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ECG Recording and Heart Rate Detection with Textile-Electronic Integrated Instrumentation

Part I

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ECG Recording and Heart Rate Detection with Textile-Electronic Integrated Instrumentation

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ABSTRACT

In this thesis is presented the whole process to design an ECG on textile and the different techniques available for its development that were found in a previous literary research. Two different circuits were built using a hybrid solution in between two different disciplines, electronics and textiles. A first ECG with a more handmade procedure using conductive painting and textiles; a second one employing a conductive ink printer and film. In both the interconnections were done on the fabric or film and the circuits were placed in three different PCB attached to them.

Experimental measurements were performed with both circuits to test their operation and reliability; even though the real purpose was to start a path for further investigation in order to achieve a functional wearable device for stress monitoring and a possibility to transfer this technology to other fields.

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Juan Manuel Rodríguez Escriche
Marc Tena Gil

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LIST OF ACRONYMS

Ag/AgCl	Silver / Silver Chloride
ATP	Adenosine Triphosphate
A-V	Atrioventricular
BPF	Band Pass Filter
CAD	Computer Aided Design
CMRR	Common-Mode Rejection Ratio
dB	Decibels
DIP	Dual In-line Package
ECG/EKG	Electrocardiogram
EEG	Electroencephalography
EMG	Electromyography
FPGA	Field Programmable Gate Array
GND	Ground
HDL	Hardware Description Language
HPF	High Pass Filter
HR	Hear Rate
HRV	Heart Rate Variability
IC	Integrated Circuit
LED	Light Emitting Diode
LPF	Low Pass Filter
MIT	Massachusetts Institute of Technology
MSDS	Material Safety Data Sheet
OA	Operational Amplifier
PCB	Printed Circuit Board
PET	Polyethylene Terephthalate
SC	Skin conductance
SCB	Stretchable Copper Board
SMD	Surface Mount Device
USB	Universal Serial Bus
VIA	Vertical Interconnect Access

CHAPTER 1.

INTRODUCTION

Nowadays, in a rapidly changing society where everyone has a lot of responsibilities and chores, stress is a common cause of poor job performance, illness, disease and sometimes risk for the own person and for the rest (think of jobs as police, firefighters, professional drivers, etc..). Rapid detection on symptoms of stress and act on them can prevent major problems.

1.1 Motivation

The motivation of this project arises during a research carried out looking up for assessment of alertness and stress with non-invasive physiological measurements (the research report is annexed at the end of the thesis); in its discussion and conclusion you can see deeply explained why finally the ECG was chosen in between all techniques that are developed for this purpose. How the ECG and the stress are related, how important is that the subject do not perceive the sensors, etc.

1.2 Goal

Develop a simple three electrodes ECG detector prototype over textile for stress assessment. This represents a first step to achieve an ECG on textile in order to have a totally flexible design without using any rigid materials

1.3 Work Done

A hybrid (textile and electronics) heart rate detector has been designed and implemented. The ECG amplifier and the peak detector were divided into three round PCBs designed with Altium's CAD software, its interconnections were printed over the textile with conductive ink. Finally several measurements with different subjects were performed to test the proper functionality of the system.

1.4 Structure of the Thesis Report

This thesis consists of six chapters, an appendix and a references section. In Chapter 1 the introduction part. Chapter 2 presents a brief background where the bases of bioelectromagnetism and ECG are explained, safety is also considered as well as a short explanation and example of electronic textiles. Chapter 3 describes the materials and methods employed to develop the whole project, meaning that all materials and techniques are listed. Other used equipment appears too. Chapter 4 describes the ECG design starting for the analog design with all its stages and its simulation; to finish this chapter the tests carried out with the textile and films where the ECG has been implemented are shown. Chapter 5 contains the validation and results, few plots demonstrate the ECG operation. Then in the last Chapter it follows the conclusion and several points that could be taken into account for future work. Notice that in the Annex is attached the research carried out, that it could be considered as the real motivation for developing this project.

1.5 Out of Scope

During the project development was decided to rule out some of the original considerations like wireless data transmission, automate the ECG signal and the peak detection capture with Labview software and a National Instruments acquisition card. As a last point a posterior signal treatment with digital processing software (Matlab for instance) was also proposed at the beginning. Notice that if this processing is developed, the analog R-R detector becomes something unnecessary.

CHAPTER 2.

BACKGROUND

A hybrid textile-electronics ECG amplifier is a complex design that involves different disciplines as follows: Bioelectromagnetism that studies the electric, electromagnetic, and magnetic phenomena, which arise in biological tissue. Biomedical engineering that is concerned in the application of science and technology to biology and medicine. Wearable electronics also known as smart textiles, which allows embedding electronics into the fabrics.

This chapter consists of a briefly introduction in the mentioned disciplines, focusing on the information relevant towards the design.

2.1 Bioelectromagnetism

Bioelectromagnetism field can be divided on different theoretical groups according to principles: Maxwell's equations and the principle of reciprocity [1] as can be seen in the figure below.

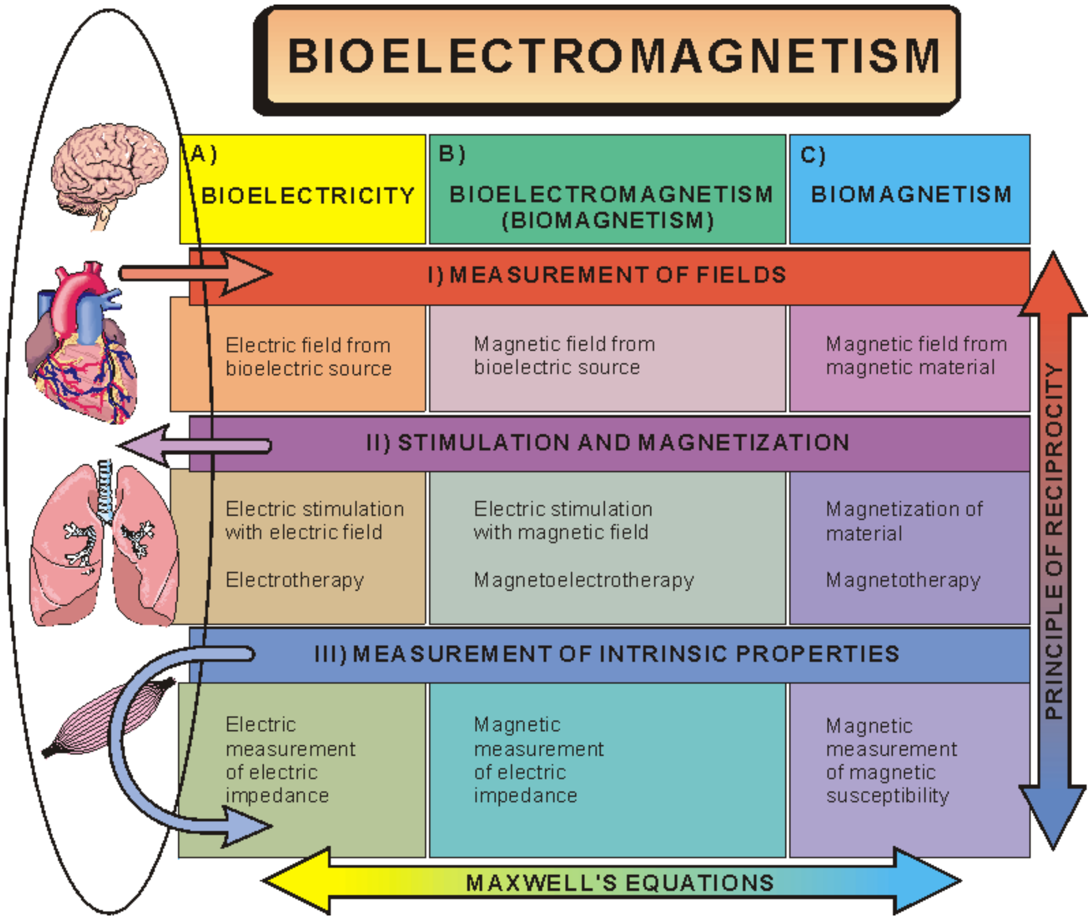

Figure 2.1 Organization of Bioelectromagnetism [1]

Owing to Maxwell's equations, depending if the phenomena studied is electric, electromagnetic or magnetic, electromagnetism may be divided into bioelectricity, bioelectromagnetism or biomagnetism respectively.

The goal of this theoretical introduction in bioelectromagnetism is to review the concepts of the ECG which is a measurement of a bioelectrical field. Therefore focusing on bioelectricity and only taking into account the measurement of fields according to the principle of reciprocity (See again figure 2.1), some electric fields can be measured. Depending on the nature of the biological tissue that generates these electric fields, they can be organized as the following table shows.

Neural cells	Muscle cells	Other tissue
Electroencephalography (EEG)	Electrocardiography(ECG)	Electro-oculography(EOG)
Electroneurography(ENG)	Electromyography(EMG)	Elecrtonystamography(ENG)
Electroretinography(ERG)		

Table 2.1 Measurements of electric fields

2.1.1 Conduction Mechanism in the Cell Membrane

Some of the organism cells as the muscle and nerve cells are embedded in a semi-permeable membrane that allows some particles to penetrate the membrane while it maintains others out. Surrounding the organism cells there are the organic liquids, these liquids are conductive solutions with charged atoms better known as ions.

There are different conduction mechanisms involved in the interchange between the internal solution and the external solution. The most important are [2]:

- **Diffusion:** Is the mechanism that tries to equilibrate the concentrations gradient of ions inside and outside the cell
- **Electric field:** Is the mechanism that tries to equilibrate the potential electric gradient of ions inside and outside the cell
- **Ion Exchanger:** An ion exchanger molecule uses the potential energy in the electrochemical gradients to pump one ionic species into the cell and another species out.
- **Ion Pump:** An ion pump molecule uses energy (in the form of ATP molecules) to pump ions against their electrochemical gradients. Is the only mechanism that requires energy thus it is called active mechanism

Main ions that participate in this exchange are Sodium (Na^+), Potassium (K^+), Chlorine (Cl^+) and Calcium (Ca^{2+}). In figure 2.2 can be observed the mechanisms used by each different ion and if the mechanisms drives the ions in or out the cell.

With all this mechanisms the cell obtains a steady state while not excited. One of the techniques to evaluate the condition of the cell is the membrane potential E_m that is the difference between the inside and outside potential.

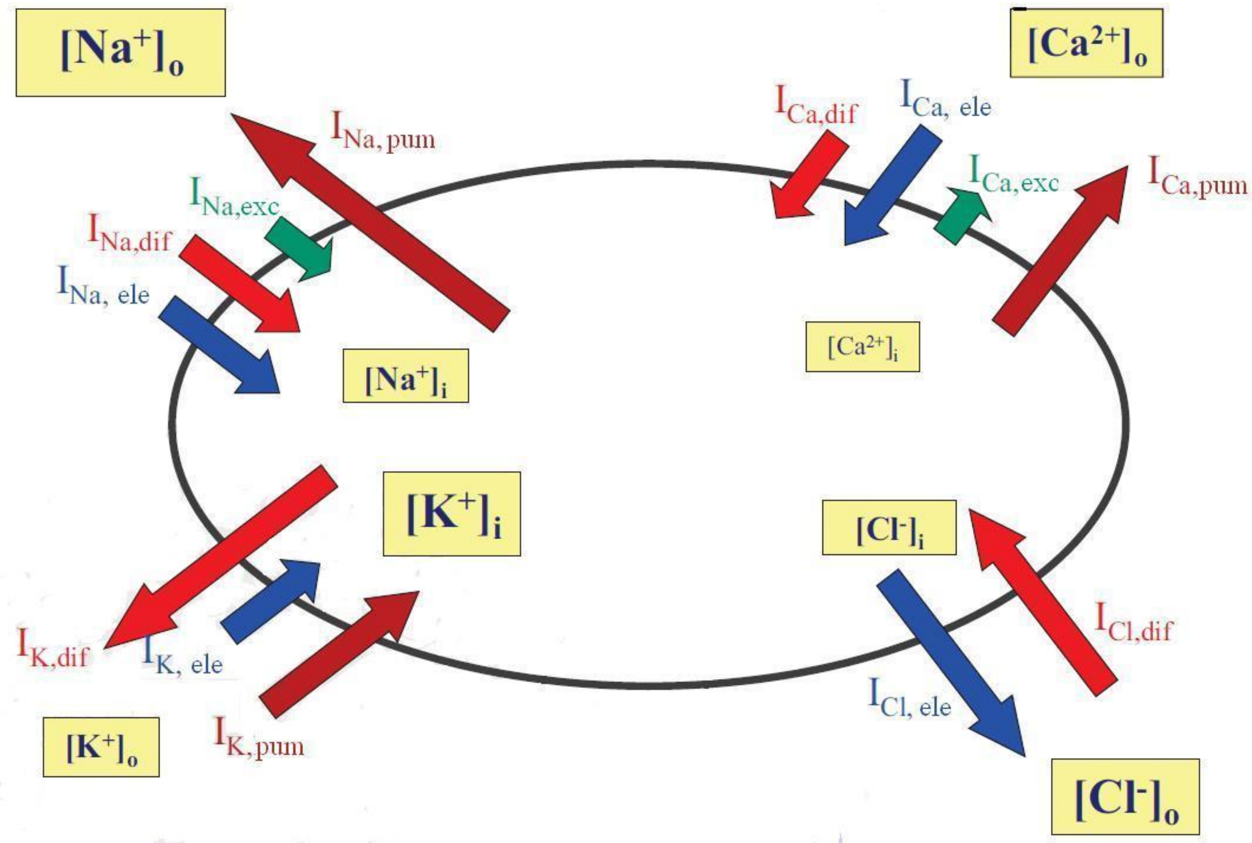

Figure 2.2 Conduction mechanisms through the membrane cell

$$E_m = E_i - E_o$$

Equation 2.1 Membrane potential

In the steady state, the muscle cells also called myocytes have approximately a -80 mV membrane potential. External current or voltage inputs will cause the potential of the membrane cell to vary towards positives values and if the variation is large enough the result is an action potential.

