DESIGN AND CONSTRUCTION OF A SMALL SCALE UNDERWATER VEHICLE WITH OBSTACLE AVOIDANCE SYSTEM

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SUPERVISOR ENDORSEMENT

"I hereby declare that I have read through this report entitle "Design and Construction of a Small Scale Underwater Vehicle with Obstacle Avoidance System" and found that it has comply the partial fulfilment for awarding the degree of Bachelor of Mechatronics Engineering.

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Date : 23 June 2015

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A report submitted in partial fulfilment of the requirements for the degree of Mechatronics Engineering

Faculty of Electrical Engineering

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STUDENT DECLARATION

I declare that this report entitle "Design and Construction of a Small Scale Underwater Vehicle with Obstacle Avoidance System" is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : Chong Ze Ming, Bryan

Date : 23 June 2015

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ABSTRACT

This report is about the Final Year Project for the development and analysis of a small scale Autonomous Underwater Vehicle (AUV) with obstacle avoidance system. AUV need to be in miniature size to ease the mobility of the AUV when it performs missions. Besides, obstacle avoidance system is preferable to be implemented in an AUV because obstacle is unpredicted in deep sea and collision might happen without this system. To develop an AUV, materials and components used have to be well considered. The sensors, motors and the hull of the AUV need to be completely watertight. Meanwhile, algorithm for obstacle avoidance and depth control mechanism need to be designed and improved to yield better outcomes. The purpose of this Final Year Project is to design and develop a low cost AUV in miniature size with obstacle avoidance system. Another objective is to analyse the performance of underwater sensors on obstacle detection and distance measurement. Up to date, the hardware and software development has been completed. Total 6 experiments have been conducted. Experiment 1 and 2 has been conducted to test the functionality of the microcontroller and DC motor. Experiment 5 also has been conducted to test light detection of common blue LED. In addition, Experiment 3, 4 and 6 have been conducted to test the functionality of Ultrasonic, Infrared and Laser sensors on distance measurement in air and underwater environment. Based on the analysis in experiments, DC brushless motor is functional in tap water even though it is not watertight. Besides, results showed blue LED can function as spectrally selective detector, which is sensitive to light wavelength from 380nm to 500nm. Furthermore, analysis demonstrated 405nm Laser sensor is a better sensor among others for short range obstacle detection in underwater environment, which can detect obstacle effectively up to 80cm. Standard deviation and root-mean-squared error has been calculated for all results to examine the accuracy and consistency. As a result, all data collected in the experiments were considered accurate.

ABSTRAK

Laporan ini adalah tentang Projek Saujana Muda yang bertujuan untuk membina dan menganalisis Robot Bawah Air (AUV) yang berskala kecil dan boleh mengelakkan halangan secara automatik. AUV perlu bersaiz kecil untuk memudahkan pergerakannya apabila misi dilaksanakan. Selain itu, sistem mengelakkan halangan secara automatik perlu ditambahkan dalam AUV kerana halangan adalah sukar diramalkan di laut dan kelanggaran mungkin berlaku tanpa sistem ini. Untuk penghasilan AUV, bahan dan komponen perlu dipilih dengan berhati-hati sebelum dimasangkan. Sensor, motor dan badan AUV itu perlu berkalis air. Di samping itu, algoritma untuk pengelakan halangan dan mekanisme kawalan mendalam air perlu direka dan diperbaiki sebaik mungkin. Tujuan Projek Saujana Muda ini adalah untuk mereka bentuk dan menghasilkan AUV dengan kos yang rendah, bersaiz kecil dan mengelakkan halangan. Selain itu, Projek Saujana Muda ini adalah bertujuan untuk menganalisis prestasi sensor dalam pengesanan halangan dan pengukuran jarak. Dalam tahap terkini, perkakasan dan perisian telah dihasilkan. Sejumlah 6 eksperimen telah dijalankan. Exsperimen 1 dan 2 telah dijalankan untuk menguji fungsi mikropengawal dan motor arus terus. Seterusnya, Eksperimen 5 telah dijalankan untuk mengkaji pengesanan cahaya dengan LED biru biasa. Di samping itu, Eksperimen 3, 4 dan 6 telah dijalankan untuk mengkaji fungsi Ultrasonik, Inframerah dan Laser sensor dalam pengukuran jarak dalam persekitaran udara dan air. Berdasarkan analisis dalam eksperimen, tanpa berus motor arus terus tanpa berus boleh berfungsi dalam air paip walaupun ia tidak berkalis air. Seterusnya, keputusan eksperimen menunjukkan LED biru boleh berfungsi sebagai pengesan cahaya terpilih, iaitu sensitif kepada panjang gelombang cahaya daripada 380nm hingga 500nm. Di samping itu, analisis menunjukkan sensor Laser 405nm adalah sensor yang lebih baik bagi pengesanan halangan yang jarak pendak dalam persekitaran air, iaitu boleh mengesan halangan dengan berkesan sehingga 80cm. Sisihan piawai dan ralat punca min kuasa dua telah dikirakan dalam semua keputusan eksperimen untuk memeriksa ketepatan dan ketekalan. Hasilnya, semua data yang dikumpul dalam eksperimen adalah tepat.

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CHAPTER 1

INTRODUCTION

This section covers the motivation, problem statement, objectives as well as scopes of this Final Year Project.

1.1 Motivation

In decades back, marine researchers started to develop Unmanned Underwater Vehicles (UUVs) to fulfill their explorations in ocean underwater. UUVs are vital in marine researches and military purposes because various kinds of missions can be performed in extreme environment without risking the human's life. Indeed, UUVs play an important role in intervention and monitoring in oil and gas industry. Moreover, UUVs also have contributed greatly in wreckage search and rescue mission [1][2][3].

UUVs can be classified into two types: the Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs). In this Final Year Project, AUV is emphasized and will be developed. AUVs are usually untethered which make them capable of long range cruising provided with sufficient power supply. Besides, AUVs is operated autonomously which allow them to perform missions without the need of human inputs [4][5]. One remarkable example of AUV is the utilisation of Bluefin-21 from the Australian Navy to perform missions for searching the black box's signals in the Southern Indian Ocean regarding the incident of missing MH370 on 8 March 2014 [6]. However, AUVs are typically expensive, heavier and larger in size because all components are embedded inside the hull.

In shallow water, the use of large AUVs is not practical since larger object has more inertia when moving around in water and it is difficult to avoid obstacle. Hence, small AUVs which are miniature in size will come useful in shallow water to perform missions because of ease for mobility as well as compact without limiting its functionality and long lasting power [2]. There are number of researchers who do researches on small AUVs. Some of the small AUVs developed are Seabird AUV (2007), Monsun II AUV (2012) and Dagon AUV (2010) [7][8][9]. One researcher named Simon A. Watson developed a spherical AUV (2011) with a dimension of 20cm in length and width, and 15cm in height. AUVs with such miniature size are known as micro-AUV [10]. The prototype developed in this Final Year Project is 35cm in length, which is an intermediate AUV in between SeaBird and Watson's. Figure 1.1 illustrates the comparison of a few small AUV examples includes the prototype of this Final Year Project.

In term of costing, AUVs are typically expensive. This is because various sensors are required to be embedded in AUVs for autonomous operation. In addition, the selection of components in compact size is more favourable in developing AUVs. As a result, higher budgets are needed for AUV's production [4]. For example, a commercialised AUV named Iver 3 Nano manufactured by OceanServer Technology even hits a price quotation of RM 185,000 [11]. Expensive AUVs are not affordable to be generally used in researches. Hence, the development of low cost AUV is a must. One solution is the deployment of cheaper material and components in constructing AUVs. Subsequently, more units of low cost AUVs can be produced at the equivalent cost of an expensive AUV.

AUVs can be in high risk in underwater as obstacles could be in anywhere. Especially for deep sea exploration, AUVs might be cruising far away from the station. These expensive assets can be breakdown and vanish if collision with obstacle happens. Therefore, implementation of obstacle avoidance mechanism can be a good measure to enhance the safety of the AUVs [5][12].

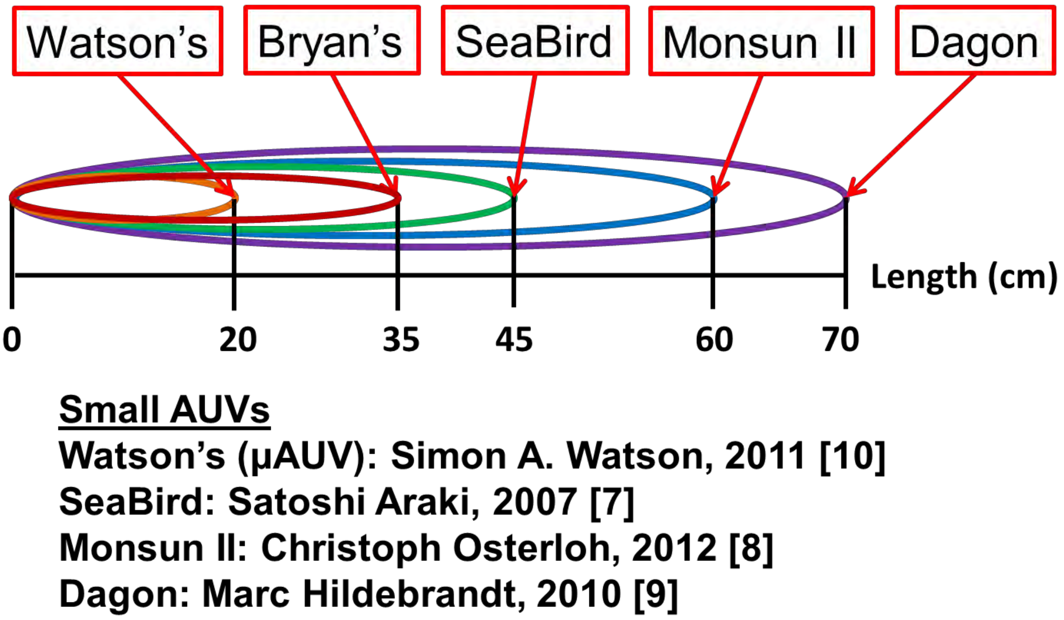

Figure 1.1: Comparison of Small AUV Examples

1.2 Problem Statement

Tremendous mechatronics knowledge is needed to design and develop this AUV. To design AUV in miniature size, the materials and components should be carefully selected in compact but sufficient to be used by studying all the characteristics and specification. The hull design required hydrodynamic to ensure the AUV receive the least friction in water during motion. In addition, the hull should be completely watertight by proper procedure with the aid of technical skills. The kinematic and dynamic of the AUV in underwater will have close relationship with the propulsion system using thrusters. Wireless connectivity between the AUV and the station is necessary because the AUV is untethered. Control algorithm is required to perform obstacle avoidance mechanism and depth control mechanism simultaneously. Selection of suitable sensor is crucial for obstacle detection within 1 meter in underwater. Weight of the AUV has to be specific to achieve stable depth control in underwater with the aid of vertical thrusting by utilizing the fundamental of buoyancy mechanism. Besides, good weight distribution in the AUV is essential to obtain good centre of gravity for stability. Competency in programming is necessary to produce less error in coding, while controlling multi sensors and thrusters in the AUV. Lastly, the AUV need to be powered as long lasting as possible.

1.3 Objectives

The objectives of this Final Year Project are:

1. To design and develop a low cost AUV in miniature size which is less than 0.5 meter in length and 0.55 meter in width.
2. To design and develop an obstacle avoidance system for an AUV in underwater.
3. To analyse the performance of underwater sensors on obstacle detection and distance measurement in underwater.

1.4 Scopes

1. The AUV is required in small scale, which is less than 0.5 meter in length, 0.55 meter in width and 5 kilogram in mass.
2. The depth rating of the AUV is 1 meter from the water surface to prevent extensive water pressure exerts towards the hull.
3. The maximum duration for the AUV activity in underwater is 1 hour per cycle to prevent humidity hazards.
4. The AUV activity is scoped in rectangular tap water pool and rounded tap water pool. The dimension of the rectangular tap water pool is 2.57 meter length × 1.35 meter width × 1.00 meter height, whereas rounded tap water pool is 1.83 meter diameter × 0.38 meter height.
5. Obstacle is needed at least 30 centimetres away from the AUV to prevent collision.
6. The microcontroller used is Raspberry Pi due to it has high processing power and up to 40 General Purpose Input Output pins.
7. Waterproof ultrasonic sensor, Infrared sensor and Laser sensor are tested for sensor performance in underwater. Laser sensor is selected as the input for the obstacle avoidance and depth control mechanisms of the AUV.
8. Performance of Laser sensor is dependent on intensity of reflected light received. Therefore, white obstacle is used to demonstrate obstacle avoidance mechanism.
9. The AUV activity is scoped in indoor under fluorescent lamp. This is because the Laser sensor is UV light dependent sensor. Under sunlight environment, the output voltage of the Laser sensor might be deviated aggressively.
10. 3-Axis accelerometer is used as input for tilt balancing mechanism of the AUV.

CHAPTER 2

LITERATURE REVIEWS

In this section, the design and basic construction of small scale AUVs from three journals has been reviewed. In addition, journals about Light Emitting Diode (LED) as photodiode and absorption spectrum of light in water have been studied to develop a Laser sensor.

2.1 Design and Basic Construction

2.1.1 Guanay II AUV

Guanay II AUV is a torpedo-shaped AUV with the extension of five fins for improvement in hydrodynamic. The AUV is 2.3 meters in length and 90 kg in mass. For hull design, fiberglass has been chosen as the outer hull material and aluminium as the material for watertight module which envelopes the electrical component parts. The AUV is controlled by a PC104 embedded computer. The depth control system has been developed with a stainless steel pneumatic cylinder in ballast tank, with the measurement by a pressure transducer. Navigation system with the combination of GPS and digital compass has been implemented for high accuracy coordination and orientation. A main DC thruster has been used for forward propulsion and two DC side thrusters for directional propulsion. The AUV is connected to base station wirelessly by implementing a radio link modem to transmit data for analysis. 24 V Nickel-Cadmium battery pack with total capacity of 21 Ah has been chosen and a DC to DC converter has been used to step down supply to 5 V and 12 V for supplying power up the AUV [13]. Figure 2.1 shows the hardware of Guanay II AUV in lateral and tail view.

(a) Lateral View (b) Tail View

Figure 2.1: The Guanay II AUV [13]

2.1.2 Dagon AUV

Dagon AUV is a hovering AUV developed in 2010 which is purposed specifically for algorithm evaluation and visual mapping. It weighs around 70 kg in air and has a depth rating of more than 150 meters. To counter high underwater pressure, strong metal alloy material has been used to develop the pressure hull body. The AUV has five DC propellers for propulsion system which two of them are for forward thrusting, two for up-thrusting and one more for side thrusting. It can be operated in tethered mode with fiber-optic link or untethered mode with acoustic modem, depends on types of analysis. The water depth of the AUV can be measured by pressure sensor and Doppler velocity log. The orientation of the AUV is controlled by Altitude Heading Reference System (AHRS) and fiber-optic gyroscope. For visual mapping purpose, scanning sonar as well as the high resolution stereo cameras have been implemented in the AUV. Intel i7 processor based controller has been selected for high processing ability in the basic operation of the AUV as well as analysis activity in several experiments. Two block of Lithium-Ion battery with total capacity of 1.5 kWh has been selected to power up the AUV [9]. Figure 2.2 shows the hardware of the Dagon AUV in different condition.

