CHANGES OF SIGNAL LEVEL DETECTION IN A RESONANT MICROWAVE CAVITY WITH VARYING CONCENTRATIONS OF GLUCOSE

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Abstract

Diabetes is the body's inability to control blood glucose levels and diabetes is a chronic disease, which is a major threat to public health. Traditionally, the measurement of glucose was achieved using invasive (skin piercing) methods which causes pain and damage to skin. A non-invasive device to test blood glucose level will avoid these drawbacks and minimise the complications of diabetes.

The main aim of the project is to investigate the relationship between varying concentrations of glucose in a water solution (to simulate blood) and the signal level within a resonant microwave cavity, which is the key to the development of a non-invasive blood glucose monitoring system. This thesis outlines the mechanical design, electronic and software design, involved in the development of such a system.

In this project, the RSSI (received signal strength indicator) measurement is used to measure the signal levels within a microwave cavity. This was taken from a one of a pair of HC-05 Bluetooth modules, one operating as a transmitter, and one operating as a receiver.

The results of experiments confirmed a significant correlation between RSSI and glucose concentration – and thus, the success of the system. As well as proving itself to be a viable non-invasive blood glucose measurement system, additional features of this system were low cost, and expandability.

List of Principal Terms and Abbreviations

RSSI	Received Signal Strength Indicator
Wi-Fi	A technology for Wireless local area networking
RF	Radio Frequency
CPU	Central Processing Unit
AHB	Advanced High-performance Bus
UART	A Universal Asynchronous Receiver/Transmitter
MP3	MPEG Layer III Audio Encoding
3D	Three-Dimensional
PC	Personal Computer
USB	Universal Serial Bus
SPP	Serial Port Protocol
AT command	A kind language from computer to control modem
Arduino board	A microcontroller development board, based on an ARM processor chip
Q(Quality factor)	2π times the ratio of the time-averaged energy stored in the cavity to the energy loss per cycle

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CHAPTER 1

INTRODUCTION

1.1 Introduction

1.2 Aim of the research

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1.1 Introduction

Diabetes is the body's inability to control blood glucose levels (Alberti and Zimmet, 1998), and diabetes mellitus is a chronic disease which is a major threat to public health (International Diabetes Federation, 2015). Currently, there are 387 million people worldwide suffering from diabetes, and it may increase by 53 percent in 2035 (*ibid*). It was estimated that every seven seconds a person dies from diabetes and 4.9 million people could lose their lives as a result of diabetes (*ibid*). In 2013, more than 21 million neonates may be affected by diabetes during pregnancy (IDF Diabetes Atlas, 2014). Besides, according to Shaw *et al* (2010), the number of adults with diabetes will increase sharply between the years 2010 and 2030. For example, there will be an increase of 69% in high-income countries, and the low-income countries will see an increase of 20%. Therefore, the high-income countries will suffer more pressure from diabetes than before. Diabetes is a chronic condition and therefore self-monitoring of blood glucose levels would be a welcome addition to aid the control of this condition, if complications such as amputations, blindness, heart disease or kidney failure are to be avoided (Vashist, 2013).

Currently, diabetes patients need to take a drop of blood from their fingertip to measure the blood glucose concentration (Malik *et al.,* 2015) which is painful, and can lead to infections, and if complications are to be avoided, this should be done four times a day (Waynant and Chenault, 1998).

For this reason, non-invasive methods have become the most feasible technology for diabetes patients, because of the zero pain and zero infection risk (Carduff *et al.,* 2013). Moreover, such techniques allow immediate and continuous monitoring. Non-invasive technology has been under development for more than 30 years, however, it is still considered to be in its infancy (So *et al.,* 2012), due to their lack of sensitivity and accuracy. Based on these drawbacks, this project focuses on a technology that will allow for the development of non-invasive blood glucose measurement devices and avoid the extra interferences.

1.2 Aim of the research

The principal aim of this research work is to establish a link between RSSI (Received Signal Strength Indicator) and glucose concentrations within a microwave cavity, which could lead to the future development of a non-invasive blood glucose measurement system. The focus will be on proving that the signal strength in a resonant microwave cavity is affected by the levels of glucose within a solution placed within it (Elkady *et al.,* 2013), – hence setting the way forward for the future development of non-invasive blood glucose monitors. The transmitter and receiver of the microwave signal will be 2.4 GHz licence-free Bluetooth transceivers, as this frequency has been shown to be useful for the detection of blood glucose levels (Dobson *et al.,* 2012), and it is free licence.

The main aim of the project is to investigate the relationship between varying concentrations of glucose in a water solution (to simulate blood) and the signal level within a resonant microwave cavity. This will be done by completing the following:

- Review the existing relevant literature for background knowledge, to develop the foundation for the project, and to keep up to date with recent developments.
- Synthesise concepts from microwave propagation, reflection and absorption of microwave energy within glucose solutions research with findings from experimental data to derive a model for the detection of varying concentrations of glucose, by

measuring the changes in amplitude of 2.4 GHz signal levels within a resonant microwave cavity through RSSI measurement.

- Create a design for the detection of varying concentrations of glucose dissolved in water, that is, for detecting varying concentration levels by measuring changes in RSSI using a resonant microwave cavity based on the literature review and experimental findings.
- Modell and refine the design using software techniques to test the validity of the design.
- Build a prototype according to the final software modelling
- Experiment with the prototype to gather data on the relationship between glucose concentrations and signal levels within the cavity
- Analyse the data to confirm the relationship
- Derive a model for the relationship, which can be used for future work

1.3 Structure of thesis

As detailed below, this dissertation is structured into eight chapters. To make the thesis more precise and concise, only the results were put in the relevant sections, and the complete workings were described in the Appendix at the end of thesis.

Chapter 1 is the introduction to the research, and outlines the aim of the research. This chapter presents some background about diabetes, an overview of the measurement technologies used for blood glucose measurement for diabetes, and the focus of this project.

Chapter 2 is a critical review of the current literature on glucose measurement technologies. It covers techniques such as Near Infrared Spectroscopy (NIR), Dielectric Spectroscopy (DES), Bio-Impedance Spectroscopy (BIS), Electromagnetic Sensing (ES), Fluorescence Technology (FT), Raman Spectroscopy (RS) and Reverse Iontophoresis (RI).

Chapter 3 introduces the current approaches being used for resonant microwave cavity based blood glucose sensors. It also presents the mechanical design of the resonant cavity, showing the theory, calculations, modelling methods and prototype testing of the resonant microwave cavity to ensure that it was resonant at the frequency employed.

Chapter 4 discusses Bluetooth modules which were used for the sensors. It also presents the electronic design, which consists of circuit design, transceivers and

Arduino program. It also covers the control, signal transmission, reception and display.

Chapter 5 presents a record of the experimental procedures employed, along with the results, analysis and discussion of the results. This chapter also includes the methods used to establish and produce the varying glucose solutions.

Chapter 6 presents the conclusion and future work.

Chapter 7 includes a full alphabetical list of the references used in the work.

Chapter 8 includes all the appendices.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

2.2 Research into existing methods

2.3 Summary

2.4 References

2.1 Introduction

Self-monitoring of blood glucose levels is an effective way to minimise the complications of diabetes (Vashist, 2013). The American Diabetes Association (1999) suggests that diabetes patients monitor their concentration of blood glucose four times a day in order to have good control of their conditions. Traditionally, the measurement of glucose was achieved using invasive (skin piercing) methods which causes pain and damage to skin. Besides, it was impossible to monitor glucose continuously which is important in some more extreme cases. To overcome these drawbacks of traditional glucose monitoring methods, non-invasive blood glucose monitoring was developed.

There are a number of approaches used in non-invasive blood glucose measurement systems. These are Near Infrared Spectroscopy (NIR), Dielectric Spectroscopy (DES), Bio Impedance Spectroscopy (BIS), Electromagnetic Sensing (ES) Fluorescence Technology (FT), Raman Spectroscopy (RS) and Reverse Iontophoresis (RI).

2.2 Research into existing methods

There are currently four main methods for the non-invasive measurement of blood glucose. These are Near Infrared Spectroscopy (NIS), Dielectric Spectroscopy (DES), Bio Impedance Spectroscopy (BIS), Electromagnetic Sensing (ES), Fluorescence Technology (FT), Raman Spectroscopy (RS) and Reverse Iontophoresis (RI). Their respective principles, benefits and disadvantages are outlined in table 2.1 below:

Table 2.1 Comparison of existing technologies

NIS	**Principles** Near Infrared Spectroscopy is based on the reflectance of skin to measure the blood glucose, and uses wavelengths between 730nm and 2500 nm.
	Benefits Near Infrared Spectroscopy has high sensitivity due to the use of photoconductive probes.
	Disadvantages It requires significant physical pressure to be applied to the sensor on the skin. There is a weak correlation between blood glucose and skin colour – so the accuracy is limited.
DES	**Principles** DES uses the principle that varying levels of blood glucose affect the dielectric properties of the blood (Naderi-Boldajia, 2015).
	Benefits The results from DES can be sensitive to the ambient environment, such as temperature, moisture and electromagnetic radiation from other sources – such as switched mode power supplies, used in power adapters.
	Disadvantages DES measures blood glucose by establishing the lowest impedance of the sample. This can be quite a lengthy process (Gelao *et al.*, 2012).

BIS	**<u>Principles</u>** This relies on the principle that skin impedance is affected by blood glucose levels. This is measured by injecting small currents into the sample, and measuring the resultant voltage. A number of samples are taken, and a statistical test is undertaken.
	<u>Benefits</u> This system is easy to use and low-cost.
	<u>Disadvantages</u> The limitation of bio impedance is that before use, the users must spend one hour to relax, due to the need for an equilibration period for the statistical analysis. Therefore, Bio Impedance Spectroscopy takes more time to take a measurement than other systems.
ES	**<u>Principles</u>** Different glucose concentrations lead to different dielectric parameters of blood. This is detected using inductive coupling rather than in current sensing – as is used in the DES system.
	<u>Benefits</u> Firstly, Electromagnetic sensing does not damage cells in the body, so it is very safe.
	<u>Disadvantages</u> It is very sensitive to the ambient environment conditions, particularly temperature.

FT	**<u>Principles</u>** There are methods that use the tracking the glucose molecules via fluorescence reagents in blood. Khalil (2004) demonstrated that the glucose concentration in tears was similar to the concentrations in blood, thus enabling non-invasive testing.
	<u>Benefits</u> It is very sensitive and non-invasive.
	<u>Disadvantages</u> There is a 30 minute delay between taking the tear sample and getting the results.
RS	**<u>Principles</u>** As Berger *et al*., (1999) reported, the molecules glucose solution can be caused to rotate by laser light. This is the principle that RS uses to test the concentrations of glucose in a non-invasive way.
	<u>Benefits</u> This technology is more stable than NIR because it is less affected by temperature.
	<u>Disadvantages</u> During this test the signal-to-noise ratio will be low because the light source's power has to be kept low to avoid skin damage.
	<u>Principles</u> This method putting a cathode and anode on the surface of skin and passing a current between them. Because glucose molecules are of neutral

RI	charge, they will be transported to and collected on the cathode which can then be tested.
	<u>Benefits</u> It is easy to use and not easily be influenced by ambient temperature and light.
	<u>Disadvantages</u> It can cause skin irritation. The accuracy is not good accuracy, and the procedure is lengthy (Sieg *et al.*, 2004).

