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

Third Year Individual Project – Final Report

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Contents

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1. Overview and Background

1.1. Abstract

It is a fact that heart attacks have always been responsible for a large number of deaths amongst the population of the world. That is why since the beginning of medicine's history, physicians have been trying to find methods of identifying their symptoms in order to deal with them promptly and save lives. One of the most efficient ways to detect these nowadays is heart monitoring. More specifically, tracking of the electrical activity of the heart can demonstrate abnormalities of its operation and immediate action can prevent fatal heart-related incidents. This would certainly contribute to a patient's longer lifetime.

There are two very important medical tools available today which enable doctors to check on the vital information of their patients and acknowledge whether there are abnormalities or not. These include the heart rate monitor and the electrocardiograph. The former one is using the technique of photoplethysmography, in which an LED emits light on the skin and the amount of it reflected to a photodiode is measured, demonstrating whether the change of blood's volume is normal during a heartbeat. The electrocardiograph is a device which uses electrodes attached to suitable parts of the body in order to produce an electrocardiogram, a graph which monitors the electrical activity of the heart by illustrating graphically whether its operation is regular. Therefore, it is understood that these two tools should be easily accessible to all people in order to effectively deal with heart-related accidents and as a result improve the life expectancy of the whole world population.

In the last decade new technology has made these measurements available directly to the patients with portable medical devices. Even though the existing state-of-the-art includes solutions which extract vital information, the categories of people who can use them are limited due to the following disadvantages:

- High cost
- Complex use of the technology
- Unable of communicating data to a doctor

The first problem constraints the use of these tools to people with limited financial background. The second disadvantage does not allow older people with inadequate technological literacy to have access to their medical information themselves. Finally, the feature of transmitting the live

measurements to a doctor, in order for a meaningful analysis to be carried out, is missing from all of the current state-of-the-art.

By considering these limitations, this project proposes the development of a low-cost medical bracelet which can be easily worn by any patient on their wrist. The measurement of heart rate and the electrocardiogram are produced in real time and are transmitted to a webpage or a mobile application, where the doctors can view the information about their patients' health and take immediate action in case of an emergency.

In order for this to be achieved three components are necessary. First of all, a heart rate sensor is required, which incorporates an LED and a photodiode, to extract the heart rate of the patient in Beats Per Minute (BPM). Furthermore, an electrocardiograph sensor is used, which uses three electrodes and measures the voltage difference between them, in order to produce the electrocardiogram. In addition, a Wi-Fi module is added in order to communicate the data from the sensors through an Internet-of-Things Cloud to a webpage and a mobile application. For all of the above, different off-the-shelf components are tested and their accuracy is compared with the Apple Watch Series 5 as a benchmark [1]. Then the most suitable ones are selected for the device depending on the cost, size and accuracy. As a last step, a custom-made bracelet is designed, 3D-printed and assembled with the circuit of the device to conclude the development of the proposed solution.

The final part concerns a discussion which assesses whether the final product has accomplished its aim in producing useful results for both patients and doctors. Also, the limitations of the technology such as the accuracy of the sensors, the battery life and the charging time are analysed and an evaluation on how they would restrict the device's use by the customers is carried out. Finally, the discussion investigates the further steps that would be followed should a marketing of the product was decided, including Intellectual Property issues.

<u>Future improvements:</u> Reduce the parts about how I was planning to do it, e.g. too many details about which components will be used and what the problems of the state-of-the-art is, put more details on the results of the technical work after it is done, focus on the content of the WHOLE report, put all additional background info in the Introduction. REDUCE SIZE

1.2. Introduction

<u>Introduction of the project, get attention with the first sentence, give a hint of what you found out</u>

through this project

Heart rate monitoring has been a priority of physicians and cardiologists since the beginning of the 20^{th} century in the effort to deal with heart-related fatal incidents. The first big invention in this field dates back to 1901, when Willem Einthoven created the first 3-lead electrocardiograph by using a string galvanometer [2]. This development revolutionized the area of physiology and in the following years many more improvements where made leading to the 12-lead electrocardiograph device as it is known now. Therefore, the end of the 20^{th} century found physicians and doctors more capable of detecting and dealing with cardiovascular problems rather than at its beginning. However, some limitations were still apparent. The measurements of heart rate and the electrocardiogram could only be taken in hospitals and medical practices, restricting patients' flexibility on monitoring their health. As a result, at the start of the 21^{st} century the focus of 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. These are incorporated in wearable devices enabling people to track their own vital measurements in real time. As a result, regular meetings to the doctor are avoided and heart abnormalities can be detected instantly leading to prompt treatment.

Undoubtedly, the advancement in medical devices should be accessible to all people regardless of age, technological literacy or financial background. That is because the data acquired by these devices are critical for everyone to stay healthy and diminish the possibility of a fatal incident. However, the latest portable medical devices, in the form of a bracelet mostly, discourage a wide range of people from using them due to increased complexity and cost or due to limited functionality of communicating data to a doctor in real time.

More specifically, some devices require connection to a nearby smart device, such as a smartphone or a tablet. These gadgets are the only way to collect the recorded data and display them for analysis and detection of potential flaws. This feature already restricts many categories of people to have their vital data measured due to limited abilities using technological equipment. There is a high possibility that the ones affected the most are old people who most of the times do not possess one of the smart devices. Ironically, they are the ones who need these devices the most, as the measurements of heart rate and ECG need to be monitored constantly so that dangerous situations can be dealt with immediately.

As it is understood taking real time and continuous measurements is the most essential feature that these devices need to incorporate. Also, the communication of these data to a specialist, such as a cardiologist, is critical so that the correct interpretation of the results can be guaranteed and prevention of undesired incidents is ensured. All of these characteristics are partially or not at all included in the medical bracelets in the market, as they pose challenges in battery life and most of all cost.

The increasing cost of development of such devices is reflected on the high selling price. It is a fact that a lot of people are not able to afford prices that start from £80 and can reach the level of £500. Hence, it is understood that there are numerous challenges to be overcome in the development of medical bracelets.

The aim of this project is 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 communication of data will be implemented through direct Wi-Fi to a cloud and the results will be displayed on a webpage and a mobile application. These two streams of displaying information will be used by doctors to track the condition of their patients and detect abnormal activity. As a result, they will be able to contact them directly and instruct them on which steps to follow.

The main objectives of the project are directly related to the features that the medical bracelet will incorporate. These include:

- Measurement of heart rate in BPM using a low-power heart rate sensor
- Measurement of the heart’s electrical activity using a low-power ECG sensor
- Communication of the above data to a cloud through direct Wi-Fi
- Display of the data on a webpage and an app in real time
- Development of app interface for doctors and patients

In order for the above to be achieved, a series of methods is followed. As a first step, testing of different sensors for heart rate and ECG is performed in order to select the ones which provide the best trade-off between cost, accuracy and size. Furthermore, the available options in Wi-Fi modules are assessed in terms of cost, speed and power consumption. A design of the overall circuit on a prototyping board follows which integrates the mentioned components with the rest of the elements such as the microcontroller and the battery. After that step is completed, the PCB is designed to maximise the performance of the circuit and improve the communication of data between the individual components.

The successful implementation of the PCB progresses the project to the software development part. During this phase, the cloud is optimized to receive the data from the Wi-Fi module. Following this, the webpage and the app are designed to collect the information and display them in a user-friendly way. Finally, an early completion of the above would allow for the 3D-printed design of the bracelet to be used with the system, otherwise an available one in the market will be used.

This report concludes the Final Year Project and summarizes the work undertaken on planning, designing and implementing the low-cost medical bracelet. First, some statistical figures related to fatal incidents from heart attacks or strokes prove the need for this device. After that, the advantages and disadvantages of state-of-the-art are thoroughly examined and the novel features of the proposed technology are pointed out. Finally, the technical details of the project are presented and a discussion of the results is included, assessing whether the project has been successful in accomplishing the main aim.

<u>Feedback:</u> excellent work overall. perhaps a bit more on state of the art / available products with referencing would have been useful.

1.3. Motivation

According to official statistics from the World Health Organization, cardiovascular diseases have been the biggest cause of death globally in the last 15 years and continue to account for the most deaths annually even today [3]. More specifically, heart-related diseases were the reason why 17.9 million people died in 2016, which represented 31% of the death causes globally. In this category of diseases, heart attacks and strokes are included and are the leading causes, being responsible for the 85% of the overall heart-related deaths. It is worth looking into how these can be diagnosed and the steps followed for their treatment.

1.3.1. Heart attack

First of all, a heart attack is a very 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]. As soon as there is a deficiency of blood to the heart muscle, the symptoms begin to appear. These can include: chest pain, sweating, dizziness, shortness of breath and many more. According to the NHS, "if a heart attack is suspected, the patient should be admitted to 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 and what type of heart attack the patient went through, in order to maximise the efficiency of the treatment [6]. It is important to note that this test needs to be performed as close to the time of the heart attack as possible in order to prevent further damage of the heart and initiate the medical care actions promptly.

Doctors and health organizations advise that in heart-attack incidents a quick detection and treatment is critical [7], 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 [8]. Taking more time than that to detect it and react could result in more detrimental effects to the cardiovascular system and fewer possibilities of survival. As a conclusion, time is of the essence when it comes to a heart attack and it is vital to be able to identify it immediately in order for the doctors to provide treatment without delay and avoid life-threatening situations.

1.3.2. Stroke

Another fatal cardiovascular disease is called a stroke. This 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) [9]. Its symptoms include inability to move parts of the body such as face muscles or the arms and the legs [10]. Furthermore, speech impediment might be observed as well as many more effects related to loss of balance, dizziness or unconsciousness. In this case, it is also crucial that the stroke is identified immediately, so that the patient can be transferred to the hospital. Then, the first actions to be taken are different kinds of tests and scans to extract information on how much the brain was effected and which treatment process should be followed. Apart from brain scans and blood tests, the heart rate is thoroughly checked in order to detect irregular heartbeat and to provide information to the doctors about its causes. NHS points out that “a stroke is a medical emergency and the patient should call 999 when it is suspected” [10], therefore no time should be wasted in the diagnosis of a stroke as it could turn into a fatal incident.

Additionally, treatment methods are most effective when performed within the first 5 hours from the occurrence. More specifically, medicine taken to remove the blood clot and sooth an ischaemic stroke can have a much bigger effect if they are taken immediately after the incident [11]. Other methods include a thrombectomy, during which a device is injected in the artery to help in restoring the blood flow by dissolving the blood clot. In this case as well, NHS advises that “it is most effective when started as soon as possible after a stroke” [11]. From the above, it can be understood that time efficiency is also vital in a stroke in order to prevent a dangerous situation for the patient.

1.3.3. Low and medium income countries

Another interesting figure is presented in the study of the World Health Organisation (WHO) on Cardiovascular Diseases (CVDs), which states that “over three quarters of CVD deaths take place in low- and middle-income countries” [12]. Therefore, the conclusion can be drawn that countries which are not able to provide a quality healthcare system, due to financial instabilities, are the ones whose citizens are more susceptible to suffer from heart-related diseases. At another point of the WHO’s report, it is mentioned that “people in low- and middle-income countries often do not have the benefit of integrated primary health care programmes for early detection and treatment” [12]. In other words, there are no medical facilities or technological advancements accessible which can aid in the detection and the healing of such diseases, posing many obstacles in these countries’ citizens to stay healthy. As a result, many people, especially those with a disadvantaged financial background, who are affected by CVDs die young because of late detection and treatment.

In an effort to deal with these world issues, the World Health Organization has composed an Action Plan for 2013-2020, which aims to reduce by 25% the risk of mortality from CVDs [13]. The plan includes 6 objectives, which need to be completed in order for the main aim to be accomplished. One of these relates to “raising the priority of the prevention and control of CVDs by international cooperation” [13] giving some suggested actions to the private sector. In these actions, an important point emphasizes the need to “promote (…) the creation of information and electronic communication technologies (eHealth) and the use of mobile and wireless devices (mHealth)” [13] in order to “empower people with noncommunicable diseases to seek early detection and manage their own condition better” [13].

From all of the above, it can be recognized that it is of paramount importance to deal with the leading cause of death globally, the cardiovascular diseases. By following and supporting the Action Plan set by the World Health Organisation, the proposed device in this paper provides early detection of the disease, enables prompt treatment of the patient, but also constitutes a low-cost solution which can be utilized in low- and middle-income countries to decrease the number of deaths due to these diseases on a global scale.

Finally, another aspect of the motivation behind the suggested technology relates to the ageing population. Old people due to reduced mobility find it difficult to schedule regular appointments with their cardiologist to track the condition of their heart. This technology would allow them to have their vital signs continuously monitored and in real time by their doctors. As mentioned before, in case of an abnormality in the blood flow early detection could save their lives.

Future improvements: FIND REFERENCES IN LIBRARY WHICH STATE THESE INFORMATION ABOUT HEART ATTACKS AND STROKES NOT ONLINE SOURCES

1.4. Statements of Aims and Objectives

Core Aims – what needed to be achieved by the project, represents the “what”

The aim of the overall project is 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 or mobile application which will be able to receive data from the bracelet and display them in a user-friendly way.

