Major Project

by Ryan Anthony Vismonte

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TIME SUBMITTED	21-APR-2016 03:17PM	WORD COUNT	23724
SUBMISSION ID	56210607	CHARACTER COUNT	138088



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Remote Controlled Bomb Disposal Robot

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Project submitted as part of the requirements for the award of BEng. (Hons) Computer Systems and Electronics

April 2016

DECLARATION FORM

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Abstract

Mankind has always strived to advance technology, a device that can be manipulated as such that would substitute for himself to perform a manual task execution primarily in a hostile environment. The concept of a robot which began to be developed with a vast selection of complex mechanics that made it possible for a machine to look and work like a human being.

This project outlines the design principle of a well-known robot widely used by security forces, public safety teams and professional researchers. This involves strategy adopted for establishing wireless communication between the remote control and the robot. The aim of this project is to design and construct a prototype of a wireless remote controlled bomb disposal robot using a Radio Frequency (RF) communication technique and an added feature of an ultrasonic sensor capable of detecting objects within range.

The main task of the project was to program two microcontrollers interfaced to a radio paired module capable of establishing a wireless communication control application. The report deals with the development of sensing (ultrasonic system) and control system (operating at a radio frequency of 868 MHz) to allow the robot to be wirelessly controlled which also includes a stand-alone visual feedback via wireless camera.

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Chapter I.

Introduction to the Background Project

1.0 Introduction

This report will address the problem of associating with bomb disposal using a robot capable of entering unsafe zone and accessing explosive devices. The report contains background research of the project along with the design decisions of its parts listing their advantages and disadvantages, implementation issues that have been found along the way and finally an evaluation after the initial and final testing. This robotic project combines elements of computing (e.g. programming language), mechanical, electrical and electronics, which are all core subjects in the field of robotics and mechatronics engineering.

Research was performed using several textbooks, a selection of internet resources such as articles, journals, and scholarly reports, all sources are referenced in **References** section.

1.1 Introductory Segment

One of the greatest threats that pose a grave and growing danger for both police forces and military forces to handle is an improvised explosive devices. For instance, in Afghanistan, there are many regular casualties recorded for each month resulting from IEDs alone since 2009. As shown on the graph below in **Figure 1.1**, a total of 2,380 coalition military fatalities in Afghanistan have occurred since 2009, with an approximate of almost 50% of the number of soldiers were killed by improvised explosive devices (IEDs) [(1)].

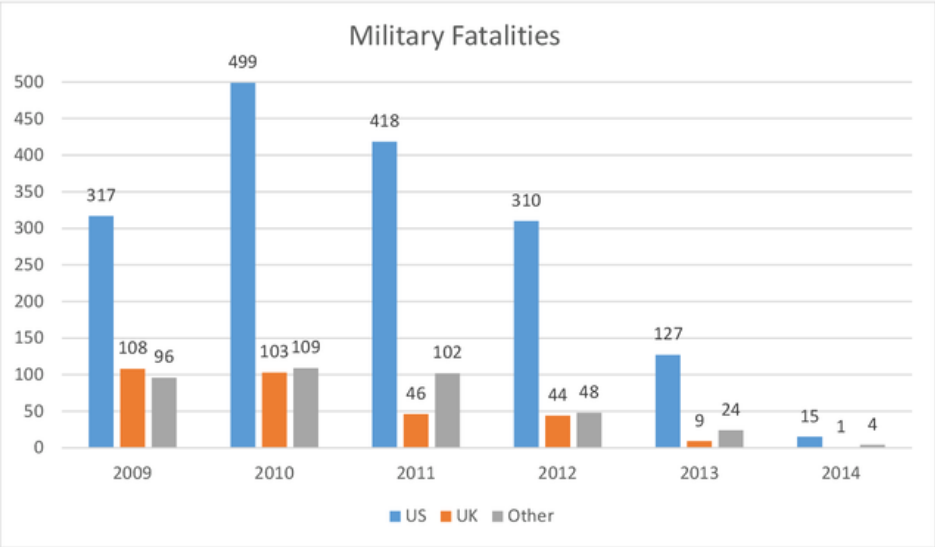


Figure 1.1 A statistic graph that shows the number of coalition soldiers who were killed in action in Afghanistan 2009-2014.

Bomb disposal robots are used to aid military bomb squad in many cases. The military currently owns an estimated number of 3,500 robots in Afghanistan. "According to statistics provided The Wall Street Journal by the U.S. military, more than 750 such robots have been lost in combat in Iraq and Afghanistan—a number that translates into many saved lives." [(2)]. This shows how robots can further reduce the risks associated when handling improvised explosives.

1.2 Project Aims and Objectives

The overall aim of this project is to design and construct a prototype of a wireless remote controlled bomb disposal robot using a Radio Frequency (RF) communication technique and an added feature of an ultrasonic sensor capable of detecting objects within range. In order to achieve the overall aim, several objectives are needed to be complete as follows:

- Design a mechanical structure for both remote control and robot base.
- Provide a live visual feedback via wireless camera and display the output to a monitor, or computer, or smartphone, etc.
- Provide a control application to manoeuvre the mobile platform and robot arm wirelessly using an RF communication technique.
- Design of an ultrasonic system that measures distance of any obstacle coming from behind which displays the output into Liquid Crystal Display (LCD) screen and generates a feedback via piezo buzzer along with a blinking Light Emitting Diodes (LED).

1.3 Introduction to the Project

In order to achieve the aim and objectives of the project, a designed robot must be capable of entering unsafe zone and interacting only using an RF remote control. The project would develop computer systems and electronic engineering, including sensor interfacing and specification, wireless communications system and embedded microcomputer systems.

An RF remote controlled bomb disposal robot will be designed to perform a wirelessly control of its arm and base by using its remote control. The prototype robot platform (hereafter referred to as 'the mobile platform' or 'the robot') operates with a pair of tank tracks which then driven by using a pair of DC motors. The robot arm operates using servo motors to perform a variety of tasks with great accuracy, depending on the application. The radio frequency technique is a communication system that has been chosen as the method for sending command in order to investigate and apply this technology to the project.

When the robot is powered on, it will automatically initialised itself to set on the standby mode waiting to receive a control commands from the remote control. When the command is received, the microcontroller processed the input signal and implement the command correspondingly to control the robot mechanism. Mobile platform drives DC motor to move

forward, backward, left or right, whereas robot arm drives servo motor to move up, down, open or close grip.

The microcontroller is used to act as a central control or brain of a robot to enable the robot platform to arrange and assign data register accordingly with remote control and its sensors. This therefore involves learning of computer based software programming for the Peripheral Interface Controller (PIC), which is used for remote control and for mechanically designed robot to control the entire system. The project also involves of learning to use the ultrasonic sensor, utilising with Pulse Width Modulation (PWM). The ultrasonic distance sensor is installed at the back of the robotic platform to act as the object detector to avoid any obstacle approaching from behind or during the reversal course of the robot. When sensor detects an object behind the robot, the ultrasonic sensor interfacing with microcontroller generates an ouput via LED along with the buzzer. This will make the operator aware that there is something behind the robot and must change its course direction. This will prevent the robot from a potential collision, depending on its operator.

In addition to this robotic project, the report will also discuss the selection and construction of the robot system and their functionalities using a PIC microcontroller to implement and control the overall system. The overall system consists of two different parts. These are the hardware and the software. The software involves of learning computer software tools such as CCS C Compiler, Proteus and MPLAB IDE. The CCS C Compiler is used to configure the chosen PIC. The Proteus is used to construct the schematic diagram and simulatation circuit for testing. Finally, the PIC is programmed using MPLAB IDE software made by Microchip Technology Incorporated.

On the other hand, the hardware is divided into two main stages which are the mechanical stage and the electronic stage. Both stages are interlinked [3]. For the mechanical stage, these are the selection of components to build the robot arm and base. The most important principle in this stage is to design a portable, cost-effective and lightweight robot to reduce the battery's power consumption. For the electronic stage, is to design and construct a prototype circuit by using the breadboard for intial and final testing. This is also where a microcontroller will be placed which controls all of the operation of the robot as well as its sensors. The result of the final section may show the robot demonstrates a control application system via wireless communication technology and the operation of the ultrasonic system.

Chapter II.
Robotics Research

2.0 Introduction

This chapter aims to discuss the word 'robot' in the world of robotics. It briefly discussed the variety of applications for robots in society and shows how it become a subject of great interest to many people nowadays.

Research was performed using several textbooks, a selection of internet resources such as articles, journals, and scholarly reports, all sources are referenced in **References** section.

2.1 Robotics

Robotics is the study of robots. These robots can be defined in many definitions because there really is no definitive definition for a robot. However, robot are loosely defined as follows:

- "Robot is an electro-mechanical device which is capable of reacting in some way to its environment, and take autonomous decisions or actions in order to achieve a specific task." [4]
- "A robot is a machine designed to execute one or more tasks repeatedly, with speed and precision. There are as many different types of robots as there are tasks for them to perform." [5]



Figure 2.1 An image of a robot in motion as it lifts its large metal leg to walk. [74]

These definitions imply that such device can only be called a robot with the condition that it involves movable mechanism which is influenced by sensing, actuation and control components. It may feature some essential characteristics such as sensing, movement, energy and intelligence.

2.1.1 Types of Robotic Control System

In many cases, the word robot usually implies for an Artificial Intelligent (AI) robot or autonomous robot. A robot can be made manually remote controlled, semi-autonomous controlled or fully autonomous. These are all parts of a robotic system but individually different based upon the level of interaction with a human.

A. Autonomous Robot

Autonomous robot is a robot that has complete control over its action, make a decision on its own, can think for itself and act upon it independently without human input [6]. Autonomous robots employ a sense process act loop, in which a robot uses some kind of sensor to sense its environment (e.g. through camera, IR sensors), processes the information or thinks about how to take an action based on the information received from its current sensory, and then proceed to take a certain action that will affect its environment (e.g. moving its joints or communicating by talking). "A robot that communicates to a human or moves its location in space would be considered to be affecting its environment.", as stated by **Knox, 2013** [7], an AI robotics

researcher. This kind of system is useful for a venture robot to operate and monitor other planets. In addition, a fully autonomous robot can [8]:

- Gain information from its surrounding area and act on its own accord.
- Work without human intervention for an extended period of time.
- Move itself throughout, analyse and adapt to unfamiliar environment without human assistance.
- Avoid situations that may damage property, harm people or itself unless those are part of its design specifications.

More specifically, an autonomous robot may learn new methods of accomplishing its tasks and adapt to its changing surroundings, similar to Artificial Intelligent (AI) that can act on its own without human control. However, autonomous robots still require regular maintenance just like any other machines.

B. Semi-autonomous Robot

On the contrary, a semi-autonomous robots share control with a human. Semi-autonomy involves trading off full control of the system, for instance, when the robot gets stuck with no possible way of getting out, it will obviously need to rely on a human operator to come up with a solution. It can also include that both a human and a robot, each provides a control signals together to create the full control signal. [7]

C. Remote Controlled Robot

A remote controlled robot is controlled manually by its human operator with an either through wireless communication system technology remote control or a standard wired remote control. Unlike autonomous and semi-autonomous robots, a remote controlled robot cannot learn or think for itself. It just simply follows the control commands of a human who operates it to interact to its surroundings.

2.1.2 Robot Applications

Robots are used in almost any situation. These robots can be made to fit for the job to help humans in some way. Roboticists develop man made mechanical device that simply perform a specific task whatever it is programmed to do and that determines the robot's purpose in life. It has a variety of modern day use whether for educational purposes, professional research task or in industry that require high degrees of speed and precision. Some of the applications for robots are as follows:

A. Amusement & Companionship



Figure 2.2 Robotic bear intended for use in hospital to keep ill people from feeling sad. [75]

A huggable robotic bear is one of the example of a smart robot companion as shown in **Figure 2.2**. It is designed to respond and act like an electronic pet to amuse people or accompany children during playtime. "Building a robot is in and of itself is fun and exciting. Robotics incorporates aspects of many disciplines including engineering (mechanical, electrical, computer), sciences (mathematics and physics) and arts (aesthetics) and users are free to use their imagination." [9] said by Benson, a senior robotic product specialist. Therefore, amusing others with a new developed creation would help others to become interested and study this field of engineering.

B. Education & Competitions



Figure 2.3 Wheeled robots that have competed in the world's largest robotics and artificial intelligence event.

Robotics competition is an exciting event that challenges teams where robots have to demonstrate its ability to accomplish a task against other teams. In an international robotic competition, it states that "teams of students are tasked with designing and building a robot to play against other teams from around the world in a game-based engineering challenge." [10] This give the project a design guideline to build either a fully autonomous, semi-autonomous or remote controlled robots to compete and a due date to get it done (time management). The idea of head to head competition for students are to be inspire, improve the individual technical skills, gain experience and manage their time effectively. Although many competitions are for school, college and university, specifically for students but several open competitions where adults and professionals alike can also compete are arising.

C. Domestic or Professional tasks



Figure 2.4 Robot vacuum cleaner designed to perform cleaning task efficiently. [76]

Domestic and service robots are electronic robotic devices that are used to perform household chores, see **Figure 2.4**. These help liberate people from unpleasant tasks and give them more freedom and security. "Professional and Service Robots are used in a variety of applications at work, in public, in hazardous environments, in locations such as deep-sea, battlefields and space" said by **Benson, 2010** [9]. This indicates that professional robots are more capable of doing things than ordinary domestic and service robots. However, professional robots are often more expensive compare to domestic robots and are more suited for a task that requires only for professional or commercial use.

D. Security & Surveillance

Security & Surveillance Robots are used in a situation where manual task execution is impossible for human. "These robots are used to venture into areas where humans either should not or cannot go" said by **Benson, 2010** [9]. For instance, in Japan where a ruined nuclear plants radiation is too dangerous for human to enter this is where a remote controlled robot comes in handy to venture into the area and display the level of devastation inside to their human operators [11]. Similarly, bomb disposal teams would prefer to stay as far away as possible from their work site interacting only using remote controlled robot to dispose or detonate explosive devices.



Figure 2.5 Security & Surveillance Robot. [77]

Chapter III.

Research & Review of Literature

3.0 Introduction

The main aim of this chapter is to research the robot and review the research done by others in the similar fields and familiar areas of interest. The general concepts, sub-systems and functionalities of the robot are covered which also includes radio frequency communication and the process of ultrasonic.

In addition, to further the understanding of this robotic project key features of the robot are briefly discussed. This section also includes a brief history and comparison research of similar product on the current market.

Research was performed using several selection of internet resources such as articles, journals, and scholarly reports, all sources are referenced in **References** section.

3.1 Bomb Disposal Robot History

The very first bomb disposal robot was originally invented by Lieutenant-Colonel Peter Miller back in 1972. It was constructed from the chassis of an electrically operated wheelbarrow and designed to carry a hook beneath a car so that it could be towed to a safe location without endangering an explosive ordnance disposal (EOD) officer. These initial "Wheelbarrow's" have been through dozens of generations over the decades and have evolved into modern bomb disposal robots capable of taking on most improvised explosive devices (IEDs) and even some of the expert made ones. [12]

3.2 Bomb Disposal Robot

Bomb disposal robot or otherwise known as EOD robot is designed for use by professional researcher or security forces. They have been integrated into military and public safety teams since they were first invented to increase the safe distance for the operator. Depending on the applied situation, bomb disposal robots are sometimes called as hazardous duty robot used for disposal of hazardous waste substances or nuclear disposal robot for the disposal of radioactive waste, and so on. These robots are one of the many tools to be use when it is too dangerous for humans to enter and execute a manual task themselves.

Security force, including the British Army, military technicians use bomb disposal robot to disarm dangerous weapons. Aside from losing a bomb technician in the field, the human cost would be critical, as said by **Tyley, 2013** [13], "training a bomb disposal officer is significantly more expensive than buying a robot. As a result, maintaining a safe distance from a potential bomb is of paramount importance and only in extreme situations will the technician enter the blast range and put their hands on the device themselves." Here is one of an example of a modern bomb disposal robot today:

CALIBER® T5 Bomb-Disposal Robotics from Icor Technology Inc.

Description: The CALIBER® T5 is the latest robotic model manufactured by Icor Technology Inc. It is small, lightweight and narrow robot built. It is a compact robot that can be deploy into the narrow area such as passages of plane, train and bus aisles. It is best suited and perfect for quick deployment as an explosive ordnance disposal (EOD) or SWAT tool. [14]



Figure 3.1 Example of an EOD Robot – The CALIBER® T5 Robot. [14]

3.2.1 EOD Robot – a review of the literature

The author *John Iovine* (2001) [15] of the book "*Robots, Androids, And Animatrons*", where he provides detailed information on various aspects when designing a robot. These includes of different types of robot parts such as robot arm design, robot mobile design, different control techniques, etc. where he also discussed different types of controlling techniques and its application in controlling robotics. There are also other related research studies to robotics like the "*Miniature Robotic Hand for Bomb Disposal*" carried out by *Rocco DiVerdi* (2012) [16], where he conducted a research and an experiment to improve the robot arm for bomb disposal using a glove to control it with an implementation of bend sensors. Although the prototype had some issues, where the mechanical structure of the robot arm did not meet his objectives because of the mechanical inconsistencies in the sensor readings which greatly affected the dexterity of the robot fingers. Therefore, further research was requried.

The following EOD robot components are similar to the ones that were reviewed:



Figure 3.2 Overview of the EOD Robot components. [81]

The robot is equipped with a robotic arm manipulator, camera and sensors. The key features of bomb disposal robot are as follows:

A. Size & Weight

The way in which robots are controlled varies with the size and weight of the robot platform. The size and weight can be a big or small factor depending on the applications. For instance, the larger the robot means it is able to lift heavier weights, however, the drawbacks of this may obviously be that it consumes more power and cannot be easily transported somewhere else

due to its size and weight. In comparison, smaller, lightweight and compact size robot can easily be carry around and transport. Small robots can also be easily navigate narrow passages with sure footed efficiency however, it is only able to lift lightweight object due to its lightweight design but perfect for quick deployment. [17]

B. Operation

The robot is used like a vehicle to move from one place to another. The robot is operated by means of a wireless controller device, which consists of a display for analysis, joysticks and several control buttons to manipulate the arm and manoeuvre the robotic platform. [17]

C. Camera

The robot can be equipped with one camera or multiple cameras which is used for sending live videos and images to display to the monitor screen device. Cameras can also be used to record video footages. This helps the operator to navigate the robot for the analysis of the surrounding area. [17]

D. Arm & Gripper

The robot has one flexible gripper for holding and manipulating purposes, where it can move in different angles. [17]

E. Sensors

The robot can be implemented with various sensors such as chemical, biological, radiological and nuclear (CBRN) sensors. These sensor notifies the operator about the hazardous of the surrounding area of the robot. Some robots have sensor feedback that enhanced visual awareness and some have additional other sensors so they can be used for more than just a bomb disposal robot. [17]

This review of a well-known robot in military was made possible by the inventor, *Lieutenant-Colonel Peter Miller,* (1972). Over the generation, robots are keep on evolving because of the increasingly advancement of the technology. The most recent study of the robot relates to the EOD was conducted by undergraduate students using the modern android application device to control the robot via any smartphones. They have titled their work as *"Wireless Control of Pick and Place Robotic Arm Using an Android Application"* (2015) [18]. Although android application is popular nowadays, this robotic project will be using an RF (radio frequency) communication technique.

3.3 Radio Frequency Communication System

Radio Frequency (RF) communication system technique have become an important component of control system technology for controlling many applications. RF signal normally refers to a wireless electromagnetic signal used as a form of communication. Radio frequency consists of radio waves in a form of electromagnetic radiation ranging from 3Hz to 300GHz. "Frequency refers to the rate of oscillation (of the radio waves.) RF propagation occurs at the speed of light and does not need a medium like air in order to travel." [19] Radio communication technique is widely used in many industries. These includes TV broadcast signal, radar systems, remote control, computer networks, etc.

According from National Instruments, Radio frequency (RF) "itself has become synonymous with wireless and high-frequency signals, describing anything from AM radio between 535 kHz and 1605 kHz to computer local area networks (LANs) at 2.4 GHz. However, RF has traditionally defined frequencies from a few kHz to roughly 1 GHz. If one considers microwave frequencies as RF, this range extends to 300 GHz." [20] The following table shows the relationship between frequency and wavelength.

Table 3.1: Frequency Band Designations. [20]

f	λ	Band	Description
30–300 Hz	10^4–10^3 km	ELF	Extremely low frequency
300–3000 Hz	10^3–10^2 km	VF	Voice frequency
3–30 kHz	100–10 km	VLF	Very low frequency
30–300 kHz	10–1 km	LF	Low frequency
0.3–3 MHz	1–0.1 km	MF	Medium frequency
3–30 MHz	100–10 m	HF	High frequency
30–300 MHz	10–1 m	VHF	Very high frequency
300–3000 MHz	100–10 cm	UHF	Ultra-high frequency
3–30 GHz	10–1 cm	SHF	Superhigh frequency
30–300 GHz	10–1 mm	EHF	Extremely high frequency (millimeter waves)

A sinusoidal wave can be described with its frequency (f) or wavelength (λ). Both are inversely proportional to each other and related to the speed of light through a particular medium. They can be expressed as: $C = f * \lambda$ where, C is the speed of light. [20]

3.3.1 Radio Frequency Transmission – a review of the literature

Back in the early 1900, the very first wireless transmission was introduced by Guglielmo Marconi. "Radio Frequency (RF) and wireless have been around for over a century with Alexander Popov and Sir Oliver Lodge laying the groundwork for Guglielmo Marconi." [20] There is a limited amount of knowledge that involves radio frequency in the past but throughout the modern time, many new developed technology devices has made it possible to further study and review of the radio frequency communication system based upon several researched papers. The majority of them were able to conduct experimental research that has lead them to reach quantitative conclusions. The research was made possible because of the rapidly growing technology that seeks for more improvement to be implemented for new devices in the future.

