Design of a Wearable Wireless Electrocardiograph
(Quick Doc)

by

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Abstract

In most modern clinics patient wait times are continuously increasing due to a shortage of physicians. Quick Doc is a device that integrates an ECG, Pulse Oximeter and a Blood Pressure monitor to gather the three main components of a medical exam. By providing this information in a faster more efficient manner the Quick Doc device aims to assist a physician in acquiring an accurate diagnosis sooner thereby reducing patient wait times. The Wearable Wireless Electrocardiogram (ECG) is one of the three components integrated into the Quick Doc device. The Wearable Wireless Electrocardiogram (ECG) aims to measure the cardiac rhythm and rate of a patient. It ensures that the QRS complex is intact for the diagnosis of cardiac arrhythmias. The ECG system is used to detect Respiratory Sinus Arrhythmia (RSA) in a case study. Design considerations that need to be taken into account when designing an ECG are discussed including special requirements for PCBs in medical applications. The ECG system involves two silver electrodes attached to the wrist of the patient from which the electrical activity of the heart is acquired, amplified, filtered and sent wirelessly to a base station for post processing. The main thrust of this project is on the acquisition of the ECG signal. The design of +/-5V dual power supply from a single 9V battery is discussed.

Keywords: ECG, Wireless, electrodes, medical PCB, +/- 5V dual power supply, instrumentation amplifier, low pass filter

Acknowledgements

Table of Contents

List of Tables

List of Figures

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Chapter 1

1. Introduction

1.1 Background

In today’s world healthcare has become a major challenge that every country faces. Here in Canada we face the daunting challenge of providing healthcare to over 2 million Canadians who cannot find a family doctor [1]. Due to a shortage of physicians we need to begin to look at ways of easing the workload on current healthcare professionals so that they can take on more patients. This is where advancements in biomedical technology come into play. There are certain basic physiological signals such as the electrical activity of the heart, temperature, the blood pressure and the blood oxygen concentration which can be measured to provide a holistic view of a patients’ health. Armed with this knowledge a physician is able to provide an accurate diagnosis faster which reduces patient wait times and the work load on our healthcare professionals.

1.1.1 Quick Doc

The Quick Doc device of which this project is a part of is a wireless diagnostic system that acquires physiological signals from a patient and transmits them wirelessly to a base station for processing. The physiological signals that this device can measure include the electrocardiogram (ECG), the blood pressure and the blood oxygen concentration. These signals are crucial when vital measurements are required in a clinical setting. By integrating these three signals into one system the Quick Doc aims to make it simpler for the physician to spot an abnormality and make a diagnosis. The goal is to implement such as system in a clinical setting, were a patient can put the device on and the vital information of the patient will be sent to base station which the physician can access. If multiple patients are using the Quick Doc system then the physician will have all the information from the patients and he/she can determine which patients are at higher risk and can tend to them first.

The wireless aspect of this project allows for a patient to move to move around and not be bound to the diagnostic device that is taking measurements. This greatly improves patient comfort. The wireless aspect of the Quick Doc system allows for it to be implemented in training and physiotherapy. Patients are currently connected by long wires to the diagnostic device and therefore have limited mobility even during cardiac stress tests. In a cardiac stress test a patient is connected to an ECG and he/she runs on a treadmill with ten electrode wires connecting to the ECG device. This is a huge problem for anyone undergoing a cardiac stress test this can be overcome by using the Quick Doc.

The underlying theme of the Quick Doc system is to create ease for the user by incorporating a wireless component. The ability to measure three vital physiological signals and transmit them wirelessly makes the Quick Doc unique.

The Quick Doc team consists of Doralice Ferreira who worked on the blood pressure portion of the project, Hamzah Qureshi who worked on the pulse Oximeter for measuring blood oxygen concentration, Kundan Thind who worked on the integration of the system as well as post processing and I worked on the electrocardiogram (ECG).

1.1.2 ECG

This project focuses on designing and building a wearable wireless electrocardiograph (ECG) which can monitor the electrical activity of the heart. An electrocardiograph (ECG) is non invasive technique that utilizes electrodes placed on the skin to capture the electrical activity of the heart [2].

The electrodes on different sides of the heart measure different parts of the heart muscle in between the electrodes. The ECG measures the overall resultant electrical vector from the contraction of the heart muscle cells. By exploiting the ECG’s ability to measure the electrical signal between a given pair of electrodes a physician is able to diagnose the any abnormalities that may exist in that portion of the heart. A clinical ECG consists of 10 electrodes which translate to 12 leads or 12 different views of the heart but this is extremely time consuming and involves the use of gels and pastes that require skin preparation in the thoracic region [3]. Given the fact that there are long wires used in clinical ECGs a patient’s mobility is severely restricted which results in patient discomfort. By using two electrodes to measure the electrical activity of the heart this project has addressed some of the issues with patient discomfort. This project has been designed so as to allow any patient to administer portions of the ECG test themselves thereby reducing the work load on healthcare professionals. All this is accomplished by reducing the number of electrodes required to perform an ECG this results in only one view of the heart instead of the 12 different views in clinical ECGs. Given that the purpose of this system is to only provide preliminary diagnosis this is sufficient. The electrodes in this project provide cardiac rate and rhythm which are adequate for a general diagnosis on the health of the heart.

1.2 Objectives

As with any engineering project the wearable wireless electrocardiograph project has certain clear objectives that were achieved during the course of the project. The first is to reduce the number of electrodes that need to be physically attached to the patient and to position the electrodes on the wrists of the patient. This allows for greater patient mobility and permits patients to self administer the ECG test if necessary. By placing the electrodes on the wrists we can reduce the time required for skin preparation. As this project utilizes silver electrodes to collect the electrical information from the heart, the employment of conductive pastes such as the Ten20 conductive paste became a necessity. By placing the electrodes on the wrists the use of conductive paste was not too much of a hassle to the patient. In comparison a clinical ECG requires the conductive paste to be applied to the thoracic region which can be hassle for the patient and the healthcare professionals. Another objective was to reduce the cost and power consumption of the ECG. The total cost of the ECG project excluding the wireless module was $29 dollars which is relatively cheap; the cost breakdown is shown in Appendix B along with a parts list. To reduce the power consumption in this project I used the AD623 low power instrumentation amplifier which allowed for a portable power supply to be designed and implemented. In the end the power supply utilizes a single 9V battery to provide the instrumentation amplifiers with the required supply voltage of +/-5V. The final objective was to provide a clean and filtered signal for post processing which can be employed to provide the cardiac rhythm and rate. This was achieved by using a passive low pass filter with a cutoff frequency of 33.86Hz.

1.3 Methodology

The electrical signal produced by the heart has a principal measurement range of 0.5 to 4mV and a signal frequency range of 0.01 to 250 Hz [4]. Given the fact that ECG voltages are extremely small one can conclude that some form of amplification is required for the signals to be displayed properly. In fact in the wearable wireless ECG project the amplification gain used is 300. There are many factors that come into play when designing an ECG such as frequency distortion, motion artifacts [5], noise due to electrical equipment and other sources etc.. Each of these issues is individually addressed in this project. For more on the techniques used to address the problems please refer to the design portion of this report. The diagnostic frequency range for a clinical ECG is from 0.01 to 150 Hz and frequency range for an ambulatory ECG is from 0.5~30 Hz [6]. Given that we are only looking for cardiac rhythm and rate we do not require the higher frequencies this also allows for removal of most motion artifacts and power noise. This project will capture the ECG waveform by using a first order low pass filter with a cutoff frequency of 15.9 Hz. This allows for a greater suppression of power noise than using a filter with cutoff at 30 Hz. The theory and reasoning behind the choice of 15.9 Hz for the cutoff is discussed in section 3 of this report.

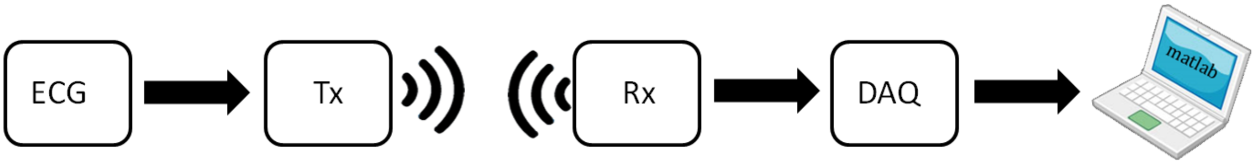


Figure 1: Depiction of the entire Wearable Wireless ECG system, Tx represents the transmitter, Rx represents the receiver, DAQ is the data acquisition unit, a computer running Matlab is also shown

In order to understand the project as a whole Figure 1 above shows the overview of the entire ECG system; which is a component of the Quick Doc device. The signal acquired from the body is transmitted using the wireless transmitter and receiver pair (Linx TMX869/RMX869). The data is then obtained by a data acquisition unit (DAQ) and sent to a computer. Using Matlab the data is processed to reveal an ECG signal. The ECG block includes the power supply, the electrodes, the instrumentation amplifier and the low pass filter. The wearable wireless ECG project will only involve the ECG block. The transmission and receiving of the wireless data as well as post processing of the data is covered by Kundan Thind as part of the Quick Doc integration.

1.4 Scope of Project

The wearable wireless ECG project can be split into three subsections they are the ECG, the power supply and the wireless component. This project will mainly focus on the ECG and the power supply section and will briefly look into the wireless module of the Quick Doc device. The wireless module integrates all the different component systems of the Quick Doc device and as such does not fall within the scope of this project. The wearable wireless ECG project will focus on the requirements for the acquisition of an ECG signal from a patient, methods of powering the ECG device and will ensure that the ECG output meets the requirements for wireless transmission using the wireless module chosen by the Quick Doc team. The ECG component of the project will involve selecting an appropriate amplifier and designing an ECG system using that amplifier. It will also include appropriate selection of electrodes as well as the design of a low pass filter with an appropriate cut-off so as to acquire the required ECG signal. As mentioned previously in the objectives the goal of this project is to create an ECG that can measure the cardiac rhythm and rate only. To power the ECG we need to build a power supply that will meet the power consumption requirements of the ECG stage, be light weight and economical. Throughout this project I will test the theory by using bread boards and the final design will have all the components on a printed circuit board (PCB). There are certain specifications that need to be met in designing medical PCBs which this project will meet.

Chapter 2

2. Literature Review

Within this section of the report we access some of work currently being accomplished in the advancement of ECG instrumentation and compare that with this wearable wireless ECG project. The Electrocardiograph (ECG) is the most widely used biomedical sensing procedure to date. The electrical output of the cardiac cycle is a definitive indicator for a wide range of physiological conditions. In the past ECG instrumentation was extremely bulky; miniaturization in recent years has enabled new applications that were never perceived before. The modernization of the ECG instrument in part due to new electrode technologies and the advancement of instrumentation amplifiers have led to wearable ECG designs. By analyzing the current advancements in this ever growing field the reader will gain a perspective of what exists in the world today.

2.1 Wireless ECG System

Patients who have survived cardiac arrest, ventricular tachycardia or other cardiac disease are at a higher risk of sudden cardiac death. Many of these patients are living at home without any kind of cardiac monitoring systems. By using a wireless and wearable monitoring system for detection of arrhythmia it is possible to alert healthcare professional to the patient’s condition so that the necessary action for an emergency rescue can occur. Advanced monitoring solutions using telecommunication systems are used for remote ECG diagnosis. Such systems can be divided into two categories real-time mode and store-and-forward mode. The systems available today are either based on standard ECG electrodes and a wired connection to a recording device or by pressing a recording device directly onto a patient’s chest when a symptom arises [7]. Recent developments in wearable biomedical sensors have opened up possibilities for continuous wireless ECG monitoring systems. This section looks at the design of a wireless ECG system that can be worn continuously for the monitoring of cardiac arrhythmias. The wearable wireless ECG (Quick Doc ECG) was used to detect Respiratory Sinus arrhythmia (RSA) in a patient. This RSA case study is discussed in the results section of the report. Many current ambulatory ECG recording equipment are dependent on the patient operating them, depending on the patient’s condition this many not be possible. This method is also time consuming. For a reliable monitoring system it is necessary to develop an automatic system that will monitor the patient and send alarm conditions to a central safety alarm system. Given the fact that time is of the essence during a cardiac arrest this device has the possibility of increasing the survival chances of a patient [8]. The idea is to develop a simple smart sensor that detect critical cardiac conditions and give early alarm signals even if the patient is unconscious or unaware of cardiac arrhythmia.

The sensor transmits the ECG information to a device on the patient. The Quick Doc ECG utilizes silver electrodes which acquire the signal and sent it to the amplification and transmission stages via short shielded wires. The wires are also twisted together to reduce noise. The Quick Doc ECG then transmits the information wirelessly to a receiver then to a computer. The Quick Doc system performs post processing on the ECG signal after acquisition but with some modifications can be made to produce real time post processed data. In the paper [9], the patient wears an ECG sensor that employs smart electronic electrodes capable of wireless transmission of ECG signals to a dedicated Hand Held Device (HHD). The HHD monitors the continuously recorded ECG signal and can detect abnormal ECG activity using an automatic arrhythmia detector. Based on this the device transmits alarm conditions to remote Clinical Alarm Station (CAS). In order to perform continuous ambulatory ECG recordings a new wireless ECG sensor has to be designed which can measure the ECG signal and transmit it continuously to the receiver in the HHD. This means that only one lead is used for the recording of the ECG signal. To accomplish this the authors (Fensli, Gunnarson and Hejlesen) used a compacted “double-electrode” with no wires connected [9]. This electrode is equipped with a wireless transmitter and battery supply for several days of continuous usage. The ECG sensor includes two electrical contact points with conducting gel applied to the patient’s skin for obtaining the signals. These points are connected electrically to the electronic circuit that consists of an amplifier, a high pass filter with a cut off of 0.5 Hz and a low pass filter with a cut off of 250 Hz [9]. The Quick Doc ECG also has a power supply and wireless transmitter thereby making it wearable and viable for continuous ECG monitoring. The power supply in the Quick Doc ECG utilizes a 9V battery and because the power consumption of the system is only 11mW. The electrode designed by the authors uses a combination of real-time mode and store-and forward mode to produce a continuous cardiac event recorder. The ECG signal is picked up by the electrode and transmitted to an RF-receiver which is connected to a standard PDA. The Hand Held Device (HHD) consists of the PDA and the RF receiver.