Objectives – individual steps to get to the aims, represents the “how”

To accomplish the successful completion of the practical work but also of the final report by the end of the year, a clear schedule needs to be designed. This will include the timeline of the objectives that need to be carried out in order to reach the main aims. For the final report these include taking care of the presentation and the content structure, but primarily writing the:

- Overview and Background sections, which include the abstract, aims, objectives, state-of-the-art
- Technical Achievement sections, which includes design, implementation, testing, results

Then, for the practical work these are:

- Components Selection/Order
- Circuit and PCB Complete Design
- Working Prototype
- Bracelet Complete Design
- 3D-print of Bracelet
- Bracelet and PCB Integration
- App Development
- Sensor Data receiving through Wi-Fi and displaying
- App Interface for Patients and Doctors

1.5. Literature Review

Check with the checklist provided in the book

1.5.1. General Introduction to the topic

When considering the future of medicine, it can be clearly foreseen that it will include wearable electronic devices. The field has already entered a new area in which there is a transition from population level to personalized healthcare [14]. This has been made possible by numerous innovative devices being developed, which include a variety of advanced biosensors, such as accelerometers, magnetometers, altimeters, GPS but with the dominant being PPG and ECG sensors. On one hand, ECGs are the most commonly used diagnostic tools in healthcare conveying useful information on the cardiac electrical cycle. On the other hand, PPG sensors deliver measurements on the heart rate of the patient, which is widely used as a helpful indicator on the physiologic status of the patient's heart. Therefore, the widespread use of these non-invasive and cost-effective sensors in the new devices can be justified as it aims to provide users with an individualized way of monitoring of their vital signs [14]. A study demonstrated that 71% of new devices included a PPG sensor which outnumbers all the other available sensors, including GPS [15]. However, these gadgets go beyond just extracting medical data. They incorporate wireless and mobile communication to transmit the real-time data to a physician or even run algorithms to predict events before they occur and prompt patients to take action, such as adjusting their medication. As a result, an individualized, continuous and passive monitoring is achieved providing great advantages for the users and doctors. These innovations have driven the market of wearable technology into a rapid growth phase and the healthcare informatics that will be generated bring the sales potential to the range of billions of dollars [16]. That is why many industry leaders, such as Apple and Fitbit, as well as start-ups invest a big share into research of user requirements in order to reinforce the market with integrated devices that provide a wide range of measurements, such as movement tracking and heart monitoring. After all, new studies bring to light the need of patients to possess these devices, as one in six consumers in the United States already use wearables including smartwatches or fitness bracelets [17]. Therefore, it is safe to say that the healthcare industry has enter an era of revolutionization.

1.5.2. Importance of the topic

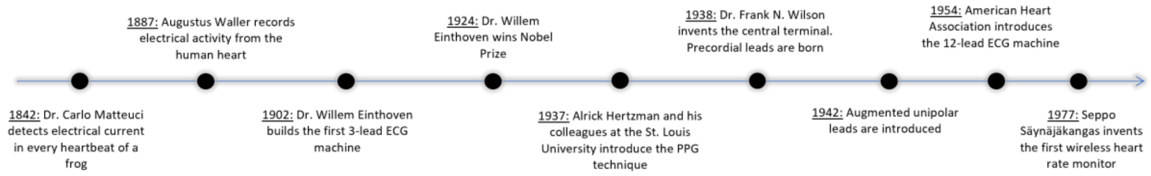
The value of the wearable devices, such as the medical bracelet developed in this project, lies on the detection and prevention of life-threatening heart conditions. The integrated PPG and ECG sensors can be vital in indicating signs of heart irregularities. More specifically, PPG sensors have many uses such as in clinical physiological monitoring, to determine heart rate, blood oxygen saturation and blood pressure, in vascular assessment to indicate arterial diseases as well as in autonomic functions to measure blood pressure and heart rate variability and many others [18]. On the other hand, the functions of an ECG sensor are equally important, as it utilized to “analyse cardiac rhythm, ischemic changes and to predict and treat acute myocardial infractions and coronary events” [19]. Furthermore, it is a useful tool in the diagnosis of cardiovascular diseases such as “cardiac dysrhythmia, congestive heart failures (CHF), coronary artery disease, heart attack, bradycardia and tachycardia” [19]. 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 promptly [20]. 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 [21]. For instance, Apple Inc. has included that feature in the development of 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 actually suffered from atrial fibrillation giving a small indication that these devices can contribute in early detection [22]. Another important advantage will be the opportunity to study ECGs more thoroughly in order to correlate patterns in the waveforms and symptoms with heart diseases and particularly in infrequent symptoms due to the continuous monitoring capability [23]. Additionally, these measurements are also significant for sport activities and as a psychophysiological status indicator, such as in stress measurements [24].

1.5.3. Historical Origins

The interest of physicians to study the electrical activity of the heart dates back in the mid of 19th century, when Dr. Carlo Matteucci, a physics professor in Italy, proved that there was electrical current associated with every heartbeat of a frog [25]. This inspired more research into the field and in 1856 physiologists managed to record a cardiac potential, which reassured them that there was electrical activity in the human heartbeat as well [26]. Then, in the early 1870s two British physiologists used a capillary electrometer to record the heart's electrical current successfully [26] before Augustus Waller, a British physiologist, published the first ever electrocardiogram from a human heart using this device combined with the electrodes placed on the back and the chest [27]. The last decade of the 19th century was a very active period for physicians who experimented with technology to detect the electrical activity of the heart and attempt to extract more useful information. The intense research became fruitful when in 1895 the Dutch physiologist Dr. Willem Einthoven refined the original capillary electrometer and had demonstrated the five deflections that occur during a heartbeat [26]. The deflections were given the names of PQRST respectively because of a mathematical tradition that had been established by Rent Descartes and which are still used in ECGs until today [26]. He then developed a highly sensitive string galvanometer – an electromechanical instrument to detect 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 which incorporated a silver-coated string which moved from side to side in the strong magnetic field of a magnet when the heart's current passed through it [26]. The oscillations of the string were magnified by a microscope and were recorded photographically to illustrate the magnitude and direction of the current. This Nobel Prize-winning invention was vital and initiated new fields of research to use the ECGs to diagnose irregular heartbeat but also to connect patterns in the graph with heart conditions such as atrial fibrillation or ischemic heart disease. In 1930, the ECG had developed that much that it could used on its own to confirm the diagnosis of myocardial infarction with certainty [25]. Around that time, another improvement came to life as Dr. Frank N. Wilson introduced the 'central terminal', the connection between the three limb electrodes, which was considered as 'ground' [25]. 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 [26]. Another milestone includes the introduction the augmented unipolar limb leads called a-VL, a-VR and a-VF which provided more thorough coverage of the area around the heart [25]. All these innovations contributed to the introduction of the 12-lead electrocardiogram in 1954 by the American Heart Association [25]. Later in the 20th century inventors started to think about making this instrument portable and more easily accessible to patients. A pioneer physicist named Norman Holter managed to implement an ambulatory electrocardiography device which could record an ECG continuously for a couple of days [28]. The Holter monitor is still used today for a limited-time continuous recording of an ECG [28]. Another pioneer Seppo Säynäjäkangas in 1977 invented the first wireless heart rate monitor as a training tool for the Finnish National Cross Country Ski Team [29]. This marked the beginning of the wearable devices industry.

Photoplethysmography also has a rich history which started in the 1930s. More specifically, the beginning of this technique was introduced by an American research group which managed to monitor blood volume changes in the human fingers with the PPG method [18]. In 1937, Alrick Hertzman and his colleagues at the St. Louis University published a paper explaining the use of a reflection technique to measure the changes of blood volume in the fingers [18]. Later on, they continued improving the technique by amplifying the signal and describing ways of avoiding sources of error, such as insufficient contact with the skin [18].

As a conclusion, many researchers contributed with their work in order for these ideas to be widespread now and to be producing life-saving results. Since the time of their invention, ECG and PPG techniques have developed by leaps and bounds and it is interesting to investigate how they are used today and the kind of results that they produce.



1.5.4. Main theoretical and experimental findings

Undoubtedly, there has been an impressive development in the portability and size of the devices which measure heart rate and produce ECG graphs since the first inventions during the 20th century. These advancements have attracted users to purchase them and utilize their features. However, there is normally questioning about how accurate the output data is and whether the machine learning algorithms to detect irregularities are efficient. Multiple studies have been conducted to assess the accuracy of marketed wearable smartwatches and medical bracelets and the results are satisfactory. First of all, a research study in 2016 examined the validity of different wireless heart-rate monitors such as FitBit Charge HR, Microsoft Band and others and after using measurements from 50 volunteers the mean absolute percentage error values ranged from 3.3% to 6.2% with the Polar RS400 HR chest strap as the benchmark [30]. Furthermore, another study investigated if smartwatches in the market could accurately measure heart rate in people with different heart conditions, such as sinus rhythm, atrial flutter and atrial fibrillation. 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 [31]. However, in the case of atrial fibrillation there was a higher deviation from the benchmark measurements with biases of around -15 heartbeats for each device [31]. Overall, this study showed that the smartwatches underestimated the heart rate in patients with atrial fibrillation, which limits their use but demonstrated good performance in all the other cases [31]. Additionally, other solutions on heart monitoring were tested for their sensitivity and specificity. More specifically, the Cardiio Rhythm Mobile Application, which measures the heart rate using PPG techniques, was examined to determine whether it could accurately detect atrial fibrillation. The results demonstrated that its sensitivity and specificity were 93.1% and 90.9% respectively, hence showing reliable performance [20]. Finally, the iTransmit study assessed the quality of measurements taken from the AliveCor Kardia Mobile device when attempting to detect atrial fibrillation after ablation and found that it had 100% sensitivity and 97% specificity when compared to a traditional transtelephonic monitor [32]. All of these results demonstrate that the devices in the market can be trusted for the measurements they produce and more value is added by their portability and miniaturized size. Nevertheless, the undergoing research is ongoing by attempting to improve the features that wearable devices provide. The recent advancements in the field promise an exciting future for the industry.

1.5.5. Recent research developments / Applications or implications of the research

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 of measuring the heart rate and producing the ECG of the patients. In order to achieve mechanical flexibility, the device need to incorporate stretchable substrates, appropriate conducting electrodes, suitable sensing materials in the millimeter range and most importantly flexible primary batteries.

The field of stretchable batteries has introduced many advancements recently such as connecting microbatteries on stretchable substrate or fabricating batteries in the shape of a cable [33]. Furthermore, there has been research on other ways of powering flexible sensors and solutions such as photovoltaics with supercapacitors or thermoelectric generators, converting the heat of the user's body to electrical energy, were suggested [33]. Although these new powering techniques of wearable sensors have enabled more creative systems to rise, they 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. Also, their location on the body needs to allow sufficient primary energy to be collected depending on its source. Furthermore, the materials used for the power source and the sensors need to be dermatologically proven, safe and nontoxic so that the integrity of the user's health is ensured [33].

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 [34]. 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 in real-time with the use of flexible polymer transistors [35]. There are multiple advantages in exploiting these innovations in future wearable devices which relate to low power consumption and measurements unaffected by body movement artefacts. Another design that exploits flexible materials in sensing is an ECG patch monitor which produces a single-lead ECG by including an ADC to convert analogue ECG signals to digital form as well as an accelerometer to remove any artefacts in the measurements caused by the movement of the body [35]. It should be noted that body activity such as movement of arms and legs poses a significant constraint on the achievable accuracy of the measurements. More specifically, the signal quality is influenced by the electrode-skin impedance and the stability 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 measurement of the heart rate. For this reason, algorithms are currently evolving to remove variations in the measurements using adaptive filters and 3D accelerometers [36].

An additional area of interest in the field of physiological sensing includes the use of electronic tattoos which can contains conventional components such as LEDs, transistors and more in microscale patterns of silicon or gallium arsenide. These systems are advanced enough to be powered wirelessly or using batteries embedded in the devices and produce ECG measurements [36].

Furthermore, promising research activities in the field of wearable devices aim to connect the sensing systems with clothes. This innovation will include microsensors embedded into textiles which will extract useful physiological data for the patient and there will be an option to communicate these to a cloud for doctors to inspect [37]. The smart textiles used incorporate textile electrodes to acquire the signals which require reliable design in order to ensure good signal quality and immunity to body movement artefacts [37]. It is believed that this technology will contribute in the comfort of the user and will be able to provide a wide range of vital data, such as breathing rate, blood pressure or body temperature 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 such as firemen. However, there are obvious difficulties in implementing this vision, as these pieces of clothes will require complicated manufacturing techniques. Also, the type of measurements required for users with specific diseases will vary hence altering the complexity of the sensing circuits. Additionally, it has not yet been determined if these technologies are water durable during washing cycles and these could cause mechanical and chemical degradation. Therefore, another aspect of biosensors that should be considered is their ability to overcome stress. All of these obstacles constitute reasons why some initial attempts for implementation have failed [37].

