Development of a medical bracelet for portable heart rate and electrocardiogram measurements

Third Year Individual Project – Final Report

April 2020

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Abstract

It is a fact that heart attacks have always been one of the biggest causes of death worldwide. The most effective way of predicting their occurrence nowadays is heart monitoring, which refers to tracking the electrical activity of the heart in order to detect abnormalities of its operation and enable immediate action. There are two important medical tools enabling heart monitoring, the heart rate monitor and the electrocardiograph (ECG). This project is related to the development of a portable medical bracelet which combines both instruments, in order to make early detection of heart irregularities easily accessible to more people. In contrast with the available state-of-the-art, this device focused on providing benefits such as low cost, less complexity of use and more effective communication of the results to the user's doctor, while also incorporating the features of sensor accuracy and neat presentation of the results on an Internet of Things (IoT) Cloud Webpage and a Mobile Application (App). The device produced heart rate measurements with error of 0.46% when compared to the benchmark device which suggests that it could be used in real-life situations to provide doctors with useful monitoring data on their patients' health condition and potentially save lives.

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1. Overview and Background

1.1. Introduction

Heart monitoring has always been the fundamental method of cardiologists in the effort to prevent heart-related fatal incidents. Since the beginning of the 20th century this field has developed by leaps and bounds. The first big invention dates back to 1901, when Willem Einthoven created the first 3-lead electrocardiograph [1]. This development revolutionized the area of physiology and led to the 12-lead electrocardiograph device as it is known now. Therefore, at the end of the 20th century doctors were more capable of detecting cardiovascular problems rather than at its beginning. However, at the start of the 21st century the focus of the medical devices' industry shifted to giving control to the patients over their own medical data. That is how the first personal health-monitoring technologies appeared.

Portable medical devices are becoming more popular these days due to the revolutionization of this industry. Sensors that can measure the heart rate or produce an electrocardiogram (ECG) have not only become more accurate but also smaller. As a result, with the aid of wearable devices regular meetings to the doctor are avoided and heart abnormalities can be detected instantly.

Undoubtedly, the advancement in medical devices should be accessible to all people regardless of age, technological literacy or financial background. However, the latest portable medical bracelets discourage a wide range of people from using them due to increased complexity and cost [2]. The ones affected predominantly are the old people who most of the times do not possess one of the smart devices. Ironically, they are the ones who mainly need these medical tools.

The aim of this project was to develop a low-cost medical bracelet which measures the heart rate and the electrical activity of the heart continuously, in real time and can be used without requiring a connected smart device. The measurements were displayed on a webpage and a mobile app. These two streams could be used by doctors to track the condition of their patients.

The main objectives of the project were the following:

- Measurement of heart rate in beats per minute (BPM) using a low-power heart rate sensor
- Measurement of the heart's electrical activity using a low-power ECG sensor
- Communication of the measured data to a Cloud through direct Wi-Fi
- Display of the data on a webpage and a mobile app in real time

In order for the above to be achieved, a series of steps was followed. First, testing of different sensors and Wi-Fi modules was performed in order to select the most suitable ones. Then, a design of the overall circuit on a prototyping board was created which integrated the mentioned components with a rechargeable battery and a battery charger. After that step, the PCB layout was developed to improve the communication between the components.

The successful implementation of the PCB enabled the progression to the software development part. During this phase, the Cloud was optimized to receive data from the device. Following this, the webpage and the app were designed to collect the information and display them in a user-friendly way. Finally, a 3D-printed model of the bracelet case was implemented.

Overall, the accuracy of the device suggested that marketing of this product would be possible and would prove to be a useful tool in continuous heart monitoring.

1.2. Motivation

According to official statistics from the World Health Organization (WHO), cardiovascular diseases (CVDs) have been the biggest cause of death globally in the last 15 years and continue to account for the most deaths annually [3]. More specifically, heart-related diseases were the reason why 17.9 million people passed away in 2016, which represented 31% of the death causes globally. In this category of diseases, heart attacks and strokes are the leading causes, being responsible for 85% of the overall heart-related deaths. Therefore, technology that would aid in the reduction of these percentages would certainly be invaluable. In order to shape a clearer view of the problem, it is worth looking into how these diseases are diagnosed and treated.

1.2.1. Heart Attack

A heart attack is a serious medical condition in which the heart is not supplied with the blood and oxygen required due to a blood clot blocking the blood’s flow in the coronary artery [4]. According to the National Health Service (NHS), “if a heart attack is suspected, the patient should be admitted to a hospital immediately” [5] in order for the effect of the heart attack to be minimal. The first test that is being carried out to the patient is an electrocardiogram. This can determine how much the heart has been affected, in order to maximise the efficiency of the treatment [5].

Doctors advise that in heart-attack cases quick detection and treatment is critical [6], in order to open the blocked artery and mitigate the effect to the patient. It is worth noting that the best period of time to heal a heart attack is within the first 2 hours after the occurrence [7] to avoid detrimental effects to the cardiovascular system. Therefore, time is critical in such incidents.

1.2.2. Stroke

A stroke occurs when the supply of blood to the brain is blocked, due to either a blood clot in arteries (ischaemic stroke) or burst of a blood vessel providing oxygen and blood to the brain (haemorrhagic stroke) [8]. In this case, it is also crucial that it is identified immediately, so that the patient can be transferred to the hospital. Apart from brain scans and blood tests, the heart rate is thoroughly checked in order to provide information about the causes. NHS points out that “a stroke is a medical emergency and the patient should call 999 when it is suspected” [9]. Moreover, medicine for treatment has a bigger effect if it is taken immediately after the incident [10]. Therefore, time efficiency is vital in a stroke as well in order to prevent a life-threatening situation.

1.2.3. Action Plan 2013-2020 by the World Health Organisation

In an effort to deal with these diseases, the WHO has composed an Action Plan for 2013-2020, which aims to reduce by 25% the risk of mortality from CVDs [11]. One of the objectives emphasizes the need to “promote (…) the creation of electronic communication technologies (eHealth) and the use of mobile devices (mHealth) (…) in order to empower people with noncommunicable diseases to seek early detection and manage their own condition better” [11].

In support of this Action Plan, the device proposed in this paper aimed at providing a solution which can be utilized to decrease the number of deaths from CVDs on a global scale but also which can be used by old people to enable early detection of their heart’s abnormalities.

1.3. Statements of Aims and Objectives

The aim of the overall project was the successful development of a working low-cost medical bracelet, which can be easily used by people of all ages. This will incorporate the features of heart rate monitoring and electrocardiography. Also, the complete design of a practical webpage and a mobile app which will receive the data and display them in a user-friendly way.

To ensure the accomplishment of the main aims, the following objectives were formulated:

- Selection of suitable electrical, mechanical and software components
- Design of the circuit’s schematic diagram and of the printed circuit board (PCB)
- Completion of a working prototype of the circuit
- Creation of the computer-aided design (CAD) of the bracelet case

- Integration of the bracelet case with the PCB
- Development of the IoT Cloud webpage and of the mobile app
- Collection and display of the sensor measurements on the webpage and the app
- Creation of a communication interface between the patients and the doctors

1.4. Literature Review

1.4.1. The Future of Medicine

In order to deliver an innovative product it is important to look into the future of medicine, which will strongly depend on wearable electronic devices. The field has already entered an era of transition from population level to personalized healthcare [12]. This has been made possible by portable devices being developed, which include advanced biosensors, such as photoplethysmography (PPG) and electrocardiography (ECG) sensors. A study demonstrated that 71% of new devices included a PPG sensor which outnumbers all the other available sensors [13]. However, these gadgets go beyond just extracting medical data. They incorporate wireless communication to transmit real-time data to a physician or even run algorithms to predict events before they occur. These innovations have driven the market of wearable technology into a rapid growth phase and the healthcare informatics generated bring the sales potential to the range of billions of dollars [14]. Also, new studies prove the public acceptance of wearable devices, as one in six consumers in the United States already owns one [15].

1.4.2. Value of PPG and ECG Measurements

The value of wearable devices, such as the medical bracelet developed in this project, lies on the detection and prevention of life-threatening heart conditions. First, PPG sensors have many uses in clinical physiological monitoring, such as to determine heart rate and blood pressure [16]. On the other hand, the functions of an ECG sensor are equally important, as it is utilized in the diagnosis of cardiovascular diseases such as “coronary artery disease, heart attack, bradycardia and tachycardia” [17]. However, one of the most serious heart problems is atrial fibrillation, which can result in stroke or heart failure if it remains undiagnosed and untreated [18]. Both PPG and ECG sensors can significantly contribute to the early detection of the disease and enable doctors to take quick action. Lately, devices using PPG have become enforced with algorithms that analyse the measured data and are able to detect signs of atrial fibrillation [19]. For instance, Apple Inc. has included this feature in its product, Apple Watch, and the Apple Heart Study performed by Stanford Medicine demonstrated that 84% of the 400,000 participants who received irregular pulse notifications from the Apple Watch actually suffered from atrial fibrillation [20]. Another important benefit is the opportunity to study ECGs in order to correlate patterns in the waveforms with symptoms of heart diseases [21]. Finally, these measurements are significant for sport activities and as a psychophysiological status indicator, such as for stress levels monitoring [22].

1.4.3. Historical Origins

A summary of the milestones related to the advancements in photoplethysmography and electrocardiography is shown in Figure 1:

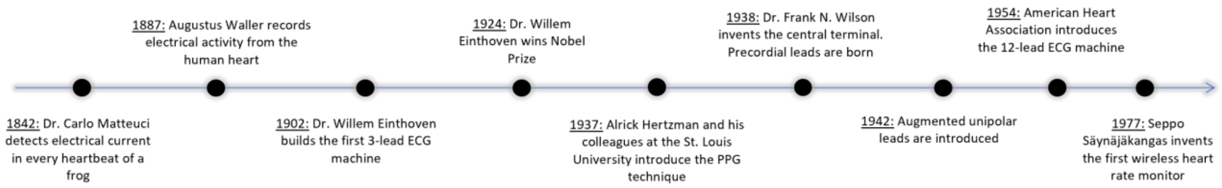


Figure 1: Historical Timeline of Electrocardiography and Photoplethysmography

Looking back at how it all started, the interest of physicians to study the electrical activity of the heart dates back to the mid of 19th century. At that time, Dr. Carlo Matteucci proved that there was electrical current associated with every heartbeat of a frog [23]. This inspired physiologists who, after a few years, managed to record electrical activity in the human heartbeat as well [24]. Then, in the early 1870s two British physiologists used a capillary electrometer to record the heart's electrical current [24] before Augustus Waller published the first ever electrocardiogram from a human heart using this device with electrodes placed on the back and the chest [1].

The intense research on the field became fruitful when in 1895 the Dutch physiologist Dr. Willem Einthoven refined the original capillary electrometer and demonstrated the five deflections that occur during a heartbeat [24]. The deflections were given the names of P,Q,R,S,T which are still used in ECGs today [24]. He then developed a highly sensitive string galvanometer – an electromechanical instrument to sense electric current – to detect the potential difference between the attached electrodes resulting from the different stages of the heart pumping blood. Finally, in 1902 the first electrocardiograph was officially introduced by Einthoven. It incorporated a silver-coated string which moved from side to side in the magnetic field of a magnet when the heart's current passed through it [24]. This Nobel Prize winning invention initiated new fields of research in connecting patterns on the ECG graphs with heart conditions such as atrial fibrillation.

Around 1930, another improvement came to life as Dr. Frank N. Wilson introduced the 'central terminal' [23]. Building on that, the American Heart Association and the Cardiac Society of Great Britain recommended the exploration of heart activity from six sites named V1 through to V6 across the precordium [24]. Another milestone includes the introduction of the augmented unipolar limb leads called a-VL, a-VR and a-VF which provided more thorough coverage of the area around the heart [23]. All these innovations contributed to the introduction of the 12-lead electrocardiogram in 1954 by the American Heart Association [23].

Later in the 20th century inventors started to think about making this instrument portable. A pioneer physicist named Norman Holter managed to implement an ambulatory electrocardiography device which could record an ECG continuously for a couple of days [25]. Finally, in 1977 another pioneer Seppo Säynäjäkangas invented the first wireless heart rate monitor as a training tool for the Finnish National Cross Country Ski Team [26].

Photoplethysmography also has a rich history which started in the 1930s. More specifically, in 1937, Alrick Hertzman and his colleagues at the St. Louis University published a paper explaining the use of this reflection technique to measure the changes of blood volume in the human fingers [16]. Later on, they continued improving the technique by amplifying the signal and describing ways of avoiding sources of error [16].

It is interesting to investigate how these techniques are used nowadays and the kind of results they produce.

1.4.4. Wearables Accuracy Assessment

Undoubtedly, there has been impressive development in the portability of devices since the first inventions in the 20th century. However, there is normally questioning behind how accurate the produced data is and whether the algorithms to detect irregularities are efficient. Multiple studies have been conducted to assess the accuracy of marketed wearable devices.

First of all, a research study in 2016 examined the validity of different wireless heart-rate monitors such as the FitBit Charge HR, Microsoft Band and after measurements from 50 volunteers the mean absolute percentage error values ranged from 3.3% to 6.2% when compared to the Polar RS400 HR chest strap as benchmark [27]. Furthermore, another study investigated if smartwatches could accurately measure heart rate in people with different heart conditions. 100 participants were tested at rest with 30 minutes of continuous monitoring. The results demonstrated that in the cases of sinus rhythm and atrial flutter the FitBit and the Apple Watch agreed strongly with the

ECG benchmark device with a low average bias of 1 heartbeat [28]. However, in the case of atrial fibrillation there was a higher deviation from the benchmark with biases of around -15 heartbeats for each device [28]. Finally, the iTransmit study assessed the measurements taken from the AliveCor Kardia Mobile device when attempting to detect atrial fibrillation and found that it had 100% sensitivity and 97% specificity when compared to a traditional transtelephonic monitor [29]. All of these results demonstrate that available wearables can be trusted for the data they produce.

1.4.5. Recent Research Developments

The trend in the research field of wearable electronics currently focusses on developing flexible and stretchable sensing circuits which will improve the user's comfort. In order to achieve mechanical flexibility, the device needs to incorporate stretchable substrates, suitable sensing materials in the millimeter range and flexible primary batteries.

The field of flexible batteries has introduced many advancements recently such as connecting microbatteries on stretchable substrate or fabricating batteries in the shape of a cable [30]. Furthermore, there has been research on other ways of powering bendable sensors such as photovoltaics with supercapacitors or thermoelectric generators, converting the heat of the user's body to electrical energy [30]. However, these powering techniques have brought new engineering challenges to the surface. These relate to the integration of the power sources with the biosensors, as they need to be physically close to the location where the signal is measured. Furthermore, the materials used need to be dermatologically proven, safe and nontoxic [30].

An innovation worth mentioning relates to an epidermal electronic system which apart from ECG measurements it can also extract temperature and strain data by attaching the device on the patient's skin. The system uses an elastic polymer backing layer on which multiple sensors are mounted along with a power and processing unit and a wireless transmission module [31]. On a similar direction, the research group led by Zhenan Bao at Stanford University demonstrated miniaturized monitoring devices with sensors in the millimeter scale which can measure the heart pulses from the wrist with the use of flexible polymer transistors [32]. There are multiple advantages in exploiting these innovations such as low power consumption and removal of body movement artefacts. Another innovative design is an ECG patch monitor which produces a single-lead ECG and includes an accelerometer to eliminate body artefacts [32].

There is no doubt that body activity poses a significant constraint on the achievable accuracy of the measurements. More specifically, the signal quality is influenced by the instability of the biomedical pads on the patient's skin. In the devices using PPG technique this limitation in addition to the artefacts due to ambient light can lead to erroneous data. For this reason, algorithms using adaptive filters and accelerometers are currently being developed [33].

Finally, promising research activities aim to connect the sensing systems with clothes. This innovation will include microsensors embedded into textiles which will extract useful physiological data [34]. The smart textiles incorporate textile electrodes which require reliable design in order to ensure good signal quality and immunity to body artefacts [34]. It is believed that this technology will be able to provide a wide range of vital data as the sensing system will cover a bigger area of the body. These measurements will be particularly helpful for specific groups of people such as athletes, disabled people and also workers in hazardous places like firemen. However, there are obvious difficulties in implementing this vision, as these pieces of clothes will require complicated manufacturing techniques to be water durable during washing cycles. This is the reason why some initial attempts for implementation have failed [34].

1.4.6. Outstanding Research Problems

A further research problem includes the lagging development in the data analytics needed to manage the enormous amount of data generated by the biosensors [12]. If the advancements in machine learning allow analysis of all the diverse measurements, then doctors will be able to master the interpretation of the information and systems will predict life-threatening events.