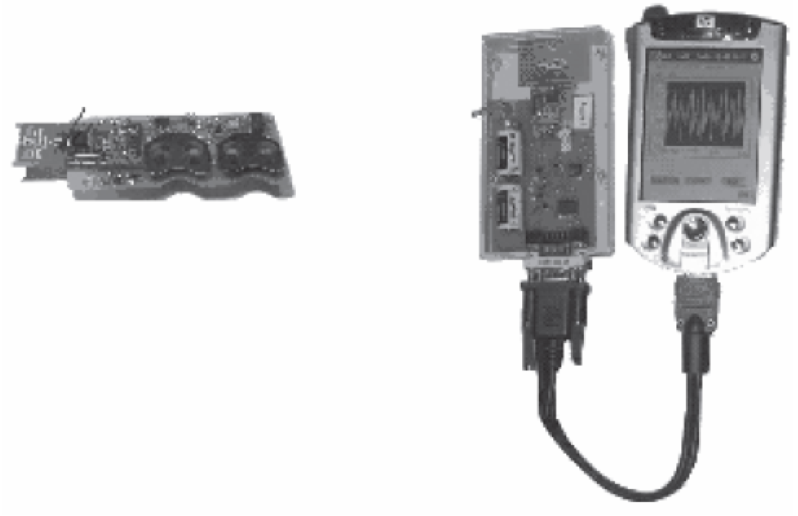


Figure 2: The electrode is shown and on the right the receiver connected to the PDA

The PDA then using GPRS transmits the alarm conditions to the remote CAS in the event of an abnormal ECG. The CAS in a hospital will give an alarm to the operator and will display the actual recorded ECG signal from the patient. The wireless module used in this system transmits at 434.44 MHz [9]. The receiver acquires the signal and converts it back into its analog form using an ADC. The PDA is connected to the receiver via a RS232 cable. The PDA contains a program in Labview which analyses the data. The Quick Doc ECG system follows a similar model in that the ECG acquired from the electrodes is amplified, filtered and then transmitted at 900 MHz [10] to the receiver when it is converted back into analog and then acquired by the DAQ which send it via an usb cable to a computer running Matlab. The electrode design in this paper involves placing two electrodes 3 cm apart from one another and building them into one unit with the electronic circuits and battery supply [11]. The electrodes are positioned directly on the patient’s chest. As the design does not use any wires from the electrodes to the amplifier there is very little power noise. In the Quick Doc ECG system there are short leads that connect the electrodes to the instrumentation amplifier and the electrodes are placed on the wrists. The Quick Doc ECG system provides the user with the cardiac rate and rhythm.

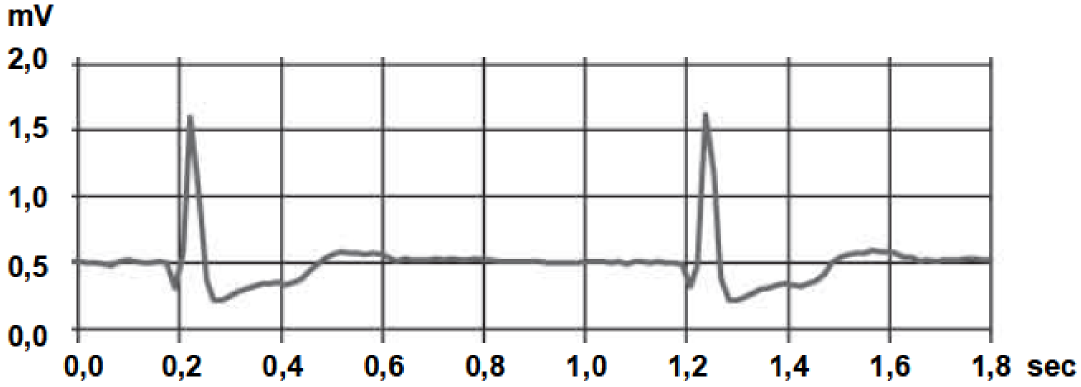


Figure 3: The ECG output from this device is shown

The output from the ECG shown in Fig. xy is comparable to the ECG obtained using the Quick Doc ECG. Note that the output from this system has a maximum output of around 1.6 mV. This is extremely small when compared to other ECG systems; the Quick Doc system has a maximum output voltage of 360mV.

2.2 Wearable ECG System

Many wearable ECG systems exist today but almost all of them use electrodes for contact with the patient’s skin. This creates a necessity for the use of conductive pastes or gels. This technique is has some inherent flaws. The material used in the manufacture of the electrode or the conductive paste could cause skin irritation and discomfort in some patients especially during exercise (undergoing cardiac stress tests) as sweat maybe present. Doing motion the electrodes can become loose thereby breaking electrical contact and creating large spikes in voltage that can saturate the instrumentation amplifiers. In the wearable wireless ECG (Quick Doc ECG) project the use of short lead wires, shielding of the wires and twisting of the lead wires has removed most motion artifacts. In the Quick Doc ECG project the silver electrodes use Ten20 conductive paste to provide a contact between the patient and the electrode. As you can see there are some disadvantages with this method of acquiring the signal but it is still the cheapest. For the previously stated reasons paste/gel free resistive contact ECG sensors have been developed but they too suffer from noise levels similar to that of the wet electrodes. Recent breakthroughs have resulted in the production of insulated bioelectrodes (IBEs). The IBEs can measure the electric potential on the skin without resistive electrical contact [12]. This combined with the fact that they have very low capacitive coupling results in a truly multifunctional electrode. The IBEs have been made possible by a combination of circuit design and the use of a low dielectric material. These electrodes allow for through-clothing measurements thereby removing the need for skin preparation all together.

The ultra-wearable, wireless, low power ECG monitoring system marries the IBE technology with a low power, wireless ECG system resulting in a unique device. The authors (Park, Chou, Bai, Matthews and Hibbs) of this study took advantage of QUASAR’s ECG sensors [13] and Eco wireless nodes [14] and combined them with IBE electrodes. The system architecture for the device was sub divided into four sub systems the ECG sensors, data sampling, wireless transmission and host interface. This is similar to the Quick Doc ECG in that they both transmit an acquired signal wirelessly using RF technology. The Quick Doc ECG uses a DAQ to acquire the received signal and sends the received signal to a computer via usb while the author’s of the study ensured that all the components required for receiving the signal, acquiring it and transmitting it to a computer are integrated in one place called the host interface. On the transmission side the authors tested three different architectures, the first one involved attaching all the ECG sensors to an ADC which has a microcontroller attached to it and then to a transmitter with a microcontroller. The second method is exactly the same as the first but there is only one microcontroller.

This method is closest to the Quick Doc ECG system which involves converting the analog ECG signal to digital and transmitting it. In the third method each of the sensors has its own ADC, microcontroller and transmitter. The QUASAR sensor is a wearable, tiny, low power ECG sensing device and the Eco is a low power wireless sensor node. Fig. 4 shows the QUASAR sensor and the Eco wireless module.

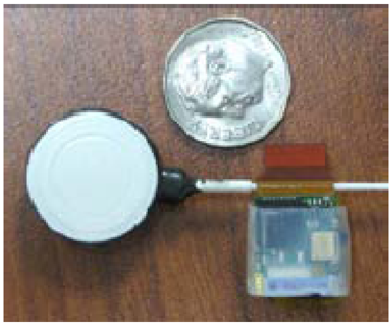


Figure 4: Shows the QUASAR sensor and the Eco wireless module.

The QUASAR sensor is a compact ECG sensor that does not require skin preparation, gels or adhesives. It not only includes the transducer but also integrated circuitry consisting of low noise amplifiers and voltage reference chips. It has an output signal range that varies from 0V to 4.5 V [12]. In comparison the Quick Doc ECG does not combine the electrode and amplifier into one small package it uses two individual electrodes attached to the amplifier via short shielded wires. The output voltage from the Quick Doc ECG is around 360mV. The power consumption for the QUASAR sensor is 1mW while that of the Quick Doc ECG is 11mW so the QUASAR senor has greater power efficiency. For the implementation of the wireless part the authors utilized the Eco wireless node. This has low power consumption and is ultra compact. The base station/host interface allows for transfer of data to the computer via three methods usb, ethernet and 802.11 b/g. The figure below shows the ECG output that was obtained by utilizing the system in the study.

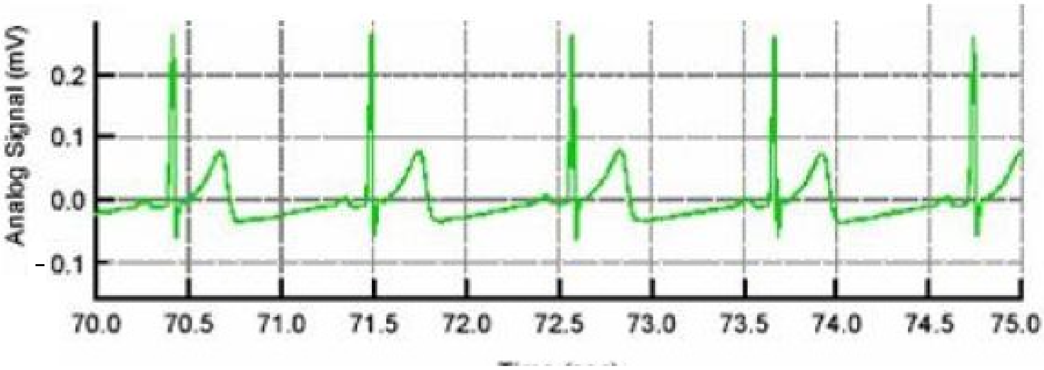


Figure xy: Shows the ECG signal acquired using this system

This ECG was acquired during a cardiac stress test and as you can see there are no motion artifacts to be found. In this acquisition they used the second system architecture which is similar to the Quick Doc ECG and is cheaper than the other acquisition architectures.

Chapter 3

3. Statement of Problem

In this section we will look at the challenges that need to be accomplished in order to create a working wearable wireless ECG. This section will include an overview of the ECG and power sections of the project. It will introduce theoretical developments that are essential for understanding the design of an ECG. The development of each of the components of the ECG has unique requirements that need to meet which will be discussed in this section. The ECG component includes the acquisition of the signal from an electrode, the amplification of the signal and the filtering of the signal. The power supply component needs to be able to power the ECG as per the requirements of the electronics that make up the ECG. We will take a look at why those electronic devices were chosen and how they perform their job.

3.1 Overview

An electrocardiograph (ECG) is a device that measures the electrical signals produced by the heart [2]. It provides the physician the ability to access the state of the cardiac tissue. The ECG uses surface electrodes to acquire the small voltages produced by the heart during the cardiac cycle. Each event during a cardiac cycle produces a waveform that forms the ECG [15]. Pairs of electrodes on different parts of the heart measure the ECG from different perspectives. For the theory behind the basics of ECG, the ECG waveform and how clinical leads work please refer to Appendix C.

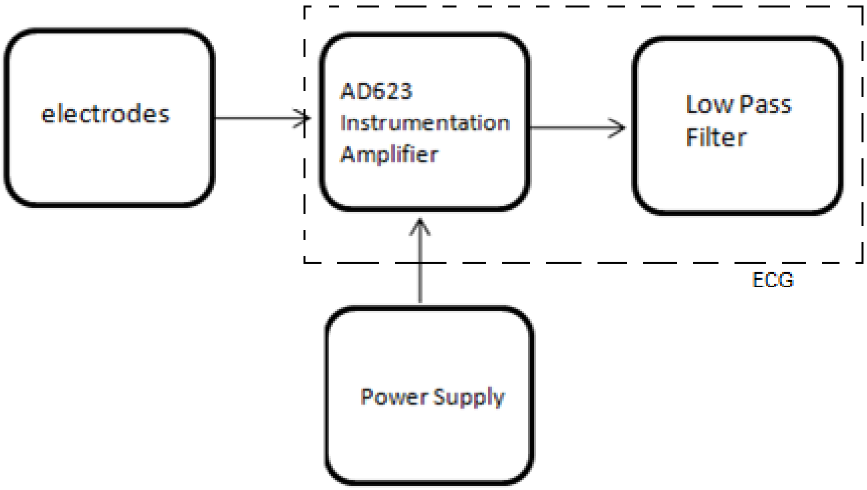


Figure 5: Shows the subsections discussed in this section and how they are related

As you can see from the Fig. 5 on the previous page the ECG is made up of an instrumentation amplifier and a low pass filter. In our design we will be using two instrumentation amplifiers. The electrodes shown in Fig. xx are required for acquisition of the ECG signal from the body. As the body acts like a giant resistor the ECG signal produced in the heart has a smaller amplitude (0.5~4mV) at the surface of the body as compared to the surface of the heart [4] [16]. This means that the electrodes have to be sensitive enough to pick up the signal produced and ensure that the signal is not lost during transmission to the amplifier. There are certain requirements for the amplifier as well it must have very high input impedance, a large CMRR and low power consumption. In this project we are only building an ECG that will provide the cardiac rate and rhythm to the physician therefore the frequency range of the ECG signal can be limited from (0.5 ~30 Hz) this is achieved by using a low pass filter [17].