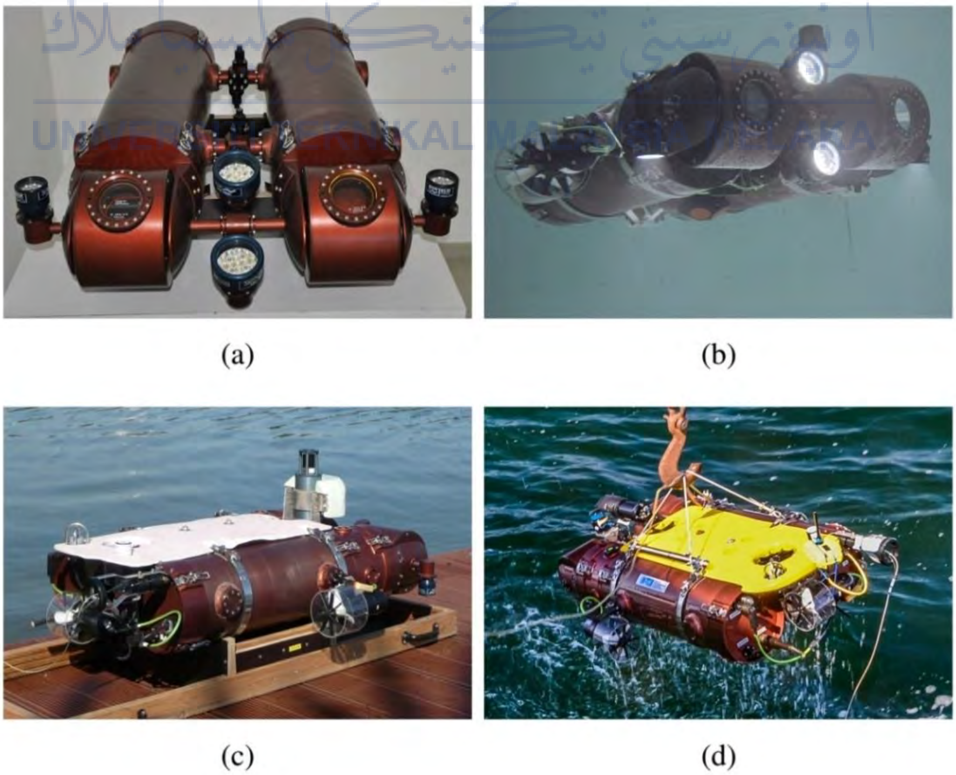

Figure 2.2: The Dagon AUV [9]

2.1.3 Stingray AUV

The Stingray AUV is a lower cost developed AUV. Unlike some common shapes of AUV such as torpedo shape and cube shape, the Stingray AUV is designed in stingray-liked biomimetic shape to achieve improved hydrodynamic. The AUV is stressed on lightweight and compact in size. Hence, lighter material and components has been used for development. In hull design, the carbon fiber material has been selected and the wings and tail are developed by 3D printing. The AUV is propelled by five propellers, two of them for forward thrusting and another three are embedded into the wings and tail for up-thrusting propulsion to stabilize vehicle orientation. To measure the depth of the AUV, a pressure sensor has been implemented. A 3-axis solid state compass which consists of magnetometer and accelerometer has been utilised to determine the orientation of the AUV. The AUV has been built in with two cameras for front and bottom view of surroundings. Besides, hydrophone has been implemented as an alternative for sonar sensor for mapping analysis. The AUV is powered by Lithium Polymer battery with two different rated voltages, one as power supply for controller and another one for propulsion system [14]. Figure 2.3 illustrates the model of the Stingray AUV.

Figure 2.3: The Design of the Stingray AUV [14]

Table 2.1 summarised the specification in design and basic construction of the AUVs in the three journals discussed previously.

Table 2.1: Summaries of Specification in Design and Basic Construction of AUVs

INTENSIVE LITERATURE REVIEW			
CRITERIA	JOURNALS		
	Design and Construction of the GUANAY-II Autonomous Underwater Vehicle [13]	Two Years of Experiments with the AUV Dagon - a Versatile Vehicle for High Precision Visual Mapping and Algorithm Evaluation [9]	The Stingray AUV: A Small and Cost-Effective Solution for Ecological Monitoring [14]
Name	Guanay II	Dagon	Stingray
Length x Width (m)	2.3 x 0.32	0.7 x 0.6	N/A
Mass (kg)	90	70	10
Depth Rating (m)	30	150	N/A
Endurance (hrs)	5	8 to 10	N/A
Hull Material	Outer: fiberglass Inner (Watertight module): Aluminum-6063 - Dimension: 1.1m x 0.25m - Thickness: 5mm	ALMg4,5Mn and AlMg3 - coating is a red coloured hard-coating	Small, lightweight, carbon fiber shell with a biomimetic design

Controller	Aewin PC104+ embedded computer, model PM6100	Two embedded PC system - Intel i7 Duo-Core 2.8GHz	Kontron ETX-CD (PC104-based) - Intel Core 2 Duo with 1.2GHz.
Power Supply	24V Nickel-Cadmium Batteries - Total Capacity: 21Ah - Mornsun DC-DC converter to supply 5V and 12V	Two 14.7 V, 50 Ah Lithium-Ion Battery - Rated Voltage: 29.3 V - Total capacity: 1.5 kWh	4 Ah 14.8 V lithium polymer battery (Controller) 8 Ah 11.1 V lithium polymer battery (Propeller)
Depth Control Sensor (Buoyancy)	GEMS 2200 Series General Purpose Pressure Transducer - Pressure Range: 0 to 6 bar	Desert-Star SSP-1 pressure sensor - Depth Range: 0-344m	SSI Technologies P51-15-S-B-I36-4.5V-R pressure sensor - Output voltage: 0.5 - 4.5 V - Pressure Range: 101 - 203 kPa - Resolution: 2.44 mm in water
Obstacle Avoidance/Visual Mapping Sensor	N/A	Micron DST Scanning Sonar - Range: 2-75m	Aquarian Audio H1a Hydrophones
Communication System	TMOD-C48 Radio Link Modem - Frequency: 403-470 MHz - Transmission Speed: 4800bps - Power: 0.1-0.5W - Max Range: 10km	Seacon Fiber-optic cable link - Diameter: 1.6 mm - Tensile Strength: 1200 N - Support full-duplex Gigabit Ethernet over 20 km length Desert-Star SAM-1 Acoustic Telemetry modem	Nav Module via TCP protocol Labjack Data Acquisition Card

Propulsion System	Main: Seaeye SI-MCT01-B brushless thruster - Voltage Input: 24V DC - Maximum force: 110N - Power: 300W - Speed: 960rpm	Five 150W brushless thrusters - 3.5 kg bollard thrust	Main: Two Graupner 2358 Voith-Schneider - managed by Scorpion Commander 45 A electronic speed controller
	2 Side: Seabotix BTD150 thrusters - Voltage Input: 24V DC - Maximum force: 25N - Power: 80W		
	Upthruster: Festo CRDNG-100-PPV-A Pneumatic Stainless Cylinder - Displacement 1500cm3 - Lineal electric actuator 200mm, 3kN power), controlled by H-bridge	BLDC V1.3 (FPGA-based) motor control electronics - Motor controller - High accuracy at low RPM	Upthruster: Three Scorpion 22mm brushless motor - managed by Castle Sidewinder 25 A electronic speed controller
Camera	N/A	2 Prosilica GE1900C GigE Camera - Stereo - Resolution: Full HD - can be rotated within 270 degree	Remote Ocean Systems CE-X-18 underwater camera
		4 Bowtech LED800/1600 Underwater	Inuktun FireEYE underwater camera

Navigation System	GPS: Magellen DG14 receiver (SBAS) - Accuracy: 0.8 degree GPS Antenna: Wi-Sys WS3910 Digital Compass - Resolution: 0.1 degree 3-axis altitude indicator	XSens MTi Altitude Heading Reference System - for Pitch and Roll axes using gravity vector KVH DSP-3000 single axis Fiber Optic Gyroscope - for Yaw axis using magnetic field Teledyne RDI Explorer DVL EXP600 (velocity log) Desert-Star VLT-3 Long Baseline Transponder Micron NAV USBL transponder - max area: 500m x500m	Ocean Server OS-3000 3-axis solid state compass
Advantages	- Good in hydrodynamic - High accuracy in coordination system	- Prolong power endurance - Good in visual imaging application - Precise to avoid obstacle	- Cost lower to be built - Lightweight and small in size - Good in hydrodynamic - Good in image capturing
Disadvantages	- Total mass is heavy - Expensive to be constructed - No obstacle avoidance mechanism	- Very expensive to be developed	- High power consumption - Less effective in avoiding obstacle

2.2 Light Detection of Light Emitting Diode (LED) as Photodiode

2.2.1 Journal: An Optical Sensing Approach Based on Light Emitting Diodes

This journal is about the analysis on the performance of light emitting diode (LED) as the photodetector in a simple optical sensing technique. The paper cited a few journals showing that the common LED can actually function as a spectrally selective photodetector. LED can actually perform well to detect light which has shorter wavelength than the light it emits. For example, a LED that emits greenish-yellow light which has the peak wavelength of about 555 nanometres can detect green light which has the peak wavelength of about 525 nm with over the of 50 nanometres spectral width. Most of the LEDs have the ability to detect a relatively narrow band of wavelengths with different sensitivity. LED sensing can act photodiode in two sensing modes which are photovoltaic and photoconductive modes. Photovoltaic mode is where the LED can produce an output voltage when it exposed to light, whereas photoconductive mode is where the LED's electrical conductivity of a circuit is controlled with the presence of light. This paper suggested the optical sensing technique in photoconductive mode; either used two LEDs or even a single LED as the light emitter and detector, depends on the electrical configuration with the microcontroller. The experiment results were favourable and proving that such optical sensing technique which is fully software configured, eliminate the needs of operational amplifier, ADC and some external components in the circuit [15].

2.3 Absorption Spectrum of Light in Water

2.3.1 Journal: Absorption Spectrum (380 – 700 nm) of Pure Water. II. Integrating Cavity Measurements

This paper is about the analysis on attenuation of light at different wavelengths in pure water. Experiments have been conducted to analyse the absorption spectrum at wavelengths from 380 nanometres to 700 nanometres in pure water at constant temperature of 22°C from measurement using integrating cavity technique. The operation of Integrating Cavity Absorption Meter (ICAM) contributed the analysis with high absolute accuracy on experiments for absorption coefficient of pure water which provided reliable results and critical evidence. Figure 2.4 shows the analysis of absorption spectrum in pure water at wavelengths from 380 nanometres to 700 nanometres at constant temperature of 22°C. Note that the maximum absorption is in the red with wavelength at 700 nanometres and the graph tends to continue increasing even in wavelength greater than 700 nanometres. In contrast, absorption is minimal in the blue with wavelength at 418 nm [16].

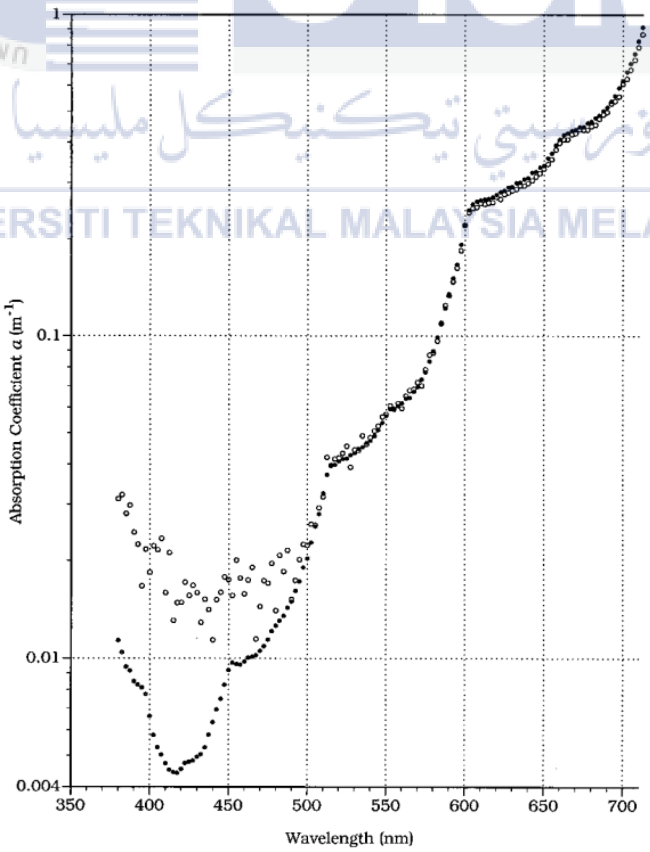

Figure 2.4: Analysis on Light Absorption Spectrum in Pure Water [16]

2.4 Summaries of Literature Reviews

To summaries, the journals which are mentioned in the literature review are good enough and informative. In design and construction of AUV, Guanay II is contributed as the hull design in this project because the hull is easier in design without sacrifice the stability in hydrodynamic. The Dagon AUV is better in overall performance, but it is relatively very expensive. Thus, prolonged battery endurance characteristic of Dagon only will be considered. In the design, the Stingray AUV gives more in flavour as it is lightweight, smaller in size and cheaper to invest. Indeed, the Stingray meets the first objective requirement.

In selection of suitable sensor, Journal 2.2.1 and Journal 2.3.1 has been reviewed and chosen. In Journal 2.2.1, Light Emitting Diode (LED) is discussed for detecting light instead of emitting light. In Journal 2.3.1, absorption spectrum of light in water has been discussed. Blue or violet light is suitable when chosen light emitter for underwater purpose because these lights are attenuated less in water. As a result, 405nm Laser sensor has been developed which has been discussed in Chapter 4 Results and Discussions.

CHAPTER 3

METHODOLOGY

This Final Year Project will require multi-stages development prior completion. The stages are hardware development, software development, experiments and analysis, and final report writing as shown in Figure 3.1. A Gantt chart has been attached in Appendix A to show the progress and planning the project working flow.

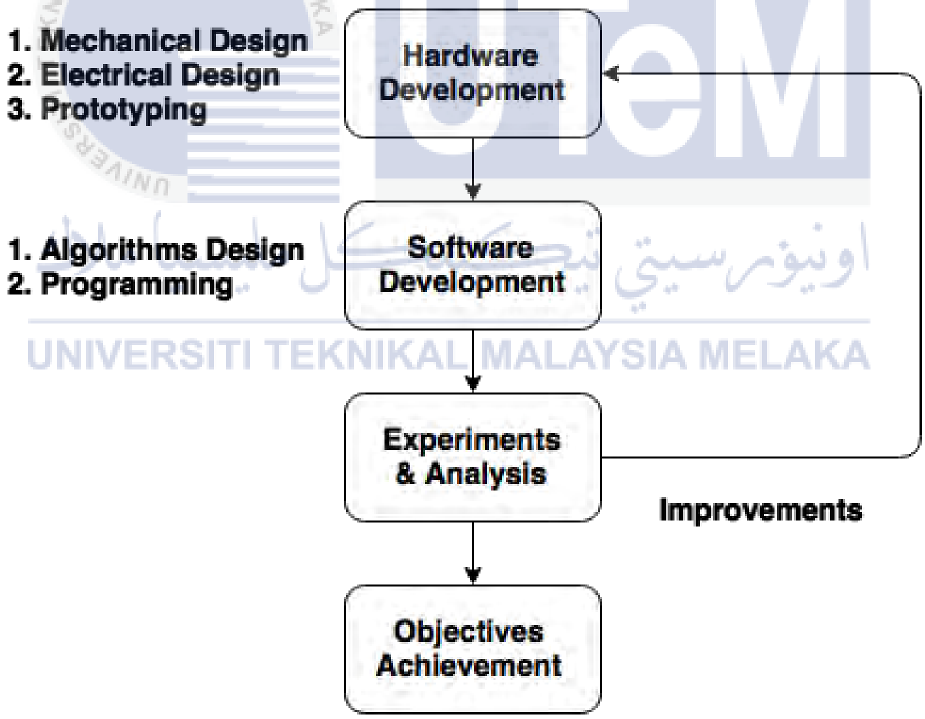

Figure 3.1: Flow Chart of Methodology

3.1 Hardware Development

In hardware development, mechanical design and electrical design has been done before prototype is being developed.