Also, the communication of medical data over the network has made people sceptical about the security of their privacy [12]. The scientific community will have to find answers in the challenge of data security as it significantly reduces the public acceptance of wearable devices. Personal health information is protected under the Health Insurance Portability and Accountability Act of 1996 [12] and hence all medical data need to be encrypted when moved across secure networks. A potential breach of personal health data would certainly be disastrous for the industry.

1.5. Consideration of Existing Solutions

Despite these challenges the field of wearable devices is a fast-growing industry which is valued at USD 472.69 Billion and is expected to reach USD 612.7 Billion by 2025 [35]. More specifically, the cardiovascular devices are likely to represent 13% to 15% of this share. Seeing this business opportunity many companies have started developing medical products to enter the market.

Wearable devices can be distinguished in two categories. On one hand, those that extract and display health data without medical monitoring, referred to as Fitness Trackers. The second group also communicates the information to a doctor which are referred to as Medical Wearables.

In the industry of Fitness Trackers, the heart-monitor called Fitbit dominates. The newest version named Fitbit Charge 3 provides features, such as continuous heart-rate tracking during everyday activities, while also monitoring the calorie burn and quality of the sleeping cycle [36]. Its major advantages include battery life of up to 7 days and an app for displaying the data. Some of the disadvantages include no detection of heart rate irregularities, no ECG measurement and a high price of £150 [36]. Furthermore, another available activity-tracker is the Letsfit Fitness Tracker. This monitor device also focuses on heart rate measurements during activities and provides similar advantages in battery life as well as in the price, which is £25. On the downside, the measurements are inaccurate and there is no alert for abnormal heart activity. Additionally, J-style Smart Wristwatch provides 24-hour heart rate and ECG monitoring with abnormal heart rate alert in a reasonable price of £25. However, it does not include communication of the data to a doctor.

When looking at the state-of-the-art available in Medical Wearables there are multiple approaches on measuring the heart rate and the ECG. First, new products such as the Zio Patch or the VitalPatch employ a patch which is attached on the patient's chest and produces a 1-lead ECG. This technique offers significant benefits in size and in comfort of use. However, both demonstrate critical disadvantages. The Zio Patch is not capable of transmitting data in real-time, but rather it records measurements on the device for two weeks and the user sends the patch back to the manufacturer, who produces a thorough report on the heart activity [37]. This procedure as well as the high price of £150 classify it as an unsuitable option for heart condition monitoring. Furthermore, the VitalPatch can only produce 1-lead ECG with limited accuracy.

Other solutions include ECG pads such as the KardiaMobile device. This technology incorporates a thin, rectangular device with two conducting pads, on which the users place two fingers in order to produce a 1-Lead ECG on the screen of a smartphone. The manufacturer has developed a mobile application which receives the data in real-time and communicates them to a doctor [38]. The second version of the device, KardiaMobile 6L, demonstrates improved accuracy [39]. Even though it provides a reliable and accurate solution, the measurements can only be recorded when the user is prompted to and not continuously. Therefore some heart irregularities might not be detected. Also, its use requires technical skills making it less accessible to older people.

A final approach includes the multi-purpose watches which amongst other features they include the heart rate and ECG measurements as well [40]. An example is the Apple Watch, whose price is high due to all the additional functions. Therefore, it is not considered as an option if the heart-monitoring functionality is the only one needed. Nevertheless, because of its accurate measurements of heart rate and ECG [28] it was used in this report as a benchmark device.

To summarize, although the available state-of-the-art provides helpful ways of producing heart rate and ECG data, it was realized that none of the devices combines all of the following features:

- Low cost
- Alerts for heart irregularities
- Communication of data to a doctor in real-time
- Continuous heart-condition monitoring
- No technical skills required by the user

1.6. Conclusions

By recognising the flaws of the existing state-of-the-art and the crucial impact that a heart monitor could have, this report presents the process of developing a medical bracelet, which will be accessible to all ages, regardless of technical literacy, and will enable instant communication of heart rate and ECG measurements to a doctor for continuous heart-condition monitoring.

The successful implementation of such device could potentially save lives and contribute to the 3rd Sustainable Development Goal set by the United Nations for 2030, which aims at securing good health and well-being for everyone at all ages [41].

2. Technical Achievement

2.1. Theoretical Development

2.1.1. Parts of the Heart

The heart is the most important muscular organ in the human body. Its main functions include receiving blood low in oxygen from the other organs and provide them with oxygen-rich blood, which enables their normal operation [42]. The heart consists of four chambers [22]:

- The right atrium, which forwards the received low-oxygen blood to the right ventricle
- The right ventricle, which forwards the received blood to the lungs to be filled with oxygen
- The left atrium, which forwards the received oxygen-rich blood to the left ventricle and
- The left ventricle, which pumps the blood to the rest of the body organs

2.1.2. Cardiac Cycle

The cardiac cycle refers to a complete cycle of operation of the heart's atria and ventricles [43]. A full cardiac cycle consists of four phases [43]:

- Atrial systole, which results from depolarization of the atria and in which the blood received by the veins is pumped into the ventricles
- Atrial diastole, during which there is relaxation of the atria after pumping the blood into the ventricles
- Ventricular systole, during which the blood flows from the right ventricle to the lungs and from the left ventricle to the rest of the body
- Ventricular diastole, during which the blood flows back to the heart into the atria

2.1.3. Heart Rate

The cardiac cycle is a periodic operation of the human body and therefore it is characterized by a frequency. This frequency is varying according to nervous, hormonal and psychological influences and it has been given the name of heart rate. Heart rate is a crucial vital sign and has become the most fundamental measurement in healthcare as it provides useful information on the physiologic condition of the heart. It is measured in Beats per Minute (BPM) [22] and with a technique called photoplethysmography (PPG). Typical values of resting heart rate are in the range between 50 and 90 BPM [44]. Values outside of this range indicate abnormal heart activity and medical help needs to be sought by the patient. The quality of the cardiac cycle can also be evaluated by the graphs generated in electrocardiography.

2.1.4. Photoplethysmography

Photoplethysmography (PPG) is an optical technique used to detect the changes in the volume of the peripheral blood flow throughout the cardiac cycle. This is achieved by integrating a system which is composed of a Light-Emitting Diode (LED) and a photodiode, a sensor sensitive to changes in light density [16]. The operation principle begins with the LED emitting light (normally green) in a wavelength compatible with the photodiode on the skin tissue. The amount of light reflected back to the sensor is measured by the photodiode and its variations are associated with changes in blood volume and blood vessel wall movement at a particular instant [16]. Figure 2 demonstrates the operation of a PPG sensor graphically. In order to achieve the best possible accuracy of measurements, the photodetector is connected to low noise circuitry including an amplifier and a high pass filter [16]. The final stage includes algorithms to convert the measurements of light intensity to the measure of heart rate in BPM. PPG sensors are often preferred by users as they are more comfortable to wear than ECG sensors. This is why they are employed in multiple commercially available wearable products and their popularity constantly grows.

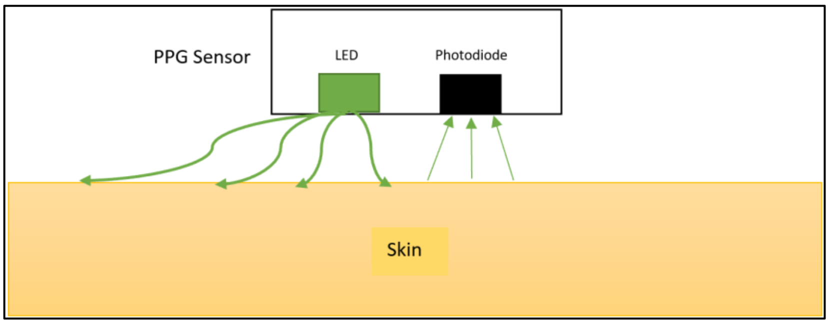


Figure 2: Operation of a PPG Sensor

2.1.5. Electrocardiography

Electrocardiography is a field of medicine which is related to the generation of electrocardiograms (ECGs). These are diagrams illustrating the electric potential of the heart over time and are produced by clinical instruments called electrocardiographs. The output graphs are widely used by doctors as diagnostic tools to provide information on the cardiac electrical cycle [22]. Additionally, by using them it is possible to detect potential heart conditions, such as atrial fibrillation [22].

Each deflection on the ECG represents a phase of the cardiac cycle [43]. More specifically:

- The P wave represents the depolarization of the atria during the atrial systole phase
- The QRS complex represents the depolarization of the ventricles during the ventricular systole phase
- The T wave represents the repolarization of the ventricles and indicates that the phase of ventricular relaxation begins

Figure 3 connects the deflections on an ECG graph with the phases of the complete cardiac cycle:

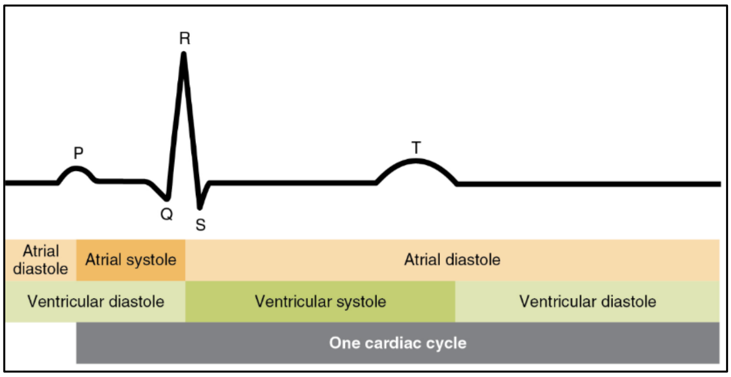


Figure 3: Deflections of an ECG Graph

Source: Retrieved from [43]

2.1.6. Placement of ECG Electrodes

The number of electrodes used for an ECG measurement can vary. It should be noted that the higher the number of electrodes the better the accuracy in the output ECG graph. There are different types of ECG graphs which depend on the number of ECG leads that they produce. The term "ECG lead" means a graphical representation of an electric potential measurement between two electrodes or a single electrode and the virtual electrode and it should not be confused with the term "ECG electrode" which is the physical sensor to measure the potential at a specific position on the body. Typical electrocardiograph instruments produce 1-lead, 3-lead, 6-lead or 12-lead ECGs. The proposed device produces a 3-lead ECG.

In the 3-lead ECG, each of the three electrodes displays a different angle of the heart contributing in a multi-angle view of its structure. The appropriate placement of the 3 electrodes corresponds to a triangle in order to give equally spaced views of the heart every 120° and it was introduced by Willem Einthoven in the so-called Einthoven's triangle shown in Figure 4 [45]. In order for the electrodes to form a triangle, these are placed in the Right Arm (RA), the Left Arm (LA) and the Left Leg (LL). There are three electric potential measurements that are performed:

- Lead I, which corresponds to the electric potential between the LA and the RA
- Lead II, which corresponds to the electric potential between the LL and the RA
- Lead III, which corresponds to the electric potential between the LL and the LA

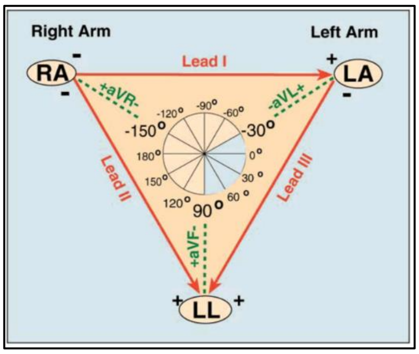


Figure 4: Einthoven's Triangle

Source: Retrieved from [45]

2.1.7. Measures of Accuracy

It is important to evaluate the accuracy of the sensors' measurements when compared to the benchmark device. In this report, the following measures of accuracy and precision were used:

- Mean value: For a set of n values, $x_1, x_2, \dots, x_n$, their mean value is given by:

$$\bar{x} = \frac{x_1 + x_2 + \dots + x_n,}{n} \quad (1)$$

- Standard Deviation (SD): For x_i being each individual measurement and $\bar{x}$ being the mean value for a set of N measurements, the standard deviation σ is given by:

$$\sigma = \sqrt{\frac{\sum(x_i - \bar{x})^2}{N}} \quad (2)$$

- Pearson Correlation Coefficient: The Pearson correlation coefficient measures the linear correlation between two variables X and Y. For $cov(X, Y)$ being the covariance of X and Y and σ_X, σ_Y their standard deviations, the Pearson correlation coefficient $\rho_{X,Y}$ is [46]:
$$\rho_{X,Y} = \frac{cov(X,Y)}{\sigma_X \sigma_Y} \quad (3)$$
- Mean Absolute Percentage Error (MAPE): For A, the measured value from the sensor and B, the value from the benchmark device for a set of N measurements, the $MAPE$ is calculated with the following formula [47]:
$$MAPE = \left(\frac{1}{N}\sum_{t=1}^{N}\frac{A-B}{B}\right) \times 100\% \quad (4)$$

Now that the theoretical knowledge required has been introduced, the focus is transferred to the procedure followed in order to implement the medical bracelet successfully.

2.2. Methods

2.2.1. Overview of Methodology

Figure 5 shows the flowchart of the methodology followed in this project:

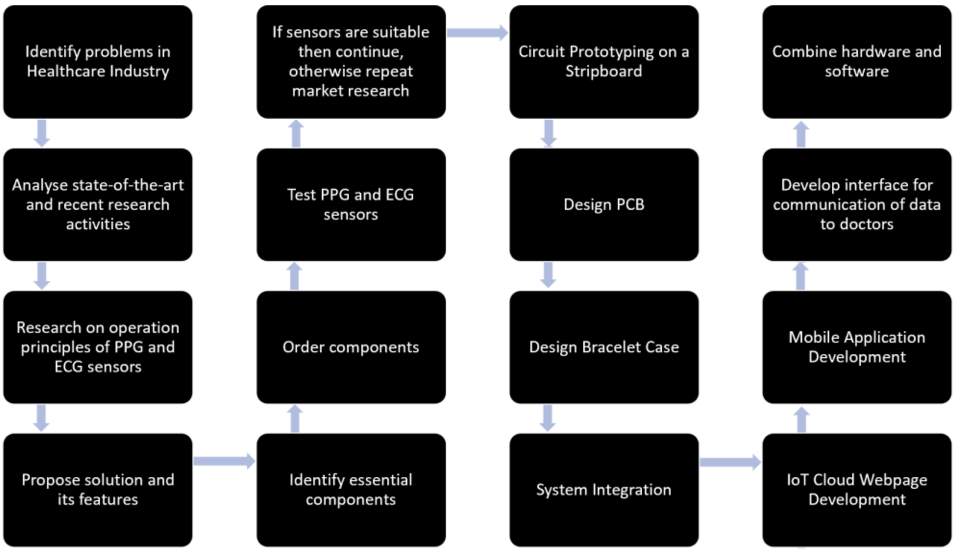


Figure 5: Methodology Flowchart

More specifically, the order of steps was the following:

- Researched on problems in healthcare industry and detected a need for a device which measures vital signs accurately, communicates them to a doctor in real-time and offers continuous monitoring without requiring technical skills
- Analysed the state-of-the-art solutions and recent research activities on the measurement of heart rate and ECG with portable medical devices
- Researched on the operation principles of the heart rate and ECG sensors and completed a literature review on the outstanding research problems
- Proposed a wireless medical bracelet which offers advantages such as simplicity of use, cost, continuous and passive monitoring, accuracy and communication of real-time data

- Completed a risk assessment classifying the project's technical and organisation risks as shown in Appendix 1
- Identified the required components such as a heart rate sensor, an ECG sensor, a Wi-Fi module, a rechargeable battery, a battery charger and platforms such as an IoT Cloud Service and a Mobile App Development Platform
- Ordered off-the-shelf components which provided merits in size and cost
- Carried out a health and safety risk assessment before the practical work started as presented in Appendix 2
- Tested the accuracy of the sensors to decide on the most suitable ones for this application
- If at least one component of each sensor was suitable then proceeded with the next steps, otherwise repeated the market research on components
- Prototyped a stripboard with all the components and the interface circuit between them
- Designed the interface circuit between the components on a PCB
- Mounted the components of the system onto the PCB
- Designed the bracelet case on a 3D CAD tool, which was implemented by 3D-printing it
- Integrated the bracelet case with the PCB and the other electrical components
- Developed an IoT Cloud webpage where the information from the sensors was displayed
- Implemented automatic notifications through e-mail in case of irregular heart activity
- Constructed an app, which displays the heart rate and ECG on the screen of a phone
- Implemented the feature of communicating the measurements to a doctor in real-time
- Combined the hardware design with the firmware to complete the product

2.2.2. Design

Overview of Components

For the implementation of the medical bracelet the following electrical components were used: heart rate sensor, ECG sensor, Wi-Fi module, rechargeable battery, battery charger and a switch. These were connected according to the schematic diagram presented in Appendix 3.