1.5.6. 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 [14]. It is already obvious that these sensors can measure a very wide range of quantities that will require algorithms to extract the important information and provide useful notifications on emergency conditions. If the advancements in machine learning become compatible with the diversity of data measurements, then doctors and physicians will be able to master the interpretation of their patient's information and systems will predict potentially life-threatening events before they occur. To achieve this target, it is crucial to determine the patterns in vital signs occurring during and before a heart condition and establish normative data ranges which give confidence in the prediction of an event.

These features can then be exploited to provide patients with automatic suggestions for therapy [18].

Measuring personal health data and communicating them over the wireless network has justifiably made people skeptical about the security of their privacy [14]. The medical community will have to find answers in the challenges of confidentiality and data security as these significantly reduce the public acceptance to the wearable devices. Personal health information is protected under the Health Insurance Portability and Accountability Act of 1996 [14] and to abide to this Act all medical data extracted need to be encrypted when moved across secure networks in order to protect patients' privacy rights. A potential breach of personal health data would certainly be disastrous for the industry and there would be no way back to a secure means of monitoring and communicating vital measurements which could save lives.

1.6. Consideration of existing solutions

The field of medical devices is a fast-growing industry which is currently valued at USD 472.69 Billion and is expected to reach USD 612.7 Billion by the year 2025 [47]. 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 and become leading players of this promising industry.

Devices that measure vital signs, such as heart rate and ECG, can be distinguished in two categories depending on their purpose. On one hand, those that extract cardiovascular data during everyday activities, such as walking, running, swimming etc. allowing the users to monitor their health data by themselves. In other words, they give easy access to the measurements, without however providing a way of communicating the data to a doctor for medical monitoring. These will be referred to in this report as Fitness Trackers. On the other hand, the second group of devices displays the measured data to the user and also communicates them to a doctor, who can keep track of the patients' health condition in real-time. These devices will be referred to as Medical Devices.

In the industry of Fitness Trackers, the heart-monitor bracelet called Fitbit dominates. The newest version named Fitbit Charge 3 Fitness Activity Tracker provides useful features for its users, such as continuous heart-rate tracking during walking, running, cycling, swimming and others, while also monitoring the calorie burn and quality of the sleeping cycle [48]. Its major advantages include battery life of up to 7 days, waterproof design and an app for displaying the data. Some of the disadvantages include no detection of heart rate irregularities, no ECG measurement and high price of £150 [48]. Furthermore, another available activity-tracker watch 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 sometimes inaccurate and it does not notify the user for abnormal heart activity. Additionally, a fitness bracelet called J-style Smart Wristwatch provides features such as 24-hour heart rate and ECG monitoring with abnormal heart rate alert in a reasonable price of £25. However, it does not involve any communication of the data to doctors in real-time.

When looking at the state-of-the-art available in Medical Devices 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 while also measuring the heart rate. This technique offers significant benefits in size as it does not include bulky cables and in comfort of use as the device operates passively and stores the data for analysis by a doctor, removing the need for the user to possess technical skills. However, both demonstrate critical disadvantages. The Zio Patch is not capable of transmitting data in real-time, but rather it records and stores measurements on the device for two weeks of monitoring. Then the user sends the patch back to the manufacturer, which produces a thorough report on the electrical activity of the heart over that two-week period [49]. Therefore, there is considerable delay from the time of the measurement until the results become available. This procedure as well as the high price of £150 classify it as an unsuitable option for heart condition monitoring. Furthermore, the VitalPatch, even though it enables real-time analysis of data, it can only produce a 1-lead ECG, which does not provide the necessary accuracy to detect heart arrythmias.

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. It can be attached on the back of a phone for easy recording of measurements. The manufacturer has developed a mobile application which receives the data in real-time and communicates them to a doctor [50]. The second version of the device, KardiaMobile 6L, demonstrates improved accuracy as it can generate a 6-Lead ECG with the addition of another electrode at the back side of the device [51]. Even though it provides a reliable and accurate solution for heart rate and ECG measurement, the measurements can only be recorded when the user is prompted to and not passively and continuously. For this reason, it is not a suitable solution for emergency situations as some heart irregularities might not be detected in the 30 seconds of a single measurement taken by this device. Also, the acquisition of data requires technical knowledge making it less accessible to older people who might struggle to use it or who might not even possess a smartphone.

A final approach includes the multi-purpose watches which amongst all the other features they provide, such as calls, messages, etc., they include the heart rate and ECG measurement as well [52]. An example of this is the Apple Watch, whose price is very high due to all the additional functionality that it offers to the user. Therefore, it is not considered as an option if the heart rate monitoring functionality is the only one needed but if all the other features are also useful to the user. Nevertheless, because of its accurate measurements of heart rate and ECG [1] it will be used in this report as a benchmark to compare performance of the different sensors available and the developed device as a whole.

To summarize, although the available state-of-the-art provides helpful solutions to produce meaningful 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 doctors in real-time
- Sufficient accuracy of the ECG measurement in order to detect heart arrythmias
- Continuous heart condition monitoring
- No technical skills required

1.7. Conclusions

By recognising the flaws of existing state-of-the-art, as presented in the “Consideration of existing solutions” section, and the crucial impact that a heart rate monitor could have in the decay of mortality rates, due to heart attacks and strokes, this report presents the process of developing a low-cost 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 [53].

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. It is located behind and to the left side of the breastbone [38]. Its main functions include receiving blood low in oxygen from the other organs and provide them with oxygen-rich blood, which allows the normal operation of many body functions [38]. This is achieved through a network of arteries and veins which connect the heart to the rest of the body, which is called the cardiovascular system.

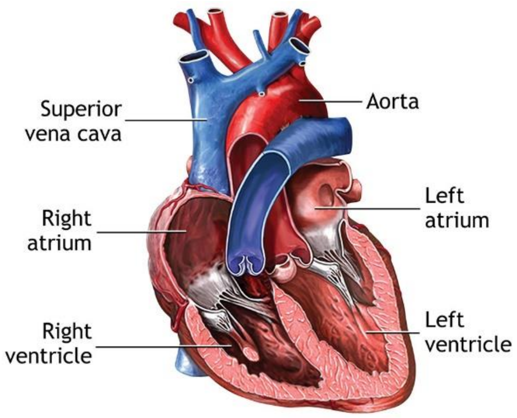
The heart consists of four chambers [24]:

- The right atrium, which receives low-oxygen blood from the veins and forwards it to the right ventricle through a valve
- The right ventricle, which receives the blood from the right atrium and forwards it to the lungs, where it is filled with oxygen
- The left atrium, which receives the oxygen-rich blood from the lungs and forwards it to the left ventricle and
- The left ventricle, which pumps the blood to the rest of the body organs

Therefore, there are two blood circulation “loops” the body, one of them through the lungs, called pulmonary circulation and one through the body, called systemic circulation.

What is remarkable about the operation of the heart is that it is self-exciting, which makes it a unique muscle in the body as it does not require a nervous stimulus for excitation as all the others.

Figure x demonstrates the chambers of the heart diagrammatically.



[39]

2.1.2. Cardiac Cycle

The cardiac cycle refers to a complete cycle of operation of the heart's atria and ventricles, in which the oxygen-low blood is received, pumped into the lungs, oxygenated blood is received by the heart and then it is forwarded to the rest of the body [40]. It is characterised by contraction of the heart muscle for a fraction of the cycle, called systole and relaxation called diastole [40]. These changes in the shape of the heart are reflected in the depolarization and the repolarization of the chambers [40]. Depolarization refers to the change of the electric charge distribution in the cells of the chamber resulting in less negative charge inside them. On the other hand, repolarization is related to the change in the charge distribution back to a negative value after depolarization. An efficient coordination between the atria and the ventricles in order to ensure normal operation of the circulation mechanism.

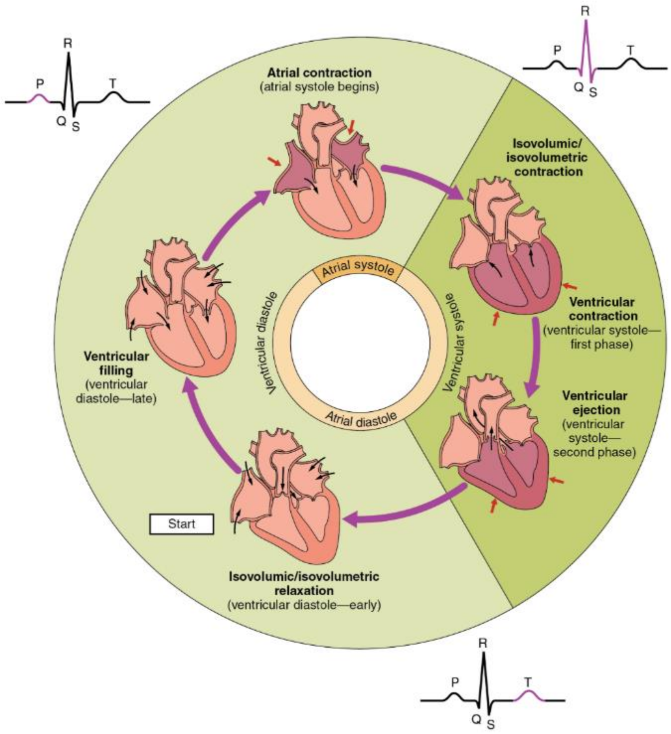
A full cardiac cycle consists of four phases [40]:

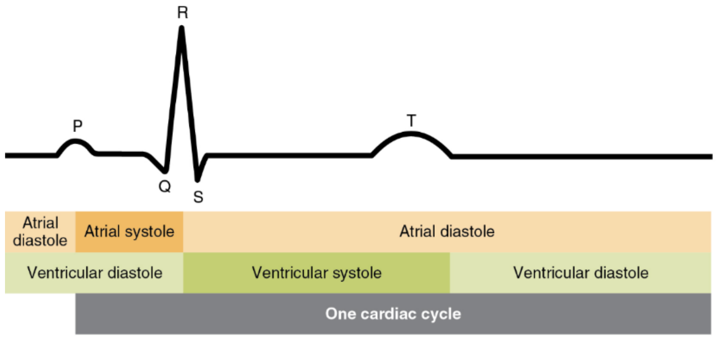
- Atrial systole, during which there is contraction of the atria and the blood received by the veins is pumped into the ventricles. This results from depolarization of the atria and lasts around 100 ms
- Atrial diastole, during which there is relaxation of the atria after pumping the blood into the ventricles
- Ventricular systole, during which there is relaxation of the atria and contraction of the ventricles. The blood flows from the right ventricle to the lungs and from the left ventricle to the rest of the body. This is a result of depolarization of the ventricles and lasts around 270 ms
- Ventricular diastole, during which there is relaxation of the ventricles. The blood flows back to the heart into the atria and eventually into the ventricles. It follows the repolarization of the ventricles and lasts approximately 430 ms.

Each deflection on the ECG represents a phase of the cardiac cycle [40]. 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

Figures y and z demonstrate the phases of the complete cardiac cycle as well as their connection with the deflections appearing in an ECG





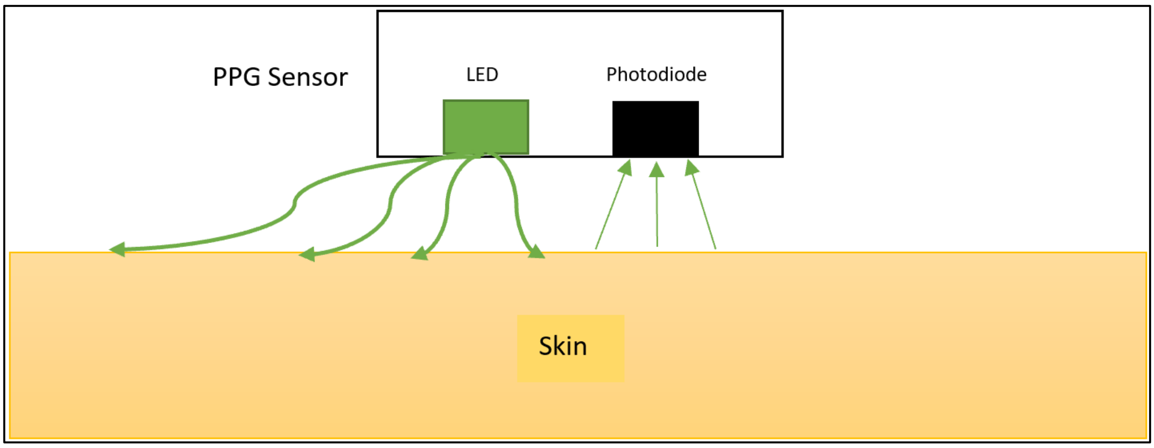
[40]

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 and fitness activities, as it provides useful information on the physiologic condition of the heart. Its unit is Beats per Minute (BPM) [24]. It is normally measured with a technique called Photoplethysmography (PPG). The quality of the cardiac cycle can also be evaluated by the graphs generated in Electrocardiography (ECG), as these illustrate the deflections corresponding to the depolarizations and repolarizations of the ventricles and atria.