Design of a Radio Frequency Data Link for the Unmanned Ground Vehicle

The following review describes the command and control data link of the radio frequency system for remote control, video, audio and data performance carried out by the researcher, development and engineering centre.

Two authors *Keith D. Hilliard and Tom Barr* (1994) [21] has begun their work by identifying the system requirements for the unmanned ground vehicle. The main requirement for the system is to develop a remote vehicle operation via Radio Frequency (RF) data link or a Fibre Optic (FO) link for special applications. They have used the RF technique to accomplish the system requirements by establishing an RF data link communication between the operator control unit and the mobile base unit with a desired specified range of operations point-to-point, non-line of sight (NLOS) as shown in **Figure 3.3**. They also carried out by adding extra feature such as video sensor imagery which allows them to use voice communication in both directions as well.

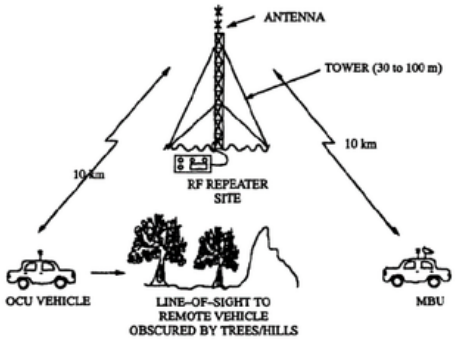


Figure 3.3 RF Data Link. [21]

After the system requirements have been identified, technical approach was to be followed. Although there are some imposing limitations that they had taken into consideration on

development of an RF data link. The use of military radio hardware for flight was investigated and proved as the only viable one. The range performance of an RF data link affects by several factors such as height of the antenna, data, video and audio performance and the available frequency in the area, where other frequency may interfere during the test experiment. They have begun their work starting with calculations for the height of the antenna to achieve the nominal required range. They have used relevant equations to estimate the radio horizon and were determined.

According to the author, *Keith D. Hilliard and Tom Barr* (1994) [21], the determined estimations is more than adequate for the task. However, the test subject is a ground vehicle based system and they also added that the "available frequencies which are Line-of-Sight (LOS) frequencies, factors such as terrain contour, vegetation, and buildings become a factor. These can effectively block the LOS between the transmitter and receiver." [21] This therefore prompted them to come up with the solution in order to resolve the blocked LOS, where the radio horizon were determined again. Thus, with the proper configuration of transmitter and receiver, the vehicles are expected to be communicating further than what is specified.

This review of the operation of the radio frequency was made possible by the founder of the wireless transmission, *Guglielmo Marconi,* (1901) [20]. The experimentations that was created and developed was carried out by *Keith D. Hilliard and Tom Barr,* (1994) [21], which was able to get a result and have drawn a conclusions for their design. Many other related research like "*A study of Radio Frequency Interference (RFI) to Automotive Radio Systems*" was conducted by two authors *JE Ferris and DL Sengupta* (1980) [22], and the most recent research in the review "*The Robot control using the wireless communication and the serial communication*" by *Jong Ahnn* (2007) [23]. All of these authors are fundamentally relevant covering different areas in different applications. These conducted research shows that radio frequency can be applied in many applications such as TV broadcasting, remote control, industrial applications, etc. Finally, the research and studies shows that with the proper configuration of the transmitter and receiver, the range of the radio frequency could be extended.

3.4 Ultrasonic

Ultrasonic is the vibration of an acoustic frequency ranging in between 16kHz and 1GHz. It is generally referred to as ultrasound, where the term 'sound' is applied to its waves with very high amplitudes. **Figure 3.4** shows the classification of ultrasound frequency. [24]

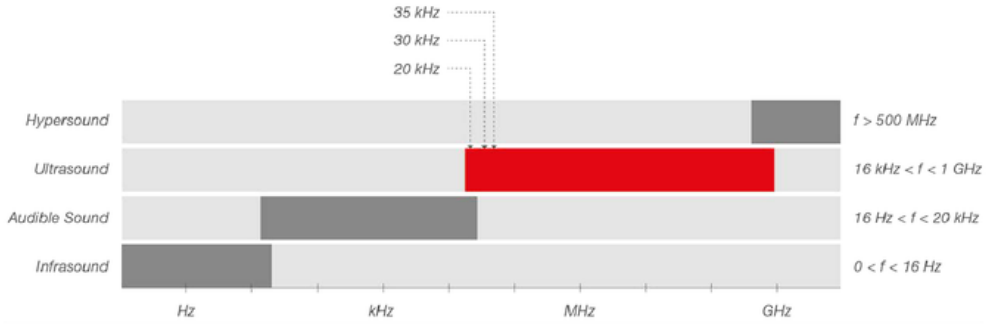


Figure 3.4 Classifications of Different Frequency Sound Range. [85]

The range of ultrasound is greater than the upper limit of the range of audible sound (range of hearings for humans) and less than the lower limit of the hypersound.

The Frequency of a Sound

Pure tone is considered to be a useful stimulus for testing auditory function. The sound pressure represents a sinusoidal wave as shown in **Figure 3.5**, when plotted against time. It has been said by Professor **Heeger** that the sound signals of a "high frequency pure tones sound like high pitches and low frequency pure tones sound like low pitches." [25] The frequency related to pitch is the rate of air pressure modulation, where the number of cycles of condensation and refraction change per second. (1 Hz = 1 cycle/sec). The unit measurement for the frequency is expressed in Hertz (Hz). Different variations of frequency and amplitude is shown in **Figure 3.6**.

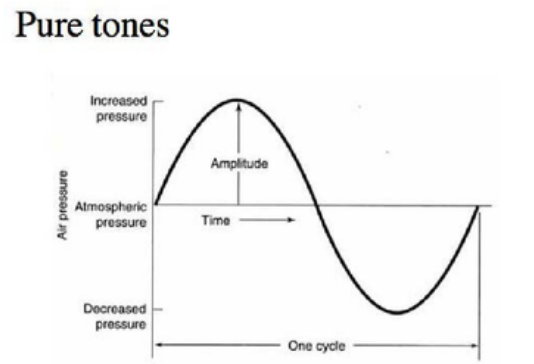


Figure 3.5 Characteristics of a pure tone. [25]

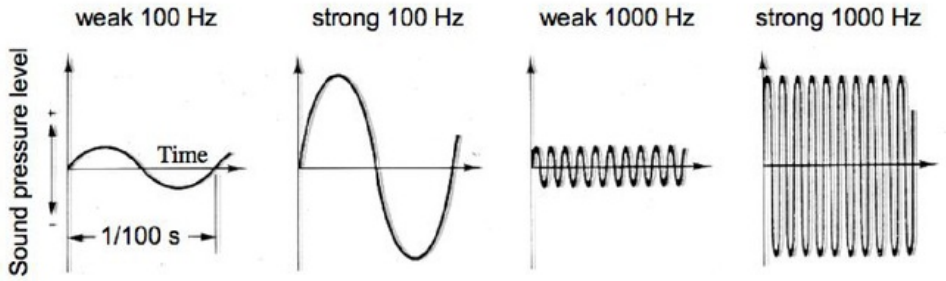


Figure 3.6 Frequency and Amplitude. [25]

3.4.1 Ultrasonic Sensor – a review of the literature

The following review describes the design and utilisation of the ultrasonic sensor as a distance measuring device. It was carried out by many other researchers such as: -

Two authors *Shamsul Arefin, Tajrian Mollick,* (2013) [26], of the *"Design of an Ultrasonic Distance Meter"* began their work by analysing the graphical characteristics of ultrasonic sensor ranger at what rate can a typical transducer produce, in which it generates a set of sound waves in the ultrasonic range, shown in **Figure 3.7**, resulting to above 18,000 hertz. This can be done by turning electrical energy into sound. Once the echo is received back it converts the sound waves into electrical energy then computation takes place and output the measurements in LCD. They also added that "the technology is limited by the shapes of surfaces and the density or consistency of the material. For example, foam on the surface of a fluid in a tank could distort a reading." [26]

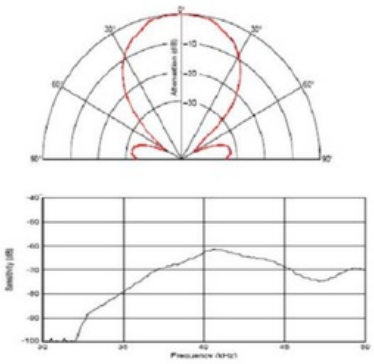


Figure 3.7 Graphical Characteristics [26]

Other influential authors of the most recent project *Prakhar Shrivastava, Praveen Kumar, Ankit Tiwari,* (2014) [27], of the "*Project Review on Ultrasonic Distance Measurement*" began their research on the limitations of the ultrasonic sensor. They have used the same principles and formula to calculate the distance. Nevertheless, their research still could prove very valuable.

3.5 Market Research

When it comes to creating a robot, many robotics company are focusing entirely on the needs of defence, public safety and industrial markets. Therefore, robotic systems with an advanced, interchangeable features are excessively overpriced and rarely available in the commercial market today. The vice-president of unmanned systems at QinetiQ North America, which manufactures the Talon robot, pointed out "If robots assembled as easily as they said, there would be a hell of a lot more in the market at lower prices. It's not easy." **Quinn, 2011** [28]. This prompted research into the products that were available on the current market.

A. Security Forces Robots

For details and comparison of the following robots, see **Appendix A**.



Figure 3.8 310 SUGV – The back-packable rugged robot. [66]



Figure 3.9 510 PACKBOT® – The man-transportable multi mission robot [66]



Figure 3.10 Talon V – QinetiQ North America's TALON® family of robots. [67]

B. Hobbyists & Educational Project Robots

For details and comparison of the following robots, see **Appendix B**.



Figure 3.11 Kuman SM5 TH wireless Wi-Fi Robot Car. [78]



Figure 3.14 Ultimate Robot. [71]

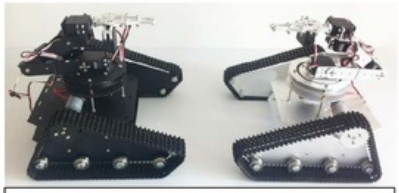


Figure 3.13 Robo-Soul TK-6A Car Creeper Truck Crawler RC Robot Base Kit with 6DOF Robot Arm. [70]



Figure 3.12 VEX Robotics Clawbot. [79]

Chapter IV.
Research Methodology

4.0 Introduction

In this chapter, the research methodology that were used are discussed as it presents a clear method and strategies when conducting a research. These method has set the ongoing project towards the right direction which also includes the list of hardware and software that were used along the course.

Research was performed using several selection of internet resources such as articles, journals, and scholarly reports, all sources are referenced in **References** section.

4.1 Research Methodology

In order to make a solid foundation of research, the layers of the 'research onion' model were studied and considered. The research onion model was originally developed by Saunders et al. It presents a clear method and strategies when conducting a research. Therefore, undertaking a particular research study, these steps of research process must be followed, "First, the research philosophy requires definition. This creates the starting point for the appropriate research approach, which is adopted in the second step. In the third step, the research strategy is adopted, and the fourth layer identifies the time horizon. The fifth step represents the stage at which the data collection methodology is identified." [29] The research onion model has multiple layers which consists of the following shown in **Figure 4.1**.

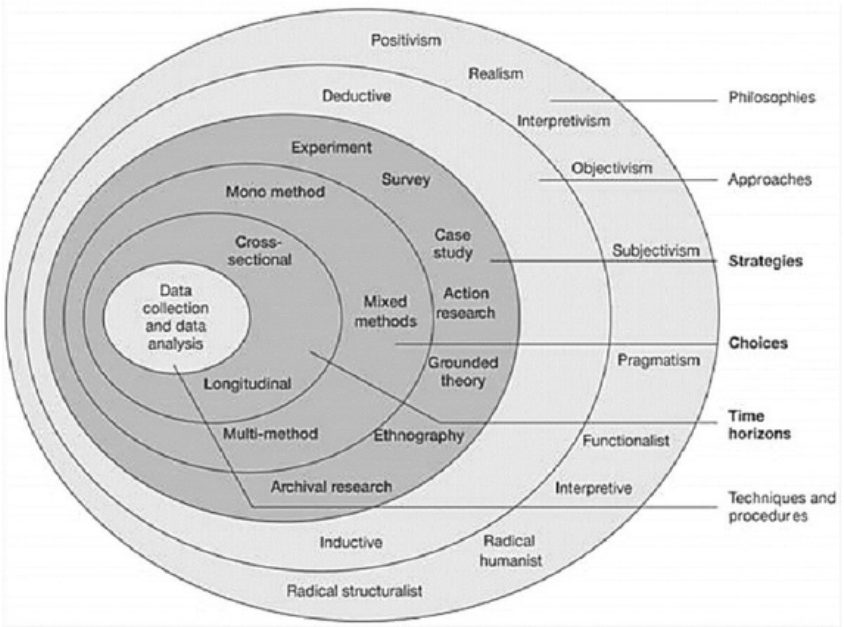


Figure 4.1 The Research Onion by **Saunders et al., (2012)** [86]

Each of the layers have a number of methods. It involves a process of working from the outer layer, peeling each layer at a time until it reaches to the centre of the onion model. More than one of the research method were selected in some of the illustrated layers of the model in **Figure 4.1**.

Layer 1 – Philosophy

Positivism

Positivism was chosen from the first outer layer from the research onion model. It is based around generating hypothesis and characterised by testing theory developed from the existing data. [30] This method can be applied to the theory and can be tested and compare to the existing data, in which it can approximately produce the same results.

Layer 2 – Approach

Deductive

Deductive was chosen from the second layer from the research onion model. It is the process that goes from theory to data, whether the data approve or disapprove this theory that were applied, still the outcome is very valuable.

Layer 3 – Strategies

Experiment & Action Research

There are two methods that will be used in the third layer from the research onion model. The experimental strategy is the first method that were used. This constructs an independent variables and observe the effect of changing conditions in dependent variables which is the aims and objectives of this project. This method generates data from the sensor that can be analysed and discussed.

The second method that were used is the action research strategy which is a very practical approach to a research. It is designed to diagnose problems and produce practical outcomes through investigation, evaluation, planning and taking actions [31]. This means that the outcome of action research strategy will be a lot efficient, develop practical and usable knowledge, in which may prove to be essential in life.

Layer 4 – Choices

Mixed methods

The fourth layer that were used is the mixed methods from the research onion model. The term mixed methods refers to the two differentiated methods: qualitative and quantitative research. Both research methods will be used for the analysis of the data that have been collected through the process of the testing stage and will prove the data collected through measurements.

Layer 5 – Time Horizons

The fifth layer is the time horizons from the research onion model. It determines the length of time of the project in regards of collecting data in either short term or long term period of time. It consists of two different methods: cross-sectional and longitudinal [30]. As name dictates, longitudinal is research type method carried out over a long period of time whereas cross-sectional is a short term study. In regards for the project, cross-sectional may well be suitable at this stage as time is of essential.

Layer 6 – Techniques and Procedures

This is the inner and final layer of the research onion model in which the most crucial part of the project. This is where all of the data collection and analysis techniques are discussed, where all decisions and tools employed and must fit in after the selection of different research methods from each layers of the research onion model.

4.2 Hardware and Software

In order to complete this robotic project, the following list of hardware devices and software applications are required:

Table 4.1: Hardware and Software lists

Hardware	Software
▪ Digital Multimeter ▪ Oscilloscope ▪ Pic Start Plus ▪ Grey board ▪ Electric Drill ▪ Nuts and bolts ▪ Screw driver ▪ Small spanner ▪ Soldering iron set ▪ Breadboard ▪ General piece of electronics (wires, LED, push buttons, resistors, capacitors, PIC, etc.)	▪ Proteus 8 Professional ▪ MPLAB IDE ▪ CCS C Compiler ▪ Microsoft Office

Chapter V.

Research & Component Selection

5.0 Introduction

In this chapter, the selection of different parts of the robot are examined and discussed. The parts of the robot area to be discussed are as follows: Robot Arm, Robot Platform, Motors & Actuators, Remote Control, Ultrasonic Sensor, Microcontroller and Wireless Camera. Each individual is thorough examined and discussed in order to determine which are the most suitable for application, efficient and cost-effective parts for the robot.

Research was performed using several textbooks, scholarly reports, journals, thesis, articles and a several selection of internet resources, all sources are referenced in **References** section.

5.1 Robot Arm

The field of robotics essentially started a study in robot manipulators. There are two important studies: robot kinematics and dynamics. **Crowder, 1998** [32] defined kinematics, "the relationships between the positions, velocities, and accelerations of the links of a manipulator, where a manipulator is an arm, finger, or leg." Moreover, the relationship between the associated forces and torques, and the motion is studied in dynamics. For more information on robot kinematics and dynamics, see **Appendix C**.

In addition, the manipulator becomes a robot when the arms and an end-effectors are attached, and the control system is implemented. [33] End-effector is a device or accessory that attach to the end of an arm such as jaw angular grippers, cameras, electromagnets, sensors, etc. The most common end-effector accessories for robot arms are grippers. The robot uses its arms and grippers to interact with the environment it is exploring. It may operate a simple one motion, while a more complex arms can operate more degrees of freedom (DOF).

5.1.1 Degrees of Freedom (DOF)

The robot arm is normally described with their number of degrees of freedom (DOF). These number of DOF is equal to the total number of independent displacements of motion, where higher number of DOF indicates an increased flexibility in positioning an end-effectors.

More specifically, the movement of the mechanical structure is motion, where its free to change position as moving up or down (heave), moving forward or backward (surge), and moving left or right (sway). Heave, surge and sway are translation in three perpendicular axes. It combines with changes in orientation through rotation termed as pitch, roll and yaw, see **Figure 5.1** [34].



Figure 5.1 The 6 DOF: Forward/Backward, Up/Down, Left/Right, Pitch, Yaw and Roll. [34]

The robot arm design can be from a simple design to a more complex design, from 2 DOF to 6 DOF, see **Figure 5.2**. A full mechanical structure robot arm commonly foremost consists of a gripper, wrist, elbow, arm, shoulder and base rotations to flexibly interact with an object near its vicinity. However, it is said that when building a robot arm, it should take into consideration

to pick as few DOF allowed for the application. The reason being was "because each degree requires a motor, often an encoder, and exponentially complicated algorithms and cost." [35]



Figure 5.2 Illustration movements from 2 DOF to 6 DOF. [82]

5.1.2 Component Selection

Each degrees of freedom of the robot arm essentially requires motors to move. Therefore, the selection for the number of DOF was mainly based foremost on the application, cost, material and manageable algorithms. The following table shows the market (cheapest) research of the robot arm as number of DOF increases, see purchase links in **Appendix D**.

Table 5.1: DOF Comparison Table.

No. of DOF	Costs	Material	Supplier	Retailer
1	£24.81	Aluminium	China	EBay UK
2	£42.10	Aluminium	Dagu	RoboSavvy
3	£50.34	Aluminium	Dagu	Dagu
4	£101.86	Metal	Lynxmotion	RobotShop
5	£112.36	Metal	DFRobot	DFRobot
6	£149.80	Aluminium	Dagu	RoboSavvy

Based on the available products and research, 2 DOF robot arm (see **Figure 4.3**) were selected due to its applicable operation, simple algorithm and reasonable price on the current market.

2 DOF robot arm



Figure 5.3 Dagu – 2 DOF Arm with Gripper and Servos. [83]

Advantages

- Simple design and less algorithm.
- Upright application to this project.
- Cost is within the budget.
- Less programming code compare to higher DOF.
- Less control buttons in the control device.

Disadvantages

- Stationary on its own.
- Must be attached or mounted onto something to be able to use.
- May lack of DOF in certain applications.
- Involves learning of DC servo motors.

5.2 Robot Platform

When it comes to building a robot choosing the right platform is one of the most important apparatus as it affects how the robot drives and manoeuvre in the area. The robot platform can be made whether for land (land-based robot), or for an air (air-based robot), or even for water (water-based robot). Some can be made with a hybrid combination; this all depends on the application of what best suited for the task. The most commonly used platforms are [9]:

- Land: wheeled, tracked and legged robots
- Aerial: helicopters and planes robots
- Aquatic: submarines, boats and swimming robots

Therefore, prototyping an EOD robot, a land-based robot has been chosen as the type of platform to use for this robotic project. Whether building it from scratch or purchasing one will not affect the project as much. Building one from scratch indicates of using raw materials such as plastic, wood and metal to construct the robotic platform. However, there are several aspects to consider when building one from scratch. First one is the selection of material itself, its price and its availability in the market. Next is the shaping and machining. When prototyping, its

best to go for materials that are easy to handle and can be easily reshape. Last is to have the right tools and equipment along with the right skills. [36] Though the downside of building one needs time and great effort to create one properly.

On the other hand, purchasing one means getting a ready-made robot kits and just assemble it. Although the designs are fixed, some can be improvised and modified accordingly to support the application. This saves time and has less effort compare to building one from scratch. All the components required comes in one whole package, including the manual for assembly.

5.2.1 Wheeled Robots



Figure 5.4 Mobile Wheeled Robot. [9]

Wheels are the most commonly used method of providing mobility to a robot. The size of the wheels varies to the size of the robot, from a few centimetres and up to thirty centimetres or more. Robots can have any number of wheels, although the most common ones are designed with 3-wheels, 4-wheels and 6-wheels. Three wheeled robot uses two wheels with two motors and a caster at one end. Four and six wheeled robots can have the advantage of having multiple motors, one drive motor connected to each wheel which reduces slip. In some rare occasion, two wheeled robots are designed with more complexity as it uses gyroscopic stabilization to provide a steady balance to its weight. In addition, there are different kinds of wheel that can give the robot a significant amount of mobility advantages when used properly. These are the omni-directional wheels and mecanum wheels, see **Figure 5.5A+B**. [9]



Figure 5.5A Omni-directional Wheel. [9]



Figure 5.5B Mecanum Wheel. [9]

5.2.2 Tracked Robots



Figure 5.6 Mobile Tracked Robot. [9]

The tracks and threads are what tanks use to travel from one place to another. It operates like a tank to easily travel over loose terrain surfaces such as sand and gravel. Although tracks do not provide an added torque force, they do gain stability by distributing the weight of the robot evenly. Additionally, a flexible track system can be better conform to a bumpy surface. And finally, it is said that "most people tend to agree that tank tracks add an aggressive look to the robot." [9] This indicates that the tracks look more aggressive than normal wheels.