Printed Circuit Board Layout Diagram

The interface circuit was then implemented on a single-layer PCB, which significantly reduced the area required for the connections. The PCB layout diagram, as designed on the PCB design automation package (Altium Designer, Version 20, Altium, California, USA), is shown in Figure 6:

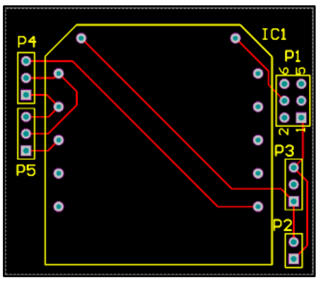


Figure 6: PCB Layout Diagram

The designators shown on the PCB layout diagram correspond to the components of Table 1:

Table 1: Designators and Components Equivalence

Designator	Component
IC1	Wi-Fi module
P1	Switch
P2	Battery charger
P3	Battery
P4	ECG sensor
P5	Heart rate sensor

3D CAD Bracelet Case Design

The mechanical design of the bracelet case was designed on a 3D CAD tool (SolidWorks, 2018, Dassault Systèmes, Vélizy-Villacoublay, France). The size of the bracelet was limited by the size of the PCB and the area needed to fit all the components of the system. Therefore, the dimensions of the bracelet are the ones shown in Table 2:

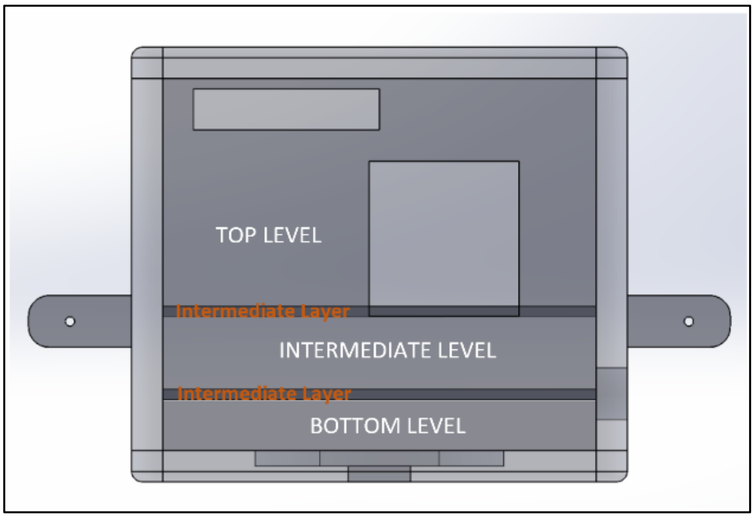
Table 2: Dimensions of Bracelet

Width	Length	Thickness
48 mm	53.5 mm	40 mm

The design of the bracelet is composed of three parts: the 3D-printed outer hollow case, the 3D-printed cover layer and the two laser-cut intermediate layers. The intermediate layers separate the mechanical configuration of the components inside the case into 3 levels:

- Top Level, which includes the PCB, the battery and the battery charger
- Intermediate Level, which includes the ECG sensor
- Bottom Level, which includes the heart rate sensor

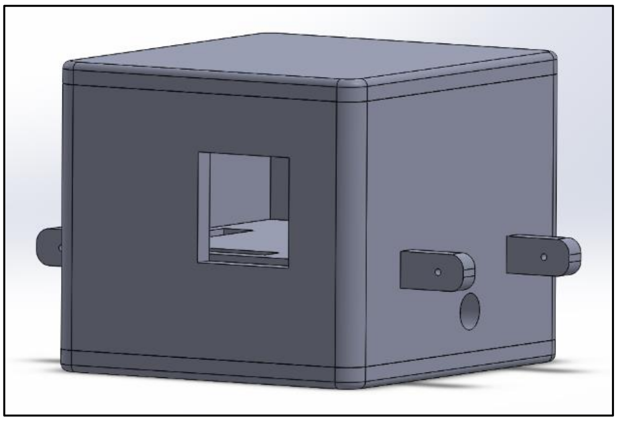
The configuration of the levels with the intermediate layers separating them is shown in Figure 7:



On the outer case, holes are included to allow for placement of the switch, the input jack port for the ECG electrodes and the mini USB B port for charging the battery.

Figure 7: Configuration of Levels

Overall, the 3D CAD design and the final product are illustrated in Figures 8 and 9:



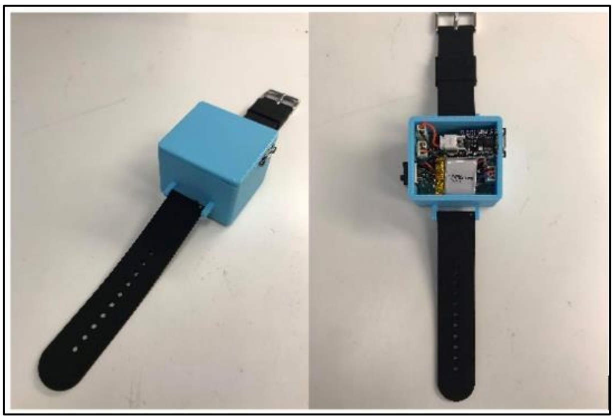


Figure 8: Bracelet Case 3D CAD Design

Figure 9: Final Physical Product

2.2.3. Implementation

Electrical Components

For the implementation of the device the following six electrical components were selected:

- DFRobot Gravity Heart Rate Monitor Sensor for Arduino
- Gravity Analog ECG Sensor for Arduino
- Beetle ESP32 Wi-Fi module
- Lithium Ion Polymer Rechargeable Battery
- Li-Ion Battery Charger Module
- Double-Pole Double-Throw Switch

Heart Rate Sensor

The heart rate sensor uses the PPG technique to record the heart activity by using two green LEDs and a photodiode, as explained in the “Theoretical Development” section. Appropriate calculations in the firmware allow conversion of the output voltage to the heart rate in BPM.

Two heart rate sensors were tested following the process explained in the “Testing” section and in the end the DFRobot Gravity Heart Rate Monitor Sensor for Arduino was selected.

The IC of the sensor incorporates the SON1303 Integrated Heart Rate Sensor, which includes the LEDs and the photodiode. Additionally, the SON3130 chip included performs amplification of the photodiode’s voltage and provides low input bias current (10 pA) and low supply current (60 μA).

This sensor satisfies the requirement of small size as its dimensions are 24 mm x 28 mm, which means it can fit on an average person’s wrist and is compatible with the size of the bracelet case. Furthermore, it demonstrated more accurate measurements than the other sensor tested, as shown in the "Results" section. Also, the cost was only 30p more expensive than the competitive sensor, therefore offering more advantages for a negligible difference in price. Table 3 demonstrates its electrical characteristics [48]:

Table 3: Electrical Characteristics of the DFRobot Gravity Heart Rate Monitor Sensor

Input Voltage	Output Voltage	Operating Current
3.3 V – 6 V (5 V recommended)	0 V – Vin (Analogue Mode), 0 V / Vin (Digital Mode)	<10 mA

ECG Sensor

Even though there were very limited choices for ECG sensors in the market, the Gravity Analog ECG Sensor for Arduino can perform a satisfactory ECG test which lies close to the output graph from the benchmark device as seen in the "Results" section.

This sensor incorporates the AD8232 Heart Rate Monitor Chip by Analog Devices, which offers low supply current (170 µA), common-mode rejection ratio (80 dB) and high signal gain (G=100) [49]. Additionally, it combines the voltage input of three electrodes to extract a 3-lead ECG graph. Also, its board dimensions are 35 mm x 22 mm, hence fitting inside the dimension range of the bracelet. Finally, its electrical characteristics are shown in Table 4 [50]:

Table 4: Electrical Characteristics of the Gravity Analog ECG Sensor for Arduino

Input Voltage	Output Voltage	Operating Current
3.3 V – 6 V (5 V recommended)	0 V – 3.3 V	<10 mA

Wi-Fi Module

A Wi-Fi module is used for the communication of the sensors' data to an IoT Cloud Service and an app, where the data is displayed. For this application, the Beetle ESP32 Wi-Fi module was selected as it provides Wi-Fi connectivity, multiple ADC channels for sampling the analogue voltages of the sensors and GPIO pins. Table 5 shows the features of this IC:

Table 5: Features of the Beetle ESP32 Wi-Fi Module

SPI Flash	SRAM	Crystal Oscillator Frequency
16 Mbits	520KB	40 MHz

The module provides a micro-USB port, in order to be able to program the board directly. Furthermore, it is compatible with the chosen programming environment (Arduino IDE, Version 1.8.11, Arduino, Italy) and software support and libraries are provided.

The Wi-Fi module supports TCP/IP and a full 802.11 b/g/n Wi-Fi MAC protocol providing speed of up to 150 Mbps, transmitting power of up to 20.5 dBm and frequency range between 2.4 GHz and 2.5 GHz [51]. The board also provides advantages in dimensions (35 mm x 34 mm).

Battery

It is critical to calculate the power budget required by the electrical components of the system in order to select a suitable power source for the design. The power consumption of the individual components is presented in Table 6:

Table 6: System Power Budget

Component	Supply Voltage V (V)	Operating Current I (mA)	Power Consumption P=VI (mW)
Heart rate sensor	3.3	10	33
ECG sensor	3.3	10	33
Wi-Fi module	3.7	120	444
Total		140	510
Estimated Efficiency			50%
Input Power Needed (mW)			1020

The medical bracelet requires a power source which also complies with the features of low mass, small size and rechargeability. Therefore, a Lithium Polymer Rechargeable Battery with nominal voltage of 3.7 V and rated capacity of 190 mAh was chosen. This power source agrees with the above requirements, as its size is 24 mm x 22 mm and it has low mass of 4.5 g [52]. Furthermore, the lifetime of the battery is calculated as:

$$t = \frac{Input\ Energy}{Input\ Power\ Needed} = \frac{3.7 \times 190 \times 10^{-3}\ Wh}{1020 \times 10^{-3}\ W} = 0.69\ h = 41.4\ min$$

Additionally, the 100% charging time is approximately 1 hour [52].

Battery Charger Module

In order to allow rechargeability of the bracelet, the RobotDyn® TP4056 Battery Charger Module was used. This module includes a microUSB port for charging and offers the features of [53]:

- Constant current of 1 A / Constant voltage of 4.2 V
- Current monitor
- Under voltage lockout
- Two status LEDs

Software Components

Two software components were necessary to receive the sensor information from the Wi-Fi module and display the results. Following the aims of the project to provide flexibility in the way that users and doctors view the data, two means of displaying information were developed, an IoT Cloud webpage (for computer users) and a mobile app (for smartphone users). These were created using the Ubidots IoT Cloud Service and the Blynk App Development Platform respectively.

On one hand, Ubidots is an IoT platform in which developers can communicate data from sensors and display them using value indicators, graphs and more. It also provides support with Arduino libraries for the Beetle ESP32 Wi-Fi module.

On the other hand, the Blynk Development Platform aids in the development of mobile applications compatible with Android OS version 4.2+ and iOS version 9+ [54]. Furthermore, Blynk apps can receive data using Wi-Fi connection from the Beetle ESP32 Wi-Fi module used here.

Mechanical Component

The electrical components on the PCB were integrated with the mechanical component of the system to provide comfort when worn on the wrist. This is the 3D-printed bracelet case.

2.2.4. Procedure

The procedure followed to create the device included interfacing the sensors with the Wi-Fi module and flashing the firmware. The code of the system was developed in an Integrated Development Environment compatible with the Wi-Fi module, the IoT Cloud Service and the Mobile App Development Platform (Arduino IDE, Ver. 1.8.11, Arduino, Italy).

In order to set up the Arduino IDE to be compatible with the Beetle ESP32 Wi-Fi module and communicate the data to the Cloud and the app, the following additional tools were needed:

- USB A to mini USB B cable
- Computer with installed Arduino IDE, Ver. 1.8.11.
- Ubidots IoT Cloud Service Account
- Blynk Mobile Application

The steps required to successfully implement the functionality of the system were the following:

- The ESP32 support for the Arduino environment was installed [55].
- The “FireBeetle-ESP32” from the “Board” options was selected.
- The “PubSubClient.h” file and the “WiFi” Arduino library were included in the project [56].
- The heart rate sensor was worn on the upper side of the left wrist.
- The three ECG electrodes were attached according to Figure 10:

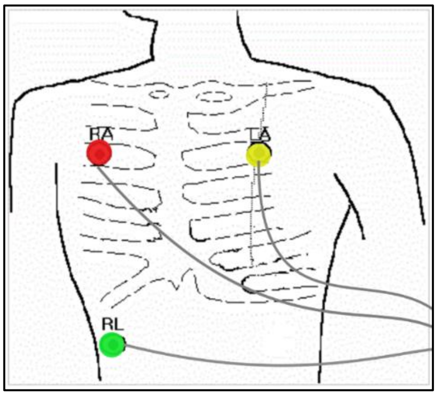


Figure 10: Attachment of ECG Electrodes

Source: Retrieved from [50]

- The Wi-Fi module was connected to the computer using the USB A to mini USB B cable.
- The main loop of the code used to implement the full functionality is shown in Appendix 4.
- In the Arduino code the WIFISSID, PASSWORD variables were replaced according to the local network and a random MQTT_CLIENT_NAME was inserted for the device.

In order to set up the Ubidots IoT Cloud environment the following steps were essential:

- A Ubidots Account was created at https://ubidots.com/.
- On the "Devices" screen, a new device was added named "esp32".
- Inside the device options, two new variables were created called "Heart-rate" and "ECG".
- Two new widgets were created, one Metric and a Double Axis graph.
- The most recent value of the "Heart-rate" variable was displayed on the Metric widget.
- The ECG Double Axis widget was linked with the "ECG" variable and it included "Time" as the x-axis and the "Amplitude" of the output voltage by the ECG sensor as the y-axis.

In order for the correct values to be displayed some changes were needed on the Arduino code:

- The Ubidots TOKEN from the Ubidots website was written to the variable in the code.
- The variable labels were specified to be the same in the code as in the Ubidots cloud.
- The device label was specified to be the same as the one in the Ubidots cloud.

Emergency notifications were set to be sent via e-mail when the heart rate of the user surpasses the 90 BPM limit, as explained in the "Theoretical Development" section.

An example of the Ubidots dashboard is shown in Figure 11:

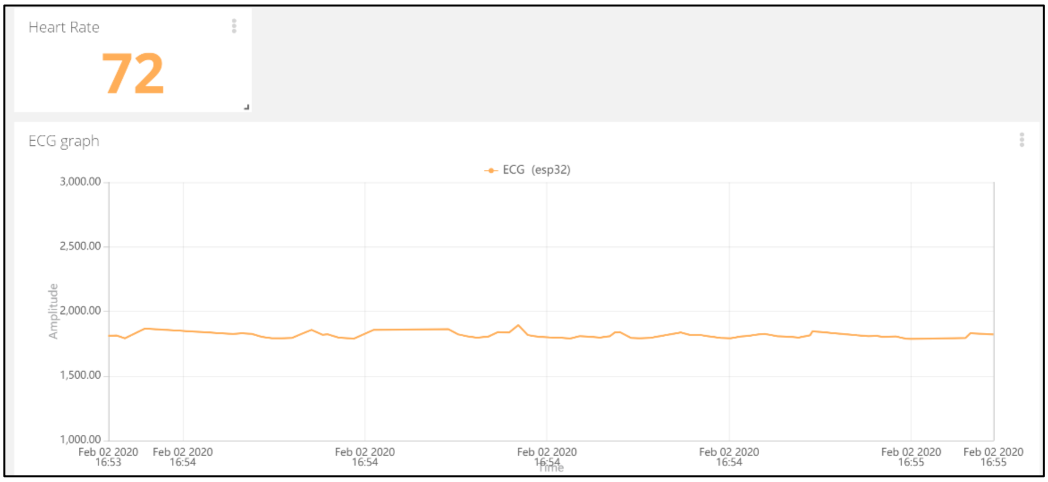


Figure 11: Example Ubidots Dashboard

In order to set up the Blynk App Development Platform the following steps were essential:

- The Blynk Mobile App was downloaded and a new project was created.
- Three new widgets were created, a Labeled Value, a SuperChart and a Notification.
- The Virtual Pins were set to be the same as in the firmware.
- A new mobile app was designed and created.