2.1.2 The Action Potential

Action potential is a term used to denote a temporal phenomena exhibited by every electrically excitable cell [2]. For a given stimulus to result in an action potential the stimulus has to be larger than some critical size, smaller subthreshold stimuli will result in an exponential decay to the resting potential without an action potential process. The fast initial depolarization of the action potential is normally caused by a large influx of sodium ions as sodium channels open in response to a stimulus. As figure 2.3 shows this is followed by repolarization as potassium ions starts flowing out of the cell in response to the new potential gradient. While responses of most cells to subthreshold inputs are usually linear and passive, the suprathreshold response (the action potential) is a nonlinear phenomenon. Due to this non-linearity most cells have a refractory period during which the cells cannot experience action potentials.

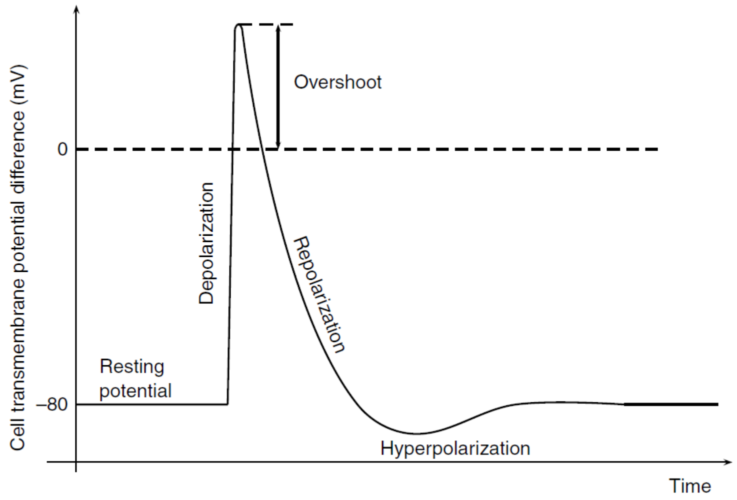

Figure 2.3 Schematic representation of an action potential in an excitable cell.

2.1.3 Action Potential Propagation Through Heart

The contraction and relaxation of the heart muscles that enables the irrigation of all the circulatory system is adequately related with the action potential propagation in the heart. When a myocyte is developing an action potential it is also contracting what means that a correct propagation of the action potential is necessary in order to pump oxygenated blood to the body and deoxygenated blood to the lungs.

First of all is important to remark the purpose of the sinus node. The sinus node is a cluster of cells situated in the upper part of the wall of the right atrium It generates action potentials in an autonomous way therefore it is called the natural pacemaker. This is possible through Sodium and Calcium channels that do not allow steady state in this cells what relies in a periodically action potential. Some neurotransmitters can vary the conductance of this channels what creates changes in the frequency of the action potential generated, mechanism that the body uses to control the heart frequency.

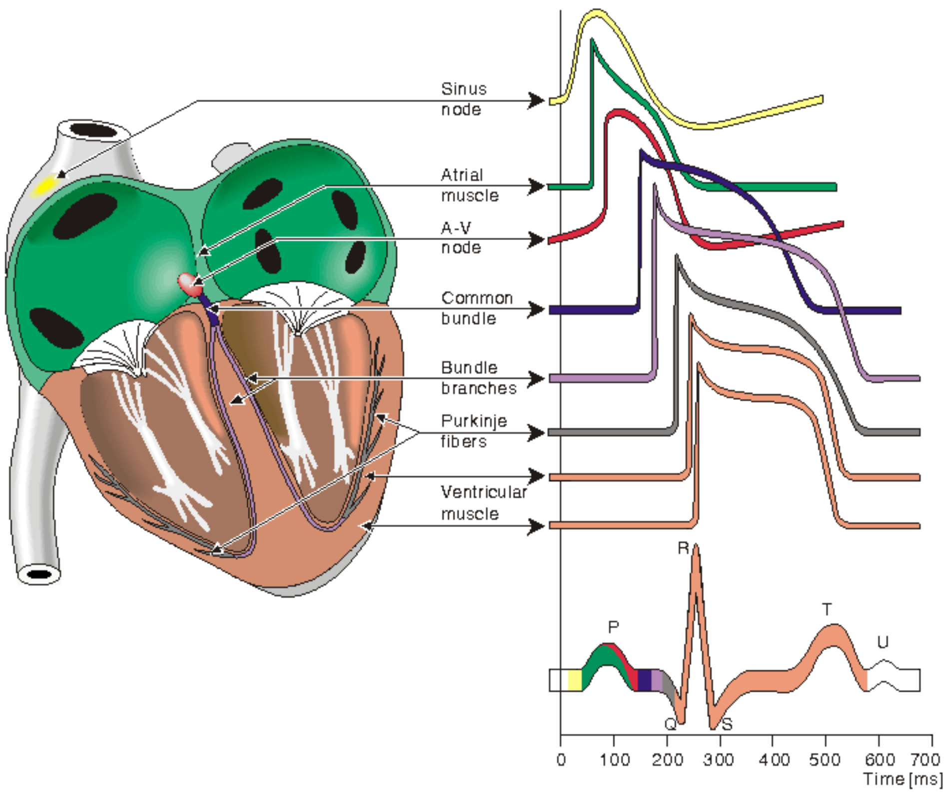

Figure 2.4 Propagation of the Action Potential through heart

Once the sinus node has generated an action potential it propagates with a certain speed through the adjacent cells to all the atrial cells. This stimulus only crosses to the ventricles via the atrioventricular node because there is cardiac skeleton, which establishes electrically impermeable boundaries between the atriums and the ventricles.

The A-V node is the only way for the action potentials to arrive the ventricles. It has two singularities. The first is a small delay, around 60 ms that allows all the atrium cells to experience the action potential before it starts to propagate in the ventricles, what means that all the atrium muscles will contract before the ventricles. The second one is that the A-V node has a refractory period wider than the usual what means that if somehow the A-V node receives more stimuli than expected, i.e. in an auricular fibrillation, it will only pass the stimulus that his refractor period allows.

The last step in the propagation refers to the action potentials through the ventricles. In the ventricles there is a fast propagation system integrated by the His bundle and the Purkinje fibers. These two systems are shown in the figure 2.4. They provide fast electrical conduction to the ventricles what implies that the ventricle contracts almost in the same time, clearly more efficient than an up-down mechanical contraction.

2.2 Biomedical Engineering

The activation sequence of the action potential in the heart leads to the production of closed-line action currents that flow in the thoracic volume conductor (considered a purely passive medium containing no electric sources or sinks). Potentials measured at the outer surface of this medium (that is, on the body surface) are referred as electrocardiograms (ECGs) [3].

2.2.1 ECG

Using a model where the heart consists of an electric dipole the activity of the heart can be represented as a vector quantity. This dipole represents the electric activity of the heart in a particular moment. In the next moment of the cardiac cycle the dipole will change its value (orientation and amplitude) because there is a variation in the electric field produced by the heart.

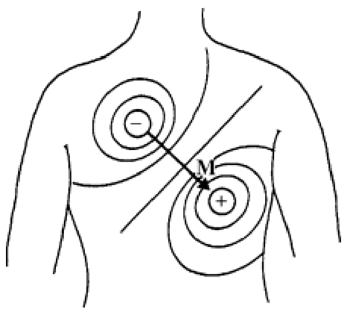

Figure 2.5 Dipole field of the heart with a maximum of R wave

This dipole moment known as the cardiac vector is shown in the figure 2.5 as *M*. In this simplified model of the heart in order to have some standard positions where locate the ECG electrodes there are defined lead vectors for the electrodes. A lead vector represents the direction that a constant cardiac vector should have to obtain maximal amplitude in the particular electrodes.

2.2.1.1 Leads System

To obtain complete information about the electrical activity of the heart more than one lead need to be considered. Generally 12 leads are used for registering the ECG signal. Six of them are in the frontal plane (the plane parallel to the ground when lying on the back) and the other six in the transverse plane (parallel to the ground when staying erect). As an example three of the frontal leads are explained, the limb leads.

The leads I, II and III often called limb leads are three bipolar leads of the frontal plane. Lead limbs include electrodes in both arms and in the left leg. The placement of the electrodes is shown in figure 2.6

In the limb leads the acquisition of two leads gives the information of the third lead, the equation 2.2 shows how to extract the information of the II lead with the I and III lead.

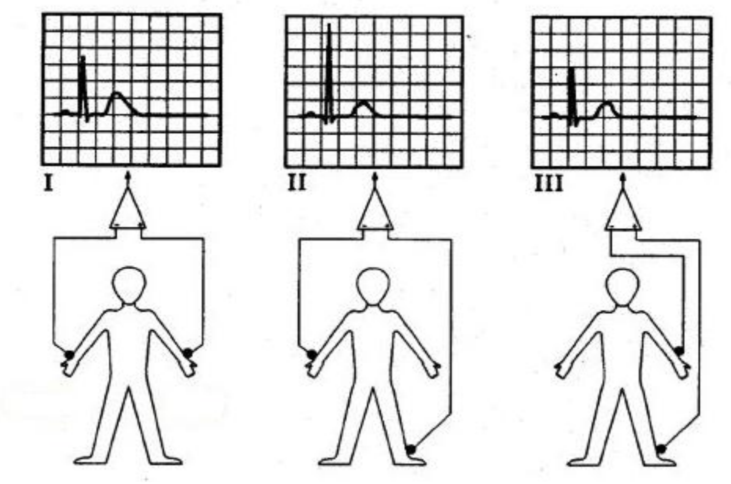

Figure 2.6 Basic connection of the limb leads

$$I + III = II$$

Equation 2.2 Limb leads relationship

2.2.2 ECG Amplifier

The target of a biopotential amplifier as the ECG is to acquire a weak bioelectric signal and maximize its amplitude without distortion, thereby it can be processed and displayed. The ECG amplifier as many other biopotential amplifiers is a voltage amplifier that involves low level measurements with high source impedances. To achieve an accurate an ECG amplifier, it must meet some requirements, these are as follows:

As the signal is obtained from bipolar electrodes, with a high common-mode voltage, the ECG amplifier must be a differential amplifier with a high CMRR.

In the ECG the electrodes have significant impedances due to the interface created by electrode-electrolyte-skin. High input impedance is required in the amplifier so it provides minimal loading of the signal.

The amplifier should be a low-noise amplifier with a plane gain in the spectrum of the heart electric signal.

Filters that take only the appropriated spectrum of the signal, avoiding unnecessary noises.

There are other important characteristics when dealing with an ECG amplifier, the safety of both, patient and equipment.

2.2.2.1 Instrumentation Amplifier

An ECG amplifier which accomplishes the most part of the requirements mentioned is a complex design. It will need a design with several blocks that can include, amplifiers, filters, circuits that increase the safety and other blocks.

One of the most important blocks in the design of an ECG amplifier is the instrumentation amplifier. This type of amplifier meets the requirements of being differential, having a high input impedance and a high CMRR. An example of instrumentation amplifier composed by three operational amplifiers is shown in the figure 2.7.

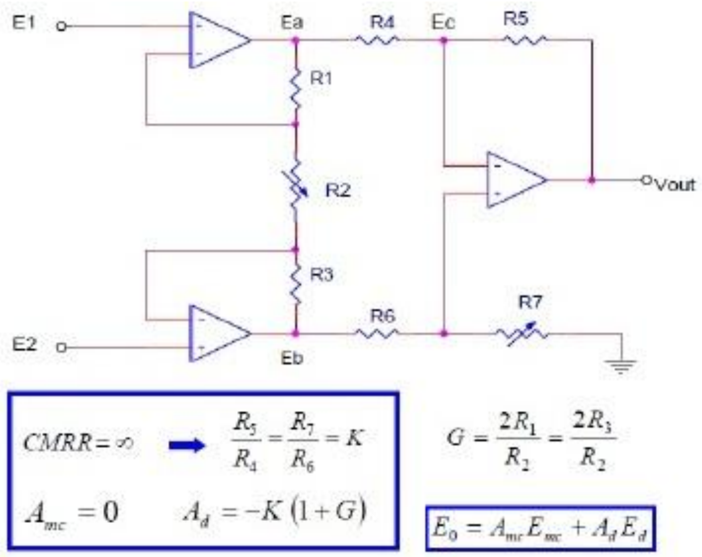

Figure 2.7 Scheme of an instrumentation amplifier and its design equation

Depending on the design sometimes are necessary more amplifiers, once used the instrumentation amplifier, the next gain blocks can be implemented with simple operational amplifiers. To reduce even more the CMRR a third electrode connected to the right leg is used; this last point could introduce a safety problem, which can be properly solved adding the active feedback technique on it.

2.2.2.2 Filters

In a biopotential amplifier is highly important to obtain only the range of the spectrum where the desired signal has significant frequency components. In every signal there are noises to avoid, but biopotential signals such as the heart electric signal is very sensitive to other noises, i.e. EMG, power line interference, electrode contacts noise.

As can be seen in the image below (Figure 2.8), some noises are out of the spectrum of the ECG signal. These noises are easily attenuated through low pass and high pass filters. Depending on the application of the ECG amplifier the pass-band can vary. For example if the only interest of the ECG amplifier is to obtain the information in the R-wave a narrow passband can be chosen.