2.1.4. Photoplethysmography (PPG)

Photoplethysmography is an optical technique 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, which is a sensor sensitive to changes in light density [18]. The system can be attached to the wrist, fingertip, ear lobe or any other capillary tissue. The operation principle is very simple and 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 [18]. Figure k demonstrates the operation of a PPG sensor diagrammatically. The PPG waveform produced can be divided into an AC component, which has a fundamental frequency proportional to the heart rate and a DC component that relates to the average blood volume. In order to achieve the best possible accuracy of measurements and reduce the size of the DC component, the photodetector is normally connected to low noise circuitry including an amplifier and a high pass filter, which also enables removing high frequency noise especially from mains power supply interference [18]. The final stage includes intelligent algorithms to convert the measurements of light intensity to the measure of Heart Rate in BPM. PPG sensors use dry sensors and are often preferred by users as they are more comfortable to wear than ECG sensors, but also because they can extract data for a wide range of quantities, such as oxygen saturation and blood pressure. This is the reason why they are employed in multiple commercially available wearable products and their popularity constantly grows.



2.1.5. Electrocardiography (ECG)

Electrocardiography is a field of medicine which is related to the generation of electrocardiograms

(ECGs). These are graphs 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 and clinicians as diagnostic tools to provide information on the cardiac electrical cycle [24]. Additionally, it is possible to make a thorough analysis on the cardiac rhythm, ischemic changes in order to detect potential heart conditions, such as atrial fibrillation, cardiac dysrhythmia, tachycardia and more [24].

Essentially, ECGs demonstrate graphically the heart's atria and ventricles depolarizations and repolarizations as explained in the previous section. These variations in the heart's electric potential is propagated in pulsating electrical waves through the skin. These are represented in the graph as five deflections, named P, Q, R, S, T, U, which were given their names from the inventor of the electrocardiograph Willem Einthoven, according to a mathematical convention originated from the French mathematician, René Descartes [24].

Figure 32 shows a conventional ECG for a normal sinus rhythm, demonstrating that the electrical activity of the heart is operating normally.

In order to extract this data, conductive electrodes need to be attached to the patient's body in appropriate positions.

2.1.6. Electrodes for Electrocardiography

The electrodes more commonly used in electrocardiography nowadays are made of silver/silver chloride and they also include an electrolyte gel, which contains free chloride ions and is applied in the contact point between the electrode and the skin [22]. Their principle of operation is based on the transduction of ionic current at the surface of human tissues to electron current which is delivered to the measuring instrument through a wire [24]. Furthermore, as the electrolyte gel is the only part in direct contact with the skin it implements the crucial functionality of passing the ion current from the skin tissue to the electrode which converts it to electron current. The electron current can then be sensed by the electrocardiograph. This type of electrodes are preferred over other available ones as they are characterized by low electrode-skin impedance, low motion artefacts and reduced noise. Additionally, they are reliable and inexpensive. However, there are drawbacks associated with their use such as skin irritation due to its adhesive properties. Moreover, the gel can dry after long period of use making it unsuitable for long-term monitoring applications. For this reason, research is currently active in the development of new types of dry electrodes which will minimize the problem of skin irritation but also provide reliability against body movement artefacts [24]. Apart from the quality of the electrodes, equal significance is posed on the body positions that the electrodes are placed on.

2.1.7. 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 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, which is the maximum possible. In this report the design of a 3-lead ECG is proposed therefore the placement of the three electrodes for this type are discussed.

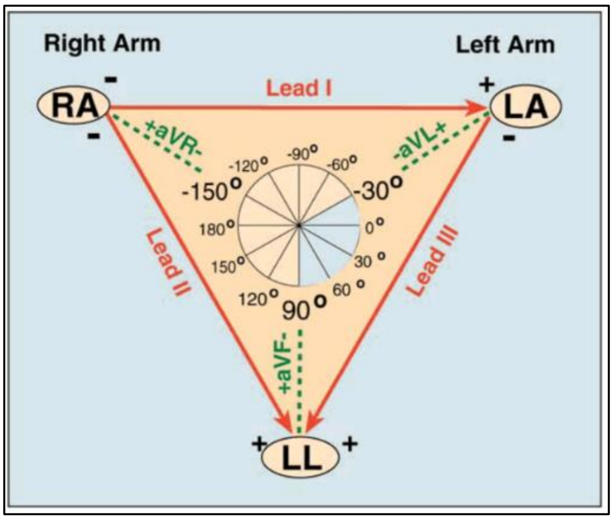
First of all, it is important to note that the placement of the electrodes needs to give a view of the heart from different angles in the vertical plane parallel to the body. In the 3-lead ECG, each of the three electrodes displays a different angle of the heart contributing in a multi-angle view of the heart's 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 [41]. In order for the electrodes to form a triangle, these are placed in the following positions [41]:

- Right Arm (RA)
- Left Arm (LA)
- Left Leg (LL)

Using these electrodes different electric potentials are measured and drawn on the ECG graphs. In a 3-lead ECG, there are three electric potential measurements that are performed and these are the following:

- 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

Einthoven's Triangle is demonstrated in Figure n



[42]

2.1.8. Measures of Accuracy

In engineering and science disciplines, it is important to be able to evaluate the accuracy in the performance of a system when compared to a reliable benchmark instrument. Two helpful measures which assess the accuracy of a device in evaluating whether a condition is present or not are the sensitivity and the specificity. On one hand, the sensitivity measures the proportion of positive cases that were actually identified by the device as positive [32]. On the other hand, the specificity measures the proportion of negatives cases that were correctly recognized by the device as negative [32]. Therefore, higher values of sensitivity and specificity demonstrate greater accuracy of the system. In this report these measures will be used to evaluate whether the medical devices can identify cases of heart conditions such as atrial fibrillation, atrial flutter as well as normal sinus rhythm when compared to 12-lead ECG instruments or ECG chest straps.

Furthermore, the accuracy and precision of the Heart-rate measurements acquired by the PPG sensors when compared to the benchmark device is evaluated by the following accuracy measures:

- Mean value: The mean value of all the individual Heart-rate values extracted by the sensor used in this project are compared to the mean value of the measurements by the benchmark device. The least difference there is between the two, the more accurate the sensor is. [43]
- Standard Deviation (SD): The standard deviation measures the amount of variation of a set of measurements from their mean value. For x_i being each individual measurement value and μ being the mean value for a set of N measurements, the standard deviation σ of the set is calculated using the following formula:

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

The smaller the σ for the set of Heart-rate measurements the more precise the sensor is. It is preferable that the standard deviation is small for both the PPG sensor used in this project and the benchmark device. [44]

- Pearson Correlation Coefficient: The Pearson Correlation Coefficient measures the linear correlation between two variables X and Y. It has the value of +1 when there is total positive linear correlation, 0 when there is no linear correlation and -1 when there is total negative linear correlation. For $cov(X, Y)$ being the covariance of X and Y and σ_X, σ_Y the standard deviations of X and Y respectively, the Pearson correlation coefficient $\rho_{X,Y}$ is calculated using the following formula:

$$\rho_{X,Y} = \frac{cov(X, Y)}{\sigma_X \sigma_Y}$$

  It is desirable that the Heart-rate measurements from the PPG sensor will have as high correlation coefficient as possible when measuring its linear correlation with the benchmark device. [45]

- Mean Absolute Percentage Error (MAPE): The MAPE measures the mean value of the error between the measurements of the Heart-rate PPG sensor and the benchmark device. For A being the value from the PPG sensor and B the value from the benchmark device for a set of N measurements, the MAPE is calculated by the following formula:

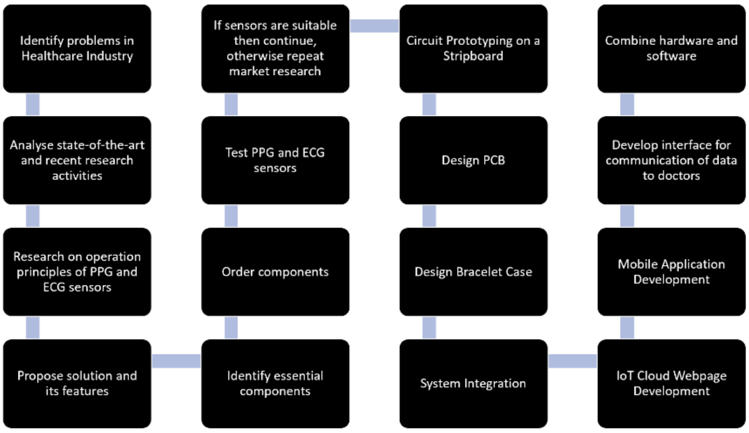
$$MAPE = \left(\frac{1}{N}\sum_{t=1}^{N}\frac{A - B}{B}\right) \times 100\%$$

  The smaller the value of MAPE, the more accurate the PPG sensor is. [46]

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

2.2. Methods

The successful implementation of the project, aiming to develop a medical bracelet for passive monitoring of the heart rate and the ECG, required a clearly defined plan. Figure y shows the Flowchart of the methodology:



More specifically, the order of steps was the following:

- Researched on problems to be solved 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, which would be particularly useful for elderly people
- Analysed the state-of-the-art solutions and recent research activities on the measurement of vital signs 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, communication of real-time data to a doctor enabling prompt action in emergency situations
- Identified what components were needed 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 Application Development Platform
- Ordered off-the-shelf components which provided merits in size and cost
- Tested the correct functionality and 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 or would produce custom-made sensors
- Prototyped a stripboard with all the system components and the interface circuit between them
- Designed the interface circuit between the components on a PCB
- Designed the bracelet case's mechanical design on a 3D CAD tool (Altium, …), which was implemented by 3D-printing it
- Integrated the PCB with the components of the system
- Assembled the bracelet case with the PCB and the other electrical components
- Developed an IoT cloud page on the Ubidots platform where the information from the sensors is sent for displaying purposes
- Implemented the feature of sending automatic warnings through SMS in case of irregular heart condition

- Constructed a mobile application using the Blynk platform, which displays the heart rate and ECG on the screen of a phone
- Improved the feature of communicating the measurements to a doctor in real-time and enabled the direct communication between patients and doctors
- Combined the hardware design with the code to complete the product and project implementation

Feedback: a flow chart to provide a high level view of the methodology followed would be helpful, In its current form the methodology appears to start immediately on the technical choice of content without any introduction with an overall picture. Overall this a good piece of work even though it lacks the precursor to the individual sections and the order and linkage between them.

2.3. Design

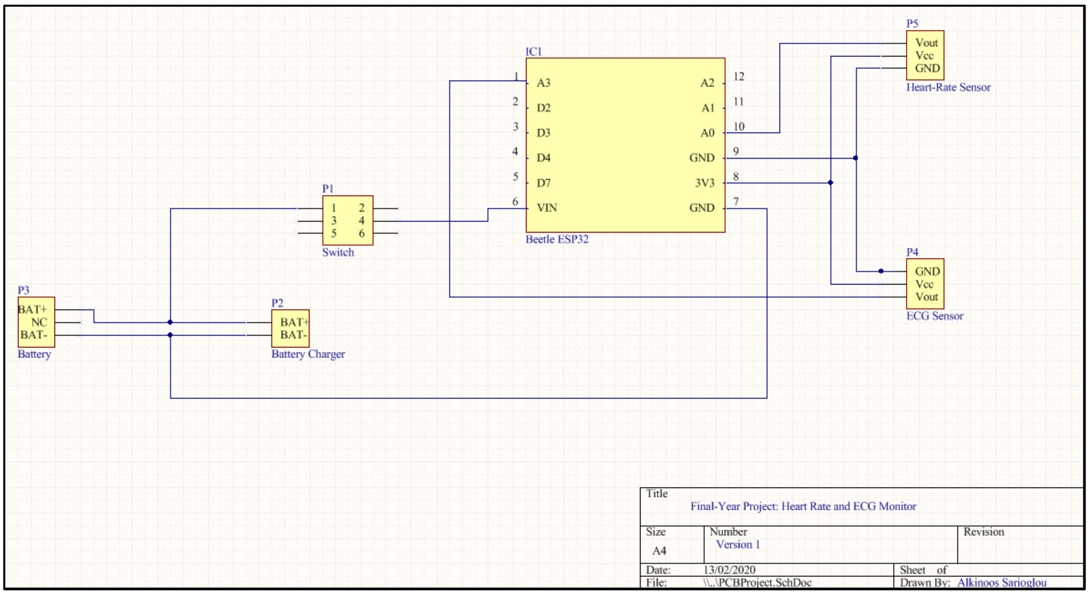
2.3.1. Overview of Components

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
- Switch

2.3.2. Schematic Diagram

The following schematic diagram shows how the electrical components of the system were connected:



The schematic diagram is designed using a PCB design automation package (Altium Designer, Version 20, Altium, California, USA).

