Electrocardiography heart monitoring using Arduino and cloud analysis

by

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1. Introduction

Background: The motivation behind my project is about introducing a novel solution to the problem of cardiovascular diseases. Cardiovascular diseases combined are the number one cause of death in the world, representing approximately 17 million mortalities globally – 32% of the total worldwide deaths. [1] There is a disproportionality here in that of these 17 million, more than 70% are in low or middle-income countries [2] such as parts of Asia, Eastern Europe and North Africa. It is clear that the less wealthy are more at risk because the majority have no access to proper healthcare.

Looking more specifically at Ireland, despite it being classed as a high-income country, the situation is similar. The most recent statistics show that of the 29,952 registered deaths in 2015, 9,249 – approximately 31% – were attributed to circulatory system diseases [3]. Huge rates of obesity in Ireland – the highest male average body mass index in Europe – combined with long hospital waiting lists mean that the Irish population are not getting the proper healthcare they need. Despite an increasing and aging population in Ireland, the budget allocation for the HSE in Ireland did not increase for a period of 7 years between 2007 and 2014 [4], and combined with private health insurance premiums increasing by almost 50% during the same period [5] results in huge numbers living with heart disease, with an average of 10,000 new cases each year [6].

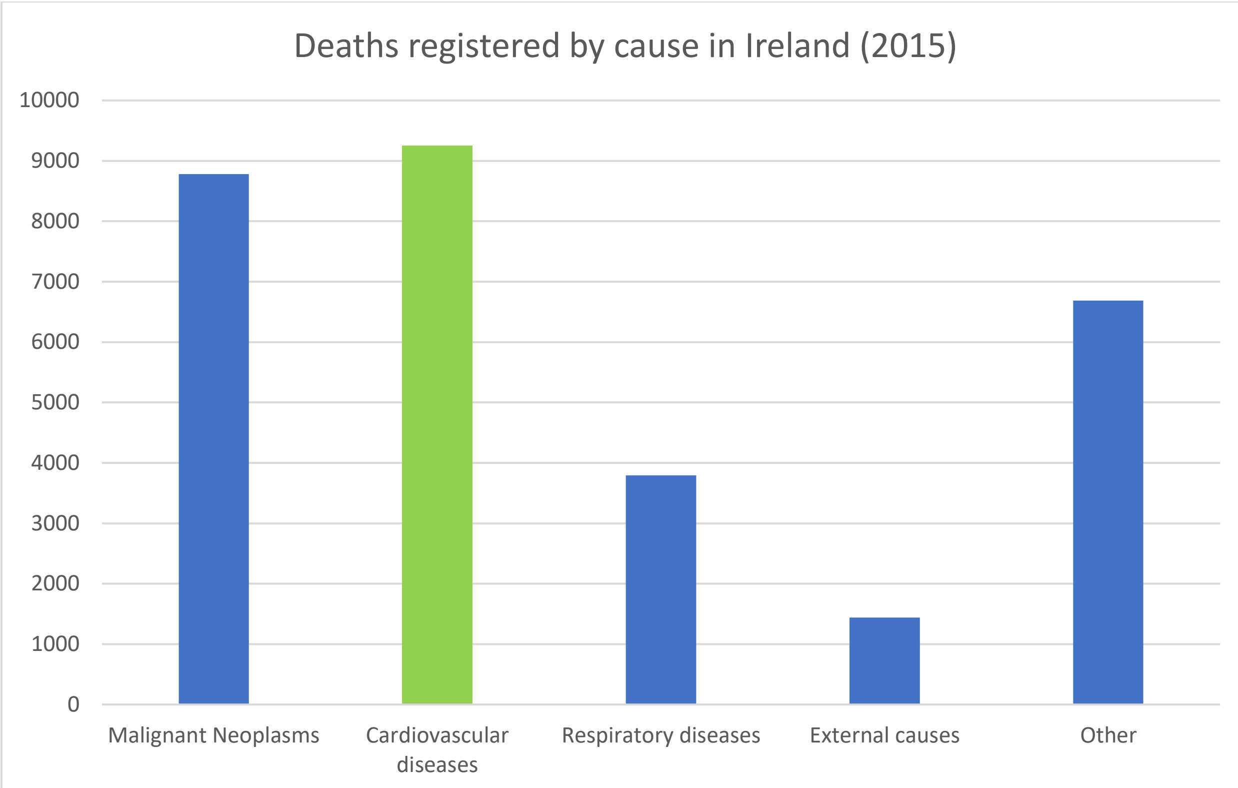

Figure 1.1 – Information obtained by the Central Statistics Office showing the main causes of registered deaths in Ireland 2015[1]