An example of the app login and main pages showing the sensor data is presented in Figure 12:

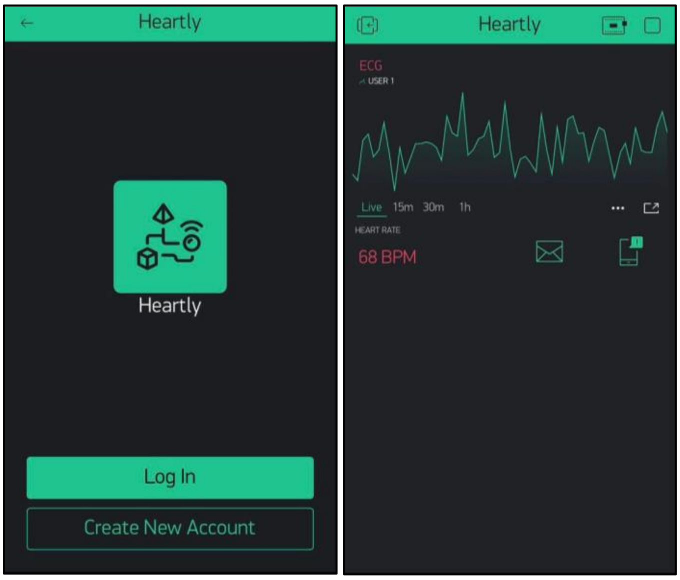


Figure 12: Example Mobile App Pages

After the successful completion of this procedure, the system was ready to take measurements from the user and communicate them for display to the IoT Cloud webpage and the mobile app.

2.2.5. Testing

Heart Rate Sensors

In order to find the most suitable heart rate sensor for this application, two sensors were tested, the DFRobot Gravity Heart Rate Monitor Sensor for Arduino and the Maxim Integrated MAXREFDES117# sensor. As a benchmark of accuracy, the Apple Watch Series 5 [28] was used.

DFRobot Gravity Heart Rate Monitor Sensor

In order to test the accuracy of this sensor, the following additional equipment was used:

- Microcontroller board (Arduino UNO, Rev3, Arduino, Italy)
- Jumper wires (Single-core)
- Computer with installed Integrated Development Environment (IDE) compatible with the microcontroller (Arduino IDE, Ver. 1.8.11, Arduino, Italy)

The following steps were followed during the testing procedure of this sensor:

- Wore on the upper side of the left wrist both the DFRobot sensor and the Apple Watch.

- Attached three wires in the connector of the DFRobot sensor as in Figure 13:

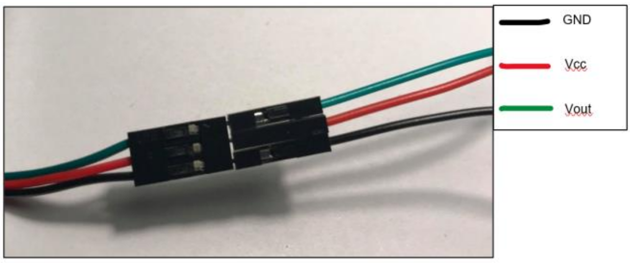


Figure 13: Attached Wires in Connector of the DFRobot Gravity Heart Rate Monitor Sensor

- Connected the DFRobot sensor with the Arduino UNO as shown in Table 7:

Table 7: Connections between Arduino UNO and the DFRobot Heart Rate Sensor

Arduino UNO	DFRobot Heart Rate Sensor
5V	Vcc
Analogue Pin A1	Vout
GND	GND

- Turned the switch on the DFRobot sensor to the “Analogue” mode.
- Downloaded the code shown in Appendix 5 to the microcontroller board.
- Turned off any light sources which could cause interference to the sensor.
- Opened the Serial Monitor on the IDE and the “Heart Rate” app on the Apple Watch.
- Recorded 1 sample per second for 80 seconds for both and input the recorded data to a spreadsheet (Microsoft Excel, Ver. 2010, Microsoft, Redmond, WA, USA).
- Repeated the process 2 times for validity.

Then the sensor’s accuracy was tested in different conditions, such as analogue and digital operation modes, above and below the wrist, with moving arm, with skin humidity and with ambient light sources. The graphs showing the outcomes are presented in the “Results” section.

MAXREFDES#117 Sensor

Using the same equipment as before, the testing procedure for this sensor was the following:

- Wore tightly on the upper side of the left wrist the Apple Watch and the sensor.
- Soldered five stranded jumper wires on the sensor’s PCB as in Figure 14:

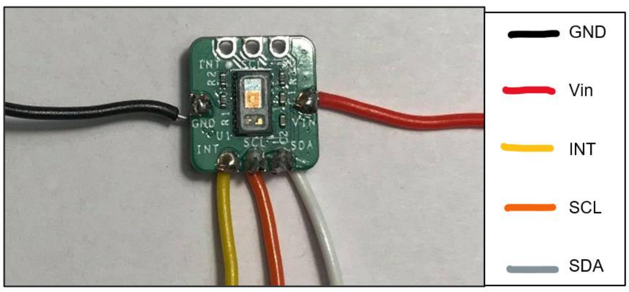


Figure 14: Soldered Wires on the MAXREFDES#117 Sensor

- Connected the MAXREFDES#117 sensor with the Arduino UNO as shown in Table 8:

Table 8: Connections between Arduino UNO and the MAXREFDES#117 Sensor

Arduino UNO	MAXREFDES#117
3.3V	Vin
GND	GND
SDA	SDA
SCL	SCL
Digital Pin 10	INT

- Downloaded the design files from the Maxim Integrated manufacturer website [57].
- Downloaded the code shown in Appendix 6 to the microcontroller board.
- Turned off any light sources which could cause interference to the sensor.
- Opened the Serial Monitor on the IDE and the "Heart Rate" app on the Apple Watch.
- Recorded 1 sample per second for 80 seconds for both and input the recorded data to the same spreadsheet.
- Repeated the process 2 times for validity.

ECG Sensor

As for the ECG sensor, there was a limited number of off-the-shelf components. For that reason, one sensor was tested, the Gravity Analog ECG sensor for Arduino. As a benchmark of accuracy, the Apple Watch was used here as well.

For testing the sensor, the same equipment was used as in the heart rate sensor testing with the addition of three biomedical sensor pads. The testing procedure included the following steps:

- Connected the biomedical pads to the electrodes and removed the plastic protection.
- Attached the electrodes on the body according to the configuration of Figure 10 and wore on the upper side of the left wrist the Apple Watch.
- Connected three wires to the pins of the sensor's connector as in Figure 15:

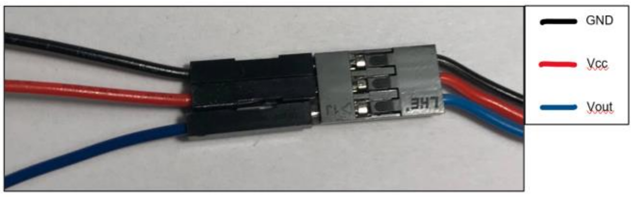


Figure 15: Attached Wires in Connector of the Gravity Analog ECG Sensor for Arduino

- Connected the ECG sensor with the Arduino UNO as shown in Table 9:

Table 9: Connections between Arduino UNO and the Gravity Analog ECG Sensor

Arduino UNO	Gravity Analog ECG Sensor
5V	Vcc
GND	GND
Analogue Pin A1	Vout

- Downloaded the sample code shown in Appendix 7 to the microcontroller board.
- Opened the Serial Plotter on the IDE and the "Heart Rate" app on the Apple Watch.
- Saved a snapshot of the recorded ECG graph from the Gravity Analog Sensor and the Apple Watch and compared the results, which are presented in the "Results" section.

Wi-Fi Modules

Two off-the-shelf Wi-Fi modules were tested to compare performance, size, cost and decide on the most suitable one for the medical bracelet. The functionality of the Wi-Fi modules was tested by transferring data from the heart rate sensor to the Ubidots IoT Cloud webpage.

ESP32-DevKitC V4 Wi-Fi module

The following additional equipment was needed:

- Prototyping board
- Heart rate sensor with three attached jumper wires as in Figure 13
- Computer with installed Arduino IDE, Ver. 1.8.11 and a USB A to mini USB B cable
- Ubidots IoT Cloud Service Account

The steps followed to test the functionality of the ESP32-DevKitC Wi-Fi module were the following:

- Installed the Arduino ESP32 support and chose the "ESP32 Dev Module" in the options.
- Connected the sensor with the Wi-Fi module on the prototyping board as in Table 10:

Table 10: Connections between the ESP32 Wi-Fi Module and the Heart Rate Sensor

ESP32 Wi-Fi module	Heart rate sensor
5V	Vcc
GND	GND
VP	Vout

- Wore on the upper side of the left wrist the heart rate sensor.
- Connected the Wi-Fi module to the computer using the USB A to mini USB B cable.
- In the Arduino code replaced the WIFISSID, PASSWORD according to the local network as well as the TOKEN from the Ubidots account and a random MQTT_CLIENT_NAME.
- Downloaded the Arduino code shown in Appendix 8 to the Wi-Fi module.
- Live update of the heart rate in BPM was shown on the Cloud webpage dashboard.

Beetle ESP32 Wi-Fi module

The same steps and code were used to test the Beetle ESP32 Wi-Fi module. The data was sent with the same efficiency as the two modules contain the same microcontroller and have similar Wi-Fi capabilities (described in the "Implementation" section). However, because the Beetle ESP32 module offers benefits in size (35 mm x 34 mm instead of 54 mm x 28 mm for the ESP32-DevKitC V4 Wi-Fi module), it is selected for the medical bracelet presented here.

2.3. Results

2.3.1. Heart Rate Sensors

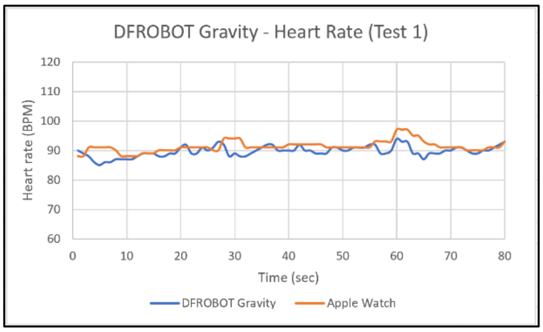
The two heart rate sensors were tested two times and their accuracy was compared to the values of the benchmark device. Then, the following accuracy metrics were calculated for comparison:

- the Mean ± Standard Deviation (SD) heart rate in BPM,
- the Pearson product-moment correlation coefficient r and
- the Mean Absolute Percentage Error (MAPE) ± SD.

These were calculated according to Equations 1-4 presented in the “Measures of Accuracy” section of the “Theoretical Development”. Following this, the selected sensor was tested under different operating conditions to examine its accuracy when compared to the benchmark device.

Selection of Heart Rate Sensor

- DFRobot Gravity Heart Rate Sensor



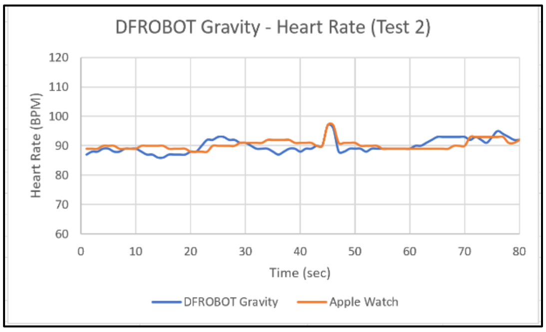
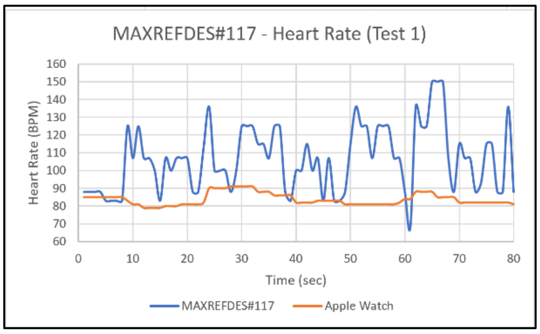


Figure 16: DFRobot – Test 1

Figure 17: DFRobot – Test 2

- MAXREFDES#117 Sensor



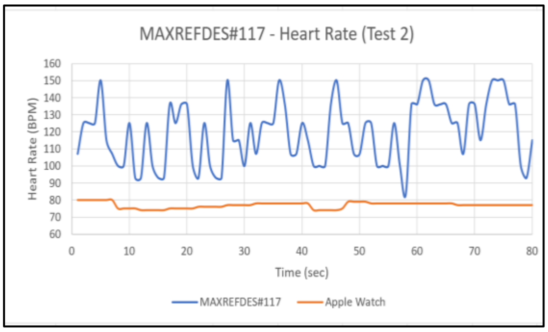


Figure 18: MAXREFDES#117 – Test 1

Figure 19: MAXREFDES#117 – Test 2

Table 11: Measures of Accuracy for the DFRobot Gravity Heart Rate Sensor

Test	Device	Mean ± SD (BPM)	Correlation Coefficient r	MAPE ± SD (%)
Test 1	Apple Watch (Benchmark)	91.3 ± 1.9	1	
	DFRobot Gravity Heart Rate Sensor	89.7 ± 1.8	0.363	-1.73 ± 2.23
Test 2	Apple Watch (Benchmark)	90.4 ± 1.7	1	
	DFRobot Gravity Heart Rate Sensor	90 ± 2.4	0.485	-0.46 ± 2.36

Table 12: Measures of Accuracy for the MAXREFDES#117 Heart Rate Sensor

Test	Device	Mean ± SD (BPM)	Correlation Coefficient r	MAPE ± SD (%)
Test 1	Apple Watch (Benchmark)	83.8 ± 3.3	1	
	MAXREFDES#117	106.3 ± 18.3	0.141	26.86 ± 21.52
Test 2	Apple Watch (Benchmark)	77 ± 1.7	1	
	MAXREFDES#117	119.2 ± 18.3	0.215	54.82 ± 23.31

Table 13: Comparison Table of the Heart Rate Sensors

Sensor	Cost	Size	Mass
DFRobot Gravity Heart Rate Sensor	£13.07	28 mm x 24 mm	300 g
MAXREFDES#117	£12.68	12.7 mm x 12.7 mm	250 g

Wrist Position

- Above Wrist

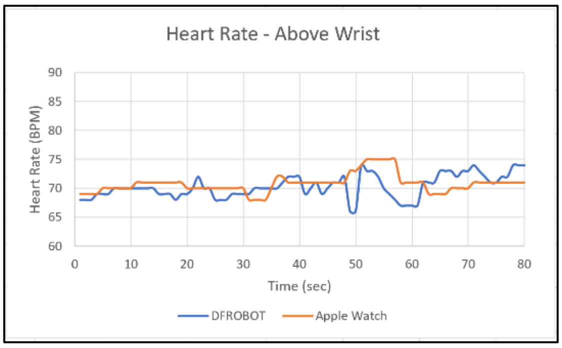


Figure 20: DFRobot – Above Wrist

- Below Wrist

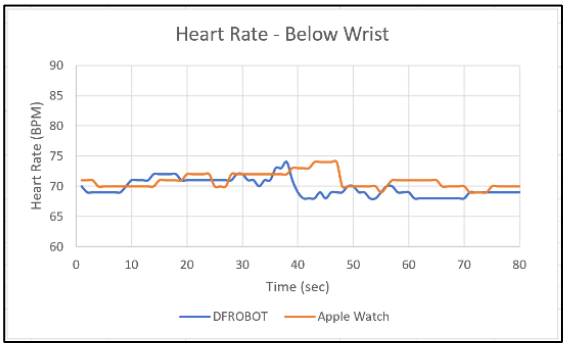


Figure 21: DFRobot – Below Wrist

Table 14: Measures of Accuracy – Wrist Position

Test	Device	Mean ± SD (BPM)	Correlation Coefficient r	MAPE ± SD (%)
Above Wrist	Apple Watch (Benchmark)	70.8 ± 1.6	1	
	DFRobot Gravity Heart Rate Sensor	70.3 ± 2	0.087	-0.68 ± 3.37
Below Wrist	Apple Watch (Benchmark)	71 ± 1.3	1	
	DFRobot Gravity Heart Rate Sensor	69.8 ± 1.5	0.156	-1.61 ± 2.45