2.3.3. Electrical Connections

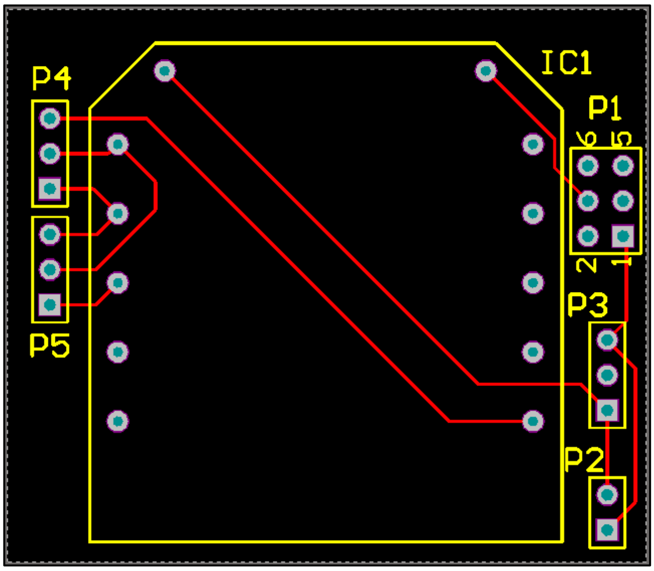
As shown in Figure r, the following electrical connections were required between the components:

Wi-Fi module	Heart Rate Sensor
3.3 V	Vcc
GND	GND
Analogue Pin A0	Vout
Wi-Fi module	ECG Sensor
3.3 V	Vcc
GND	GND
Analogue Pin A3	Vout
Wi-Fi module	Battery
VIN	BAT+

GND	BAT-
Battery Charger	Battery
BAT+	BAT+
BAT-	BAT-

2.3.4. Printed Circuit Board Layout Diagram

The interface circuit was then implemented on a single-layer PCB, which significantly reduced its size making it easier to include in a medical bracelet device and less disturbing for the users. The PCB Layout diagram as designed on the PCB design automation package (Altium Designer, Version 20, Altium, California, USA) is demonstrated below:



The designators shown on the PCB Layout Diagram of Figure 2 correspond to the following components:

Designator	Component
IC1	Wi-Fi module
P1	Switch
P2	Battery Charger

P3	Battery
P4	ECG Sensor
P5	Heart-Rate Sensor

2.3.5. 3D-CAD Bracelet Case Design

The final part of the Design phase relates to the mechanical design of the bracelet case, which included the electronics. The bracelet was designed on a 3D CAD tool (SolidWorks, Version, Company, City, Country).

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 were decided to be:

Width	48 mm
Length	53.5 mm
Thickness	40 mm

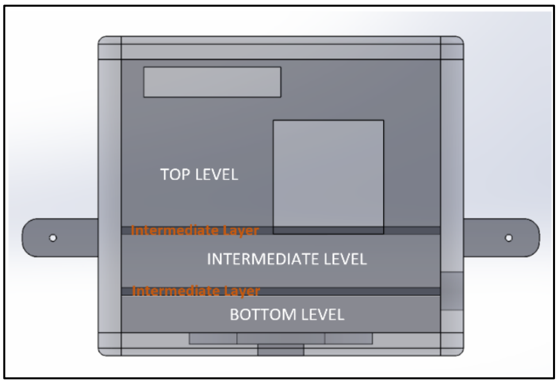
The mechanical design of the system is composed of the following parts:

- Outer hollow Case (3D-printed)
- Cover Layer (3D-printed)
- 2 intermediate layers (Laser-cut)

The 2 intermediate layers separate the mechanical configuration of the components inside the case into 3 levels:

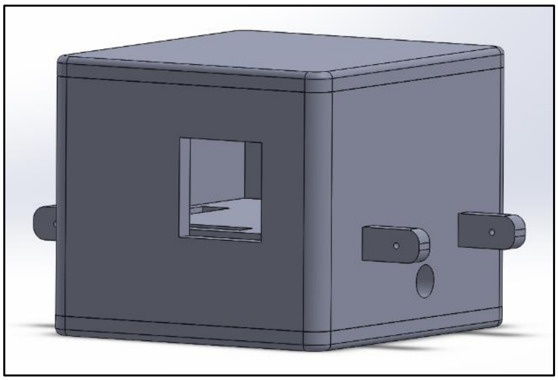
- Top Level, which includes the PCB, the Battery and the Battery Charger
- Intermediate Level, which includes the ECG sensor
- Bottom Level, which includes the Heart Rate sensor

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

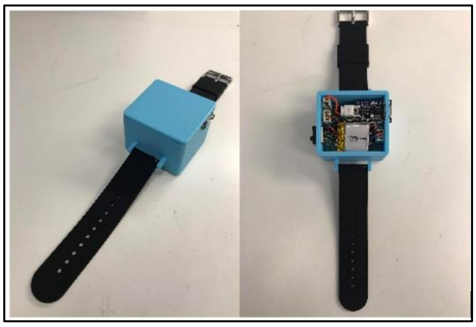


On the Outer Case, holes are included to allow for placement of the switch, the jack input port for the ECG electrodes and the mini USB B port for charging the battery.

Overall, the high-level view of the bracelet case is the following:



Then, the electrical components are inserted in the bracelet case and a watch strap is attached to produce the final product:



2.4. Implementation

2.4.1. Electrical Components

<u>How is the circuit designed, circuit diagrams, PCB diagram, 3D-CAD design of the bracelet</u>

For the implementation of the medical bracelet 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 technique of Photoplethysmography (PPG) to record the heart activity. Its operation is based on two green LEDs which emit light on the skin of the patient and on a photodiode in the sensor which measures the reflected light from the skin tissues. The photocurrent produced is then converted to an output voltage through a loading resistor. Appropriate calculations in the code allow conversion of the output voltage to the value of heart rate of the patient in BPM.

Two Heart Rate Sensors were tested, as described in the Testing section, in order to decide on the most suitable one and in the end the DFRobot Gravity Heart Rate Monitor Sensor for Arduino was selected for this application.

The integrated circuit (IC) of the sensor incorporates the SON1303 Integrated Heart Rate Sensor, which includes the LEDs and the photodiode. Additionally, the SON3130 chip is included which performs amplification of the photodiode's voltage and provides the following advantages:

- Low input bias current of 10 pA
- Low supply current of 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 a bracelet. Furthermore, it demonstrated more accurate measurements than the MAXREFDES117# sensor, which lay closer to the data extracted from the benchmark device as shown in the Results section. Finally, the cost was only 30p more expensive than the competitive sensor, therefore offering more advantages for a negligible difference in price.

Some of its electrical characteristics include [54]:

Input Voltage	3.3 V – 6 V (5 V recommended)

Output Voltage	0 V – Vin (Analogue Mode) , 0 V / Vin (Digital Mode)
Operating Current	<10 mA

Table 1: Electrical Characteristics of the DFRobot Gravity Heart Rate Monitor

ECG Sensor

As seen in the Theoretical Development section, the operation of the ECG sensor is based on the monitoring of the electric potential from the different electrodes attached in separate parts of the body which are then combined to give the output ECG graph.

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 on a patient 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 great benefits [55] such as:

- Low supply current of 170 µA
- Common-mode rejection ratio of 80 dB
- High signal gain (G=100)

Additionally, it combines the voltage input of three electrodes attached to the appropriate positions on the body, as described in the Theoretical Development section, to extract a 3-lead ECG graph.

As the size is an important factor of the device as well, this IC’s dimensions are 35 mm x 22 mm, which fits inside the dimension range of the bracelet.

Finally, its electrical characteristics include [56]:

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

Table 2: Electrical Characteristics of the Gravity Analog ECG

Wi-Fi Module

A Wi-Fi module is used for the communication of the Heart Rate data and the ECG output voltage to an IoT Cloud Service, where the data is displayed in a user-friendly environment.

For this application, the Beetle ESP32 Wi-Fi module was selected as it provides Wi-Fi and Bluetooth connectivity, multiple ADC channels for sampling the analogue voltages of the sensors and GPIO pins.

This IC offers the following features:

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

Table 3: Features of the Beetle ESP32 Wi-Fi

The module provides a micro-USB port, in order to be able to program the board directly. Furthermore, the board 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 the frequency range is between 2.4 GHz and 2.5 GHz [57].

The board provides advantages in size as well, as its dimensions are 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 n:

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 to certain features:

- Rechargeability
- Small size
- Low mass

Therefore, it was decided that the medical bracelet would be powered by a Lithium Polymer Rechargeable Battery with nominal voltage of 3.7 V and rated capacity of 190 mAh. 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 [58]. Furthermore, according to the power budget calculated above the lifetime of the battery will be:

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

Additionally, the charging time is approximately 1 hour [58].

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 from a separate power source and offers the following features [59]:

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

2.4.2. Software Components

Two software components are necessary to be able to receive the information of heart rate and ECG from the Wi-Fi module and display the results in a user-friendly environment. One of the aims of the project is to provide flexibility in the way that users and doctors view the results, therefore two means of displaying information were developed, an IoT Cloud Service (for computer users) and a mobile application (for smartphone users). These were created by using the:

- Ubidots IoT Cloud Service and the
- Blynk App Development Platform

On one hand, Ubidots is an IoT platform in which developers can easily communicate data from sensors and display them using different means of presentation, such as Line Charts, Graphs, Histograms and more. It provides support with Arduino libraries for multiple Wi-Fi modules such as the Beetle ESP32 used in this application.

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+ [60]. Furthermore, Blynk applications can receive data using Wi-Fi connection from a diverse set of Wi-Fi modules, including the ESP32 module used here.

2.4.3. Mechanical Component

The electrical components on the PCB were assembled with the mechanical component of the system to provide ease of use by the patients. This is a:

- 3D-printed bracelet case

The bracelet case has a compact design in order to fit all of the components in a small area.

2.4.4. Procedure

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).

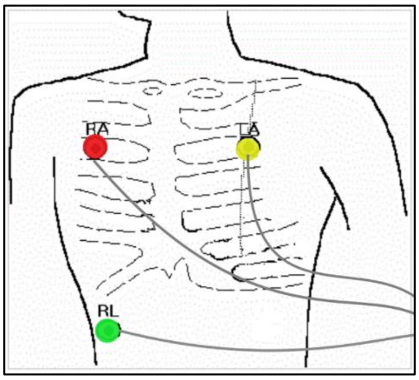
In order to set up the Arduino IDE to be compatible with the Beetle ESP32 Wi-Fi module and communicate the data to the Cloud, the following additional equipment/tools were needed:

- USB A to mini USB B cable

- Computer with installed Arduino IDE, Ver. 1.8.11.
- Ubidots IoT Cloud Service Account

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

- The Arduino IDE environment was initiated and the ESP32 support for the Arduino environment was installed so that the ESP32 Wi-Fi module could be accessed [61].
- The “FireBeetle-ESP32” from the “Board” options in the “Tools” drop-down menu was selected.
- The .zip file for the “PubSubClient.h” file was downloaded and included it as a library in the Arduino project along with the “WiFi” Arduino library [62].
- The strap was attached on the heart-rate sensor, so that it took the form of a bracelet.
- The heart-rate sensor was worn on the left wrist very tightly with the sensor touching the upper side of the wrist.
- The biomedical pads with the conductive gel were connected to the ECG electrode cables.
- The three ECG electrodes on the user’s body were attached according to the following figure:



The connections made are summarized in the following table:

ECG Electrodes	Body parts
RA or R	Right part of the chest or Right arm
LA or L	Left part of the chest or Left arm
RL or F	Right part of the abdomen or Right leg

- 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 A.
- 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.
- The Arduino code was downloaded to the Wi-Fi module, which communicated the data to the Ubidots Cloud Service and the Blynk Mobile Application.

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

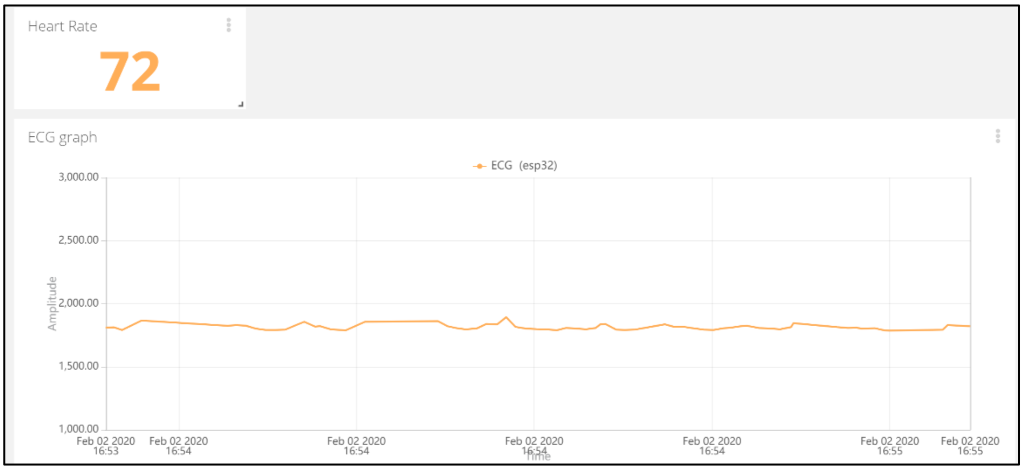
- A Ubidots Account was created at https://ubidots.com/.
- On the "Devices" screen, a new device was added named "esp32".
- Inside the device options, two new variables were created called "Heart-rate" and "ECG", which were assigned the instantaneous values of heart rate in BPM and the electric potential measured by the ECG device in order to produce the ECG graph respectively.
- On the "Dashboard" screen, two new widgets were created. One of them was a Metric and displayed the live measurement of the heart rate in BPM. The other one was a Double Axis graph, which demonstrated the live ECG graph of the user.
- The Heart-rate Metric widget was linked with the "Heart-rate" variable created before and the most recent value was displayed.
- The ECG Double Axis widget was linked with the "ECG" variable created before 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 was extracted from the website, by selecting "API Credentials" from the drop-down menu after clicking on the User image, and it was copied to the corresponding 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.