2.3 Summary

Based on the discussions of various non-invasive technologies, there are two principles used for measuring blood glucose level with non-invasive techniques, namely:

1. Measuring the cellular changes which can cause changes in permittivity and conductivity
2. Measuring the signal attenuation to determine the blood glucose level due to the changes in the absorption of liquid

This research will focus on the second point which is measuring the signal level changes with different concentrations of glucose in water. The next chapter will demonstrate that the signal strength in a Resonant Microwave Cavity (RMC) is affected by the levels of glucose within a solution (Elkady *et al.,* 2013), hence setting the way forward for future non-invasive testing of blood samples. Chapter 4 will present the source and receiver of the microwave signal, which will be 2.4 GHz license-free Bluetooth transceivers. The received signal will be digitized for processing by a microprocessor based system – which is an Arduino open-source system.

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CHAPTER 3

MECHANICAL DESIGN

CAVITY DESIGN

3.1 Introduction

3.2 Initial design concepts

3.2.1 Research Radio Wave Technology

3.2.2 Features of Resonant Microwave Cavity (RMC)

3.3 Cavity design

3.3.1 Producing the resonant microwave cavity design

3.3.2 Building the system

3.4 Summary

3.5 References

3.1 Introduction

As explained in Chapter 1, the main aim of this research is to investigate the relationship between varying concentrations of glucose in water solution and the signal level in a resonant cavity. This reason for choosing a cylindrical resonant microwave cavity is because it has low radiation losses, high Q (Quality factor) and high sensitivity (Jackson, 1999).

This chapter will introduce the function of microwave resonant cavity regarding two aspects:

1. Modelling the system in software using MATLAB to confirm the design performs according to specifications
2. Build a prototype system based on the software modelling and sample under test

3.2 Initial design concepts

3.2.1 Research Radio Wave Technology

Radio frequency (RF) is electromagnetic radiation in the frequency range from 3 KHz to 300 GHz. The microwave band is between 300MHz to 300 GHz. This electromagnetic radiation is absorbed by varying degrees by according to the material (Moore, 2009).

In the past few years, RF technology required in Machine-to-Machine (M2M) communications and Electronic-Health (eHealth) (Adibi, 2012) has been increasing seen as a non-invasive way to measure blood glucose levels. RF is the technology used to transfer data in Wi-Fi and Bluetooth applications. These are increasingly used technologies, which much focus on developing low power, integrated sensor, and miniaturized devices (Chen *et al*., 2011). Radio frequency technology supports the possibility of transferring information wirelessly with other devices. Hence, it is a good platform for smart, self-monitoring devices in the future. It also allows for the development of continuous monitoring devices.

The electromagnetic spectrum from 3 MHz and 30 GHz (radio bands) are classified as follows: High Frequency (HF, 3-30 MHz), Very High Frequency (VHF, 30-300 MHz), Ultra High Frequency (UHF, 300 MHz-3 GHz) and Super High Frequency (SHF, 3 GHz-30 GHz), and they selectively used according to their individual characteristic (Skolnik, 1962). Typical applications are shown in table 2.2.

Table 3.1 General RF Features

Band name	**Frequency**	**Examples**
High Frequency(HF)	3–30 MHz	Communications, over-the-horizon radar.
Very High Frequency (VHF)	30–300 MHz	Land mobile and maritime mobile communications, amateur radio, and short range communications.
Ultra High Frequency(UHF)	300–3000 MHz	ZigBee, Bluetooth, short range communications.
Super High Frequency(SHF)	3–30 GHz	Radio astronomy, radar.

Blood glucose management is seen as a critical issue in many areas of the world, of researchers exploring the possibility of using a resonant cavity as a non-invasive way to measure blood glucose levels (Lee *et al*., 2000). Dobson *et al* (2012) first demonstrated the relationship between glucose concentrations within a water solution and the absorption of electronic radiation within a resonant microwave cavity. The need for continuous blood glucose monitoring is an important driver of ongoing research (Mendelson *et al*., 1990).

3.2.2 Features of Resonant Microwave Cavity (RMC)

The resonant microwave cavity forms an integral part of the unit as it maximises the signal level at the resonant frequency, and also prevents microwave leakage, and hence, radiation losses (Jackson, 1999). The resonant microwave cavity consists of a cylindrical waveguide with two conductive plates at the ends. However, as the frequency increases, the dimension of the cavity needs to be reduced in order to be a fraction of the wavelength to ensure resonance. Additionally, the resonant frequency is also affected by the cavity geometry, the period of the signal and dominant mode (Pollack and Stump, 2002). In an ideal lossless resonator, when the resonance occurs, the electricity and magnetic energy sustain each other. At the same time, a standing wave field is also produced, due to the microwave reflections within the cavity walls. The loaded Q is determined by the internal and external losses within and without the cavity. Internal losses depend upon the conductivity of the cavity walls and the medium within. External losses depend upon the loading effects of the external circuity.

The microwave band was chosen as it allows relatively small resonant cavities to be developed due to its comparatively short wavelengths, meaning that the resonant cavity can be comparatively small in size. At resonance, maximum power is transmitted from the transmitter, and the receiver signal is also maximised (Pollack and Stump, 2002; Pozar, 2012).

As mentioned above, the signal strength in a resonant microwave cavity (RMC) is affected by the levels of glucose within a solution (Elkady *et al.,* 2013). Hence, the theoretical framework was based on the fact that different concentrations of blood glucose absorb different amounts of the signal.

Figure 3.1 shows the design of the glucose concentration monitor based on a resonant cavity with an integrated transmitter and receiver. At this stage, the interaction between the different components of the process, that is, the signal source (Tx), and the sample (glucose powder with water solution) absorbed signal and received signal will be considered, which will be measured by detecting changes in RSSI t the receiver (Rx).

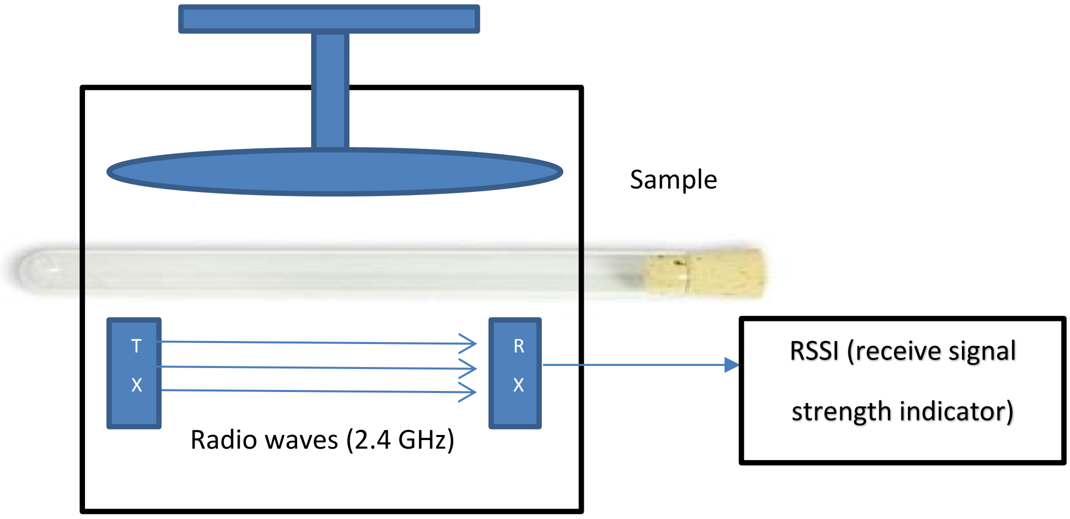

Figure 3.1 Theoretical framework

The signal source was supplied by the transmitter (TX), and captured using the receiver (RX). The output signal will be measured by use of the received signal strength indicator (RSSI). In this application designating the TX as the master, and the RX the slave.

3.3 Cavity design

3.3.1 Producing the resonant microwave cavity design

MATLAB, EIDORS and NETGEN were used to produce the design for the RMC, TX and RX. NETGEN is a kind of three-dimensional (3D) tetrahedral mesh generator; EIDORS was used to provide open algorithms source and MATLAB is a platform to support NETGEN and EIDORS.

The cavity height is depending on the resonant frequency. As discussed in Chapter 2, frequency chosen for this research was 2.4 GHz.

Based on the wavelength formula：

$$\lambda = c/f \tag{3.1}$$

Where λ is wavelength, c is electromagnetic wave speed in free space which is $3 \times 10^8\ m/s$ (Temes, 1998), f is the frequency of wave in Hertz.

Therefore

$$\lambda = 3 \times 10^8/2.4 \times 10^9 = 12.5\ cm \tag{3.2}$$

When the cavity length is equal to 1/2 or an integer multiple of the wavelength, the cavity will become resonant due to the resultant standing waves. Therefore, the cavity height H should be calculated below:

$$H = \lambda/2 = 6.25\ cm \tag{3.3}$$

Therefore, the height of this cavity was 6.25 cm whilst the diameter (which is arbitrary – that is, has no affect on the resonant frequency) was chosen to be 7 cm in order to accommodate test tubes with the solution under test. After the dimensions of resonant cavity were calculated, MATLAB, EIDORS and NETGEN were used to produce the model of the proposed resonant cavity and transceivers as shown in Figure 3.2 (See the program in Appendix 1).

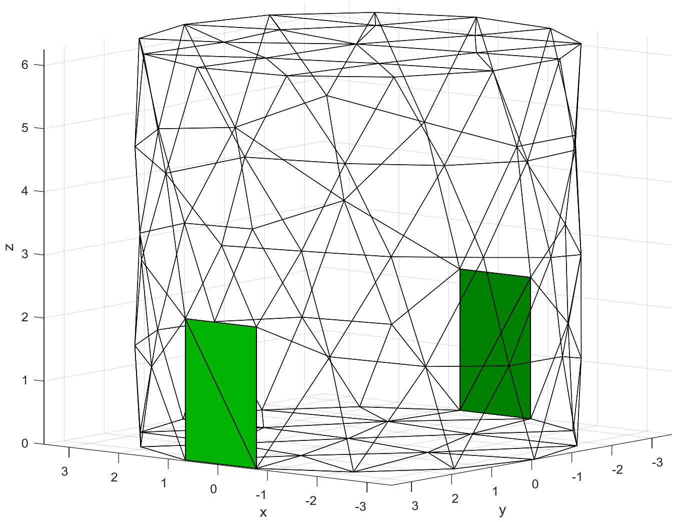

Figure 3.2 Design result of half wave resonant cavity

As Figure 3.2 shows, Z axis represents the height of cavity, X and Y axis represents the diameter. The green planes represent the TX and RX.