3.1.1 Mechanical Design

The hardware was designed in SolidWorks CAD software. The prototype was decided to be designed in torpedo shape which is symmetrical for left and right side for good hydrodynamic. To achieve miniature size, the prototype was targeted to be designed less than 0.5 meter in length, 0.55 meter in width and 5kg in weight. As a result, the prototype was designed for 0.35 meter in length and 0.375 meter in width. Plastic was selected as the material for the hull design because it is cheap and durable. Figure 3.2 shows the isometric and three plane views of the prototype design.

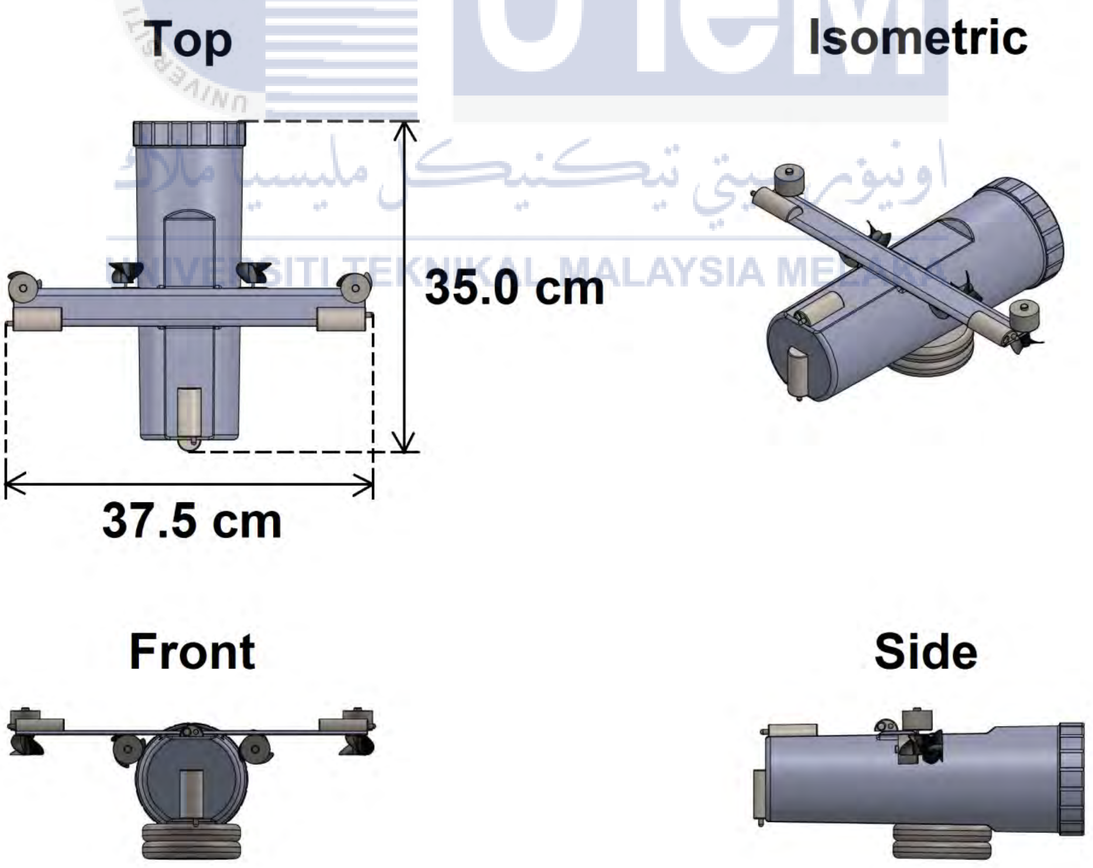

Figure 3.2: Isometric and Three Plane Views of Prototype Design

The prototype was designed to have four underwater sensors for detection of obstacle. These sensors were mounted to front, left, right and bottom of the hull. Besides, a pairs of wings was mounted at the middle top of the hull to increase the stability of the prototype. Four propellers were attached to the wings for propulsion system of the prototype: two of them as vertical thrusters and another two as horizontal thrusters. The propulsion system was designed well to control the orientation of the prototype which includes 3-axis coordination as well as yaw-axis and roll-axis rotation.

In addition, weight was mounted to the middle bottom of the hull. The purpose is the lower the centre of gravity of the prototype. The farther the distance between centre of gravity and centre of buoyancy, the more stable the prototype is even if it is being tilted by water waves.

3.1.2 Electrical Design

The embedded system in the prototype was designed. There are 3 parts in the embedded system, which are microcontroller, input module and output module. Figure 3.3 shows the overview of the embedded system design in block diagram. Besides, the schematic diagram of the circuit design has been attached in Appendix B.

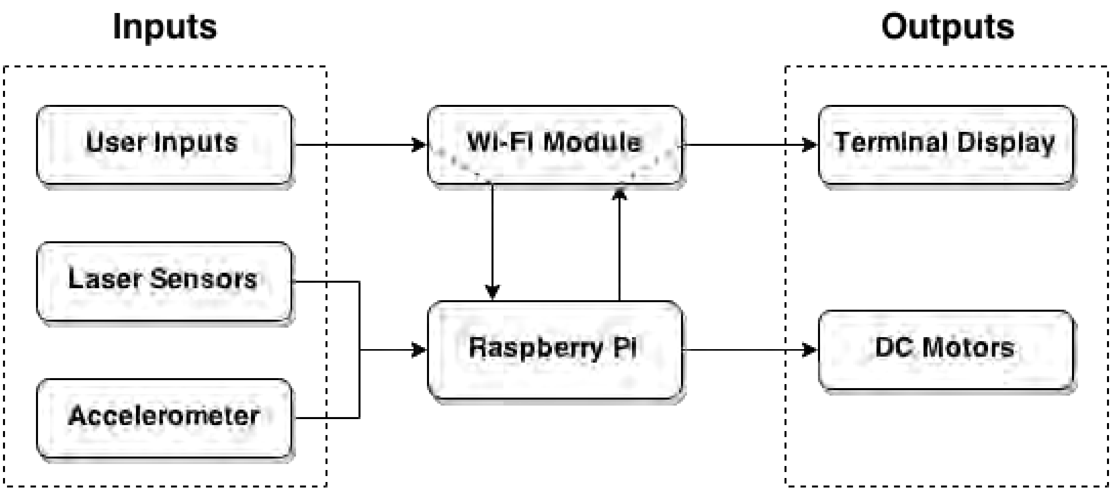

Figure 3.3: Block Diagram of the Embedded System Design

Raspberry Pi Model B+ has been chosen as the micro-controller the prototype, because it has high processing power (700 MHz) which has the ability to deal with a large number of inputs and outputs in real time process. Besides, it consists of 40 General Purpose Input Output pins which is sufficient to be utilised.

For wireless connectivity, Adafruit miniature Wi-Fi module was selected a modem device for Raspberry Pi. Note that there are only a few Wi-Fi adapters available in markets which are fully compatible with Raspberry Pi. Figure 3.4 shows the Wi-Fi module plugged in the USB port of Raspberry Pi to provide wireless connectivity.

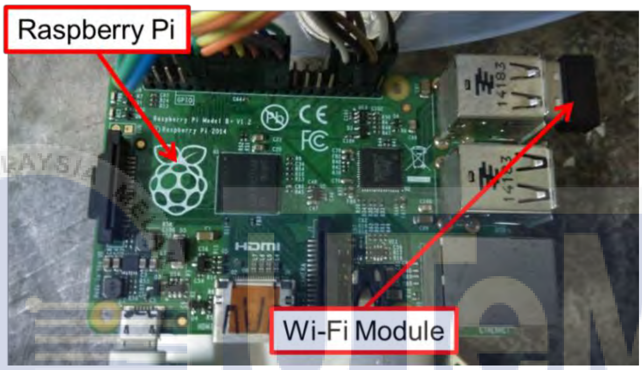

Figure 3.4: The Raspberry Pi and Adafruit Miniature Wi-Fi Module

Mitsumi M31E-1 DC brushless motor was selected as the propeller. With specification of 6V rated voltage and 150mA rated current, the motor were able to deliver sufficient torques to the propeller blades in underwater. The motor can drive up to 3000rpm rated speed without load. Figure 3.5 shows the Mitsumi M31E-1 DC brushless motor with propeller blade mounted at the wings of the prototype.

Figure 3.5: Mitsumi M31E-1 DC Brushless Motor with 3.9mm Propeller Blade

Several sensors have been tested by conducting experiment. These sensors were ultrasonic sensor, infrared sensor and laser sensor. After analysis from results, laser sensor was chosen due to it can measure desired distance better than other sensors in underwater. The laser sensor consists of 2 components which were a 405nm 20mW focusable laser dot module as emitter and a typical 5mm blue LED as receiver. The laser sensor works in the same way similar to infrared sensor, which emit blue violet (405nm wavelength) laser beam and receive the reflected laser beam in certain level of intensity. Figure 3.6 shows the Laser sensor which comprises a Laser dot module and a blue LED fasten at rounded transparent Perspex.

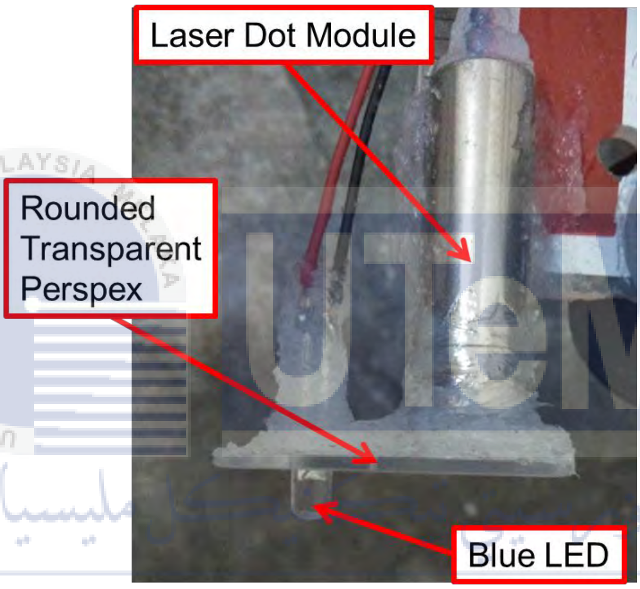

Figure 3.6: Laser Sensor

A 3-axis accelerometer has been used to take input from angle measurement of roll-axis of the prototype for tilt balancing. Figure 3.7 shows the accelerometer.

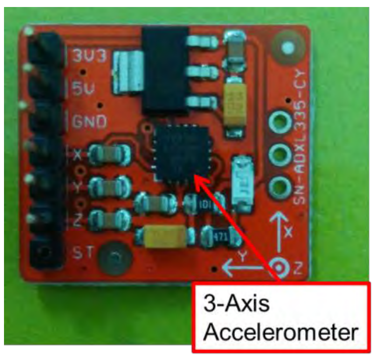

Figure 3.7: 3-Axis Accelerometer

To power up the prototype, two Xiaomi 10400mAh power banks with 5V output voltage were used; one of them as the power supply for the micro-controller and another one as the external power source to all propellers. The output current delivered by the power bank can reach 2.1A. Figure 3.8 shows the power bank.

Figure 3.8: Xiaomi 10400mAh Power Bank

In the electrical circuit, a MCP 3008 analogue digital converter (ADC) was needed. This is because there is no ADC built in the Raspberry Pi. The MCP 3008 ADC has 8 channels for analogue inputs and provides 10-bit resolutions. Its sampling rate is up to 200k samples per second. Besides, a 3VDC 5-pins electromechanical relay has been used as a switch of the power supply for DC motors. In addition, 4 set of L293D H-bridge motor drivers has been used; where 2 of them for controlling 4 DC motors, 1 of them for controlling 4 laser modules and another 1 for triggering the relay.

3.1.3 Prototyping

The prototype development was completely DIY. The costing to develop the prototype has been summarised and attached in Appendix C. A bottle was selected as the hull of the prototype. The bottle can contain up to 2 litres of water. The size of the bottle was very important because it must have sufficient space to envelope all electrical components and at the same time maintain its miniature scale. The bottle cap has a rubber band at the end of the track. The bottle was tested several times in underwater to ensure the bottle is capable of fully watertight. Figure 3.9 shows the bottle cap with rubber band in the track.

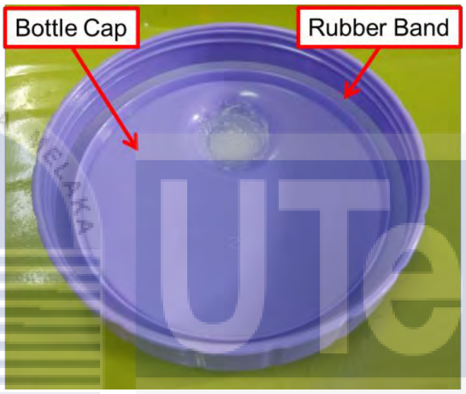

Figure 3.9: Bottle Cap with Rubber Band

Two dumbbells with a total weight of 1kg were fastened together and attached at the middle bottom of the hull. Besides, 20 cent stacks has been adhered on both power banks in increase the weight of the prototype. Trial and error method has been used to test the buoyant force of the prototype in underwater by adding or removing 20 cent one by one.

To make laser sensors, 39mm rounded transparent Perspex was used to fasten both laser dot module and blue LED. The Perspex was drilled by 5mm drill head for housing the blue LED. Figure 3.6 shows the Laser sensor which comprises a Laser dot module and a blue LED.

Each motor is fixed with a nylon propeller blade. The propeller blade has 3 blades with a diameter of 3.9cm. It fits to the shaft of the motor which is 2mm in diameter. Figure 3.5 shows with propeller blade fasten with the motor mounted at the wings of the prototype.

The Sensors and propellers were sealed by using clear silicon sealant to make sure these components were completely waterproof. It is necessary to wait for at least 6 hours after the sealant is applied for fully bonding.

The 30 cm long plastic ruler was selected as the wings and fastened at the middle top of the hull. At the position of 0cm and 30cm of the ruler scale, two small holes have been made by 2mm drill head and 2 vertical propellers were mounted on the small holes with screw. In addition, at the position of 8cm and 22cm of the ruler scale, two small holes have been made by 4mm drill head and 2 small L-shaped metal bracket were fasten to them with screw and 2 horizontal propellers were mounted on the metal bracket with screw.

The top surface the hull was drilled by 1mm drill head to form a total of 24 small holes, to allow all sensors and propeller outside the hull to be connected with the micro-controller in the hull by 1mm single core wires. These small holes were then sealed from inside and outside of the hull. Figure 3.10 shows the top view of the prototype which explains the locations of the plastic ruler, Laser sensors and DC brushless motors, and wire connection via 24 small holes.

