three different bytes. Once data is rearranged it has to be rescaled for current resolution \[\frac{V_{\text{REF}}}{(2^{23} - 1)}\] to be understandable.

Post-processing
Once data is correctly interpreted, post-processing labours can begin. That is filtering, peak detection and plotting. High and low pass Butterworth filters have been defined for both, electrocardiogram and pulse with selectable cut-off frequencies. After filtering, a basic peak detection is done using the “findpeaks” function of MATLAB. A minimum peak distance of 0.3 seconds is defined since pulses above 200 are not expected from a resting subject. Last, the different stages of filtering of the signals are represented and mean pulse computed from the peaks.

Figure 16. Flow diagram of MATLAB Script
3. **PCB design**

3.1. **Development boards**

For the development and validation of the circuits integrated in the final PCB, several circuits have been used until reaching the final stage of design. First objective was to have a functional prototype capable of acquiring signals from a subject. For this purpose, a previously developed ADS1294 board was used along with a Adafruit Feather M0 placed on a breadboard which facilitates the interconnection of devices by cables instead of soldering them.

![Figure 17 a. ADS1294 development board](image1)

![Figure 17 b. Adafruit Feather M0](image2)

**Figure 17. ADS1294 and Feather M0 used during development**

In figure 17 a, three different regions can be differentiated on the ADS1294 board: acquisition (green square), power (red square) and SPI header (blue square). In this board, three out of four differential channels had been routed. One of them is used to acquire the electrocardiogram signal and another one to acquire the pulse signal through photoplethysmography. Finally, the remaining channel is not used at this stage since there is no need for a third channel without two photoplethysmograph devices.

The SPI compatibility of the ADS1294 is used to establish communication with the Adafruit Feather M0 board. When a data conversion is done, the result is send as explained in section 2.2. Feather M0 is a commercial board ready to use. Only modification is a decoupling capacitor since the 3.3 V regulated voltage from the M0 is used as power source. Pin 11, 12 and 13 are used as drivers to gates of MOSFETs and are in control of the LEDs on the SFH7050. The OSRAM SFH 7050 has been placed onto a protoboard with its conditioning circuit.

![Figure 18. BioMon Eco 1 from ILS featuring a OSRAM SFH7050](image3)
In figure 19, the completely development board can be seen. For powering all the system, the USB connection of a laptop is used. Internal regulator of the Feather M0 is in charge of supply all the devices with a 3.3 V. Notice that in order to protect our subjects and avoid noises from the electrical net, the laptop has to be unplugged from net and using its own battery.

![Figure 19. Final development board](image)

All the modules of the design can be observed: photoplethysmography in orange, electrocardiogram in violet, reference generator in red, Adafruit Feather M0 in cyan and ADS1294 in green.

3.2. PCB design

The development software used for the designing of the circuits and boards of this project is Altium Designer 14.3. Altium is a software from Altium Limited that combines multiple features and functionalities in a unique environment. It has the capability to edit a schematic and lay out the printed circuit board in the same software. Altium also contains tools for components and libraries creation, making it easy to reuse efforts from one project to another.

For this project a library of components has been designed as well as different schematics for all the circuits and a PCB following the lines of the Adafruit Feather M0 to ease interconnection with this device.

3.2.1. Board Implementation

Since many of the components are specific of this project and there are no predefined devices, a library has been created in order to have all the components with its schematic and PCB layout organized and with easy access. That allow to export to any other Altium project any of this components in case future development will be done.
In figure 20, the main schematic of the project, the **Acquisition_Wing.SchDoc**, can be observed. It contains four different blocks where all the circuits and components has been placed separately to clarify structure.

- **Front End**: Electrocardiogram connectors and SFH 7050 component.
- **Data Acquisition**: conditioning of signals to connect at ADS1294.
- **ADS 1294**: Schematic of the acquisition device.
- **Ports**: External ports replicated from the Feather M0 to ease interconnection.