3.3.2 Building the system

Based on the proposed model, and a number of experimental prototypes described in Appendix 2, the final system was produced and is shown Figure 3.3. This figure shows the:

- Cylindrical RMC - Figure 3.3(a)
- The TX and RX - Figure 3.3(b)
- Tuning mechanism - Figure 3.3(c)
- Test tube insertion apertures - Figure 3.3(a) and Figure (b)

Figure 3.3(a) Cylindrical RMC

Figure 3.3(b) The TX and RX

Figure 3.3(c) Tuning mechanism

The cavity was made of aluminium. This was chosen as it is an excellent conductor of electricity, light in weight, and easy to machine to a very flat/smooth surface (which is essential in this application). The tuning mechanism provided a way of electrically adjusting the length of the resonant cavity, for fine tuning to resonance. The test tube insertion apertures provided the means of physically inserting sample into the RMC.

3.4 Summary

This chapter focused on introducing the cylindrical resonant microwave cavity from the initial design concepts through to final cavity design. The initial discussion focused on the relationship between glucose solution levels, and their attenuation affect in a RMC. The reasoning behind the choice of Bluetooth TX and RX, choice of materials, and the physical dimensions of the RMC was demonstrated. There then followed a discussion of the design refinement and manufacture, with an explanation for the approaches taken.

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CHAPTER 4

ELECTRONIC DESIGN TRANSCEIVERS AND ARDUINO PROGRAM

4.1 Introduction

4.2 Initial design concepts

4.2.1 Wi-Fi module - Esp8266

4.2.2 Bluetooth

4.3 Electronic design and test

4.3.1 Transceivers-HC-05

4.3.2 Arduino Microcontroller

4.3.3 Circuit design and test

4.4 Summary

4.5 References

4.1 Introduction

The Bluetooth trademark was created by Eriksson in 1994 with modest sensitivity and low power requirements which was endorsed as 802.15.1 by the IEEE (Fette *et al*., 2007). Bluetooth RF modules are used for short-range data communications. This could include applications such as exchanging data between two phones, or a wireless keyboard and a PC (Burbank *et al*., 2013).

In this research, Bluetooth modules were used as transmitters and receivers to test the signal level in a resonant cavity, controlled by an Arduino open-source microcontroller board (Arduino.cc). As Chapter 3 mentioned, in a resonant microwave cavity, the signal strength is affected by the levels of glucose within a solution. It means that the level of attenuation of the signal can be used as an indicator of glucose levels.

The cavity's physical design has been described in last chapter. In this chapter the electronic design will be introduced from three aspects: initial design concepts, circuit design and testing.

4.2 Initial design concepts

This section critically analyses the literature on wireless technologies from different perspectives. The two most common methods used for short-range signal transmission are Wi-Fi and Bluetooth. Both operate 2.4 GHz, thus allowing the relatively small dimensions of the cavity, and also because it is a 'license free' band.

4.2.1 Wi-Fi module - Esp8266

Recently, as the demand for short-range data communication increases, this in turn has driven the rapid development and increased capabilities of Wi-Fi technologies (Chen, Hsia and Liao, 2009). The use of a Wi-Fi module is an effective and easy way to enable microcontroller based system to communicate with other wireless devices. The fact that the radio band used is license free, the modules low cost and easy to use along with a high reliability makes Wi-Fi modules an extremely attractive proposition. The wireless modules were already populated with system-on-chip (SOC) wireless devices onto a much more user friendly Wi-Fi module. This addresses the problems of limited space, and also supplies sufficient output power for this application (ESP8266EX Datasheet, 2015). The Esp8266 Wi-Fi module has the additional advantage that it requires only single 3.3 V power supply. Wi-Fi is an ideal protocol for home automation, industrial wireless control, sensor networks, wearable electronics and position beacons.

A Wi-Fi adapter enables wireless internet access to variety of microcontroller-based designs by using the Central Processing Unit (CPU) Advanced High-performance Bus (AHB) bridge interface or Universal Asynchronous Receiver Transmitter (UART) interface which forms the interface between the RF and digital components of the system. The adapter also contains the 2.4 GHz transmitter and receiver which form the nexus of the communications system (Espressif Systems, 2013).

Small size and wireless internet capability form the major characteristics of the Esp8266 Wi-Fi module which makes it ideal for use in smart control projects, handheld systems, such as, as might be found in MPEG Layer III Audio Encoding (MP3) players, mobile phones and medical instrumentation. The output power of the Esp8266 is + 19.5 dBm in 802.11b mode, and the receiving sensitivity is -72 dBm, some other modes utilise a reduced out power (Liu, Wang, Lee and Wang, 2007).

4.2.2 Bluetooth

Bluetooth is also a data transmission protocol, although its range a much shorter than Wi-Fi (Stallings, 2009; Firmansyah, and Grezelda, 2014). It is used in applications such as the wireless connection of earphones to music players and mobile phones, and wireless keyboards and mice to computers.

Bluetooth devices consist of two main components, which are the core and the profile. There are different communication protocols available, which have to be matched amongst the communicating devices such as Bluetooth radio, baseband link controller, link manager protocol, logical link control and adaptation protocol, service discovery protocol, transport layer and interoperability. The protocols used also depend on the application of the system (Verma, Singh, and Kaur, 2015).

The frequency of Bluetooth operation is between 2.4 GHz and 2.48 GHz which is an industrial, scientific and medical (ISM) licence free band. The master can exchange data with specific slaves although many may be paired at the same time. Finally, Bluetooth is a low cost and low power technology, which makes it a good choice for medical instrumentation applications (Haartsen, 2000). There are three different application dependent power levels that are available:

Table 4.1 Bluetooth power classes (Rasid and Woodward, 2005)

Class	**Maximum Power**	**Operating Range**
Class 1	100 Mw(20 dBm)	100 meters
Class 2	2.5 Mw(4 dBm)	10 meters
Class 3	1 Mw(0 dBm)	1 meter

The HC-05 Bluetooth module, which is a Class 2 device was chosen for this research. The HC-05 has a low transmitter power of =<4dBm which is lower than the aforementioned Wi-Fi module. It also has a received signal strength indicator (RSSI), which, as its name suggests, can provide a relative indication of the received signal strength (HC-05 master/slave Bluetooth module datasheet, 2016). It is generally used to measure the propagation of the signal in enclosed spaces (Almaula and Cheng, 2006).

The electronic design covered two aspects which are the digital side and the radio frequency side. These are the Arduino and Bluetooth modules respectively. As mentioned above, Bluetooth has the benefits of small size, low power and licence-free operation, and to enable this, a HC-05 Bluetooth module (ITead Studio, 2016) was used. This module was chosen, as it enabled access to the RSSI levels within the cavity. This RSSI information is supplied in digital format, hence the need for a microcontroller (in this case, an Arduino Uno board) (Arduino.cc) to decode it. The Arduino was also used to supply the digital control codes to the Bluetooth TX and RX modules. It also supplied the DC power to the Bluetooth modules.

An overview of the proposed system is shown in Figure 4.1 below:

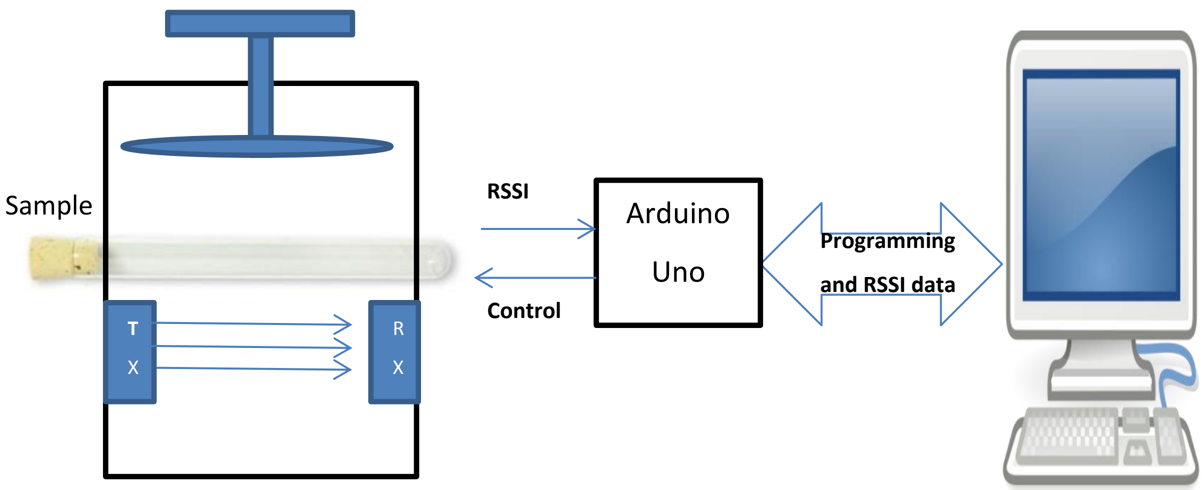

Figure 4.1 An overview of the proposed system

Figure 4.1 shows the transmitter and receiver as fitted within the cavity, along with the Arduino controller. The Arduino was used to send the necessary control signals to the transmitter and receiver, and also collect and decode the RSSI data from the receiver, which in turn represents changes in signal level within the cavity. Then the Arduino is programmed by use of a PC via a USB connection. When the Arduino has decoded the RSSI information, this is passed back to the PC for analysis using Excel.

4.3 Electronic design and test

4.3.1 Transceivers - HC-05

The HC-05 Bluetooth transceivers support Serial Port Protocol (SPP) and wireless serial connection, and operates on 2.4 GHz, with a 3.3 V power supply. Due to the 3.3 V supply, the logic signals are 3.3 V, and the chip would be damaged if connected directly to the Arduino 5 V logic. There is another 3.3 V variant of the HC-05 module, which although is based on 3.3 V logic, the pins are 5 V tolerant, allowing for direct connection to the Arduino. This is the EGBT-045MS (EGBT-045MS Bluetooth Module, 2016), and was the one used in this project.

The EGBT-045MS has two modes of operation, these being master and slave (HC Serial Bluetooth Products User Instructional Manual, 2014). In this subject, two EGBT-045MS modules were used as transceivers. The TX was set as master, and the RX as slave. Even EGBT-045MS module has 34 pins, although only 5 pins were needed for the master module (TX), and 2 pins for the slave module (RX). The EGBT-045MS module pinout configuration is shown in Figure 4.2.

Figure 4.2 EGBT-045MS module pin out configuration

For the module, TX, RX, VCC, GND and KEY pins were used, and their functions are given below:

- TX pin: This transmits data to the RX pin of the controller UART.
- RX pin: This receives data from the TX pin of the controller UART.
- VCC pin: Voltage supply which can be in the range 3.6V to 6V.
- GND pin: Zero volts.
- KEY pin: Mode switch input. The AT commands are enabled this pin is high.

There is a test function of EGBT-045MS to test received signal strength using an AT command. In addition, EGBT-045MS uses AT commands to work or change the default settings, such as the baud rate, and slave/master selection. The AT commands were sent from the computer via the Arduino. Table 4.1 and table 4.2 shows the AT commands which were used in this research.