Analogue vs Digital Mode

- Analogue

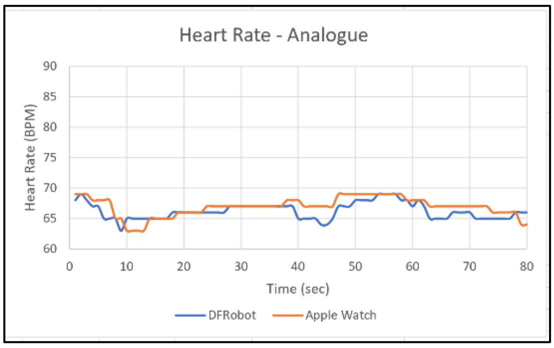


Figure 22: DFRobot - Analogue

- Digital

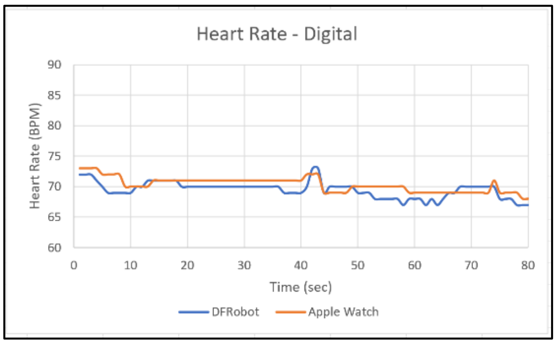


Figure 23: DFRobot – Digital

Table 15: Measures of Accuracy – Analogue vs Digital Mode

Test	Device	Mean ± SD (BPM)	Correlation Coefficient r	MAPE ± SD (%)
Analogue Mode	Apple Watch (Benchmark)	66.9 ± 1.5	1	
	DFRobot Gravity Heart Rate Sensor	66.2 ± 1.3	0.662	-1.04 ± 1.81
Digital Mode	Apple Watch (Benchmark)	70.3 ± 1.2	1	
	DFRobot Gravity Heart Rate Sensor	69.5 ± 1.3	0.641	-1.16 ± 1.52

Arm Moving

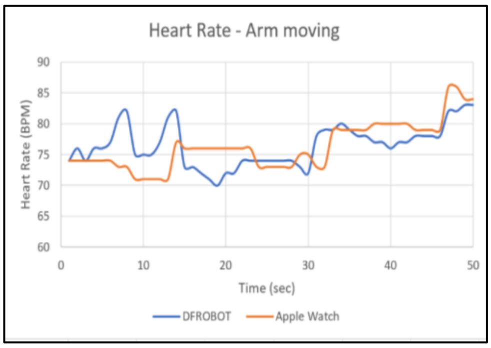


Figure 24: DFRobot – Arm Moving

Test	Device	Mean ± SD (BPM)	Correlation Coefficient r	MAPE ± SD (%)
Arm Moving	Apple Watch (Benchmark)	76.4 ± 3.8	1	
	DFRobot Gravity Heart Rate Sensor	76.5 ± 3.3	0.465	0.3 ± 5

Table 16: Measures of Accuracy – Arm Moving

Humid Skin

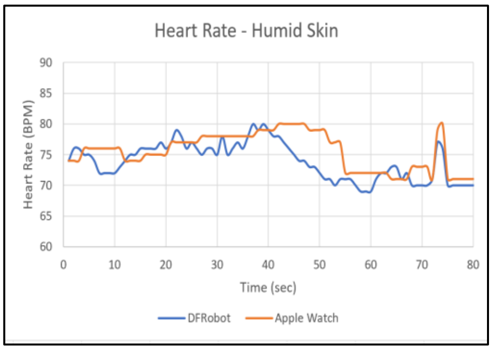


Figure 25: DFRobot – Humid Skin

Test	Device	Mean ± SD (BPM)	Correlation Coefficient r	MAPE ± SD (%)
Humid Skin	Apple Watch (Benchmark)	75.6 ± 3	1	
	DFRobot Gravity Heart Rate Sensor	74 ± 3	0.662	-2.09 ± 3.2

Table 17: Measures of Accuracy – Humid Skin

Ambient Light

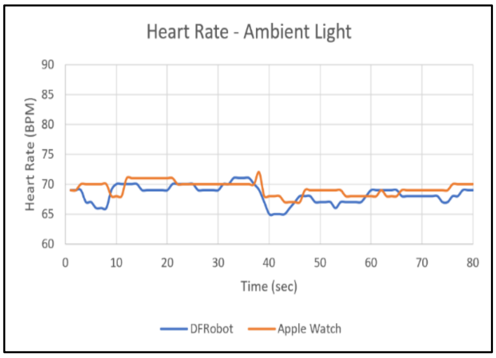


Figure 26: DFRobot – Ambient Light

Test	Device	Mean ± SD (BPM)	Correlation Coefficient r	MAPE ± SD (%)
Ambient Light	Apple Watch (Benchmark)	69.3 ± 1.1	1	
	DFRobot Gravity Heart Rate Sensor	68.3 ± 1.5	0.494	-1.42 ± 1.94

Table 18: Measures of Accuracy – Ambient Light

2.3.2. ECG Sensor

Following the assessment of the heart rate sensor, testing on the Gravity Analog ECG sensor was performed. Initially, the ECG signal produced was passed through a Dynamic Signal Analyzer (National Instruments NIELVISmx, Ver. 19.0.0, National Instruments, Austin, TX, USA):

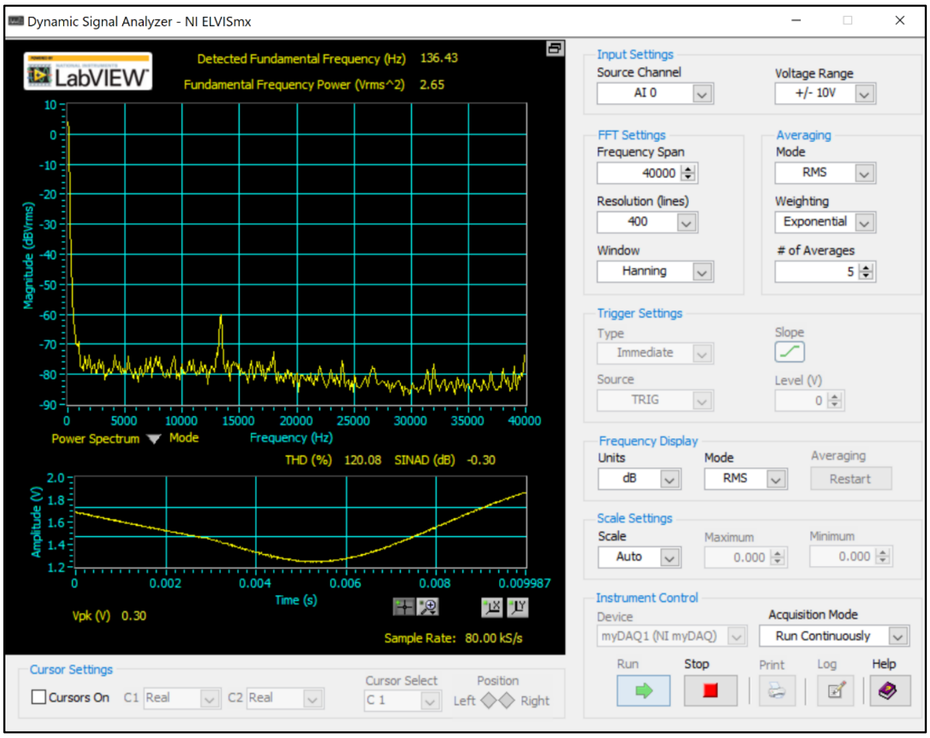


Figure 27: Dynamic Signal Analyzer Output of the ECG Signal

Afterwards, the ECG sensor was tested as explained in the “Testing” section. The comparative graphs generated by the Gravity Analog ECG sensor and the Apple Watch are shown below:

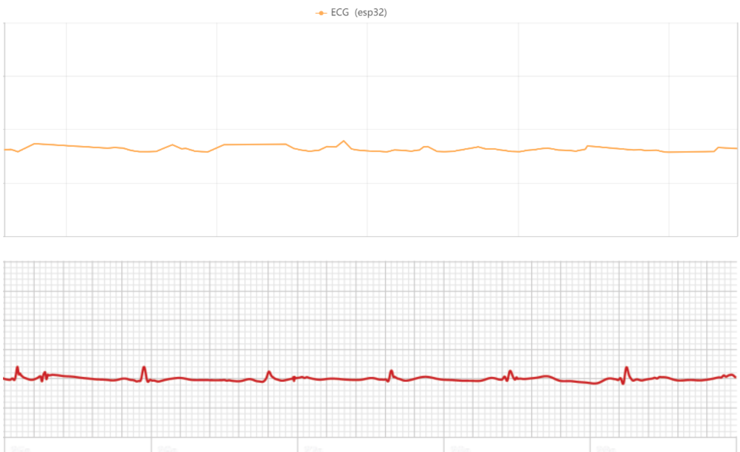


Figure 28: Comparative ECG Graphs - Gravity Sensor (yellow line) and Apple Watch (red line)

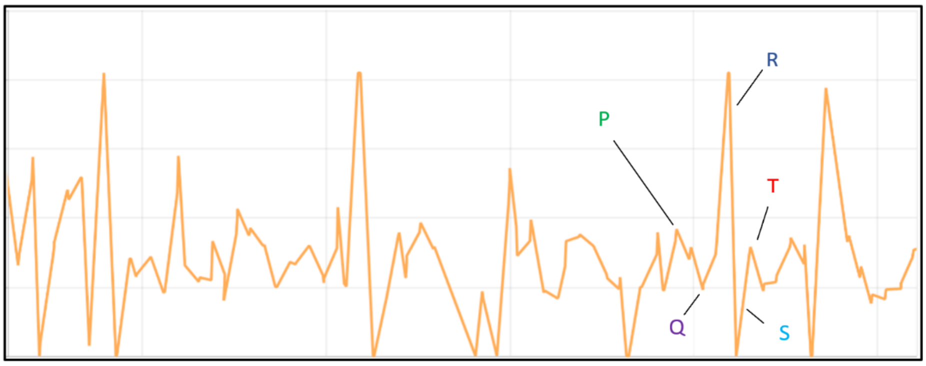


Figure 29: Deflections on the Output ECG Graph of the Gravity Analog ECG Sensor

2.4. Discussion and Analysis

2.4.1. Comments on the Results

It is obvious from Figures 16-19 that the DFRobot Gravity Heart Rate Sensor was more accurate than MAXREFDES#117. Tables 11-12 confirm that it extracted measurements which lay closer to the benchmark device, because its MAPE was -1.73% and -0.46% when compared to 26.82% and 54.82% of absolute percentage error for the MAXREFDES#117. Also, its correlation coefficients were bigger, which shows greater agreement in the points of variant heart rate with the benchmark device. Even though the MAXREFDES#117 sensor offers benefits in cost and size, as seen in Table 13, it cannot be considered a suitable sensor due to poor accuracy. Consequently, the DFRobot Gravity Heart Rate Sensor was selected.

Moreover, Figures 20, 21 and Table 14 demonstrate that the position of the bracelet does not significantly influence the measurements, thus there is no particular preference for this option. Figures 22, 23 and Table 15 illustrate that in Analogue Mode the measurements had higher correlation coefficient and lower MAPE, hence the Analogue Mode was chosen.

From Figure 24 and Table 16 it was noticed that the sensor showed accurate heart rate when the arm was moving but with unavoidable deviation at times due to movement artefacts. Also, the MAPE and the correlation coefficient proved that the sensor would operate accurately under real-life conditions. The next assessment was performed under conditions of humidity on the skin of the user. Figure 25 and Table 17 show that the sensor's measurements lay close to the benchmark's values therefore suggesting solid performance in sport activities as well.

Figure 26 and Table 18 illustrate that the sensor's sensitivity was not influenced significantly by the ambient light as it demonstrated good MAPE and correlation coefficient. Hence, it was verified that the selected heart rate sensor can perform satisfactorily in all normal operating conditions. Next, the analysis of the ECG signal on the Dynamic Signal Analyzer in Figure 27 suggested that its fundamental frequency was 136.43 Hz, which had power of 2.65 W. Furthermore, it was apparent that there was broadband noise included in the signal, which degraded the quality of the signal and resulted in Signal-to-Noise-and-Distortion-Ratio (SINAD) of -0.3 dB or 0.97 in linear scale. By using a simulation package, a single pulse of the ECG graph was filtered with low-pass filters of different cut-off frequencies in order to observe whether its shape would be improved. The results, appearing in Appendix 9, showed that because the noise was broadband the low-pass filters were not able to completely remove it as a part of the useful signal was erased as well. Consequently, a suitable adaptive filter would have a better performance, since it would be able to separate the noise and track it. Its design would be included as part of the future improvements. Additionally, the comparative ECG graphs in Figure 28 demonstrated similarities in the shape of the pulses generated by the two sensors. However, it was observed that the signal extracted by the Gravity Analog ECG sensor contained noise which prevented some pulses from being clearly visible. A closer look into the graph shows the noise present, illustrated in Figure 29, which is caused by body movement artefacts. Nevertheless, the basic deflections named PQRST of a medical ECG graph, as presented in the "Theoretical Development" section, are still visible. Overall, the results proved that the device could operate accurately under real-life conditions. Apart from the accuracy, it is useful to assess the cost of production as well. More specifically, for the integration of one unit of the medical bracelet the expenses required are shown in Table 19:

Table 19: Cost Analysis of a Single Unit

Item	Cost
Heart rate sensor	£20.91
ECG sensor	£21
ECG electrodes	£3.07
Wi-Fi module	£11.53
Battery	£5.36
Battery charger	£1.51
Switch	£2.60
PCB fabrication	£3.5
Bracelet case 3D-print	£10
Intermediate layers laser-cut fabrication	£1
Watch strap	£14
OVERALL	£94.48

The overall cost is reasonable for a medical bracelet and even though higher than some of the state-of-the-art solutions, it instead provides combined advantages of continuous monitoring and real-time communication of data to a doctor, which are not found together in the marketed products. It is also crucial to mention that in case of a measurement irregularity the information is directly displayed on the IoT Cloud webpage and the mobile app display screen, which can be used to send alerts to doctors and allow them to assess their patient's condition in real time. Most importantly, the device does not require advanced technical skills, which is useful for the older people. This is because the bracelet does not require a nearby connected device to operate and transmit the measurements. However, keeping in mind the power budget demanded by the components employed on the bracelet, the battery used allows continuous monitoring for approximately 40 minutes. It is understood that the power solution provided currently is not ideal for daily use by the patients. Therefore, one of the future improvements would be to optimize the power consumption of the electrical components and use innovative power sources with higher power output. This issue is discussed more extensively in the “Future Work” section.

2.4.2. Limitations and Possible Failings

During the testing process, there were multiple noise sources which limited the achievable accuracy of the sensors. These artefacts are likely to influence the measuring ability of the device in real-life conditions as well. For the heart rate sensor these are summarised as:

- Noise due to ambient light
- Noise due to movement of the arm

It is a fact that motion artefacts are produced because the contact point between the sensor and the skin is unstable. During the testing phase in this project all the appropriate precautions were taken to ensure the best possible accuracy of the measurements, such as shading of the surrounding area [16] and elimination of any movement of the arm. Nevertheless, the conditions will not be ideal in real-life use of the device, therefore these artefacts will influence the accuracy of the actual measurements. It is understood that these types of noise pose significant obstacles in the wearable devices industry and current research activities aim to provide solutions, such as de-noising algorithms which use adaptive filters and accelerometers to remove these artefacts [58]. On the other hand, for the ECG sensor noise sources include:

- Noise due to body movement
- Noise due to humidity of the body
- Noise due to surrounding muscle activity
- Noise due to body’s static electricity

During the testing phase, these were mitigated by absence of body’s and muscles’ movement but in real-life situations these could have a significant impact on the values measured. The inaccuracy in the measurements would also influence the decision-making algorithm of the IoT Cloud Service, as it could potentially send erroneous emergency notifications or even worse no indication of alarming condition in case of a heart irregularity. For this reason, it is critical to note that this device should not be considered a medical device at this stage of development.

2.5. Future Work

2.5.1. Reducing Size

A considerable limitation with the present design relates to the size. Even though the length and the width of the bracelet case are ideal for a wrist bracelet (48 mm x 53.5 mm), its thickness, which is 40 mm disrupts the comfort of the user. Therefore, a future improvement would be to create a custom System-on-Chip, which would integrate custom-made sensors suitable for the application with the Wi-Fi module in very limited area allowing overall reduction of the bracelet case size. The thickness of the device would ideally be cut down to 5 mm.

2.5.2. Minimising the Power Requirements and Cost

The important step of customising the design would optimise the power consumption of the components as well, because resources such as memory, ADCs and filters would be shared. As a result, the energy requirements would significantly be reduced allowing for smaller flexible batteries or even photovoltaic cells to be used [30]. Consequently, the optimisation of the technology would significantly decrease the cost of £94.48 and make it accessible to more people.