Each of these blocks contain the basic schematics for sensors, signal conditioning, acquisition and ports for external communication. In appendix I is possible to find all the schematics and PCB layouts for the board. Some of them will be briefly explained next.

**Figure 20. Acquisition_Wing.SchDoc**

The **Front_End.SchDoc** block contains the sensors for each one of the signals that will be acquired. In case of electrocardiogram, a couple of pads are placed to solder the cables that go to the dry electrodes. For pulse acquisition by photoplethysmography, the SFH 7050 is there placed, with nets connecting anodes and cathodes to the corresponding conditioning circuit.

The **Data_Acquisition.SchDoc** contains a second level of hierarchy, formed by three sub-blocks that contain electrocardiogram conditioning, photoplethysmography conditioning with LED drivers and reference voltage level generation. These are the same circuits already explained in section 2.2.

The **ADS1294.SchDoc** contains the ADS1294 chip with the recommended capacitor placement and hardware pin configuration recommended from manufacturer for this design. Channels not used are shorted to VDD and SPI connections are passed to next block.

The **Ports.SchDoc** contains the headers corresponding to the Feather M0 board. The most important ones are the three channels to drive the LEDs, the SPI header and the power supply connections.

Once all the circuits are represented and interconnected, the PCB layout has to be made. In Figure 21, a 3D representation of the designed board can be seen.
Some considerations have been considered while placing components onto PCB:

- ADS1294 has been placed below the board since it’s the largest component and was difficult to make it fit the board and route all the connections, since PCB is really small.
- Electrocardiogram circuit has been placed as far as possible from any source of interferences. Even so, the effects of Bluetooth transmission through Norman nRF51822 integrated chip on the Feather M0 over the ECG acquisition are unknown.
- Only one photodiode could be integrated since the bottom part of the board is covered by the Feather M0. To be able to acquire both finger and wrist pulse an additional board should be made refurbishing the shape of Acquisition Wing but placing the corresponding devices.

The board has been manufactured at “SeeedStudio.com”, global supplier and PCB manufacturer. Some rules had to be followed when designing the PCB layout due to the technologies that SeeedStudio uses for different price ranges. For this board, FR4-TG130 dielectric and 1oz copper has been used to cheapen production costs since there is no need to go under certain restrictions for the components used and space available:

<table>
<thead>
<tr>
<th>Items</th>
<th>Description</th>
<th>Specs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric Constant</td>
<td></td>
<td>4.2-4.7</td>
</tr>
<tr>
<td>Dielectric Separation thickness</td>
<td></td>
<td>0.075 - 5.0</td>
</tr>
<tr>
<td>Available Board Copper Weight</td>
<td>1oz, 2oz, 3oz.</td>
<td></td>
</tr>
<tr>
<td>Minimum trace spacing / width</td>
<td></td>
<td>For 1oz, 4/4mil, 5/5mil, 6/6mil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For 2oz, 10/10mil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For 3oz, 15/15mil</td>
</tr>
<tr>
<td>Minimum distance between trace and copper pour</td>
<td></td>
<td>≥8mil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≥12mil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≥15mil</td>
</tr>
<tr>
<td>Minimum distance between vias (plated holes)</td>
<td></td>
<td>Aim to prevent Ion migration</td>
</tr>
<tr>
<td>Minimum distance between via (plated holes) and trace</td>
<td></td>
<td>≥15mil</td>
</tr>
<tr>
<td>Annular Rings</td>
<td></td>
<td>≥0.152mm/6mil</td>
</tr>
<tr>
<td>Outer Layer Copper Thickness</td>
<td>0.035-0.07(1oz-2oz)</td>
<td></td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---------------------</td>
<td></td>
</tr>
<tr>
<td>Drilling Hole Diameter (Mechanical)</td>
<td>0.2 - 6.3mm</td>
<td></td>
</tr>
<tr>
<td>Width of Solder Mask Dam</td>
<td>Normal: ≥0.32mm for Green ≥0.35mm for Other colours</td>
<td></td>
</tr>
<tr>
<td>Circuit to edge</td>
<td>≥0.3mm</td>
<td></td>
</tr>
<tr>
<td>Minimum distance between inner trace and non-plated hole</td>
<td>≥0.2mm/7.87mil</td>
<td></td>
</tr>
<tr>
<td>Minimum silkscreen height/trace width</td>
<td>height ≥0.5842mm /23mil trace width ≥0.1016mm /4mil</td>
<td></td>
</tr>
<tr>
<td>Minimum distance between pad and silkscreen</td>
<td>≥0.1524mm/6mil</td>
<td></td>
</tr>
<tr>
<td>Minimum distance between pad and silkscreen</td>
<td>≥0.1524mm/6mil</td>
<td></td>
</tr>
<tr>
<td>Minimum milling slot width</td>
<td>≥0.8mm</td>
<td></td>
</tr>
<tr>
<td>Slot Tolerance(Mechanical)</td>
<td>±0.15mm</td>
<td></td>
</tr>
</tbody>
</table>