5.2.3 Component Selection

It is difficult to choose between the two platforms because each system provides certain features and performances. Moreover, when compared side by side, each system has its own strengths and weaknesses. Therefore, choosing the best system out of the two depends on several factors like traction, suspension and its ability to steer. The traction is greater if tracks are used instead of wheels for best results over loose terrain. The performance of the suspension system is significantly important relating to traction to keep the tracks or wheels on the ground. Finally, the wheels have an advantage of having a good manoeuvrability when it comes to steering compared to tracks. [37]

The selection for mobile platform to be use in this robotic project is down to its ability to accommodate the robotic arm with a good stabilisation. Therefore, the tracked mobile were selected because of several reasons. It has a great reduce slip compare to wheeled ones, it evenly distributes the weight of the robot and it can travel easily to a loose terrain.

Based on the available products and research, the Devastator Tank Mobile Platform (see **Figure 5.7**) were selected due to its applicable operation, simple design and affordable price on the current market. See purchase links in **Appendix D**.

Devastator Tank Mobile Platform



Figure 5.7 Devastator Tank Mobile Platform. [84]

Advantages

- High strength aluminium alloy which makes it extremely solid and durable.
- Outstanding mobility across even the toughest terrains.
- High speed motors and premium tracks.
- High performance suspension.

Disadvantages

- Less manoeuvrability which require more power when turning.
- Difficult to repair or replace the tracks.

5.3 Motors & Actuators

Actuators and motors are what makes the robot move. The word 'actuator' was described by **Benson** as "a device that converts energy (in robotics, that energy tends to be electrical) into physical motion. The vast majority of actuators produce either rotational or linear motion. For instance, a DC motor is therefore a type of actuator." [9] The rotational actuator is the most commonly used type of actuators that transform electrical energy into a rotating motion. Rotational actuator consists of two main mechanical parameters: torque and rotational speed. The torque is a moment of force produce at a given distance, usually expressed in Newton-meter (Nm) whereas rotational speed is the result of the motor speed that rotates the output shaft, usually measured in revolutions-per-minute (RPM). [38] [39]

5.3.1 Electric Motor

Electric motors are often used as the final control element in positional or speed control systems. There are two main categories that classified motors: Alternating Current (AC) motors and Direct Current (DC) motors [40]. The basic principles involved between AC motors and DC motors can be seen in **Appendix E**.

A. AC Motors

AC motors can be classified into two groups: single phase and poly phase. Each group is further subdivided into induction and synchronous motors. Single phase motors are used for low power

requirements whereas the poly phase motors are used for higher power requirements. Induction motors tend to be cheaper compare to synchronous motors and are thus very widely used. [40]

AC motors are rarely used in mobile robots since the majority of the robots are powered by DC batteries. Electronic components use DC, therefore, it is more convenient to have the same type of power supply running for the actuators as well. AC motors are commonly used in industrial applications where high torque is required. It operates when motors are connected to the AC mains or wall outlet. [41]

B. DC Motors

DC motors are a continuous rotational type of actuators that convert electrical energy into mechanical energy. It achieves this by producing a continuous angular rotation that allows wheels, fans, etc. to rotate [42]. DC motor is constructed with a stationary field winding (stator) and rotating armature winding (rotor), where stator is the stationary part while rotor is the rotating part of the DC motor. There are magnets on the stator and a coil on the rotor that generates a magnetic charge by supplying current onto it. The brush has an important role in the motor, as **Clemson** has stated that "Brushes are responsible for transferring current from the stationary DC voltage source to the spinning rotor. Depending on the position of the rotor its magnetic charge will change and produce motion in the motor." [43] They are mainly used in applications where speed control, servo control or positioning control are required.

Brushed DC Motor



Figure 5.8 DC Motor. [9]

Brushed motor is one the basic type of DC motors. It is commonly used actuator for producing continuous movement where the speed of rotation can easily be controlled if speed control is required. They are widely used motors in many applications, whether buying a toy or incorporate the motor into the robot when building one. Brushed motors comes in several variations, however, permanent magnet motor is what used extensively in robotics either for experiment educational purposes or for professional and hobbyists robot builders. It comes in a variety of shapes and sizes, although it is usually in a cylinder shape (see **Figure 5.8**). It features an output shaft that rotates at high speeds and usually rotates in the range of 5,000 to 10,000 RPM. Additionally, unlike other electric motor types, brushed motors do not require a controller to

switch current. It can operate in a rotation of clockwise (CW) and counter-clockwise (CCW). Generally this type of motor is cheap, small and can easily be controlled. [9] [41]

Components of a DC Motor

The Brushed DC motors consists of the following components:

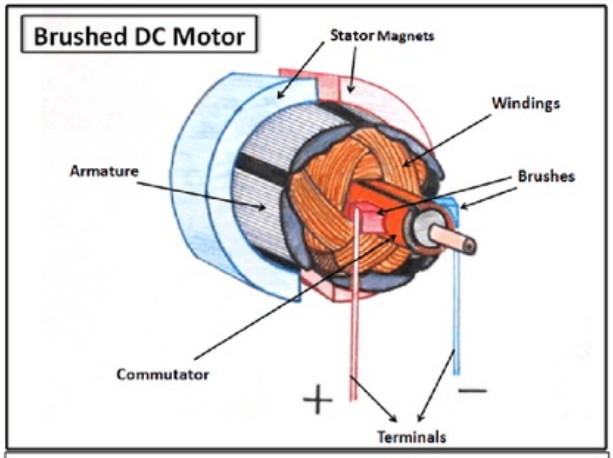


Figure 5.9 Overview of the Brushed DC Motor components. [43]

Stator: The stator which includes either a permanent magnet or electromagnetic windings. It generates a stationary magnetic field around the rotor. [43]

Armature: The armature is made up of multiple coils of wire mounted around in slots on a cylinder of magnetic material. These coil of wires generate a magnetic field when energized by the external current. The magnetic field poles thus generated by this rotor field are attracted to the opposite poles which generated by the stator field then repelled by the similar poles. This causes the armature to rotate freely. [43]

Commutator: The ends of each armature coil are connected to the adjacent segments of a segmented ring called the commutator, usually made of copper and mounted on the rotating shaft. The commutator with electrical contacts made to the segments through carbon contacts. The current + and – is supplied to the commutator segments with the help of brushes. [40] [43]

Brushes: as the motor starts to rotate, the brushes slides over the commutator segments. This explains how magnetic field was created "the variable magnetic field in different arms through

the commutator segments attached to the windings. Hence, a dynamic magnetic field is generated in the motor when a voltage is applied across the brushes." [43]

The robotic platform that were selected previously (see **Figure 5.7**) came with a pair of high speed motors. More specifically, two brushed DC motors.

C. Servo Motors

Servo motors are small and very energy efficient that utilized in many applications. It allows these features to be used to operate in a variety of applications such as RF remote controlled toy cars, robots and quadcopters. Now that servo motors are being used in many applications, the price for these motors has gone down significantly, also due to mass production. The variety in terms of sizes, technology and strength of servo motors has increased. They are also widely used for industrial applications, manufacturing, robotics, pharmaceutics, etc. [44]



Figure 5.10 Hitec Standard Heavy Duty Servo. [44]

Servo motors are designed to provide a two directional speed control either controlled accelerations or decelerations as well as motion control. They are also used in a wide variety of positioning applications. [45] It has also been described by Benson, senior robotics specialist, that "servo motors are types of actuators that rotate to a specific angular position, and were classically used in more expensive remote controlled vehicles for steering or controlling flight surfaces." [9]

The majority of these motors can only rotate for around half a circle (about 180˚ degrees). A typical servo motor normally consists of a small DC motor, drive gears, control circuit and a rotary potentiometer (see **Figure 5.11**). These servo motors have three wires: ground, supply voltage and a control pulse signal. The control wheel has gears that attached to the small DC motor. When the motor rotates, the resistance of the potentiometer changes, this therefore precisely regulate the control circuit of the

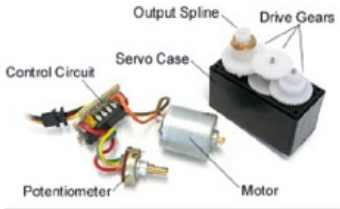


Figure 5.11 Overview components of a typical Servo motor. [44]

motors movement and its rotational direction. Control circuit and potentiometer work accordingly to enable the motor and stop the output shaft at specified angle.

The robotic arm that were selected previously (see **Figure 5.3**) came with a pair of motors. More specifically, the 2 DOF robot arm has two DC servo motors. One servo for gripper and the other servo for the arm.

5.4 Remote Control

Mobile robots are controlled through programming and can perform different tasks depending on the applications. As it was discussed in *Chapter II: 2.1.1 Types of Robotic Control System (pages 6-7)*, robots can be programmed as an autonomous, semi-autonomous or remote controlled robots. Apart from autonomous robots, robots can be controlled by any means of remote control devices. These remote control devices include two variations of controlling methods that can be differentiated as either wired control or wireless control.

5.4.1 Wired Remote Control

Wired remote control is far most the easiest way to control a robot. It comes with a handheld controller physically connected to the robot with a wire cable. It consists of multiple switches, buttons, joysticks, etc. on the controller that allows a user to control the robot. Since it is a non-intelligence robot, it is considered to be more remote controlled machine than robots. [9]

5.4.2 Wireless Remote Control

Wireless remote control incorporates a more complex electronics compare to wired one. It is designed to wirelessly control a device within specified range or object in another location. The most popular two-way communication module device being used up until now are the Infrared (IR) and Radio frequency (RF). An RF is usually an electronic device that uses transmitter and receiver module, which is a matched pair frequency in order for it to work. In almost similar way, IR also uses transmitter and receiver module in order to function. However, IR requires a line of sight between its transmitter and receiver at all times.

Although wireless remote control commonly operates via infrared signals and radio frequency, in regards of the advancement of technology, many new wireless module has emerged recently

such as Bluetooth and Wi-Fi. Bluetooth is a wireless technology (in a form of radio) that is used to exchange data but only limited to a short distance. While on the other hand, the Wi-Fi is also a technology that uses radio waves to provide network connectivity, which is now also another option to control a robot. [46] [47]

5.4.3 Component Selection

Radio Frequency (RF)

In this project, the chosen wireless communication technology technique is the radio frequency for controlling application of the robotic system. Wireless radio frequency technology is defined as "The rate of oscillation of frequency of alternating currents and radio waves which carry radio waves in the frequency range of 3 kHz to 300 GHz." [48] The frequency remote consists of a small pre-built transmitter (Tx) and receiver (Rx). Tx circuit is placed and connected to the remote circuitry whereas Rx circuit is placed and connected to the receiving end (e.g. mobile robot, drones, etc.). A control signal command is produced when input is sent from Tx in the form of electromagnetic waves (radio waves) of radio frequency then received by Rx to control the device remotely. The control signal received can be used by any means to control a compatible communication purpose device.

When selecting a frequency band for the RF module, the legal requirements must be taken into consideration because not all of the available frequency is legal in the area for use. "From 1.8.1981, model control equipment is exempt from the requirement of a Licence under Section 1 (1) of the Wireless Telegraphy Act 1949 subject to the terms, provisions and limitations set out in parts 1 and 2 respectively of the Statutory Instrument 1980 No. 1848." [49] The following lists below are the legal frequency available in the UK [50]:

- 26.96 to 27.28 MHz
- 34.945 to 35.305 MHz
- 40.66 to 41.00 MHz
- 433.050 to 434.790 MHz
- 434.04 to 434.79 MHz
- 458.5 to 459.5 MHz
- 868 MHz
- 2.4 GHz
- 5.8 GHz

RF Module

An RF module is a small pre-built circuit. It usually comes in paired frequency, in this case, the chosen frequency for the project is 868 MHz. The RTFQ1 is the Tx (see **Figure 5.12**) and RRFQ2 is the Rx (see **Figure 5.13**).



Figure 5.12 RTFQ1 [87]



Figure 5.13 RRFQ2 [87]

Advantages

- Long range transmission for up to 250 metres.
- The setup can be relatively easy.
- Omni directional. (signals are not entirely blocked and can penetrate through walls)

Disadvantages

- Frequency interference.
- Low data rate. (simple commands only)
- Limited by law and regulations. (need licenses for other channels)

In addition, the remote control will have multiple push buttons to interact with the mobile robot correspondingly.

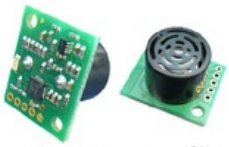
5.5 Ultrasonic Sensor

Ultrasonic sensors are commonly used for a wide variety of applications such as non-contact presence, distance measuring, etc. The ultrasonic module consists of two round sensor device: trigger and echo, where trigger acts like a transmitter whereas echo acts like a receiver. As it was discussed in *Chapter III: 3.4 Ultrasonic (pages 17-18)*, ultrasonic sensor use sound waves. It emits ultrasonic waves from its transmitter through the air that reflect off from any solid object. The reflected sound wave is received back to the other sensor through its receiver. Then the system measures the time taken for the echo to return and calculates the distance from the object using the speed of sound shown in the medium (see **Figure 3.4**).

5.5.1 Component Selection

There is a wide variety of ultrasonic sensors currently on the market. Besides from brands, each sensor differs from one another in terms of mounting configuration and electronic features. In regards to acoustic, the sensor also operates at different range frequencies and have different radiation patterns. The following selection for sensors were compared and considered:

Table 5.2: Ultrasonic Sensors Comparison Table

 SRF02 Sensor [51]	 HC-SR04 Sensor [52]	 US-100 Sensor [53]
Price: £11.99	Price: £1.99	Price: £5.79
Function: Single Transducer	Function: Trig & Echo	Function: Trig & Echo
Range: 16cm – 6m	Range: 2cm – 400cm	Range: 2cm – 350cm
Frequency: 40KHz	Frequency: 40KHz	Frequency: 40KHz
Power: 5v, 4mA	Power: 5V, 15 mA	Power: 3V – 5V, 3.5 mA
Trigger Input: TTL	Trigger Input: TTL	Trigger Input: TTL
Echo Output: TTL	Echo Output: TTL	Echo Output: TTL
Dimension: 24*20*17mm	Dimension: 45*20*15mm	Dimension: 20*45mm

Based on the available products and comparison research, the HC-SR04 were selected due to its applicable operation, simple design and the cheapest out of the three on the current market. Although it has the highest current consumption rating from the comparison table, the device was mainly selected because it is affordable. Since the cost have a higher implementation priority than power consumption, therefore the HC-SR04 will be used for the project to keep the budget under control. See purchase links in **Appendix D.**

Advantages

- Medium range measurement
- Relatively inexpensive
- Ideal for quiet environments (inaudible to humans)

Disadvantages

- Limited to sensing distance
- Surface may affect the readings (it has to be flat or solid object)
- Environmental factors can affect ultrasonic response

5.6 Microcontroller

In essence, the microcontroller is considered to be a small computer. It is often referred to as a central control or brain in a robot because it is usually the one responsible for the execution of the program (e.g. computations, communications, etc.). Technopedia defines microcontroller as a computer that is "present in a single integrated circuit which is dedicated to perform one task and execute one specific application." [54] These microcontrollers are normally found in almost any electronic devices such as telephones, watch, robots, etc.

Microcontroller is used to interact in the outside world through programming instructions. It consists of multiple analogue and digital pins. These pins are used as the electrical signal connections. Digital use binary inputs in two states: 1 (on/high) and 0 (off/low). On the other hand, analogue is used when input conditions are variably changing, usually referred to as analogue voltage signals. This signals can be measure through the use of an analogue to digital converter (ADC) since most of the modern microcontroller has a built in ADC. [55]

Most of the modern microcontroller has a special hardware built into them, indicates that these devices can do more than just a basic function. These includes a universal asynchronous receiver/transmitter (UART), Serial Peripheral Interface (SPI), and Inter-Integrated Circuit (I^2C). This features are used for communicating to other devices.

5.6.1 Microcontroller Selection

In the selection for the right microcontroller, there are quite a few things that need to be considered. According from the two authors *Paul Horowitz and Winfield Hill* (2015) [56] of a very well-known book "*The Art of Electronics*", they have discussed the area to the point where it simply narrow down by any means on how to select a microcontroller. The factors that need to be looked at (depending on the applications) are as follows:

a. Ports (analogue, digital, and communication)
b. Internal functions (e.g. PWM, LCD drivers, converters, etc.)
c. Compute speed
d. Memory and their size (e.g. EEPROM, RAM, etc.)
e. Package configuration
f. Power consumption and suspend modes
g. Software programming, simulation, and in-circuit debugging tools.

When making a decision for the required number of hardware interfaces needed, there are two general types that need to take into account. The first type is the communication interfaces and the second type is digital I/O, analogue I/O, optional internal or external oscillator, etc. This interfaces leads to the total number of pins that will be required when selecting the right microcontroller. The number of pins needed for the 'receiver' microcontroller is listed as follows:

- 3 pins for ultrasonic sensor
- 2 pins for servo motors
- 1 pin for lights switch
- 8 pins for test switch
- 7 pins for LCD
- 3 pins for LEDs
- 1 pin for RF receiver
- 4 pins for H-bridge motor driver IC
- 2 pins for external oscillator (optional)

Therefore, an estimated total of 31 minimum pins are required for a microcontroller receiver.

After filtering through the specifications of PIC16F family from the microchip website [57], the results can be cut down significantly, making the selection for the right microcontroller a lot easier. Like in example, the crystal oscillator needed for the project is a minimum of 4MHz and a pin count of 40. The system then updates the specifications with the same value that were put in through the summary table, see **Figure 5.14**.

5K Pricing	Program Memory Size (Kbytes)	RAM (bytes)	EEPROM / HEF	Pin count	Max. CPU Speed MHz	Peripheral Pin Select (PPS)	Internal Oscillator
$1.63	7	256	256 / HEF	40	20	No	8 MHz, 32 kHz
$1.78	14	368	256 / HEF	40	20	No	8 MHz, 32 kHz
$2.03	7	256	256	40	20	No	8 MHz, 32 kHz
$2.17	14	352	256	40	20	No	8 MHz, 32 kHz

Figure 5.14 Selection Summary of the Available PIC for Receiver.

Table 5.3: Comparison Table of PIC16F for Receiver

PIC16F877		PIC16F914	
Program Memory Type	Flash	Program Memory Type	Flash
Program Memory (KB)	14	Program Memory (KB)	7
CPU Speed (MIPS)	5	CPU Speed (MIPS)	5
RAM Bytes	368	RAM Bytes	256
Data EEPROM (bytes)	256	Data EEPROM (bytes)	256
Digital Communication Peripherals	1-UART, 1-A/E/USART, 1-SPI, 1-I2C1-MSSP(SPI/I2C)	Digital Communication Peripherals	1-UART, 1-A/E/USART, 1-SPI, 1-I2C1-SSP(SPI/I2C)
Capture/Compare/PWM Peripherals	2 CCP	Capture/Compare/PWM Peripherals	2 CCP
Timers	2 x 8-bit, 1 x 16-bit	Timers	2 x 8-bit, 1 x 16-bit
ADC	8 ch, 10-bit	ADC	8 ch, 10-bit
Temperature Range (C)	-40 to 85	Comparators	2
Operating Voltage Range (V)	2 to 5.5	Segment LCD (pixels)	96
Pin Count	40	Temperature Range (C)	-40 to 125
		Operating Voltage Range (V)	2 to 5.5
		Pin Count	40
		Cap Touch Channels	8

In the same manner, the number of pins needed for the 'transmitter' microcontroller is listed as follows:

- 8 pins for push buttons
- 8 pins for test LEDs
- 1 pin for RF transmitter
- 2 pins for external oscillator (optional)

Therefore, an estimated total of 19 minimum pins are required for a microcontroller transmitter.

5K Pricing	Program Memory Size (Kbytes)	RAM (bytes)	EEPROM / HEF	Pin count	Max. CPU Speed MHz	Peripheral Pin Select (PPS)	Internal Oscillator
$1.37	7	256	256 / HEF	28	20	No	8 MHz, 32 kHz
$1.49	14	368	256 / HEF	28	20	No	8 MHz, 32 kHz
$1.72	7	256	256	28	20	No	8 MHz, 32 kHz
$1.93	14	352	256	28	20	No	8 MHz, 32 kHz

Figure 5.15 Selection Summary of the Available PIC for Transmitter.