2.5.3. Increasing Accuracy

Undoubtedly, the accuracy of heart rate and ECG measurements is also a crucial feature of the device. Steps to increase accuracy would include addition of an accelerometer on the device, which would measure the rotation of the user's position and in cooperation with adaptive filters it would remove the unwanted artefacts produced due to the body's movement. Another innovative idea is the use of wireless ECG electrodes. Its implementation would allow removing the bulky wired electrodes and provide stronger attachment to the skin. These improvements would potentially boost the accuracy of the measurements to within 0.1% error (when compared to 0.46% now) and would allow the device to secure clearance or approval by the Food and Drug Administration (FDA), which recognises wearable devices that are safe to be used and provide meaningful information. Only under these circumstances should the bracelet be considered a medical device and have chances of entering the market.

2.5.4. Enhancing the Presentation of Results

Additionally, advancements in the presentation of the results would begin with the addition of an LCD screen on the bracelet case, which would display the real-time heart rate and possibly the ECG signal. This extension would also allow the users to connect to the Wi-Fi access point they wish.

Regarding the platforms that were used to display the results, they both offered significant benefits for the quick development of applications for this project, however as they are general-purpose application platforms they had limitations in the presentation of data that could be achieved. An example is related to the accuracy of the ECG graph, which could not be represented as a medical ECG measurement. Furthermore, using these it was not possible to develop applications which enabled the direct communication between doctors and patients. As a result, a custom-made webpage and an app would be developed to allow all the features to be presented accurately to both the doctors and the patients.

2.5.5. Securing the Produced Data

Finally, it would be crucial to secure the personal health data acquired by the device against any breach of information in order to protect the legal rights of the patients [12]. This would be achieved by encoding and decoding the data over the network and by developing highly protected platforms which will not compromise the privacy of the users.

2.6. Conclusion

Overall, the astonishing features of medical wearables need to be accessible to everyone, regardless of age or technological literacy. During this project, the successful development of a wearable device which provides continuous heart monitoring was achieved reinforcing the above goal. Despite the flaws of the design, including battery lifetime and size, the device demonstrated accurate measurements, effective display of the results on a webpage and a mobile app and notifications generation when heart abnormalities were detected.

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4. Appendices

<u>Statement on the effect of the pandemic on the project's progress:</u> There was no significant effect on the progress of the project due to the closure of University buildings in March and April 2020. All the planned objectives related to the practical work were achieved before the lockdown.

4.1. Appendix 1

<u>Project Technical and Organisation Risk Assessment</u>

Table 20: Project Technical and Organisation Risk Assessment

Risk Title	Risk Description	Likely Consequences	Schedule Impact	Existing Mitigation Measures in Use
Data loss or corruption	Loss of data related to the project.	Project progress impeded significantly. Also, loss of marks as a result of being unable to complete objectives.	Minor to significant depending on the amount of data lost.	Ensure all data is backed up in at least two, physically separate locations at least once per week.
Order late arrival	An order of components arrives late in the University.	Slow progression of the project. The deadlines and milestones are not met.	Minor as other tasks can be sacrificed to find additional time and make up for the late arrival.	Order placed early in the semester to allow for time flexibility.

Risk Title	Risk Description	Likely Consequences	Schedule Impact	Existing Mitigation Measures in Use
Hardware/Components Replacement	If the components ordered initially did not meet the expectations then new components will need to be found.	Slow down the progress of the project. Potentially prevent the successful delivery of objectives.	Significant as it is possible that the main aim of the project will not be met if the appropriate components are not found.	Careful research and validation of the research results on the sensors to be purchased.
New Hardware Testing	The time taken to test the new hardware purchased to replace the old components.	Slow down the progress of the project. Possible to miss deadlines and not deliver the objectives.	Significant due to the time constraints of the project.	Careful research before purchasing components.
Redesign bracelet	Redesigning the bracelet in CAD tools to fix errors and 3D-printing it again.	Delay the successful delivery of the project. Waste time that could be used in the development of the sensor or the app.	Significant due to the time constraints of the project.	Careful design with all the dimensions specified.

4.2. Appendix 2

Health and Safety Risk Assessment

Table 21: Health and Safety Risk Assessment

General Risk Assessment Form

Date: (1) 10/10/2019	Assessed by: (2) Alkinoos Sarioglou	Checked / Validated* by: (3)	Location: (4) C34 Sackville Street Building	Assessment ref no (5)	Review date: (6)
Task / premises: (7) Practical development work in student laboratory C34, Sackville Street Building					
Activity (8)	**Hazard (9)**	**Who might be harmed and how (10)**	**Existing measures to control risk (11)**	**Risk rating (12)**	**Result (13)**
Wrong use of electrical components	Component polarity wrong	Worker and all lab users Injury, Burn Component burnt, blown up, Fire	Read the instructions carefully on how to use the component	LOW	A

Date: (1)	Assessed by: (2)	Checked / Validated* by: (3)	Location: (4)	Assessment ref no (5)	Review date: (6)
10/10/2019	**Alkinoos Sarioglou**		**C34 Sackville Street Building**		

Task / premises: (7)

Practical development work in student laboratory C34, Sackville Street Building

Activity (8)	**Hazard** (9)	**Who might be harmed and how** (10)	**Existing measures to control risk** (11)	**Risk rating** (12)	**Result** (13)
Use of electrical equipment	Electric shock or fire	Worker and all lab users Severe Injury or death	All equipment used in the laboratory is tested beforehand for correct functionality and is used according to the manufacturer's instructions	LOW	A
Measurements – low voltage (<30V DC)	Electric shock, Components overheating, Skin burn	Worker and all lab users Severe Injury or death	Caution on first power-up, Limit supply current, Avoid close visual inspection of circuits not validated to be working correctly, Avoid touching components which could overheat, Ensure measurement probes are attached before power-up	LOW	A
Soldering	Skin burn, Breath irritation	Worker and all lab users Skin burn or Injury	Turn on the fume extractor, take extra care when soldering components not to come in contact with the soldering lead	LOW	A

Date: (1) 10/10/2019	Assessed by: (2) Alkinoos Sarioglou	Checked / Validated* by: (3)	Location: (4) C34 Sackville Street Building	Assessment ref no (5)	Review date: (6)
Task / premises: (7) Practical development work in student laboratory C34, Sackville Street Building					

Activity (8)	Hazard (9)	Who might be harmed and how (10)	Existing measures to control risk (11)	Risk rating (12)	Result (13)
Moving around the laboratory	Fall Tripping on laboratory equipment	Worker and other lab users Injury	Careful arrangement of lab equipment Personal belongings stored in specific rooms	LOW	A
Working on computer	Eye irritation, Back pain	Worker Injury, Sight decline	Take regular break off the screen and take care to keep a good posture using a good desk chair	LOW	A
Food and Drink	Electric shock, Toxic contamination	Worker Poisoned by food	No food to be consumed in the lab	LOW	A
Use of hand tools	Sharp tools	Worker Cut, Eye injuries	Correct tools are used for the specific activity Use PPE for extra safety	LOW	A

4.3. Appendix 3

Schematic diagram and electrical connections between the system components

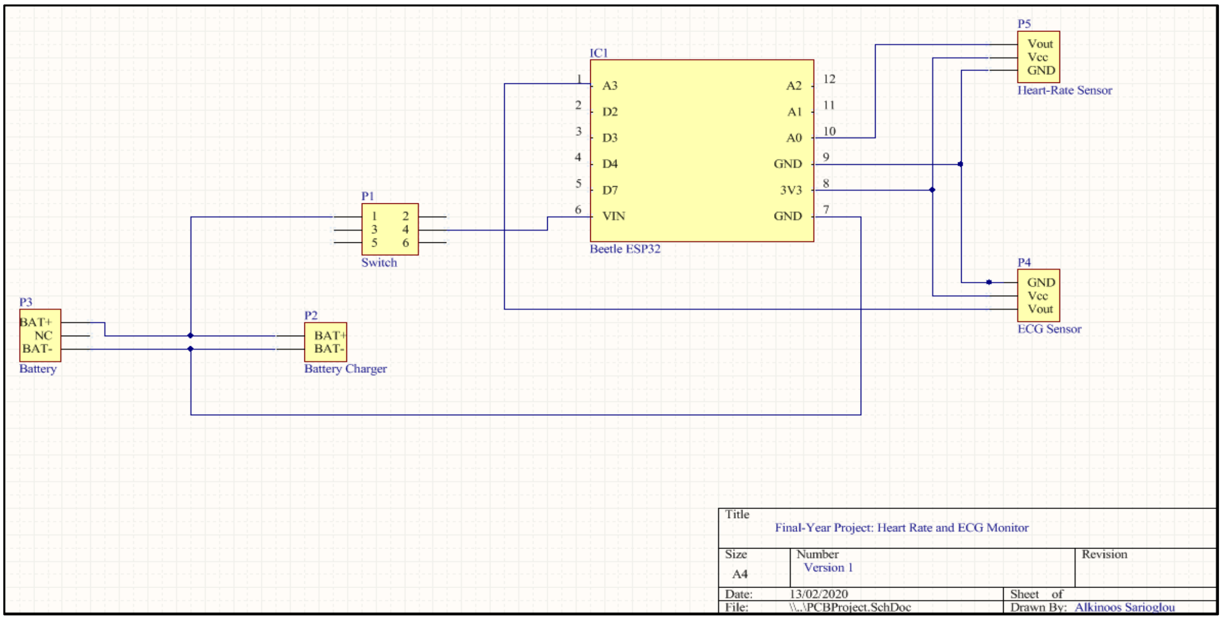

Figure 30: Schematic Diagram

The schematic diagram in Figure 30 was designed using a PCB design automation package (Altium Designer, Version 20, Altium, California, USA). Table 22 shows the electrical connections required:

Table 22: Electrical Connections between System Components

Wi-Fi module	Heart rate sensor
3.3V	Vcc
GND	GND
Analogue Pin A0	Vout
Wi-Fi module	**ECG sensor**
3.3V	Vcc
GND	GND
Analogue Pin A3	Vout
Wi-Fi module	**Battery**
VIN	BAT+
GND	BAT-
Battery Charger	**Battery**
BAT+	BAT+
BAT-	BAT-

4.4. Appendix 4

Code for full system functionality

```
/*!

  This program collects the Heart-rate and ECG data and communicates them
  to the Ubidots IoT Cloud Service Webpage and to the Blynk Mobile App

  CREDITS TO:
  @author linfeng(Musk.lin@dfrobot.com)
  Copyright (C) <2015>  <linfeng>
The code of the above person was taken and modified to fit the needs of
the Final-Year project of Alkinoos Sarioglou
  CREDITS TO:
  Blynk is a platform with iOS and Android apps to control
  Arduino, Raspberry Pi and the likes over the Internet.
  You can easily build graphic interfaces for all your
  projects by simply dragging and dropping widgets.
  Blynk library is licensed under MIT license
  This example code is in public domain.
  /**************************************************************
  Download latest Blynk library here:
  https://github.com/blynkkk/blynk-library/releases/latest
 **************************************************************/

/****************************************
   Wi-Fi ESP32
 ****************************************/

#include <WiFi.h>
#include <PubSubClient.h>
/* Comment this out to disable prints and save space */
#define BLYNK_PRINT Serial
#include <WiFi.h>
#include <WiFiClient.h>
#include <BlynkSimpleEsp32.h>
#define WIFISSID "********" // Put your WifiSSID here
#define PASSWORD "********" // Put your wifi password here
#define TOKEN   "********" // Put your Ubidots' TOKEN
#define MQTT_CLIENT_NAME "bracelet" // MQTT client Name, please enter
your own 8-12 alphanumeric character ASCII string;
//it should be a random and unique ascii string and different from all
other devices
// You should get Auth Token in the Blynk App.
// Go to the Project Settings (nut icon).
char auth[] = "********";
float ecg_data;
int heart_rate_data;
/****************************************
   Define Constants
 ****************************************/
#define VARIABLE_LABEL "sensor" // Assing the variable label
#define DEVICE_LABEL "esp32" // Assig the device label
// https://industrial.api.ubidots.com/api/v1.6/devices/?type=heartly
char mqttBroker[]  = "industrial.api.ubidots.com";
char payload[100];
```

```
char topic[150];
// Space to store values to send
char str_sensor[10];
#define VARIABLE_LABEL_ECG "ecg-sensor" // Assing the variable label
#define SENSOR 35 // Set the A3/IO35 as SENSOR
BlynkTimer timer;
bool turn = true;
uint8_t rateValue;
/****************************************
   Auxiliar Functions
 ****************************************/
WiFiClient ubidots;
PubSubClient client(ubidots);
/****************************************
   Heart - Rate sensor
 ****************************************/
#define heartratePin 36
#include "DFRobot_Heartrate.h"
DFRobot_Heartrate heartrate(ANALOG_MODE); ///< ANALOG_MODE or
DIGITAL_MODE
/****************************************
   Functions
 ****************************************/
void callback(char* topic, byte* payload, unsigned int length) {
  char p[length + 1];
  memcpy(p, payload, length);
  p[length] = NULL;
  Serial.write(payload, length);
  Serial.println(topic);
}
void reconnect() {
  // Loop until we're reconnected
  while (!client.connected()) {
    Serial.println("Attempting MQTT connection...");
    // Attemp to connect
    if (client.connect(MQTT_CLIENT_NAME, TOKEN, "")) {
      Serial.println("Connected");
    } else {
      Serial.print("Failed, rc=");
      Serial.print(client.state());
      Serial.println(" try again in 2 seconds");
      // Wait 2 seconds before retrying
      delay(2000);
    }
  }
}
/* ECG Data  */
// This function sends Arduino's up time every second to Virtual Pin (5).
// In the app, Widget's reading frequency should be set to PUSH. This
means
// that you define how often to send data to Blynk App.
void myTimerEvent()
{
  // You can send any value at any time.
  // Please don't send more that 10 values per second.
  ecg_data =  analogRead(SENSOR); // Read ECG Data
  if (rateValue)  heart_rate_data = rateValue;    // Read Heart Rate Data
  Blynk.virtualWrite(V5, ecg_data); // Send ECG Data
```

```
  Blynk.virtualWrite(V3, heart_rate_data); // Send Heart Rate Data
}
/***************************************
   Main Functions
 ***************************************/
void setup() {
  Serial.begin(115200);
  WiFi.begin(WIFISSID, PASSWORD);
  Blynk.begin(auth, WIFISSID, PASSWORD);
  // Setup a function to be called every second for sending the values to
the Mobile App
  timer.setInterval(300L, myTimerEvent);
  // Assign the pin as INPUT
  pinMode(heartratePin, INPUT);
  pinMode(SENSOR, INPUT);
  Serial.println();
  Serial.print("Waiting for WiFi...");
  while (WiFi.status() != WL_CONNECTED) {
    Serial.print(".");
    delay(500);
  }
  Serial.println("");
  Serial.println("WiFi Connected");
  Serial.println("IP address: ");
  Serial.println(WiFi.localIP());
  client.setServer(mqttBroker, 1883);
  client.setCallback(callback);
}
void loop() {
  if (!client.connected()) {
    reconnect();
  }
  Blynk.run();
  timer.run(); // Initiates BlynkTimer, running timer every second
  if (turn == true) {
    sprintf(topic, "%s%s", "/v1.6/devices/", DEVICE_LABEL);
    sprintf(payload, "%s", ""); // Cleans the payload
    sprintf(payload, "{\"%s\":", VARIABLE_LABEL); // Adds the variable
label
    heartrate.getValue(heartratePin); ///< A1 foot sampled values
    rateValue = heartrate.getRate(); ///< Get heart rate value
    if (rateValue)  {
      Serial.println(rateValue);
      dtostrf((float)rateValue, 4, 0, str_sensor);
      sprintf(payload, "%s {\"value\": %s}}", payload, str_sensor); //
Adds the value
      Serial.println("Publishing BPM data to Ubidots Cloud");
      turn = false;
      client.publish(topic, payload);
      client.loop();
    }
    delay(20);
  }
  else if (turn == false) {
    sprintf(topic, "%s%s", "/v1.6/devices/", DEVICE_LABEL);
    sprintf(payload, "%s", ""); // Cleans the payload
    sprintf(payload, "{\"%s\":", VARIABLE_LABEL_ECG); // Adds the
variable label
```

```
    float sensor = analogRead(SENSOR);
    /* 4 is mininum width, 2 is precision; float value is copied onto
str_sensor*/
    dtostrf(sensor, 4, 2, str_sensor);
    sprintf(payload, "%s {\"value\": %s}}", payload, str_sensor); // Adds
the value
    Serial.println("Publishing ECG data to Ubidots Cloud");
    turn = true;
    client.publish(topic, payload);
    client.loop();
    delay(10);
  }
}
/*********************************************************************
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  Contact: Musk.lin@dfrobot.com
**********************************************************************/
```