*Table 2: PCB manufacturer rules*
4. Measurements

This section will cover the measurements obtained through devices and volunteers to ensure that circuit performed as expected.

Measurements of ECG had been first taken with an Arrhythmia Patient Simulator. This device produces different waveform types, for Adult electrocardiogram and Paediatric electrocardiogram, has selectable rates from 30 to 300 BPM with an accuracy of 1%. It also can produce more than 20 different arrhythmia patterns and has the possibility of simulating different artefacts like 50/60 Hz, muscle, baseline and respiration.

![Fluke PS410 Arrhythmia Patient Simulator](image)

Figure 22. Fluke PS410 Arrhythmia Patient Simulator

With this device three different measures at different beats per minute has been taken, 30, 80 and 120 BPM. Once measures where made correct, a sample from subject one was taken.

![Comparison between non-processed and processed signals](image)

Figure 23 b. Comparison between non-processed and processed signals

![Filtering and peak detection process](image)

Figure 23 a. Filtering and peak detection process

![Measure obtained with Fluke PS410 at 80 BPM](image)

Figure 23 c. Measure obtained with Fluke PS410 at 80 BPM

Figure 23. Electrocardiogram Samples

In figure 23b can observed how post-process in a computer helps defining a clearer signal, even if QRS complex detection can be achieved without this post-processing. When capturing signals from a living subject, movement and noise artefacts difficult the detection. Using the device, a rather clean wave is produced although some sampling artefacts are observed.
For the pulse measurement by photoplethysmography no device has been used and direct measurement over subject has been done. Measures has been taken into the finger and wrist to evaluate which position would be better when measuring pulse. In figure 24, the comparison between finger and wrist can be observed. Final decision has been to make measurements on the finger since better detection is observed.

![Figure 24 a. PPG on finger](image)
![Figure 24 b. PPG on wrist](image)

**Figure 24. Comparison of photoplethysmography signals**

While taken PPG signal, different artefacts have been observed due to high pass filter or movement of the subject:

![Figure 25 a. Artefact due Notch filter](image)
![Figure 25 b. Noise artefacts](image)
![Figure 25 c. Movement artefacts](image)

**Figure 25. Different artefacts detected during measures**

In figure 25 a, an oscillation at the beginning of the sampling can be observed, produced by the response of the notch filter. Due that artefact, the setup time to start taking measures is around 250 ms. Also, having the prototype mounted on breadboard produces interferences that can be seen in figure 25 b. Additionally, in figure 25 c can be seen the type of artefacts that movement and pressure change over the photodiode can produce. Even so, good detection can be achieved after post-processing.