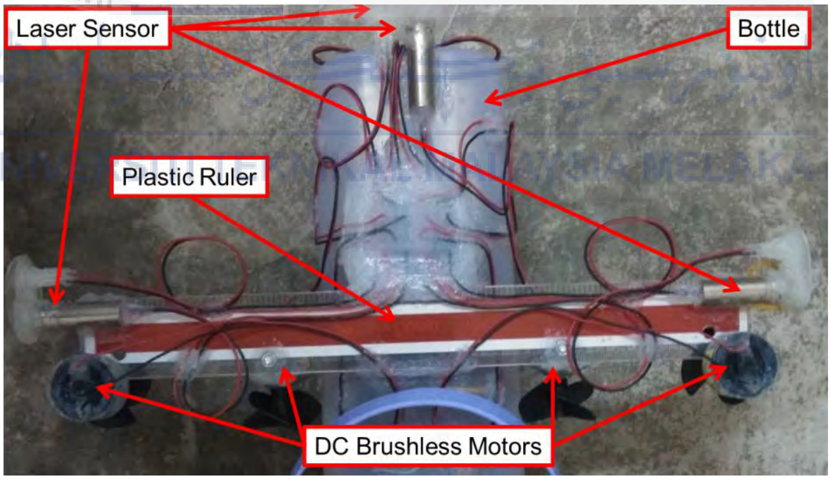

Figure 3.10: Top View of the Prototype

3.2 Software Development

3.2.1 Obstacle Avoidance and Depth Control Algorithms Design

The goals of designing algorithms are to make decision on how to avoid the obstacle and maintain desired position level of the prototype from the floor simultaneously. To perform obstacle avoidance mechanism, laser sensors which mounted at front, left and right of the hull played the important role as the eyes of the prototype. In addition, laser sensor which mounted at the bottom of the hull was measuring the water depth from the prototype.

To design algorithms, the first thing to be considered is the distance between the front of the prototype and obstacle. When the prototype comes near to obstacle, it needs to decide whether turn left or right and even reverse when necessary. If the space from left side is greater than right side, the prototype will turn left to locate itself in bigger space, and vice versa. If the prototype is too near to the obstacle, it needs to reverse to prevent being bang into obstacle. On the contrary, the prototype will move forwards if there is no obstacle in front of it. While forwarding, it will slightly turn right if left side is too near to obstacle, and vice versa.

The second thing to be considered is the depth control of the prototype in underwater. The prototype will submerge until certain depth level in underwater. When reaching the specific depth level, it will stop moving downwards and try to maintain its position level. This process can be done by vertical thrusting to move downwards and buoyant force to move upwards.

3.2.2 Programing

The operating system running in the Raspberry Pi was Raspbian, based on Debian system which uses Linux kernel. The language used to compose the programme was C language. To interface with the Raspberry Pi's GPIOs, WiringPi library need to be installed to the Raspbian system. All the coding written has to be compiled by GCC compiler, which is pre-installed in the Raspbian system. Basically, a programme was written based on the algorithms created to take input reading of distance measurement from laser sensors and control the outputs of 4 DC motors includes the direction and Pulse Width Modulation. Both algorithms as mentioned above can be done simultaneously and looped rapidly by running program in Raspberry Pi due to the microcontroller has high processing power. Once the program is executed, it loops for 500 counts and then stops for safety purposes. The programme coding has been attached in Appendix D.

3.3 Experiments and Analysis

The purpose of conducting experiment is to achieve objective. Table 3.1 shows the mapping of all experiments with the related objectives of this FYP. There are 7 experiments which relate to the 3 main objectives.

Table 3.1: Mapping of All Experiments with Related Objectives

Objective \ Experiment	1	2	3	4	5	6
1	✓	✓				
2					✓	✓
3			✓	✓	✓	✓

Experiment 1 has been carried out to test the performance of the Raspberry Pi when controlling the DC motor using PWM function. Experiment 2 has been carried out to test the functionality the DC brushless motor in different types of water. Experiments 3 and 4 have been carried out to analyse the performance of Ultrasonic and Infrared sensors respectively on distance measurement in air and underwater environment. For Experiment 5, light detection of blue LED with different wavelength has been analysed. For Experiment 6 and 7, the performance of Laser sensor has been analysed on distance measurement and obstacle detection for 5 types of obstacle in air and underwater environment. All experiments have been conducted in the condition as discussed in Chapter 1 scopes.

For Experiment 3 to 6

For Experiment 3 to 6, overview of the equipment is described as follows:-

a. Tap Water Pool

There were two types of pool used in experiments, which were rectangular and rounded in shape. For rectangular pool, the dimension is 2.57m length × 1.35m width × 1.00m height, whereas rounded tap water pool is 1.83m diameter × 0.38m height. Figure 3.11 shows the rectangular tap water pool and Figure 3.12 shows the rounded tap water pool.

Figure 3.11: Rectangular Tap Water Pool

Figure 3.12: Rounded Tap Water Pool

b. Measuring Tape

The measuring tape as in Figure 3.13 was used in the experiments to measure distance of the obstacle from the sensor. It has a length of 3.5m.

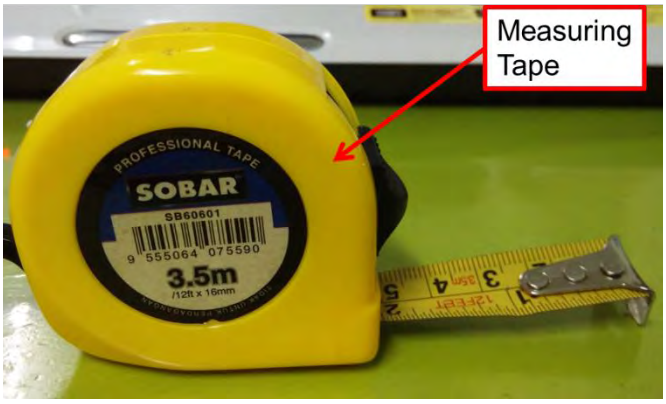

Figure 3.13: Measuring Tape

c. Station (PC)

The station was a computer which able to connect wirelessly with the Raspberry Pi to triggers program and obtains reading from the sensors. Readings obtained were in resolution steps after analogue output voltage from the sensor were converted to digital form via ADC in Raspberry Pi. Figure 3.14 shows the station.

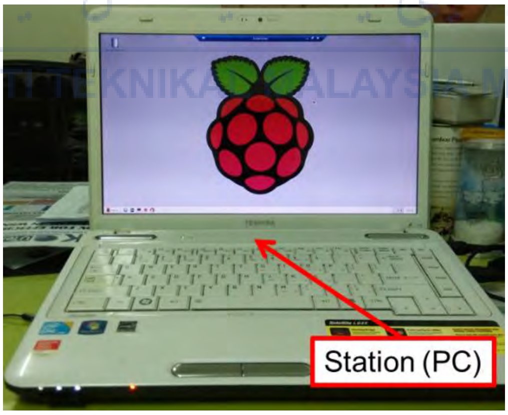

Figure 3.14: Station (PC)

d. Multimeter

Multimeter as shown in Figure 3.16 was used in the experiments to obtain analogue readings from sensors.

e. Sensors

There were three types of sensors to be tested in the experiments, which were Ultrasonic sensor, Infrared sensor and Laser sensor as shown in Figure 3.15 to 3.17.

Figure 3.15: Ultrasonic Sensor

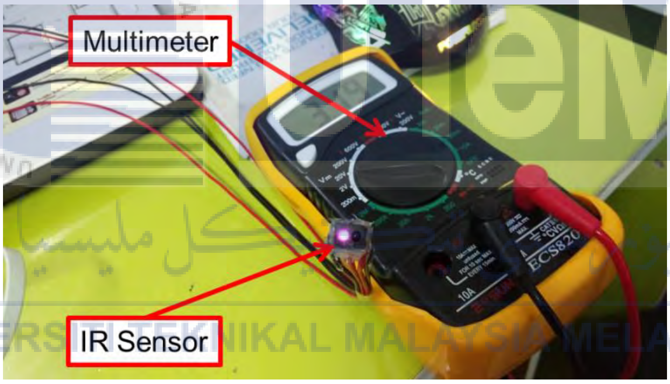

Figure 3.16: Infrared Sensor and Multimeter

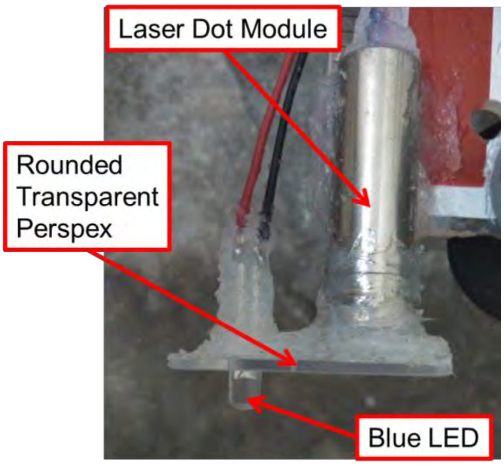

Figure 3.17: Laser Sensor

f. Obstacle

Obstacle was basically a 30cm × 30cm transparent Perspex with a protractor attached on it. The Perspex was framed so that it is perpendicular to the floor. Weight has been added to the bottom of the frame to lower its centre of gravity for stability of the obstacle. There were five types of obstacle to be used in the experiments, which were transparent Perspex, shiny white paper, white paper, grey paper and black paper as shown in Figure 3.18 and 3.19. Each paper was pasted on the transparent Perspex as the particular colour of obstacle. Experiment 5 and 6 were repeated after obstacle was changed from one to another.

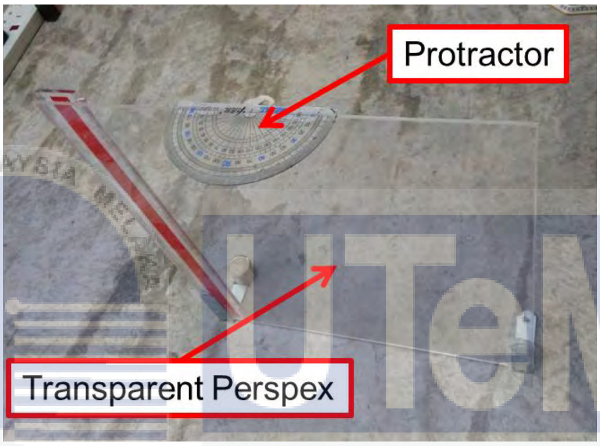

Figure 3.18: Transparent Perspex and Protractor

Figure 3.19: Shiny White, White, Grey and Black Papers

g. Protractor

Protractor was attached perpendicularly on top of the obstacle as shown in Figure 3.18 to make sure the obstacle surface is perpendicular to the sensor.

For Experiments 3 to 6, calculations has been done on mean and standard deviation of 5 data collected for every distance, based on the formulas as follows:

$$Mean, \mu = \frac{V_i + V_{i+1} + V_{i+2} + \cdots + V_N}{N} = \frac{V_1 + V_2 + V_3 + V_4 + V_5}{5} \quad (3.0)$$

$where \quad V_i = Output\ Voltage\ in\ Data\ i \quad and \quad N = Number\ of\ Data\ Set$

$$Standard\ Deviation, \sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(V_i - \mu)^2} = \sqrt{\frac{1}{5}\sum_{i=1}^{5}(V_i - \mu)^2} \quad (3.1)$$

Therefore,

$$\sigma = \sqrt{\frac{(V_1-\mu)^2+(V_2-\mu)^2+(V_3-\mu)^2+(V_4-\mu)^2+(V_5-\mu)^2}{5}} \quad (3.2)$$

3.3.1 Experiment 1: Controlling DC Brushless Motor (FYP 1)

The purpose to conduct this experiment is to test the performance of the Raspberry Pi when controlling the DC motor using PWM function. This experiment is related to the Objective 1 of this FYP.

Objective: To control a DC motor with hardware PWM function in forward and reversed directions using Raspberry Pi.

Parameters:
Manipulated Variable: Time
Responding Variable: Output voltages of the DC motor obtained from the multimeter

Equipment:
1. Raspberry Pi
2. DC brushless motor
3. Plastic Blade
4. L293D motor driver
5. Multimeter

Procedures:

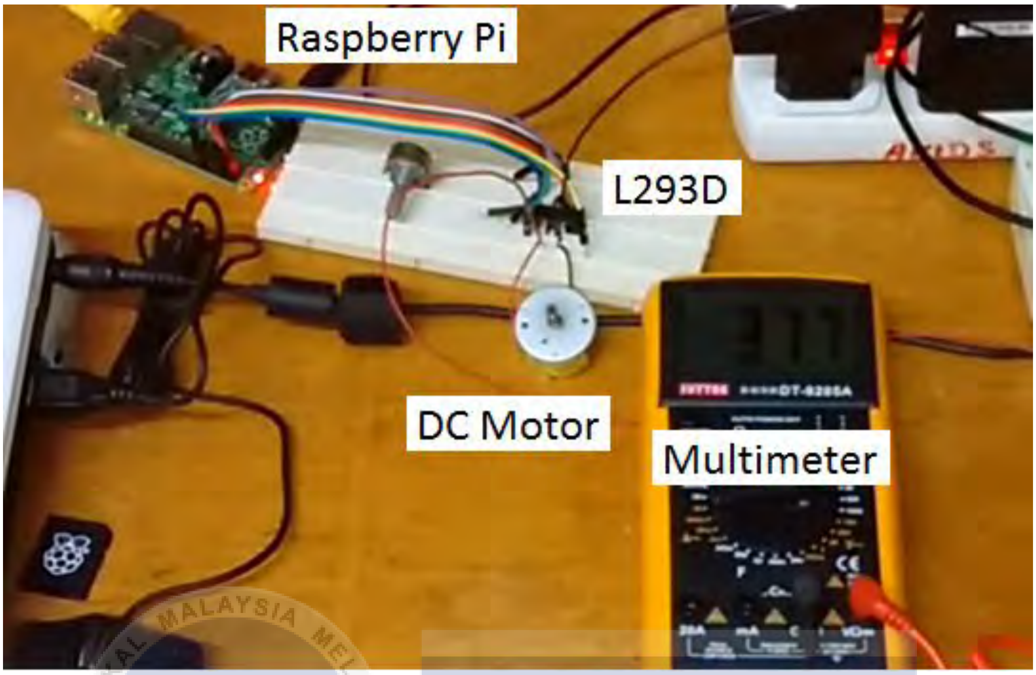

Figure 3.20: Set Up of Experiment 1

1. The experiment was set up as shown in Figure 3.20.
2. The Raspberry Pi was programmed to test the hardware PWM function.
3. A DC brushless motor was connected to appropriate GPIO of the Raspberry Pi.
4. A plastic blade was attached to the shaft of the DC motor.
5. The multimeter was connected parallel to the DC motor to measure PWM output voltage.
6. The programme was executed.
7. The direction of DC motor rotates were observed.
8. Video was recorded.
9. Table was tabulated after the experiment was conducted. The table was attached in Appendix E.
10. Results were analysed.

3.3.2 Experiment 2: Functionality of DC Brushless Motor in Water (FYP 1)

The purpose to conduct this experiment is to test the performance of the DC brushless motor in the water even though the DC motor is not waterproof. This experiment is related to the Objective 1 of this FYP.

Objective: To examine the functionality of DC brushless motor in different type of water.