It is clear that current implementations for monitoring and treatment are not enough. According to the Irish Heart Foundation, “heart failure in Ireland is set to dramatically increase”. Without proper healthcare treatment, heart failure can lead to cardiac arrest which can cause permanent brain damage after just 5 minutes, eventually leading to total shutdown of the body’s vital organs and eventual death. Regular monitoring and early diagnoses can help to expose underlying lingering issues in the circulatory system.

[1] http://www.cso.ie/en/releasesandpublications/ep/p-vsys/vitalstatisticsyearlysummary2015/

Project Aim: The problem this project aims to address is how to properly and easily monitor a patient's circulatory system to tackle the increasing issue of heart disease. The ability to automate the monitoring process could help to reduce cardiovascular disease mortality rate, as well as the reduction in healthcare costs in the public health service and in individual patient healthcare premiums. The aim of the project is to develop a novel and cost-effective solution for the heart monitoring process, to provide an initial diagnosis to uncover any abnormalities or underlying issues.

My focus for this project is on developing a low-cost solution to this problem for lower-income areas. As mentioned previously, these lower-income countries are most at risk to CVD and would benefit most from this proposed approach. Additionally, I hope to make the diagnosis process simpler and quicker by providing automated analysis. By running data analytics continuously, automated analysis could be very beneficial for non-specialist GPs and hereby reduce the costs associated with expensive specialists.

Proposed Approach: The project has two main objectives I wish to focus on.

First is the hardware used to monitor the patient's heart health, to accurately measure and transmit the data to the cloud at regular intervals. I opted to use an Arduino Uno microcontroller with Wi-Fi connectivity. The Arduino is a low cost and low power solution and allows the connectivity of various modules, including the ECG heart rate monitor module I used.

The second objective is to develop algorithms to perform data analysis on the patient's heart data. Analysis is performed on the cloud using ThingSpeak. ThingSpeak is an internet of things cloud platform which integrates MATLAB for data analytics. MATLAB is a proprietary programming language and is quicker for prototyping and numerical computing compared to traditional programming languages like Java and Python. Using data analytics, the objective is to detect abnormalities in patient heart health and give quick preliminary results.