Table 4.2 AT Command used for Slave Module

AT Command	Respond
AT	OK
AT+IAC?	9e8b33
AT+ADDR?	Get address of slave module

Table 4.3 AT Command used for Master Module

AT Command	Respond
AT	OK
AT+INIT	OK
AT+IAC=9e8b33	OK
AT+CLASS=0	OK
AT+INQM=1,10,48	OK
AT+INQ	RSSI

There are two modes of operation, which are the command mode and data mode. In this case, command mode was used, which required the KEY pin to be set high.

4.3.2 Arduino Microcontroller

As Figure 4.3 shows, the system has two components, which are the Arduino board (a), and its integrated development environment (IDE) (b). The IDE was used to write the program (known as a sketch in Arduino terminology), which then in turn, was uploaded to the Arduino board.

Figure 4.3 (a) Arduino UNO board

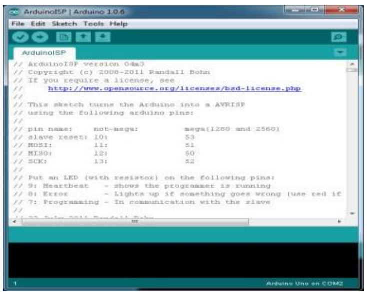

Figure 4.3 (b) Arduino IDE

An Arduino UNO board is a kind of microcontroller board, based on an ARM processor (Arduino.cc, 2016). The specifications are shown below in table 4.3.

Table 4.4 Specifications for the Arduino Uno Microcontroller (Arduino.cc, 2016)

Microcontroller	ATmega328P
Operating Voltage	5 V
Input Voltage (recommended)	7-12 V
Input Voltage (limit)	6-20 V
Digital I/O Pins	14 (of which 6 provide PWM output)
PWM Digital I/O Pins	6
Analog Input Pins	6
DC Current per I/O Pin	20 mA
DC Current for 3.3 V Pin	50 mA
Flash Memory	32 KB (ATmega328P) of which 0.5 KB used by bootloader
SRAM	2 KB (ATmega328P)
EEPROM	1 KB (ATmega328P)
Clock Speed	16 MHz
LED_BUILTIN	13
Length	68.6 mm
Width	53.4 mm
Weight	25 g

4.3.3 Circuit design and test

The Arduino's digital connections enable both 5 V inputs and outputs, which worked well with the 5 V tolerant pins on the Bluetooth modules. However, for the purpose of ensuring safety (no damage), a voltage divider was uses to reduce the 5 V output from the Arduino board to 3.3 V as shown in Figure 4.4.

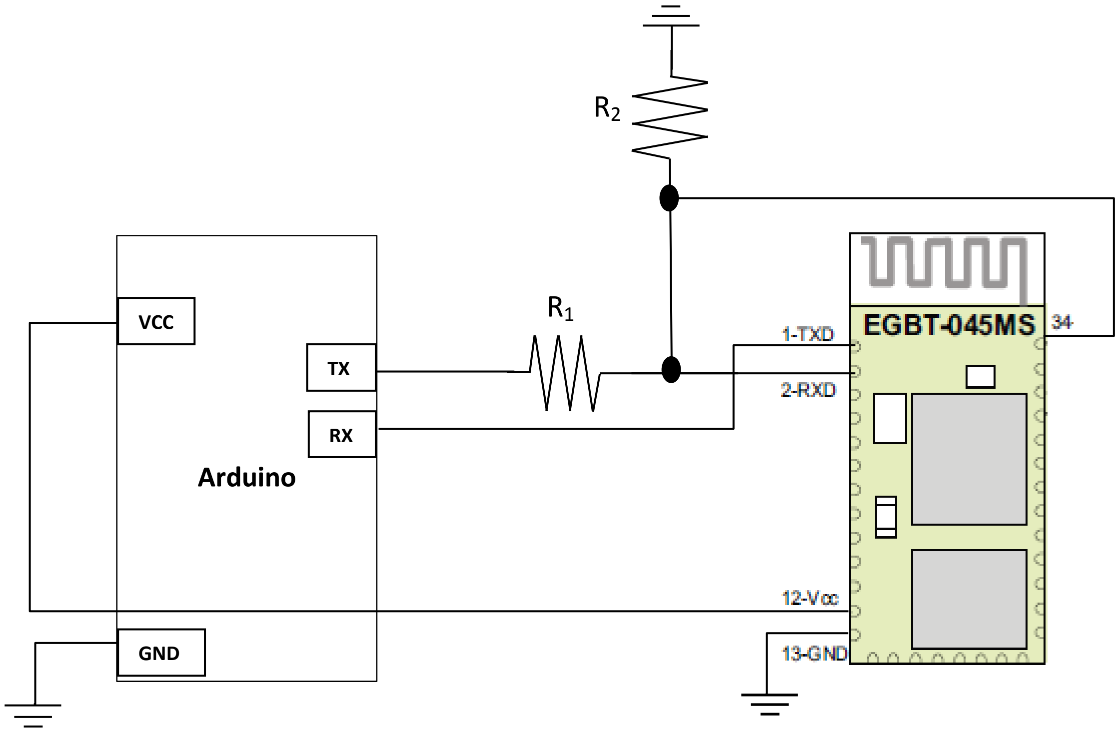

Figure 4.4 Circuit arrangements to divide the output voltage of Arduino

As can be seen

$$V_{\mathrm{RXD}} = \frac{R_1}{R_1+R_2} V_{\mathrm{TX}} \quad (4.1)$$

Where V_{RXD} is the data input to the Bluetooth device which is the voltage from Arduino's TX pin supplied. R_1 and R_2 form a potential divider for the V_{RXD}(3.3 V) which is suitable to supply to the RX pin of Bluetooth module.

The AT commands to the transceivers are sent via the Arduino IDE. The transceiver status signals are also returned via the Arduino IDE (See the program in Appendix 3). Figure 4.5 shows the Arduino IDE and the system hardware.

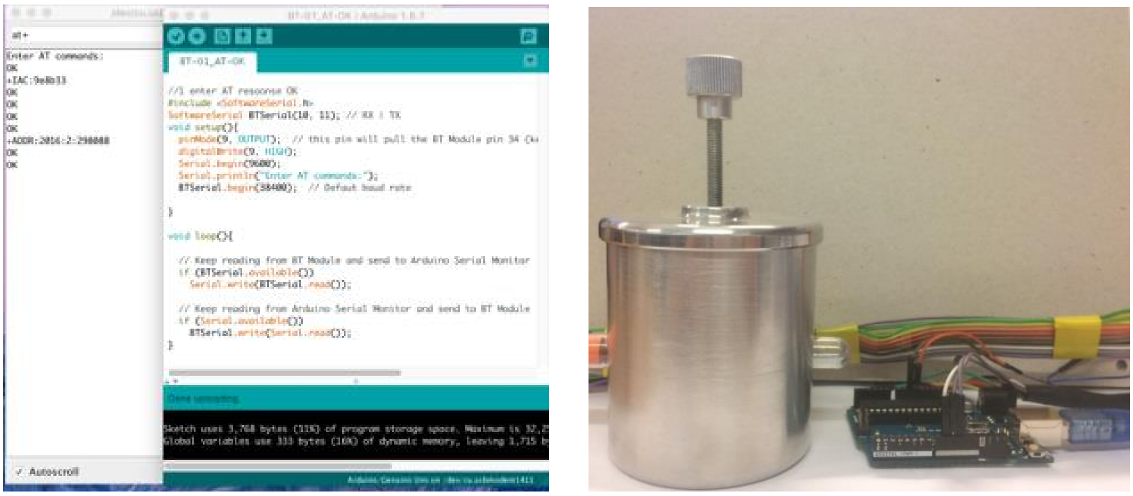

Figure 4.5 Arduino IDE and the system hardware

4.4 Summary

Ideally, medical instrumentation should be low cost, easy to use, and resilient. Wi-Fi and Bluetooth modules are both low cost, and comparatively easy to use. They also operate at a frequency which is high enough to enable a small size resonant cavity to be used. An additional benefit is that they are free licence devices (Wankhade *et al.,* 2015). However, after reviewing the data and the advantages and disadvantages of both, the Bluetooth module proved to be more suitable than the Wi-Fi module.

This chapter has described the electronic and software design which consists of a pair of Bluetooth transceivers within a resonant cavity and an Arduino board with its associated controller. The characteristics of the Bluetooth and Arduino modules were also being discussed. In the next chapter, samples within the resonant cavity will be used to determine any relationship between glucose concentration and the signal level. The RSSI will be interrogated, and the resultant data will be presented in scatter plots.

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CHAPTER 5

EXPERIMENTAL RESULTS AND DISCUSSION

5.1 Introduction

5.2 Research into sample

5.2.1 Blood glucose

5.2.2 Features of sample

5.3 Experimental method

5.4 Experimental results

5.4.1 Preliminary test

5.4.2 First test

5.4.3 Second test

5.4.4 Third test

5.4.5 Fourth test

5.5 Discussion of results

5.6 Summary

5.7 References

5.1 Introduction

This chapter shows the results of experiments which were repeated 5 times to confirm the relationship between varying concentrations of glucose solution and the signal level within the resonant cavity. The preliminary test was to make sure the system actually worked, and the following tests were to establish the relationship between glucose concentrations and signal level. The variances of concentration levels were extended as the experiments progressed. The results were then used to establish optimum conditions for the experimental. All the data from the experiments is shown in Appendix 4.

5.2 Research into sample

5.2.1 Blood glucose

There are a number of factors that contribute to the symptomatic levels of diabetes, the most serious is high blood glucose levels (hyperglycaemia) (Causes of Diabetes, 2016). Glucose also known as dextrose is a kind of sugar, and is produced from fat and protein in the body. Different countries have their own methods of measuring glucose level. For example, America uses milligrams of glucose per decilitre of blood; while, in UK people prefer millimoels glucose per litre (mmol/l) (What is a normal blood sugar level, 2016). In this subject mmol/l will be chosen.

According to Blood Sugar Level Ranges (2016), the ordinary blood sugar level ranges are based on the different type of diabetes, the recommended target blood glucose level ranges are shown below:

Table 5.1 Nice recommended target blood glucose level ranges (Global diabetes community, 2016)

Target Levels by Type	**Upon waking**	**Before meals (pre-prandial)**	**At least 90 minutes after meals (post prandial)**
Non-diabetic*		4.0 to 5.9 mmol/l	under 7.8 mmol/l
Type 2 diabetes		4 to 7 mmol/l	under 8.5 mmol/l
Type 1 diabetes	5 to 7 mmol/l	4 to 7 mmol/l	5 to 9 mmol/l
Children w/ type 1 diabetes	4 to 7 mmol/l	4 to 7 mmol/l	5 to 9 mmol/l

Glucose sugar means glucose content, therefore in this research, different amounts of glucose will be dissolved in a constant volume water to simulate different blood glucose concentrations. Most researchers choose D-glucose for their experiments, because D-glucose was commonly in nature and easily dissolved in water. The molecular formula of D-glucose is $C_6H_{12}O_6$, and this is used to calculate the molecular weight, as shown in table 5.2 and equation 5.1.