Parameters:

Manipulated Variable: Time

Responding Variable:

1. Current of the DC motor obtained from the multimeter
2. Observation in water quality

Equipment:

1. Raspberry Pi
2. DC brushless motor
3. Glass of water
4. Salt
5. Multimeter

Procedures:

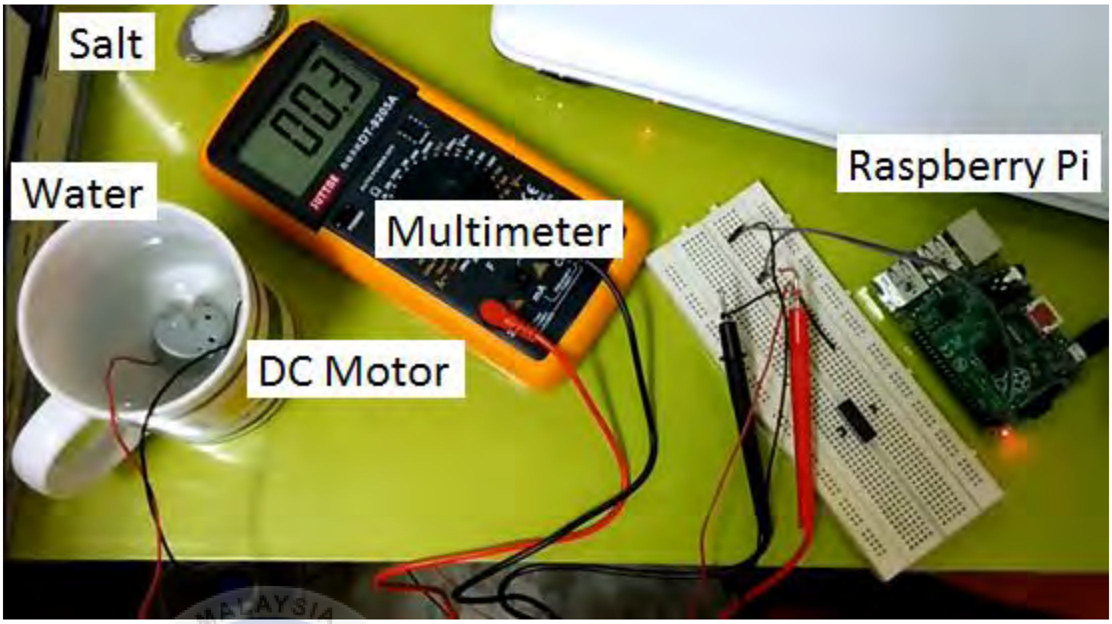

Figure 3.21: Set Up of Experiment 2

1. The experiment was set up as shown in Figure 3.21.
2. An unmodified DC Motor was placed into a glass of tape water.
3. The motor was powered by Raspberry Pi.
4. Current was measured by multimeter which was connected series to the DC motor.
5. The motor and water in the glass were observed and recorded for 15 minutes with every 1 minute interval.
6. Next, salt was added into the water.
7. Step 4 and Step 5 were repeated again.
8. Table 4.1 was tabulated after the experiment is conducted.
9. Results were analysed.

3.3.3 Experiment 3: Distance Measurement of Ultrasonic Sensor in Air and Underwater Environment (FYP 2)

The purpose of conducting this experiment is to test the distance measurement of obstacle from ultrasonic sensor in air and underwater. This experiment is related to the main Objective 3 of this FYP.

Objective: To analyse the performance of ultrasonic sensor on distance measurement in air and underwater.

Parameters:

Manipulated Variable:

i. Distance of the obstacle
ii. Types of medium (air and water)

Responding Variable: Output voltage from ultrasonic sensor, V

Equipment:

1. Ultrasonic sensor
2. Obstacle
3. Protractor
4. Raspberry Pi
5. 3.5 m measuring tape
6. Rectangular tap water pool
7. Station (PC)

Procedures:

Part A: Distance Measurement in Air Environment

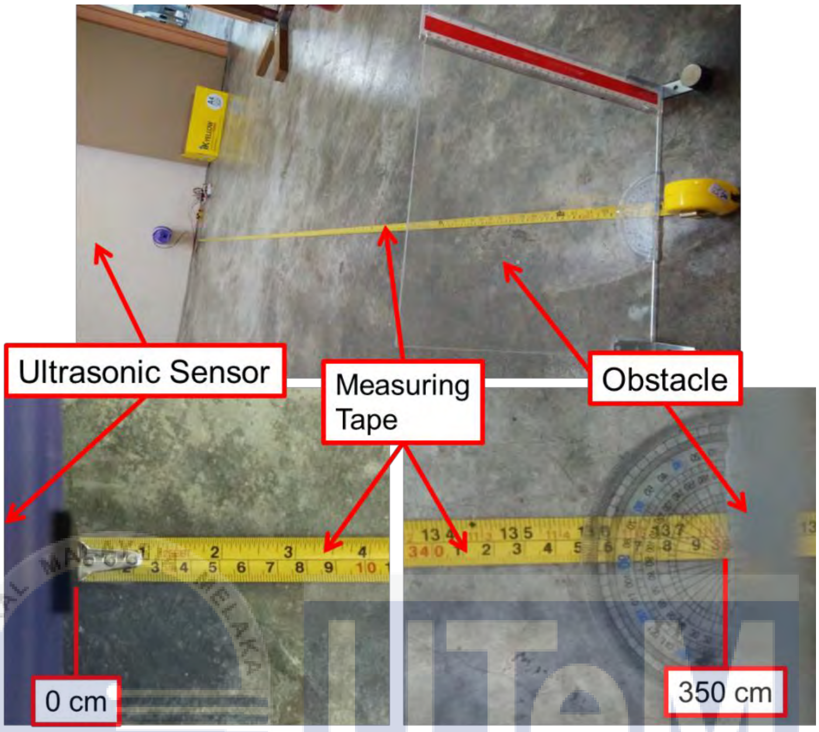

Figure 3.22: Set Up of Experiment 3 in Air Environment

1. First, the experiment was set up for air environment as shown in Figure 3.22. The experiment was carried out for 5 times.
2. Measuring tape was extended at least 3.5m and attached to the floor.
3. The ultrasonic sensor was fixed at the position of 0m and faced straight to the measuring tape.
4. Obstacle was placed perpendicular to the sensor with the aid of protractor at the position of 3.5m on the measuring tape.
5. The Raspberry Pi was connected the station to allow displaying sensor measurement from ultrasonic sensor in real time.
6. Program was executed and sensor measurement in term of output voltage was taken.
7. The obstacle was moved towards the ultrasonic sensor by 10cm and measurement was recorded.
8. Step 7 was repeated until the obstacle reached the position of 0.1m on the measuring tape.

9. Table was tabulated after the experiment was conducted. The table was attached in Appendix F.
10. The results were analysed. Mean, standard deviation, and root mean squared error were calculated to analyse the accuracy of data obtained.

Part B: Distance Measurement in Underwater Environment

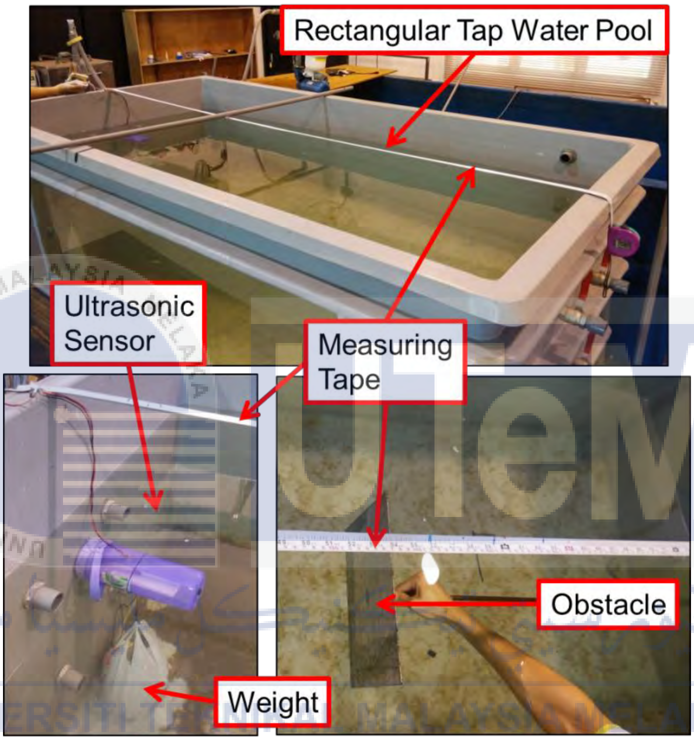

Figure 3.23: Set Up of Experiment 3 in Underwater Environment

1. First, the experiment was set up for underwater environment as shown in Figure 3.23. The experiment was carried out for 5 times.
2. Measuring tape was extended at least 2.5m and attached to the 2 opposite edges of rectangular tap water pool.
3. Ultrasonic sensor was submerged into water with the aid of weight. The sensor was fixed at the position of 0.3m and faced straight to the measuring tape.
4. Obstacle was held perpendicular to the sensor with the aid of protractor at the position of 2.1m on the measuring tape.
5. The Raspberry Pi was connected the station to allow displaying sensor measurement from laser sensor in real time.

6. Program was executed and sensor measurement in term of output voltage was taken.
7. The obstacle was moved towards the ultrasonic sensor by 10cm and measurement was recorded.
8. Step 7 was repeated until the obstacle reached the position of 0.4m on the measuring tape.
9. Table was tabulated after the experiment was conducted. Note that all distances in the experiment were deducted by 0.3m since the sensor was fixed at the position of 0.3m on the measuring tape. The table was attached in Appendix F.
10. The results were analysed. Mean, standard deviation, and root mean squared error were calculated to analyse the accuracy of data obtained.

Calculations

a. Output Voltage

The ultrasonic sensor is a digital module. Typically the sensor output digital value to the micro-controller. In order make comparison with analogue sensors such as Infrared and Laser sensors, formula for analogue output voltage has been derived from the typical formula. The formula for distance measurement of Ultrasonic sensor is shown as follows:-

In Air:

$$Distance\ in\ cm = \frac{Width\ of\ Echo\ Pulse\ in\ \mu s,\ T}{58} \tag{3.3}$$

$Let \quad Max. Effective\ Distance = 330\ cm$, due to limitation of sensor

$Max.\ T = 330 \times 58 = 19140\ \mu s$

$$Output\ Voltage = \frac{Width\ of\ Echo\ Pulse\ in\ \mu s,\ T}{19140} \times 3.3\ V \tag{3.4}$$

Where full PWM = 3.3V. Output Voltage can be taken from PWM pins in the Raspberry Pi.

In Water:

$$Speed\ of\ Sound\ in\ Water\ \cong\ Speed\ of\ Sound\ in\ Air \times 4.3$$

$$\frac{Distance\ in\ cm}{4.3} = \frac{Width\ of\ Echo\ Pulse\ in\ \mu s,\ T}{58}$$

$$Max.\ T = \frac{330}{4.3} \times 58 = 4455\ \mu s$$

$$Output\ Voltage = \frac{Width\ of\ Echo\ Pulse\ in\ \mu s,\ T}{4455} \times 3.3\ V \qquad (3.5)$$

Where full PWM = 3.3V. Output Voltage can be taken from PWM pins in the Raspberry Pi. Desired output voltage in particular distance also can be calculated.

b. Root-Mean-Square Error

To analyse the accuracy of the data collected, Root-Mean-Square Error has been calculated.

$$RMS\ Error = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(V_i - V_D)^2} = \sqrt{\frac{1}{5}\sum_{i=1}^{5}(V_i - V_D)^2} \qquad (3.6)$$

$$where \quad V_i = Output\ Voltage\ in\ Data\ i \quad and \quad V_D = Desired\ Output\ Voltage$$

Therefore, $RMS\ Error = \sqrt{\frac{(V_1-V_D)^2+(V_2-V_D)^2+(V_3-V_D)^2+(V_4-V_D)^2+(V_5-V_D)^2}{5}}$ (3.7)

3.3.4 Experiment 4: Distance Measurement of Infrared Sensor in Air and Underwater Environment (FYP 2)

The purpose of conducting this experiment is to test the distance measurement of obstacle from infrared sensor in air and underwater. This experiment is related to the main Objective 3 of this FYP.

Objective: To analyse the performance of infrared sensor on distance measurement in air and underwater.

Parameters:

Manipulated Variable:

i. Distance of the obstacle
ii. Types of medium (air and water)

Responding Variable: Output voltage from infrared sensor, V

Equipment:

1. Infrared sensor
2. Obstacle
3. Protractor
4. Multimeter
5. 3.5 m measuring tape
6. Rounded tap water pool
7. Station (PC)

Procedures:

Part A: Distance Measurement in Air Environment

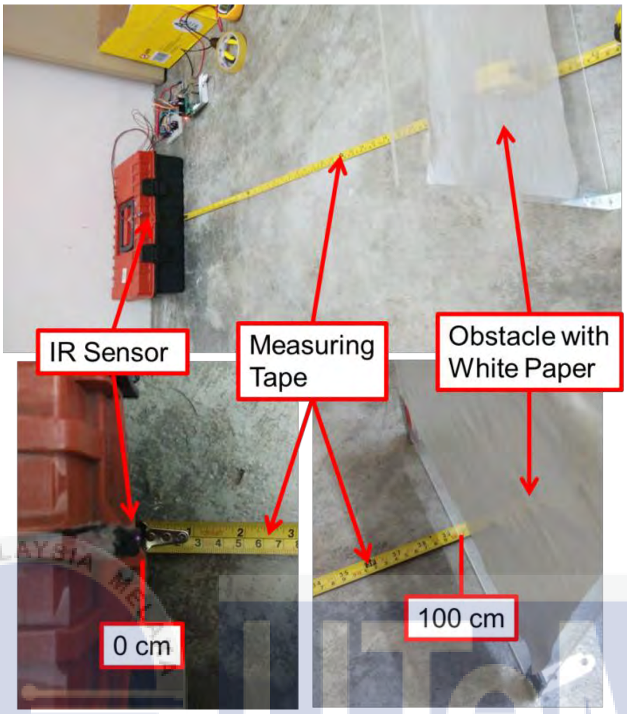

Figure 3.24: Set Up of Experiment 4 in Air Environment

1. First, the experiment was set up for air environment as shown in Figure 3.24. The experiment was carried out for 5 times.
2. Measuring tape was extended at least 1.0m and attached to the floor.
3. The infrared sensor was fixed at the position of 0m and faced straight to the measuring tape.
4. Obstacle was placed perpendicular to the sensor with the aid of protractor at the position of 1.0m on the measuring tape.
5. Multimeter was probed parallel to the receiver of the infrared sensor to measure output voltage in real time.
6. The obstacle was moved towards the infrared sensor by 10cm and measurement was recorded.
7. Step 6 was repeated until the obstacle reached the position of 0m on the measuring tape.
8. Table was tabulated after the experiment was conducted, as attached in Appendix G.
9. The results were analysed. Mean and standard deviation were calculated to analyse the accuracy of data obtained.