After the successful completion of this procedure, the system was ready to take measurements from the user, communicate them to the IoT Cloud and the Mobile application, and display them for analysis by a doctor.

An example of the dashboard displaying the Heart Rate measurement in BPM and the ECG graph is shown:



In order to set up the Blynk App Development Platform and create the Mobile App which will display the results the following steps were essential:

ADD STEPS ON THE APP DEVELOPMENT

2.5. Testing

What components are used, how they are connected

2.5.1. Introduction

For each of the individual parts of the system, different off-the-shelf components were tested in order to select the most suitable one for this application according to the design specifications and priorities.

2.5.2. Testing of Sensors

Heart – rate sensor

In order to find the most suitable heart rate sensor for this application, two sensors are tested. These are the following:

- DFRobot Gravity Heart Rate Monitor Sensor for Arduino
- Maxim Integrated MAXREFDES117#: Heart-rate and Pulse-oximetry monitor

As a benchmark of accuracy, the Heart Rate app on the Apple Watch Series 5 © [1] is used as well.

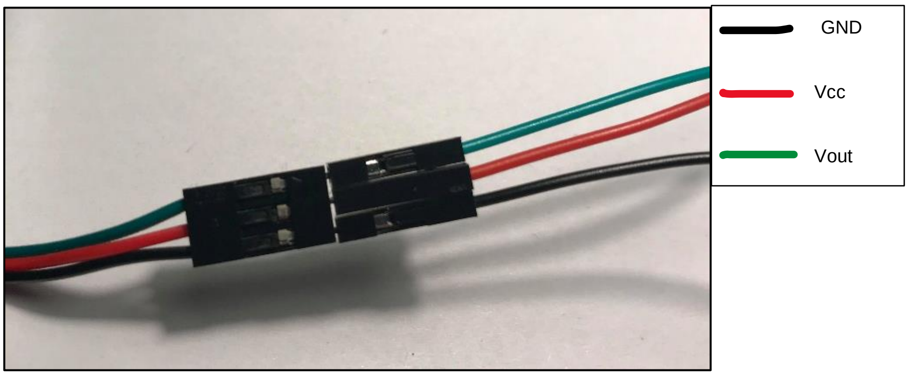
For the DFRobot Gravity Heart Rate Monitor Sensor:

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

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

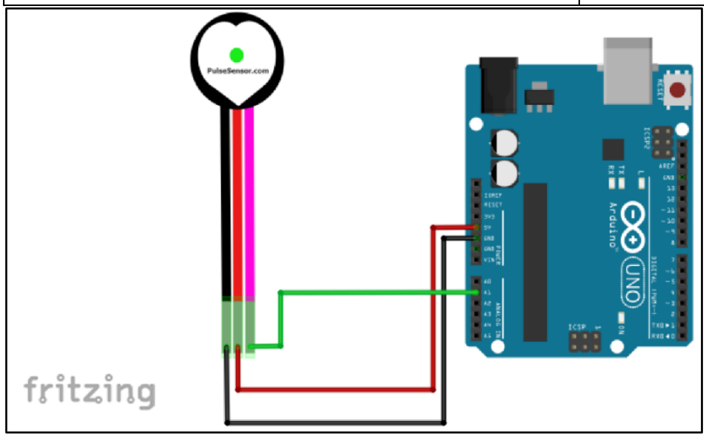
The steps followed for the set-up of the testing procedure are:

- Wear on the left wrist very tightly both DFRobot sensor and the Apple Watch Series 5 with the sensor touching the upper side of the wrist.
- Attach three stranded jumper wires in each of the pins of the female connector at the end of the DFRobot sensor.



- Make the following connections of the DFRobot sensor to the Microcontroller board. For the Arduino UNO the connections are the following (mention connections – add diagram):

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



- Turn the switch on the sensor to the “Analogue” mode.
- Connect the Arduino UNO to the computer.
- Navigate to the GitHub page of the DFRobot sensor and download the libraries and the example code needed [63].
- Open the “DFRobot_Heartrate_Analog_Mode” file on the IDE and download the code shown in Appendix B to the Microcontroller board.
- Turn off any light sources which might cause interference to the sensor.
- Open the Serial Monitor.
- Open the Heart Rate app on the Apple Watch.
- Record a video showing both live measurements from the Apple Watch and the Serial Monitor for the DFRobot Gravity Heart Rate Sensor.
- Take 1 sample per second for 80 seconds.
- Input the recorded data to a spreadsheet (Microsoft Excel, Ver. 2010, Microsoft, Redmond, WA, USA).

- Plot a graph to show the accuracy of the sensor related to the measurements of the Apple Watch.
- Repeat process 3 times for validity of measurements.

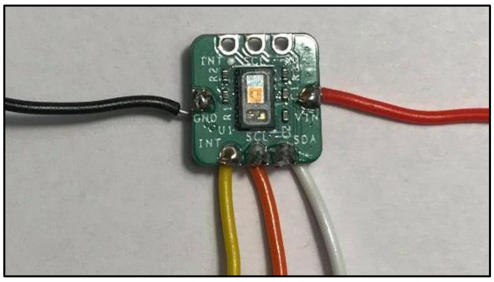
Then the sensor's accuracy is tested in many different conditions, such as analogue and digital operation modes, above and below the wrist, with the arm moving during the measurement, with wet arm and with ambient light sources turned on. The graphs demonstrating the outcomes are presented in the Results section.

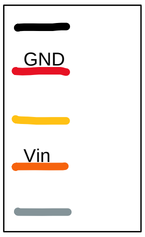
<u>For the MAXREFDES#117 Sensor:</u>

In order to test the accuracy of this sensor, the same additional equipment as above is used.

The steps required for the set-up of the testing procedure are the following:

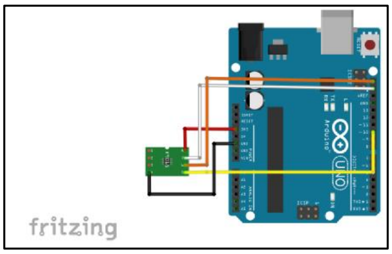
- Wear tightly on the left wrist the Apple Watch with the sensor touching the upper side of the wrist.
- Solder five stranded jumper wires in each of the pins of the sensor PCB.





- Connect the MAXREFDES#117 sensor to the Microcontroller board. The connections to the Arduino UNO in this case are:

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



- Connect the Arduino UNO to the Computer.
- Navigate to the Maxim Integrated manufacturer website and download the design files which include an example code [64].
- Open the "RD117_ARDUINO" file on the IDE and download the code shown in Appendix C to the Microcontroller board.
- Turn off any light sources which might cause interference to the sensor.
- Open the Serial Monitor.
- Open the Heart Rate app on the Apple Watch.
- Record a video showing both live measurements from the Apple Watch and the Serial Monitor for the MAXREFDES#117 Sensor.
- Take 1 sample per second for 80 seconds.
- Input the recorded data to a spreadsheet (Microsoft Excel, Ver. 2010, Microsoft, Redmond, WA, USA).
- Plot a graph to show the accuracy of the sensor related to the measurements of the Apple Watch.
- Repeat process 3 times for validity of measurements.

The sensor is then tested under the same conditions as the DFRobot Sensor in order to compare performance and decide on the most suitable sensor for the device.

ECG Sensor

As far as the Electrocardiograph (ECG) sensor is concerned, there is a limited number of off-the-shelf components. For that case, one sensor is tested, the Gravity Analog ECG sensor for Arduino.

As a benchmark of accuracy, the Heart Rate app on the Apple Watch Series 5 [1] is used here too.

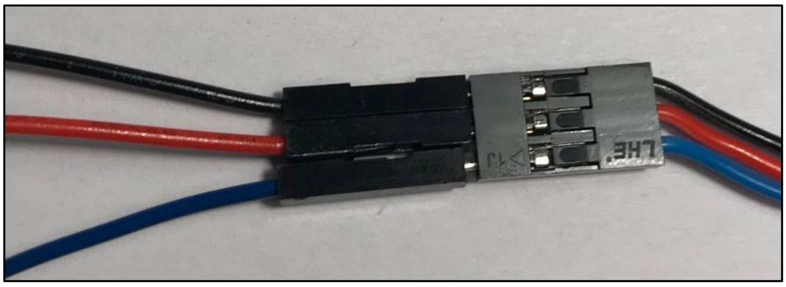
In order to test the accuracy of this sensor, the following additional equipment is used:

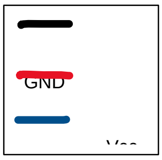
- Microcontroller Board (Arduino UNO, Rev3, Arduino, Italy)
- Jumper Wires (Single-core)
- Computer with installed Integrated Development Environment compatible with the Microcontroller (Arduino IDE, Ver. 1.8.11, Arduino, Italy)
- 3 x Biomedical Sensor Pads

The testing procedure includes:

- Connect the biomedical pads to the three electrodes and remove the plastic protection.

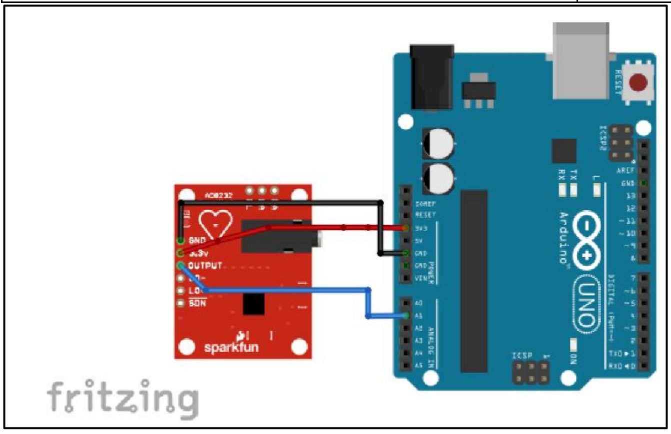
- Attach the three electrodes on the body of the user according to the configuration explained in the “Implementation” section (Figure k – mention the one for the placement of the electrodes in that section).
- Wear on the left wrist very tightly the Apple Watch Series 5 with the sensor touching the upper side of the wrist.
- Attach three stranded jumper wires in each of the pins of the female connector at the end of the Gravity Analog ECG sensor.





- Make the following connections of the ECG sensor to the Microcontroller board. For the Arduino UNO the connections are the following:

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



- Connect the Arduino UNO to the computer.
- Navigate to the GitHub page of the DFRobot sensor and use the sample code given [65].
- Open the sample code, shown in Appendix D, on the IDE and download it to the Microcontroller board.
- Open the Serial Plotter.
- Open the Heart Rate app on the Apple Watch.
- Save a snapshot of the recorded ECG graph recorded from the Gravity Analog Sensor.
- Save the ECG graph recorded from the Apple Watch into a PDF and compare the results, which are demonstrated in the “Results” section.

Wi-Fi Modules

The data acquired by the sensors will be transmitted to the network by using a Wi-Fi module. Two off-the-shelf components are tested to compare performance and by considering further parameters such as size and cost to decide on the most suitable one for the medical bracelet. The functionality of the Wi-Fi modules is tested by transferring data from the heart-rate sensor to the Ubidots IoT cloud, in order to display them in a user-friendly environment.

<u>For the ESP32-DevKitC V4 Wi-Fi module:</u>

The following additional equipment is needed:

- Prototyping board
- Heart – rate sensor with three attached jumper wires (the same wires as before)
- USB A to mini USB B cable
- Computer with installed Arduino IDE, Ver. 1.8.11.
- Ubidots IoT Cloud Service Account

The steps followed to successfully test the functionality of the ESP32-DevKitC Wi-Fi module include:

- Open the Arduino IDE environment.
- Install the ESP32 support for the Arduino environment so that the ESP32 Wi-Fi module can be accessed.
- Select the “ESP32 Dev Module” from the “Board” options in the “Tools” drop-down menu.
- Download the .zip file for the “PubSubClient.h” file and include it as a library in the Arduino project along with the “WiFi” Arduino library.
- Place the Wi-Fi module on the prototype board.
- Make the following connections from the Heart-rate Sensor to the Wi-Fi module on the prototype board:

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

- Wear on the left wrist very tightly the heart-rate sensor with the sensor touching the upper side of the wrist.
- Connect the Wi-Fi module to the Computer using the USB A to mini USB B cable.

- In the Arduino code replace the WIFISSID, PASSWORD according to the local network as well as the TOKEN from the Ubidots account and a random MQTT_CLIENT_NAME.
- Download the Arduino code, shown in Appendix E, to the Wi-Fi module, which will communicate the data to the Ubidots Cloud Service.
- Live update of the heart rate in Beats per Minute (BPM) appears in the Dashboard of the device.