4.5. Appendix 5

Code for testing the DFRobot Gravity Heart Rate Sensor with the Arduino UNO

```
/*!

  This program tests the functionality of the Gravity Heart Rate Sensor
with the Arduino UNO

  CREDITS TO:
  @author linfeng(Musk.lin@dfrobot.com)
  Copyright (C) <2015>  <linfeng>
  The code of the above person was taken and modified to fit the needs of
the Final-Year project of Alkinoos Sarioglou */

#define heartratePin A3
#include "DFRobot_Heartrate.h"

DFRobot_Heartrate heartrate(ANALOG_MODE); ///< ANALOG_MODE or
DIGITAL_MODE

void setup() {
  Serial.begin(115200);
}


void loop() {
  uint8_t rateValue;
  heartrate.getValue(heartratePin); ///< A1 foot sampled values
```

```
  rateValue = heartrate.getRate(); ///< Get heart rate value
  if(rateValue)  {
    Serial.println(rateValue);
  }
  delay(20);
}

/******************************************************************
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  it under the terms of the GNU General Public License as published by
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  You should have received a copy of the GNU General Public License
  along with this program.  If not, see <http://www.gnu.org/licenses/>.
  Contact: Musk.lin@dfrobot.com
 ******************************************************************/
```

4.6. Appendix 6

<u>Code for testing the MAXREFDES#117 Heart Rate Sensor with Arduino UNO</u>

```
/******************************************************************

* This program takes the heart rate data from the MAXREFDES#117 Heart
Rate Sensor

* The code below was taken and modified to fit the needs of the Final-
Year project of Alkinoos Sarioglou

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* ownership rights.
****************************************************************/

#include <Arduino.h>
#include "algorithm.h"
#include "max30102.h"

//if Adafruit Flora development board is chosen, include NeoPixel library
and define an NeoPixel object
#if defined(ARDUINO_AVR_FLORA8)
#include "adafruit_neopixel.h"
#define BRIGHTNESS_DIVISOR 8  //to lower the max brightness of the
neopixel LED
Adafruit_NeoPixel LED = Adafruit_NeoPixel(1, 8, NEO_GRB + NEO_KHZ800);
#endif

#define MAX_BRIGHTNESS 255

#if defined(ARDUINO_AVR_UNO)
//Arduino Uno doesn't have enough SRAM to store 100 samples of IR led
data and red led data in 32-bit format
//To solve this problem, 16-bit MSB of the sampled data will be
truncated.  Samples become 16-bit data.
uint16_t aun_ir_buffer[100]; //infrared LED sensor data
uint16_t aun_red_buffer[100];  //red LED sensor data
#else
uint32_t aun_ir_buffer[100]; //infrared LED sensor data
uint32_t aun_red_buffer[100];  //red LED sensor data
#endif
int32_t n_ir_buffer_length; //data length
int32_t n_spo2;  //SPO2 value
int8_t ch_spo2_valid;  //indicator to show if the SPO2 calculation is
valid
int32_t n_heart_rate; //heart rate value
int8_t  ch_hr_valid;  //indicator to show if the heart rate calculation
is valid
uint8_t uch_dummy;

// the setup routine runs once when you press reset:
void setup() {

#if defined(ARDUINO_AVR_LILYPAD_USB)
  pinMode(13, OUTPUT);  //LED output pin on Lilypad
#endif

#if defined(ARDUINO_AVR_FLORA8)
  //Initialize the LED
  LED.begin();
  LED.show();
#endif

  maxim_max30102_reset(); //resets the MAX30102
  // initialize serial communication at 115200 bits per second:
```

```
  Serial.begin(115200);
  pinMode(10, INPUT);  //pin D10 connects to the interrupt output pin of
the MAX30102
  delay(1000);
  maxim_max30102_read_reg(REG_INTR_STATUS_1,&uch_dummy);  //Reads/clears
the interrupt status register
  while(Serial.available()==0)  //wait until user presses a key
  {
    Serial.write(27);       // ESC command
    Serial.print(F("[2J"));    // clear screen command
#if defined(ARDUINO_AVR_LILYPAD_USB)
    Serial.println(F("Lilypad"));
#endif
#if defined(ARDUINO_AVR_FLORA8)
    Serial.println(F("Adafruit Flora"));
#endif
    Serial.println(F("Press any key to start conversion"));
    delay(1000);
  }
  uch_dummy=Serial.read();
  maxim_max30102_init();  //initialize the MAX30102
}

// the loop routine runs over and over again forever:
void loop() {
  uint32_t un_min, un_max, un_prev_data, un_brightness;  //variables to
calculate the on-board LED brightness that reflects the heartbeats
  int32_t i;
  float f_temp;

  un_brightness=0;
  un_min=0x3FFFF;
  un_max=0;

  n_ir_buffer_length=100;  //buffer length of 100 stores 4 seconds of
samples running at 25sps

  //read the first 100 samples, and determine the signal range
  for(i=0;i<n_ir_buffer_length;i++)
  {
    while(digitalRead(10)==1);  //wait until the interrupt pin asserts
    maxim_max30102_read_fifo((aun_red_buffer+i), (aun_ir_buffer+i));
//read from MAX30102 FIFO

    if(un_min>aun_red_buffer[i])
      un_min=aun_red_buffer[i];  //update signal min
    if(un_max<aun_red_buffer[i])
      un_max=aun_red_buffer[i];  //update signal max
    Serial.print(F("red="));
    Serial.print(aun_red_buffer[i], DEC);
    Serial.print(F(", ir="));
    Serial.println(aun_ir_buffer[i], DEC);
  }
  un_prev_data=aun_red_buffer[i];
  //calculate heart rate and SpO2 after first 100 samples (first 4
seconds of samples)
```

```
  maxim_heart_rate_and_oxygen_saturation(aun_ir_buffer,
n_ir_buffer_length, aun_red_buffer, &n_spo2, &ch_spo2_valid,
&n_heart_rate, &ch_hr_valid);

  //Continuously taking samples from MAX30102.  Heart rate and SpO2 are
calculated every 1 second
  while(1)
  {
    i=0;
    un_min=0x3FFFF;
    un_max=0;

    //dumping the first 25 sets of samples in the memory and shift the
last 75 sets of samples to the top
    for(i=25;i<100;i++)
    {
      aun_red_buffer[i-25]=aun_red_buffer[i];
      aun_ir_buffer[i-25]=aun_ir_buffer[i];

      //update the signal min and max
      if(un_min>aun_red_buffer[i])
        un_min=aun_red_buffer[i];
      if(un_max<aun_red_buffer[i])
        un_max=aun_red_buffer[i];
    }

    //take 25 sets of samples before calculating the heart rate.
    for(i=75;i<100;i++)
    {
      un_prev_data=aun_red_buffer[i-1];
      while(digitalRead(10)==1);
      digitalWrite(9, !digitalRead(9));
      maxim_max30102_read_fifo((aun_red_buffer+i), (aun_ir_buffer+i));

      //calculate the brightness of the LED
      if(aun_red_buffer[i]>un_prev_data)
      {
        f_temp=aun_red_buffer[i]-un_prev_data;
        f_temp/=(un_max-un_min);
        f_temp*=MAX_BRIGHTNESS;
        f_temp=un_brightness-f_temp;
        if(f_temp<0)
          un_brightness=0;
        else
          un_brightness=(int)f_temp;
      }
      else
      {
        f_temp=un_prev_data-aun_red_buffer[i];
        f_temp/=(un_max-un_min);
        f_temp*=MAX_BRIGHTNESS;
        un_brightness+=(int)f_temp;
        if(un_brightness>MAX_BRIGHTNESS)
          un_brightness=MAX_BRIGHTNESS;
      }
#if defined(ARDUINO_AVR_LILYPAD_USB)
      analogWrite(13, un_brightness);
#endif
```

```
#if defined(ARDUINO_AVR_FLORA8)
      LED.setPixelColor(0, un_brightness/BRIGHTNESS_DIVISOR, 0, 0);
      LED.show();
#endif

      Serial.print(F(", HR= "));
      Serial.print(n_heart_rate, DEC);

      Serial.print(F(", HRvalid="));
      Serial.print(ch_hr_valid, DEC);

      Serial.print("\n");

    }
    maxim_heart_rate_and_oxygen_saturation(aun_ir_buffer,
n_ir_buffer_length, aun_red_buffer, &n_spo2, &ch_spo2_valid,
&n_heart_rate, &ch_hr_valid);
    delay(300);
  }
}
```

4.7. Appendix 7

<u>Code for testing the Gravity Analog ECG Sensor with the Arduino UNO</u>

```
/*!
* This program takes the ECG data from the Gravity Analog ECG Sensor
* The code below was taken and modified to fit the needs of the Final-
Year project of Alkinoos Sarioglou
* @file HeartRateMonitor.ino
* @brief HeartRateMonitor.ino  Sampling and ECG output
*  Real-time sampling and ECG output
* @author linfeng(490289303@qq.com)
* @version  V1.0
* @date  2016-4-5
*/
const int heartPin = A1;
void setup() {
  Serial.begin(115200);
}
void loop() {
int heartValue = analogRead(heartPin);
Serial.println(heartValue);
delay(100);
}
```

4.8. Appendix 8

<u>Code for testing the ESP32-DevKitC Wi-Fi module</u>

```
/*!
  This program collects the Heart-rate data and communicates them to the
Ubidots IoT Cloud Service webpage using the ESP32-DevKitC Wi-Fi module
  CREDITS TO:
  @author linfeng(Musk.lin@dfrobot.com)
  Copyright (C) <2015>  <linfeng>
  The code of the above person was taken and modified to fit the needs of
the Final-Year project of Alkinoos Sarioglou
*/
/******************************
 * Wi-Fi ESP32
 ******************************/
#include <WiFi.h>
#include <PubSubClient.h>
#define WIFISSID "********" // Put your WifiSSID here
#define PASSWORD "********" // Put your wifi password here
#define TOKEN   "********" // Put your Ubidots' TOKEN
#define MQTT_CLIENT_NAME "bracelet" // MQTT client Name, please enter
your own 8-12 alphanumeric character ASCII string;
/****************************************
 * Define Constants
 ****************************************/
#define VARIABLE_LABEL "sensor" // Assing the variable label
#define DEVICE_LABEL "esp32" // Assig the device label
char mqttBroker[]  = "industrial.api.ubidots.com";
char payload[100];
char topic[150];
// Space to store values to send
char str_sensor[10];
#define VARIABLE_LABEL_ECG "ecg-sensor" // Assing the variable label
#define SENSOR A0 // Set the A0 as SENSOR
bool turn = true;
/****************************************
 * Auxiliar Functions
 ****************************************/
WiFiClient ubidots;
```

```
PubSubClient client(ubidots);
/**************************************
 * Heart - Rate sensor
 **************************************/
#define heartratePin A3
#include "DFRobot_Heartrate.h"
DFRobot_Heartrate heartrate(ANALOG_MODE); ///< ANALOG_MODE or
DIGITAL_MODE
/**************************************
 * Functions
 **************************************/
void callback(char* topic, byte* payload, unsigned int length) {
  char p[length + 1];
  memcpy(p, payload, length);
  p[length] = NULL;
  Serial.write(payload, length);
  Serial.println(topic);
}
void reconnect() {
  // Loop until we're reconnected
  while (!client.connected()) {
    Serial.println("Attempting MQTT connection...");
    // Attemp to connect
    if (client.connect(MQTT_CLIENT_NAME, TOKEN, "")) {
      Serial.println("Connected");
    } else {
      Serial.print("Failed, rc=");
      Serial.print(client.state());
      Serial.println(" try again in 2 seconds");
      // Wait 2 seconds before retrying
      delay(2000);
    }
  }
}
/***************************************
 * Main Functions
 ***************************************/
void setup() {
  Serial.begin(115200);
```

```
  WiFi.begin(WIFISSID, PASSWORD);
  // Assign the pin as INPUT
  pinMode(heartratePin, INPUT);
  Serial.println();
  Serial.print("Waiting for WiFi...");
  while (WiFi.status() != WL_CONNECTED) {
    Serial.print(".");
    delay(500);
  }
  Serial.println("");
  Serial.println("WiFi Connected");
  Serial.println("IP address: ");
  Serial.println(WiFi.localIP());
  client.setServer(mqttBroker, 1883);
  client.setCallback(callback);
}
void loop() {
  if (!client.connected()) {
    reconnect();
  }
  if (turn == true){
      sprintf(topic, "%s%s", "/v1.6/devices/", DEVICE_LABEL);
      sprintf(payload, "%s", ""); // Cleans the payload
      sprintf(payload, "{\"%s\":", VARIABLE_LABEL); // Adds the variable
label
      uint8_t rateValue;
      heartrate.getValue(heartratePin); ///< A1 foot sampled values
      rateValue = heartrate.getRate(); ///< Get heart rate value
      if(rateValue)  {
        Serial.println(rateValue);
        dtostrf((float)rateValue, 4, 0, str_sensor);
        sprintf(payload, "%s {\"value\": %s}}", payload, str_sensor); //
Adds the value
        Serial.println("Publishing BPM data to Ubidots Cloud");
        turn = false;
        client.publish(topic, payload);
        client.loop();
      }
      delay(20);
```

```
  }
  else if (turn == false) {
      sprintf(topic, "%s%s", "/v1.6/devices/", DEVICE_LABEL);
      sprintf(payload, "%s", ""); // Cleans the payload
      sprintf(payload, "{\"%s\":", VARIABLE_LABEL_ECG); // Adds the
variable label
      float sensor = analogRead(SENSOR);
      /* 4 is mininum width, 2 is precision; float value is copied onto
str_sensor*/
      dtostrf(sensor, 4, 2, str_sensor);
      sprintf(payload, "%s {\"value\": %s}}", payload, str_sensor); //
Adds the value
      Serial.println("Publishing ECG data to Ubidots Cloud");
      turn = true;
      client.publish(topic, payload);
      client.loop();
      delay(100);
  }
}
/*****************************************************************
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  Contact: Musk.lin@dfrobot.com
 *****************************************************************/
```

4.9. Appendix 9

Simulation output graphs from filtering an ECG pulse with different low-pass filters