The power supply used in the design of the ECG has to be able to support a current draw of 1.1mA and needs to be able to work with a single 9V battery. The design of the power supply took advantage of the Max232 driver/receiver chip that contains a capacitive voltage generator. By using the LM 78xx and 79xx we are able to produce the required supply voltage (+/-5V). The design of the power supply is discussed in the design section of this report. Schematics for the power supply are available in Appendix A.

3.2 Electrode Theory

In order to measure and record potentials and currents in the human body it is necessary to provide an interface between the body and the electronic measuring device. This interface function is carried out by electrodes. An electrode in contact with a biological medium is like a transducer in that it converts ionic current flow in the medium into electronic flow in the electrical circuit of the device. The type and size of the electrode is determined by the event itself, the anatomical location and the dimensions of the bioelectric generator. In the case of the ECG the signal range is from 0.5~4mV and the frequency range of the signal is from 0.01~250Hz [4]. Given these values modern

ECG systems use a variety of different electrodes to obtain the ECG signal. One of those techniques is the use of a silver electrode with some form of conductive gel/paste. This is the technique that I have employed in the wearable wireless ECG. The choice of amplifier is determined by the electrical characteristics of the electrodes, for our choice of the AD623 we need to look at the theory behind the silver surface electrode. Electrode skin interfaces can be shown as electrically equivalent circuits made from capacitors and resistors [16]. Fig. 6 shows the electrical equivalent circuit for a silver electrode in contact with the skin through the conductive paste.

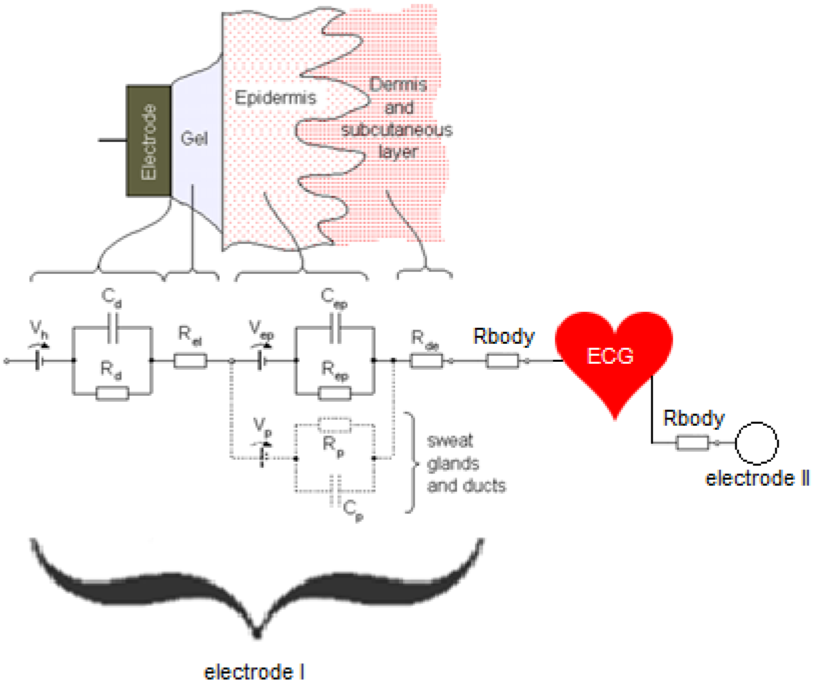


Figure 6: Shows the electrical equivalent circuit when a the silver electrode is placed against the body

The ECG signal produced by the cardiac tissue loses signal strength by the time it reaches the skin due to the internal resistance of the body. The internal resistance of the body is mainly due to the presence of muscle and bone through which the ECG signal must travel. The ECG is only acquired by measuring the difference in half-cell potentials between electrode I and electrode II to give us potential differences (in mV) [18]. The skin has two major layers the epidermis and the dermis and subcutaneous layer. The dermis and subcutaneous layers are modeled as resistances since they are mainly composed of fat and have no electrical properties. The top layer of the epidermis is semi permeable to ions which enables electrical conductivity. This is modeled by the RC circuit shown above. The gel/conductive paste is modeled as a resistance and the electrode/electrolyte interface is a RC circuit [16]. Fluids secreted by the sweat glands also affect the properties of the skin and therefore cause a fluctuation of the ECG signal. In the circuit shown in Fig. xx the battery V_h symbolizes the half-cell potential of the electrode [18]. From all of this we can gather that any changes in the electrical properties of the skin will result in changes in the ECG signal. In order to prevent these fluctuations we have to prepare the skin by abrasion of the top layer of the epidermis this process also reduces the resistance of the skin. By using conductive paste we have improved the conductive properties of the skin [16]. When the electrode is attached to the body it will initially have a very high impendence as the conductive paste has yet to diffuse into the skin but after while it will normalize, this is important to remember when taking measurements. The last part of electrode theory will focus on motion artifacts and how they are created. The silver electrode develops a double layer of charges when it is in contact with the electrolyte (conductive paste). When the electrode/electrolyte contact is disturbed during motion; the half-cell potential of one of the electrodes changes relative to the other. This generates a sudden potential difference between the electrodes which results in motion artifacts in the ECG signal. When the motion of the electrode stops the double layer is re-established and the initial half-cell potential is obtained again. But the danger is in the fact that a sudden spike in voltage can saturate the instrumentation amplifiers. Variations in the skin/electrolyte interface can cause motion artifacts as well [16]. To prevent motion artifacts ensure that the skin is prepared properly and the electrodes are placed correctly.

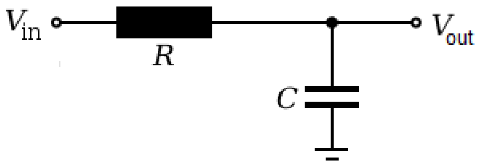
3.3 Instrumentation Amplifier Theory

The choice of instrumentation amplifier is crucial for the entire project as there are specific requirements that need to be met in order to be able to acquire an ECG signal.

The very small ECG signal acquired from the silver electrode will be accompanied by a large ac common-mode component (up to 1.5V) and a large variable dc common-mode component (300mV). The common-mode rejection ratio specified by the Association for the Advancement of Medical Instrumentation (AAMI) is 89 dB minimum for a clinical ECG and 60 dB for an ambulatory ECG [6]. The CMRR of the AD623 instrumentation amplifier is greater than 90 dB for a gain of 10 dB. This project has two AD623 instrumentation amplifiers the first one has a CMRR greater than 70 dB and the second instrumentation amplifier has a CMRR greater than 90 dB [20]. The requirements for an ambulatory ECG as well as those for a clinical ECG have been met by using multiple instrumentation amplifiers. The CMRR is calculated by dividing the differential gain by the common mode gain of the amplifier. The electrode/skin interface has complex impedances that range from 1K to 1M ohms. This impedance is dependent on the skin condition and its preparation, the equivalent impedance of the electrodes (Silver electrodes have a resistance of 450 ohms at 10Hz), the fat volume underneath the skin which as we saw in the electrode theory has impedance and the resistance of the body [21]. An increase in the electrode/skin impedance is expected is expected when measuring signals in the 0.01 to 1 Hz range as the capacitive component of the skin would be much higher [16]. High input impedance would prevent the formation of voltage dividers between the electrode/skin impedance and the input of the amplifier. The AD623 has very high input impedance due it being outfitted with input buffers [20]. The use of two instrumentation amplifiers prevented saturation of the amplifier when the gains were high. By using a process of trial and error I settled on an overall gain of 300 for the system. The AD623 is a relatively cheap instrumentation amplifier with a cost of $6.18/unit. The power consumption of the amplifier is also very low as this project involves the project being portable it was important that the instrumentation amplifier worked with a power supply from a 9V battery.

3.4 Low Pass Filter

A low pass filter is a filter that allows low frequency signals to pass but reduces the amplitude of signals with frequencies higher than the cut-off [22]. There are many different types of low pass filter circuits each one responds differently to a changing frequency. Examples of low pass filter circuits include the simplest filter - first order RC , Butterworth filter, the Chebyshev filter, Bessel filter to name a few. The characteristics of a low pass filter can be summed up by its cutoff frequency and its rate of frequency roll off. Every low pass filter attenuates the input power by -3dB at the cutoff frequency. But the amount of additional attenuation for higher frequencies is determined by the order of the filter [22]. What this means is that a second order filter will attenuate the higher frequencies more steeply than a first order filter. The frequency response of a low pass filter is generally represented by a Bode plot. The Bode plot is a graph of the logarithm of a transfer function versus the frequency (plotted in log-frequency). The filter used in this project is a first order RC filter. The RC filter consists of a resistor in parallel with a capacitor [22]. On the left hand side of Fig. xx you can see the basic RC filter circuit used in this project. V_{in} is the input voltage from the instrumentation amplifier and V_{out} is the output to the wireless module. The resister value of R is 10K and the capacitor value is 1uF. The transfer function for this filter shown on the right hand side of Fig. xx along with the formula for calculation of the cutoff frequency (f_c).



$$H(s) = \frac{V_o(s)}{V_i(s)} = \frac{1}{1 + s\,RC}$$

$$f_c = \frac{1}{2\pi RC}$$

Figure 7: Shows the RC filter circuit, transfer function and the formula for fc

By using the formula given in Fig.7 we can find the cutoff frequency f_c. $f_c = 1/(2\pi*10k*1u) = 15.91$ Hz. As the ambulatory ECG requires a frequency range of between 0.5~30 Hz you are probably wondering why the cutoff for this is 15.91 Hz. At first I used a cutoff of 33Hz for this filter but this did not attenuate the 60 Hz to the extent that the ECG was visible. I could have used a filter with a higher order but then the filter would have to be active which would have resulted in more power being drawn from the single 9V battery. After experimenting for some time with different resistor and capacitor values I found that a 15.9 Hz cutoff is perfect for my purposes of obtaining the cardiac rate and rhythm. The cut-off does not remove the ECG signal it only suppresses the higher frequencies of the ECG waveform. This means that the QRS complex which is crucial finding the cardiac rate and rhythm is still present in the output waveform from the filter. As the post processing is completed on a computer using digital filters, any noise that was not fully suppressed by the analog filter will be removed. By using the transfer function shown above I created a Bode plot to demonstrate what the filter response looks like this is shown below in Fig. 8.

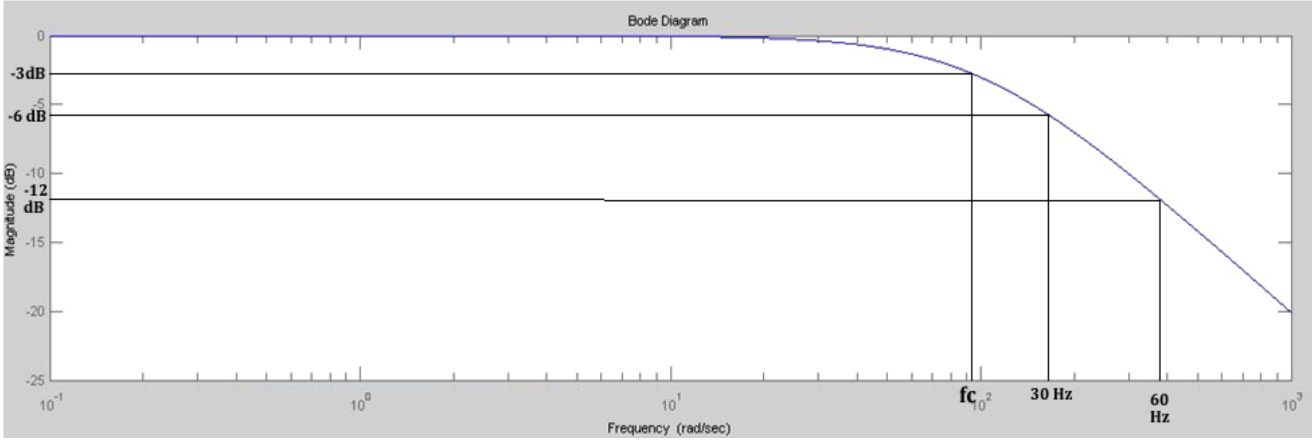


Figure xy: Shows the magnitude Bode plot for the response of the RC filter

As you can see from the Bode plot the cutoff frequency of 15.9 Hz produces an attenuation in the gain of -3 dB but because this is a first order filter the response is not steep and therefore the attenuation at 30 Hz is only -6dB. But when we look at 60Hz the attenuation is at -12 dB double that of the attenuation on the highest ECG frequency. What this means is that even though some of the ECG frequencies around 30 Hz will be suppressed they will still be larger than the noise and therefore the ECG wave form is intact. For the phase plot and the Matlab code for implementing a Bode plot please refer to Appendix D.

3.5 Power Supply

The power supply for the ECG consists of two main components the voltage regulator and the Max232 [23] which contains a capacitive voltage generator. The goal of the power supply is provide the required power supply to the instrumentation and to provide the reference/ground for the ECG. The instrumentation amplifier requires a +/-5V power supply for it to function properly as per the design of this project. Another requirement for the power supply is that it works with a single 9V battery. A detailed schematic is found in Appendix A and more information on the power supply is found in the design section of this report. In this section I will be giving an overview of the voltage regulator and the Max232 used in this project.