Table 5.2 Molecular mass of atom

Atom	**Number in Molecule**	**Atomic Weight**	**Total Mass**
C	6	12.0107	72.0642
H	12	1.00794	12.09528
O	6	15.9994	92.9964

The units of molecular weight are grams per mole and it is the mass of one mole of a substance. Therefore, the molecular weight of D-glucose is calculated as shown below:

$$Molar\ mass\ of\ glucose\ \ C_6H_{12}O_6 = C_6 + H_{12} + O_6 = 180.15588 g/mol \quad (5.1)$$

5.2.2 Features of sample

Varying glucose solutions as outlined above were used as test samples when detecting the signal level changes in the resonant microwave cavity. The α-anomer and β-anomer are components of glucose and in the human body, and form an important source of energy. When glucose was dissolved in the water, the percentage of α-anomer and β-anomer will become about 33% and 77%. Before using the glucose/water solution, there are some limitations that need to be considered:

- Store temperature: room temperature (20 to 22 °C)
- Melting point: 146 °C (α-D-glucose), 150 °C (β-D-glucose)
- Solubility in water: 909 g/l (20 °C)

5.3 Experimental method

Due to problems of accessibility, safety and ethics is being not possible to use blood for the testing of the system. And since the aqueous solution of glucose has become the most widely accepted and frequently used within diabetes experiment area (Choi *et al*., 2016), this is the approach taken here. Therefore, this research used glucose/water solutions as test samples.

It was very important to make sure that the conditions for each experiment were the same. For instance, the solubility of glucose in the water increases with temperature (Pratumvinit, 2016). To this end, it was ensured that only the concentration of glucose solution was changed during testing, and the temperature was kept at a constant 20°C. Disposable tubes were used to avoid cross contamination. The same volume of water was used in every experiment, with only the amount of glucose being changed. This ensures that any variations in RSSI are due to varying concentrations of glucose.

Frequently, Molarity is chosen to describe the concentration of a solution, which is equal to the moles of solute (glucose powder) over the litres of solution (water). The concentration of glucose solution was calculated by molarity formula:

$$\mathrm{M(Molarity)} = \frac{\mathrm{m}}{\mathrm{L}} \tag{5.2}$$

Where m is moles of solute, L is litres of solution. Therefore the mole of glucose is $\mathrm{m} = \mathrm{M} \times \mathrm{L}$, and the moles of glucose can be converted into grams. Glucose powder as an independent value should be controlled.

In this subject, the concentration of glucose was the independent variable x, with the percentage RSSI change as the dependent variable y. Every test started with a pure water reference sample, for the establishment of the datum RSSI ($\mathrm{X_0}$). Then the following RSSI were compared with $\mathrm{X_0}$ to get the change in RSSI ($\mathrm{X_0} - \mathrm{X_x}$). Using the change value ($\mathrm{X_0} - \mathrm{X_x}$) divided by $\mathrm{X_0}$ and multiplied by 100% gives the percentage value y, as shown in equation 5.2 below.

$$y(\%) = \frac{X_0 - X_x}{X_0} \times 100\% \tag{5.2}$$

All the data from the Bluetooth transceivers were in hexadecimal format, and before the calculations, these were converted to decimal.

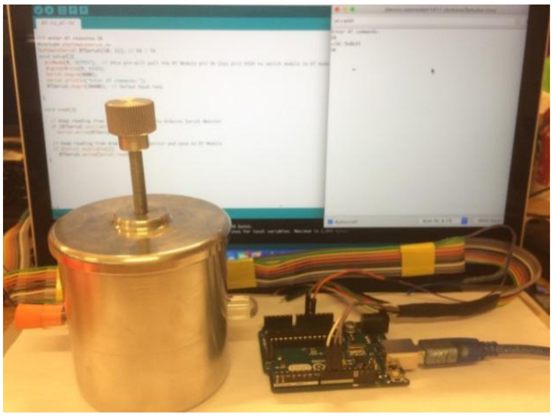

Figure 5.1 Experimental Setup

Figure 5.1 shows the completed system. The Arduino and computer were used to configure the two Bluetooth modules as a master and a slave. Later on, these were used to send control messages to transmitter and receiver. Once the slave (receiver) will receives the signal in the cavity, and the commands to the master (transmitter). Finally, the RSSI measurements were uploaded to the PC via a USB connection. All the results were presented in scatter plots which show the relationship between signal level detection and varying concentrations of glucose in water solution.

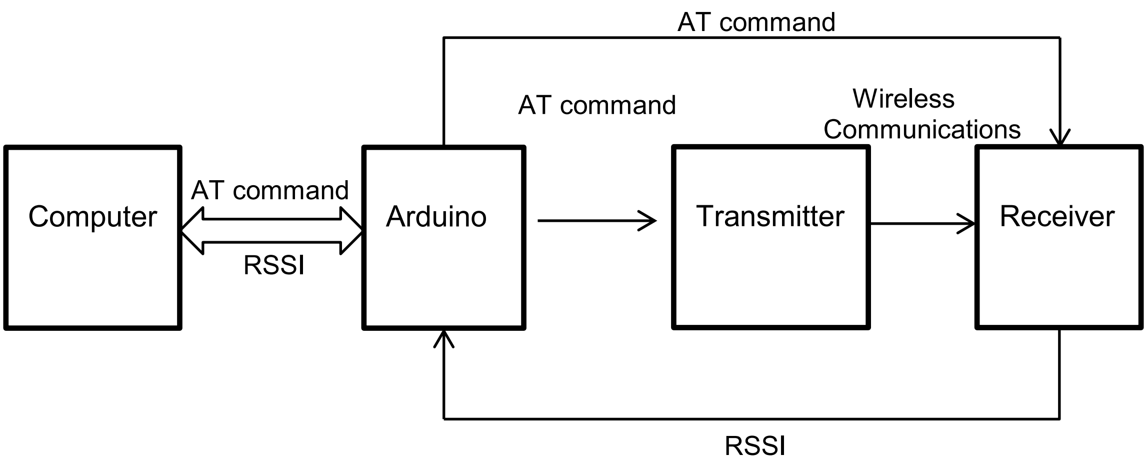

Figure 5.2 Workflow of system

5.4 Experimental results

5.4.1 Preliminary test

Following the first runs with pure water to establish the datum conditions, the concentration's range of initial samples was from 0 mol/l to 1.373810128 mol/l, the volume of water was 0.02 L and temperature was 20°C. In this test, nine samples were considered in three parts, as explained below:

- Part 1 was chosen from the lower concentration of glucose, which was from 0 mol/l to 0.02775374 mol/l.
- Part 2 was chosen from the middle concentration of glucose, which was from 0.679966629 mol/l to 0.707720369 mol/l.
- Part 3 was chosen from the higher concentration of glucose which was from 1.346056388 mol/l to 1.373810128 mol/l.

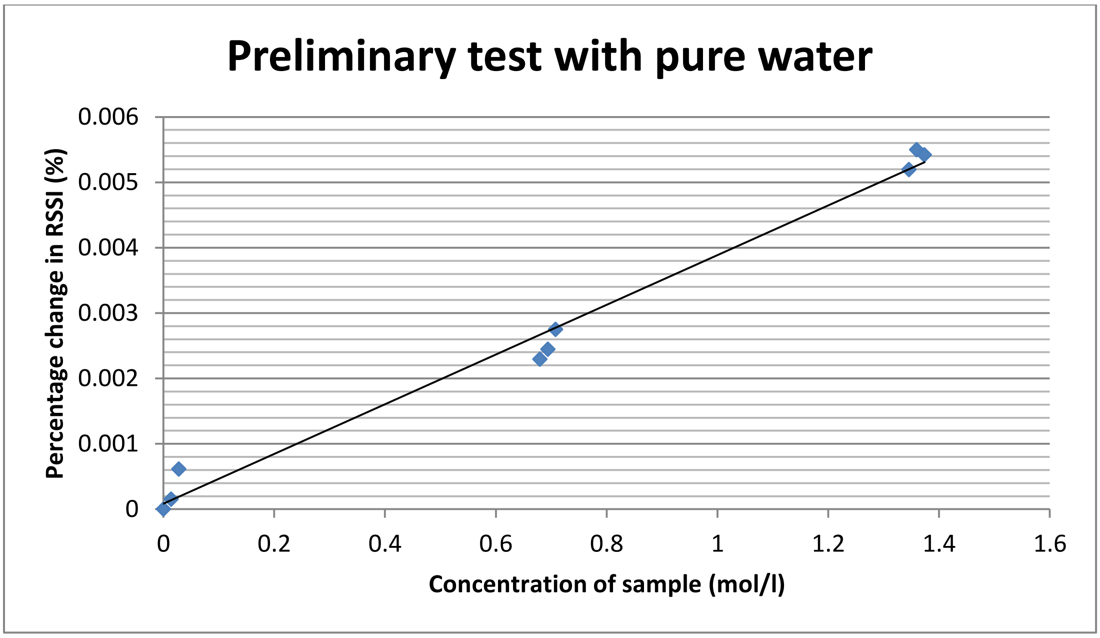

Figure 5.3 Preliminary test results

Figure 5.3 shows that a linear relationship between glucose concentrations and RSSI has been identified. The next step was to perform a statistical test, the R^2 value, often called ‘goodness of fit’, and used to describe the extent of the linear relationship between the values (Significance of the R^2 value, 2016). The range of R^2 values is from 0 to 1. An R^2 value of 1 denotes a perfectly linear relationship between the two variables, whilst a value of 0 denotes no relationship. It can be automatically calculated by EXCEL and is shown in the top right hand corner of Figures 5.4 to 5.7. The horizontal axis in scatter plots shows the concentration of glucose within the water, the vertical axis shows the percentage change in RSSI.

5.4.2 First test

The first test used 100 samples with the difference of concentration between samples of 0.0138 mol/l. This produced a pleasing result in that higher concentration of the sample produced higher percentage changes in RSSI. Moreover, as can be seen from the graph, a clear linear relationship was show, with an R^2 value of 0.5847 which denotes a significant correlation.