- Original Signal

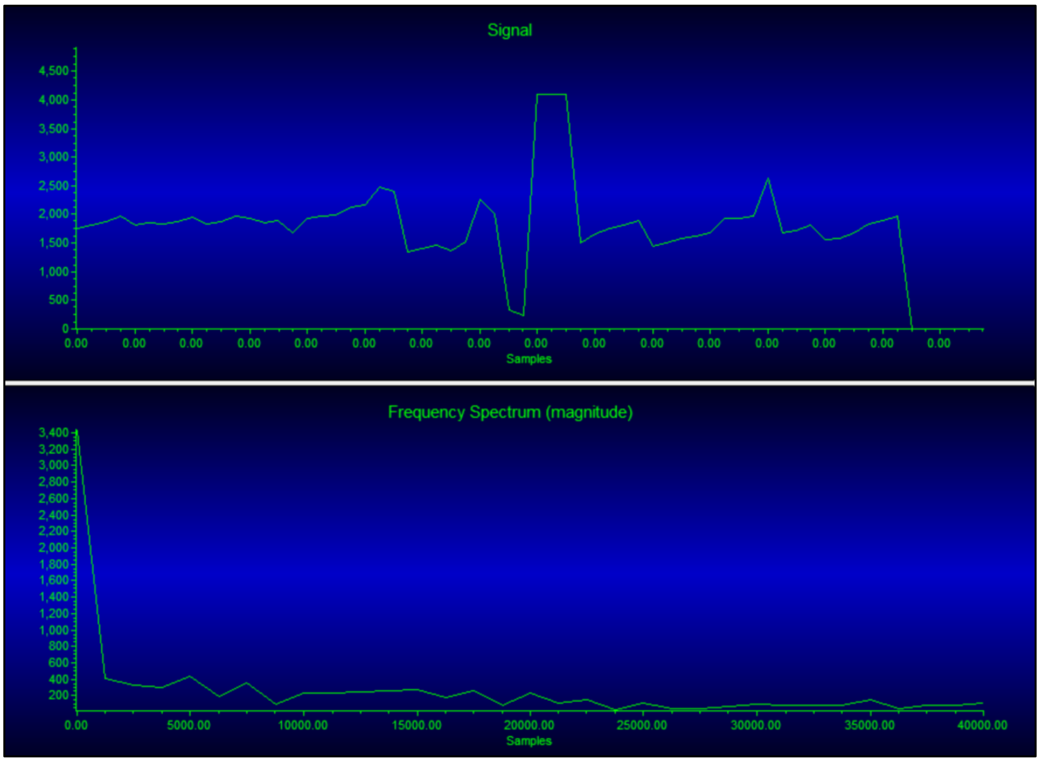

Figure 31: Original ECG Pulse

- Low-pass filter with cut-off frequency of 10 kHz

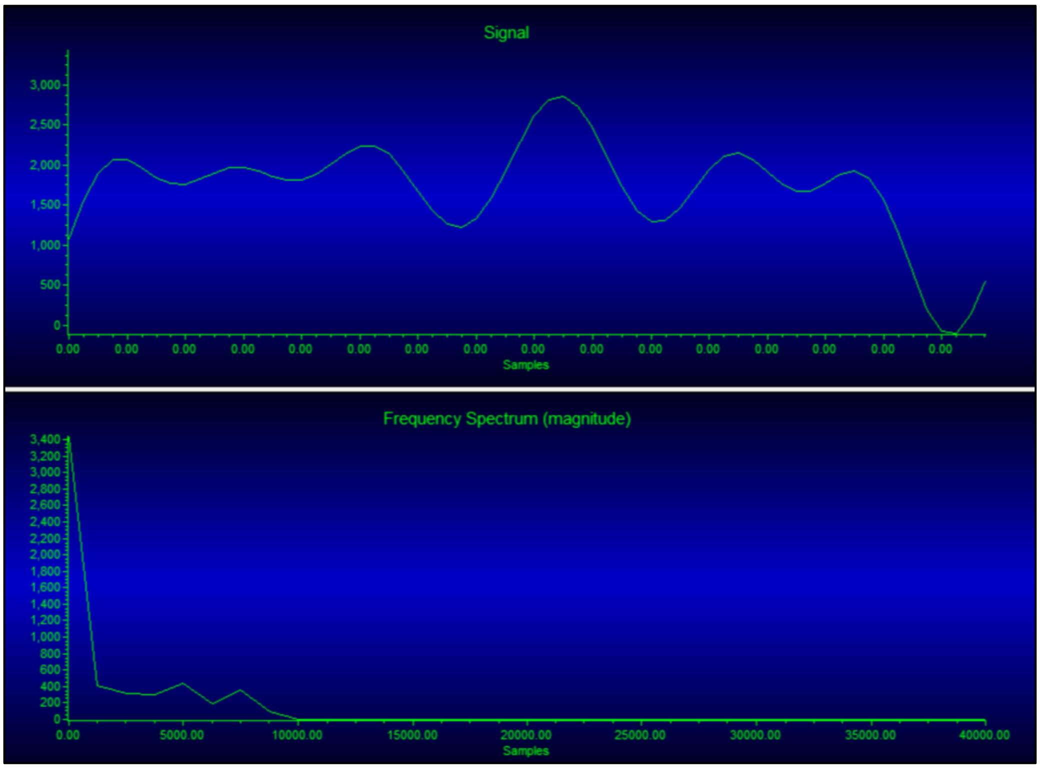

Figure 32: Low-Pass Filter – 10 kHz

- Low-pass filter with cut-off frequency of 15 kHz

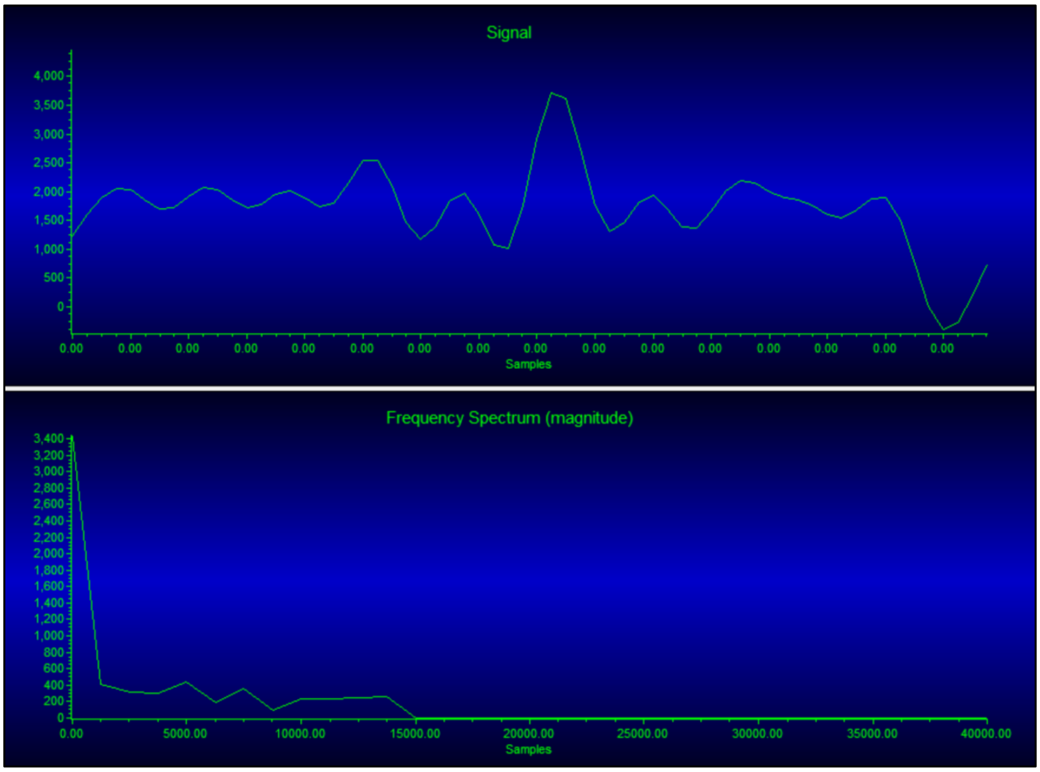

Figure 33: Low-Pass Filter – 15 kHz

- Low-pass filter with cut-off frequency of 20 kHz

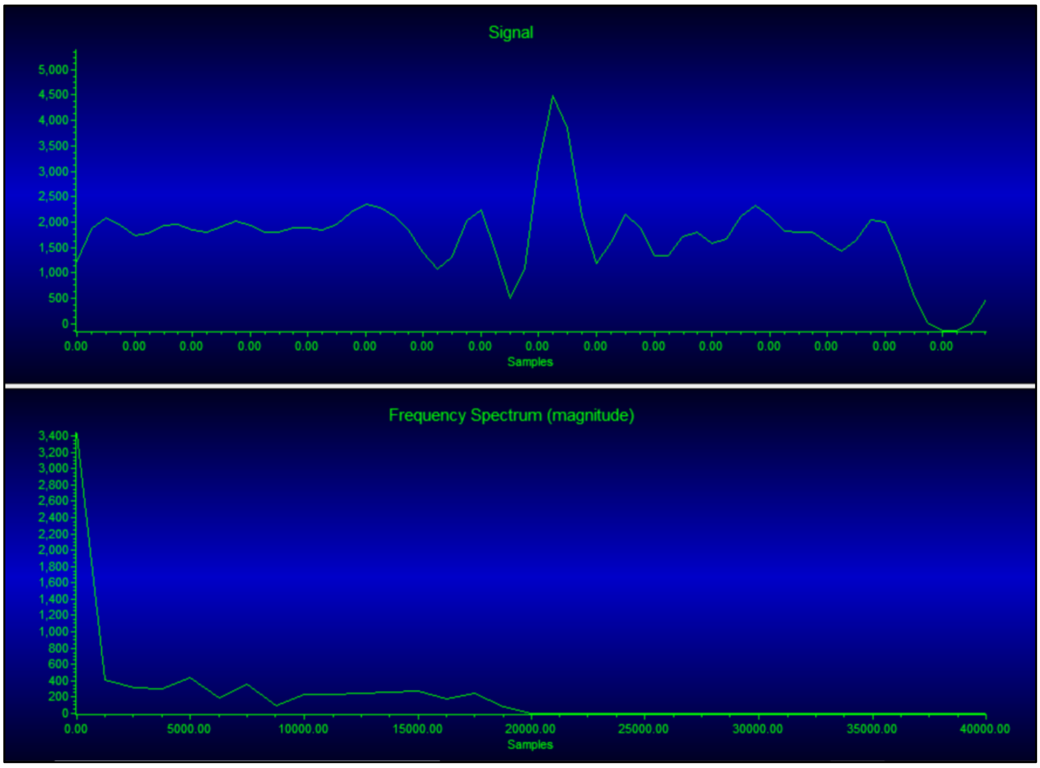

Figure 34: Low-Pass Filter – 20 kHz

- Low-pass filter with cut-off frequency of 25 kHz

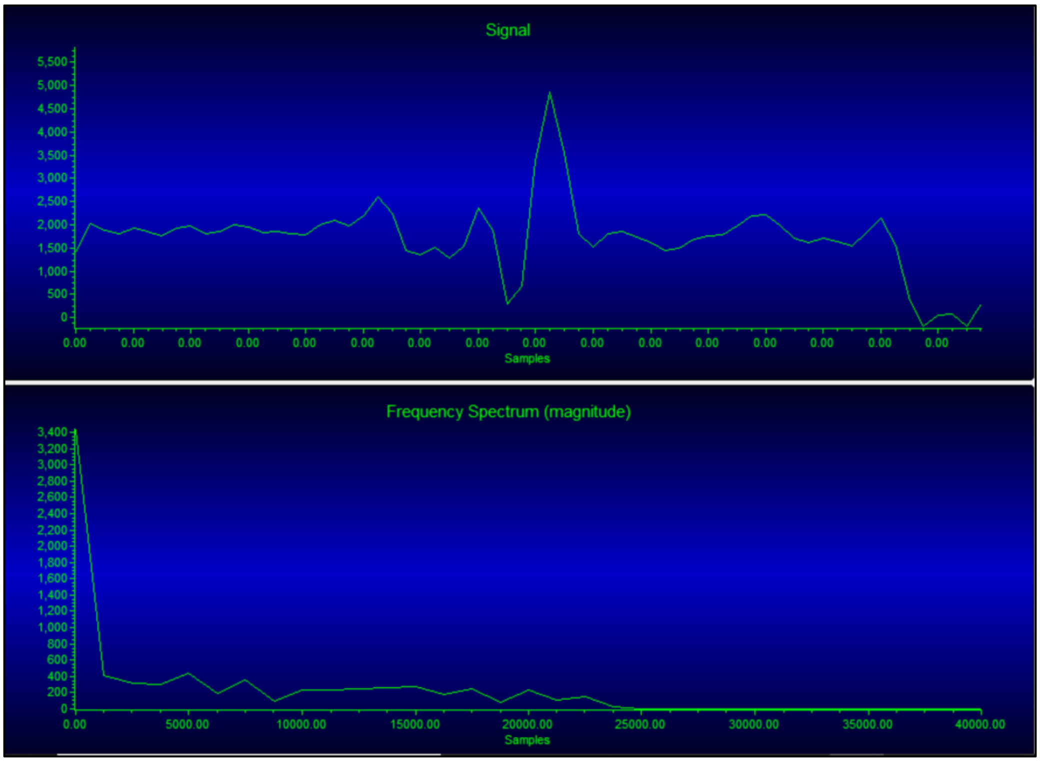

Figure 35: Low-Pass Filter – 25 kHz

- Low-pass filter with cut-off frequency of 30 kHz

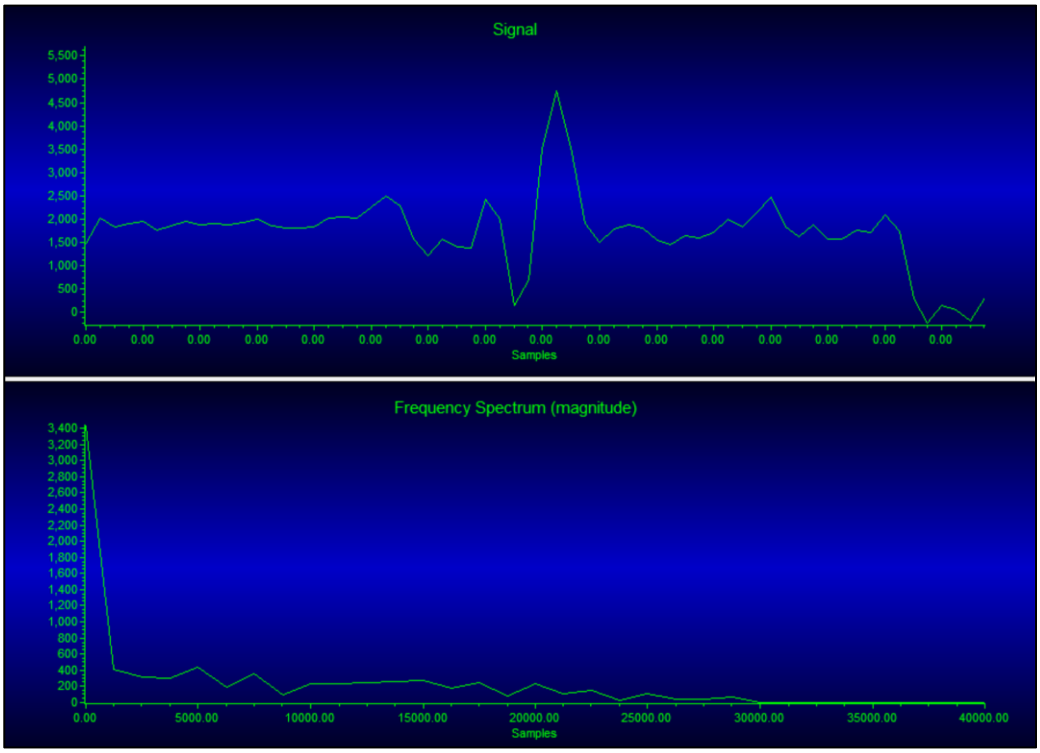

Figure 36: Low-Pass Filter – 30 kHz

- Low-pass filter with cut-off frequency of 35 kHz

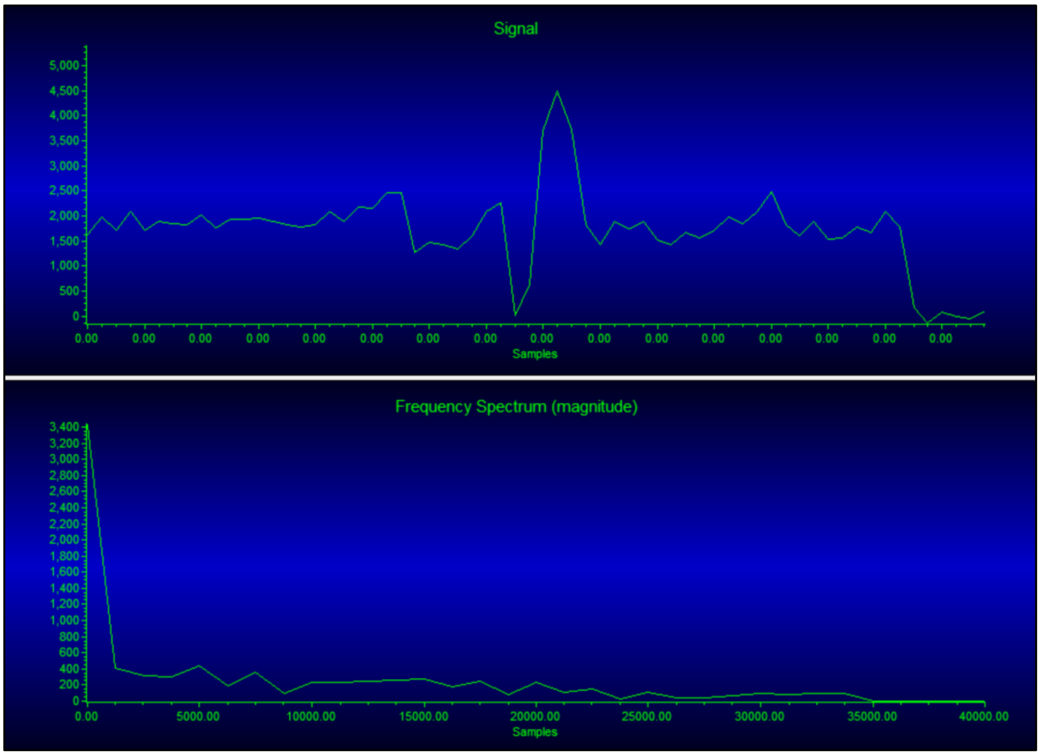

Figure 37: Low-Pass Filter – 35 kHz

The simulation output graphs shown in Figures 31-37 were produced with the "Fourier Processor" program created by Prof Patrick Gaydecki at the University of Manchester. To get access to the program please contact Prof Gaydecki at: patrick.gaydecki@manchester.ac.uk.