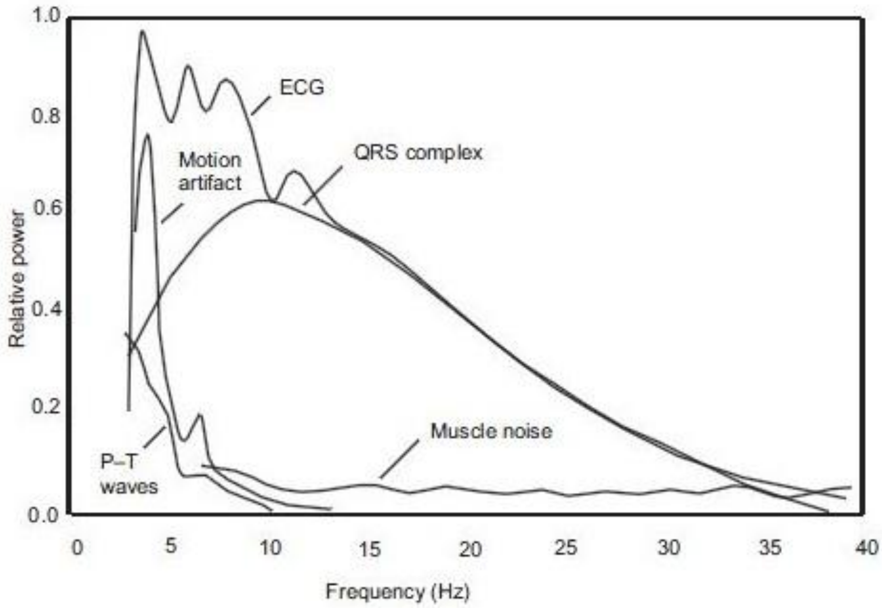

Figure 2.8 ECG and noise [11]

To extenuate other sources of noise with frequency components in the same range than the ECG signal such as the power line interference, specific filters must be used. In Europe the power line works at 50 Hz and it is a usual noise to deal with. A notch filter at this frequency will attenuate this interference. An implementation example of the 50 Hz Notch double T filter is shown in the figure 2.9.

$$f_0 = \frac{1}{2 * \pi * R * C}$$

$$C = 47nF \quad R = 68k\Omega$$

Equation 2.3 50Hz Filter equations

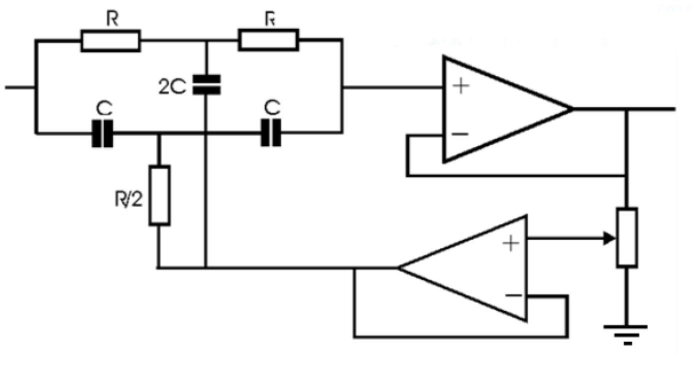

Figure 2.9 50Hz Filter

2.2.3 Safety

It is quite evident that safety should be a much contemplated topic and must be taken into account carefully, obviously patient's health have to be valued over all. Whatever the application or purpose that involves connecting a person to electronic equipment connected to the power grid implies a risk to the patient/user for its health due to the possible effects of the current flow through the body.

In the current effects on human body there are a few factors to be considered. Magnitude (the more the worst), frequency (the human body impedance varies with the frequency, therefore the way it affects depends on it. Curiously the 50 Hz from the grid is one of the worst frequencies that could have been chosen for power carriage because it allow an easy flow along the body (most dangerous range is [10, 500] Hz. Exposures, around 100ms are very influenced for the weight and for the current input/output points in the body, longer shocks than 0.5 or 1 seconds will lead fatally to a ventricular fibrillation, hereby death. For instance, a very low intensity current across the heart can be instantly lethal).

The worst case is when the patient is connected directly to ground via the measurement device. A bad connection or an isolation failure could drive the current through the patient's body. In order to avoid this problem, the precautions to take into account are: isolate the subject from the system with an isolated instrumentation amplifier and a separated ground reference than the circuit one, isolate the power system and active feedback on third electrode using the common voltage as reference.

2.2.3.1 Active Feedback in Third Electrode

This technique consists on using active feedback in the third electrode referred to a level proportional to the common patient voltage with opposite sign. Its effect is to reduce the impedance from third electrode without reducing the subject safety. The following picture shows a general schematic with the patient and the third electrode.

As the equations show, the common voltage is inverted and amplified, which finally results in an equivalent impedance for the third electrode reduced by the factor in the equation 2.5.

$$u_0 = A * u_{MC}$$

$$A = -\frac{R_2}{R_1}$$

Equation 2.4 Third electrode equations

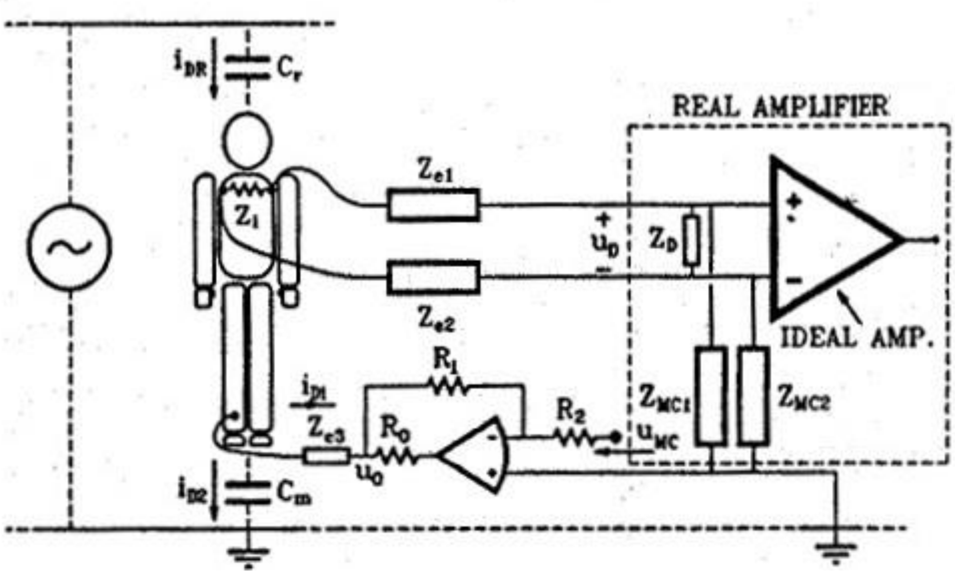

Figure 2.10 Active feedback

Patient safety is not interfered by this amplifier thanks to R_0 which function is to limit the current when U_{MC} rises. At the same time the common voltage gets reduced by the same factor. It is important to notice that these equations are just valid meanwhile the amplifier is working in its linear operation, therefore is very important not to saturate the amplifier giving a large value to the gain (to reduce U_{MC} would be optimal the biggest gain that was possible to reach).

$$Z_{eq} \simeq \frac{Z_{e3}}{1 - A}$$

Equation 2.5 Equivalent impedance

2.2.4 Wearable Electronics

Electronic components in conjunction with advanced fibers composed of man-made textiles combines the fields of materials science and electronics. Such 'smart' textiles, also known as electronic or e-textiles, are able to sense and respond to external stimuli. Innovations in this field will enable advanced and challenging applications in healthcare and important industries in the electronics area. In wearable electronics, the smart textile applications range from medical monitoring of physiological signals such as heart-rate, guided training of athletes, aid to emergency first-responders and commercial applications where electronics including remote control devices, displays and keyboards are integrated into every-day clothing.

Unlike bioelectromagnetism and biomedical engineering that are fields deeply investigated which have evolved during the years and with many reference books, wearable electronics is a novel field without reference books and established information. Therefore the best way to expose some of the interesting information in this field is with a review on few smart textiles projects.

In order to create tools that support the generation of the European Research, the European Commission establishes the Framework Programme for Research and

Technological Development. In the Sixth Framework Programme that include activities in the period 2002-2006 seven [4] projects were related with smart textile and flexible wearable systems. The Stella project is a sample that shows what the research on smart textiles can do.

2.2.4.1 Stella Project

Stella project consisted of developing stretchable electronics for large area application for use in health care systems, wellness clothes and for integrated electronics in stretchable parts and products. In the Stella project several [5] systems and applications were developed, here three final applications are shown.

2.2.4.2 Stella Activity Monitor

This device is a wireless activity monitor composed by a flexible and stretchable textile package that can be joined to straps of different lengths. The activity monitor transmits three axial acceleration data through a wireless module. The electronic design has been split into five separated boards connected with SCB technology where conductive copper tracks are deposited on a poly-urethane substrate. The five separated boards can be seen in the next figure and they are the battery, the power management, the accelerometer sensor, the microprocessor and the wireless transmitter [5].

Figure 2.11 Activity monitor

2.2.4.3 Verhaert Infant Respiratory Monitor

A second example of application in the Stella Project is a infant respiratory monitor that measures both the abdominal and chest elongation of the breast. Similar to the Stella activity monitor, this system is encapsulated in a cloth and can be clipped onto a baby pajama.

The design is based on the Rubbery Ruler [6], a flexible elastic sensor that measures in an accurately way extension and contractions over long periods of time. In this integrated version of the sensor, a similar concept of small parallel capacitor has been deposited on the SCB technology. The system also includes the onboard processing electronics that will advice with an optical and a noise signal in case of alarm, i.e. no breathing activity.

In the next figure a baby dummy wearing a pajama with the sensor cloth clipped on can be seen.

Figure 2.12 Verhaert Infant Respiratory Monitor

CHAPTER 3.

MATERIALS & METHODS

3.1 Introduction

In this chapter, the materials and methods used and implemented to execute this thesis work will be explained. First of all in the materials section the software used in the design and simulation procedure will be shown, after that the material used for the physical implementation will be presented. Finally the methods section will show a short description of the ECG signal acquisition and the peak detector besides the physical implementation process.

3.2 Software

3.2.1 Matlab

Programming environment for algorithm development, data analysis, visualization, and numerical computation.

Figure 3.1 Matlab Logo

3.2.2 MIT-BIH Arrhythmia Database

The MIT-BIH Arrhythmia Database [7], [8] contains 48 half-hour excerpts of two-channel ambulatory ECG recordings, obtained from 47 subjects studied by the BIH Arrhythmia Laboratory between 1975 and 1979. Twenty-three recordings were chosen at random from a set of 4000 24-hour ambulatory ECG recordings collected from a mixed population of inpatients (about 60%) and outpatients (about 40%) at Boston's Beth Israel Hospital; the remaining 25 recordings were selected from the same set to include less common but clinically significant arrhythmias that would not be well-represented in a small random sample.

3.2.3 Altium

Altium Designer is a unified electronic product development environment, involving the major of aspects in the electronic development process. In this project the following aspects of the Altium Software have been used:

- Front-end design and capture
- Signal circuit simulation

- Physical PCB design

Figure 3.2 Altium Logo

Altium Designer includes edition tools and software engines useful to perform almost any step in the development process of an electronic product. The edition, compilation and process of all documents are performed within the Altium Designer environment. The software supports tools too, such as FPGA route software, or third party HDL simulation and synthesis software. The Design Explorer Integration Platform is in the layer below Altium Designer, it brings together Altium Designer's several editors and software engines. It also provides a consistent interface across all the tools and editors. Depending on the specific license purchased the set of features and functionality that is available will vary. The Altium Designer environment allows the user to set up the workspace in a fully customizable way.

3.3 Instrumentation

3.3.1 Oscilloscope Tektronik MSO2012

This Oscilloscope includes two analog channels that were used to visualize the ECG and pulse detection signals simultaneously. It also has an USB port to easily store the information in a memory stick.

3.4 Materials

3.4.1 3M Electrodes

The electrode area is 4cm x 3,2cm, it is an Ag/AgCl electrode with radiolucent gel, and repositionable. It is used especially recommended for cardiac monitoring, event detection, telemetry and Holter for adults and pediatrics use. The up side consists of soft cloth and in the down side is covered with conductive adhesive gel. None skin preparation needed.

Figure 3.3 3M Electrode

3.4.2 Silver Conductive Paint

Electrolube Silver Conductive Paint SCP003 provides a thin, smooth, adherent, flexible film of high electrical conductivity on a wide range of substrates, including plastics, paper, wood, textiles, glass, ceramics and metals. It can be applied by brushing, spraying, dipping, or a pencil and will dry at room temperature.

Figure 3.4 Silver Conductive Paint

3.4.3 Silver Conductive Grease

CircuitWorks Silver Conductive Grease provides maximum electrical and thermal conductivity, proven lubrication properties, and protection from moisture, oxidation, and other environmental hazards. This system utilizes an advanced silicone lubricant that is compatible with metal, rubber, and plastic.

Figure 3.5 Silver Conductive Grease

3.4.4 Silver Conductive Pen

CircuitWorks Silver Conductive Pen CW2200 makes instant highly conductive silver traces on circuit boards. Is used in prototype, rework, and repair of circuit boards by linking components, repairing defective traces, and making smooth jumpers. The silver traces dry in minutes and have excellent adhesion to most electronic materials.

Figure 3.6 Silver Conductive Pen

3.4.5 Conductive Epoxy

CircuitWorks Conductive Epoxy is a two part, silver epoxy used in prototype, repair, and general conductive bonding applications. CW2400 features strong mechanical bonds, excellent electrical conductivity, and quick room temperature curing. CircuitWorks conductive epoxy bonds aggressively to a wide variety of materials.

Figure 3.7 Conductive Epoxy

3.4.6 Textiles

Two different kinds of woven fabrics were used in this work, chosen in between the set that was available. For the first prototype a black woven fabric was use as PCB in where the paths are deposited manually with silver paint. The second fabric was woven and coated in one side with white PET and was used as protective layer on both prototypes, to protect and isolate the paths of both PCBs.

3.4.7 Refillable Cartridge

The Cartridge is the model 14A black ink from Lexmark (18C2080). The refilling process is going to be explained in the methods section.

3.4.8 Conductive Ink

The nano ink 9101 is a silver Conductive Ink 50 ml water based and manufactured by Methode Development.

3.4.9 Films

Among the films provided by the Methode Electronics, the one selected to implement the prototype was the labeled 3G Clear PET treated for enhanced adhesion.

→3G White PET treated for enhanced adhesion.

→Opaque PET

3.4.10 PCB

A two layer printed circuit board from EzPCB [9] manufacturer was used. This enterprise has a worldwide online ordering service, they also offer an assembling service but it was decided to be done by ourselves.

The electronic parts (SMD) of the design were soldered on the top layer, both layers (top and bottom) were used to route the paths.

3.5 Methods

3.5.1 Signal Processing for Simulation

In order to design and validate the algorithm to detect HR from ECG measurements, few signals from the MIT-BIH Arrhythmia Database have been adapted using Matlab enabling the simulate of the HR detection circuit in Altium.