Table 5.3: Comparison Table of PIC16F for Transmitter

PIC16F873		PIC16F913	
Program Memory Type	Flash	Program Memory Type	Flash
Program Memory (KB)	7	Program Memory (KB)	7
CPU Speed (MIPS)	5	CPU Speed (MIPS)	5
RAM Bytes	192	RAM Bytes	256
Data EEPROM (bytes)	128	Data EEPROM (bytes)	256
Digital Communication Peripherals	1-A/E/USART, 1-SPI, 1-I2C1-MSSP(SPI/I2C)	Digital Communication Peripherals	1-UART, 1-A/E/USART, 1-SPI, 1-I2C1-SSP(SPI/I2C)
Capture/Compare/PWM Peripherals	2 CCP	Capture/Compare/PWM Peripherals	1 CCP
Timers	2 x 8-bit, 1 x 16-bit	Timers	2 x 8-bit, 1 x 16-bit
ADC	5 ch, 10-bit	ADC	5 ch, 10-bit
Temperature Range (C)	-40 to 85	Comparators	2
Operating Voltage Range (V)	2 to 5.5	Segment LCD (pixels)	60
Pin Count	28	Temperature Range (C)	-40 to 125
		Operating Voltage Range (V)	2 to 5.5
		Pin Count	28
		Cap Touch Channels	5

PIC16F873 & PIC16F877

Since there were no special or specific hardware requirements for this robotic project, selecting one out of the two microcontrollers from each comparison table will not affect any area at all. Therefore, microcontrollers PIC16F873 and PIC16F877 were selected. Although these two PIC microcontrollers do not have an internal oscillator like PIC16F913 and PIC16F914, they were mainly selected because of their availability during the design and the ongoing implementation process of the prototype, which was convenient at a time and also has saved time to proceed early on for the project. The compatibility of the PIC was also crucial matter during the selection process because it must be compatible with the software (e.g. MPLAB) that are available in the vicinity to allow the PIC to be programmed.

In addition, when it comes to the selection of microcontrollers, the most commonly used microcontrollers tend to have more successive rate because of a large supporting community that have used it in a similar situation. This could simplify the design phase that normally takes up a bit of time to work on. The community may share their experience of successes or even failures that can be avoided to save time, in which could prove very valuable.

5.7 Wireless Camera

The wireless camera will have its own transmitter and receiver system. This provides a wireless connection from the mobile robot to the control application system. Therefore, any small wireless camera that can be mounted on the mobile robot will be suitable for viewing purposes.



Figure 5.16 Wireless IP Mini Camera. [90]

The Wireless IP Mini Cam MD81 Sport were chosen as the camera for the robot. This provides a visual area of analysis of the robot. It was chosen due to its compact size, applicable operation and reasonable price, see purchase links **Appendix D**. It supports a live feed view transmission for a compatible devices such as tablets, iPad, smartphones, etc. It also features of having a micro SD card slot for recording and it's a low powered consumption device which ensure a long working time.

Chapter VI.
Design

6.0 Introduction

In this chapter, the entire design of the system is discussed through simulation tests on the Proteus. The system design areas to be discussed are as follows: voltage regulator to regulate power supply, DC motor control, ultrasonic system, RF communication control, LED control and the full circuit design of the robot and remote control. All of the simulation test that were obtained are accompanied with brief explanations and descriptions.

Research was performed using several textbooks, scholarly reports, journals, thesis, articles and a several selection of internet resources, all sources are referenced in **References** section.

6.1 Design System

The prototype for the robot must now be designed based upon the components that were selected previously and implement them accordingly. The following diagrams below shows the basic system of the bomb disposal robot to illustrate the initial concepts of the design.

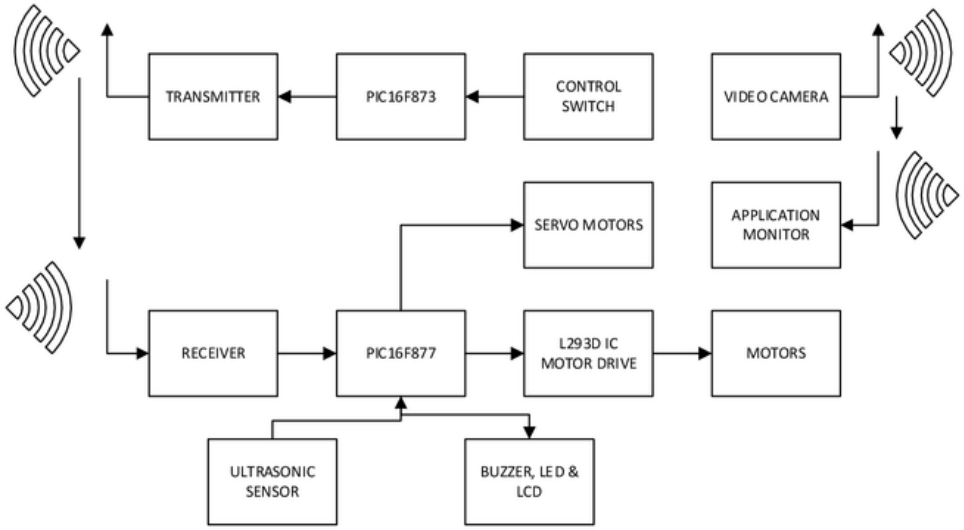


Figure 6.1 System Block Diagram of the Remote Controlled Robot.

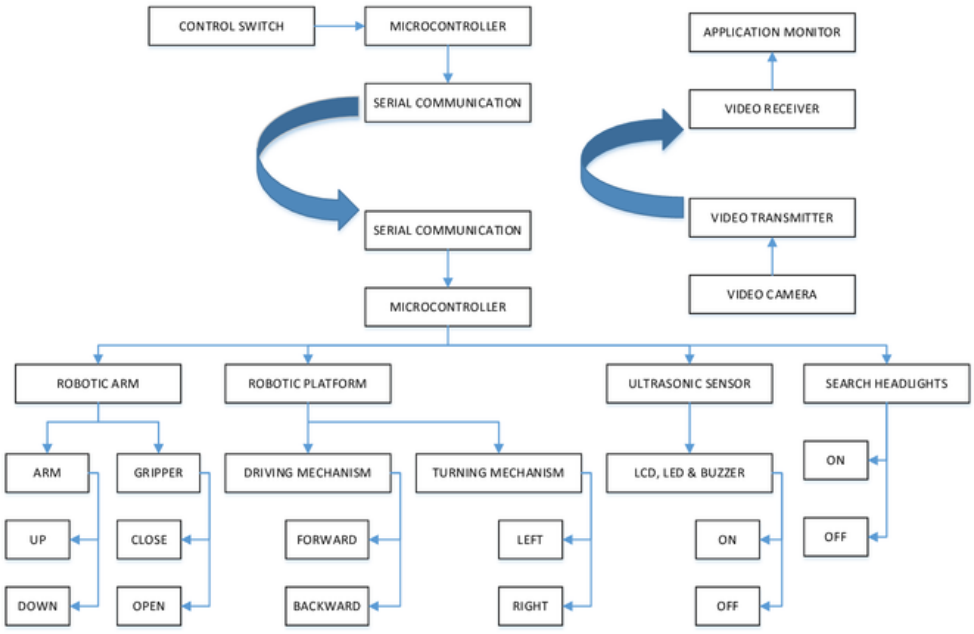


Figure 6.2 System Structure Diagram of the Remote Controlled Robot.

6.2 Voltage Regulator

Voltage regulators are generally used in electronic systems to provide a desired output voltage. The most commonly used voltage regulators are 3.3V and 5V regulators. These two voltage regulators are required for the system to provide a maximum voltage rating in the particular area of the circuit. The pre-built transmitter circuit (see **Figure 5.11**), requires to operate at 3.3V, therefore the use of 3.3V voltage regulator is crucial as the maximum voltage rating for this particular device. Aside from the pre-built transmitter circuit, the system requires a steady of 5V regulated supply to operate. The voltage regulator has 3 pins: an input, an output and a ground. **Figure 6.3** shows one of the example of voltage regulator device with an input, ground and output pins respectively.

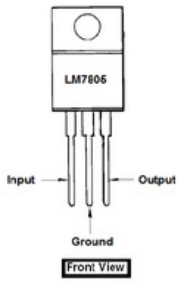


Figure 6.3 5V Voltage Regulator. [88]

Figure 6.4 shows the setup of a typical voltage regulator using the simulation software Proteus which shows the output voltage being 5V. The power supply that were used to power the circuit is a 9V DC battery. The supply is connected to the capacitors and to the voltage regulator. Capacitors are used to filter any undesired noise coming from the power supply which prevents them from entering to the circuit.

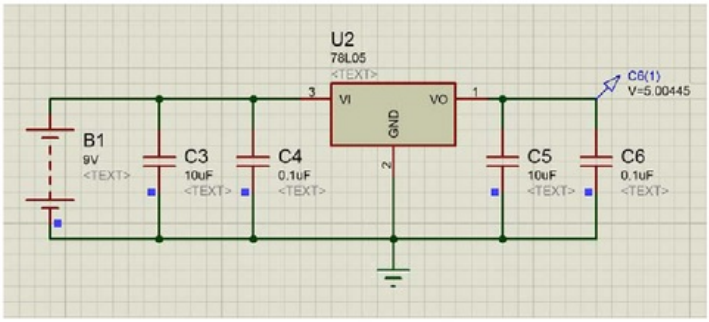


Figure 6.4 5V Voltage Regulator.

6.3 DC Motor Control

As it was discussed in *Chapter V: 5.3 Motors & Actuators (pages 31-35)*, in general, robots usually require two motors or more to move and perform a particular action. Motors usually requires a significant amount of current, therefore the motor driver must be present to take the small current control signal and then amplify it into a larger current signal that can further drives a motor. "Motor driver is basically a current amplifier which takes a low-current signal from the microcontroller and gives out a proportionally higher current signal which can control and drive a motor. In most cases, a transistor can act as a switch and perform this task which drives the motor in a single direction." [58]

H-Bridge

H-bridge is used to control the motors polarity. It contains four switching element that controls and turns the motor in a desired direction. **Figure 6.5** shows the H-bridge circuit with four switching elements labelled as A, B, C and D. The switching elements are usually field effect transistors (FET) or bi-polar junction transistors (BJT). When switches are turned either on or off, the motor can be driven in different directions as follows [58]:

1. When switches A and D are on, it will make the motor rotate clockwise
2. When switches B and C are on, it will make the motor rotate anti-clockwise
3. When switches A and B are on, it will stop the motor (Brakes)
4. Turning off all the switches gives the motor a free wheel drive
5. Lastly turning on A and C at the same time or B and D at the same time, it will short the entire circuit.

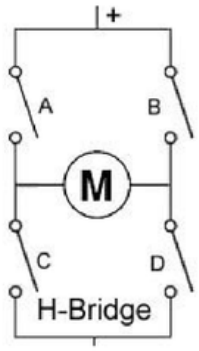


Figure 6.5 H-Bridge. [58]

6.3.1 L293D IC Control

L293D is a typical motor driver which allows DC motor to be control in both directions. It works on a similar concept with an H-Bridge. The L293D chip consists of two H-Bridge built in inside the integrated circuit which can rotate two dc motors simultaneously. It is usually used in robotic applications for controlling DC motors. **Figure 6.6** shows the L293D IC diagram [59].

There are two enable pins on the L293D: pin 1 and pin 9. These two pins represent the capability of driving either of the motor at each side. To drive the motor with left H-Bridge,

the pin 1 must be set on high state. Likewise, to drive the motor with right H-Bridge, the pin 9 must be set on high state. If neither of the two are set on high state, then the motor will be on its stopping position. [59]

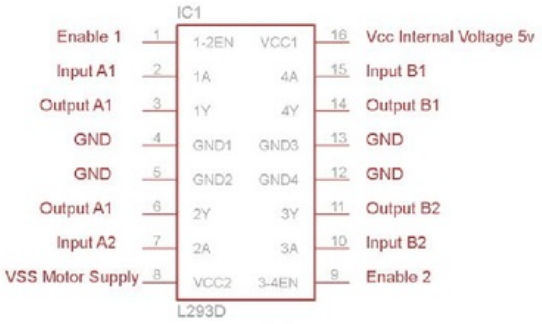


Figure 6.6 L293D IC. [59]

There are four input and four output pins on the L293D. Right input regulates the rotation of the motor connected across the right side and left input regulates the rotation of the motor connected across the left side. The motors are rotated on the basis of the inputs provided across the input pins as High 1 or Low 0. [59]

Table 6.1: Logic Truth Table of Left H-Bridge

Input 1 (A1), pin 2	Input 2 (A2), pin 7	Motor 1 – Output (A1) Direction
High	Low	Clockwise (*or counter-clockwise*)
Low	High	Counter-clockwise (*or clockwise*)
Low	Low	Stop (*no rotation*)
High	High	Forced Stop (*no rotation, shorted*)

These results from the logic truth table will function exactly the same for the other side of the H-Bridge. **Figure 6.7** shows the initial setup of the L293D IC on the simulation software Proteus:

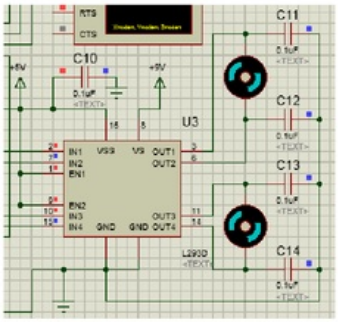


Figure 6.7 L293D IC with motors.

The test switch for manual control would be set up with pull down 10k resistors. This means that the input for the programming for the microcontroller needs to read it as high and when let go the microcontroller would see it and set it as low. **Figure 6.8** shows the design for the input test switch for manual control of the robot on the Proteus:

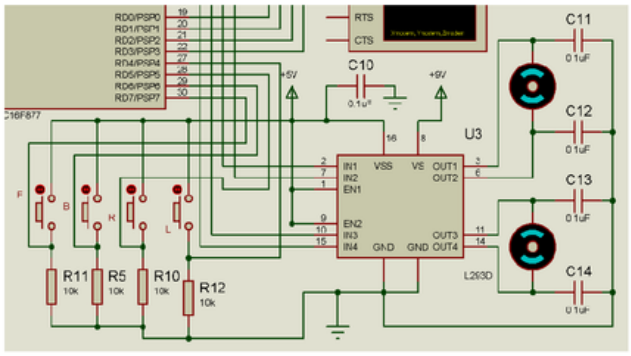


Figure 6.8 Manual Control Switch for the Mobile Platform.

6.3.2 Servo Motor Control

As it was discussed in *Chapter V: 5.3.1: C. Servo Motors (pages 34-35)*, servo motors are widely used for robotics. They are built with electronic circuit inside for controlling the DC motor rotation, direction and position. There are two types of servo motors: standard servo and continues servo. Standard servo can rotate for up to 180 degrees whereas continues servo can rotate for up to 360 degrees.

The servo motor use Pulse Width Modulation (PWM) signal for controlling the DC motor inside the servo. Unlike the normal PWM being used with an ordinary DC motor, it was said that "this PWM signal is not use for controlling the rotation speed, instead it is use for controlling the motor direction or position." [60] The servo motor operates on 50Hz of PWM frequency, which means that the PWM signal is in a range period of 20ms. The control circuit inside of the servo motor will respond to the PWM signal width. The pulse signal can be varied from 0.7ms to 2.0ms as follows: (see **Figure 6.9**)

- Pulse width of 0.7ms to 1ms makes the servo motor to rotate clockwise
- Pulse width of 1.5ms makes the servo motor to rotate to its centre or neutral axis
- Pulse width of 1.7ms to 2ms makes the servo motor to rotate counter-clockwise

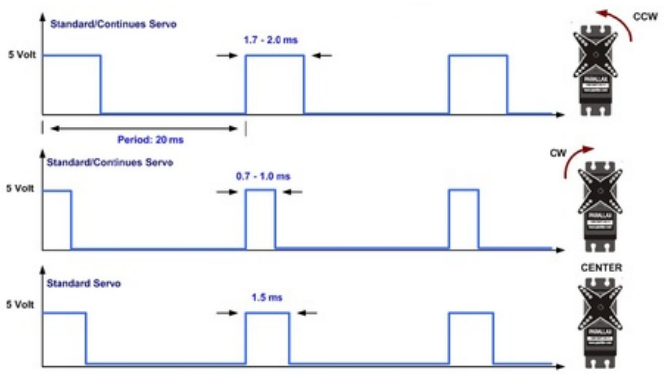


Figure 6.9 Servo Motor PWM Timing Diagram. [60]

These PWM values was attempted through simulation on Proteus to control servo motors. The first PWM that were run through simulation was for the neutral position. 1.5ms PWM width at 50Hz which is shown in **Figure 6.10** and **Figure 6.11**.

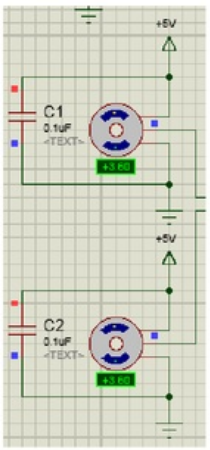


Figure 6.10 Servo Motors.

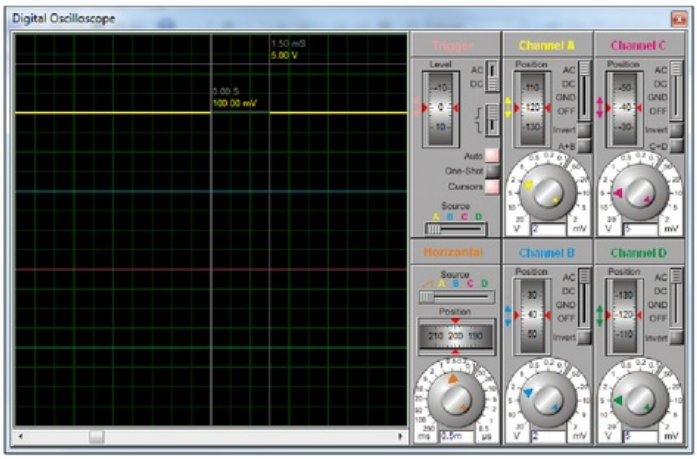


Figure 6.11 Proteus Oscilloscope Readings of 1.5ms PWM width at 50Hz.

As shown from the above diagram, a PWM of 1.5ms moves the servo motor to its neutral position. **Figure 6.11** shows the 1.5ms PWM width and **Figure 6.10** shows the servo motors when positioned at its centre axis. Although the angle of the two servo motors is not at zero degree, +3.60 was still close enough to be considered that it was at zero position. The angle of the two servo motors can be calibrated through programming.

The second PWM that were run through simulation was for the clockwise rotation. 0.7ms to 1.0ms PWM width at 50Hz which is shown in **Figure 6.12** and **Figure 6.13**.

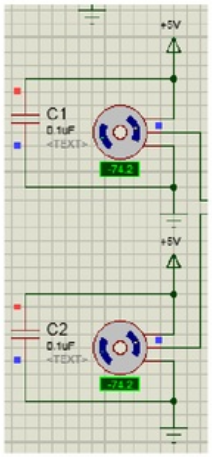


Figure 6.12 Servo Motors.

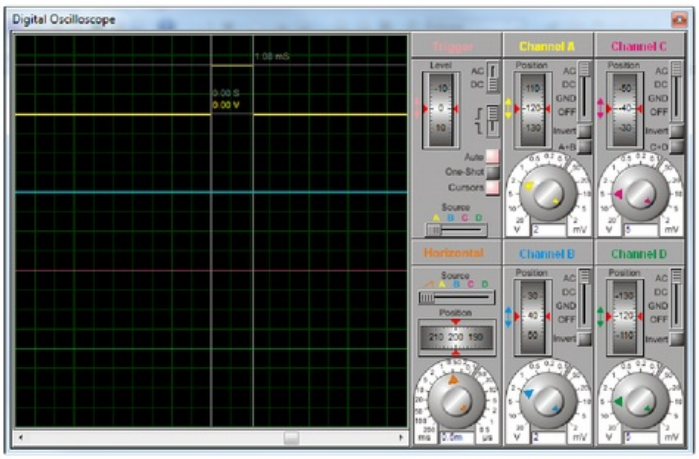


Figure 6.13 Proteus Oscilloscope Readings of 1ms PWM width at 50Hz.

As shown from the above diagram, a PWM of a maximum 1ms has made the servo motor to move to clockwise. **Figure 6.13** shows the 1.08ms PWM width, which is slightly above 1ms and **Figure 6.12** shows the servo motors when positioned at its maximum clockwise position. The servo motors are programmed to be position at -74.2 degrees to prevent the servo motors from forcing itself to go all the way down and stop DC motor in a specified degree range.

Finally, the last PWM that were run through simulation was for the clockwise rotation. 1.7ms to 2.0ms PWM width at 50Hz which is shown in **Figure 6.14** and **Figure 6.15**.

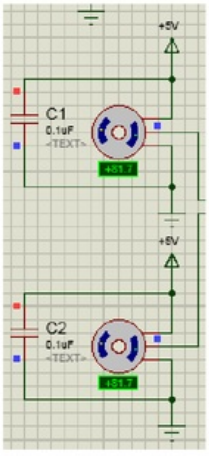


Figure 6.14 Servo Motors.

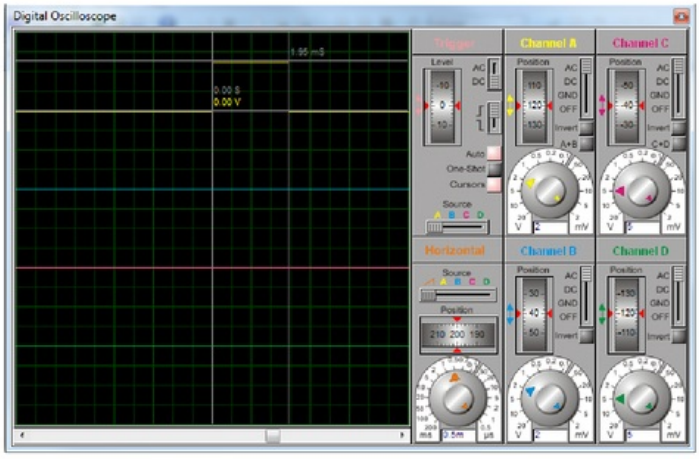


Figure 6.15 Proteus Oscilloscope Readings of 2ms PWM width at 50Hz.

As shown from **Figure 6.14** and **Figure 6.15**, a PWM of a maximum 2ms moves the servo motor to counter-clockwise position. **Figure 14** shows the 1.95ms PWM width, which is slightly lower to 2ms and **Figure 6.15** shows the servo motors when positioned at its maximum counter-clockwise position. The servo motors are programmed to be position at +81.7 degrees to prevent the servo motors from forcing itself to go all the way up and stop DC motor in a specified degree range.