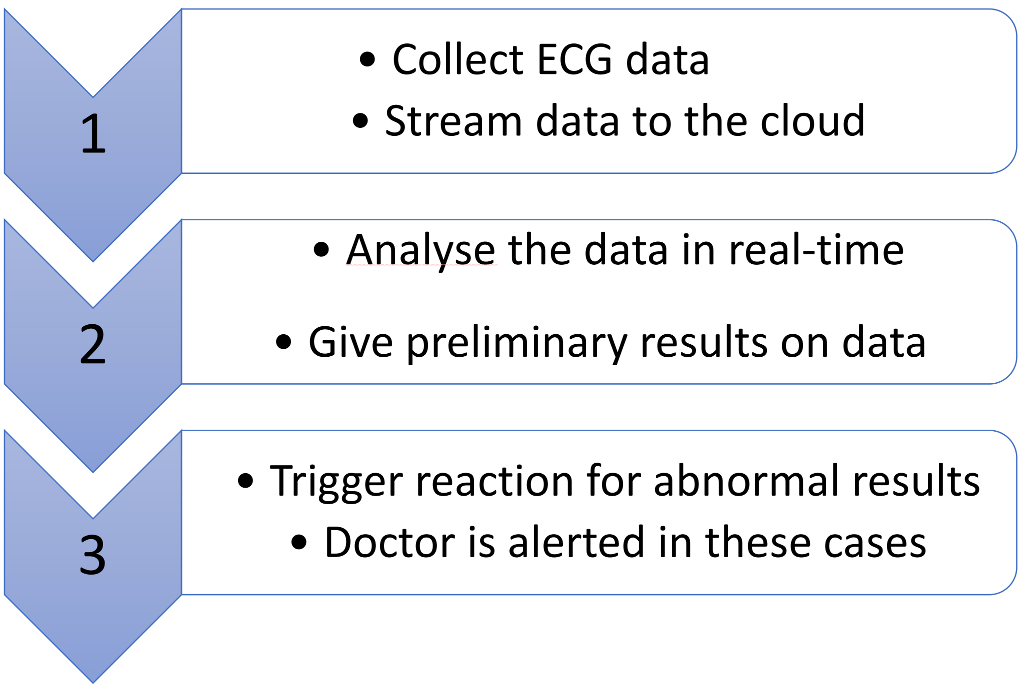

Figure 1.2 – Project approach/breakdown

2. Background Reading

2.1 Internet of Things

The basis of this project revolves around the internet of things (IoT). The IoT is the idea of "anything that can be connected, will be connected". The idea was first introduced by Kevin Ashton, a British entrepreneur who coined the term in 1999 to catch the attention of P&G executives [7]. Since then, the IoT has grown tremendously in popularity, with the last decade seeing billions of new connected devices. The rise in popularity can be attributed to better internet infrastructure for wirelessly connecting devices, the introduction of cloud computing for easily scaling processing resources and Moore's Law, which results in circuitry sizes shrinking constantly – this is most notable in the wearables industry where the devices need to be as small as possible.

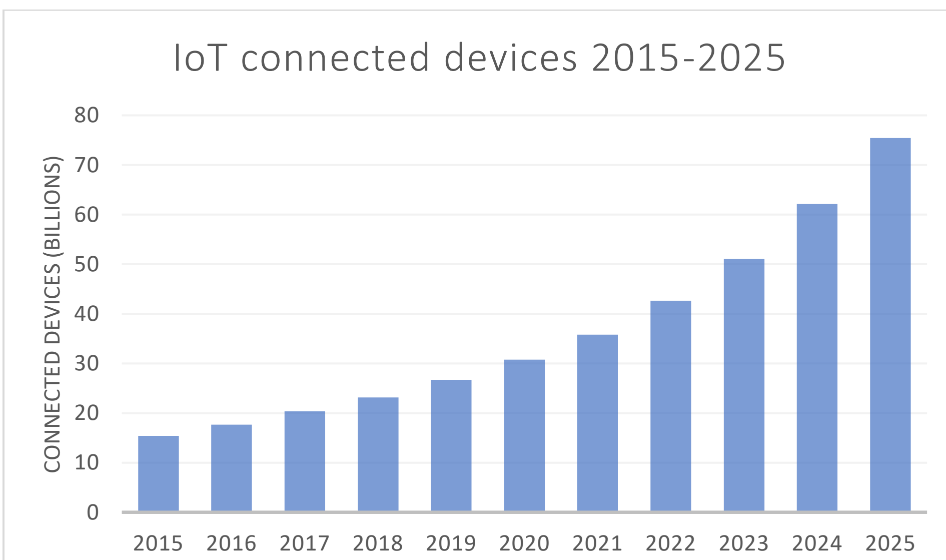

Figure 1.3 – IoT trend showing estimated connected devices (in billions) from 2015 to 2025[2]

[2] https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/

2.2 Heart Rate Monitoring (HRM)

The two most common forms of patient heart rate monitoring are photo plethysmography (PPG) and electrocardiography (ECG). PPG is a low-cost optical based monitoring system. The light-based system detects blood volume changes by illuminating the skin and uses a photodetector to measure the variations in light intensity associated with the changes in blood perfusion [8].

PPG monitoring is a non-invasive form of heart rate monitoring and is therefore considered far more convenient compared to ECG, however it is less commonly used in the medical field. The main reasons for this is that ECG is more accurate due to directly measuring the electrical signals produced by the heart, whereas PPG uses electrical signals which are derived from reflected light changes due to heart activity. In addition, ECG is also capable of delivering more heart metrics compared to PPG, so as to better understand the patient's condition [9] [10].