<u>For the Beetle ESP32 Wi-Fi module:</u>

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. 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.

2.6. Results

2.6.1. Heart-rate sensors

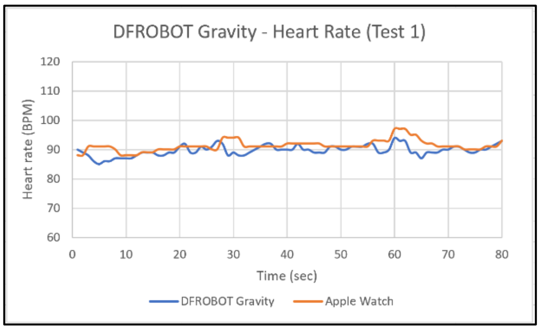
The two Heart-rate sensors selected for comparison were the DFRobot Gravity Heart Rate Sensor and the MAXREFDES#117. These two sensors were tested two times and their accuracy on measuring the Heart-rate in BPM was compared to the values of the benchmark device by plotting a comparative graph. Then, some accuracy metrics are calculated to compare quantitatively the accuracy of the two sensors. More specifically, these are:

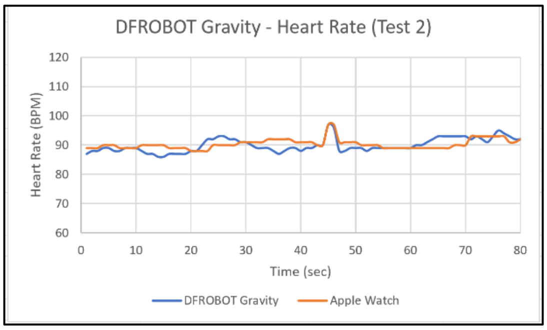
- the Mean ± Standard Deviation (SD) heart rate in BPM,
- the Pearson product-moment correlation coefficient r and
- the Mean Absolute Percentage Error (MAPE) ± SD.

These are calculated according to the guidelines presented in the “Measures of Accuracy” section of the Theoretical Development. Following this, the selected sensor was tested under different operating conditions in order to examine its accuracy and precision when compared to the benchmark device. The results are presented here.

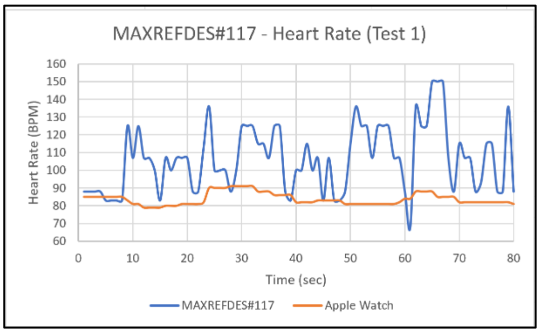
Selection of Heart-Rate Sensor

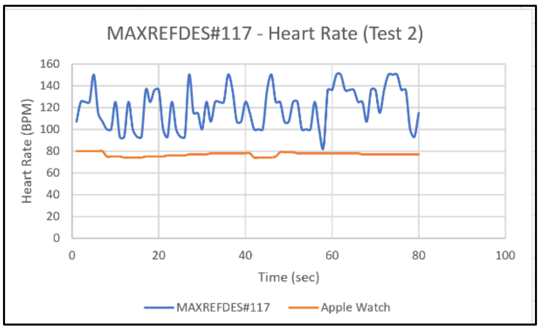
- DFRobot Gravity Heart Rate Sensor





- MAXREFDES#117 Sensor





Even though it is obvious from the graphs that the DFRobot Gravity Heart Rate Sensor is more accurate than the MAXREFDES#117, it is useful to extract the previously mentioned measures of accuracy which demonstrate that. Tables k and l illustrate the calculated measures according to the individual measurements taken from the two sensors and the corresponding values from the benchmark device.

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	90 ± 2.4	0.485	-0.46 ± 2.36

	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

As seen from the Tables, DFRobot Gravity extracted measurements which lay closer to the benchmark device, because the 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 where bigger, which shows greater agreement in the points of variant heart rate with the benchmark device. Further comparisons related to cost, size and weight presented in Table m:

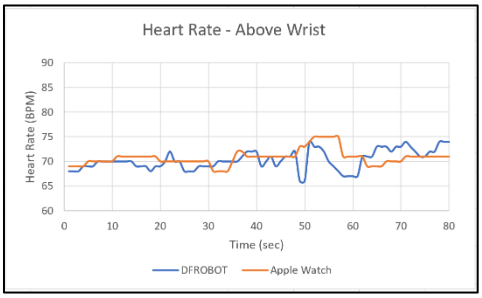
Sensor	Cost	Size	Weight
DFRobot Gravity Heart Rate Sensor	£13.07	28 mm x 24 mm	300 g
MAXREFDES#117	£12.68	12.7 mm x 12.7 mm	250 g

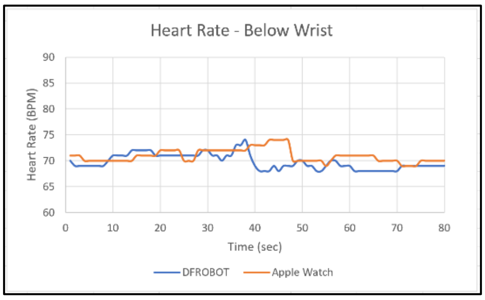
Even though the MAXREFDES#117 Sensor offers benefits in cost and size, it cannot be considered a suitable sensor for this application due to poor accuracy. Furthermore, the DFRobot Gravity Heart Rate Sensor provides great accuracy for negligible difference in cost and size that does not pose considerable limitations in the size of the device.

Consequently, the comparative graphs and tables demonstrate that the DFRobot Gravity Heart is the most suitable PPG sensor for this project. The next factor to be determined was the position of the sensor on the wrist which could the sensor's measurements are more accurate when it is worn above or below the wrist bone.

Wrist Position

- Below Wrist
- Above Wrist





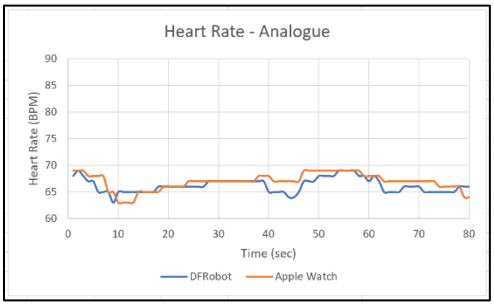
Test	Device	Mean ± SD (BPM)	Correlation Coefficient r	MAPE ± SD (%)
Above Wrist	Apple Watch (Benchmark)	70.8 ± 1.6	1	
	DFRobot Gravity Heart Rate Sensor	70.3 ± 2	0.087	-0.68 ± 3.37

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

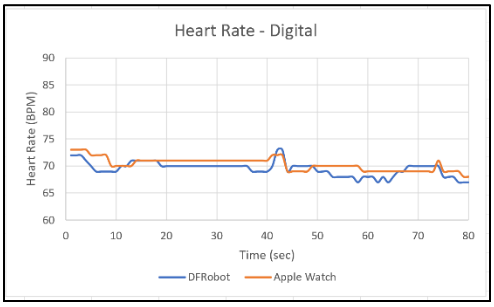
The accuracy measures demonstrate that when the sensor is placed below the wrist bone it has a bigger correlation coefficient but also a higher MAPE than when it is placed above. It is apparent that the position does not influence the measurements significantly, therefore there is no particular preference for this option. Following this, it is interesting to look into the accuracy of measurements when the output voltage is in analogue or digital form.

Analogue vs Digital Mode

- Analogue



- Digital

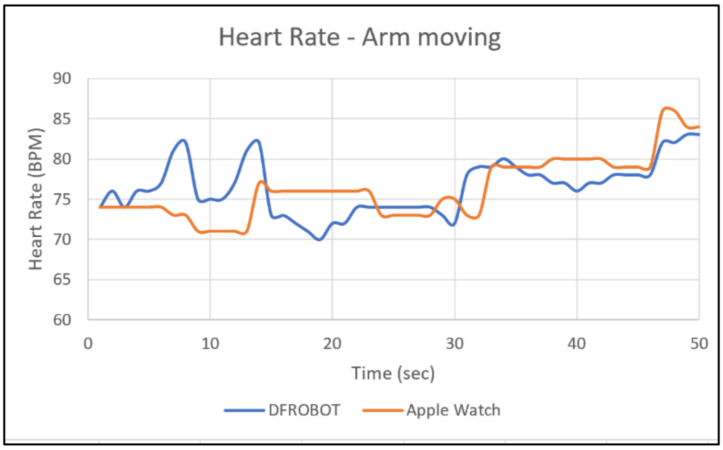


Test	Device	Mean ± SD (BPM)	Correlation Coefficient r	MAPE ± SD (%)
Analogue Mode	Apple Watch (Benchmark)	66.9 ± 1.5	1	
	DFRobot Gravity Heart Rate Sensor	66.2 ± 1.3	0.662	-1.04 ± 1.81

Test	Device	Mean ± SD (BPM)	Correlation Coefficient r	MAPE ± SD (%)
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

The comparative graphs and tables for the two modes illustrate that in Analogue Mode the measurements have higher correlation coefficient and lower MAPE, hence the Analogue Mode is more accurate and it is used in the operation of the sensor in the medical bracelet.

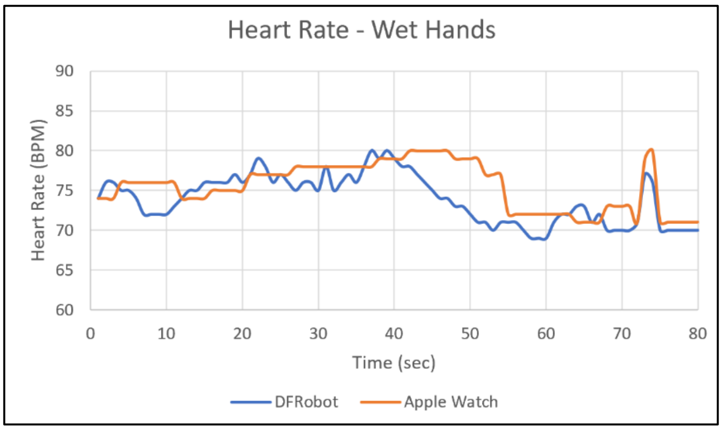
Arm Moving



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

Figure a and Table b present the results of the examination of the sensor's accuracy in real-life conditions, hence with the arm moving. It is fortunate that the sensor demonstrated strong agreement with the benchmark device with a Mean heart rate of 76.5 BPM when compared to 76.4 BPM of the Apple Watch. Also, the MAPE was 0.3% and the correlation coefficient was at the level of 0.465 which shows that the sensor would operate accurately under real-life conditions.

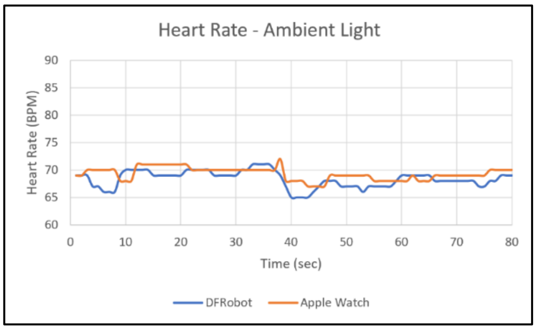
Wet Hands



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

The next assessment of accuracy was performed under conditions of humidity on the skin of the user. Again, the sensor's measurements lay close to the benchmark's values therefore resulting in a MAPE of -2.09% and correlation coefficient of 0.662.

Ambient Light



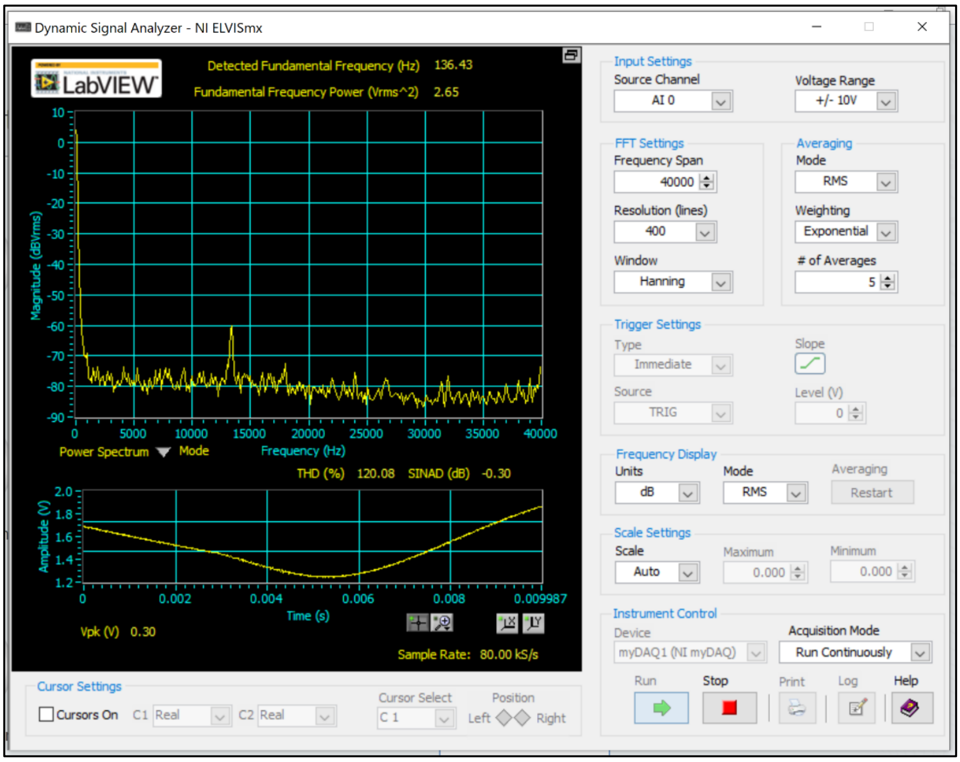
Test	Device	Mean ± SD	Correlation	MAPE ± SD (%)

		(BPM)	Coefficient r	
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

Finally, the sensor was tested under conditions with interfering ambient light. In that case as well the sensor's sensitivity was not influenced significantly as it demonstrated a MAPE of -1.42% and correlation coefficient of 0.494. This proves that the DFRobot Gravity Heart Rate Sensor can perform satisfactorily in all normal operating conditions.