The ideal angle degree position for these servo motors can be achieved if program values are set correctly. The ideal angle are as follows:

- Neutral position is zero degree
- Clockwise is -90 degree
- And counter-clockwise is +90 degree

However, the clockwise and counter-clockwise will be set to +5 and -5 from their ideal maximum angle for safety measures for the servo motors. Therefore, a new ideal angle for clockwise which is -85 degree and counter-clockwise which is +85 degree. As a result, the program is then subject to change to run and do more testing until these servo motors achieved their ideal position.

6.4 Ultrasonic Sensor

As it was discussed in *Chapter V: 5.5 Ultrasonic Sensor (pages 37-38)*, the module HC-SR04 ultrasonic sensor will be used for this project. It works similar to sonar, it emits an ultrasonic wave at 40kHz which travels and bounce back to the sensor module if there is an obstacle on its path. The sensor module generates ultrasonic wave when trig is set on a high state for 10us. This will then send out an 8 cycle of sonic burst through the air at the speed of sound in the medium and it will be received by the echo, see **Figure 6.16** and **Figure 6.17**. The echo pin output the time in microseconds (us) the ultrasonic wave has travelled. [61]

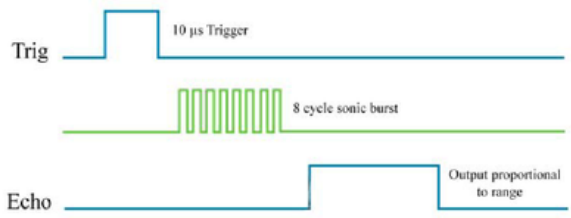


Figure 6.16 Timing diagram of the Ultrasonic Sensor. [63]

The formula for ultrasonic module is as follows:

$$D = V * T/2$$

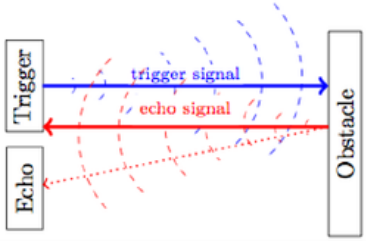


Figure 6.17 Sound Echo Phenomenon. [64]

Where, D is the distance of the object, V is the speed of sound and T is the measured time for trig signal to complete its round trip. The division by 2 in the formula is due to the fact that the measured time is for the total round trip of the signal. [64] Varying temperature condition affects the speed of sound in the air. The formula is therefore:

$$V = 331m/s + (0.6m/s/C) * T$$

Where T is the temperature of the air measured in degrees Celsius (°C) and V is the speed of a sound measured in meter/second (m/s). Using the formula above at an assumed temperature of 20°C to determine the speed of sound. Therefore speed of sound is approximately *340m/s* or *0.034cm/us*. [63] Applying the speed of sound to the formula for ultrasonic module to determine the distance in centimetre (cm) as follows [62]:

$$D = T * 0.017$$

Figure 6.18 shows the simulation on the Proteus for the ultrasonic sensor module. There were no library for ultrasonic sensor module in Proteus, therefore pattern generator was used instead to present as an ultrasonic sensor device for the sake of running a simulation test. The pattern generator represents itself as an echo device that receives frequency from the trig. It imitates the echo device from an ultrasonic sensor module and can set its counter in any range as a distance measurement on the Proteus. **Figure 6.18** and **Figure 6.19** shows output of the pattern generator that represents the distance on the simulation.

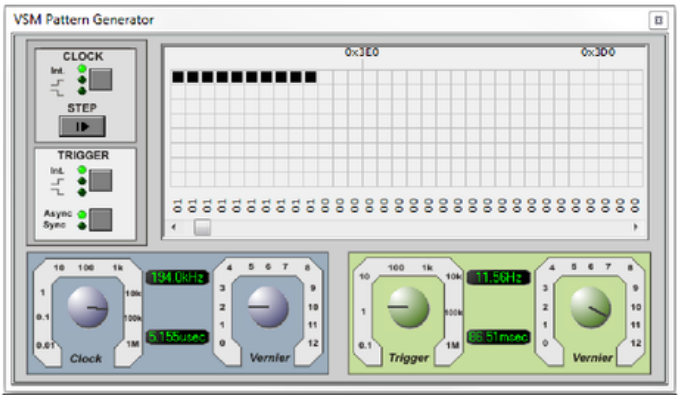


Figure 6.18 Pattern Generator as an Ultrasonic Sensor Simulation.

The virtual terminal is used to print out the output that were programmed. In this case, the pattern generator was set on 16, therefore the virtual terminal shows the output of the mimicked sensor on the simulation as a distance measurement.



Figure 6.19 Virtual Terminal used for Ultrasonic Sensor.

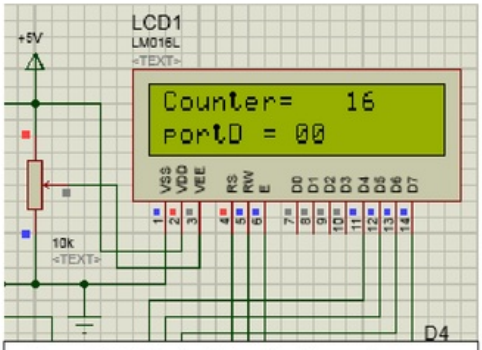


Figure 6.20 LCD simulation for Ultrasonic Sensor.

A 16x2 LCD was used and connected to the microcontroller in 4-bit mode. The way LCD works was briefly discussed in the book "*The Art of Electronics*" *(pages 1028-1030)* [56]. It functions similar to virtual terminal in which it outputs the print out command from the program. The **Figure 6.20** shows the output of the counter value which was set on the pattern generator. The determined formula will be used to measure the distance in cm. This will display the computed value onto the LCD.

The output frequency is shown in **Figure 6.21**. This represents the output proportional to range received by the echo of the ultrasonic sensor module. The time measured is the trig signal that has completed its round trip, therefore measuring the time taken of the selected counter 16 would be:

160us – 10us = **150us**.

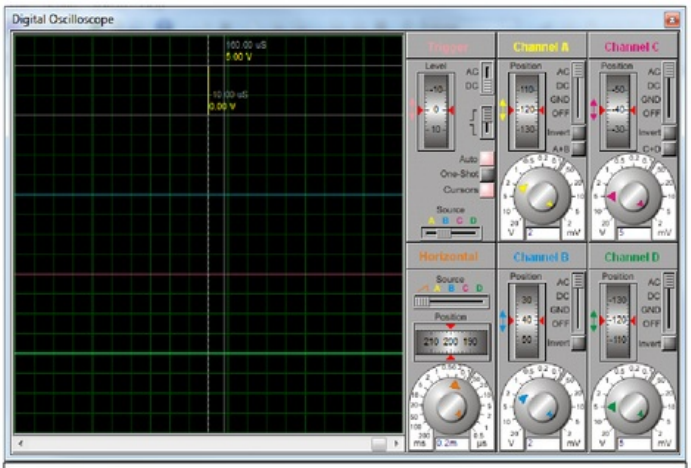


Figure 6.21 A Generated Output Frequency for Ultrasonic Sensor Simulation.

The counter on the pattern generator were set at a value of 16 as an echo. The following diagram below shows the simulation for the ultrasonic sensor output.

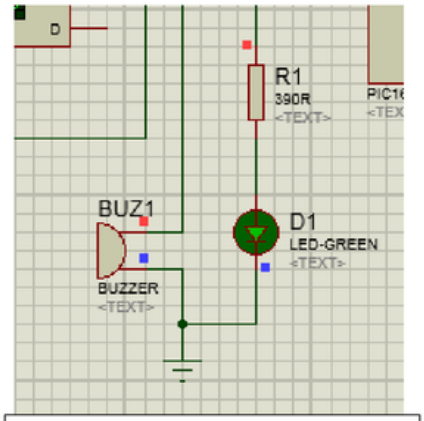


Figure 6.22 Counter within specified range.

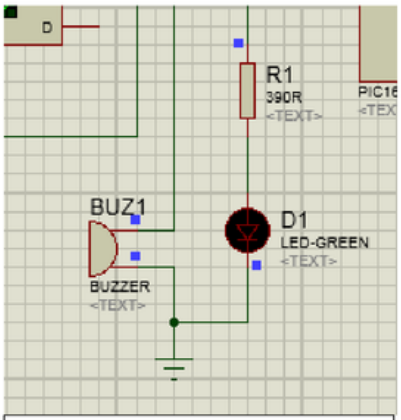


Figure 6.23 Counter out of the range.

Figure 6.23 is in a low state meaning there is no obstacle or object on its path. While on the other hand, **Figure 6.22** shows that when object is within the specified range, the buzzer along with LED will produce an on and off output.

6.5 RF Communication Control

As it was discussed in *Chapter III: RF Communication System (pages 14-16)*, the radio frequency is a radio waves in a form of electromagnetic radiation between 3 KHz to 300GHz, which are widely used for communications. The RF control were discussed in *Chapter V: Remote Control (pages 35-37)*, which has a paired of frequency for receiver and transmitter.

Since computers can only understand numbers, therefore an ASCII code were used to represent texts in computers, see **Appendix F** for ASCII code table [66]. The ASCII code were used to control the motors for simulation on the Proteus to present as a binary number because the data signal that being sent from transmitter to receiver are in a form of binary numbers. **Figure 6.24** and **Figure 6.25** shows the representation of RF communication on the Proteus using ASCII code.

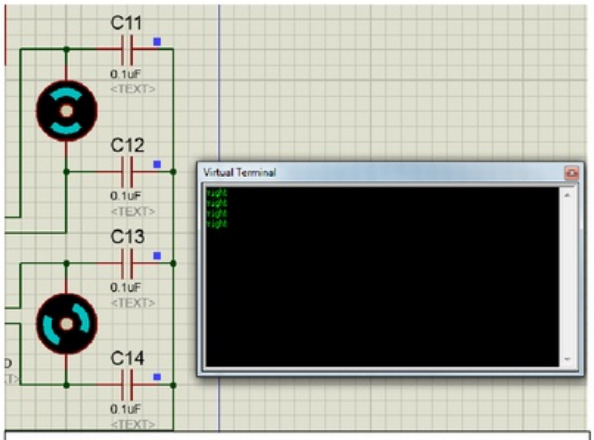


Figure 6.24 DC motors control using ASCII code.

Figure 6.24 shows the simulation for controlling a DC motor using an ASCII code to represent as a transmitting and receiving module system. In this case, the command for 'right' that corresponded from ASCII code table is (backspace) which represent as 0000 1000 in binary.

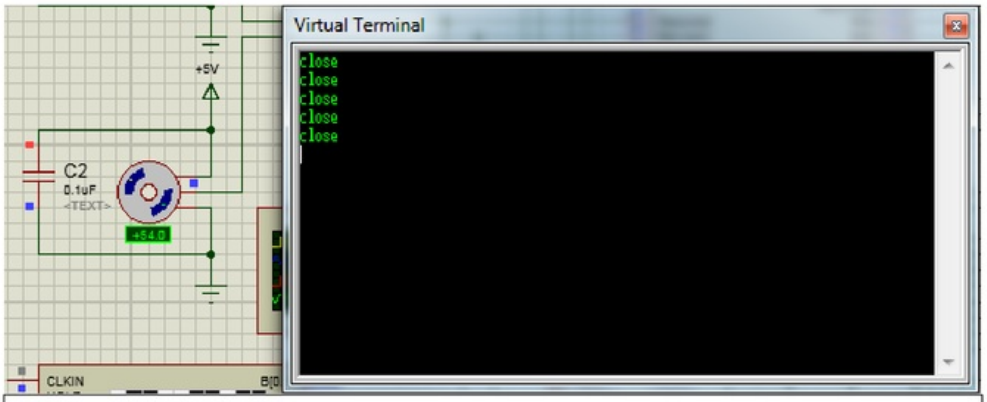


Figure 6.25 DC servo motors control using ASCII code.

Figure 6.25 shows the simulation for controlling a DC servo motor using an ASCII code to represent as a transmitting and receiving module system. In this case, the command for 'close' that corresponded from ASCII code table is (spacebar) which represent as 0010 0000 in binary.

6.6 LED Control

To control to power the LED, a resistor must be put in place connected across in series with LED to limit the current coming from the power supply. This therefore, does not potentially damage the components. Looking at the datasheet, LED have a "forward voltage" characteristic which is often labelled as Vf on the datasheets. This forward voltage is the amount of voltage drop or lost in the LED during its operation at a certain reference current, with a rated current of an approximately 20mA. Vf mainly depends on the colour of the LED. The following table below shows the voltage drop across of different LED colour [65]:

Table 6.2: Different LED colours varies voltage drop

Colour	Voltage Drop	Colour	Voltage Drop
Red	1.8V	Pure-Green	3.3V
Orange	1.8V	Blue	3.3V
Yellow	1.8V	White	3.3V
Yellow-Green	1.8V	UV	3.3V

To ensure that the correct resistor is applied, the following formula was used:

$$Desired\ Resistor\ Value = \frac{\text{Power Supply Voltage} - \text{LED Forward Voltage}}{\text{Current}}$$

The LED colour that was selected for the lights are white. Therefore:

$$Desired\ Resistor\ Value = \frac{5\text{V} - 3.3\text{V}}{20\ \text{mA}}$$

$$Desired\ Resistor\ Value = \frac{5\text{V} - 3.3\text{V}}{20\ \text{mA}}$$

$$Desired\ Resistor\ Value = 85\ \Omega$$

As calculations suggest, a resistor value of 85Ω is required, therefore a 100Ω NPV (Nearest Preferred Value) resistors are used for the lights.

The following two diagrams below shows a simple set up for the LED circuit:

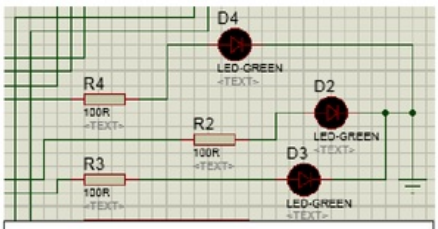


Figure 6.26 LED OFF.

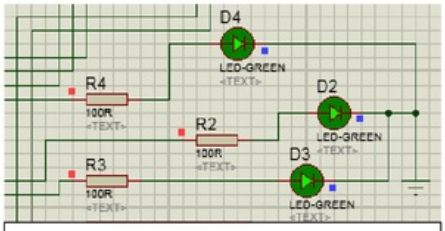


Figure 6.27 LED ON.

During initialisation, all three LEDs are set to low as shown in **Figure 6.26** meaning all are off. When switch is pressed, the microcontroller sets the LED to high state (ON) as shown in **Figure 6.27** until the switch is pressed again which would take it then to low state. It toggles the LED by switching the push button on and off. **Note:** 100Ω resistors are placed, however, there were no available white LED colour on the Proteus, therefore, a green LED was used for simulation.

6.7 Bomb Disposal Robot Circuit

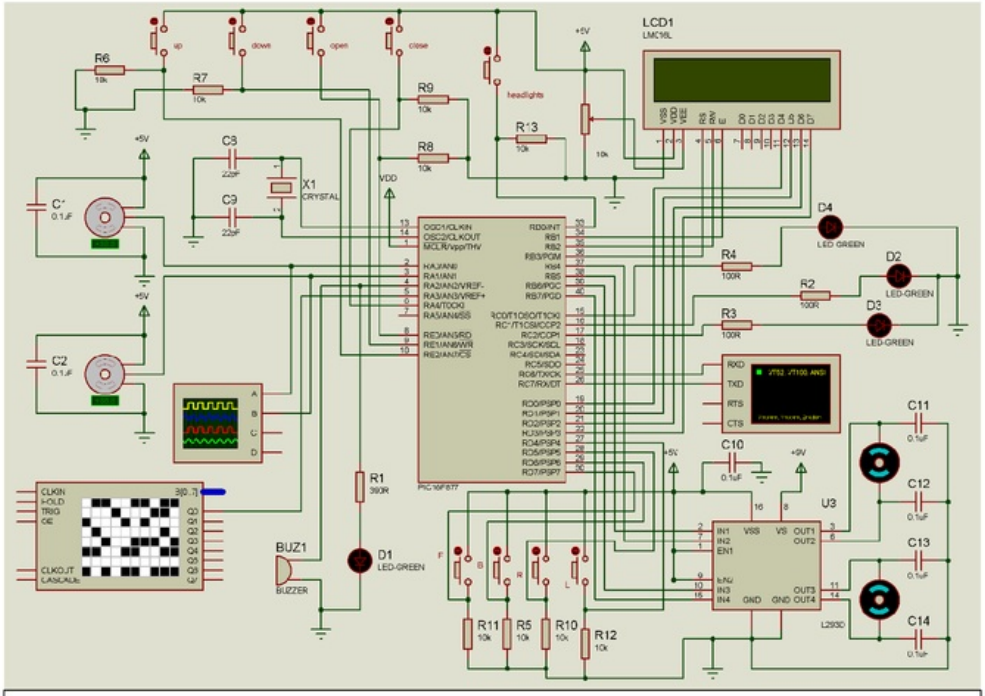


Figure 6.28 Bomb Disposal Robot Circuit.

Figure 6.28 shows the full circuit of the robot which consists of 5V regulator, microcontroller, receiver, servo motors, ultrasonic system including LCD, LEDs, L293D for DC motors and multiple test switch.

6.8 Wireless Remote Control Circuit

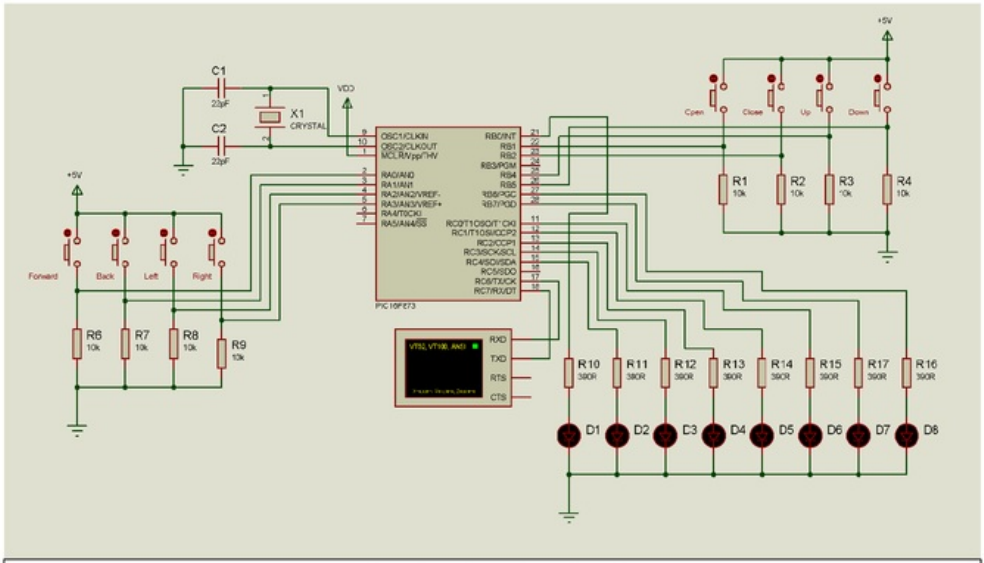


Figure 6.29 Transmitter Circuit.

Figure 6.29 shows the full circuit of the remote control which consists of 5V regulator, 3.3V regulator, microcontroller, transmitter, multiple switch and test LEDs.

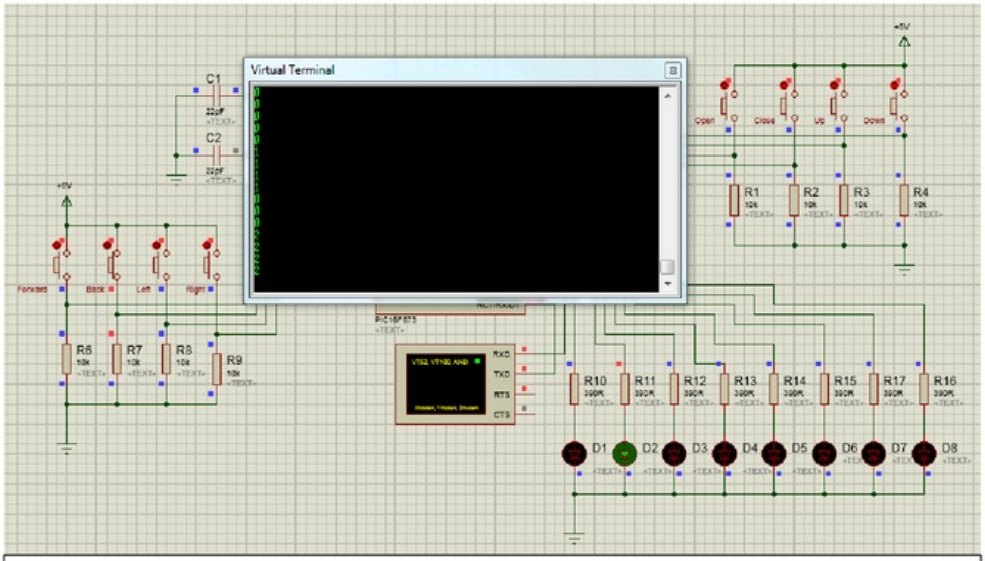


Figure 6.30 Transmitter Circuit.

Figure 6.30 shows a simulation of the transmitter sending data byte over to the receiver. The LEDs turns to high state correspond to each switch until let go which then turns it back to low.

Chapter VII.
Implementation

7.0 Introduction

In this chapter, it contains all the methodologies and tests that were carried out on the project. In which continuing the designs that were created from the previous chapter, implementing the designs from software simulations to hardware. All of the tested results that were obtained are accompanied with brief explanations and descriptions.