The functions used to adapt the signal are the following:

```
function [C]=signal_vpwl()

%Path where the function is
cd('C:\Users\MARC\UPV\ASIB\Prácticas\PRACTICA
4\Student_1.01_versionalumno\SmallSignals')
%1st load 1-lead signal in Matlab with leedat

signal=leedat;
signal=signal(1,:); %first signal is separated(there are 2 signals in each
file)

%2nd resample the signal from 360Hz to 90 Hz

signal_90=resample(signal,1,4);
%3rd Generate the time array (in this case the array has 2500 points)

t=0:1/90:(length(signal_90)-1)/90;

%4th Normalize the signal suppressing dc and set the maximum amplitude to
0.005

signal_90=signal_90-mean(signal_90);
signal_90=signal_90/max(abs(signal_90));
signal_90=signal_90/200;
```

```
%5th Generate an auxiliary variable that has the time and the signal
interspersed in order to adjust the data to Altium .pwl format

C=zeros(1,2*length(signal_90));
close()
figure()
plot(t,signal_90)
for i = 1:length(signal_90)
C(2*i-1)=t(i);
C(2*i)=signal_90(i);
end

%fid = fopen('C:\Users\MARC\UPV\BORAS\PFC\Altium Project 3\prueba.pwl', 'w');
fid = fopen('C:\Users\MARC\Desktop\prueba.pwl', 'w');

%fwrite(fid,C,'integer*4');
fprintf(fid ,'%f ', C);
fclose(fid);


%6th In Altium create a VPWL part and choose fullpath in properties->Models->
Edit
```

3.5.2 Conductive Ink Printer Development Kit from Methode Electronics

To produce the second prototype a specific development kit manufactured by Methode Electronics was used. In addition to a Lexmark printer a model X2670, the 9101 conductive ink and the film with the surface treated coating film.

3.5.3 Cartridge Refilling

This procedure was needed because ink cartridges provided by the manufacturer were the Lexmark 14 cartridge type instead of the Lexmark 14a.

After researching on the topic, a cartridge Lexmark 14a was bought because it can be refilled not like the 14, that is intended for single use.

Several steps were needed to success the refilling:

1. Break cartridge sealing and sand the rough corners.
2. Clean the sponge where the black ink is stored with water under the tap and also cleaning with some tissue the interior of the cartridge.
3. Put back the sponge in the cartridge and inject on it 15ml of the conductive ink with a syringe from the 50 ml extra bottle provided by the manufacturer.
4. Seal the cartridge.
5. Calibrate the printer following the manual.

3.5.4 PCB Interconnection on Textile

As a first approach to achieve the intended goal of this project, it was decided to transfer the pattern to a one side coated textile and draw the paths and pads with silver conductive paint. The first step was to print with black ink in a regular film the pattern, to cut it afterwards with a cutter, stick it to the textile and paint it. The next step was to attach the three round PCBs to its corresponding place. Finally just needed to insert the batteries on its holders and pinch the wires to the pads and to the electrodes to check the circuit operation. It did work as it was supposed by design and simulations.

A large register of problems must be noticed in this point:

- The painting was absorbed by the textile so it spread out of its pattern and needed several passes to keep the connectivity of the track to be able to drive electrical current through. It was needed to paint several areas few more times due to connectivity loss, especially in the circuit inputs (paths to electrodes pads connections).
- This absorption made the design looks terrible and special precaution must be taken in the area where the paths are placed closer. To control intertrack distance, or track/pad width was impossible.

3.5.5 PCB on Film

In the second approach and with all necessary materials and the printer completely operational, the design was printed with inkjet technology on a PET coated film.

Few steps were necessary. To start, after the printing tests in which the film was chosen and the printer set up, the conductive epoxy was mixed up and got ready to stick the circular PCB to the film. Notice that the connections were done through the VIAs placed around the PCB and to the conductive pads on the film. After the PCBs were placed properly in its position with the epoxy, it was immediate to check that there was connectivity in the whole design, just a few hours were needed for the epoxy to dry. All straight its function was tested as with the previous textile trial. All results were positive and hereby, the physical implementation could be considered as terminated.

3.5.6 Printing Tests

The manufacturer kit was tested successfully, just needed to be taken into account to position the coated side of the films properly in the printer. Different printing orientation was used as it is shown in the Figure 3.8. Vertical orientation was chosen due to print head marks. Double printing pass (paths resistance decreases roughly to half its value with the second one) was tested too. A trial to print out with more ink amount (increasing printing quality in the printer settings) was also carried out. Notice that following the data provided by the manufacturer, the resistance has a stable value after 100 minutes.

Two more tips to care about are being careful to scratch the ink in order not to remove a section of path and break the conductivity and place carefully the tester point measurements because they can also scratch the ink with the same result.

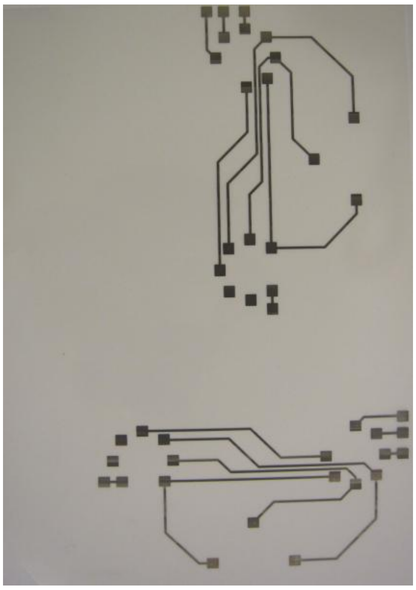

Figure 3.8 Orientation test

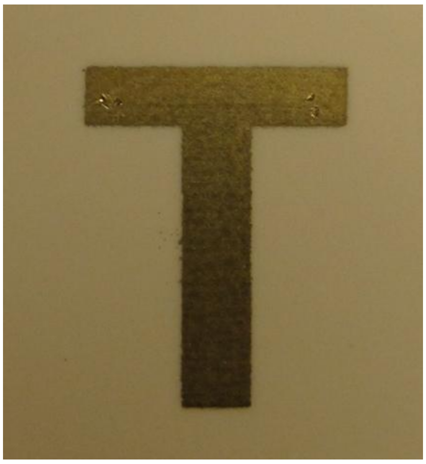

Figure 3.9 Conductivity test

Several available PET films were tested and the clear film with surface treatment for increase the adhesion was selected. Finally the 3G Clear PET was chosen because of its better flexibility, transparency and increase adhesion.

4.1 Introduction

This chapter has been decided to be an independent section due to its importance in the project. Considerable amount of time was invested in this part because re-design was needed for meeting the final goal in the project due to technological, time and other issues that influenced in all those decisions.

4.2 Development

As a first design approach and with first requirements for the project, the whole ECG spectrum for acquiring the complete PQRST (see figure 2.4) was going to be acquired. In this design the filters included the range in between 2Hz and 150Hz with a gain of 62dB (roughly 1150 in linear units). A notch filter to eliminate the 50Hz from the power grid was also implemented. An active feedback for the third electrode was added in order to reduce the common signal level in the patient and to maintain stable the transistor's quiescent point in the instrumentation amplifier where the electrodes are connected. It is important that the amplifier for this third electrode is connected to the common mode voltage and a resistor with a large resistance value in between to comply with safety guidelines (See 2.2.3 Safety).

Other point to notice is that several trials were conducted to eliminate the amplification extra stage. It was tried to implement the gain in the Sallen-Key filter, even reordering the different circuit stages but the frequency response resulted very altered and changing, so finally it was decided to reject the idea and keep the extra gain amplifier.

To avoid extending beyond necessary this chapter, only the final design will be explained.

Finally it was decided that the goal of the project would become to detect the heart rate using a LED, for which is often required the detection of the R wave, so all filters were re-designed to filter the QRS complex and extra electronics were added to be able to detect the R-wave, that is the maximum point of the ECG signal. A detail of the filtering appears in the image below.

At that point of the project was decided to eliminate the 50 Hz filter (even though the power will not interfere with 50Hz because batteries are being used, some 50 Hz noise still gets coupled) and to replace all third electrode electronics to a simple resistor connected to ground. Note that this action is not increasing patient risk because the ground reference in the design is the middle point in between two batteries.

A new paradigm was proposed in order to simplify the design because of the difficulty that developing everything in textile resulted too complicated and the technology needed for it is not totally developed. The final implementation is a hybrid solution where the circuit is distributed into three round PCBs and the interconnection in between them as well as the access to the pads is done printing over a PET.

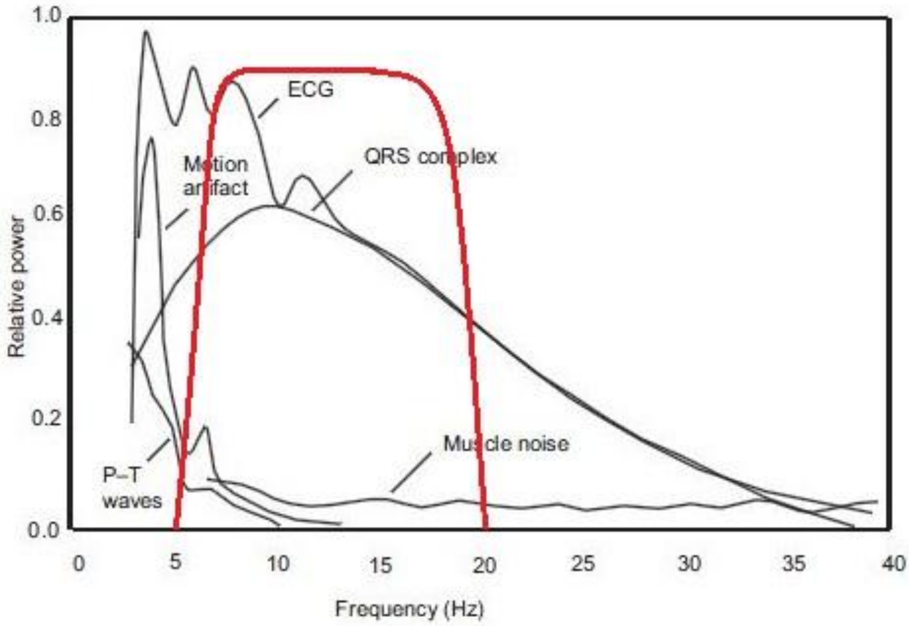

Figure 4.1 ECG and noise power spectrum [11]

4.3 Design

The design of this ECG amplifier includes instrumentation amplifier, filtering and gain stages, peak detector and power. A brief explanation of the functionality and its design of each stage are going to be stated.

4.3.1 Instrumentation Amplifier

To reduce the number of electronic parts involved in the design, it was decided to use an IC for the instrumentation amplifier.The chosen IC is the AD620 which is well suited for medical applications. The advantages of using an IC are basically a CMRR upper than 120dB and the possibility of varying the gain with a single resistor avoiding to design it and to place several parts and its interconnections.

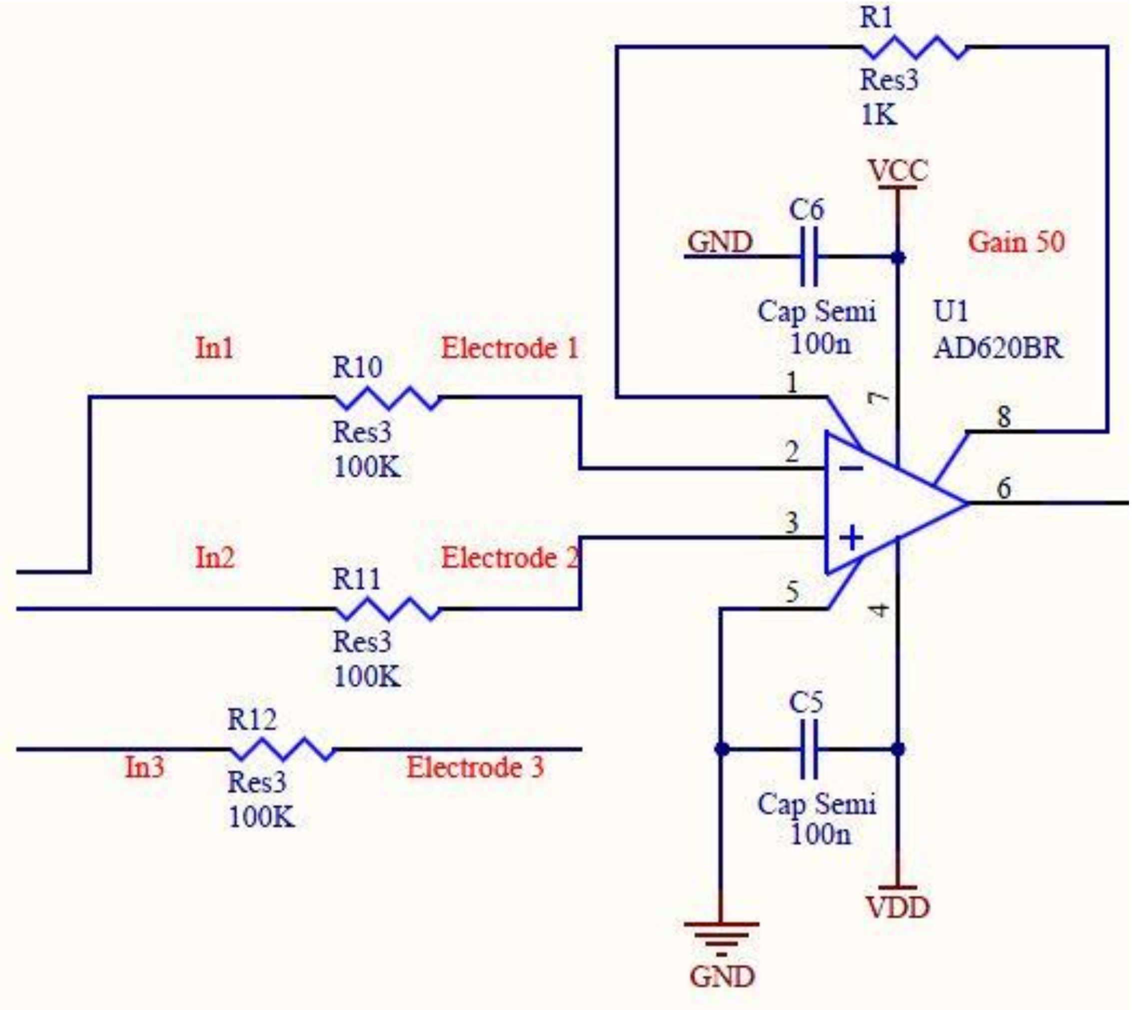

Figure 4.2 Input stage. Instrumentation amplifier

The theoretical desired gain value is 50. Using a $R_G = 1k\Omega$ resistor a gain of 50.4 is obtained. Two capacitors are set to avoid noise in the IC.

$$G = 1 + \frac{49.4\ \text{k}}{R_G}$$

Equation 4.1 Gain Equation

4.3.2 Filtering

Most of the power spectrum from QRS is contained in the [5-20] Hz range. The baseline problem, electrodes movement, EMG (muscle noise) and power grid interference are filtered already, as well the P and T waves. In order to achieve this spectrum range, two different filters are used, the HPF and the LPF, therefore as a result a BPF.