2.3 Electrocardiography

Electrocardiography (ECG) is a method of heart monitoring that measures the electrical activity of the heart. When discussing electrocardiography, we are mainly concerned with the upper and lower chambers of the heart – the atria and ventricles.

An ECG signal is represented in the form of a PQRST waveform as shown in Figure 1.4. The waveform consists of three separate components; the *P* wave represents the depolarization of the atria of the heart, the *QRS* complex represents the depolarization of the ventricles and the *T* wave is the repolarization of the ventricles [11].

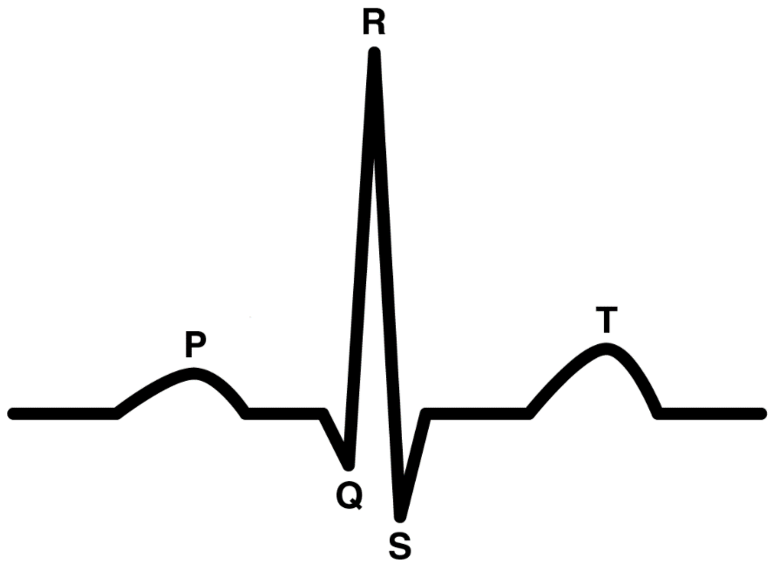

Figure 1.4 – ECG waveform showing the cardiac cycle in the form of a PQRST wave

2.4 Electrocardiogram Analysis

ECG testing can uncover abnormal heart rhythms, previous heart attacks, indications of cholesterol and more. Specific symptoms can be diagnosed by examining the different sections of the waveform of the patient's ECG data, so more effective treatment can be given.

The standard ECG waveform is a signal plotted with voltage vs. time. Before the digitisation of the medical field, the signal was measured using analogue methods and the output was displayed on ECG paper. ECG paper looks like standard scientific graph paper, divided into large and small boxes, where each large block represents 0.2 seconds horizontally and 0.5mv vertically.

There is a wide array of metrics to consider when performing ECG analysis, the majority of which can be separated into two categories [12]:

1) Interval metrics which measure the time – in milliseconds – between various sections of the ECG waveform. In particular, the *PR*, *QRS* and *QT* intervals are most commonly analysed, where PR represents the interval between the peaks of the *P* wave and the *R* wave and so on.

1.1) The *QT* interval is important when analysing a patient's heart health. It is the interval between the start and end of ventricular depolarization and repolarization respectively. A lengthy *QT* interval is a symptom of ventricular tachyarrhythmias, a risk factor for sudden cardiac arrest, and is the focus of many medical studies relating to cardiac analysis. Since the *QT* interval is dependent on the heart rate, the interval is corrected, usually using one of the following logarithmic equations, where *RR* is the interval between successive *R* complex peaks [13] [14]:

i) *Bazett's formula (HR 60-100bpm):*

$$QTcB = \frac{QT}{\sqrt{RR}}$$

ii) *Fridericia's formula (HR <60bpm & >100bpm):*

$$QTcF = \frac{QT}{\sqrt[3]{RR}}$$

1.2) The heart rate variability (HRV) is the analysis of the heart's beat-to-beat variation, and is a good indicator of the overall heart health of the patient. A high HRV means that the heart can effectively change heart rate depending on the activity level, and indicates greater cardiovascular fitness and more resilience to stress or disease. On the contrary, a low HRV indicates that the patient is more susceptible to heart attacks, strokes etc. There are several methods of analysing HRV, the most common is the *root mean square of successive differences* (RMSSD) method [15]. RMSSD measures the average interval between successive *QRS* peaks in the ECG signal – known as an *RR* interval.

$$RMSSD = \sqrt{(RR_1 - RR_2)^2 + (RR_2 - RR_3)^2 + (RR_3 - RR_4)^2 + \cdots}$$

2) Amplitude metrics which measure the height of the peaks in the cardiac waveform, specifically the *P*, *R* and *T* peaks. The amplitude is measured in millivolts. Normal amplitude levels depend on the age and gender of the patient.