3.5.1 Voltage Regulator

A voltage regulator is an electrical regulator designed to automatically maintain a constant voltage level [24]. The voltage regulators used in this project are the LM 7805 for +5V and LM 7905 for -5V. The LM 7805 has a maximum output current of 1A while the LM7905 has a maximum current output of 1.5A [25] [26]. Both the voltage regulators have short circuit protection which is important for biomedical applications. The patient must be shielded from any leakage currents that may arise. Given the fact that we are using a 9V battery in this project the currents involved are too small to cause any harm to patient. The standard 9V battery only provides a maximum current output of 600mA. The LM 78xx and 79xx are self contained voltage regulators so there is no need for additional components [25] [26]. As they are based on linear voltage regulators input current required has to be equal to the output current. Since the input voltage has to be higher than the output voltage for them to operate the total input power is higher than the power they provide. This makes them less efficient than other voltage regulators but they are very economical.

3.5. 2 Max232

The Max232 is a dual driver/receiver that includes a capacitive voltage generator which can generate +/- 8.5 V from a +5V input [23]. The Max232's CMOS based switched-capacitor voltage converters invert and multiply the positive input voltage of 5V to the output voltage of +/-8.5V. The max output current from the Max 2432 is only 10mA. This still allows for the operation of the instrumentation amplifiers. There are two voltage regulators after this stage in the circuit to bring the voltage down to the desired +/-5V.

Chapter 4

4. Design Procedures

4.1 Design Overview

In designing the wearable wireless ECG I broke the project down into three separate components each of which were addressed individually. The three components to this project are as follows the ECG, the power supply and the transmitter and the receiver for implementation of the wireless. The ECG component consists of the AD623 instrumentation amplifier and a low pass filter.

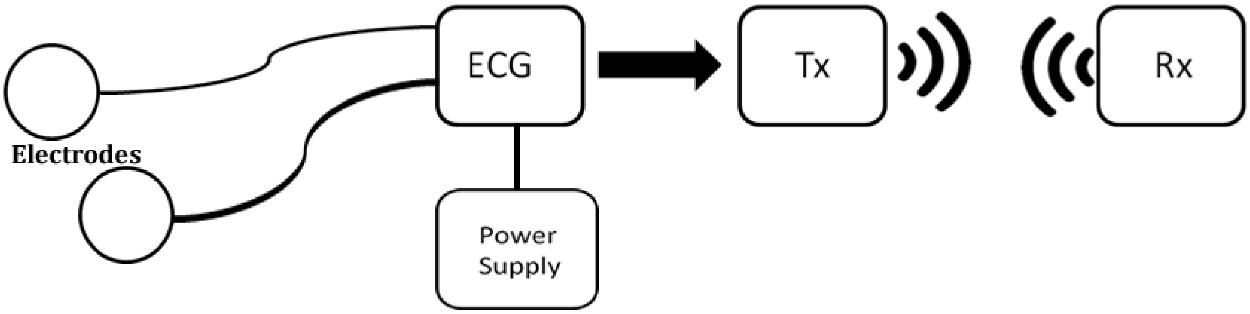


Figure 9: Shows an overview of the components included in the wireless ECG project

The power supply consists of a 9V battery, voltage regulators and the Max 232 chip. The power supply converts +9V from the battery to +/- 5V to power the instrumentation amplifiers of the ECG. As the wireless was a standard on all the components of the Quick Doc device we had to choose a transmitter receiver pair that was compatible for the transmission of the pulse oximeter signal, the blood pressure signal as well as the ECG signal. The wireless component of the Quick Doc system was chosen as the Linx TMX869/RMX869. In designing the wearable wireless ECG certain challenges had to be overcome the fact that ECG signals are very small in the 0.5 ~ 4 mV range meant that amplification gain had to be high [4]. But when tested with a single amplification stage the signal acquired was causing the amplifier to saturate. This led me to the introduction of two stages. Furthermore the instrumentation amplifier had to have a very high

Common Mode Rejection Ratio (CMRR) in order to account for the common mode component on the signal. The removal of the common mode component is crucial so that there is 60Hz power noise removal [16]. Another major issue was the power supply, how do you produce a +/-5V power supply from a 9V battery? This was achieved by using low power amplifiers and the Max232 chip. The electrodes that were chosen for the ECG were silver electrodes as I was unable to find any dry electrodes I had to make do with the silver electrodes. The wires from the electrode to the ECG amplifier were shielded to prevent further noise. Motion artifacts were minimized by reducing the length of the wires from the electrodes on the patient to the ECG amplifier [19].

4.1 Power Supply

Any power supply intended to be used with medical equipment has to be safe for patients. When designing the power supply for the ECG I decided to utilize a 9v battery instead of mains power. This ensured that the power supply had low current output and had portability. The power supply had to be light weight, portable and cost-effective. I also had to ensure that there was enough current to power the amplifiers. The ground provided by the power supply was used as the reference for the ECG. This entails that the signals were measured relative to this ground.

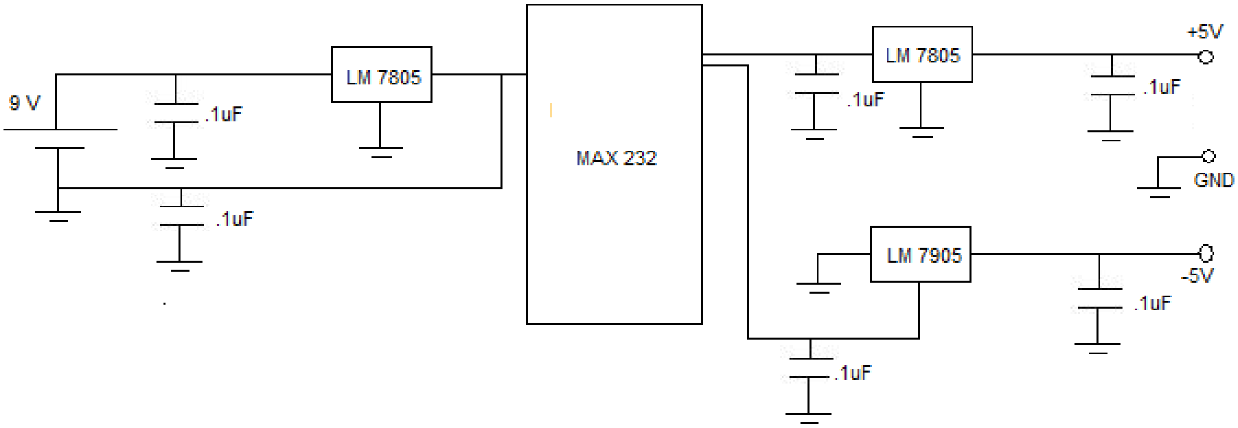


Figure 10: Shows the overview of the power supply stage

The 9V battery proved a +9V and a ground, the +9V when through two capacitors to the LM 7805 voltage regulator which converts +9V to +5V for the Max232 to utilize.

The Max232 is a dual driver/receiver that includes a capacitive voltage generator which can supply positive and negative voltage levels from a single +5V power supply. By utilizing this capacitive voltage generator I was able to produce the +5/-5V from the 5V input. The output (+/-5V) is then passed through a LM 7805 voltage regulator and a LM 7905 respectively. These voltage regulators ensure that the output is a constant +/-5V. Finally before sending the output to the ECG amplifiers I added two capacitors. All the capacitors used in this circuit design have a value of 0.1uF. The reason I am able to get a +/- 5V swing from a 9V battery is due to the simple fact that there is very little current drawn from the battery which results in very little power consumption. The output current from the Max232 is 10mA. The input current required for standard operation of the instrumentation amplifiers are at a low 550uA. The maximum current drawn by the instrumentation amplifiers from the Max232 is only 1.1mA given the configuration of the ECG circuit. This enables me to acquire the +/- 5V required from a 9V battery. The total power consumption by the instrumentation amplifiers is 11mW. For the calculation behind this value please refer to Appendix E. Since the only components that require power in this system are the ECG instrumentation amplifiers total power consumption of the ECG stage is 11mW. Note that the power supply does not provide power to the wireless transmitter.

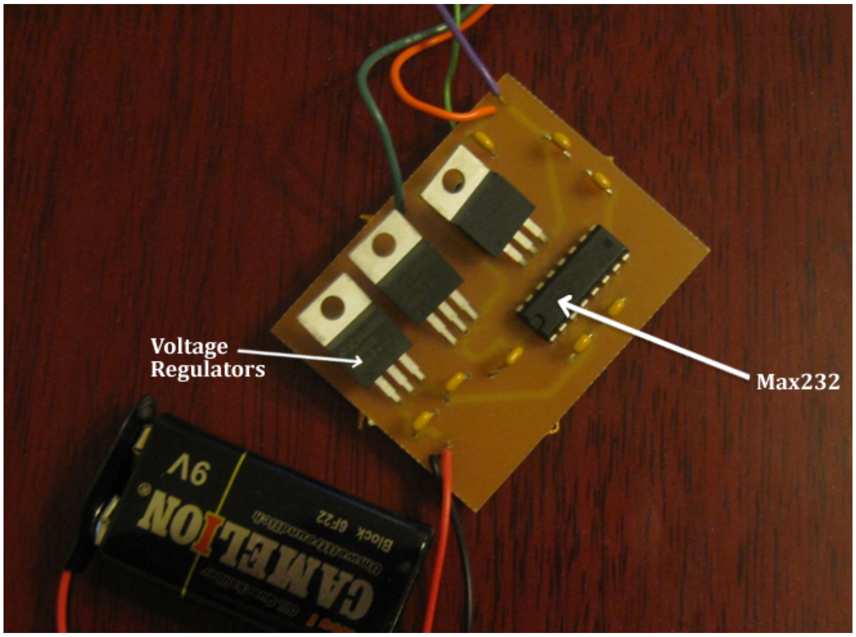


Figure 11: Shows the power supply with a 9V battery

The above figure shows the power supply on a printed circuit board (PCB), this allowed for the power supply to be mobile and lightweight. I utilized Eagle to design the PCB for the power supply. Usually for power supplies large traces are needed but as I am using very low currents the 10mm traces were sufficient. For the EAGLE schematic and board layout please refer to Appendix A.1.

4.2 Electrocardiograph (ECG)

The ECG signal has a range of 0.5~4mV and a frequency range from 0.01~250Hz [4]. In this project we are looking at the cardiac rate and rhythm and for this kind of standard monitoring the frequency range has to be from 0.5~30Hz [6]. The clinical ECG utilizes 10 electrodes to produce a 12 lead view of the cardiac tissue [3]. This allows the physician diagnose the state of the cardiac tissue from 12 different perspectives. For more information on the different views of the heart please refer to Appendix C. The ECG utilizes only two electrodes; the left electrode from the patient is connected to the ground of the power supply and acts as a reference electrode. This is a unipolar electrode setup thereby providing only the cardiac rate and rhythm. The short length of the wires from the electrodes to the ECG stage ensures that there are minimal motion artifacts. The output signal voltage post the ECG stage is 360mV therefore this stage has an amplification gain of approximately 300. For the calculations relating to this value please refer to Appendix E.

The amplifier used in this system is the AD623 instrumentation amplifier which has a very high CMRR and a maximum gain of 1000 [20]. By choosing an amplifier with a very high CMRR I have been able to reduce the 60Hz power noise. This design has two AD623 instrumentation amplifiers the first one has a CMRR greater than 70 dB and the second instrumentation amplifier has a CMRR greater than 90 dB [20]. As stated in the theory section this is sufficient for the purposes of an ambulatory ECG. Another method that was implemented for the removal of noise was the use of shielded wires from the electrode to the amplifier. Not only is the AD623 economical it has a low input bias current of 25 nA and a maximum offset voltage of 200 uV. The AD623 has a single external-gain setting resistor (Rg) through which the amplification gain is controlled. The AD623 is an instrumentation amplifier which basically means that it is a type of differential amplifier that has input buffers. This results in a very high input resistance which is important because of the electrode/skin interface. These buffers eliminate the need for input impedance matching. The AD623 has very low DC-offsets, low drift, low noise, high open-loop gain, high CMRR and very high input impedances [20]. All these characteristics mentioned above together with the fact that the AD623 costs $6.18 dollars make it the ideal amplifier for this project. To fully utilize the amplification capabilities of the AD623 without causing it to saturate, I decided to have multiple amplification stages.

In the design overview shown below in Fig. 12, the pre-amplification stage has an amplification gain of 3. This is followed by the amplification stage which has a gain of 100. The final section of the ECG stage is the passive low pass filter with a cut-off of 15.9Hz. As you can see from Fig. 5 the electrode connected to the left arm is grounded to the battery of the device. This allows for the ECG to measure an electrical vector with reference to this thereby providing an electrical view of the heart. This enables the physician to diagnose the cardiac muscle in that one view. As mentioned previously the goal of this project is to build an ambulatory ECG which can measure cardiac rate and rhythm and this was achieved.