7.1 Voltage Regulator

As discussed from the previous chapter, voltage regulator is required to limit the voltage going through the circuit. Apart from the transmitter which requires 3.3V, the rest of the electronic components runs with an approximation maximum input of 5.5V rating. Voltage regulator has two capacitors (10uF & 0.1uF) on both sides of the input and output. The voltage regulator measurement for the robot is shown in **Figure 7.1**.

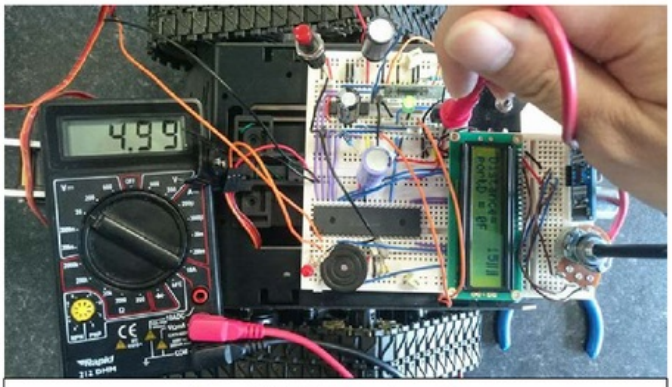


Figure 7.1 5V Voltage Regulator

The robot was being powered by six AA alkaline batteries rated at 1.5V each. Therefore, the battery should be at around 9V. The measured voltage supply is shown in **Figure 7.2.**

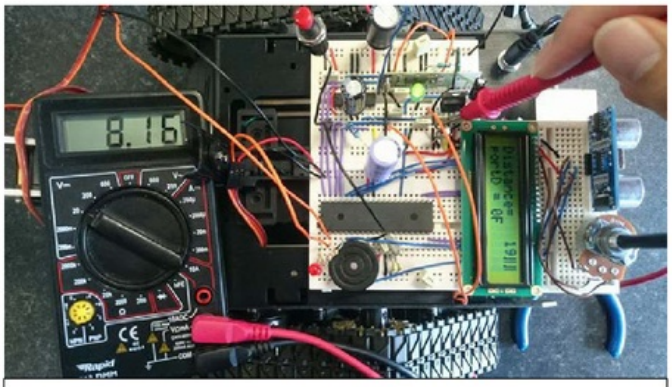


Figure 7.2 9V Battery Supply

There was a large amount of voltage drop as shown in **Figure 7.2**. Possibly because of the excessive resistance of a high amperage circuit, meaning not enough current to power the entire system. Therefore, it may well be necessary to add another power source across the other area of the circuit.

Voltage regulators for the controller are as follows:

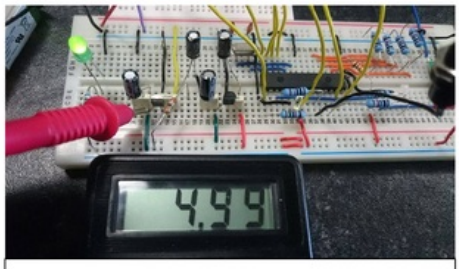


Figure 7.3 5V Voltage Regulator

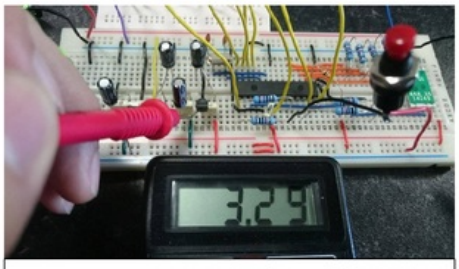


Figure 7.4 3.3V Voltage Regulator

As shown from the above diagrams, voltage regulators are implemented onto the remote control to provide a stable 5V supply mainly for microcontroller and a 3.3V supply for transmitter pre-built circuit.

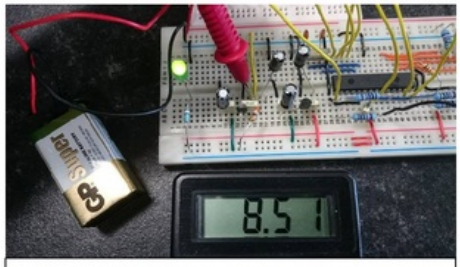


Figure 7.5 9V Battery Supply

Figure 7.5 shows the voltage supply for the remote control using a typical 9V battery.

7.2 Construction of the Robot Base

As it was discussed in *Chapter V: 5.1 & 5.2 component selections*, the robot arm and robot platform that were selected are used for the project. The mechanical construction of the robot platform and robot arm can be seen in **Appendix G**. The fully mechanical constructed prototype robot is shown in **Figure 7.6**. Combining a moving robot platform with a robot arm are still referred to as a sub class of robotic arms. However, as it was discussed in *Chapter 5.1.1 DOF (pages 26-27)*, the robot platform have a 2 DOF differential drive (two DC motors), therefore, by adding a 2 DOF robot arm (two DC servo motors) would give the robot arm a total sum of 4 DOF.

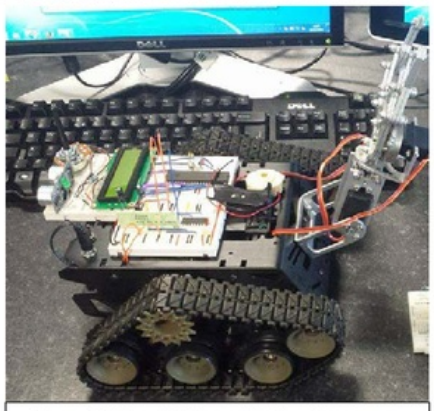


Figure 7.6 Bomb Disposal Robot Prototype.

7.2.1 Robot Arm Control

After the code was programmed into the microcontroller by using the test switch push button, it can manually control DC motors and servo motors. The circuit that were created was tested and checked in the digital oscilloscope to prove that it can generate a pulse width to control the servo motors.

Figure 7.7 shows the initialisation of the servo motors to its neutral position as it was programmed to perform. As shown from the reading output, it clearly shows that it has a 1.5ms PWM.

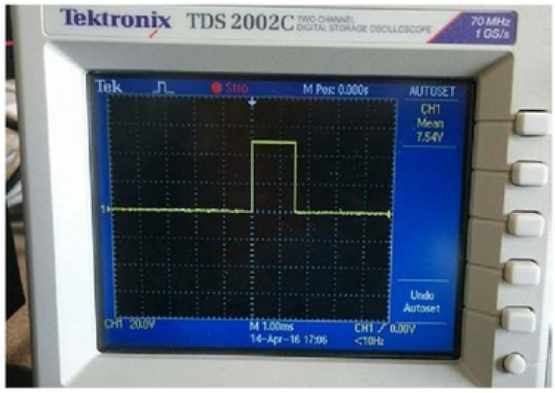


Figure 7.7 Digital Oscilloscope Readings of 1.5ms PWM width at 50Hz.

Figure 7.8 proves that the output from microcontroller generates a 1ms PWM that can control servo motor to rotate to its clockwise position as shown in the digital oscilloscope.



Figure 7.8 Digital Oscilloscope Readings of 1ms PWM width at 50Hz.

Likewise, **Figure 7.9** proves that the output from microcontroller generates a 2ms PWM that can control servo motor to rotate to its counter- clockwise position as shown in the digital oscilloscope.



Figure 7.9 Digital Oscilloscope Readings of 2ms PWM width at 50Hz.

7.2.2 Ultrasonic Sensor

As it was discussed in *Chapter V: 5.5 Ultrasonic Sensor (pages 37-38)*, the module HC-SR04 ultrasonic sensor will be used for this project. The ultrasonic module has 4 pins: 5V voltage supply, trig, echo, and ground respectively. The ultrasonic system was implemented onto the robot base as shown in **Figure 7.10**.

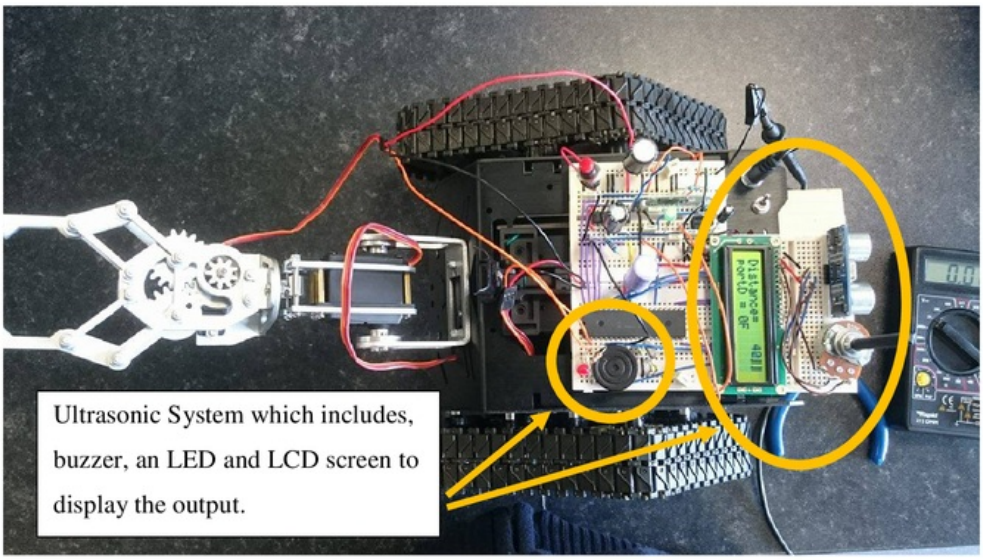


Figure 7.10 Ultrasonic Sensor Mounted onto the Robot base.

Figure 7.11 shows the 10us high pulse is being sent by the trig pin, programmed in microcontroller to send to the sensor, therefore the sensor produce an 8 cycle sonic burst at 40kHz as it was discussed in *Chapter VI: 6.1.3 Ultrasonic Sensor (pages 52-53)*.

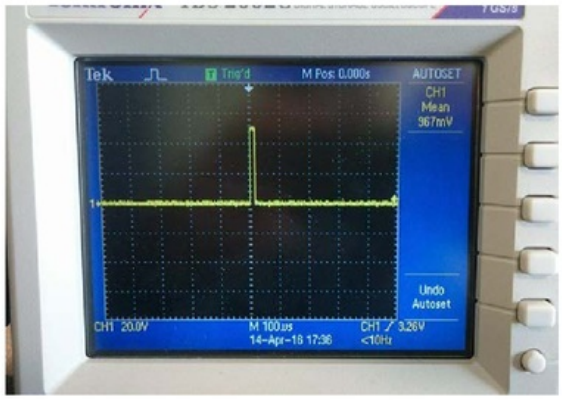


Figure 7.11 Digital oscilloscope readings of 10us generated by Trig at 40kHz.

When the sensor hears the echo it can determine the time between producing the burst and receiving its echo. More specifically, the signal that was generated by trig pin has returned to echo pin which determines the time.

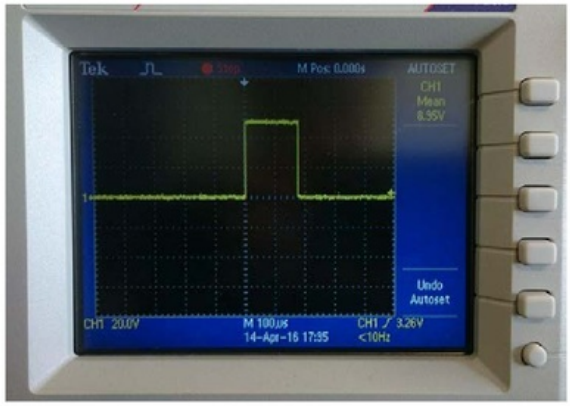


Figure 7.12 Digital oscilloscope readings of 180us generated by Echo to communicate back to microcontroller

Figure 7.12 shows the echo generated a high pulse for a length that equal to how long it took the signal to return to the echo pin produced by trig. The length of the pulse is proportional to how far away the object were.

The ultrasonic sensor were programmed to detect any object within a value of 20. Therefore, any object on its path within this specified range will trigger the Piezo buzzer and red LED on and off. **Figure 7.13** shows the practical testing of the ultrasonic sensor.

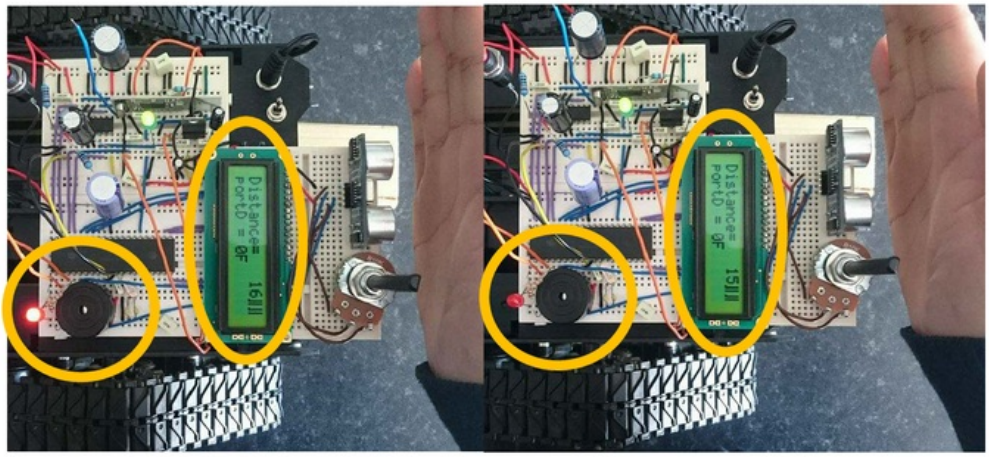


Figure 7.13 Practical testing of Ultrasonic Sensor.

When something gets in range the buzzer and LED goes on and off as shown from the above demonstration. This also calculates the distance of an object as shown from the LCD. However, the unit measurement of the distance in the LCD is not properly set due to time constraints.

7.2.3 Lights

As it was discussed in *Chapter VI: 6.1.5 LED Control (pages 57-58)*, the setup for LEDs are really simple. There are yellow wires connecting 3 output pins from microcontroller to the LEDs. **Figure 7.14** shows the lights assembly for the robot. The 100Ω are placed to keep the current draw below 20mA per LED.

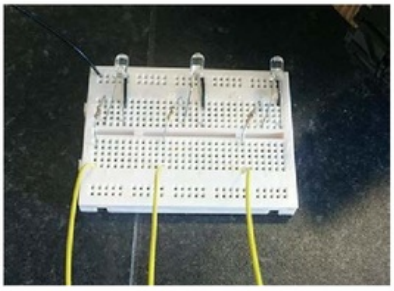


Figure 7.14 LED assembly.

The LEDs are implemented inside the mobile robot to provide a visibility when the area is too dark for robot to explore. **Figure 7.15** shows practical test of the lights when switching the push button on and off.

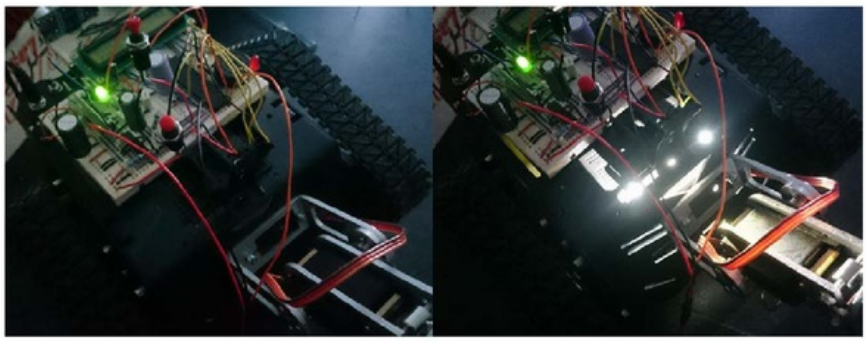


Figure 7.15 Practical testing of lights that can be turned on and off.

7.3 Construction of the Remote Control

As it was discussed in *Chapter V: 5.4 Remote Control (pages 35-37)*, the remote control that were selected to be build is a wireless remote control type system using an RF communication technique. The following figure below shows the circuit of the wireless remote control without the switches and LEDs.

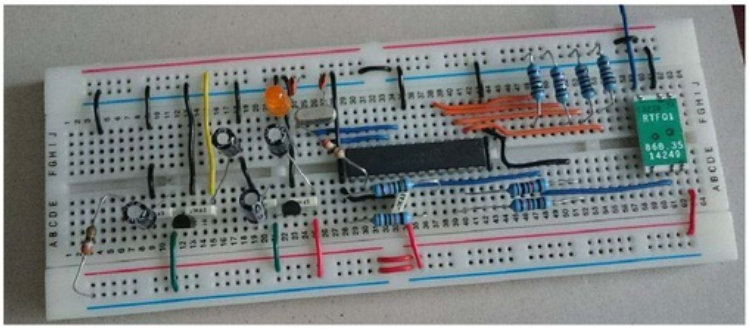


Figure 7.16 Wireless Remote Control Circuit.

The mechanical design and construction for the wireless remote control can be seen in **Appendix G**.

After the code was programmed into the microcontroller by using the switch push button, the test LEDs lights up correspondingly to an input. This indicates that it was sending a command

control which is a data byte in a form of radio waves through the transmitter of the remote control. The diagram below shows the demonstation of a circuit when the push button is switched, the output LED lights up accordingly as shown in **Figure 7.17**.

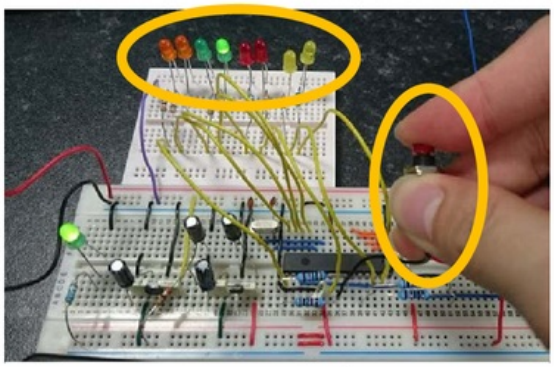


Figure 7.17 Transmission of Data Bytes

These push button switches gives input for the microcontroller and encode the data into serial form. The serial data will then transmitted via the transmitter antenna through the air.

7.4 Radio Frequency Communication

After the construction of both transmitter and receiver circuit, the two circuits were put to the test to see if the communication between these two paired module are established when power is turned on. The first test is shown in **Figure 7.18**. It shows that the transmitter was sending an inverted data byte, therefore, the designed circuit needed to be change.

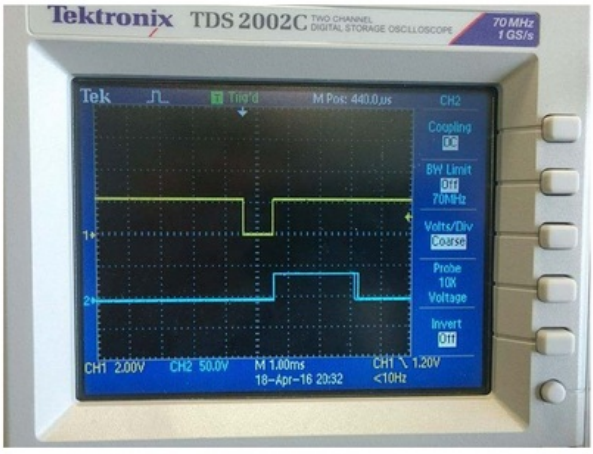


Figure 7.18 Digital Oscilloscope readings for establishement of Radio Frequency Communication between the paired module.

In the remote control, the transmitter circuit was configured by adding a transistor and resistors to reverse the inverted data byte being sent by the transmitter. As a result, the next test for the establishment of radio frequency communication between the paired module is shown down below.

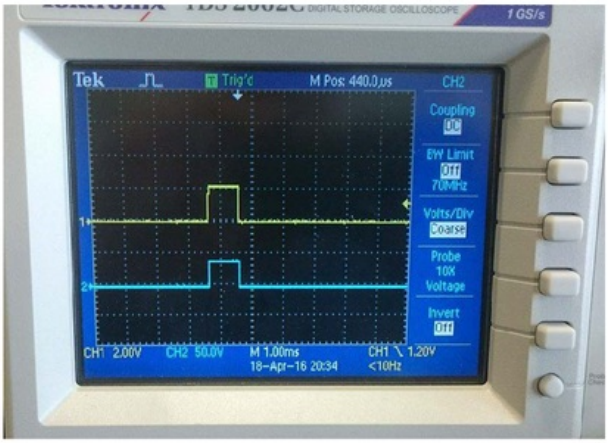


Figure 7.19 Digital Oscilloscope readings for establishement of Radio Frequency Communication between the paired module.

Figure 7.19 proves that the Tx and Rx paired module frequency have been established and communicating to one another. The Tx is sending a data transmission and the Rx is recieveing the same data byte transmission signal as shown from the oscilloscope.

7.5 Other Testing

Before the initial testing of the prototype, all of the motors of the robot was checked and tested to ensure that they are in a working order. A good source was found on how to test a servo motors by using 555 timer as shown in **Figure 7.20**. With this circuit, it can teset both directions of the servo motor, clockwise and counter-clockwise.

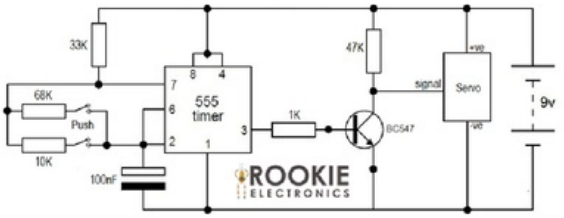


Figure 7.20 Servo Testes Circuit by Rookie Electronics. (91)

During the initial testing, the power source of the robot was checked. The robot was playing up, turning itself on and off in a set of interval time. Therefore, it was put into the test and checked in oscilloscope. The result is shown in **Figure 7.21**. The problem that have been found was that the power source were not supplying enough through the entire system due to the brownout timer triggering at a certain threshold. It resets the microcontroller back from the top with all variables set back to zero which then executes the program again. This was the first implementation issues that have been found. As a result, a separate power source was added to the circuit of the robot.