Using the simplest HPF you could find as the next figure shows (first order passive HPF). The equation belonging to implemented design also appears beside the circuit. The cut-off frequency is 5 Hz. With the commercial available discrete components C = 1μF and R = 32kΩ the calculated frequency is 4,97Hz.

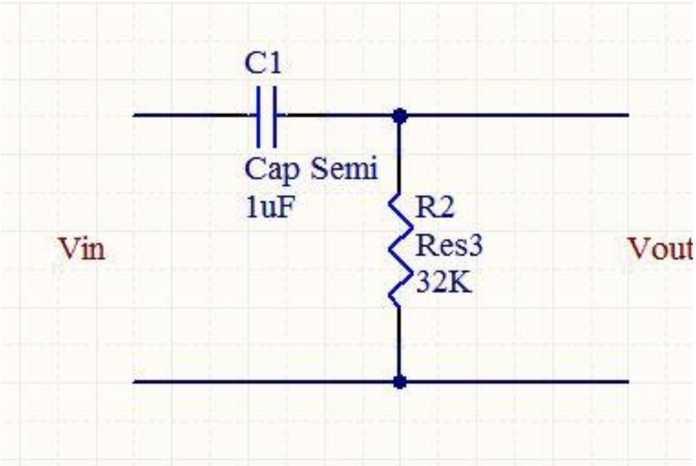

Figure 4.3 HPF

$$f_c = \frac{1}{2 * \pi * R * C}$$

Equation 4.2 Cut-off frequency

As a second filtering stage a very common structure is used, the Sallen-key LPF with 0 dB of gain. The next image shows its circuit connection.

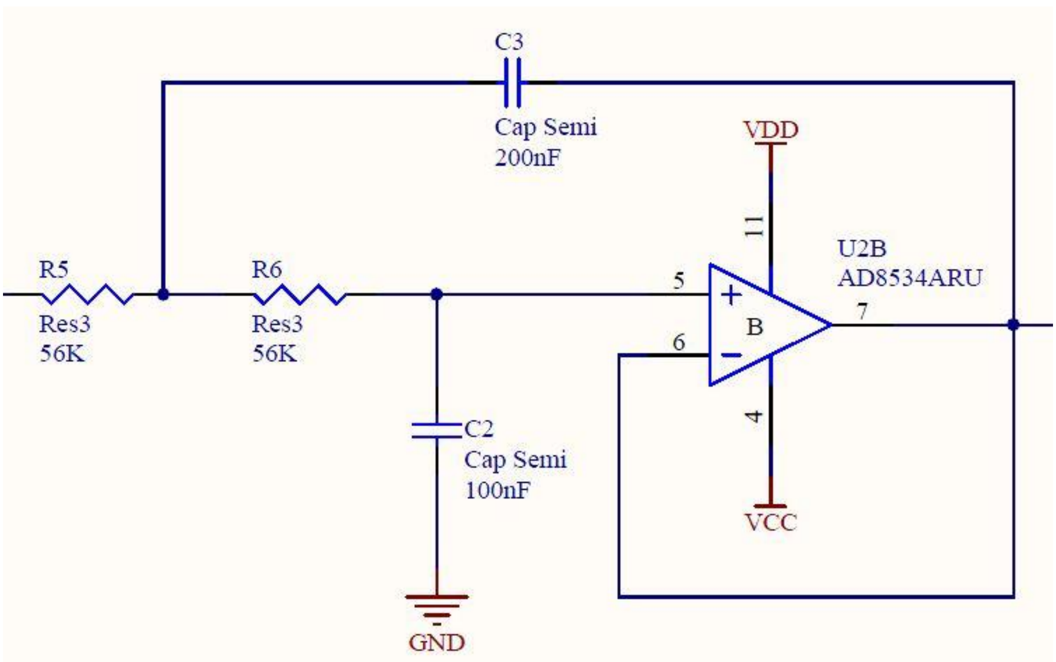

Figure 4.4 Sallen-Key filter

Design equation and conditions:

$$f_c = \frac{1}{2 * \pi * R * C}$$

$$C = C_2 = 2 * C_3$$

$$R_5 = R_6 = 0{,}707 * R$$

$$C = 100n\mathrm{F}\ R = 80k\Omega$$

Equation 4.3 Sallen-key design equations

Using real components $R_5 = R_6 = 56k\Omega\ and\ C_2 = 2 * C_3 = 100nF$ the final cut-off frequency is 19,89Hz.

4.3.3 Gain Stage

This stage consists in a single non-inverting amplifier, which follows the next equation. The linear gain obtained is 23 (27,23 dB). Connected to this IC, it is also possible to appreciate two capacitors to avoid noise as in the instrumentation amplifier IC.

$$V_{out} = V_{in} * (1 + \frac{R_4}{R_3})$$

Equation 4.4 Non inverting OA gain

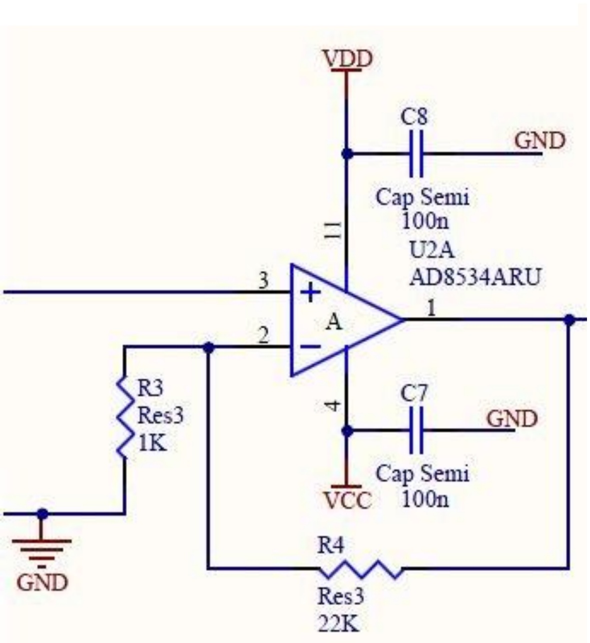

Figure 4.5 Gain stage

4.3.4 Peak Detector and Comparator

In this circuit (figure 4.6) a change in signal amplitude does not vary the amplifier gain, but instead varies the threshold, so it is an adaptive threshold detector that follows the equations shown above this text. This scheme shortens the adaptation time. The amplitude of the preceding QRS complex determines the new threshold. The first operational amplifier acts as a half-wave rectifier and a peak detector. As the charging time constant is very small, the capacitor C quickly assumes a voltage corresponding with the previous signal peak. It is highly sensitive to beat-by-beat variations and transients. For example, a transient or even a high previous beat can drive the threshold quite high, since it depends only on the previous peak value. A smaller capacitor discharge time constant could reduce the threshold quickly, but it would get too low and triggering could occur on small artifacts and P waves [10].

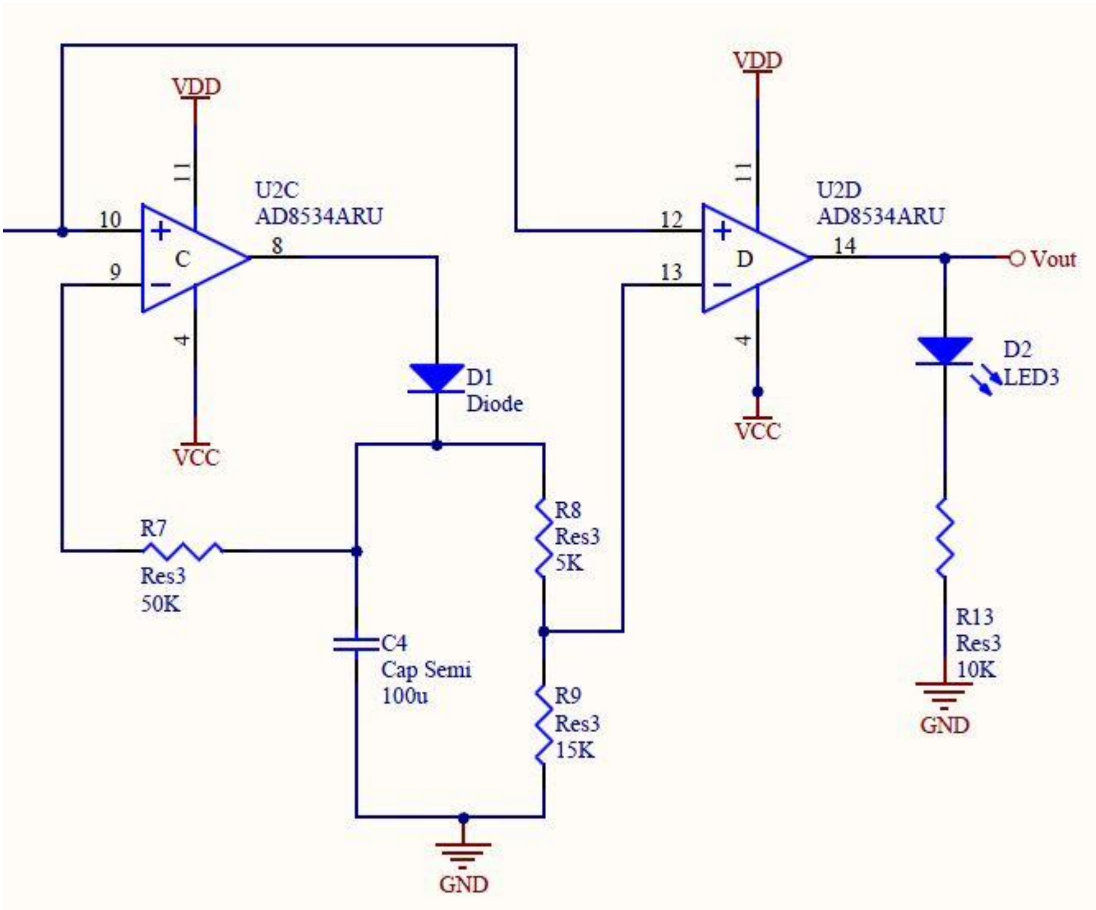

Figure 4.6 R-R Detector

$$V_{12} = \left[\frac{R_9}{R_8 + R_9}\right] * V_{D1} * e^{\left(-\frac{t}{\tau}\right)}$$

$$\tau = (R_8 + R_9) * C_4 = 5s$$

Equation 4.5 Design equations

4.3.5 Power Supply

The power supply of the system consists basically in two batteries connected in series. The middle point is GND, the one that will be the ground reference. Therefore in VCC there is +3V referred to GND and in VDD there is -3V referring same point. Symmetric voltage supply is used in order to provide higher gain values to the circuit

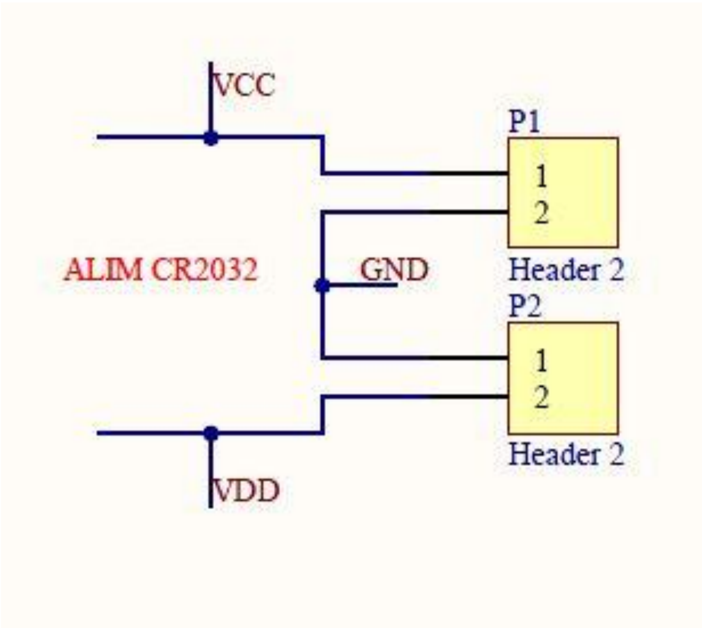

Figure 4.7 Power Scheme

4.4 Simulation

Not much to comment in this section, just to show that as it was expected, using an ECG record from the MIT-BIH arrhythmia database with baseline noise and its processing mentioned in **3.5.1 Signal Processing for Simulation** is possible to detect the heart rate. The figure 4.8 shows the detector working properly, a detail of a single detection is pictured afterwards in figure 4.9.