Part B: Distance Measurement in Underwater Environment

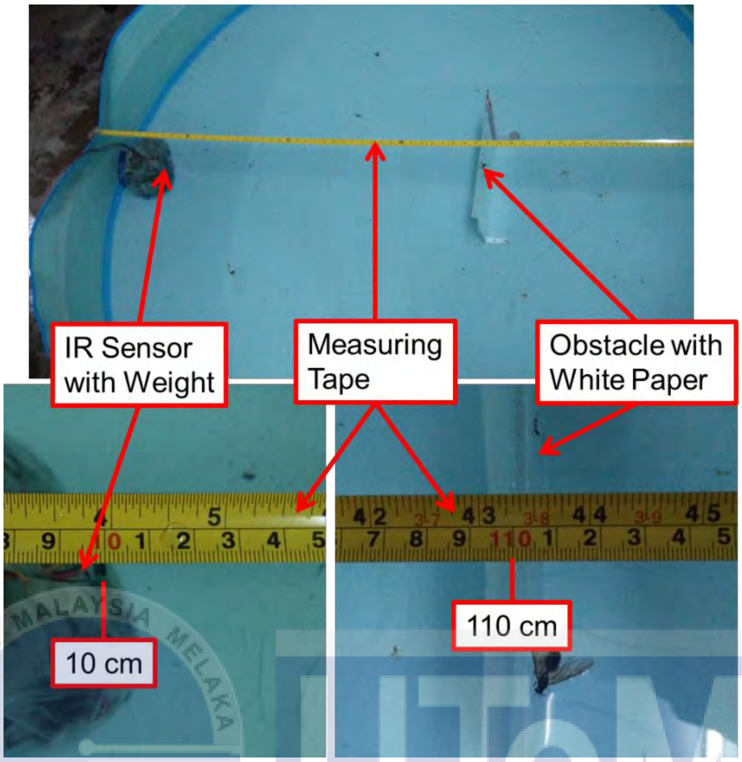

Figure 3.25: Set Up of Experiment 4 in Underwater Environment

1. First, the experiment was set up for underwater environment as shown in Figure 3.25. The experiment was carried out for 5 times.
2. Measuring tape was extended at least 1.8m and attached to the 2 opposite edges of rounded tap water pool.
3. Infrared sensor was submerged into water with the aid of weight. The sensor was fixed at the position of 0.1m and faced straight to the measuring tape.
4. Obstacle was held perpendicular to the sensor with the aid of protractor at the position of 1.1m on the measuring tape.
5. Multimeter was probed parallel to the receiver of the infrared sensor to measure output voltage in real time.
6. The obstacle was moved towards the infrared sensor by 10cm and measurement was recorded.
7. Step 6 was repeated until the obstacle reached the position of 0.2m on the measuring tape.
8. After that, the obstacle was moved towards the infrared sensor by 1cm and measurement was recorded.

9. Step 8 was repeated until the obstacle reached the position of 0.1m on the measuring tape.
10. Table was tabulated after the experiment was conducted. Note that all distances in the experiment were deducted by 0.1m since the sensor was fixed at the position of 0.1m on the measuring tape. The table as attached in Appendix G.
11. The results were analysed. Mean and standard deviation were calculated to analyse the accuracy of data obtained.

3.3.5 Experiment 5: Light Detection of Blue LED with Different Light Wavelengths (FYP 2)

The purpose of conducting this experiment is to test the functionality of the blue LED as a spectrally selective photodetector with different wavelengths of light. This experiment was conducted to validate the findings in Journal 2.2.1. This experiment is related to the main Objective 2 and 3 of this FYP.

Objective: To analyse the functionality of blue LED as a spectrally selective photodetector with presence of different wavelengths of light.

Parameters:
Manipulated Variable: Wavelength of light
Responding Variable: Output voltage from blue LED, V

Equipment:
1. Blue LED
2. Raspberry Pi
3. Station (PC)
4. Visible light spectrum software with adjustable wavelengths in http://academo.org/demos/wavelength-to-colour-relationship/

Procedures:

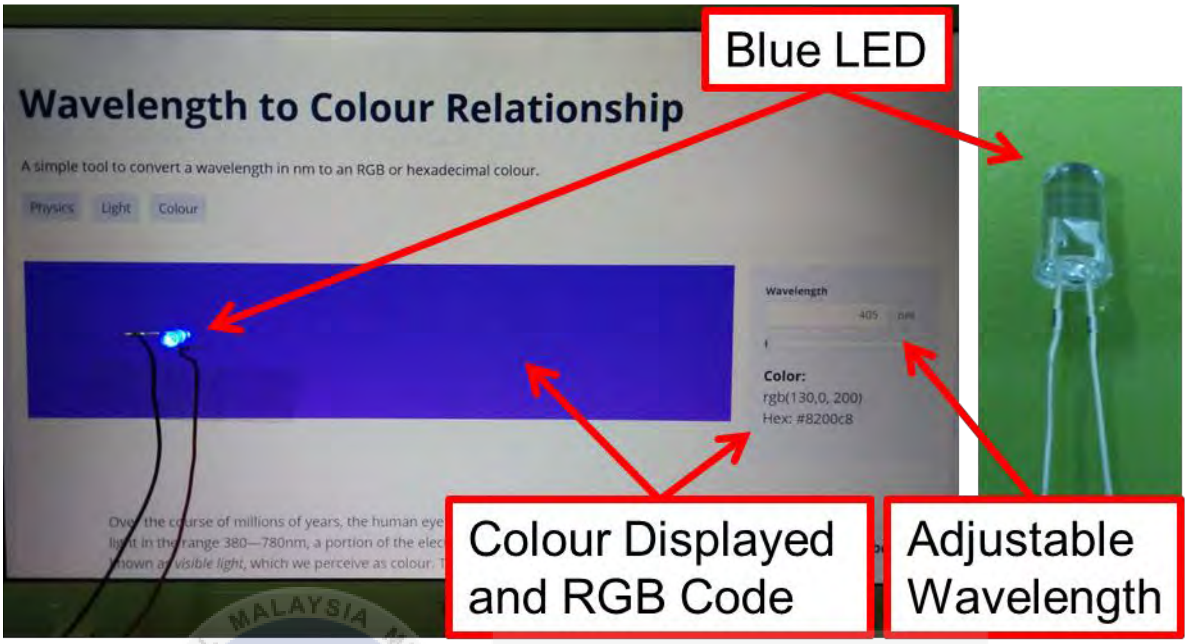

Figure 3.26: Set Up of Experiment 5

1. First, the experiment was set up as shown in Figure 3.26. The experiment was carried out for 5 times.
2. A common blue LED was used as a photodetector. The terminal of the LED was wired to Raspberry Pi. Then, the blue LED was fastened on the the display of the station.
3. The Raspberry Pi was connected the station to allow displaying output voltage reading from blue LED in real time.
4. Visible light spectrum software was utilised to expose different wavelengths of light to the blue LED. Note that colour of light depends on its wavelength.
5. The wavelength was adjusted at 380 nm.
6. Program was executed and output voltage reading was taken.
7. The wavelength was adjusted by adding 10 nm and measurements were recorded.
8. Step 7 was repeated until the wavelength was adjusted at 780 nm.
9. Tables based on different wavelengths were tabulated after the experiment was conducted. These tables were attached in Appendix H.
10. The results were analysed. Mean and standard deviation were calculated to analyse the accuracy of data obtained.

3.3.6 Experiment 6: Distance Measurement of Laser Sensor in Air and Underwater Environment (FYP 2)

The purpose of conducting this experiment is to test the distance measurement for obstacles with different colours from laser sensor in air and underwater. This experiment is related to the main Objective 2 and 3 of this FYP.

Objective: To analyse the performance of laser sensor on distance measurement in air and underwater.

Parameters:

Manipulated Variable:

i. Distance of the obstacle
ii. Colours of obstacle
iii. Types of medium (air and water)

Responding Variable: Output voltage from laser sensor, V

Equipment:

1. Laser sensor
2. Shiny white paper, white paper, grey paper, black paper and transparent Perspex as obstacle
3. Protractor
4. Raspberry Pi
5. 3.5 m measuring tape
6. Rounded tap water pool
7. Station (PC)

Procedures:

Part A: Distance Measurement in Air Environment

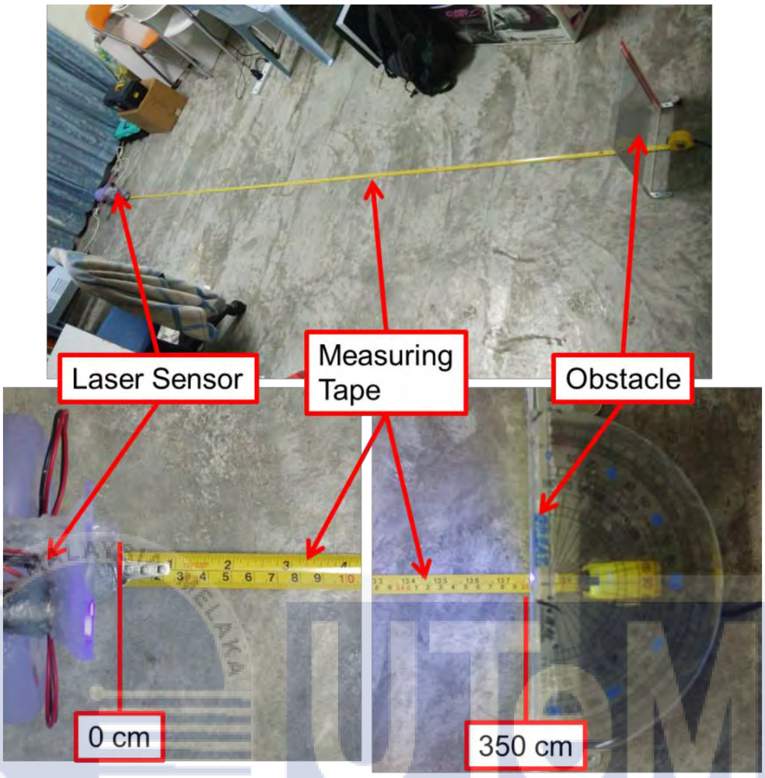

Figure 3.27: Set Up of Experiment 6 in Air Environment

1. First, the experiment was set up for air environment as shown in Figure 3.27. The experiment was carried out for 5 times.
2. Measuring tape was extended at least 3.5m and attached to the floor.
3. The laser sensor was fixed at the position of 0m and faced straight to the measuring tape.
4. Shiny white paper obstacle was placed perpendicular to the sensor with the aid of protractor at the position of 3.5m on the measuring tape.
5. The Raspberry Pi was connected the station to allow displaying sensor measurement from laser sensor in real time.
6. Program was executed and sensor measurement in term of output voltage was taken.
7. The obstacle was moved towards the laser sensor by 10cm and measurement was recorded.
8. Step 7 was repeated until the obstacle reached the position of 0.1m on the measuring tape.

9. The whole experiment was repeated by changing obstacle to white paper, grey paper, black paper and transparent Perspex.
10. Tables based on different obstacles were tabulated after the experiment was conducted. These tables were attached in Appendix I.
11. The results were analysed. Mean and standard deviation were calculated to analyse the accuracy of data obtained.

Part B: Distance Measurement in Underwater Environment

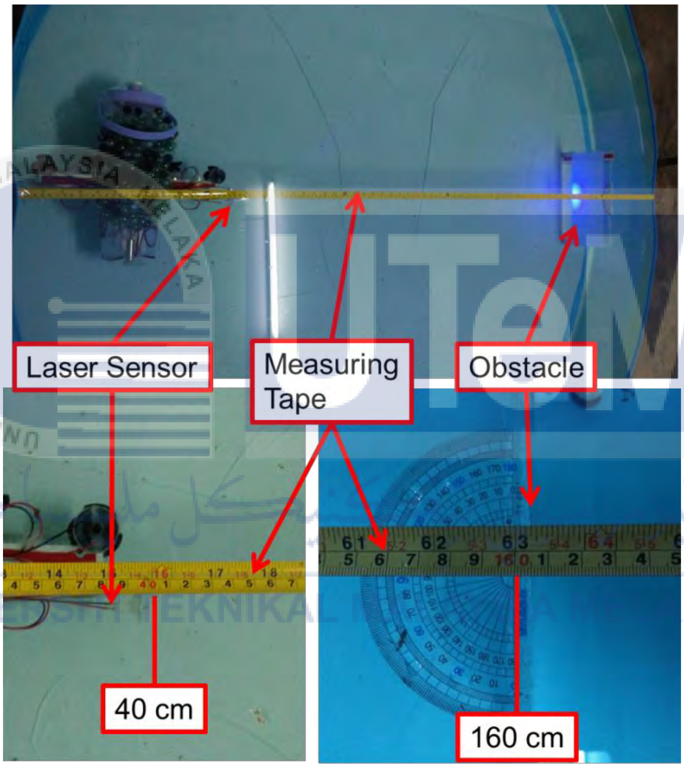

Figure 3.28: Set Up of Experiment 6 in Underwater Environment

1. First, the experiment was set up for underwater environment as shown in Figure 3.28. The experiment was carried out for 5 times.
2. Measuring tape was extended at least 1.8m and attached to the 2 opposite edges of rounded tap water pool.
3. Laser sensor was submerged into water with the aid of weight. The sensor was fixed at the position of 0.4m and faced straight to the measuring tape.

4. Obstacle was held perpendicular to the sensor with the aid of protractor at the position of 1.6m on the measuring tape.
5. The Raspberry Pi was connected the station to allow displaying sensor measurement from laser sensor in real time.
6. Program was executed and sensor measurement in term of output voltage was taken.
7. The obstacle was moved towards the laser sensor by 10cm and measurement was recorded.
8. Step 7 was repeated until the obstacle reached the position of 0.5m on the measuring tape.
9. The whole experiment was repeated by changing obstacle to white paper, grey paper, black paper and transparent Perspex.
10. Tables based on different obstacles were tabulated after the experiment was conducted. Note that all distances in the experiment were deducted by 0.4m since the sensor was fixed at the position of 0.4m on the measuring tape. These tables were attached in Appendix I.
11. The results were analysed. Mean and standard deviation were calculated to analyse the accuracy of data obtained.

CHAPTER 4

RESULTS AND DISCUSSSIONS

This section describes the results of this Final Year Project which include the completed prototype, obstacle avoidance and depth control algorithms, and more importantly the results and analysis of all experiments.

4.1 Completed Prototype

The prototype was completed. Dimension of the prototype is 35cm height × 37.5cm width × 13.5cm height. The mass of the prototype is 2.795kg. As mentioned in Chapter 3 Methodology, the prototype is able to perform obstacle avoidance mechanism and depth control mechanism with the aid of 4 Laser sensors and 4 propellers. However, the prototype is not perfect. The prototype will slightly turn left when it thrusts forwards. This indicated that the hydrodynamic and kinematic of the prototype were not good, due to low precision of prototyping. Besides, some lens of Laser sensors have filled with water due to collisions in many testing. Yet, in overall the prototype still in good condition. Figure 4.1 to 4.4 illustrates the isometric, front, top and side view of the prototype.