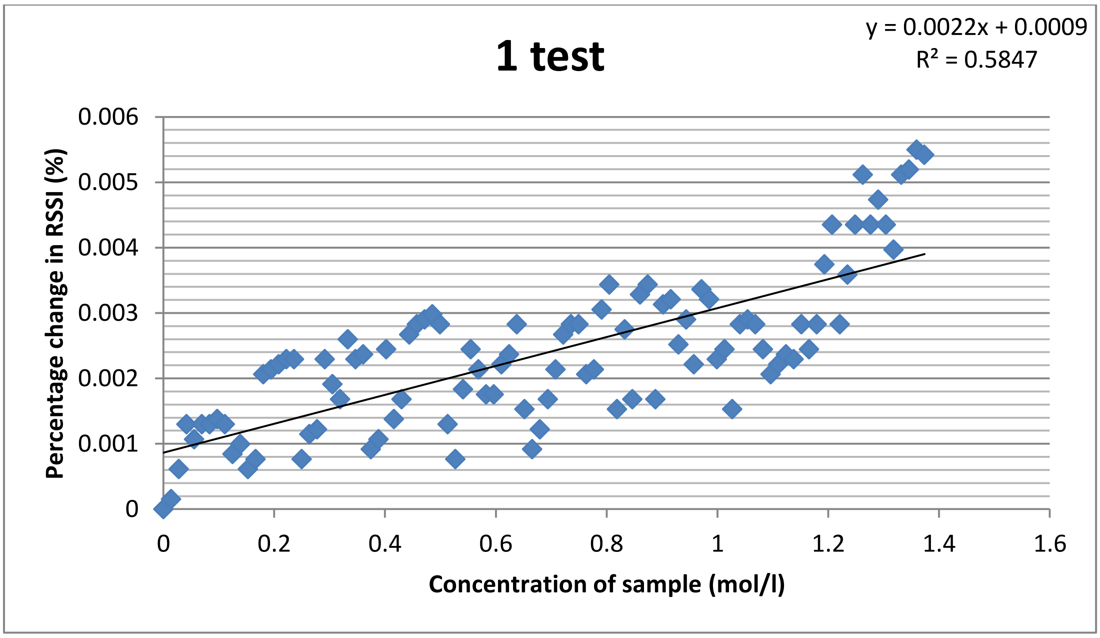

Figure 5.4 First test 100 samples’ results

5.4.3 Second test

The second test used wider variations of concentration of sample, increasing from 0.0138 mol/l to 0.2775374 mol/l. This test run produced an $R^2 = 0.6171$, which is an even better correlation than produced by test one. As expected, greater changes in RSSI were demonstrated too. The second test results were shown below in Figure 5.5.

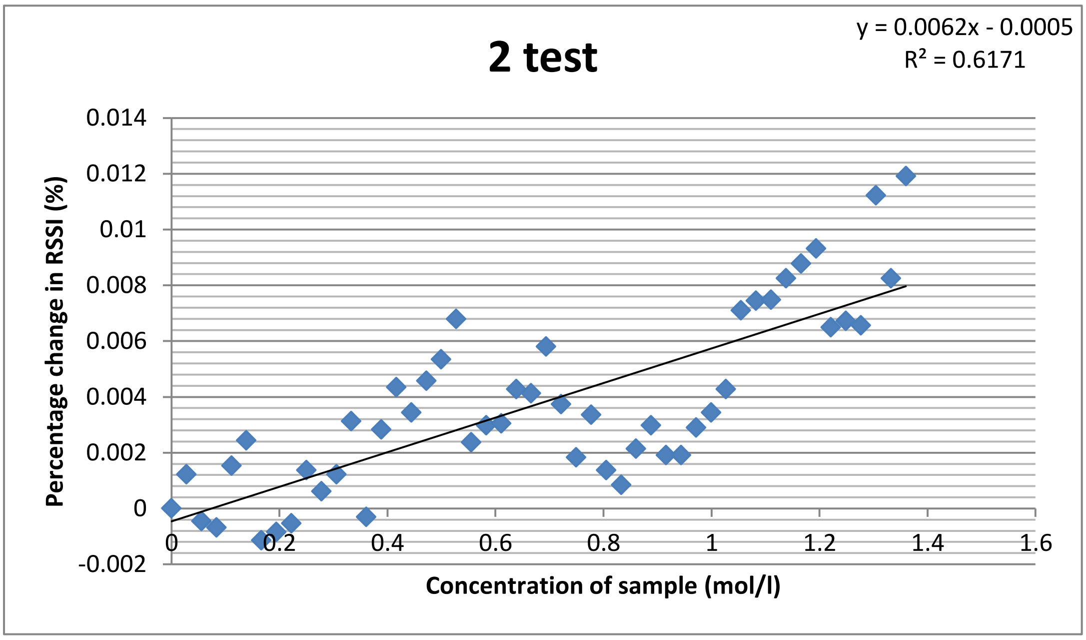

Figure 5.5 Second test 50 samples' results

5.4.4 Third test

Again for this test, the variation of concentration between different samples was extended from 0.02775374 mol/l to 0.111 mol/l. In this test run, 18 samples were prepared for this test because the limitation of glucose's solubility in water at 20 °C. The results of third test were shown below:

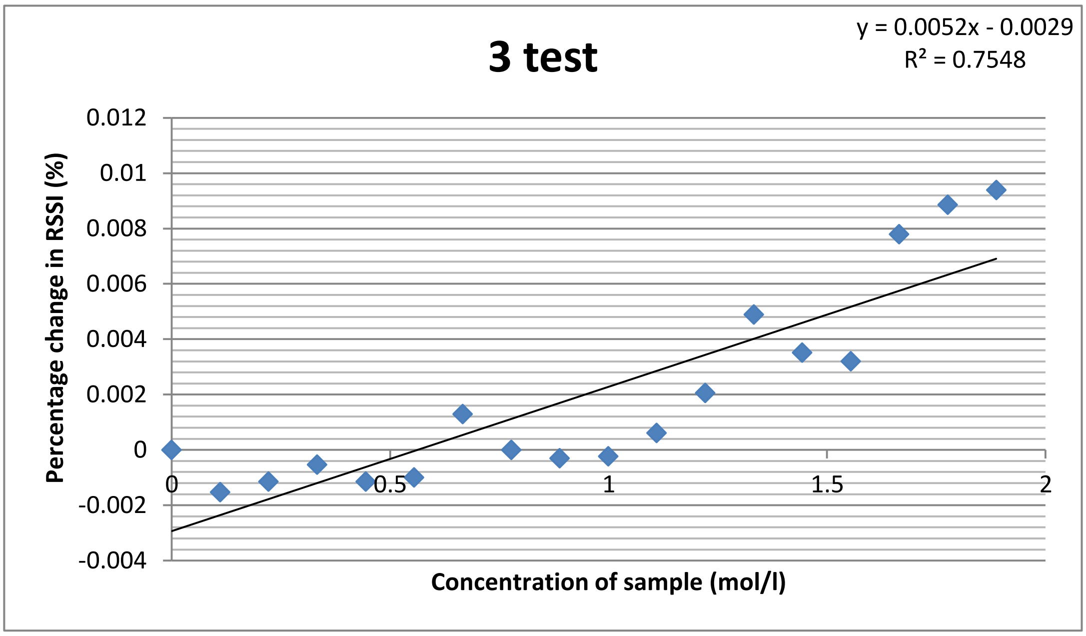

Figure 5.6 Third test 18 samples' results

A very clear relationship between the concentration of sample and the percentage change of RSSI was showed in Figure 5.6. Also shown is that the R^2 increased to 0.7548, which demonstrates a highly significant correlation.

5.4.5 Fourth test

For the fourth test, the variation of concentration levels was increased to 0.111 mol/l. The results of this even better than the third test, as shown in Figure 5.6. It also shows that the R^2 value has increased to 0.7924.

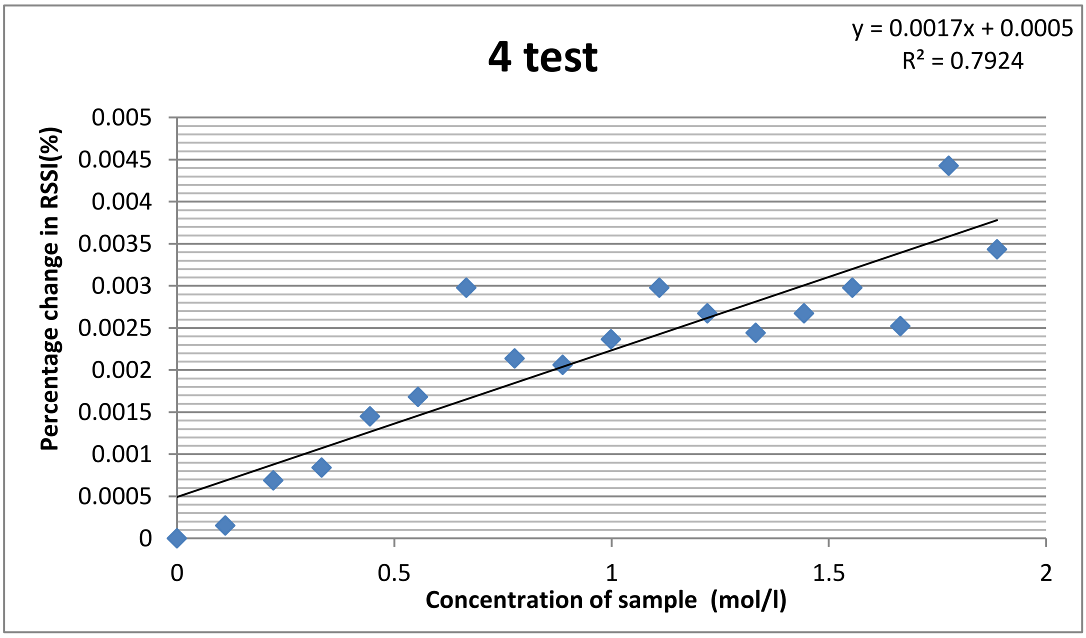

Figure 5.7 Fourth test 18 samples' results

5.5 Discussion of results

The purpose of this subject was to investigate the relationship between varying concentrations of glucose in a water solution and the signal level within a resonant microwave cavity. This research has positively demonstrated a linear relationship, with a significant correlation between these variables.

As Figures 5.3 to 5.7 show, all the results showed a positive correlation between glucose concentrations and RSSI levels. Table 5.1 which contains a summary of the test data, also demonstrates increasing R^2 correlations.

Table 5.3 Four Times Tests Details

Test Name	**Sample Number**	**Difference of Concentrations**	**R^2**
1	100	0.01387687 mol/la	0.5847
2	50	0.02775374 mol/l	0.6171
3	18	0.11101496 mol/l	0.7548
4	18	0.11101496 mol/l	0.7924

In this subject, to reduce the measurement error from system, every sample were tested 10 times then get the mean value of the data. Additionally, some tests were duplicated to ensure the validity of the data. As Chapter 5 mentioned, the third and fourth test more clearly demonstrated the relationship between varying concentrations of glucose and changes in RSSI. In these tests, the number of samples was limited to 18 samples, due to the limitation of glucose's solubility at 20°C.

5.6 Summary

Compared to the other methods and technologies (as discussed in Chapter 2), this system has the following advantages:

- This can operate as a stand-alone device
- As it is based on an open-source controller and software, it is simpler to modify in the future
- It could be expanded to communicate with Bluetooth devices (such as mobile phones) to enable remote monitoring by physicians
- It is non-invasive

5.7 References

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CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

6.2 Future work

6.3 References

6.1 Conclusion

As discussed in Chapter 1, diabetes has become a major threat to public health (International Diabetes Federation, 2015) and the self-monitoring of blood glucose levels is a developing trend. The aim of this research was to design and develop a system to confirm that could be used to detect varying concentrations of glucose in water solution, through measuring changes of RSSI with a resonant microwave cavity, which has the potential to be further developed into a stand-alone, self-administered blood glucose measurement system.