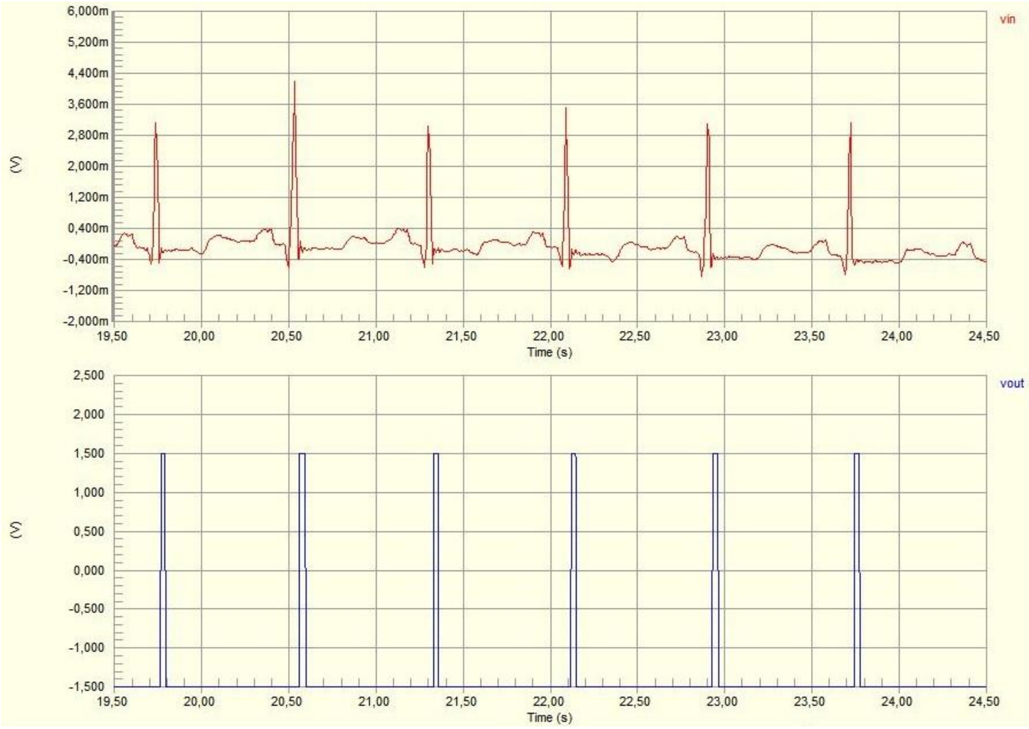

Figure 4.8 Simulation output

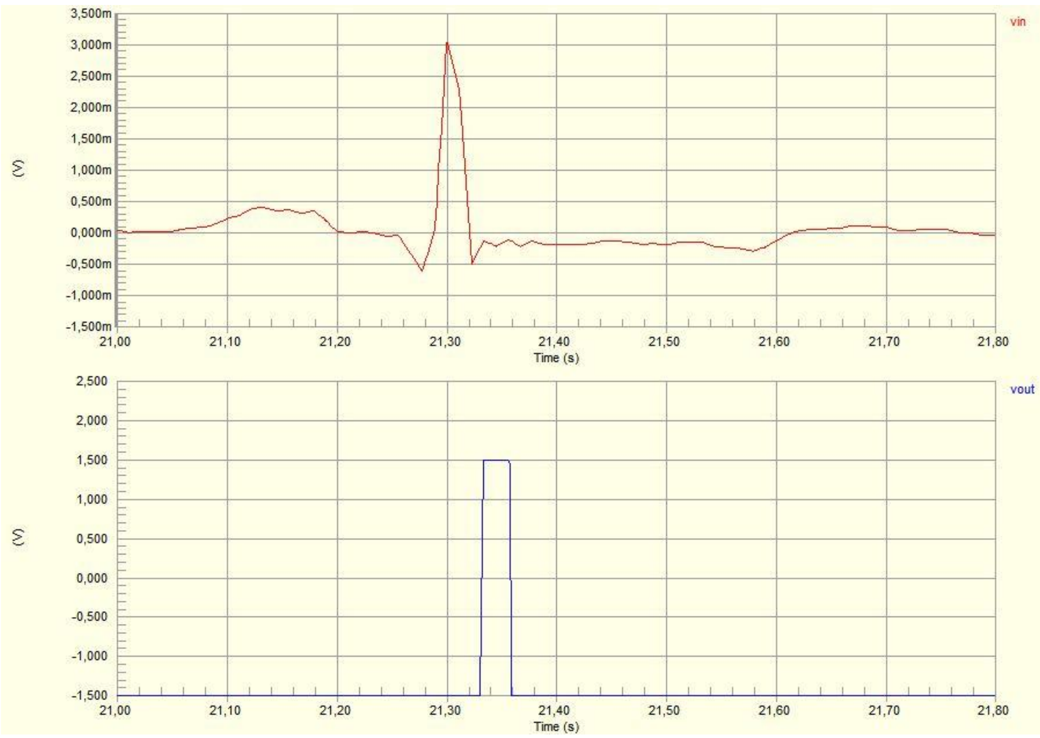

Figure 4.9 Peak detection detail

4.5 Test Board

The next natural step is to mount the circuit in a test board before doing the PCB design and order its production. For this stage all components were ordered in DIP format despite for the AD8534 (it has four operational amplifiers inside) in which an adaptor was necessary because it is just available in SMD format.

All the montage was carried out and tested for first time with a real ECG signal from a subject and the obtained results were as expected.

4.6 PCB on Textile

The methodology and problems that occurred on its development are better explained in chapter three at section **3.5.4.** A short review is listed here.

1. Print the template in a film.
2. Cut it as a negative pattern.
3. Cut the piece of chosen textile.
4. Apply the conductive pen to the pattern.
5. Remark over the pen with the silver painting.
6. Check connectivity and repaint problematic areas.

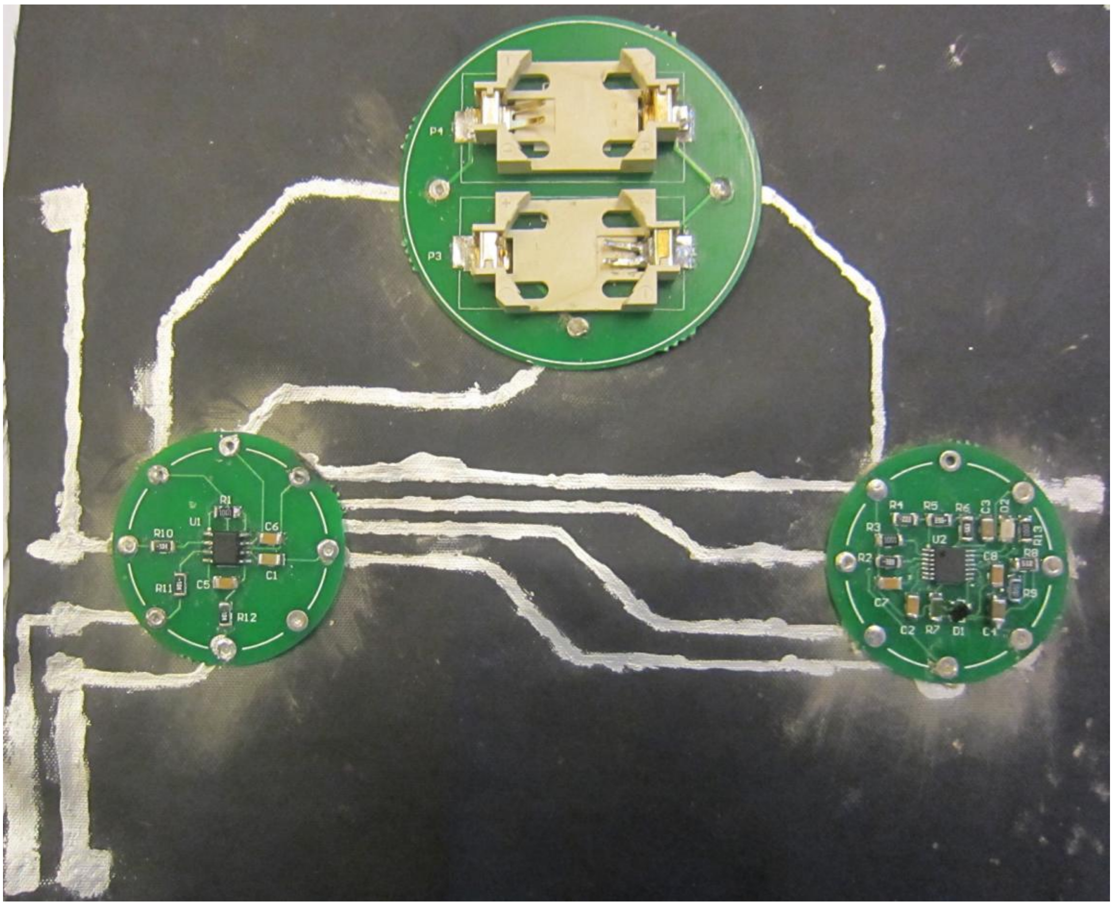

Figure 4.10 Textile ECG detector

4.7 PCB on Film

The procedure to implement this second ECG detector was easier and much shorter than the first one once all materials and the printer were ready. The steps followed are listed below:

1. Two printing passes on the film (increases its conductivity).
2. Soldering all components to the PCB
3. Attach the circular boards to its correct position on the film with the conductive epoxy and let it dry long enough.
4. Insert the batteries.
5. Connect the wires to the electrodes and to the pads.

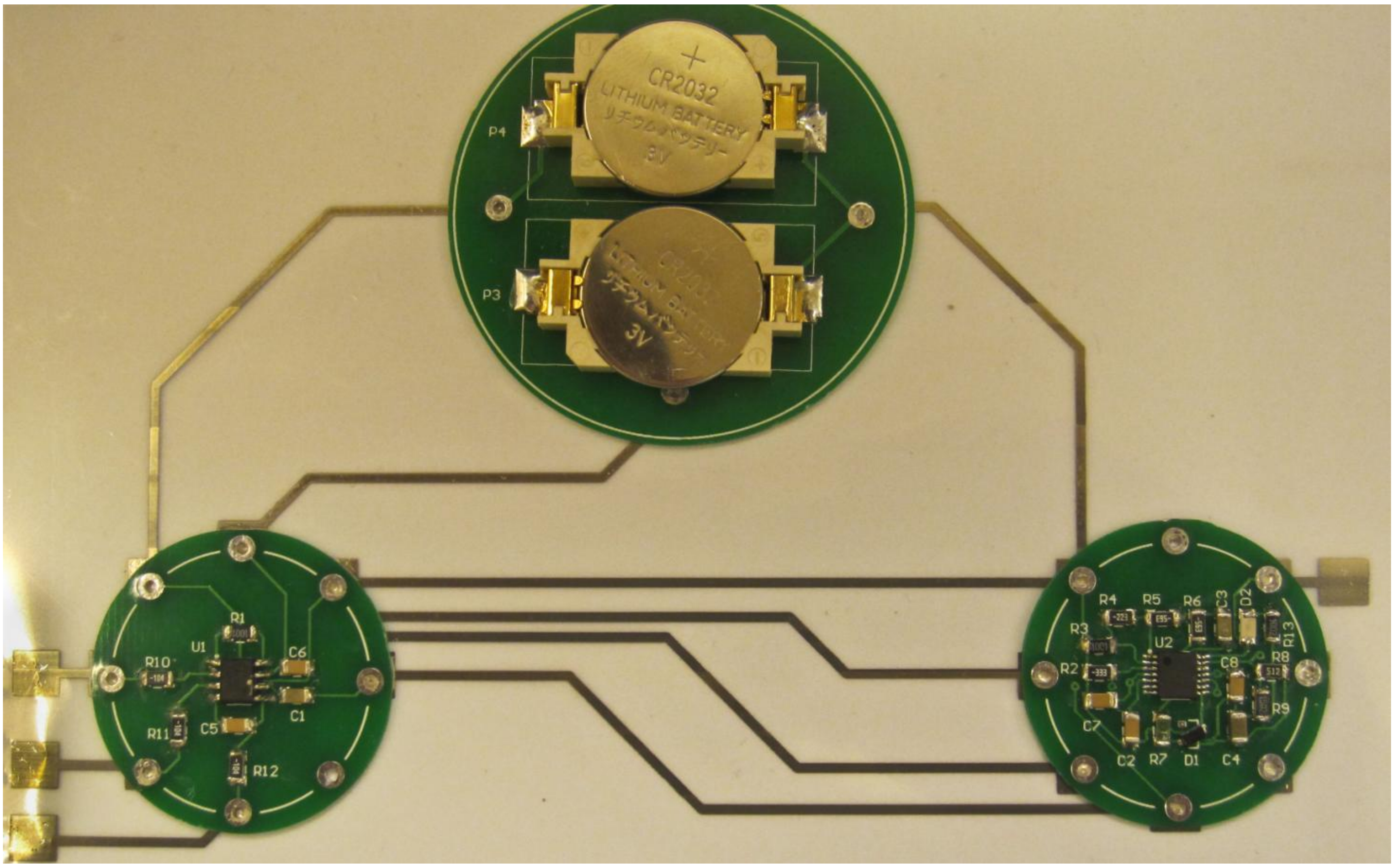

Figure 4.11 Film ECG detector

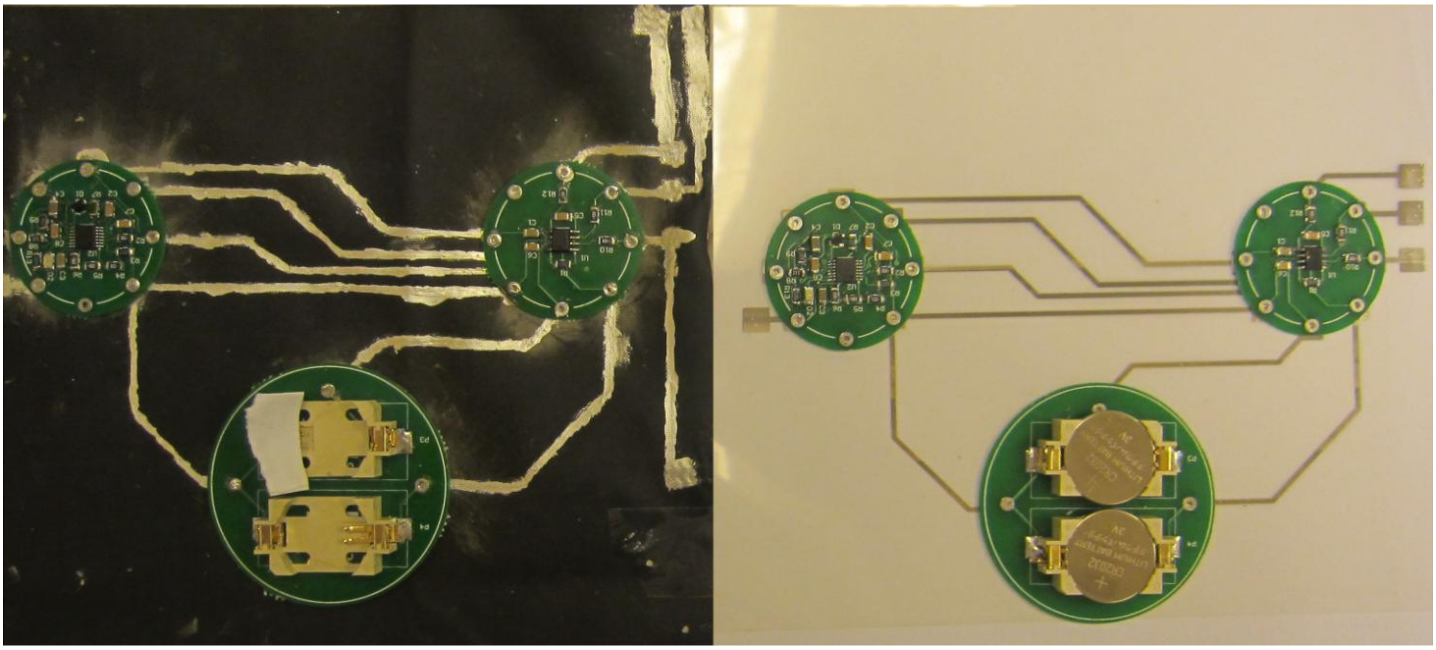

Figure 4.12 Comparison between both implementations

As it is visible the qualitative leap from first approach to the final version is quite substantial, but the most important is the improvement in the stability.