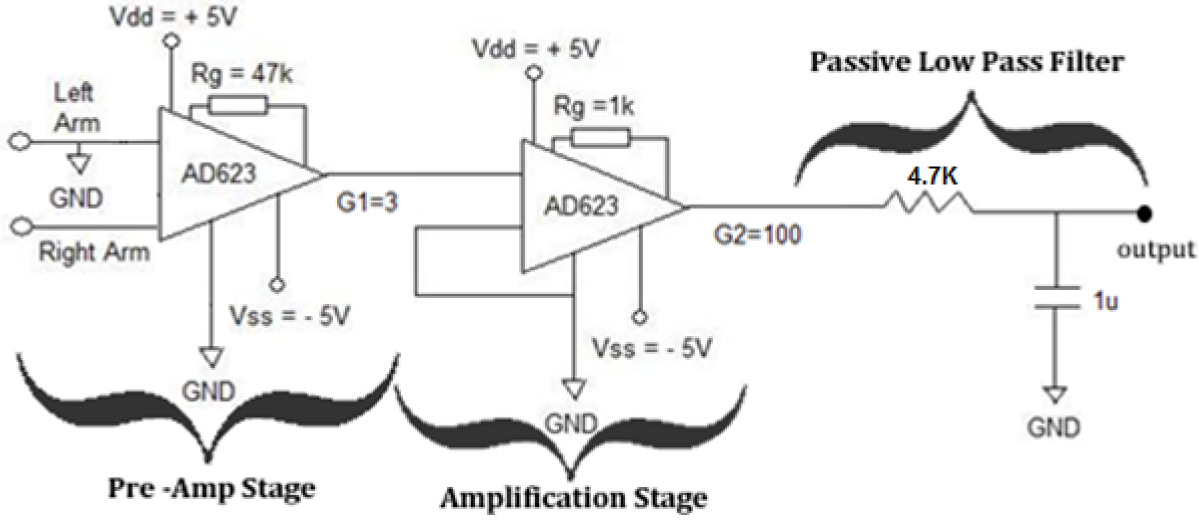


Figure 12: Shows the overview of the ECG stage and its sub-sections

The pre-amplification stage consists of an instrumentation amplifier with a gain of 3 and the two electrodes attached to the patient. The gain is achieved by setting Rg to be 47K.As previously mentioned the electrode on the left arm is connected to ground this creates a reference for the ECG signal to be measured from. This is basically the ground electrode think of this as having zero electrical potential now be comparing this to the signal produced by the heart we acquire an electrical vector. Since the center of the heart has zero potential our electrical vector points outward from the center of the heart. By measuring the potential from the right wrist and comparing it to this we have created a unipolar lead from which the ECG signal is acquired. For more information on the theory behind the leads and how this works please refer to Appendix C. The pre-amplification stage allows for the removal 60Hz power noise thanks in part to the AD623 instrumentation amplifier. The wires used to connect the electrodes to the amplifier in stage are shielded to prevent the addition of 60Hz noise. By also ensuring that the wires are twisted we can further reduce noise.

The amplification stage contains a second AD623 connected in such a way that it acts as a normal amplifier with a gain of 100. The advantage of doing this is that the CMRR of the system as whole increases when compared to using a normal operational amplifier. The increase in gain is produced by placing setting the value of Rg to be 1K. The final stage is consists of a first order RC low pass filter with a cutoff frequency of 15.9Hz. The first order RC low pass filter was chosen with a cutoff of 15.9 Hz because this allowed the ambulatory ECG to be captured while removing the 60Hz power noise. In the beginning I was experimenting with different capacitor and resistor value to determine the best option. It was found that a 10K resistor along with a 1uF capacitor were the best combination for the device. This filter is capable of removing most of the 60Hz noise. Even though the cut-off is at 15.9 Hz the QRS complex of the ECG as well as most other components are not removed from the signal. There are minimal DC offsets which can be removed during post processing. One final issue that came up was the floating ground if the patient has not been grounded properly the ECG signal begins to float and this can be easily remedied by ensuring that the electrode on the left hand is placed properly as this is the ground electrode.

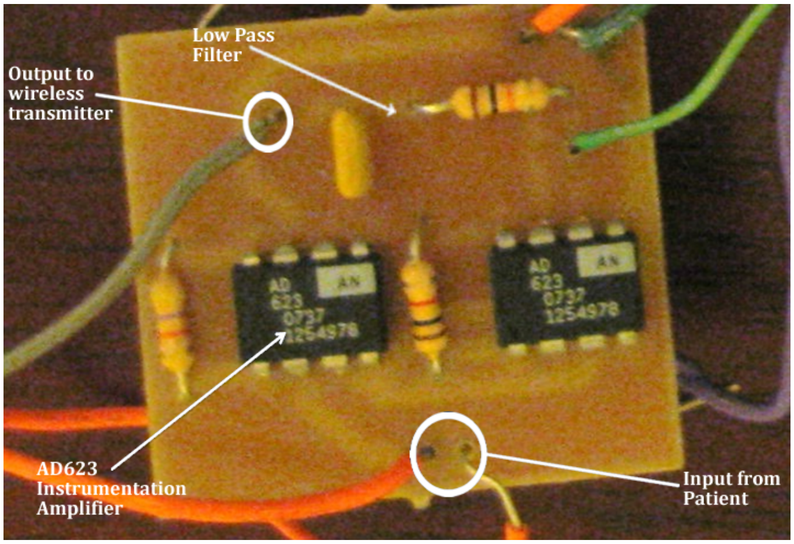


Figure 13: Shows the ECG stage

When designing the PCB for this stage I had to take into consideration the issues involved with designing printed circuit boards for medical applications. A ground plane must be added to the PCB to prevent 60Hz power noise contamination of the ECG signal. Additionally when designing the PCB on EAGLE I ensured that the traces were small and that they did not turn at 90 degree angles. As this project involves a wearable wireless ECG I also ensured that the board was small (1.25”x 1.25”). For the EAGLE schematic and board layout of the ECG stage please refer to Appendix A.2.

4.3 Wireless

The wearable wireless ECG uses the same wireless transmitter/receiver pair as the rest of the Quick Doc device components. This was done so as to allow for easy integration of the components that make up the Quick Doc device. The wireless module used in the Quick Doc system is the Linx TMX869/RMX869 transmitter/receiver pair. This wireless module is capable of detecting and transmitting the ECG signal as well as the other physiological signals provided by the Quick Doc device. It transmits in the 900MHz range and has an effective range of 500 feet [10]. This allows the patient to move around thereby increasing patient comfort.

Chapter 5

5. Results and Discussion

In this section we will look at the results obtained from this ECG system and take a look at a case study involving an actual patient with Respiratory Sinus Arrhythmia (RSA). The patient preparation for the testing involves placing two silver electrodes on the patient’s wrists. The procedure for electrode placement involves minimal epidermal abrasion using an alcohol swipe to remove the dead skin and sweat. This is followed by the application of Ten20 conductive paste to the area where the electrodes are to be placed. The conductive paste allows for better signal acquisition. I was unable to acquire capacitive electrodes which are still in the experimental stage. The capacitive electrodes would have allowed for no skin preparation or addition of conductive paste. The electrode wires used for the signal acquisition were short and twisted so as to avoid motion artifacts and reduce electromagnetic noise. Finally the electrodes were held in place using medical tape similar to that used in clinical ECGs.

5.1 Normal Electrocardiograph (ECG)

The test subject for this section of the results is a 21 year old male. The subject has no known heart condition and therefore has a normal ECG. An ECG consists of the PQRST and U waveforms where the P wave corresponds to the atrial depolarization, the QRS complex corresponds to the depolarization of the ventricles and the T wave corresponds to the repolarization of the ventricles. For more information on the ECG waveform please refer to Appendix C. The QRS complex is extremely important for the measurement of heart rate, as it is the segment of the ECG with the largest amplitude. This large amplitude is due to the fact that the ventricles have a greater mass than the atria and therefore the cardiac cells in that region produce a larger depolarization wave. By utilizing the QRS complex a peak detection algorithm can be employed to measure the heart rate in Matlab. The duration, amplitude and morphology of QRS complexes are such that they can also be used to diagnose cardiac arrhythmias, conduction abnormalities, ventricular hypertrophy and myocardial infarction. As you can see this complex is the most important segment of the ECG. In the design of the ECG I mentioned that for an ambulatory ECG the frequency ranges from 0.5 to 30 Hz [6] but as you can see even by having a passive RC low pass filter with a cut off of 15.9 Hz most of the ECG signal is still recovered. The signal shown below in Fig. 7 is prior to using the wireless module, as you can see the QRS waveform is clearly visible in the oscilloscope. There is minimal noise and no motion artifacts. There was however a bit of a floating ground which can be attributed to an improper ground electrode connection.

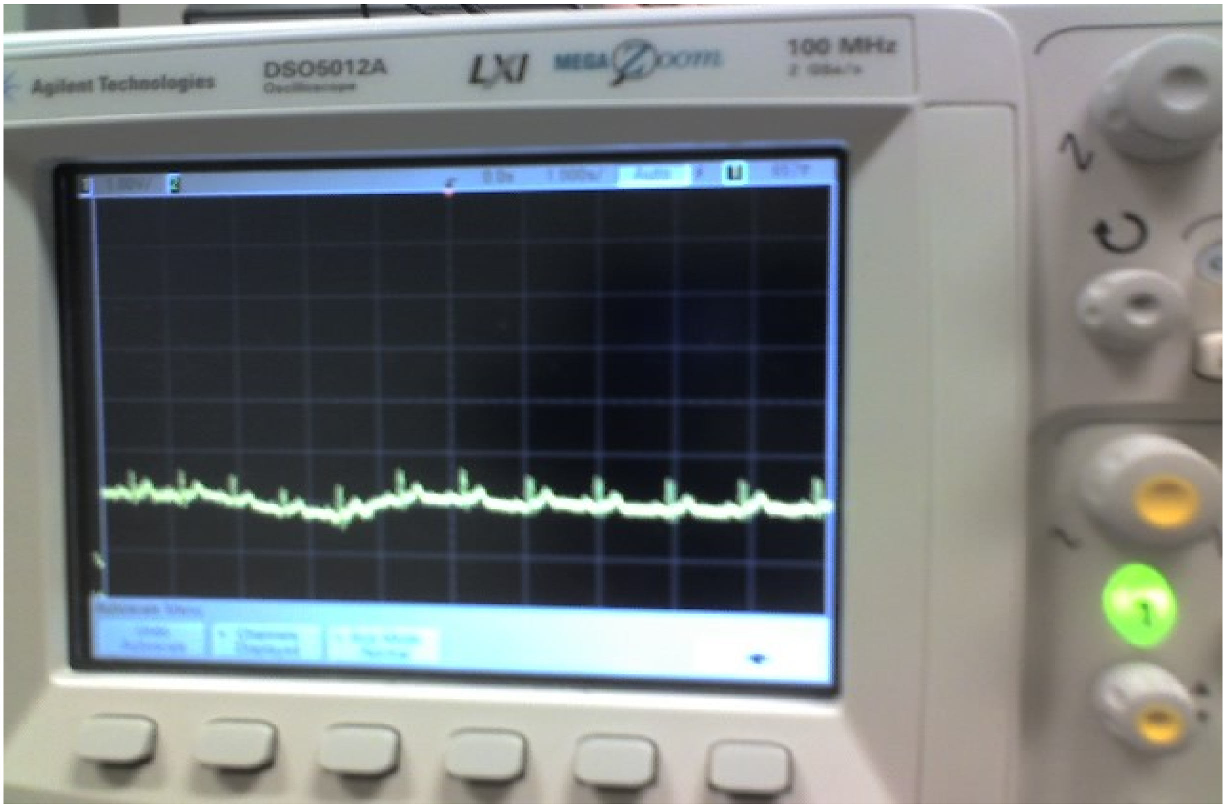


Figure 14: Shows the ECG waveform prior to wireless transmission

The amplitude of this ECG signal was around 360mV. That is using a gain of 300. There was also a DC offset present in the signal. This DC offset can be removed by using a simple passive RC high pass filter. In this particular system the wireless transmitter/receiver pair removed the DC offset so the high pass filter was not required.

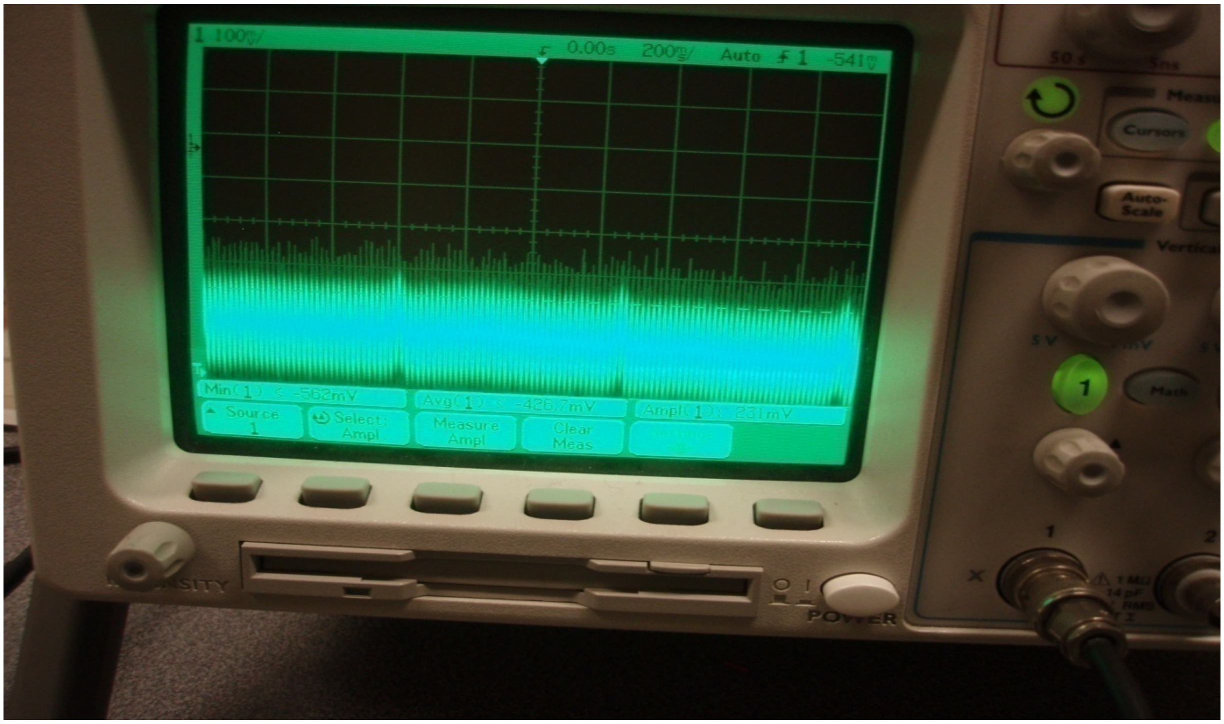


Figure 15: Shows the ECG waveform post wireless transmission

The figure shown above (Fig. 15) shows the signal post transmission before being sent to the DAQ. As you can see there is a large amount of noise that has been added to the signal during the transmission process. This transmission noise can be significantly reduced by placing the transmitter/receiver module on a printed circuit board (PCB) with a ground plane. The ground plane is a layer of copper added to the PCB during manufacture. The ground plane appears to most signals as an infinite ground potential and can therefore reduce noise. The ECG waveform is still intact and the QRS complex is clearly seen even with the addition of noise. There is no DC offset after the transmission process as the analog signal was first converted into digital and then transmitted. This process removed any inherent DC offset that was present in the ECG signal. The noise that was added to the ECG signal during transmission can be removed using post processing techniques in Matlab. It is not viable to build an active 3th order low pass filter with a cutoff of 30Hz on the transmission end as each of the different components of the Quick Doc device require a different cut-off but using Matlab it is relatively easy to apply such as filter digitally to the signals during post processing. In fact the post processing for the ECG signal involved using several such digital filters with orders ranging from 3rd to

5th on top of this a heart rate counter was also added. Fig. 9 shows the signal prior to the post processing. The green dots on the R (refer to Appendix C) peak of the QRS complex indicate the peaks that were used to measure the heart rate [27].