This has been achieved in three main steps which are:

- Literature review to gain knowledge of the existing methods of blood glucose measurement, and also to gain knowledge of the technologies used in this research
- Design and test of the system to confirm correct operation
- Conducting experiments to confirm the system's ability to detect varying levels of glucose concentration

The first stage is to conduct a review of the existing systems and identify the possibilities of using microwave techniques in the system. In Chapter 2, microwave techniques were examined in detail, and in particular, the effect of varying concentrations of glucose on the received signal levels. Following this, the existing methods were compared to the new approach taken in this research. Based on the results of this comparison, a system comprising of a microwave resonant cavity and two Bluetooth modules was developed. The benefits of the resonant cavity and Bluetooth are described below:

- It blocks interference from other signal sources
- Low radiation losses

Bluetooth:

- Low cost
- Low power
- RSSI – received signal strength indicator which was used to measure received power by program and microcontroller
- Free licence

Based on the first stage, the second stage is to design a system to detect the varying concentrations of glucose using a resonant cavity and two Bluetooth modules as transceivers. This included cavity design (Chapter 3) and electronic design (Chapter 4). A 2.4 GHz frequency signal is supplied to the cavity by the Bluetooth module – HC-05. This causes a microwave field within the cavity. In this research, RSSI was used to measure the signal strength variations within the resonant cavity in relation to varying glucose concentrations within cavity. This was done by collecting the RSSI data from the Bluetooth receiver through use of an Arduino microcontroller.

The final stage was to perform experiments to extract the varying signal strength parameter - RSSI and analysis them for correlations with glucose concentrations. This was done by performing five sets of tests, and presenting the data in scatter plots, as shown in Figures 5.3 to 5.7. As these figures show, as the glucose concentration levels increased, the RSSI decreased, due to the absorption of microwave energy by the glucose molecules. To confirm the possibility of a linear relationship, an R^2 statistical analysis was performed on the data. R^2 value values in the range of 0.5847 to 0.7924 demonstrated significant levels of linear correlation.

As can be seen from the findings, and original contribution to the development of a microwave based, non-invasive blood glucose measurement system has been established.

6.2 Future work

1. Improve the accuracy and sensitivity of the system by using improved transmitters and receivers.
2. Develop the smart system- access the internet and combined the computer or Mobile phone (IP address, Bluetooth)
3. Develop algorithms to predict future blood glucose levels, to avoid hyperglycaemia (too much blood sugar) and hypoglycaemia (blood sugar too low).
4. Reduce the size of the system
5. Make a fully stand-alone system that does not need a computer, by using a more powerful microcontroller, along with an LCD display.

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CHAPTER 8

APPENDICES

8.1 Appendix 1 MATLAB program

8.2 Appendix 2 Resonant microwave cavity schematic

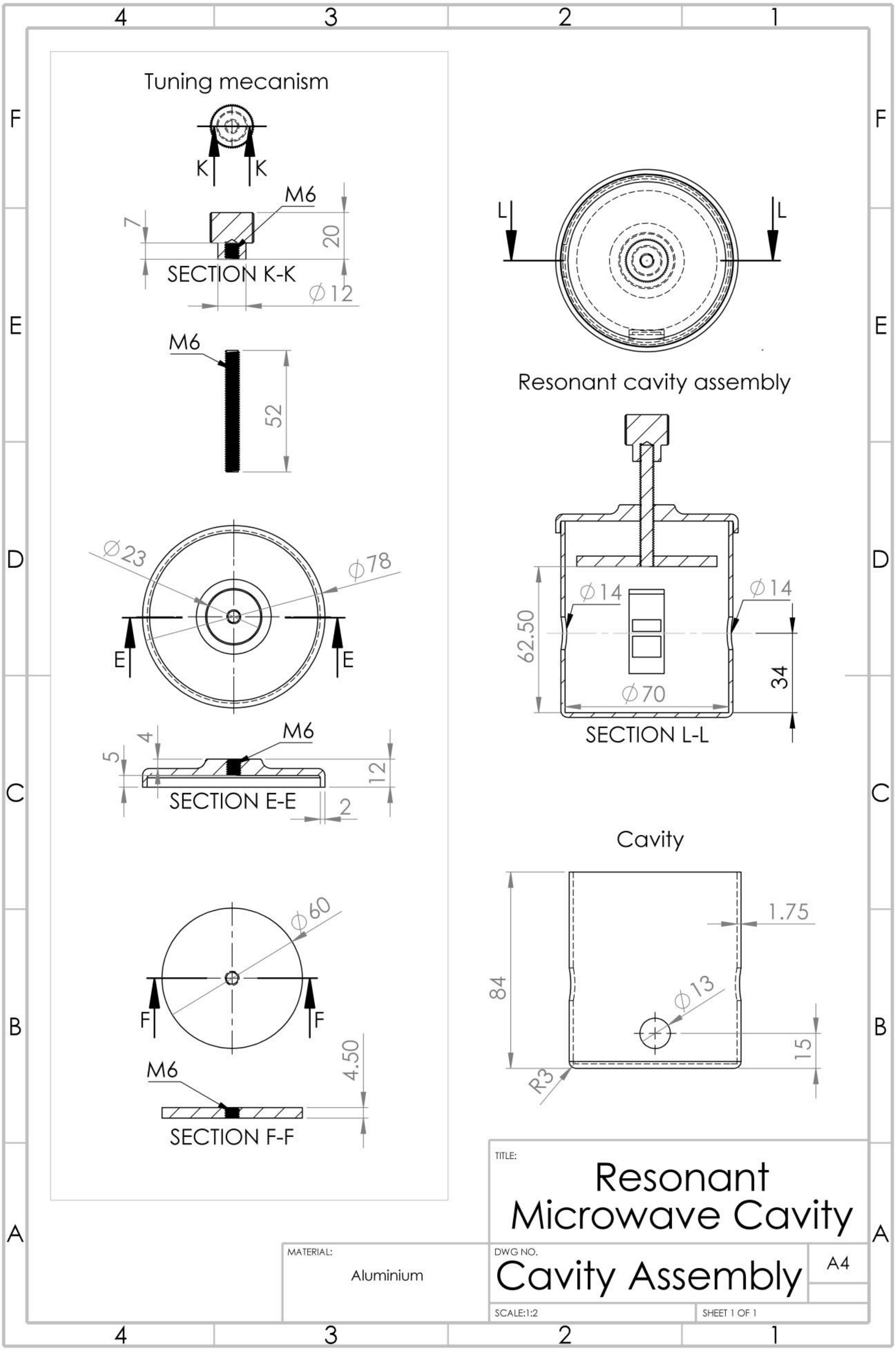
8.3 Appendix 3 Arduino program

8.4 Appendix 4 Experimental data

8.1 Appendix 1 MATLAB program

```
run C:\eidors\eidors\startup.m % USE THIS ALWAYES FOR Windows

shape_str = ['solid cyl    = cylinder (0,0,0; 0,0,1; 1); \n', ...

            'solid bottom = plane(0,0,0;0,0,-1);\n' ...

            'solid top    = plane(0,0,1;0,0,1);\n' ...

            'solid mainobj= top and bottom and cyl -maxh=3;\n'];

elec_pos = [  -1,  0,  1.5,   1,  0,  0;

               1, 0,  1.5,  -1,  0,  0];

elec_shape=[1.43,2.48];

elec_obj = {'cyl','cyl'};

fmdl= ng_mk_cyl_models([6.25,3.5],[2,1],[1.43,2.48]);

img= mk_image(fmdl,1);

show_fem(img);
```

8.2 Appendix 2 Resonant microwave cavity schematic



Product Title:

Resonant Microwave Cavity Schematic

Purpose:

- It blocks interference from external signal sources
- Low radiation losses

Performance:

It can keep the signal from transmitter and receiver stable and block interference from other signal sources

New or special features:

- Low cost
- Small size

Materials:

Aluminium

Physical dimensions:

- Height: 62.5mm
- Diameter: 70mm

8.3 Appendix 3 Arduino program

```
//1 enter AT resoonse OK

#include <SoftwareSerial.h>

SoftwareSerial BTSerial(10, 11); // RX | TX

void setup(){

  pinMode(9, OUTPUT);  // this pin will pull the BT Module pin 34 (key pin) HIGH
to switch module to AT mode

  digitalWrite(9, HIGH);

  Serial.begin(9600);

  Serial.println("Enter AT commands:");

  BTSerial.begin(38400);  // Defaut baud rate

}

void loop(){

        // Keep reading from BT Module and send to Arduino Serial Monitor

        if (BTSerial.available())

          Serial.write(BTSerial.read());

        // Keep reading from Arduino Serial Monitor and send to BT Module

        if (Serial.available())

          BTSerial.write(Serial.read()); }
```

8.4 Appendix 4 Experimental data

- **Table A1 Preliminary test results**

Sample number	Weight of sample(g)	Volume(l)	Concentration (mol/l)	RSSI	Percentage (%)
0	0	0.02	0	65504.85	0
1	0.05	0.02	0.01387687	65504.75	0.00015266
2	0.1	0.02	0.02775374	65504.45	0.000610642
3	2.45	0.02	0.679966629	65503.35	0.002289907
4	2.5	0.02	0.693843499	65503.25	0.002442567
5	2.55	0.02	0.707720369	65503.05	0.002747888
6	4.85	0.02	1.346056388	65501.45	0.005190455
7	4.9	0.02	1.359933258	65501.25	0.005495776
8	4.95	0.02	1.373810128	65501.3	0.005419446

- **Table A2 First test 100 samples' results**

Sample number	Weight of sample(g)	Volume(l)	Concentration (mol/l)	RSSI	Percentage (%)
0	0	0.02	0	65504.85	0
1	0.05	0.02	0.01387687	65504.75	0.00015266
2	0.1	0.02	0.02775374	65504.45	0.000610642
3	0.15	0.02	0.04163061	65504	0.001297614
4	0.2	0.02	0.05550748	65504.15	0.001068623
5	0.25	0.02	0.06938435	65504	0.001297614
6	0.3	0.02	0.08326122	65504	0.001297614
7	0.35	0.02	0.09713809	65503.95	0.001373944
8	0.4	0.02	0.11101496	65504	0.001297614
9	0.45	0.02	0.12489183	65504.3	0.000839632
10	0.5	0.02	0.1387687	65504.2	0.000992293