By collecting a patient's heart data and performing data analysis, we can compare the collected patient metrics to standard reference figures to uncover abnormalities and give diagnoses.

3. Literary Review

There are various commercial and experimental solutions for ECG monitoring.

3.1 Commercial Solutions

Traditionally, ECG monitoring was performed with sensors that the patient would wear for 24-48 hours – known as a Holter monitor. After this period, the physician would perform analysis on the patient data.

Over the past few years, there has been an increase in the number of commercial health monitoring systems. This can largely be attributed to advances in technology, allowing for low-power ultra-portable solutions for wearables, and the rise in popularity of the Internet of Things for connectivity.

3.1.1 MoMe Kardia

The MoMe Kardia System by InfoBionic is an automated cardiac monitoring ECG system developed in Massachusetts. The system performs remote monitoring for patients with cardiac arrhythmias [16], allowing physicians to view the patient's data and make diagnoses. The first generation involved transmitting data via Bluetooth to a mobile phone, which acts as a tether to the internet [17]. Feedback proved this to be quite limiting, so a second-generation device was introduced, which uses cellular data to upload directly to the cloud. The aim of the device is to speed up the diagnosis process by allowing the physician to diagnose remotely.

3.1.2 HeartCheck ECG Device

The HeartCheck ECG Device is another portable commercial solution for ECG monitoring. It is a handheld device, rather than a wearable, and is designed to be used to test for arrhythmias at regular intervals at different activity levels. The patient uses their hands to provide an ECG reading, and the device stores up to 200 thirty second readings locally. The data must be transferred manually to a computer where the physician can perform analysis on the patient's data [18].

3.1.3 Difference to proposed system

The two aforementioned commercial devices, as well as plenty of other commercial devices, provide accurate ECG readings. They do not, however, provide an all-in-one solution to heart monitoring. In the case of the HeartCheck ECG Device, the applications are limited since the data is stored locally and must be manually transferred and analysed. The patient also has to hold the device in their hands for readings, so it isn't designed for continuous monitoring. The MoMe Kardia System is more similar in design to the proposed design, in that it provides continuous streaming of patient ECG data to the cloud. It does not however, provide autonomous analysis. This is where I aim to improve the heart monitoring process, by providing analytical results to patient data in real-time.

3.2 Research-based Solutions

ECG monitoring has also been the focus of various research-based projects in recent years.

A research team at the Pukyong National University in South Korea created a non-contact system for ECG monitoring. The system uses capacitive coupled sensors placed on an office chair, which collect ECG data from the patient non-intrusively by measuring the capacitance formed between the body and electrodes [19].

The system benefits from being non-intrusive, but the user is confined to the chair. Additionally, although the patient's data is uploaded to the cloud, minimal analysis is performed – only heart rate monitoring.

Carleton University conducted research on an IoT based remote patient monitoring ECG system. The system uses an IOIO microcontroller board to collect cardiovascular data from a patient using ECG electrodes, and a mobile device which connects to the board via Bluetooth. The mobile device acts as a tether to the internet, and can also be used for visualisation. The data is stored locally on an SD card.

The system has similarities to the proposed design, in that it uses a small-form, low-cost microcontroller for collecting of data, but it lacks the ability to stream to the cloud and analyse the data in real time [20].

4. Work to date

4.1 Foreword

I initially worked on an update to a project developed by students in the National University of Singapore under my supervisor Dr Deepu John. The project involved continuing development on a cloud-based platform for real-time healthcare monitoring using wearable sensors. Work on the project began with updating the source code for the mobile and web application, as well as researching and familiarising myself with the technologies and services that were new to me, namely Node.js and Node-RED. Node.js is an open-source run-time environment used for executing JavaScript code server-side. The project uses Node-RED – a flow-based development tool for IoT communication – to handle database management.