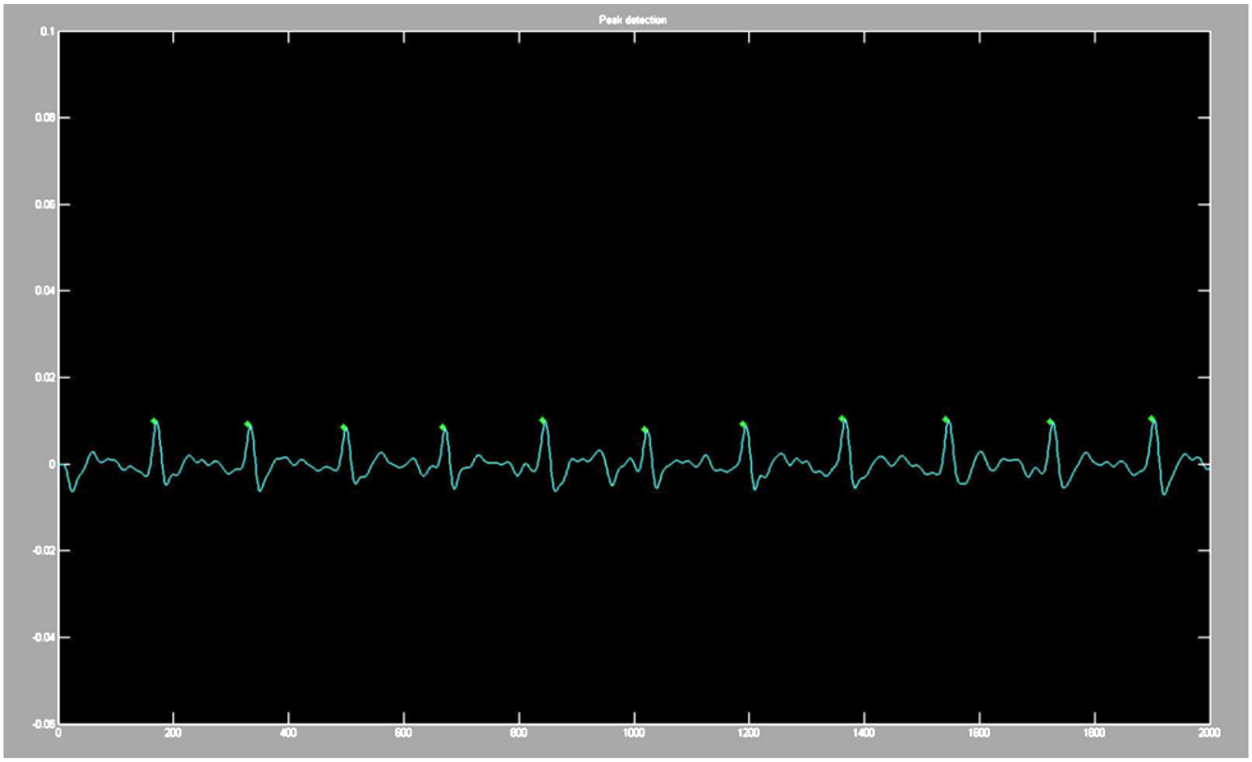


Figure 16: Shows the post processed ECG waveform the heart rate was calculated to be 63beats/min

The QRS complex is clearly visible as are the P and T wave forms. As you can see the cardiac rhythm and rate are clearly visible in this ECG which was one of the project’s main goals. Note that the rhythm is regular; that is each beat is an equal time interval away from the next beat. By finding the time interval between each of the peaks we can find the heart rate of the patient. The patient here has a normal resting heart rate of 63beats/min which was acquired by using a peak detection algorithm to identify the R wave and then using the time interval between the peaks. By counting the number of peaks in a 10 second interval and then multiplying by 6 you can get the beats/min. As we are only looking at one section of the electrical activity in the heart we can compare this to one lead from a clinical ECG. The clinical ECG shown below in Fig. 10 is a normal ECG acquired from a patient with no known cardiac issues.

Figure 17: Shows one lead of the clinical ECG acquired from a normal patient

As you can see comparatively the wearable wireless ECG is able to reproduce a single lead view with great accuracy. The view Shown in Fig. 10 was from the aVF lead of a clinical ECG. The aVF lead is a unipolar lead whose positive is attached to the left leg. This lead provides a +90 degree axial view of the heart. The lead that the wireless ECG project mimics is the unipolar aVR lead which is measured from the right arm. This lead produces an ECG signal that is inverted. In this project the inverted ECG was turned around when measurements were acquired by simply switching the wires from the output [2].

5.2 Case Study of Respiratory Sinus Arrhythmia (RSA)

In this case study I measured the ECG waveform of a 20 year old female patient with Respiratory Sinus Arrhythmia (RSA) using the wearable wireless ECG. Respiratory Sinus Arrhythmia is a form of cardiac arrhythmia that results in variation of the heart rate during the breathing cycle [28]. The heart rate increases during inspiration and decreases during expiration. The heart rate is controlled by the medulla oblongata in the brain stem. The medulla oblongata decreases the heart rate through the vagus nerve. During expiration (breathing out) cells in the medulla oblongata are activated and the heart rate slows down. But during inspiration (breathing in) the cells are not activated and therefore the heart rate increases. This event can be seen on an ECG as subtle changes in the R-R (the time lapse between two consecutive R waves in the QRS complex) interval synchronized with respiration. The R-R interval is shortened during inspiration leading to a faster heart rate [29]. Fig. 18 displays the RSA phenomenon using the signal acquired from the patient through the wearable wireless ECG.

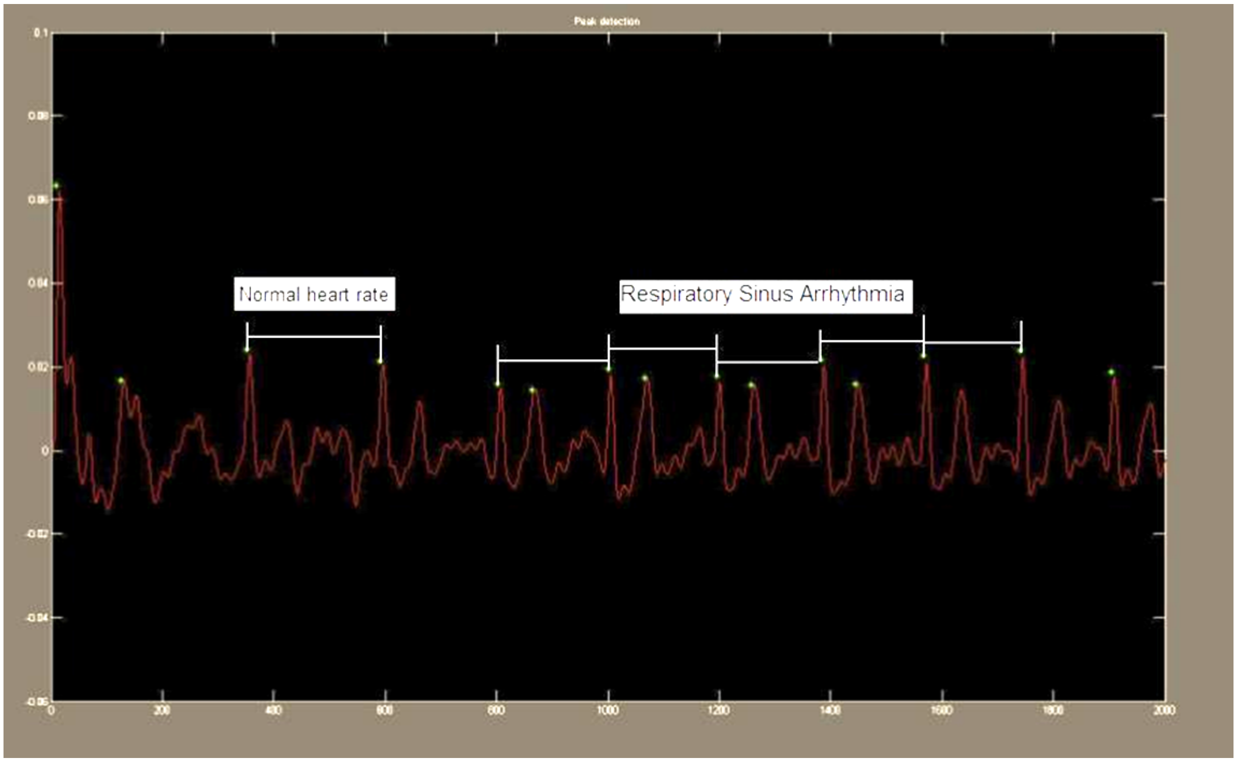


Figure 19: Shows the post processed ECG waveform for the patient with RSA

The normal heart rate of the patient is shown on the left hand side of Fig. 10. The heart rate is normal and the patient is expiring. During inspiration shown on the right there are several peaks resulting from the cells in the medulla oblongata not being able to stimulate the vagus nerve to lower the heart rate back to normal. As you can see the time between the R-R peaks is shorter on the right hand side than on the left. This indicates that the patient’s heart rate has increased on the right when compared to the normal heart rate. You will also notice that the patient has a very large T wave. This maybe to a variety of reasons and we cannot come to a conclusive diagnosis using this system as we are only taking into account a single section of the myocardial muscle. As set out from the beginning this system is only used to measure the cardiac rate and rhythm which in turn limits the ECG to only being able to detect certain cardiac arrhythmias, the heart rate and cardiac arrest.

By ensuring that a clean signal which contains most of the ECG information (<15.9 Hz) I have been able to acquire important information about the cardiac rhythm and rate. As shown above in the case study this information can be used to diagnose certain cardiac arrhythmias as the QRS complex is still intact. By looking at only one portion of the myocardial muscle I maybe limiting the number of different diagnosis that could have perhaps been conducted using this device. Nut the purpose of the device is not to replace the clinical ECG but to compliment it by providing the physician a new tool that can give him/her the ability to look into the general health of a patient's heart in a matter of minutes instead of the usual 2~3 hours. This ECG also provides an accurate measurement of the heart rate of a patient and given the fact that it is wireless allows for greater patient comfort.