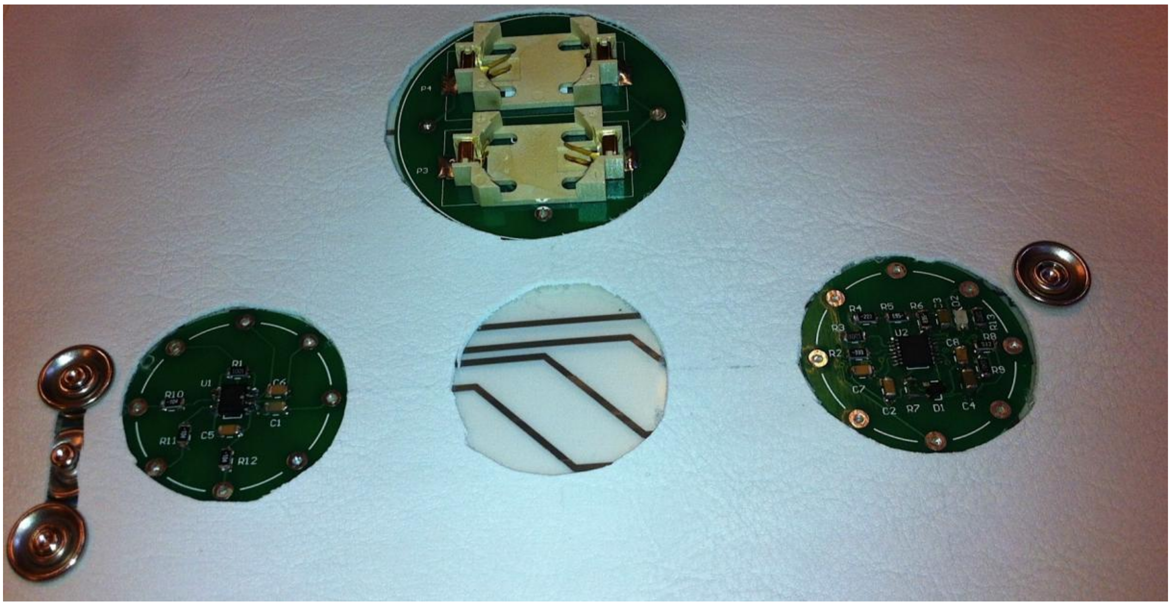

Figure 4.13 Final result on film

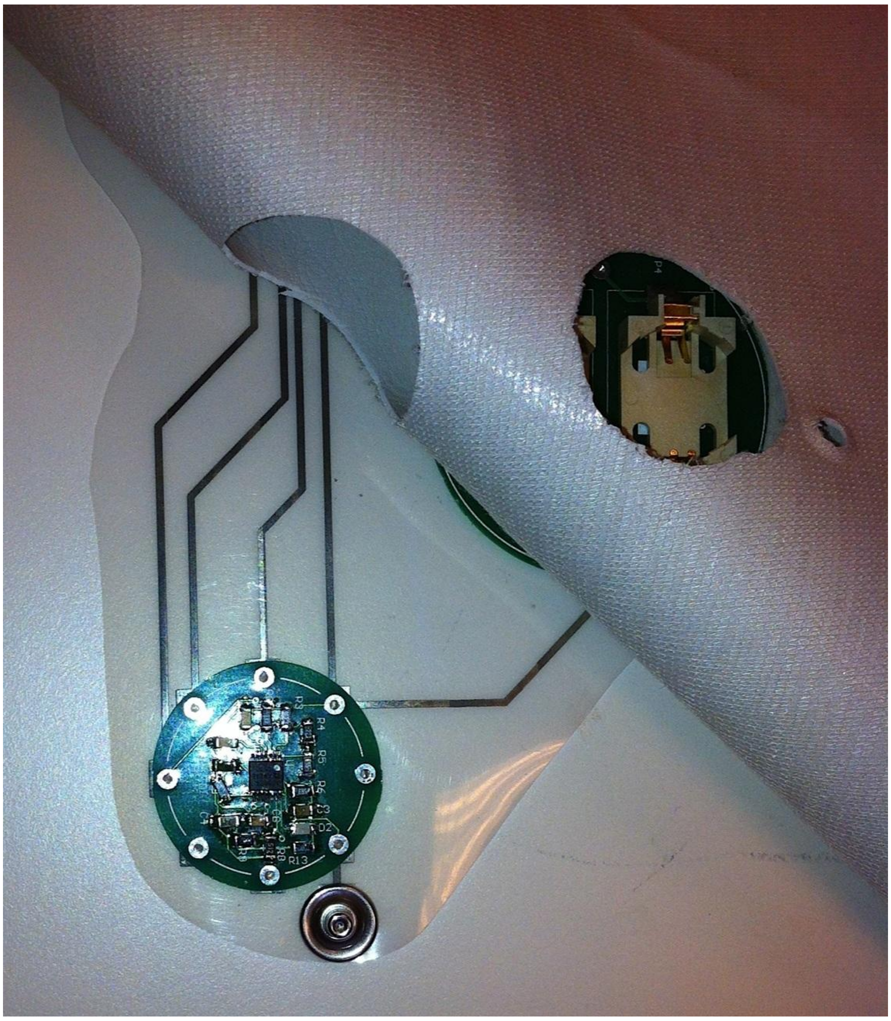

Figure 4.14 Detail of final result on film

After testing the circuits and verify that everything worked properly few tests with both circuits were done. None of the people who participated in these tests had significant cardiac problems, thereby the signals acquired match with the sinus rhythm.

In this chapter the results consist of measures taken with the oscilloscope of both the ECG and the peak detection signal. As two circuits were developed (textile and film) the results of both are going to be shown. The signals are plotted with Matlab without any process, thanks to the USB port that the Tektronik oscilloscope has.

5.1 PCB on Textile plots

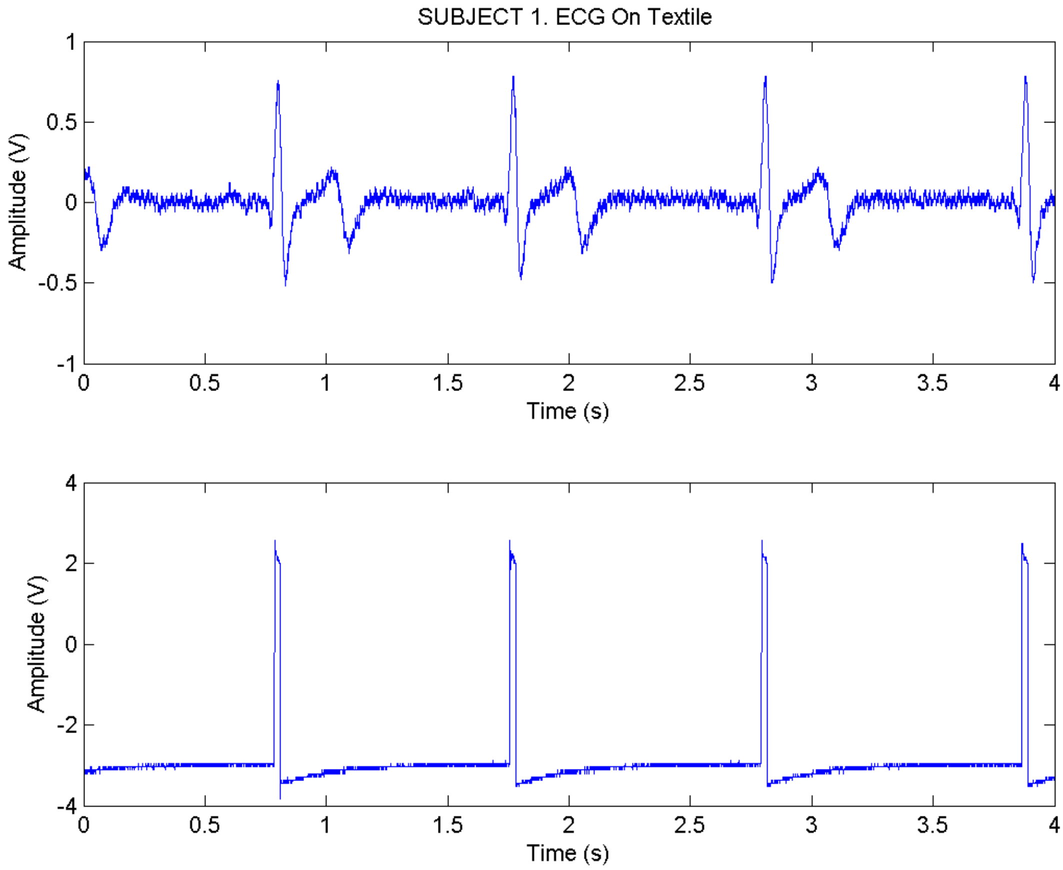

Figure 5.1 Subject 1, recording 1

In this first recording of four seconds (no longer registers are necessary to show its operation) from the first subject and the textile ECG, it is possible to observe a regular sinus rhythm and an accurate detection. Some noise is also visible over the pure ECG signal. It is something that could be expected because the electronics involved in the circuit were reduced to the bare minimum. A more precise signal could be acquired improving the filtering stages and adding the 50 Hz filter for the power grid; other facts could also be taken into account to enhance a bit more its quality, like shielded cables, active feedback, etc.

In the second recording (figure 5.2) for the same subject and same ECG, it is obvious that the noise level is higher than for the first register.