As my career interests for what follows UCD changed, I wanted to incorporate more hardware elements into the project. I proposed a new direction for the project, and my supervisor Dr Deepu John was happy to support me in my new endeavours.

4.2 Hardware

With the new hardware-centred approach came evaluating different possible hardware solutions for heart monitoring. The three main features required were low-cost, low-power and small form factor. The two most viable solutions found were the Arduino microcontroller and the Raspberry Pi single-board computer.

Raspberry Pi’s are generally used as all-purpose computers, running the Linux operating system to perform multiple different operations. Arduinos are simple microcontrollers which run a single program repeatedly, and are far simpler to use compared to a Raspberry Pi.

Since an Arduino’s main purpose is to interface with various connected modules and sensors, there exists a huge range of libraries which add functionality and facilitate ease of use. The proposed design is to collect data using hardware, and to abstract the analysis and computation of data to the cloud and so the family of Arduino microcontrollers was chosen.

The current hardware solution involves an Arduino Uno microcontroller, connected to an IO expansion shield which allows for connection of sensors and modules. An ESP8266 Wi-Fi microchip with integrated TCP/IP protocol stack is used for reliably transmitting data to the cloud. Finally, I use an analogue electrocardiogram (ECG) sensor to collect patient heart health data. The ECG sensor uses a three-lead connection to get a clear PQRST wave from the signal.

4.3 Cloud

Analysis on the patient heart data is to be performed in the cloud. This is done for a number of reasons:

i) Abstracting the data analysis to the cloud reduces the computational power, reducing power consumption of the Arduino

ii) We are not limited in terms of the programming language to use for data analysis when using the cloud. If we wanted to perform the analysis onboard the Arduino, we are limited to the Arduino programming language, which is a set of C/C++ libraries.

iii) The real-time analysis and patient result data can be accessed from anywhere in the world via the cloud. This is useful for continuous monitoring scenarios, when the patient is wearing the device at home and the healthcare professional wants to monitor the patient's data.

I determined the best cloud solution to be ThingSpeak. ThingSpeak is an open-source internet of things (IoT) platform for collecting and analysing sensor data. ThingSpeak integrates MATLAB, which allows us to run MATLAB code on patient data at regular intervals.

MATLAB is a proprietary programming language for numerical computing and statistics, and is much quicker to develop algorithms in, compared to standard programming languages like C++ and Java. MATLAB offers a huge selection of toolboxes or libraries to extend functionality.

Using the results obtained from the data analysis, we can trigger reactions. Applications for this could be a system to alert the doctor if the patient's heartbeat is abnormal.

5. Future work

The future work of this project revolves heavily around data analysis of ECG data. I have identified what I believe to be the next few stages of the project plan, which are as follows:

i) Feature extraction and classification on the characteristics of the ECG signal, to identify various sections of the *PQRST* waveform.

ii) Perform data analysis on the signal, to identify arrhythmias and abnormalities in the patient data. Comparing the results obtained in analysis to standard metrics for a normal healthy heart, I can suggest possible specific cardiovascular diseases. Included in Figure 5.1 below are a sample of ECG metrics for a healthy patient's heart. These metrics depend somewhat on the patients age, gender and activity level.

iii) Using the results gathered during data analysis, some form of diagnosis can be made about the patient's heart health. Sinus bradycardia, sinus tachycardia and sinus arrhythmia can be diagnosed by examining the rhythm of the heart. Other cardiovascular disease can be diagnosed by examining the *P* and *T* waves, as well as the *QRS* complex.

Interval Metrics (seconds)	**Amplitude Metrics (in millivolts)**
RR interval: 0.6 – 1.0	P-wave: 0.25mV
PR interval: 0.12 – 0.20	R-wave: 1.60mV
QT interval: 0.4 – 0.43	T-wave: 0.1 – 0.5mV

Figure 5.1 shows a sample of the most common metrics measured when performing ECG analysis

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