Chapter 6

6. Conclusions and Recommendations

6.1 Conclusions

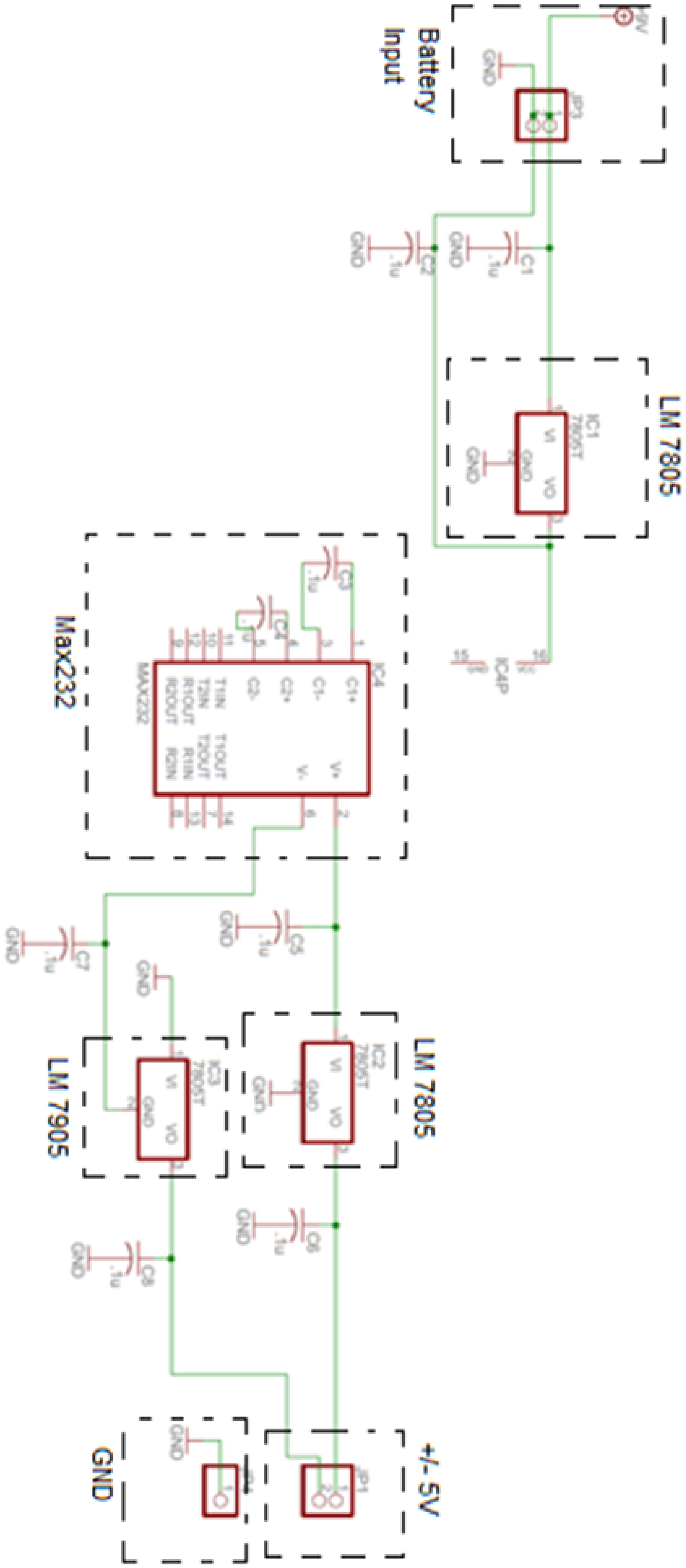
The wearable wireless ECG system has achieved the objectives that were laid out at the beginning of the project. The ECG system is able to detect an ECG signal and amplify it to the required level for wireless transmission. It can gather information about the cardiac rhythm and rate. By utilizing a power supply that requires a single 9V battery the ECG system is portable. The use of low power instrumentation amplifiers has allowed the system to become power efficient. In using a first order RC filter the ECG system has suppressed some of the high end frequencies of the ECG waveform but as you can see from the results section this has not affected the ECG adversely. The main QRS complex is even visible after transmission via the wireless module. The output voltage from the ECG is detected by the wireless transmitter which is crucial if we want to transmit the signal. Most of the 60Hz noise is removed in the ECG due to the shielding in the short electrode wires as well as the instrumentation amplifiers. There are no motion artifacts mainly due to the short electrode wires. The Ten20 conductive paste was found to be a hassle during the course of this project.

6.2 Recommendations

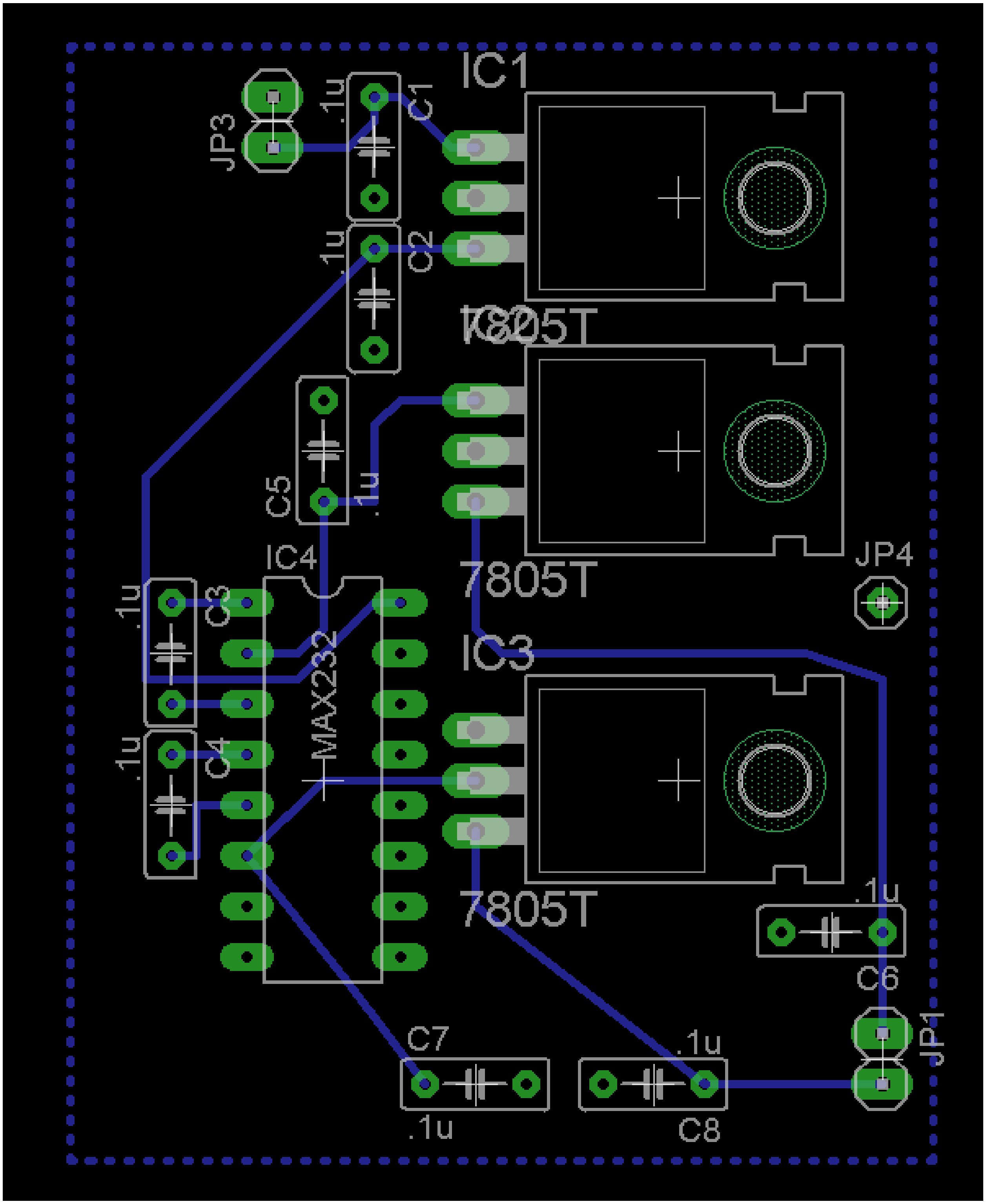
As with any project there is always room for improvement. One of the changes I would like to implement is to compliment the passive low pass filter with a notch filter at 60Hz. Further experimentation with the instrumentation amplifiers is possibility maybe use a newer more expensive instrumentation amplifier. The most fascinating recommendation to explore would be to replace the silver electrodes with the new insulated bioelectrodes. Improvements on the project include combining the two electrodes into a single electrode separated by a distance of 3 cm and positioning it on the chest. This would eliminate the need for electrode wires and would greatly reduce the noise in the system.

Appendix A

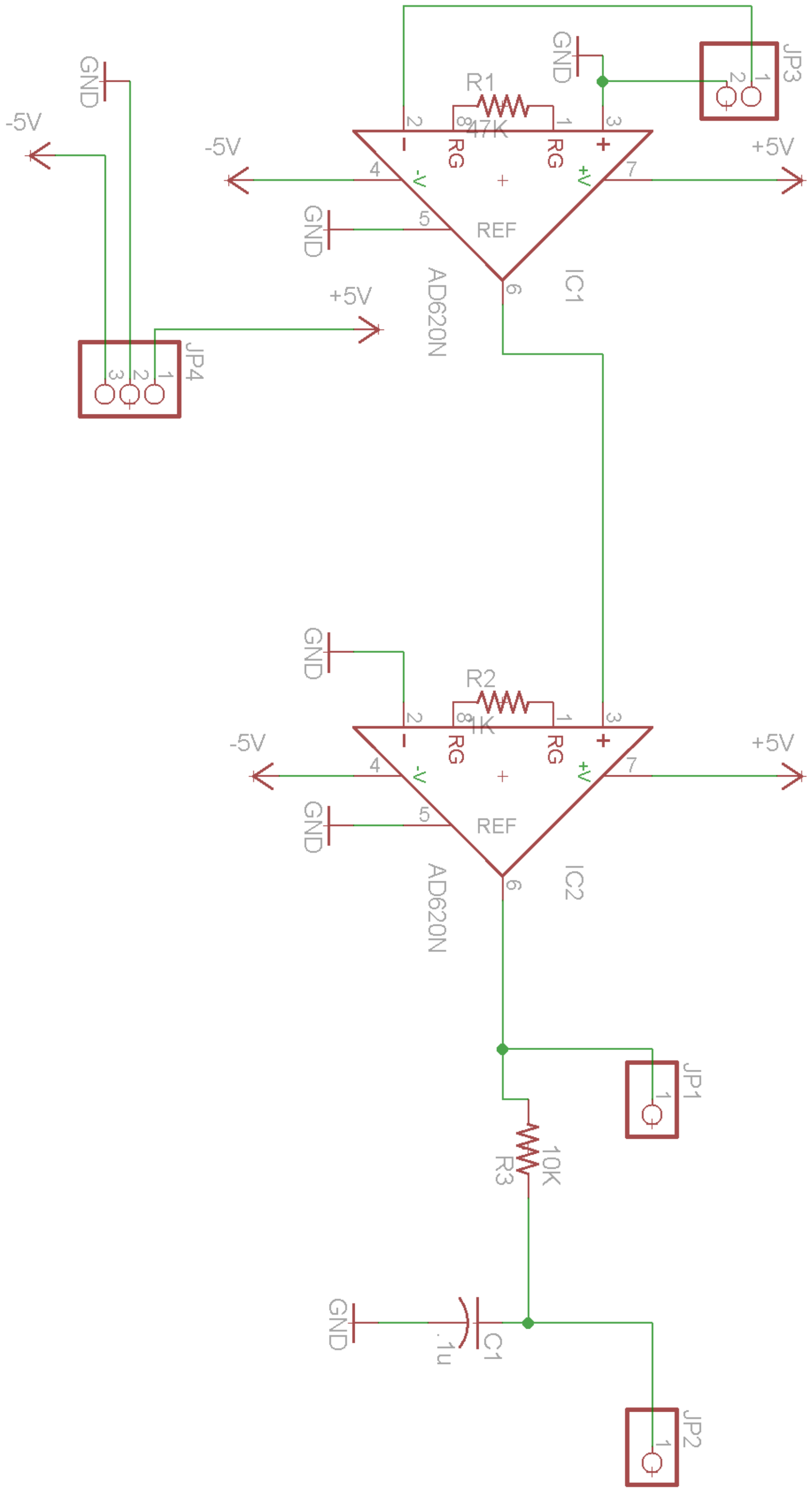
Appendix A.1.1 – Schematic of the Power Supply



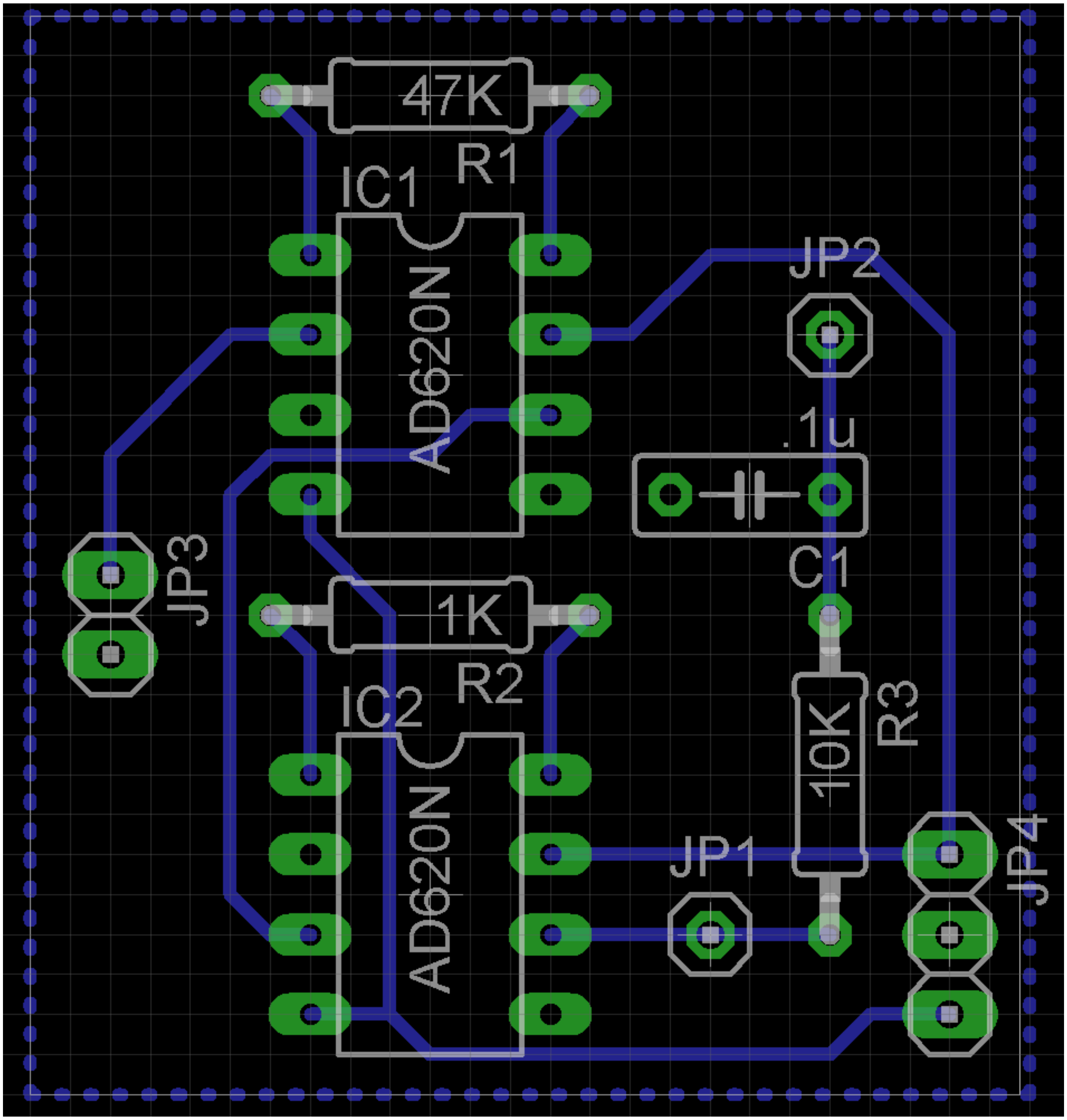
Appendix A.1.2 – Board Layout for the Power Supply