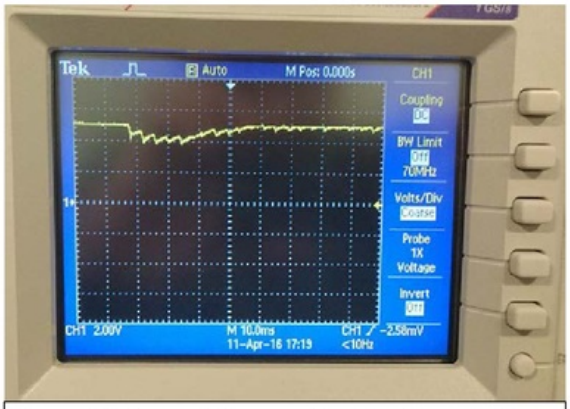


Figure 7.21 Brownout Timer resetting the microcontroller.

Table 7.1: Materials and Cost for the Prototype

Parts	Quantity	Cost	Supplier
2 DOF Robot Arm	1	£42.10	Dagu
Tank Mobile Platform	1	£35.62	RoboSavvy
Wireless Camera	1	£19.99	eBay UK
Ultrasonic sernsor module	1	£1.70	eBay UK
Greyboard	2	£1.99	eBay UK
Nuts & bolts	2 packs	£2.48	Screwfix
Total Budget	£103.88		

The rest of the electronic components was provided by university.

Chapter VIII.
Evaluation

8.1 Project Evaluation

The prototype was made after the initial research of the project. This has helped put forward of the idea for consideration when selecting parts for the robot.

Not all listed objectives were achieved. A stand alone camera has its own communication system connected to a mobile phone via Wi-Fi and it was reliably able to wirelessly provide a visual analysis when mounted on the robot. The ultrasonic system worked well in returning the echo to determine the distance of any object or obstacle approaching from behind. Although the measurement unit in the output LCD were not properly set due to the time constraint, the LED and piezo buzzer has worked effectively. The mechanical construction of the robot was fairly easy along with the remote control, however, the complexity of the program took most of the time when the designed circuit was finished.

The RF communication system was established however, the robot did not respond to control command signals from the transmitter. Although it is fully operational when Tx microcontroller and Rx microcontroller are directly connected to one another. As a result, the circuit was diagnosed first using fault finding techniques. The robot can be manually tested using the test switch pins programmed to the microcontroller for manual execution task of the robot. When test switch was placed, it was used to test all the control for motors which includes

PWM control and resulting with a fully operational robot in the end. DC motors, servo motors and lights worked effectively. Therefore, the issue is down to the main program. The code is needed to be change because there is an issue residing in the program when sending a data byte transmission over to the receiver. Thus, more time was given in an attempt to succeed of achieving the main aim of the project but unfortunately, due to the time constraint the issue was not fully resolved.

Chapter IX.
Conclusion & Recommendation

9.1 Project Conclusion

In conclusion, the majority of the basic requirements for bomb disposal robot was achieved, although the wireless communication system still has an ongoing issue that needs to be resolved. Aside from that, all other features that was planned has worked effectively.

The ultrasonic sensor was mounted onto the robot which utilised with PWM, by sending a burst cycle from trig pin which then receives by echo pin to determine the time taken which then calculates the distance and output to LCD. Although the measurement unit were not properly adjusted to either metric (cm) or imperial system (inch). This has been a great feature to the robot to act as the object detector coming from behind with an output LED along with a piezo buzzer.

Though the robot did not achieve the main aim of the project, the robot is still fully functional via wired control. It can be controlled using manual switch which has been referred to as 'test switch' throughout the course. Servo motors utilised with PWM, it automatically initialised itself to set on its centre axis when powered on then drives servo motor to rotate clockwise or

counter-clockwise. Whereas mobile platform drives DC motor to move forward, backward, left or right.

The camera has its own communication system that has provided the operator a viewing live feed of the robot, so no testing has been made with these. The program however was the biggest issue found after the initial testing. Simulation through Proteus did not show any fault but when applied in real time, it unveiled the issues.

Overall, the element of time management and time constraints contributed to the progress of the project report. Perhaps if less time had been spent for the selection design of the project and more time on studying the programming language then apply this to the project, the chosen wireless communication system which was the RF technique would have been achieved.

9.2 Project Recommendation

Possible further work that can be achieved for this robotic project are as follows:

- Implementation of an analogue joystick for smooth manoeuvre control of the robot.
- Increase the number of DOF making the robot arm more versatile.
- Integrate a small screen with the remote control for easy viewing of the status of the robot.
- Include selection for a precise calculation for a required power source to run the entire system.

Chapter X.
Reflection

10.1 Reflection

Progressing through the project in regards with designing and completing the set aims and objectives proved to be really challenging. By understanding the basic fundamental flow of the process on how things works and apply this knowledge to the report and compare it to other professional report shows the persons level that is currently on. Initially there were no knowledge based when it comes to designing a robot and how each parts works correspond to the wireless remote control. Then here after, the report enabled an increase in knowledge and understanding in the process of addressing through the problem and an attempt to solve it by using the tools that are currently available for the purpose of analysis, design and research.

During the research, it was apparent that there can be loads of ways to design a robotic system. It made clear that before the problem can be solved, the problem must be identified first and understand how is it called a problem. Then the basic understanding of all the components needed that are part of the requirements comes next and then implement the simplest possible solution to satisfy the user.

As progressing through the project, the knowledge of programming a language using the new CCS C compiler along with Proteus to run simulation software and MPLAB to program the the two microcontrollers, that were available in the vicinity has began to improve. These

knowledge drastically improved over the last few months of writing a code for the two microcontrollers. Further understanding of this process that sends commands to allow the ultrasonic sensor to do its thing and motors to be controlled are set as they supposed to. These are useful as they use pulse width modulation which is well-known throughout the digital and could be a valuable knowledge to have on how pulse width modulation works and how they can be programmed to control devices.

The knowledge of using digital oscilloscope and probes to allow all the certain areas of the project to be analysed has increased. By using these tools it also allowed the certain areas to be diagnosed when issue has emerged. One example is the wireless communication system such as radio frequency technique proved to be the hardest part of the project. The two programmed microcontrollers are fully functional when directly connected together but when wirelessly sending data bytes transmission, the robot did not respond. Although according to the scope the two module (Tx & Rx) are communicating to one another, Rx is receiving data bytes being sent by Tx. The issue is still present but unfortunately the time has fallen too short leaving the wireless control nonperformance. Apart from that, the other objectives were achieved and has succeeded.

Overall, conducting this report has enabled a clear understanding in how they work through studying different areas one at a time until the set objectives are achieved. The time though was one of the fundamental issue that was on the way because there are more things that is needing to be looked at and done in so little time. It was close on achieving a fully functional robot, however, the lack of time due to various circumstances made the wireless remote control not functional.. This was an enjoyable and valuable fulfilling experience. The time management could be improved the next time, as time management impacted greatly the final outcome of the report.

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http://www.dtic.mil/dtic/tr/fulltext/u2/a284997.pdf

http://static.micromo.com/media/wysiwyg/Applications/Aerospace/PDF/MachineLab-Case_Study_MICROMO.pdf

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http://research.ibm.com/people/j/jhc/pubs/jhc-mred.pdf

Appendices

1. Appendix A: Security Forces Robot

1.1 310 SUGV

Supplier: Endeavor Robotics

Price: Need to request a quote



Description: "The 310 SUGV is a portable, single-person-lift robot with dexterous manipulation for dismounted and mobile operations. The 310 SUGV provides operators with a highly mobile, less than 30 lbs (13.6 kg) robot solution that climbs stairs, manipulates objects and speeds down-range at more than 6 mph (10 km/h)." [66]

1.2 510 PACKBOT®

Supplier: Endeavor Robotics

Price: Need to request a quote



Description: "Modular, adaptable and expandable, the 510 PackBot can perform bomb disposal, surveillance and reconnaissance, CBRN detection and HazMat handling operations. Quickly configured based on mission needs, PackBot easily climbs stairs and navigates narrow passages with sure-footed efficiency, relaying real-time video, audio and sensor data while the operator stays at a safer, standoff distance." [66]

1.3 TALON® V

Supplier: QinetiQ North America

Price: Need to request a quote



Description: "TALON V is the only tactical, mid-sized robot that has successfully completed TARDEC's Interoperability Profile (IOP) testing. Its enhanced electronics and software is designed to provide open architecture, increased performance, flexibility and system level modularity." (67)

1.4 Dragon Runner 20

Supplier: QinetiQ North America

Price: Need to request a quote



Description: "The Dragon Runner 20 (DR-20) is a highly specDR20webialized unmanned system that provides situational awareness. The DR-20 is uniquely suited for ordnance disposal, reconnaissance, security, military operations and first responder applications. The Dragon Runner 20 Small Unmanned Ground Vehicle (SUGV) provides a rugged, flexible solution to ordnance disposal, reconnaissance, inspection and security in military and first responder applications. Originally designed for the U.S. Marine Corps, the basic model of the Dragon Runner 20 SUGV weighs in at only 20 pounds, measuring just 12.2 inches wide, 16.6 inches long and 6 inches high. Although not much larger than a child's remote-controlled vehicle, this powerful robot packs an array of mission-ready capabilities." (68)

Features Comparison Table

 310 SUGV [66]	 510 PACKBOT® [66]	 TALON® V [67]	 Dragon Runner 20 [68]
▪ Portable, can be easily carried and deployed ▪ Weighs less than 30 lbs (13.6 kg) with the manipulator and batteries installed and can be made to fit into packs with 9" by 28" clearances (22.9 x 71.1 cm) ▪ Can lift as much as 22 lbs (10 kg) ▪ Equipped with wide-angle, colour, infrared and zoom cameras ▪ Long mission duration ▪ Supports numerous disruptor solutions	▪ Man-transportable ▪ Deployable in less than two minutes ▪ Can reach speeds of 5.8 mph (9.3 km/h) ▪ Overcomes stairs, obstacles and debris ▪ Submersible in three feet (0.9m) of water and is operational in all-weather environments ▪ Supports more than 20 disruptors and a broad array of sensors	▪ Supports plug and play with third party components ▪ Tool-less track tensioning system ▪ Up to 1080i HD video, dual purpose thermal/daytime zoom camera ▪ Sufficient torque to climb a 46° staircase ▪ Speeds greater than 6.5 mph ▪ Heavy Lift, Multiple Degree-of-Freedom Arm Manipulator ▪ Gigabit Ethernet backbone with six external ports ▪ User-defined graphical interface and programmable manipulator pre-sets	▪ Small and lightweight ▪ Can lift up to 10 pounds with its manipulator arm ▪ Pan/tilt/zoom cameras ▪ Microphone for listening capabilities ▪ Day and night cameras ▪ Flexible and reliable ▪ Impressive Dexterity ▪ Enhanced RF operating capabilities

		▪ Flexible controller options ▪ Improved serviceability ▪ 16 total I/O ports including IOP A and B connectors	

2. Appendix B: Hobbyists & Educational Project Robots

2.1 VEX Clawbot Kit

Supplier: VEX Robotics

Price: £137.99

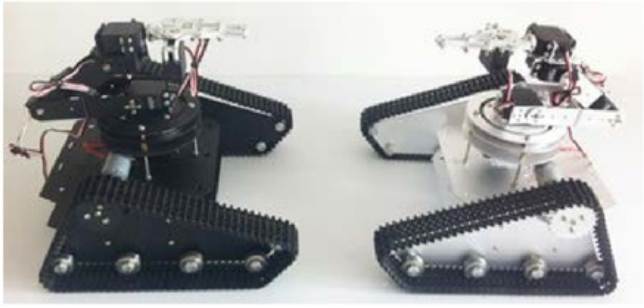


Description: "The Clawbot Mobile Robot w/ Gripper Kit is the foundation robot kit in the VEX Robotics Design System. Included as the basic robot in all kits, the step by step instructions guide users in assembling the robot as they learn to work with the VEX Robotics Design system." [(69)] Although the VEX Robot Control System is not included with the price stated above, it can be purchased separately for additional £227.99.

2.2 Robo-Soul TK-6A

Supplier: Robot-Soul, China

Price: £179.60



Description: The Robo-Soul TK-6A Robot with 6-DOF robot arm is one of the foundation kit to start building your very own robot. The main body is made from aluminium alloy that makes the robot lightweight. The chassis is designed to accept the addition 6-DOF robot arm and perfectly well balanced with tank trunks platform. The robot is capable of carrying up to a 5lbs (2.3 kg) payload. [70]

2.3 Ultimate Robot Kit

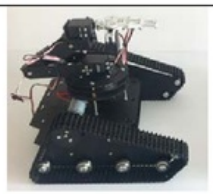
Supplier: Cool Components

Price: £368.30



Description: "The Ultimate Robot Kit is a comprehensive robot kit for beginners to explore the robotic world or experts to build complex robots. It contains everything you need to construct your robot dreams: metal geared motors, Arduino-compatible controller, programmable RGB LED strip, different kinds of sensors, robotic gripper and other mechanical parts." [71]

Features Comparison Table

 VEX Clawbot [69]	 Robo-Soul TK-6A [70]	 Ultimate Robot Kit [71]
▪ Clawbot Mobile Robot with Gripper Kit ▪ Includes 4 motors, structural metal, fasteners, wheels, and gears ▪ Foundation robot kit in the VEX Robotics Design System ▪ 300+ parts ▪ This kit may require additional components	▪ Main body adopts 2mm thickness aluminium alloy, high hardness, light weight ▪ Enhanced nylon caterpillar band, could disassemble by oneself, length adjustable ▪ Reserve gimbals mount hole to install mechanical arm ▪ 6-DOF mechanical arm included, adopts LD-1501MG servo ▪ Metal gear motor, 10 steel bearing ▪ Reverse sensor install hole for second development ▪ Adopts dozens of steel spring gasket for shock absorption	▪ Great for learning robotics, electronics and Arduino programming ▪ Build more than 10 robotic projects ▪ Aluminium extrusion structure ▪ Easy wiring, no soldering required ▪ Bluetooth connection lets you control your robot with your smartphone or tablet

3. Appendix C: Robot Kinematics and Dynamics

3.1 Kinematics

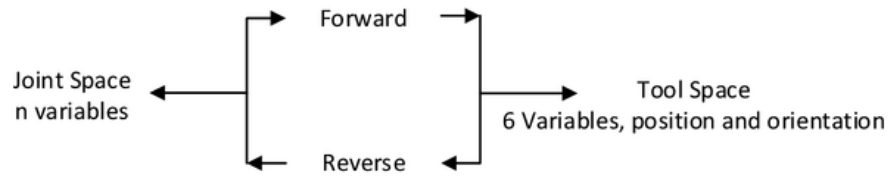
Kinematics presents the forward and reverse kinematics of robots. In the kinematic analysis of manipulator position, there are two separate problems to be solve. These are the forward kinematics and the reverse kinematics.

Direct or forward kinematics "involves solving the direct transformation equation to find the location of the hand in terms of the angles and displacements between the links. The angles and displacements between the links are called joint coordinates and are described with link variables, while the location of the hand in space is described with Cartesian coordinates. Reverse kinematics involves solving the inverse transformation equation to find the relationships between the links of the manipulator from the location of the hand in space." [18]

Inverse or reverse kinematics is "the more difficult problem to solve and, for some manipulators, closed form solutions cannot be found. However, constraints are usually placed on manipulator design so that the inverse solution can be found; without this, the robot is difficult to control in Cartesian space. The inverse kinematic solution for a manipulator is usually derived from the direct kinematic transform, so direct kinematics will be discussed first. Before we discuss the direct kinematic algorithm in detail, we will develop a method for assigning coordinate frames to links. To assign a coordinate frame to a link, the relationship between it and the previous link must be understood. This relationship comprises the rotations and translations that occur at the joints." [32]

Summary:

Forward Kinematics	Computation of the position, orientation and velocity of the end effector, given the displacements and joint angles.
Reverse Kinematics	Computation of the joint displacements and angles from the end effectors position and velocity



3.2 Dynamics

Dynamics presents a detailed discussion of robot dynamics. "It describes why and how a motion occurs when forces and moments are applied on massive bodies. The motion can be considered as evolution of the position, orientation, and their time derivatives. In robotics, the dynamic equation of motion for manipulators is utilized to set up the fundamental equations for control." [33] In the robot dynamics motion, there are two problems. These are the direct dynamics and the inverse dynamics.

Direct dynamics "is easier to solve when the equations of motion are in hand because it needs differentiating of kinematics equations. The first problem includes robots statics because the specified motion can be the rest of a robot. In this condition, the problem reduces to finding forces such that no motion takes place when they act. However, there are many meaningful problems of the first type that involve robot motion rather than rest. An important example is that of finding the required forces that must act on a robot such that its end-effector moves on a given path and with a prescribed time history from the start configuration to the final configuration." [33]

Inverse dynamics "is more difficult to solve since it needs integration of equations of motion. However, the variety of the applied problems of the second type is interesting. Inverse dynamics is essentially a prediction to find the robot motion for all future times when the initial state of each link is given." [33] It developed techniques to derive the equations of motion in this part for a robot.

More information on Textbook: Theory of Applied Robotics.
Kinematics: Rotation Kinematics pp.33-80, Orientation Kinematics pp.91-136, Motion Kinematics pp.149-220, Forward Kinematics pp.233-308, Inverse Kinematics pp.325-370, Velocity Kinematics pp.437-476
Dynamics: Acceleration Kinematics pp.529-570, Motion Dynamics pp.581-630, Robot Dynamics pp.641-714.

4. Appendix D: Purchase Link

4.1 Robot Arm

1 DOF

- http://www.ebay.co.uk/itm/like/281085144683?limghlpsr=true&hlpv=2&ops=true&viphx=1&hlpht=true&lpid=122&chn=ps&googleloc=9045393&poi=&campaignid=207297426&device=c&adgroupid=13585920426&rlsatarget=pla-142405556466&adtype=pla&crdt=0&ff3=1&ff11=ICEP3.0.0-L&ff12=67&ff13=80&ff14=122&ff19=0
- http://www.robotshop.com/uk/lynxmotion-a-style-gripper-kit-servo.html
- http://www.aliexpress.com/item/freeshipping-Metal-Manipulator-robot-arm-Gripper-Claw-clip-1-DOF-for-robotic-paw-mechanical-arm-diy/32609653995.html?spm=2114.40010508.4.88.FV2cPn

2 DOF

- https://robosavvy.com/store/dagu-2dof-robot-arm-with-gripper-and-servos-21cm.html
- http://www.robotshop.com/uk/dagu-aluminum-gripper-with-servos.html

3 DOF

- http://www.dagurobot.com/goods.php?id=70
- http://www.ebay.co.uk/itm/3-DOF-Mechanical-Arm-Claw-Steering-Gear-Bracket-3-Axis-with-Gripper-for-robotic-/121146257424

4 DOF

- http://www.robotshop.com/en/lynxmotion-al5d-robot-arm-hardware-4dof.html

5 DOF

- http://www.dfrobot.com/index.php?route=product/product&product_id=227#.VwjyuKQrLDc

6 DOF

- http://www.dfrobot.com/index.php?route=product/product&product_id=192&search=robotic+arm&description=true#.VwjzH6QrLDc
- http://www.alibaba.com/product-detail/6-dof-robot-arm-gripper-for_60407360501.html
- https://robosavvy.com/store/dagu-6dof-robot-arm-with-gripper-and-servos-50cm.html

4.2 Robot Platform

https://robosavvy.com/store/devastator-tank-mobile-platform.html

4.3 Ultrasonic Sensor

- http://www.gearbest.com/sensors/pp_226738.html?currency=GBP&gclid=CNjG86zZk8wCFYdAGwodwhEM5g
- http://www.hobbytronics.co.uk/srf02-ultrasonic-rangefinder?utm_source=google&utm_medium=googleshopping&utm_campaign=googlebase&gclid=CNv7mqHZk8wCFUQcGwodxPYN9w
- http://www.ebay.co.uk/itm/HC-SR04-Ultrasonic-Distance-Measuring-Module-Transducer-Sensor-for-Arduino-UK-/161877152661?hash=item25b0a15395:g:FJ4AAOSw14xWN6SB

4.4 Wireless Camera

http://www.ebay.co.uk/itm/Wireless-IP-Camera-Mini-Camcorder-Cam-MD81-Sport-DV-DVR-Camera-Wifi-Camera-UK-/401102733246?hash=item5d6395ffbe:g:f3oAAOSwy5ZXB0Oe

5. Appendix E: Motors

The basic principles of AC motors and DC motors are:

1. "A force is exerted on a conductor in a magnetic field when a current passes through it. For a conductor of length L carrying a current I in a magnetic field of flux density B at right angles to the conductor, the force F equals BIL." (40)
2. "When a conductor moves in a magnetic field then an e.m.f. is induced across it. The induced e.m.f. e is equal to the rate at which the magnetic flux ϕ swept through by the conductor changes (Faraday's law), i.e. $e = -d\phi/dt$. The minus sign is because the e.m.f. is in such a direction as to oppose the change producing it (Lenz's law). For this reason it is often referred to as a back e.m.f." (40)

More information on Textbook:
Mechatronics – Electronic control systems in mechanical engineering
Chapter 6: Mechanical Actuation Systems pp.122-127.