2.6.2. 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, …). The completion of a Dynamic Signal Analysis produced the following results:

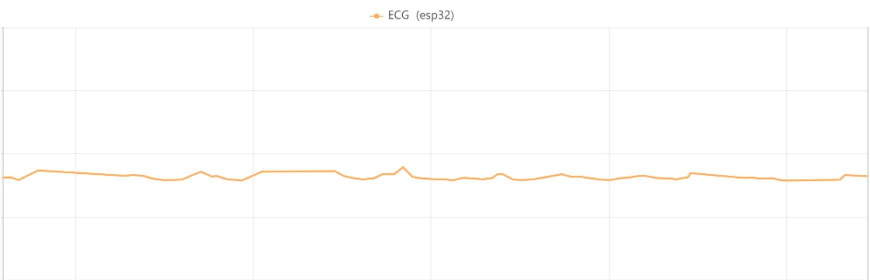


As the Dynamic Signal Analyzer indicates at the top of Figure n, the fundamental frequency of the

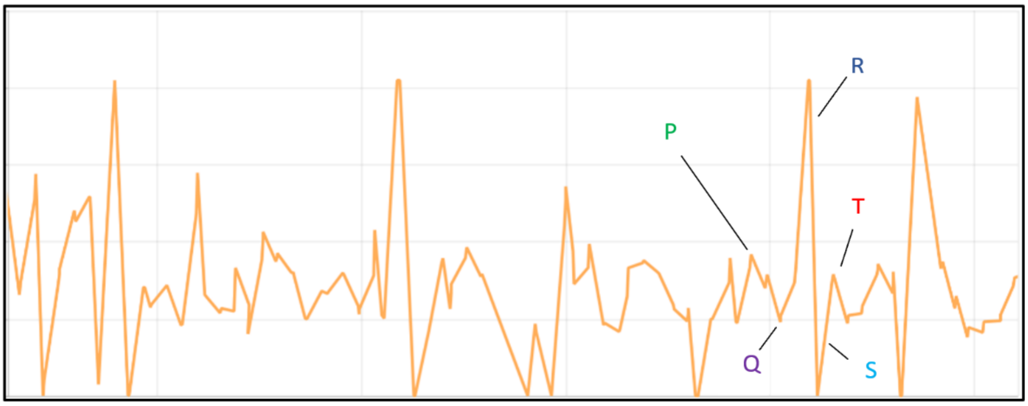
ECG signal is 136.43 Hz, which has power of 2.65 W. Furthermore, it is apparent that there is noise included in the signal occupying the range of frequencies over 1 kHz, which degrades the quality of the signal and results in Signal-to-Noise-and-Distortion-Ratio (SINAD) of -0.3 dB or 0.97 in linear scale, as shown in the middle of Figure n. As a result, a suitable FIR filter would certainly benefit the quality of the signal produced, in order to remove the noise outside of the signal bandwidth. This would be included as part of the future improvements and it would contain the following characteristics:

- Band-pass filter with centre frequency of 136 Hz
- Blackman window applied for reduction of the side lobes
- Linear-phase to preserve the shape of the signal
- 511 or 1023 taps to ensure effective filtering

Afterwards, the ECG sensor was tested with the Arduino UNO board as explained in the "Testing" section. At the same time, the Heart Rate app on the Apple Watch was activated to produce the ECG graph as well. The graphs generated by the Gravity Analog ECG sensor and the Apple Watch are shown in Figures u and v respectively:



The graphs demonstrate similarities in the shape of the pulses. However, it can be observed that the signal extracted by the Gravity Analog ECG sensor contains noise which prevents some pulses from being clearly visible. This noise is related to muscular activity, body movement and other reasons which are discussed more extensively in the "Discussions and Analysis" section. By looking closer into the graph, the noise present in the signal can be seen, as illustrated in Figure i. Nevertheless, the basic deflections named PQRST of a medical ECG graph, as presented in the "Theoretical Development" section, are still visible:



The signal degradation due to noise is likely to be mitigated with the implementation of the FIR filter as discussed before.

2.7. Discussions and Analysis

2.7.1. Reminder of Purpose of Work

Medical bracelets are proved to be useful tools in monitoring the heart condition of their users passively and intelligent algorithms can warn on suspicious irregularities in order to prompt immediate action.

2.7.2. Comment on the Results

An assessment of the device's merits draws the conclusion that it first provides significant advantages in cost of production. More specifically, for the integration of one unit of the medical bracelet the following expenses were required:

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 whereas these are not provided combined in the majority of the marketed products currently, as explored in the "State-of-the-art" section. It is also important to mention that in case of a heart rate or ECG measurement irregularity the information can directly be displayed on the IoT Cloud Service and the Mobile Application display screen, which can be used to send emergency notifications to doctors and allow them to assess their patient's condition in real-time. Most importantly, as mentioned in the Introduction, the device does not require advanced technical skills to be used, which is very useful for the older people, who belong to the category that needs these wearables devices the most. This is because the bracelet does not require any interaction with the user or a nearby connected device but can just be worn on the patient's wrist and the measurements are directly transmitted to the IoT Cloud Service and the Mobile App for demonstration. Furthermore, keeping in mind the power budget required for the components employed on the bracelet, as presented in the "Implementation" section, 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, the first priority of 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.

Moreover, concerning the accuracy with which this medical bracelet can perform heart monitoring appropriate calculations were performed in the "Results" section. These demonstrated that the Heart-rate Sensor selected can be used in real-life conditions as its measurements had Mean

Absolute Percentage Error values of 0.3% when the body was moving, -2.09% with skin humidity and -1.42% with ambient light interference. Overall, the absolute error percentage of -0.46% under normal breathing operating conditions provides confidence in the measurements extracted by the device in real-time which can be useful indicators on whether a heart irregularity occurs. Should this happen, it will be reported by the algorithm run on the IoT Cloud Service and on the Mobile Application.

2.7.3. Limitations and possible failings

During the testing procedure of the heart rate and ECG sensor, there were multiple sources of noise which limited the achievable accuracy. 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 hand

It is a fact that motion artefacts are produced because the contact point between the sensor and the skin is unstable therefore giving rise to unwanted noise in the measurements. 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 [66] and elimination of any movement of the hand. 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 this type of noise poses 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 the artefacts and improve performance [67].

On the other hand, for the ECG sensor these are the following:

- 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 movement and the muscles but in real-life situations they 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 yet.

2.8. Future Work

2.8.1. Improving Accuracy

Undoubtedly, the accuracy of heart rate and ECG measurements is the most crucial feature of a wearable device. Therefore, this would be one of the most fundamental improvements included in future work. This 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. The implementation of these would allow removing the bulky wired electrodes and provide strong attachment to the skin, which would further decrease the impact of motion artefacts. Moreover, the ECG signal's quality would be enhanced with the use of an FIR filter removing the noise involved beyond the signal's bandwidth, as discussed in the "Results" section. These improvements would boost the confidence on the accuracy of the measurements 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.

2.8.2. Improving Size

Another considerable limitation 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 height, which is 40 mm disrupts the comfort of the user. Therefore, another future improvement would be to create a custom System-on-Chip for the application, which would integrate custom-made sensors suitable for the application and the Wi-Fi module in very limited area and would allow overall reduction of the bracelet case size.

2.8.3. Improving the Power Requirements and Cost

The important step of customising the design would optimise the power consumption of the components as well, because the bulky wiring would be removed and the 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 [32]. Forms of energy that could be used to power the system could also include energy produced by the human body, such as muscle movement, footsteps etc [32]. As a direct consequence, the customisation and optimisation of the technology would significantly decrease the overall cost of £94.48 and make it accessible to many more people.

2.8.4. Improving the Presentation of Results

Advancements in the presentation of the results would initiate 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 router they wish.

Regarding the platforms that were used to display the results, i.e. Ubidots IoT Cloud Service and Blynk Mobile Application Development Platform, they both offered significant benefits for the quick development of applications for this project, however as they are general-purpose application platforms they have limitations in the presentation of data that can be achieved. An example lies on the accuracy of the ECG graph, which cannot be represented as a medical ECG measurement, due to the simplicity of the graphs on the IoT Cloud Service used here. Furthermore, it is not possible to develop applications which enable the direct communication between doctors and patients. As a result, a custom-made platform and mobile application would be developed to allow the full range of features to be presented accurately to both the doctors and their patients.

2.8.5. Improving the Security of Data

Finally, as mentioned in the “Literature Review” section, it will 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 patients [14]. This will primarily be achieved by encoding and decoding the data over the network and developing highly protected platforms which will not compromise the privacy of the users.

2.9. Conclusions

Overall, the astonishing features of wearable devices need to be accessible to every person, regardless of age or technological literacy. During this project, the successful development of a medical bracelet which provides continuous heart monitoring was achieved and that way the benefits of wearable electronics can be made available to everyone. Future advancements in the sensors' accuracy, size and power requirements would allow eventually this product to become FDA approved or cleared and therefore available in the market of portable medical devices.

3. References

- Referencing: give full publication details, use reference managers/install one of them -> adjusts the numbering if you change the order or add new references (e.g. Endnote software), DO NOT JUST USE ONLINE REFERENCES, books also
- Articles with DOI numbers mean they are published, they won't get lost
- DO NOT cite Wikipedia as a reference. (open-source material)
- Web of Science/Scopus: databases to find papers related to your work, chance to reference

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[66] https://iopscience-iop-org.manchester.idm.oclc.org/article/10.1088/0967-3334/28/3/R01/pdf -> For example, artefact can arise from ambient light interference but can be reduced in several ways: by suitable probe attachment to the skin (e.g. using a dark Velcro wrap-around cuff), by further shading of the study site area and performing measurements in subdued lighting, and by electronic filtering (e.g. light modulation filtering, Webster (1997)). [For Heart sensor part]

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algorithms being developed right now which aim to improve the performance of the PPG sensor in movement or exercise]

4. Appendices

4.1. Appendix 1

<u>Code for Full System Functionality</u>

```
/*!

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

  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 "BBFF-i9my0HFS82A1erpp5Z58rXDOEfRnqP" // 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

/****************************************
   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 35 // Set the A3/IO35 as SENSOR
```

```
bool turn = true;

/****************************************
   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);
    }
  }
}


/****************************************
   Main Functions
 ****************************************/
void setup() {
  Serial.begin(115200);
  WiFi.begin(WIFISSID, PASSWORD);
  // 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();
  }

  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(10);
  }

}

/***************************************************************
  Copyright (C) <2015>  <linfeng>
  This program is free software: you can redistribute it and/or modify
  it under the terms of the GNU General Public License as published by
  the Free Software Foundation, either version 3 of the License, or
  (at your option) any later version.
  This program is distributed in the hope that it will be useful,
  but WITHOUT ANY WARRANTY; without even the implied warranty of
  MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.  See the
  GNU General Public License for more details.
  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
 ***************************************************************/
```

4.2. Appendix 2

Code for testing the 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)
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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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  Contact: Musk.lin@dfrobot.com
 *****************************************************************/
```

4.3. Appendix 3

Code for testing the MAXREFDES#117 Heart Rate Sensor with Arduino UNO

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

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

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*************************************************************/
#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);
  }
}
```

4.4. Appendix 4

Code for testing the Gravity Analog ECG Sensor with the Arduino UNO

```
/*!

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

* This program tests takes the ECG data from the Gravity Analog ECG
Sensor

* @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);

}
```

4.5. Appendix 5

<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 using the ESP32-DevKitC Wi-Fi module



  CREDITS TO:

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  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 "BBFF-NfWOcO3Li4tQPZq3NaRX1EHJI2WuSz" // 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



/***************************************

 * 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

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

5. Presentation and Content (not included but marked)

5.1. Formatting

5.2. Spelling

5.3. Grammar

5.4. Figures

5.5. Tables

5.6. Diagrams