Appendix A.2.1 – Schematic of the ECG



Appendix A.2.2 – Board Layout for the ECG



Appendix B - Parts list and Cost of Project

Part	**Value**	**Device**	**Cost**
ECG:			
C1	1u	Standard through hole Capacitor	0.1
IC1	AD623	Analog - Digital	6.18
IC2	AD623	Analog - Digital	6.18
R1	47k	Standard through hole Resistor	0.1
R2	1k	Standard through hole Resistor	0.1
R3	10k	Standard through hole Resistor	0.1
Cost of PCB	n/a	n/a	2.5
Power Supply:			
C1	.1u	Standard through hole Capacitor	0.1
C2	.1u	Standard through hole Capacitor	0.1
C3	.1u	Standard through hole Capacitor	0.1
C4	.1u	Standard through hole Capacitor	0.1
C5	.1u	Standard through hole Capacitor	0.1
C6	.1u	Standard through hole Capacitor	0.1
C7	.1u	Standard through hole Capacitor	0.1
C8	.1u	Standard through hole Capacitor	0.1
IC1	LM 7905	Voltage Regulator (-5V)	2.22
IC2	LM 7805	Voltage Regulator (+5V)	2.31
IC3	LM 7805	Voltage Regulator (+5V)	2.31
IC4	MAX232	Driver/Receiver	1.19
Cost of PCB	n/a	n/a	5
Wireless:			
Transmitter	TMX/869	Linx TMX 869	18.37
Receiver	RMX/869	Linx RMX/869	22.72
Total Cost of Project in CND			70.18
Cost of Project Excluding Wireless in CND			29.09

Appendix C

Appendix C.1 - ECG Basics

The electrocardiogram (ECG) is a representation of the electrical events of the cardiac cycle. Each event has a distinctive waveform, the study of these waveforms results in a better understanding of a patient’s cardiac tissue. The recording of electrical signals of the heart is achieved by using electrodes on the skin. Electrodes on different sides of the heart measure the activity in different parts of the heart. Electrical impulses from the Sinoatrial Node (SAN) stimulate the heart muscle cells to contract. The SAN is the pacemaker of the heart it generates electrical impulses that trigger cardiac contraction. The SAN is located in the right atrium of the heart. The ECG measures the overall electrical vector from the heart muscle cells during each event of the cardiac cycle. The ECG basically takes a three dimensional picture of the electrical axis of cardiac muscle cells. Each pair of electrodes capture an electrical vector across them. This is then used by a physician to diagnose any abnormalities in the myocardium.

Appendix C.2 - ECG Waveform

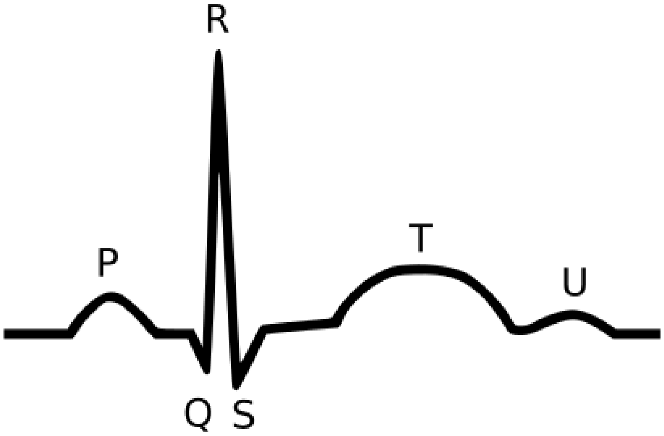


Figure 20: Shows the clinical ECG waveform

The Fig. xx above shows the ECG tracing that is acquired from a normal patient it is made up of all the different waveforms that are a component of the cardiac cycle (PQRST and U). The ECG corresponds to the electrical activity that results when the cardiac muscle cells in the atria and ventricles contract. The P wave is created during normal atrial depolarization this is the first stage of the cardiac cycle. The QRS complex is created when ventricular depolarization occurs due to the fact that the ventricles contain more mass than the atria the QRS complex is larger than the P wave. The T wave is created during ventricular repolarization the time between the S and T waves is known as the ST segment. Finally we have the U wave which is not always visible in an ECG. The U wave is thought to represent the repolarization of the Purkinje fibers. The U wave always follows the T wave.

Appendix C.3 - Clinical ECG Leads

Leads are electrodes that measure the difference in potential between either two different points on the body (bipolar leads) or one point on the body and a reference point with zero electrical potential located in the center of the heart (unipolar leads). The clinical ECG has 12 leads but only 10 electrodes. A lead refers to the recording of the electrical activity of the heart from a certain perspective. The 12 leads are as follows the standard leads (I,II and III) which are bipolar, the augmented leads (aVF,aVL,aVR) which are unipolar and the V leads (V1-V6) which are also unipolar. The clinical ECG collects all the information from the electrodes placed on the skin and by comparing each electrode with a corresponding electrode it creates a lead. Given the fact that each lead looks at the heart from a certain perspective a physician can get a full view of the electrical activity of the heart from which he/she can diagnose cardiac diseases.

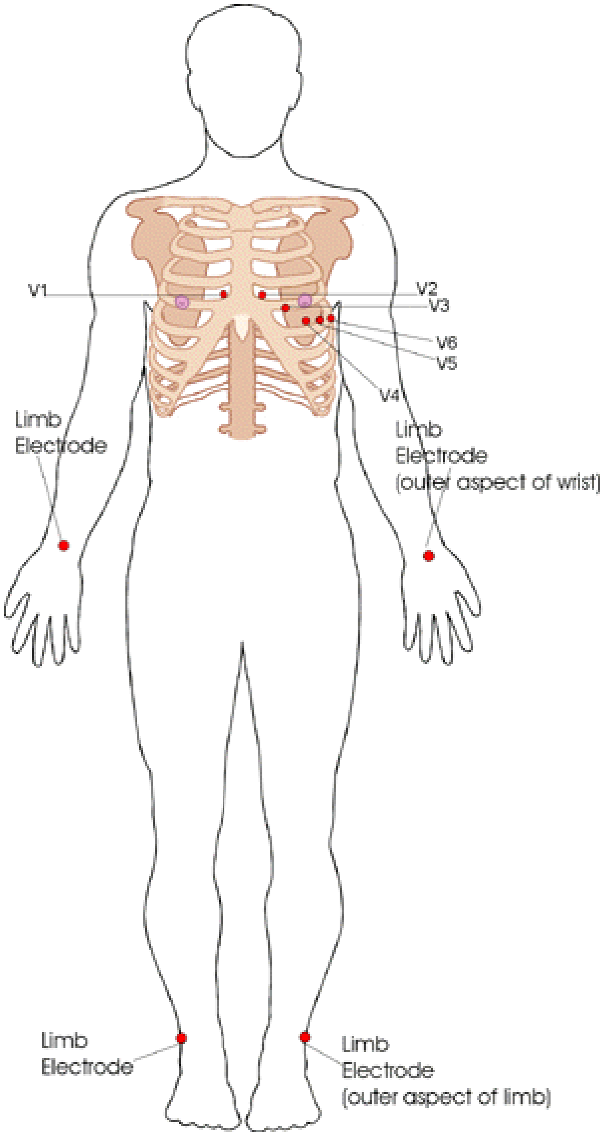
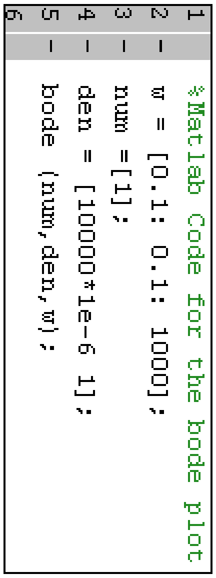
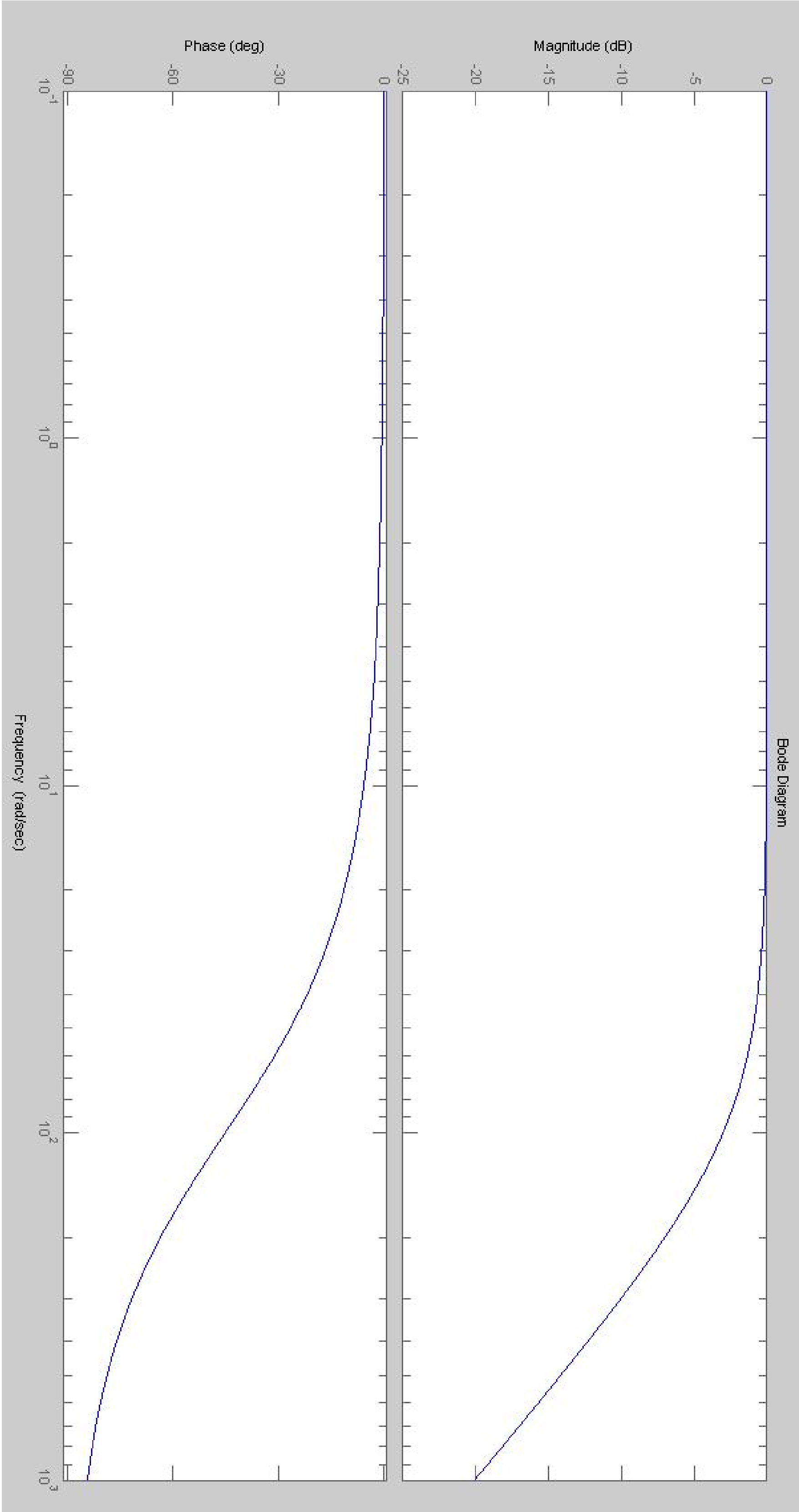


Figure 21: Shows the electrode positions in a clinical ECG

Appendix D - Bode Plot and Matlab Code



```
%Matlab Code for the bode plot
w = [0.1: 0.1: 1000];
num =[1];
den = [10000*1e-6 1];
bode (num,den,w);
```



Appendix E - Calculations

G_1 – Gain of first instrumentation amplifier

$$G_1 = 1 + \frac{100K}{47K} = \underline{\underline{3.12}}$$

G_2 - Gain of second instrumentation amplifier.

$$G_2 = 1 + \frac{100K}{1K} = \underline{\underline{101}}$$

Power of the amplifiers.

↳ Input voltage = 10V

Current draw = 1.1mA.

$$\therefore P = VI$$
$$= 10 \times 1.1mA$$
$$= \underline{\underline{11mW}}$$

Supply current per amplifer = 550μA.

∴ Total supply current = 550μ x 2

$$= \underline{\underline{1.1mA}}.$$

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