11	0.55	0.02	0.15264557	65504.45	0.000610642
12	0.6	0.02	0.16652244	65504.35	0.000763302
13	0.65	0.02	0.18039931	65503.5	0.002060916
14	0.7	0.02	0.19427618	65503.45	0.002137246
15	0.75	0.02	0.20815305	65503.4	0.002213577
16	0.8	0.02	0.22202992	65503.35	0.002289907
17	0.85	0.02	0.23590679	65503.35	0.002289907
18	0.9	0.02	0.24978366	65504.35	0.000763302
19	0.95	0.02	0.26366053	65504.1	0.001144953
20	1	0.02	0.2775374	65504.05	0.001221284
21	1.05	0.02	0.29141427	65503.35	0.002289907
22	1.1	0.02	0.30529114	65503.6	0.001908256
23	1.15	0.02	0.319168009	65503.75	0.001679265
24	1.2	0.02	0.333044879	65503.15	0.002595228
25	1.25	0.02	0.346921749	65503.35	0.002289907
26	1.3	0.02	0.360798619	65503.3	0.002366237
27	1.35	0.02	0.374675489	65504.25	0.000915963
28	1.4	0.02	0.388552359	65504.15	0.001068623
29	1.45	0.02	0.402429229	65503.25	0.002442567
30	1.5	0.02	0.416306099	65503.95	0.001373944
31	1.55	0.02	0.430182969	65503.75	0.001679265
32	1.6	0.02	0.444059839	65503.1	0.002671558
33	1.65	0.02	0.457936709	65503	0.002824218
34	1.7	0.02	0.471813579	65502.95	0.002900549
35	1.75	0.02	0.485690449	65502.9	0.002976879
36	1.8	0.02	0.499567319	65503	0.002824218
37	1.85	0.02	0.513444189	65504	0.001297614

38	1.9	0.02	0.527321059	65504.35	0.000763302
39	1.95	0.02	0.541197929	65503.65	0.001831925
40	2	0.02	0.555074799	65503.25	0.002442567
41	2.05	0.02	0.568951669	65503.45	0.002137246
42	2.1	0.02	0.582828539	65503.7	0.001755595
43	2.15	0.02	0.596705409	65503.7	0.001755595
44	2.2	0.02	0.610582279	65503.4	0.002213577
45	2.25	0.02	0.624459149	65503.3	0.002366237
46	2.3	0.02	0.638336019	65503	0.002824218
47	2.35	0.02	0.652212889	65503.85	0.001526605
48	2.4	0.02	0.666089759	65504.25	0.000915963
49	2.45	0.02	0.679966629	65504.05	0.001221284
50	2.5	0.02	0.693843499	65503.75	0.001679265
51	2.55	0.02	0.707720369	65503.45	0.002137246
52	2.6	0.02	0.721597239	65503.1	0.002671558
53	2.65	0.02	0.735474109	65503	0.002824218
54	2.7	0.02	0.749350979	65503	0.002824218
55	2.75	0.02	0.763227849	65503.5	0.002060916
56	2.8	0.02	0.777104719	65503.45	0.002137246
57	2.85	0.02	0.790981589	65502.85	0.003053209
58	2.9	0.02	0.804858459	65502.6	0.00343486
59	2.95	0.02	0.818735329	65503.85	0.001526605
60	3	0.02	0.832612199	65503.05	0.002747888
61	3.05	0.02	0.846489069	65503.75	0.001679265
62	3.1	0.02	0.860365939	65502.7	0.0032822
63	3.15	0.02	0.874242809	65502.6	0.00343486
64	3.2	0.02	0.888119679	65503.75	0.001679265

65	3.25	0.02	0.901996549	65502.8	0.003129539
66	3.3	0.02	0.915873419	65502.75	0.003205869
67	3.35	0.02	0.929750289	65503.2	0.002518897
68	3.4	0.02	0.943627158	65502.95	0.002900549
69	3.45	0.02	0.957504028	65503.4	0.002213577
70	3.5	0.02	0.971380898	65502.65	0.00335853
71	3.55	0.02	0.985257768	65502.75	0.003205869
72	3.6	0.02	0.999134638	65503.35	0.002289907
73	3.65	0.02	1.013011508	65503.25	0.002442567
74	3.7	0.02	1.026888378	65503.85	0.001526605
75	3.75	0.02	1.040765248	65503	0.002824218
76	3.8	0.02	1.054642118	65502.95	0.002900549
77	3.85	0.02	1.068518988	65503	0.002824218
78	3.9	0.02	1.082395858	65503.25	0.002442567
79	3.95	0.02	1.096272728	65503.5	0.002060916
80	4	0.02	1.110149598	65503.4	0.002213577
81	4.05	0.02	1.124026468	65503.3	0.002366237
82	4.1	0.02	1.137903338	65503.35	0.002289907
83	4.15	0.02	1.151780208	65503	0.002824218
84	4.2	0.02	1.165657078	65503.25	0.002442567
85	4.25	0.02	1.179533948	65503	0.002824218
86	4.3	0.02	1.193410818	65502.4	0.003740181
87	4.35	0.02	1.207287688	65502	0.004350823
88	4.4	0.02	1.221164558	65503	0.002824218
89	4.45	0.02	1.235041428	65502.5	0.003587521
90	4.5	0.02	1.248918298	65502	0.004350823
91	4.55	0.02	1.262795168	65501.5	0.005114125

92	4.6	0.02	1.276672038	65502	0.004350823
93	4.65	0.02	1.290548908	65501.75	0.004732474
94	4.7	0.02	1.304425778	65502	0.004350823
95	4.75	0.02	1.318302648	65502.25	0.003969172
96	4.8	0.02	1.332179518	65501.5	0.005114125
97	4.85	0.02	1.346056388	65501.45	0.005190455
98	4.9	0.02	1.359933258	65501.25	0.005495776
99	4.95	0.02	1.373810128	65501.3	0.005419446

- **Table A3 Second test 50 samples' results**

Sample number	Weight of sample(g)	Volume(l)	Concentration (mol/l)	RSSI	Percentage (%)
0	0	0.02	0	65504.95	0
1	0.1	0.02	0.02775374	65504.15	0.001221282
2	0.2	0.02	0.05550748	65505.25	-0.00045798
3	0.3	0.02	0.08326122	65505.4	-0.00068697
4	0.4	0.02	0.11101496	65503.95	0.001526602
5	0.5	0.02	0.1387687	65503.35	0.002442564
6	0.6	0.02	0.16652244	65505.7	-0.00114495
7	0.7	0.02	0.19427618	65505.5	-0.00083963
8	0.8	0.02	0.22202992	65505.3	-0.00053431
9	0.9	0.02	0.24978366	65504.05	0.001373942
10	1	0.02	0.2775374	65504.55	0.000610641
11	1.1	0.02	0.30529114	65504.15	0.001221282
12	1.2	0.02	0.333044879	65502.9	0.003129534
13	1.3	0.02	0.360798619	65505.15	-0.00030532
14	1.4	0.02	0.388552359	65503.1	0.002824214
15	1.5	0.02	0.416306099	65502.1	0.004350816
16	1.6	0.02	0.444059839	65502.7	0.003434855
17	1.7	0.02	0.471813579	65501.95	0.004579807
18	1.8	0.02	0.499567319	65501.45	0.005343108
19	1.9	0.02	0.527321059	65500.5	0.00679338
20	2	0.02	0.555074799	65503.4	0.002366233
21	2.1	0.02	0.582828539	65503	0.002976874
22	2.2	0.02	0.610582279	65502.95	0.003053204
23	2.3	0.02	0.638336019	65502.15	0.004274486

24	2.4	0.02	0.666089759	65502.25	0.004121826
25	2.5	0.02	0.693843499	65501.15	0.005801088
26	2.6	0.02	0.721597239	65502.5	0.003740175
27	2.7	0.02	0.749350979	65503.75	0.001831923
28	2.8	0.02	0.777104719	65502.75	0.003358525
29	2.9	0.02	0.804858459	65504.05	0.001373942
30	3	0.02	0.832612199	65504.4	0.000839631
31	3.1	0.02	0.860365939	65503.55	0.002137243
32	3.2	0.02	0.888119679	65503	0.002976874
33	3.3	0.02	0.915873419	65503.7	0.001908253
34	3.4	0.02	0.943627158	65503.7	0.001908253
35	3.5	0.02	0.971380898	65503.05	0.002900544
36	3.6	0.02	0.999134638	65502.7	0.003434855
37	3.7	0.02	1.026888378	65502.15	0.004274486
38	3.8	0.02	1.054642118	65500.3	0.0070987
39	3.9	0.02	1.082395858	65500.07	0.007449819
40	4	0.02	1.110149598	65500.05	0.007480351
41	4.1	0.02	1.137903338	65499.55	0.008243652
42	4.2	0.02	1.165657078	65499.2	0.008777963
43	4.3	0.02	1.193410818	65498.85	0.009312273
44	4.4	0.02	1.221164558	65500.7	0.006488059
45	4.5	0.02	1.248918298	65500.55	0.00671705
46	4.6	0.02	1.276672038	65500.65	0.006564389
47	4.7	0.02	1.304425778	65497.6	0.011220526
48	4.8	0.02	1.332179518	65499.55	0.008243652
49	4.9	0.02	1.359933258	65497.15	0.011907497

- **Table A4 Third test 18 samples' results**

Sample number	Weight of sample(g)	Volume(l)	Concentration (mol/l)	RSSI	Percentage (%)
0	0	0.01	0	65499.85	0
1	0.2	0.01	0.11101496	65500.85	-0.001526721
2	0.4	0.01	0.22202992	65500.6	-0.001145041
3	0.6	0.01	0.333044879	65500.2	-0.000534352
4	0.8	0.01	0.444059839	65500.6	-0.001145041
5	1	0.01	0.555074799	65500.5	-0.000992369
6	1.2	0.01	0.666089759	65499	0.001297713
7	1.4	0.01	0.777104719	65499.85	0
8	1.6	0.01	0.888119679	65500.05	-0.000305344
9	1.8	0.01	0.999134638	65500	-0.000229008
10	2	0.01	1.110149598	65499.45	0.000610688
11	2.2	0.01	1.221164558	65498.5	0.002061073
12	2.4	0.01	1.332179518	65496.65	0.004885507
13	2.6	0.01	1.443194478	65497.55	0.003511458
14	2.8	0.01	1.554209437	65497.75	0.003206114
15	3	0.01	1.665224397	65494.75	0.007786277
16	3.2	0.01	1.776239357	65494.05	0.008854982
17	3.4	0.01	1.887254317	65493.7	0.009389334

- **Table A5 Fourth test 18 samples' results**

Sample number	Weight of sample(g)	Volume(l)	Concentration (mol/l)	RSSI	Percentage (%)
0	0	0.05	0	65507.75	0
1	1	0.05	0.11101496	65507.65	0.000152654
2	2	0.05	0.22202992	65507.3	0.000686942
3	3	0.05	0.333044879	65507.2	0.000839595
4	4	0.05	0.444059839	65506.8	0.00145021
5	5	0.05	0.555074799	65506.65	0.001679191
6	6	0.05	0.666089759	65505.8	0.002976747
7	7	0.05	0.777104719	65506.35	0.002137152
8	8	0.05	0.888119679	65506.4	0.002060825
9	9	0.05	0.999134638	65506.2	0.002366132
10	10	0.05	1.110149598	65505.8	0.002976747
11	11	0.05	1.221164558	65506	0.00267144
12	12	0.05	1.332179518	65506.15	0.002442459
13	13	0.05	1.443194478	65506	0.00267144
14	14	0.05	1.554209437	65505.8	0.002976747
15	15	0.05	1.665224397	65506.1	0.002518786
16	16	0.05	1.776239357	65504.85	0.004426957
17	17	0.05	1.887254317	65505.5	0.003434708