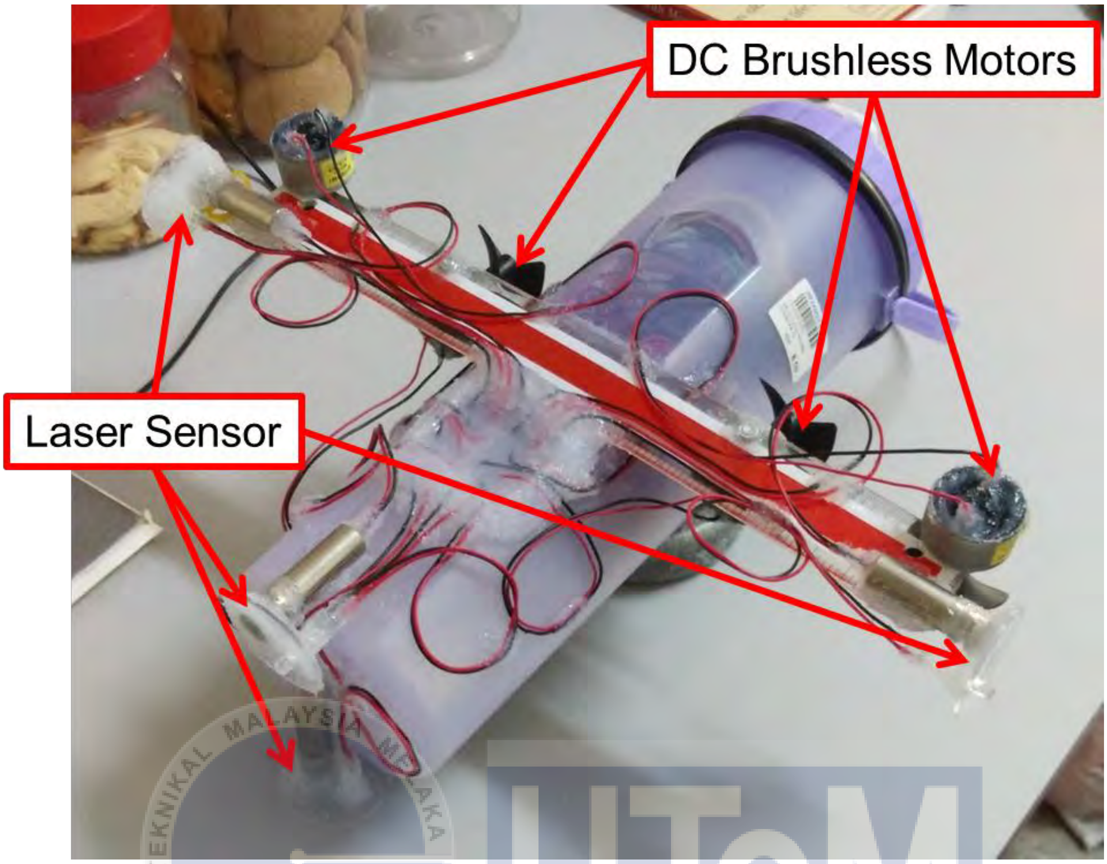

Figure 4.1: Isometric View of the Prototype

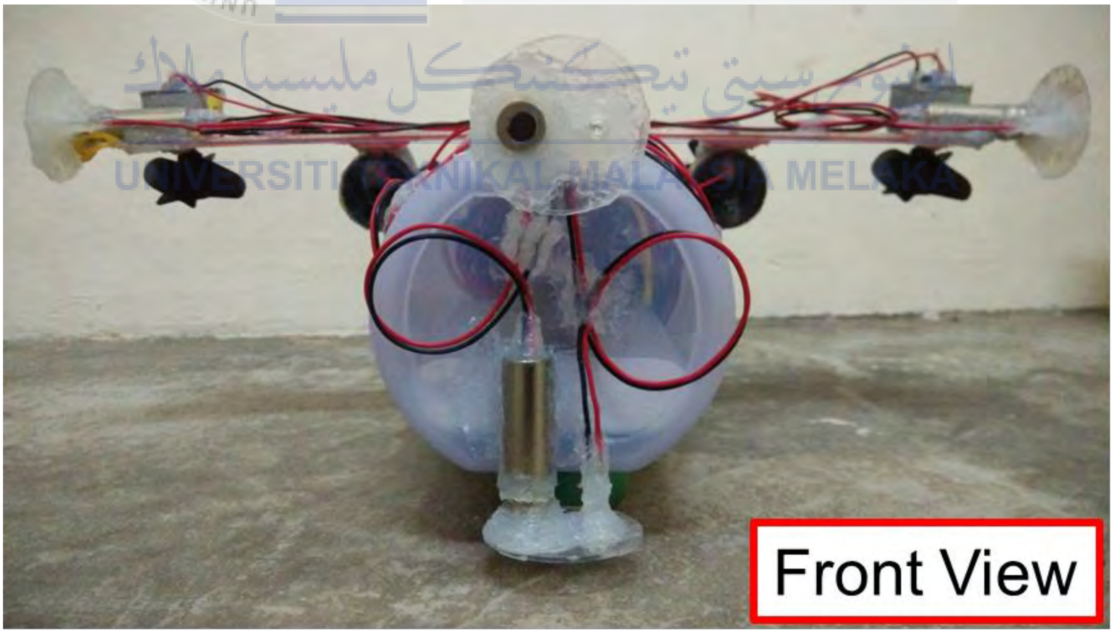

Figure 4.2: Front View of the Prototype

Figure 4.3: Top View of the Prototype

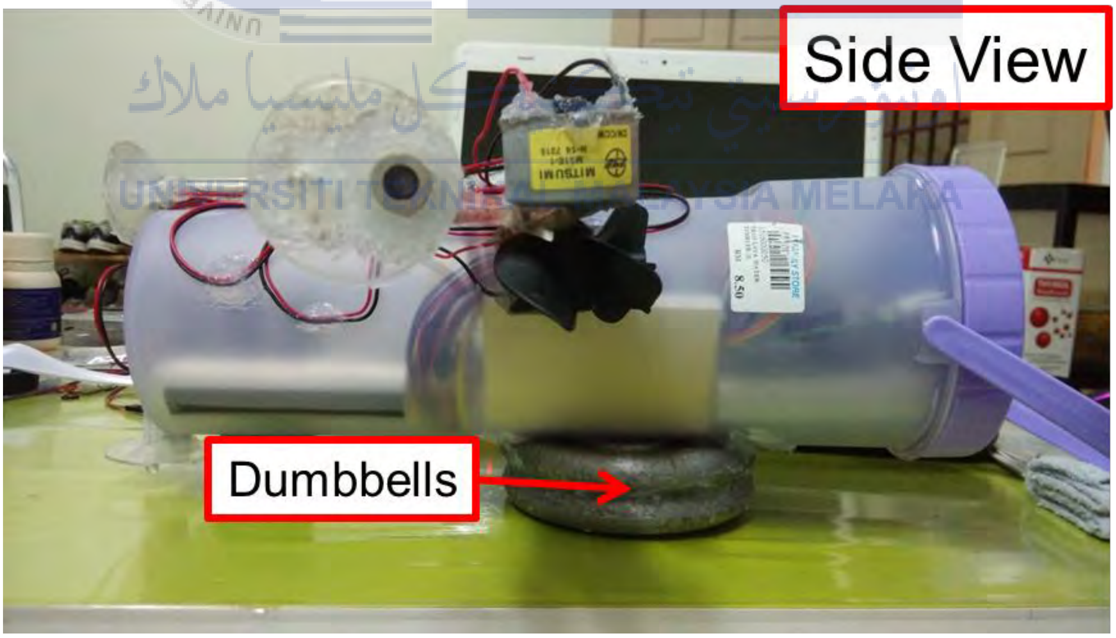

Figure 4.4: Side View of the Prototype

4.2 Obstacle Avoidance and Depth Control Algorithms

Figure 4.5 illustrates the obstacle avoidance and depth control algorithms. By implementing the algorithms, the prototype is able to perform obstacle avoidance mechanism and depth control mechanism. However, error happens with certain conditions.

For obstacle avoidance mechanism, the prototype is cannot to avoid obstacle when the Laser did not reaches the obstacle. This due to Laser is collimated in one direction only. Collision may occur if the obstacle has missed the Laser.

For depth control mechanism, the position level of the prototype is fluctuating in underwater. First, this is due the intensity of the reflected Laser is different while the prototype moving, especially when the pool floor was dirty. Next, the Laser sensor might have delay while sensing reflected Laser.

Through many cycles of testing, the algorithm was improved. Calibration is needed while improving the algorithm to create less errors. A demonstration video was recorded to show how the prototype behaves in underwater with obstacle.

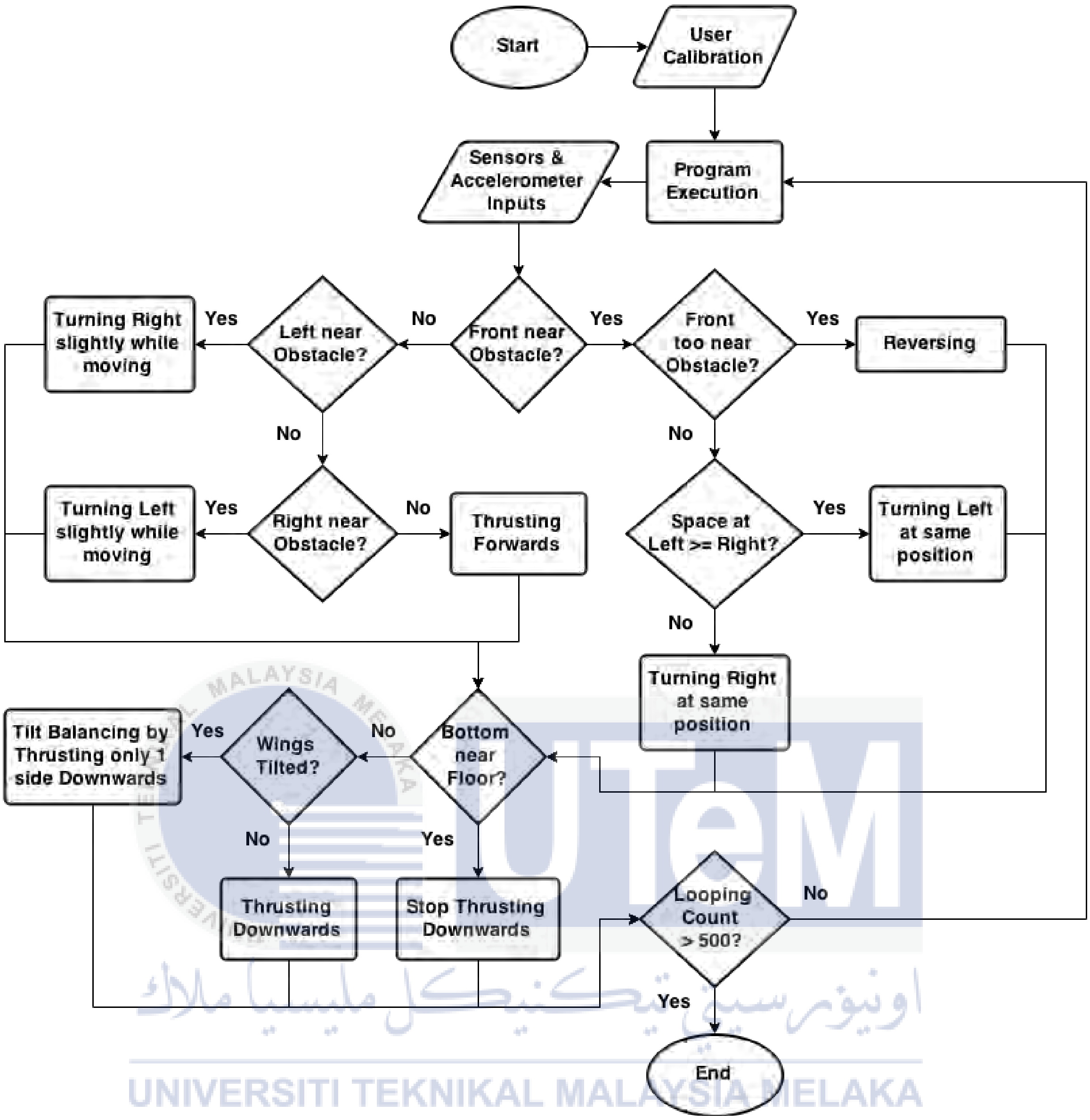

Figure 4.5: The Obstacle Avoidance and Depth Control Algorithms

4.3 Analysis on Experiments

4.3.1 Experiment 1: Controlling DC Brushless Motor

Table has been tabulated for results of this experiment and attached in Appendix E.

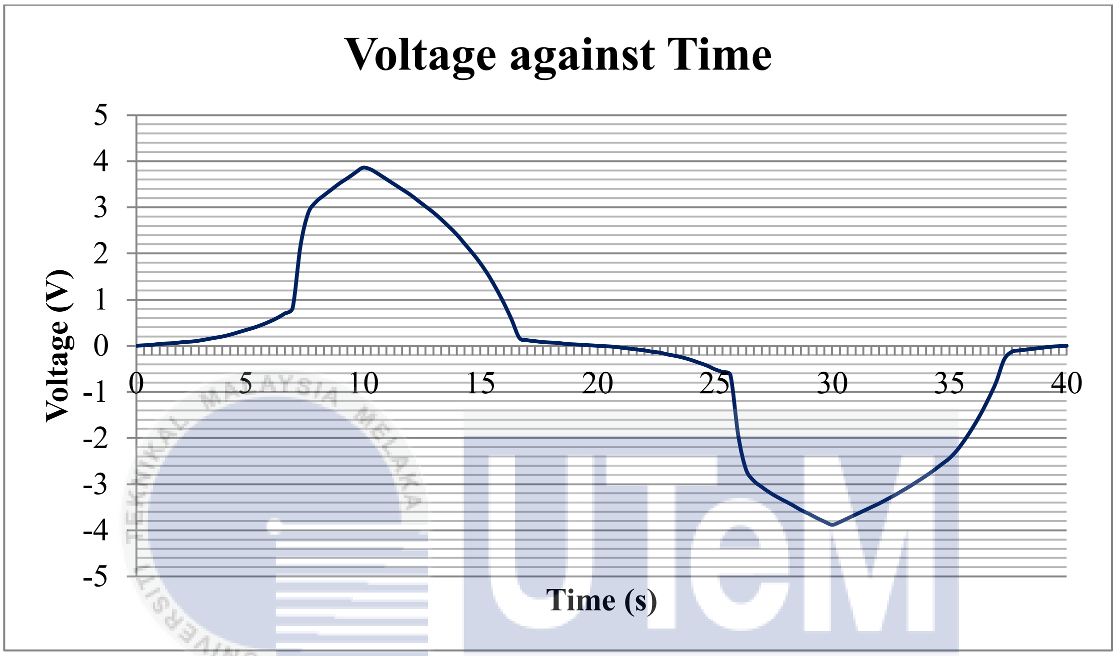

Figure 4.6: Analysis on the Direction and Output Voltage of DC Motor

Figure 4.6 illustrates the direction and output voltage of DC motor in graph. During the experiment, the DC motor was controlled by hardware PWM function with the aid of L293D motor driver. From observation in video, the plastic blade was seen changing from clockwise to counter-clockwise direction by varying the PWM. Note that the full PWM voltage output was 3.9 V.