6. Appendix F: ASCII Code Table

Decimal - Binary - Octal - Hex – ASCII
Conversion Chart

Decimal	Binary	Octal	Hex	ASCII	Decimal	Binary	Octal	Hex	ASCII	Decimal	Binary	Octal	Hex	ASCII	Decimal	Binary	Octal	Hex	ASCII
0	00000000	000	00	NUL	32	00100000	040	20	SP	64	01000000	100	40	@	96	01100000	140	60	`
1	00000001	001	01	SOH	33	00100001	041	21	!	65	01000001	101	41	A	97	01100001	141	61	a
2	00000010	002	02	STX	34	00100010	042	22	"	66	01000010	102	42	B	98	01100010	142	62	b
3	00000011	003	03	ETX	35	00100011	043	23	#	67	01000011	103	43	C	99	01100011	143	63	c
4	00000100	004	04	EOT	36	00100100	044	24	$	68	01000100	104	44	D	100	01100100	144	64	d
5	00000101	005	05	ENQ	37	00100101	045	25	%	69	01000101	105	45	E	101	01100101	145	65	e
6	00000110	006	06	ACK	38	00100110	046	26	&	70	01000110	106	46	F	102	01100110	146	66	f
7	00000111	007	07	BEL	39	00100111	047	27	'	71	01000111	107	47	G	103	01100111	147	67	g
8	00001000	010	08	BS	40	00101000	050	28	(	72	01001000	110	48	H	104	01101000	150	68	h
9	00001001	011	09	HT	41	00101001	051	29	)	73	01001001	111	49	I	105	01101001	151	69	i
10	00001010	012	0A	LF	42	00101010	052	2A	*	74	01001010	112	4A	J	106	01101010	152	6A	j
11	00001011	013	0B	VT	43	00101011	053	2B	+	75	01001011	113	4B	K	107	01101011	153	6B	k
12	00001100	014	0C	FF	44	00101100	054	2C	,	76	01001100	114	4C	L	108	01101100	154	6C	l
13	00001101	015	0D	CR	45	00101101	055	2D	-	77	01001101	115	4D	M	109	01101101	155	6D	m
14	00001110	016	0E	SO	46	00101110	056	2E	.	78	01001110	116	4E	N	110	01101110	156	6E	n
15	00001111	017	0F	SI	47	00101111	057	2F	/	79	01001111	117	4F	O	111	01101111	157	6F	o
16	00010000	020	10	DLE	48	00110000	060	30	0	80	01010000	120	50	P	112	01110000	160	70	p
17	00010001	021	11	DC1	49	00110001	061	31	1	81	01010001	121	51	Q	113	01110001	161	71	q
18	00010010	022	12	DC2	50	00110010	062	32	2	82	01010010	122	52	R	114	01110010	162	72	r
19	00010011	023	13	DC3	51	00110011	063	33	3	83	01010011	123	53	S	115	01110011	163	73	s
20	00010100	024	14	DC4	52	00110100	064	34	4	84	01010100	124	54	T	116	01110100	164	74	t
21	00010101	025	15	NAK	53	00110101	065	35	5	85	01010101	125	55	U	117	01110101	165	75	u
22	00010110	026	16	SYN	54	00110110	066	36	6	86	01010110	126	56	V	118	01110110	166	76	v
23	00010111	027	17	ETB	55	00110111	067	37	7	87	01010111	127	57	W	119	01110111	167	77	w
24	00011000	030	18	CAN	56	00111000	070	38	8	88	01011000	130	58	X	120	01111000	170	78	x
25	00011001	031	19	EM	57	00111001	071	39	9	89	01011001	131	59	Y	121	01111001	171	79	y
26	00011010	032	1A	SUB	58	00111010	072	3A	:	90	01011010	132	5A	Z	122	01111010	172	7A	z
27	00011011	033	1B	ESC	59	00111011	073	3B	;	91	01011011	133	5B	[	123	01111011	173	7B	{
28	00011100	034	1C	FS	60	00111100	074	3C	<	92	01011100	134	5C	\	124	01111100	174	7C	|
29	00011101	035	1D	GS	61	00111101	075	3D	=	93	01011101	135	5D	]	125	01111101	175	7D	}
30	00011110	036	1E	RS	62	00111110	076	3E	>	94	01011110	136	5E	^	126	01111110	176	7E	~
31	00011111	037	1F	US	63	00111111	077	3F	?	95	01011111	137	5F	_	127	01111111	177	7F	DEL

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ASCII Conversion Chart.doc Copyright © 2003, 2012 Donald Weiman 22 March 2012

Dec	Hx	Oct	Char	Dec	Hx	Oct	Html	Chr	Dec	Hx	Oct	Html	Chr	Dec	Hx	Oct	Html	Chr
0	0	000	NUL (null)	32	20	040		Space	64	40	100	@	@	96	60	140	`	`
1	1	001	SOH (start of heading)	33	21	041	!	!	65	41	101	A	A	97	61	141	a	a
2	2	002	STX (start of text)	34	22	042	"	"	66	42	102	B	B	98	62	142	b	b
3	3	003	ETX (end of text)	35	23	043	#	#	67	43	103	C	C	99	63	143	c	c
4	4	004	EOT (end of transmission)	36	24	044	$	$	68	44	104	D	D	100	64	144	d	d
5	5	005	ENQ (enquiry)	37	25	045	%	%	69	45	105	E	E	101	65	145	e	e
6	6	006	ACK (acknowledge)	38	26	046	&	&	70	46	106	F	F	102	66	146	f	f
7	7	007	BEL (bell)	39	27	047	'	'	71	47	107	G	G	103	67	147	g	g
8	8	010	BS (backspace)	40	28	050	(	(	72	48	110	H	H	104	68	150	h	h
9	9	011	TAB (horizontal tab)	41	29	051	)	)	73	49	111	I	I	105	69	151	i	i
10	A	012	LF (NL line feed, new line)	42	2A	052	*	*	74	4A	112	J	J	106	6A	152	j	j
11	B	013	VT (vertical tab)	43	2B	053	+	+	75	4B	113	K	K	107	6B	153	k	k
12	C	014	FF (NP form feed, new page)	44	2C	054	,	,	76	4C	114	L	L	108	6C	154	l	l
13	D	015	CR (carriage return)	45	2D	055	-	-	77	4D	115	M	M	109	6D	155	m	m
14	E	016	SO (shift out)	46	2E	056	.	.	78	4E	116	N	N	110	6E	156	n	n
15	F	017	SI (shift in)	47	2F	057	/	/	79	4F	117	O	O	111	6F	157	o	o
16	10	020	DLE (data link escape)	48	30	060	0	0	80	50	120	P	P	112	70	160	p	p
17	11	021	DC1 (device control 1)	49	31	061	1	1	81	51	121	Q	Q	113	71	161	q	q
18	12	022	DC2 (device control 2)	50	32	062	2	2	82	52	122	R	R	114	72	162	r	r
19	13	023	DC3 (device control 3)	51	33	063	3	3	83	53	123	S	S	115	73	163	s	s
20	14	024	DC4 (device control 4)	52	34	064	4	4	84	54	124	T	T	116	74	164	t	t
21	15	025	NAK (negative acknowledge)	53	35	065	5	5	85	55	125	U	U	117	75	165	u	u
22	16	026	SYN (synchronous idle)	54	36	066	6	6	86	56	126	V	V	118	76	166	v	v
23	17	027	ETB (end of trans. block)	55	37	067	7	7	87	57	127	W	W	119	77	167	w	w
24	18	030	CAN (cancel)	56	38	070	8	8	88	58	130	X	X	120	78	170	x	x
25	19	031	EM (end of medium)	57	39	071	9	9	89	59	131	Y	Y	121	79	171	y	y
26	1A	032	SUB (substitute)	58	3A	072	:	:	90	5A	132	Z	Z	122	7A	172	z	z
27	1B	033	ESC (escape)	59	3B	073	;	;	91	5B	133	[	[	123	7B	173	{	{
28	1C	034	FS (file separator)	60	3C	074	<	<	92	5C	134	\	\	124	7C	174			|
29	1D	035	GS (group separator)	61	3D	075	=	=	93	5D	135	]	]	125	7D	175	}	}
30	1E	036	RS (record separator)	62	3E	076	>	>	94	5E	136	^	^	126	7E	176	~	~
31	1F	037	US (unit separator)	63	3F	077	?	?	95	5F	137	_	_	127	7F	177	&#127;	DEL

Source: www.LookupTables.com

7. Appendix G: Robot Assembly

7.1 Mobile Platform Assembly



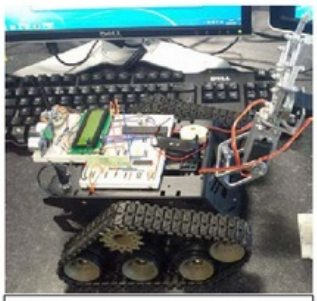
Mobile platfom was assembled by following the included instruction.





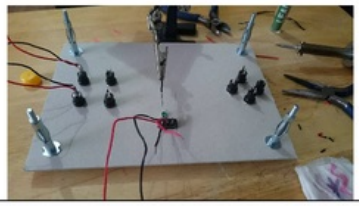




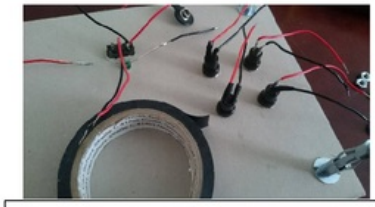


Fully constructed prototype robot

7.2 Remote Control Assembly

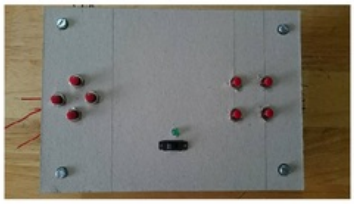


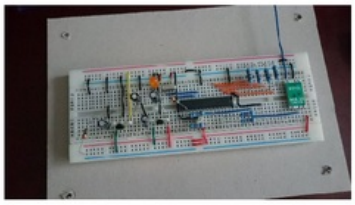
All switches are placed on the greyboard and soldered including LED.

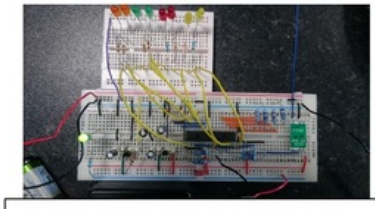


The soldered switches was covered with electric tape to prevent short ciruiting.









The micrcontroller were programmed and now ready for testing.



Fully constructed remote control prototype to control the robot.





8. Appendix H: Program Code

8.1 Transmitter Code

main.c

```
#include <main.h>

void main()
{
char Txbyte=0;  //Set back to zero

        while(TRUE)
        {//TODO: User Code*/
                Txbyte=0;       //Set it back to zero bits
                if(input(PIN_A0))       //Forward
                {
                   bit_set(Txbyte,0);  //send data byte 0
                  output_high(PIN_B0); //turn LED on
                }
                else
                {
                   output_low(PIN_B0); //turn off LED
                }

                if(input(PIN_A1))       //Back
                {
                   bit_set(Txbyte,1);  //send data byte 1
                  output_high(PIN_C4); //turn LED on
                }
                else
                {
                   output_low(PIN_C4); //turn off LED
                }

                if(input(PIN_A2))       //Left
                {
                   bit_set(Txbyte,2);  //send data byte 2
                  output_high(PIN_C3); //turn LED on
                }
                else
                {
                   output_low(PIN_C3); //turn off LED
                }

                if(input(PIN_A3))       //Right
                {
                   bit_set(Txbyte,3);  //send data byte 3
                  output_high(PIN_C2); //turn LED on
                }
                else
                {
                   output_low(PIN_C2); //turn off LED
                }

                if(input(PIN_B1))       //Open Grip
                {
                   bit_set(Txbyte,4);  //send data byte 4
                  output_high(PIN_C1); //turn LED on
                }
                else
                {
                   output_low(PIN_C1); //turn off LED
                }

                if(input(PIN_B2))       //Close Grip
                {
                   bit_set(Txbyte,5);  //send data byte 5
                  output_high(PIN_C0); //turn LED on
                }
                else
                {
                   output_low(PIN_C0); //turn off LED
                }

                if(input(PIN_B4))       //Arm Up
                {
                   bit_set(Txbyte,6);  //send data byte 6
                  output_high(PIN_B7); //turn LED on
                }
                else
                {
                   output_low(PIN_B7); //turn off LED
                }

                if(input(PIN_B5))       //Arm Down
                {
                   bit_set(Txbyte,7);  //send data byte 7
                  output_high(PIN_B6); //turn LED on
                }
                else
                {
                   output_low(PIN_B6); //turn off LED
                }
                delay_ms(200); //transmission delay
                printf("%c",Txbyte);    //output to virtual terminal
        }
}

```

8.2 Receiver Code

main.c

```
#include <main.h>

//LCD Module Connections
#define LCD_ENABLE_PIN PIN_B1
#define LCD_RS_PIN PIN_B3
#define LCD_RW_PIN PIN_B2
#define LCD_DATA4 PIN_D0
#define LCD_DATA5 PIN_D1
#define LCD_DATA6 PIN_D2
#define LCD_DATA7 PIN_D3
//End LCD Module Connections

#include <lcd.c>
unsigned long int a=1500, g=1500;       //Set a pulse for servo motor neutral position
short int light_flag=0;                 //declare flag to set back to zero as 1 bit
short int forward=0, backward=0, left=0, right=0, open=0, close=0, up=0, down=0;        //Declared an integer variable as 1 bit

//Prototype Functions
void move_platform(void);
void arm_initialise(void);
void arm_movement(void);
void grip_movement(void);
void lights(void);
void ultrasonic(void);
void manual_control(void);
void get_control_word(void);
//End of prototype Funcitions

void main()
{
   unsigned long int value=0;
   setup_timer_0(RTCC_INTERNAL|RTCC_DIV_256|RTCC_8_bit);      //65.5 ms overflow

   lcd_init();
   lcd_putc("Device On");
   output_low(PIN_C0);  //initialise LED, set to low
   output_low(PIN_C1);
   output_low(PIN_C2);
   arm_initialise();

   while(TRUE)
   {//TODO: User Code
      get_control_word();
      manual_control();
      move_platform();
      arm_movement();
      grip_movement();
      lights();
      ultrasonic();
   }

}
//END OF MAIN

//Decoder coding starts here:
void get_control_word(void)
   {
      char inputs;
      forward=0;backward=0;
      left=0;right=0;
      up=0;down=0;
      open=0;close=0;
      if(kbhit())
         {
            inputs=getch();
            lcd_gotoxy(1,2);
/*          if(RS232_ERRORS & 0x09)
               {
                  printf(lcd_putc,"errors = %X     ",(RS232_ERRORS & 0x09));
                  forward=0;backward=0;left=0;right=0;up=0;down=0;open=0;close=0;
               }
            else
               {
*/                printf(lcd_putc,"inputs = %d     ",inputs);   //display the radio input byte

            switch(inputs)      // decode the data being sent by Rx
                  {
                     case 1:    forward=1;
                                printf("forward\n\r");
                                break;
                     case 2:    backward=1;
                                printf("backward\n\r");
                                break;
                     case 4:    left=1;
                                printf("left\n\r");
                                break;
                     case 8:    right=1;
```

```
                    case 8:    right=1;
                               printf("right\n\r");
                               break;
                    case 16:   open=1;
                               printf("ropen\n\r");
                               break;
                    case 32:   close=1;
                               printf("close\n\r");
                               break;
                    case 64:   up=1;
                               printf("up\n\r");
                               break;
                    case 128:  down=1;
                               printf("down\n\r");
                               break;

                    default:   forward=0;backward=0;   //set data byte back to zero
                               left=0;right=0;
                               up=0;down=0;
                               open=0;close=0;
                               break;
                   }
//             }

         }

         delay_ms(100);
   }
//END code for decoder

//initialise the servo motors to neutral position
void arm_initialise(void)
   {
      long int q;
      for (q=0;q<2;q++)
         {
            output_high(PIN_A0);
            delay_us(1500);  //generate 1.5ms pulse at 50hz ceneter position
            output_low(PIN_A0);
            delay_ms(25);

            output_high(PIN_A1);
            delay_us(1500);  //generate 1.5ms pulse at 50hz ceneter position
            output_low(PIN_A1);
            delay_ms(25);
         }
   }
//END CODE for neutral position

//Ultrasonic module code starts here:
void ultrasonic(void)
   {
     unsigned long int counter=0;
     char words[5];
     int z=0;

      // trigger module
      output_low(PIN_A5);       //Clears the trigger
      delay_us(3);              //Low state for 3us

      // ping the module
      output_high(PIN_A5);      //Sets the trigger on high
      delay_us(10);             //High state for 10us
      output_low(Pin_A5);       //Sets the trigger back to low
      counter=0;                //Sets the counter back to zero

      while(!input(PIN_A3))
      {
      }
      while(input(PIN_A3))
      {
         counter++;             //starts the counter for each pulse that sent
      }

       printf("count= %Lu\n\r",counter);        //print to virtual terminal
       lcd_gotoxy(1,1);                         //printing display axis
       lcd_putc("Counter=");                    //display output to LCD
       sprintf(words,"   %lu ",counter);        //display counter output to virtual terminal
       z=0;                                     //Sets back to zero
       while(words[z]!=0)              //Sets condition for word while loop when not equal to zero
         {
            lcd_putc(words[z]);         //display output to LCD
            z++;
         }

        if(counter<20) output_toggle(PIN_A2);  //set counter then generates a sound and toggle led output if hit below the specified range
        else output_low(PIN_A2);               //if there is no obstacle sets output to low
```

```
        else output_low(PIN_A2);              //if there is no obstacle sets output to low
   }
//END of Ultrasonic code

//SERVO MOTORS CODE starts here:
void arm_movement(void)
   {
      long int q;

      if(input(PIN_E2) | (up))           // arm up
         {
            a-=50;                       //control steps of the motor
//          if(a<1050) a=1050;           //limits the servo motor from forced open
            for (q=0;q<2;q++)
               {
                  output_high(PIN_A0);
                  delay_us(a);           //generate 1ms pulse at 50hz centre position
                  output_low(PIN_A0);
                  delay_ms(25);
               }
         }

      if(input(PIN_E1) | (down))         // arm down
         {
            a+=50;                       //control steps of the motor
//          if(a>1900) a=1900;           //limits the servo motor from forced close
            for (q=0;q<2;q++)
               {
                  output_high(PIN_A0);
                  delay_us(a);           //generate 1ms pulse at 50hz centre position
                  output_low(PIN_A0);
                  delay_ms(25);
               }
         }
    }

void grip_movement(void)
   {
      long int q;

      if(input(PIN_E0) | (open))         // grip open
         {
           g-=50;                  //control steps of the motor
//         if(g<1050) g=1050;   //limits the servo motor from force open
           for (q=0;q<2;q++)
               {
                  output_high(PIN_A1);
                  delay_us(g);  //generate 1ms pulse at 50hz centre position
                  output_low(PIN_A1);
                  delay_ms(25);
               }
         }

      if(input(PIN_A4) | (close))        // grip close
         {
            g+=50;                  //control steps of the motor
//          if(g>1900) g=1900;  //limits the servo motor from force closed
            for (q=0;q<2;q++)
               {
                  output_high(PIN_A1);
                  delay_us(g);  //generate 1ms pulse at 50hz centre position
                  output_low(PIN_A1);
                  delay_ms(25);
               }
         }
    }
//END CODE FOR SERVO MOTORS

//MANUAL CONTROL code starts here:
void manual_control(void)
     {
       if(manual==1)   //when manual is set to 1 from file header then do the following commands
          {
             if(input(PIN_D7)) forward=1; else forward=0;
             if(input(PIN_D6)) backward=1; else backward=0;
             if(input(PIN_D5)) left=1; else left=0;
             if(input(PIN_D4)) right=1; else right=0;
          }
     }
//END CODE FOR MANUAL CONTROL

//L293D MOTOR DRIVE CODE starts here:
void move_platform(void)
     {
/*       lcd_gotoxy(1,2);
         printf(lcd_putc,"portD = %X",input_d());       //display the output of PORT D
*/       if(forward)//move forward
```

```
259  */       if(forward)//move forward
260           {
261           output_high(PIN_B5);    //set L293D as 1
262           output_low(PIN_B4);     //set L293D as 0
263           output_high(PIN_B6);    //set L293D as 1
264           output_low(PIN_B7);     //set L293D as 0
265           }
266
267           if(backward)    //move backwards
268           {
269           output_low(PIN_B5);     //set L293D as 0
270           output_high(PIN_B4);    //set L293D as 1
271           output_low(PIN_B6);     //set L293D as 0
272           output_high(PIN_B7);    //set L293D as 1
273           }
274
275           if(left)        //turn left
276           {
277           output_low(PIN_B5);     //set L293D as 0
278           output_high(PIN_B4);    //set L293D as 1
279           output_low(PIN_B6);     //set L293D as 0
280           output_low(PIN_B7);     //set L293D as 0
281           }
282
283           if(right)       //turn right
284           {
285           output_low(PIN_B5);     //set L293D as 0
286           output_low(PIN_B4);     //set L293D as 0
287           output_low(PIN_B6);     //set L293D as 0
288           output_high(PIN_B7);    //set L293D as 1
289           }
290
291           if(!(forward | backward | left | right))       //no buttons pressed so stop motors.
292           {
293           output_low(PIN_B5);     //set L293D as 0
294           output_low(PIN_B4);     //set L293D as 0
295           output_low(PIN_B6);     //set L293D as 0
296           output_low(PIN_B7);     //set L293D as 0
297           }
298       }
299  //END CODE for L293D
300
301  //LIGHTS CODE STARTS HERE:
302  void lights(void)
303    {
304         if(input(PIN_B0))       //turn the led on or off when input is pressed
305         {
306           if(!light_flag)
307           {
308               output_toggle(PIN_C0);   //turn LED on when set as high;
309               output_toggle(PIN_C1);   //then turn LED off when set low
310               output_toggle(PIN_C2);
311               light_flag=1;            //set flag to 1
312           }
313         }
314         else
315         {
316           light_flag=0;               //set flag to 0
317         }
318    }
319  //END CODE for lights
320
```