Finally, measurements with whole system (Figure 19) have been taken synchronizing electrocardiogram and pulse signals in order to measure the pulse arrival time of the subject. For these measures basic guidelines has been followed:

- Seat subject with arms resting on table and back straight.
- One electrode on each hand pressed against the palm.
- Photodiode on right hand index.
- Avoid contact between arms and hands to correctly obtain electrocardiogram.
Measures from different subjects has been obtained. Subject’s data is shown in Table 3.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27</td>
<td>174</td>
<td>105</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>162</td>
<td>64</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>167</td>
<td>56</td>
</tr>
<tr>
<td>4</td>
<td>26</td>
<td>163</td>
<td>49</td>
</tr>
<tr>
<td>5</td>
<td>28</td>
<td>168</td>
<td>78</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>168</td>
<td>75</td>
</tr>
</tbody>
</table>

*Table 3. Subject’s data*

Different measurements obtained can be seen in Figure 26 a and 26 b for subjects 1 and 2 respectively.

![Figure 26 a. Subject’s 1 measure](image1)

![Figure 26 b. Subject’s 2 measure](image2)

*Figure 26. Output from MATLAB script for Measuring*

A close up of the PAT signals for easy understanding is represented in figure 27.
In this figure, noise on the ECG signal can be seen on subject 2 measures, but since peaks are clearly visible, the peak detection works fine and PAT can be computed.

A summary of results for all subjects is presented in table 4, with a 95 % level of confidence using a coverage factor of 2.

<table>
<thead>
<tr>
<th>Subject</th>
<th>PAT ± 2σ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>306.6 ± 10.3</td>
</tr>
<tr>
<td>2</td>
<td>358.06 ± 26.5</td>
</tr>
<tr>
<td>3</td>
<td>324.3 ± 11</td>
</tr>
<tr>
<td>5</td>
<td>340 ± 31.3</td>
</tr>
</tbody>
</table>

Table 4. PAT results for the evaluated subjects

Last, measurements with the printed board cannot be done at the time of writing this document since the shipment was delayed. Seeing the results obtained with the development prototype, less noise in the measures is expected due integration.

---

1 Plots for every subject measurement can be seen in appendix IV.
5. **Budget**

In this section, basic economic estimation is made in order to evaluate the costs of developing and producing the PCB. Development hours plus components will be considered.

Time spent on the development of this project has been of the order of 12 hours per week along 34 weeks. If this hours are evaluated as done by a trainee engineer, a cost of 8 €/hour is estimated. Table 5 shows a time distribution for the hours spend in each of the tasks needed to fulfil this project.

<table>
<thead>
<tr>
<th>Jobs</th>
<th>Time Spend (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Search of information</td>
<td>10</td>
</tr>
<tr>
<td>Study of information</td>
<td>10</td>
</tr>
<tr>
<td>Development boards start up</td>
<td>15</td>
</tr>
<tr>
<td>Scripting/Programming</td>
<td>20</td>
</tr>
<tr>
<td>Measurements</td>
<td>15</td>
</tr>
<tr>
<td>Board design</td>
<td>20</td>
</tr>
<tr>
<td>Documentation</td>
<td>10</td>
</tr>
</tbody>
</table>

*Table 5. Distribution of time over all the tasks realized*

Table 6 contains the bill of materials for one prototype. Unitary cost of components vary in function of how many are bought so quantity should be reflected as well:

<table>
<thead>
<tr>
<th>Component Description</th>
<th>Quantity (PCB)</th>
<th>Min. Units</th>
<th>Units Bought</th>
<th>Cost (€/un)</th>
<th>Device Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC0603B104K500CT COND, CERÁ MULT, X7R, 100NF, 50V, 0603</td>
<td>13</td>
<td>10</td>
<td>100</td>
<td>0.0111</td>
<td>0.1443</td>
</tr>
<tr>
<td>MC0603B102K500CT COND, CERÁ MULT, X7R, 1NF, 50V, 0603</td>
<td>4</td>
<td>10</td>
<td>20</td>
<td>0.011</td>
<td>0.011</td>
</tr>
<tr>
<td>C1608X5R1H105K080A8 COND, CERÁ MULT, X5R, 1UF, 50V, 0603</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>0.118</td>
<td>0.472</td>
</tr>
<tr>
<td>GRM188R60G226MEA0D COND, CERÁ MULT, X5R, 22UF, 4V, 0603</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>0.265</td>
<td>0.265</td>
</tr>
<tr>
<td>GRM1885C1H5R6DA01D COND, MLCC, C0G/NP0, 5.6PF, 50V, 0603</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>0.036</td>
<td>0.036</td>
</tr>
<tr>
<td>MCWR06X1000FTL RES, PELÍC GRUESA, 100R, 1%, 0.1W, 0603</td>
<td>3</td>
<td>10</td>
<td>100</td>
<td>0.0022</td>
<td>0.0066</td>
</tr>
<tr>
<td>MCWR06X1001FTL RES, PELÍC GRUESA, 1K, 1%, 0.1W, 0603</td>
<td>3</td>
<td>10</td>
<td>100</td>
<td>0.0022</td>
<td>0.0066</td>
</tr>
<tr>
<td>MC0603W0603510K RES, PELÍC GRUESA, 10K, 5%, 0.063W, 0603</td>
<td>2</td>
<td>10</td>
<td>100</td>
<td>0.006</td>
<td>0.012</td>
</tr>
<tr>
<td>MC0603W0603539K RES, PELÍC GRUESA, 39K, 5%, 0.063W, 0603</td>
<td>2</td>
<td>10</td>
<td>100</td>
<td>0.0059</td>
<td>0.0118</td>
</tr>
<tr>
<td>MCWR06X10003FTL RES, PELÍC GRUESA, 100K, 1%, 0.1W, 0603</td>
<td>1</td>
<td>10</td>
<td>100</td>
<td>0.0021</td>
<td>0.0021</td>
</tr>
<tr>
<td>MCWR06X10004FTL RES, PELÍC GRUESA, 1M, 1%, 0.1W, 0603</td>
<td>3</td>
<td>10</td>
<td>100</td>
<td>0.0022</td>
<td>0.0066</td>
</tr>
<tr>
<td>22125S-12SG-85 TOMA, PCB, 1 FILA, 12V/85</td>
<td>1</td>
<td>1</td>
<td>10</td>
<td>0.139</td>
<td>0.139</td>
</tr>
<tr>
<td>SLW-116-01-T-S CONECTOR, HEMBRA, 16 POS, 1 FILA, 2.54MM</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1.56</td>
<td>1.56</td>
</tr>
<tr>
<td>2N7002BK MOSFET, N CH, 60V, 0,35A, SOT23</td>
<td>3</td>
<td>1</td>
<td>15</td>
<td>0.458</td>
<td>1.374</td>
</tr>
<tr>
<td>Osram LED, Cob - BioMon</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>2.244</td>
<td>2.244</td>
</tr>
<tr>
<td>ADS1294IPAG IC, AFE, 24BIT, 32KSPS, 4CH, 64TQFP</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>22.85</td>
<td>22.85</td>
</tr>
</tbody>
</table>
Additionally, the PCB production also had a cost. They were ordered at SeeedStudio.com at a cost of 4.95 $ per 10 PCBs. That made a cost of 0.495 $ per PCB plus shipment fees. At the moment of buying the PCBs, U.S. dollar ($) was around 0.85 €, that is the conversion used to calculate the total cost of the prototype.

In summary, estimated cost of project on table 7:

<table>
<thead>
<tr>
<th>Product</th>
<th>Units</th>
<th>Cost (€/un)</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human resources (h)</td>
<td>408</td>
<td>8.00</td>
<td>3264.00</td>
</tr>
<tr>
<td>Components</td>
<td>1</td>
<td>37.62</td>
<td>37.63</td>
</tr>
<tr>
<td>PCB</td>
<td>1</td>
<td>0.42</td>
<td>0.42</td>
</tr>
<tr>
<td>Adafruit Feather M0 BLE(^2)</td>
<td>1</td>
<td>25.46</td>
<td>25.46</td>
</tr>
<tr>
<td>Additional Fees</td>
<td>1</td>
<td>16.05</td>
<td>16.05</td>
</tr>
<tr>
<td>MATLAB and Simulink Student Suite</td>
<td>1</td>
<td>69.00</td>
<td>0.00(^3)</td>
</tr>
<tr>
<td>Altium Designer 17</td>
<td>1</td>
<td>7000.00</td>
<td>0.00(^4)</td>
</tr>
<tr>
<td>Prototype alone</td>
<td></td>
<td></td>
<td>79.56</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>3343.56</td>
</tr>
</tbody>
</table>