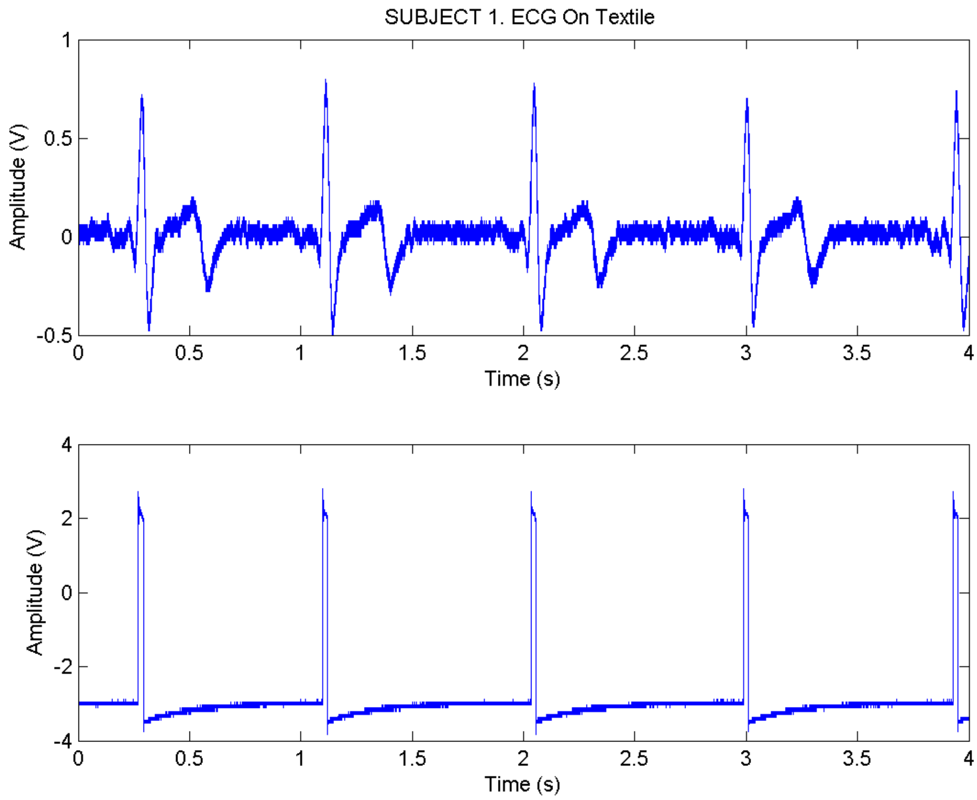

Figure 5.2 Subject 1, recording 2

5.2 PCB on Film Plots

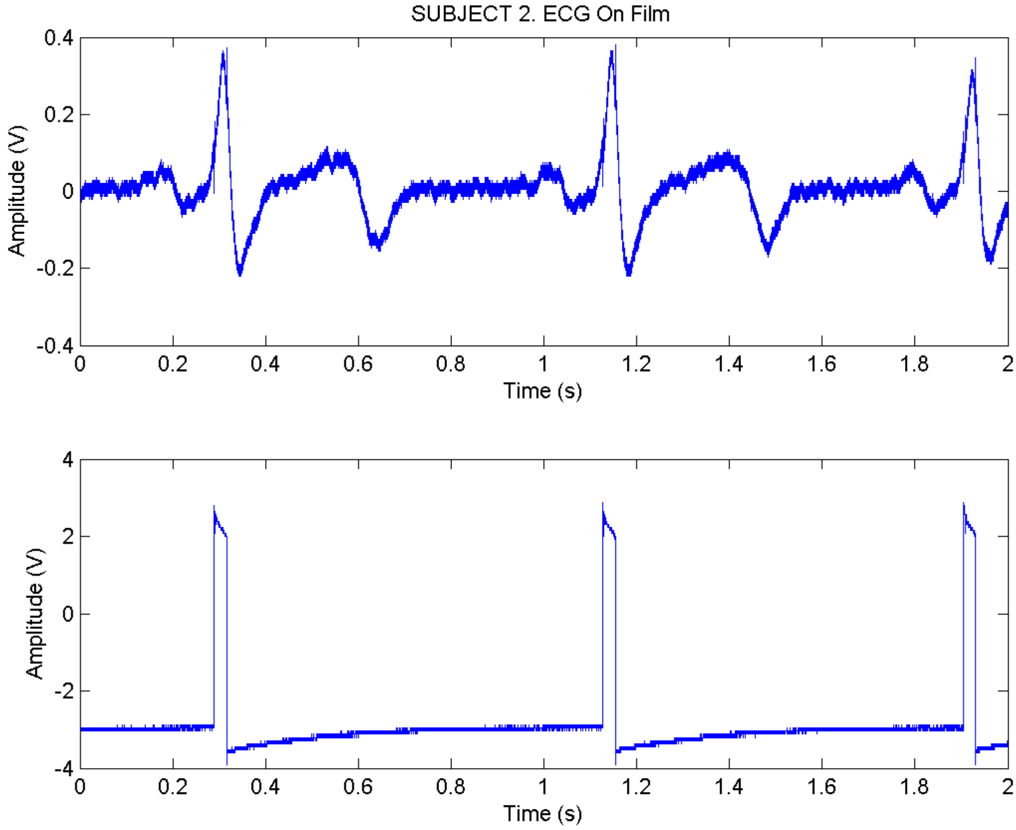

Figure 5.3 Subject 2, recording 1

In this second section of results another subject is tested with the other circuit, the ECG on film. Better results were expected from this circuit due to its better reliability, thing that cannot be really appreciated because of not any of the improvements that would make a difference have not been developed, it was not the goal of this project having a very sharp signal, the real aim was to make a step into the textile electronic integration in the medical area. No further tests with more subjects or under other conditions were performed.

Not much more to comment about these two recordings (figures 5.3 & 5.4) despite that on the figure 5.4 is possible to see how the ECG amplitude goes decreasing in the last 3 beats and how the detection is still good, having a closer look on the heart rate detection is possible to see how the rate is a bit faster on those commented last beats.

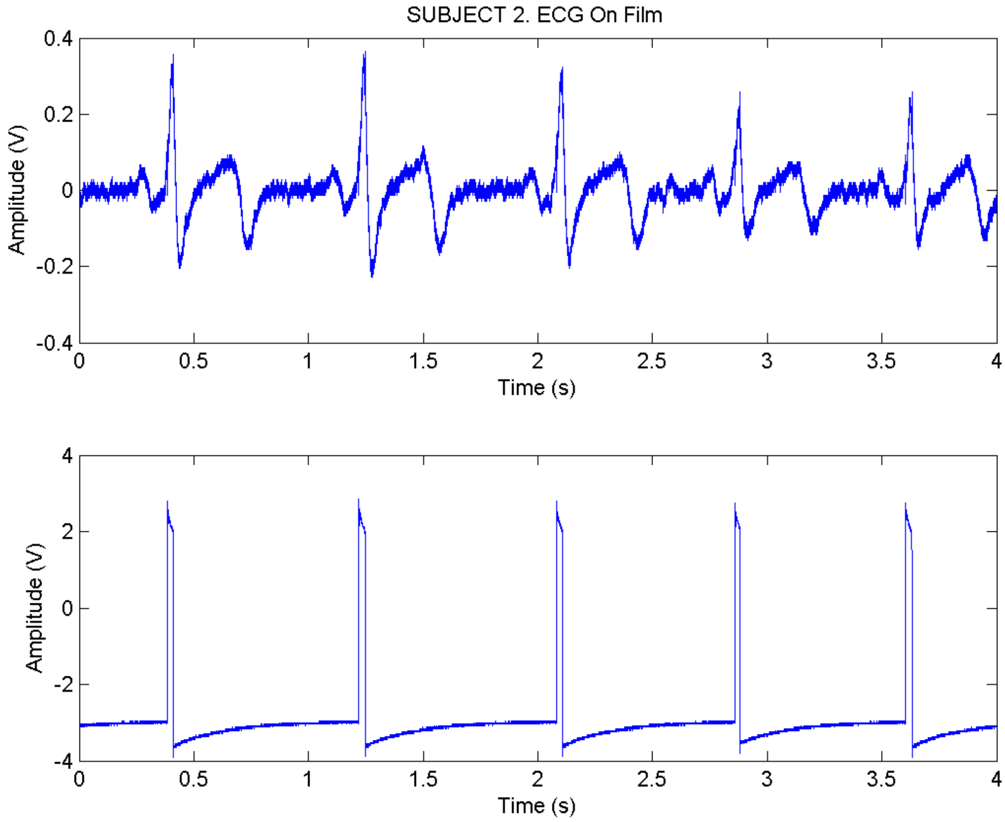

Figure 5.4 Subject 2, recording 2

6.1 Conclusion

Attempting to implement a stress detector, a research in non-invasive measurements was carried out. Based on the conclusions it was decided to design an ECG recorder and heart rate detector based on textiles.

Due to issues related with the present situation of the wearable electronics technology, a redesign was necessary in order to make the project affordable. It consisted on implementing a hybrid design where the circuit was distributed into three round PCBs and the interconnection in between was done using printed electronics techniques on stretchable substrates. Two different models were carried out, one on a film and another one on a textile. Tests were executed with both models in the ECG acquisition and in the heart rate detection with successful results.

Despite the main goal consisting on develop a simple three electrodes ECG detector prototype on textile for stress assessment was not achieved, the attainment of a medium-term goal, a hybrid system that works properly satisfy the authors. Future work will be necessary if the final goal want to be reached.

This is a first step in order to obtain full textile circuits that can help to improve the life style, not only in the health field but in countless fields. Many years of studies and research will be needed to create a solid technology that allows the humanity to integrate all kind of wearable electronics into his garments.

6.2 Future Work

After demonstrate that the hybrid design prototype works properly acquiring the ECG signal and detecting the R-wave, future work, especially in the e-textile area, is needed in order to improve the usability and power of a textile ECG.

Some of the possibilities to enhance the initial design are:

Implement the ECG totally over a textile as it was the first idea in this thesis. This technology still has to evolve to be viable a full electronic design without using any rigid support for the components. Other point to take into account is that with the actual technology the components and paths get fast deteriorated with the washing, daily use and stretching, so further research is also required in this field.

When the technique to integrate the components in the textile would be mature, another way to have a better system would be to increase the filters order and adding the 50 Hz rejection filter that was omitted to confer ease to the circuitry and its textile ensemble.

Flexible plain batteries have been in development and research in the last few years this is an optimal option to reduce the size, weight and to improve the flexibility of the mentioned system. Mention that in the project, one of those three PCBs was totally occupied by the batteries and its holders. Another extra for the power would be to redesign for using single supply amplifiers reducing to just one battery.

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Technological approaches to assessment of alertness and stress with non-invasive physiological measurements.

Introduction

Nowadays ,in a rapidly changing society where everyone has a lot of responsibilities and chores, stress is a common cause of poor job performance, illness, disease and sometimes risk for the own person and for the rest (think of jobs as police, firefighters, professional drivers, etc..). Rapid detection on symptoms of stress and act on them can prevent major problems. A real-time personal stress monitor based on a device implemented with a textile ECG would help in that innovative task. Here it is presented a literary research carried out before starting the thesis; it pretends to evaluate the available technologies for this stress and alertness assessment, detection and its analysis.

Research Methodology

The proceed basically will consist in a deep research of papers and articles in the HB INSPEC´s database, IEEEXplore and Google searcher with related issues to assessment and stress diagnostics. In first instance, a very generic research with topics related with "Technological approaches to assessment of alertness and stress with non-invasive physiological measurements" such as stress monitoring, mental load monitoring, stress detection ECG and so on; some of the searches provided lots of results, some other almost none and some a big amount without any relation with our investigation. To continue focusing on the important results and narrowing the list, extra keywords were added to restrict the number of results. The sort of papers obtained for each topic was classified in function of the method used for obtaining a response of the stress and alertness in persons. After set in order all the articles, we read all of them and checked the most important references. Once this was done we collected the articles that concern to our issue To improve the initial research in the INSPEC database we checked the intern references of the most important papers and downloaded a certain amount of them.

Skin Conductance

The references encountered in the literature show that SC is a good measure of the sympathetic activation which is related with the stress reaction. Although few records were found, all of them are quite recent (the oldest is from 2005).

Few records, nine, were found related with the use of SC as an indicator of stress. Only one of them [1] refers to SC as a separate system to detect stress. The rest of the references combine SC with other physiological signals in order to evaluate the stress level. [2 & 3] Use SC and HRV together in a stress detection system for real time situations. [4-6] Consider SC with Blood Volume Pulse, Pupil Diameter and Skin Temperature in a system for detecting stress on computer users. SC has also been used with EMG and ECG to infer the emotional state of a user in a human-robot interaction

[7] and detect stress in driving situations [8]. The last record [9], uses SC besides oximetry pulse to detect the alertness and mental stress on drivers as well.

Electroencephalography

The strong correlation between EEG power spectra in each frequency band to the mental state makes the EEG one of the best physiological measures to detect stress. Recent studies [10] based on the frontal asymmetry theory demonstrate that the relation between alpha and beta waves ratio in left and right hemisphere can be used to indicate the existence of stress.

When research about detection of stress and alertness involving physiological measures has been done, most of the results in it are related with EEG. The search of keywords as “stress EEG” or “alertness EEG” in the INSPEC database produce many results, most of them deal in a general way with the issue.

Based on the results of the research and considering EEG as one of the main indicators of stress level and alertness, a limited number of articles related with EEG were reported in here [10-15].

[10] Does a review of previous works using the EEG signal as input for stress evaluation. [11] Use EEG to classify workload on pilots during task executions. In the area of alertness and drowsiness [12, 13, 41] realize an analysis on driver’s fatigue. On [14] a study involving military and civilian volunteers show that high frequency EEG may be applied for electroencephalographic monitoring of cognitive performance. A real-time detection of alertness model based on multi-channel EEG power spectra estimation was presented on [15].

Heart Rate Variability

HRV reflects the cardiac events and represents one of the most important markers to detect mental stress and ease to implement. We selected in total twenty-five papers for this section.

Most of found papers behave towards how to relate, measure and interpret the stress and mental load with HRV measured through the ECG, [16-32] remark that [20] uses breath monitoring. The key point is to detect the stress early enough to avoid major problems and its consequences.

Based on the previous conducted research, the next classification is appropriate according to the topics that have been used for the investigation and its target.

As you can appreciate in the following sources enumeration, one of the most developed fields related with the HRV is the measurement of the mental load and stress assessment through the ECG [16-32].

As second point, we tackled the multiple measurements systems, which use different kind of techniques to achieve better and more reliable results [33-35]. Despite of this, HRV is not a very extended method because it is still under research and development, but it is being pointed as the future leading trend. Just a few papers are going to be listed, but it is possible to find some extra amount with deeper research if it is considered necessary.

The third point in relevance we want to remark is the HRV with Stress Response Inventory. It tries to relate the HRV with stress through different type of forms and in a different selection of scenarios with external controlled stimulus [36-39]. [38 & 39] combines the photoplethysmography as an extra tool to diagnose.

The fourth spot is taken by HRV combined with EEG to detect lack of alertness. EEG is one of most developed applications in driving monitoring fatigue and drowsiness. Another extended development field is the evaluation and control of mental load in risky jobs [13 & 40].

Discussion

The main purpose of stress assessment is to prevent people about health problems and possible accidents in work environment and a large list of scenarios.

Referring to the non-invasive methodologies collected in this report, SC, EEG, and HRV are the most suitable techniques to detect stress and lack of alertness have been deeply developed and studied. Other techniques as eye and mouth tracking, blood pressure, skin temperature, etc. have been considered but they were less attractive for our goal. It does not mean that a good combination of these different methods will not provide satisfactory results.

We have been focused in non-invasive single measurement data acquisition motivated by a future possible implementation of the sensor, despite that multiple parameters sensing makes easier the data interpretation, they are more powerful and provide trusty results.

One point that must be considered is that if we are trying to measure the stress of the subject, it is important that the person under test does not perceive the sensor/s to avoid acting unwittingly over the sympathetic system and therefore increasing its stress level, just because of the thought of being constantly monitored and consequently registering non reliable results. We think that probably the best of the three selected candidates is the HRV through the ECG measurements with the novelty of smart textiles for integrate the system in clothing and with possibility of wireless data transmission for total motion independency.

Conclusion

Several studies have been trying to link stress, lack of alertness and emotional states to physiological signals. As seen in the available literature EEG, HRV and SC are the most used methods up to know. These methods are non-invasive which makes them perfect for implement real-time stress detection systems.

SC detects the sympathetic activation of the body, directly related with the stress of a subject. Due to its limitations it has been used normally with other physiological signals in a multiple measurement system. By contrast both EEG and HRV are physiological signals that can be used alone in order to detect or assess in stress and alertness issues as literature shows.

Many studies use EEG as the main signal to detect stress, EEG is also known for its relation with sleep phases, which is interesting in applications related with alertness and drowsiness. In any case we consider HRV as a valuable method in order to make real-time stress detection and assessment of alertness not only based on the results given on the available literature, but on the ease and comfort that a mobile device such as a textile ECG can bring.

Nevertheless, the trend in stress detection is using multiple measurements to conform a system that can achieve lower error rates. Multiple measurements are against the ease and comfort in mobile devices but are by far the best solution because most of the signals cannot disassociate sympathetic and parasympathetic activation if collected alone.

Finally it is important to remark that although these techniques had been used during last 40 years, is in the last decade when wireless applications and small devices can handle a huge amount of data where real-time systems has sense. Therefore it is expected to notice a high increase in real-time applications or devices related to stress detection as well as new studies in the field.

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