Table 7. Total estimated cost of the prototype design

Prototype itself, have a cost around 80 €. Buying in great quantities and developing a controller board like Feather M0 or looking for a more economic one, would reduce the effective cost of the prototype. Also, the human resource, for development and integration, has a huge impact on the cost of the prototype.

\(^2\) No Adafruit Feather M0 BLE has been bought, they were provided by the laboratory staff.
\(^3\) MATLAB can be used for free with an UPC account.
\(^4\) Free-Trial version of Altium has been used to develop the board.
6. **Conclusions and future development:**

6.1. **Conclusions**

This project was about developing a board that was capable of capture electrocardiogram and pulse by means of photoplethysmography and compute from them the PAT.

The conditioning block has fulfilled its duty acquiring those signals and sending to a computer. Sampling frequency has drop from 1 kHz to around 300 Hz due to Feather M0 slowing down the data transmission. The frequency is still enough good to capture both signals with enough resolution although.

Some noise is still visible in both signals. With the PCB, this noise is expected to be reduced. Even though the system has presented robust against noise and different type of lights, it would be better to avoid all the possible sources of noise as well as movement when measures are taken.

PAT measuring algorithm works quite well even with peak detection fails but it has a lot of room to improve. It helps having long measurements of one minute or so to compute better measurement.

6.2. **Future Work**

First issue to solve is to test the board and ensure that it works as expected. Once this has been validated, there is some room for new functionalities to be added to the board:

- Use the IR LED included on the SFH 7050 as a distance detector to start measuring samples when distance is below certain threshold.
- Use Bluetooth capabilities of Feather M0 BLE to send the data wirelessly to a computer or smartphone and present the data there.
- Design a case for the prototype including battery and other components if needed
- Make a study regarding limitations of the pulse by photoplethysmography on different parts of the wrist-hand to find the best place to take this measure.
- Add a gyroscope/accelerometer to detect movement of the subject and avoid capturing those samples since they hinder the measurements.

Apart from these new functionalities that could be added, it would be good to make a second version of the board fixing the errors encountered when testing the board.

As a final conclusion, a lot of work can still be done to improve this device and to make it feasible to use to monitoring people that has certain needs.
Bibliography:


Appendices:

I. **Altium files**
   Available in Appendices/Acquisition_Wing_v1.1.pdf

II. **Arduino acquisition code**
    Available in Appendices/adsDriver

III. **MATLAB data processing**
     Available in Appendices/MATLAB_Script
IV. **Subject Measures**

Subject 1

![Graphs showing Subject 1's measures](image1)

Subject 2

![Graphs showing Subject 2's measures](image2)
Subject 3

Subject 4
Subject 5

Subject 6
**Glossary**

BLE: Bluetooth low energy  
BMP: Beats per minute  
DC: Direct current  
ECG: Electrocardiogram  
GUI: Graphic user interface  
GPIO: General Purpose Input/Output  
HRV: Heart rate variability  
IR: Infra-red  
LED: Light emitting diode  
MOSFET: Metal-oxide-semiconductor Field-effect transistor  
PAT: Pulse arrival time  
PC: Personal computer  
PCB: Printed circuit board  
PGA: Programmable gain amplifier  
PPG: Photoplethysmography  
PWTT: Pulse wave travel time  
RLD: Right leg drive  
SPI: Serial Peripheral Interface  
SPS: Samples per second  
TIA: Transimpedance amplifier  
UART: Universal Asynchronous Receiver-Transmitter  
USB: Universal Serial Bus