4.3.2 Experiment 2: Functionality of DC Brushless Motor in Water

Table 4.1: Results Obtained in Experiment 2

Time (min)	Tap Water		Salt Water	
	Current (A)	Observation	Current (A)	Observation
1	0.03	Clean	0.05	Clean
2	0.03	Clean	0.05	Clean
3	0.03	Clean	0.05	Clean
4	0.03	Clean	0.06	Oil on water surface
5	0.03	Clean	0.06	Oil on water surface
6	0.03	Clean	0.07	Oil on water surface
7	0.03	Clean	0.08	Slightly Yellowish
8	0.03	Clean	0.08	Slightly Yellowish
9	0.03	Clean	0.09	Yellowish
10	0.03	Clean	0.09	Yellowish
11	0.03	Oil on water surface	0.10	Yellowish
12	0.03	Oil on water surface	0.11	Brownish
13	0.03	Oil on water surface	0.12	Brownish
14	0.03	Oil on water surface	0.15	Dark Brownish
15	0.03	Oil on water surface	0.16	Dark Brownish

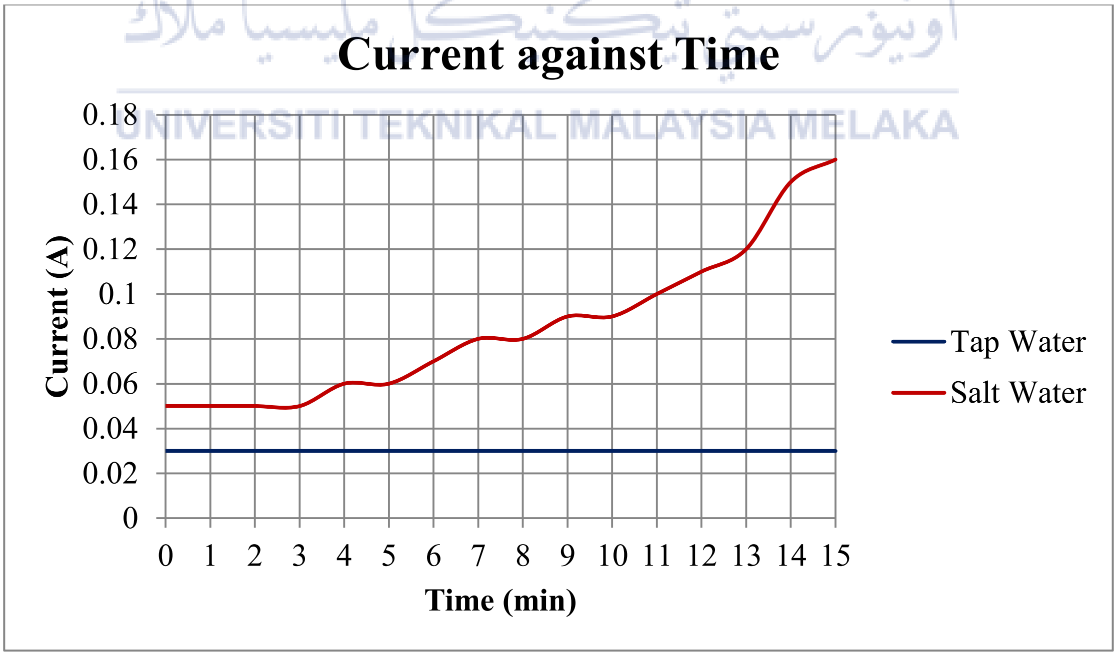

Figure 4.7: Analysis on Currents of DC Motor in Tap Water and Salt Water in 15 Minutes

(a) Observation for Tap Water (b) Observation for Salt Water

Figure 4.8: Results of Testing DC Motor in Water after 15 Minutes

During the experiment, the DC motor was placed into a glass of tape water. The motor was powered up directly by 5V output from Raspberry Pi and tested for 15 minutes. From observation, the DC motor works fine in tape water. Table 4.1 was tabulated after results were obtained in Experiment 2. Figure 4.7 shows the current measured by the multimeter was constant for tap water during the experiment is carried out. The tap water was still clear after the experiment and only a little bit of lubricant oil appeared on the water surface as shown in Figure 4.8 (a).

After that, a spoon of salt was added into the water. The experiment was continuing conducted. For the first 3 minutes observation during the experiment, the salt water was clear. After that, contaminations were occurred in the salt water and getting serious. Table 4.1 was tabulated after results were obtained in Experiment 2. Figure 4.7 shows the current measured by the multimeter was increasing for salt water during the experiment is carried out. After 15 minutes, the DC motor stopped working and the salt water was in dark brownish colour shown in Figure 4.8 (b). It was taken out from the salt water and the connection between wire and motor’s anode was found damaged. It was deduced that electrolysis process has been occurred because the metal plate of anode has been depleted. The current measured was initially higher because electrical conductivity of salt water is greater than tap water. The current measured was keep increasing when the salt added are more solute in water.

4.3.3 Experiment 3: Distance Measurement of Ultrasonic Sensor in Air and Underwater Environment

Ultrasonic sensor measurement is taken with Raspberry Pi in term of time delay from each echo received. The readings are then converted into voltages. Table has been tabulated for results of this experiment and attached in Appendix F.

Part A: Distance Measurement in Air Environment

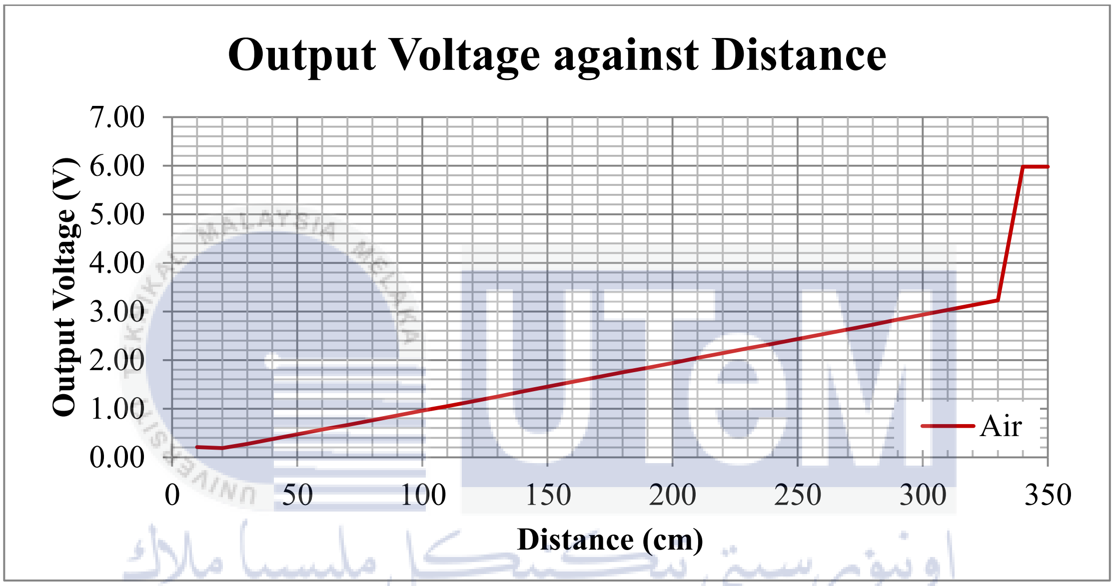

Figure 4.9: Analysis on Output Voltages of Ultrasonic Sensor for Distance Measurement in Air Environment

In Figure 4.9, the graph obtained is considered a linear graph, where the effective measurement should be taken from 20cm up to 330cm. Beyond this range, the ultrasonic sensor used could not perform reliable distance measurements.

For distances less than 20cm, the sensor constantly gave reading of 0.21V instead of showing proper value which is proportional to the distance. Similar to distance more than 330cm, the sensor constantly showed 5.98V instead of showing proper value which is proportional to the distance. This is due to the limitation of the sensor. It can be said that the ultrasonic sensor has a range of blind spots in distance measurement. The range of blind spots is less than 20cm and more than 330cm.

Part B: Distance Measurement in Underwater Environment

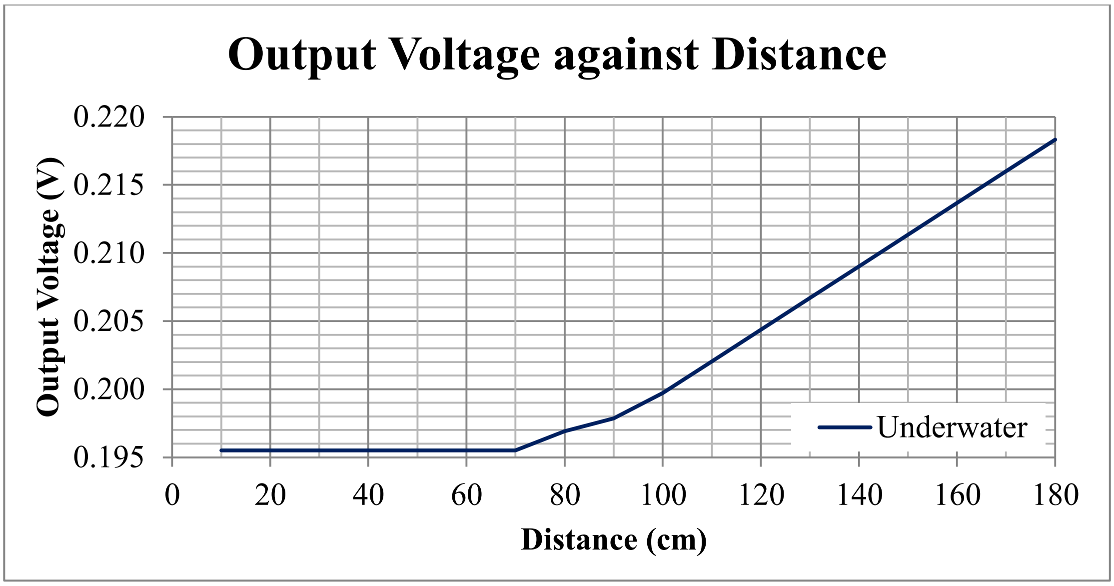

Figure 4.10: Analysis on Output Voltages of Ultrasonic Sensor for Distance Measurement in Underwater Environment

In Figure 4.10, the graph can be explained in 2 parts. The first part is the distance measurement from 10cm to 70cm. In this range, the readings of the sensor remain constant, which are 0.196V even though the obstacle moved away the sensor from 10cm to 70cm. The second part is the distance measurement from 70cm to 180cm. In this range, the graph obtained is considered a linear graph where the readings of the sensor are proportional to the distance.

Speed of sound in water is about 4.3 times as compared to sound in air. With same time taken, assumption can be made that distance of sound travelling is 4.3 times longer in underwater environment as compared to air environment. For same distance, time taken for receiving sound echo after the single sound wave is emitted is assumed 4.3 times shorter in underwater environment compared to air environment. Due to limitation of the sensor, the sensor could not measure the sound echo and showed constant reading of 0.196V in distance measurement less than 70cm. Thus, the sensor readings for underwater environment have much lower output voltage which is from 0.196V to 0.218V in distance measurements from 70cm to 180cm.

Part C: Comparison of Distance Measurements in Air and Underwater Environments

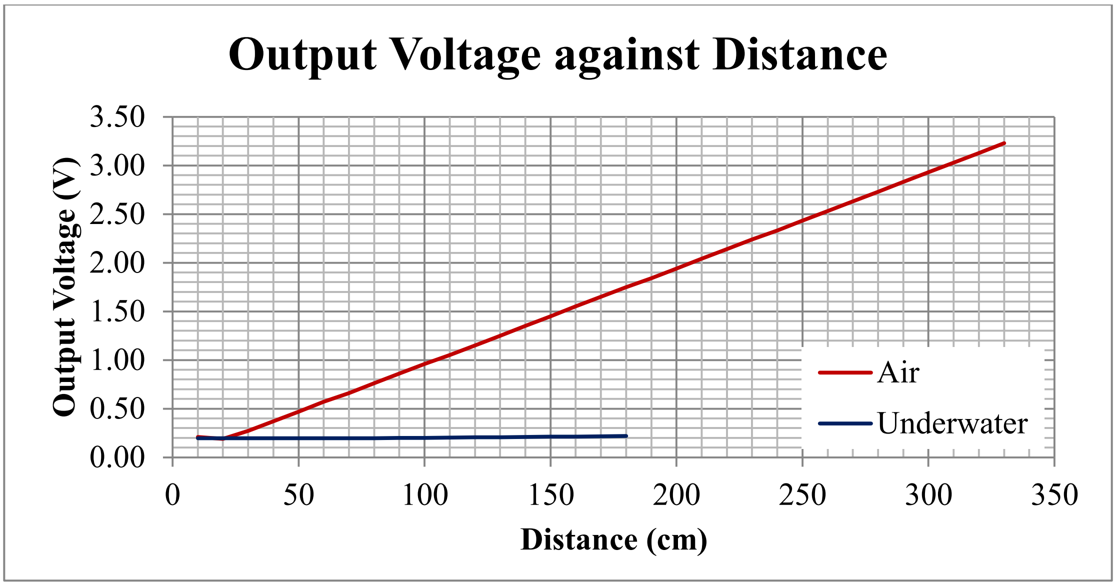

Figure 4.11: Comparison on Output Voltages of Ultrasonic Sensor for Distance Measurement in Air and Underwater Environment

Figure 4.11 shows the comparison of voltage readings of the ultrasonic sensor between air and underwater environments. Based on Figure 3, assumption can be deduced for underwater environment where the sensor reading will be linearly increasing in distance measurement which more than 180cm until limitation of the sensor.

Analysis Findings

1. In air, effective range: 20 cm <= X <= 330 cm.
2. In underwater, effective range: X >= 70 cm. Ultrasonic is suitable for long range detection.

Calculations for Mean, Standard Deviation and RMS Error

For example, distance at 80cm in underwater environment:-

$$Mean, \mu = \frac{V_1 + V_2 + V_3 + V_4 + V_5}{5} = \frac{0.196 + 0.198 + 0.198 + 0.196 + 0.198}{5} = 0.197\ V$$

$$Standard\ Deviation, \sigma = \sqrt{\frac{(V_1 - \mu)^2 + (V_2 - \mu)^2 + (V_3 - \mu)^2 + (V_4 - \mu)^2 + (V_5 - \mu)^2}{5}}$$

$$\sigma = \sqrt{\frac{(0.196 - 0.197)^2 + (0.198 - 0.197)^2 + (0.198 - 0.197)^2 + (0.196 - 0.197)^2 + (0.198 - 0.197)^2}{5}} = 0.001\ V$$

$$RMS\ Error = \sqrt{\frac{(V_1 - V_D)^2 + (V_2 - V_D)^2 + (V_3 - V_D)^2 + (V_4 - V_D)^2 + (V_5 - V_D)^2}{5}}$$

$$Desired\ Output\ Voltage, V_D = 0.186\ V$$

$$RMS\ Error = \sqrt{\frac{(0.196 - 0.186)^2 + (0.198 - 0.186)^2 + (0.198 - 0.186)^2 + (0.196 - 0.186)^2 + (0.198 - 0.186)^2}{5}}$$

$$RMS\ Error = 0.011\ V$$

For consistency, standard deviation for every distance has been calculated. The highest standard deviation is 0.005 V at distance of 250cm in air environment and most of the distances have zero standard deviation. Since all standard deviations are very near to 0, it can be deduced that all data collected in the experiment is very consistent.

For accuracy, RMS error for every distance has been calculated. In air environment, the highest RMS error value is 2.580 V at distance of 340cm and followed by 350cm. The rest of the data from distance of 20cm to 330cm give a range of RMS error from 0.010 V to 0.072 V. At the distance of 10cm, RMS error generated is 0.110. Hence, distance above 340cm shows very big RMS error, whereas for distance below 340cm the Ultrasonic sensor give quite accurate output voltage except at distance of 10cm. It can be deduced that the Ultrasonic sensor can measure distance effectively from 20cm up to 330cm.

For accuracy in underwater environment, the highest RMS error value is 0.201 V at distance of 180cm and the lowest is 0.011 V. The data from distance of 70cm to 100cm give a range of RMS error in less than 0.050 V. The lowest RMS error value is 0.011 V at the distance of 80cm. Hence, output voltage at distance in between 70 and 100 has higher accuracy. The output voltage at distance from 70cm to 100cm has big error. It may be due to the limitation of the sensor or the formula derived as shown in Equation 3.5 is wrong.

4.3.4 Experiment 4: Distance Measurement of Infrared Sensor in Air and Underwater Environment

Table has been tabulated for results of this experiment and attached in Appendix G.

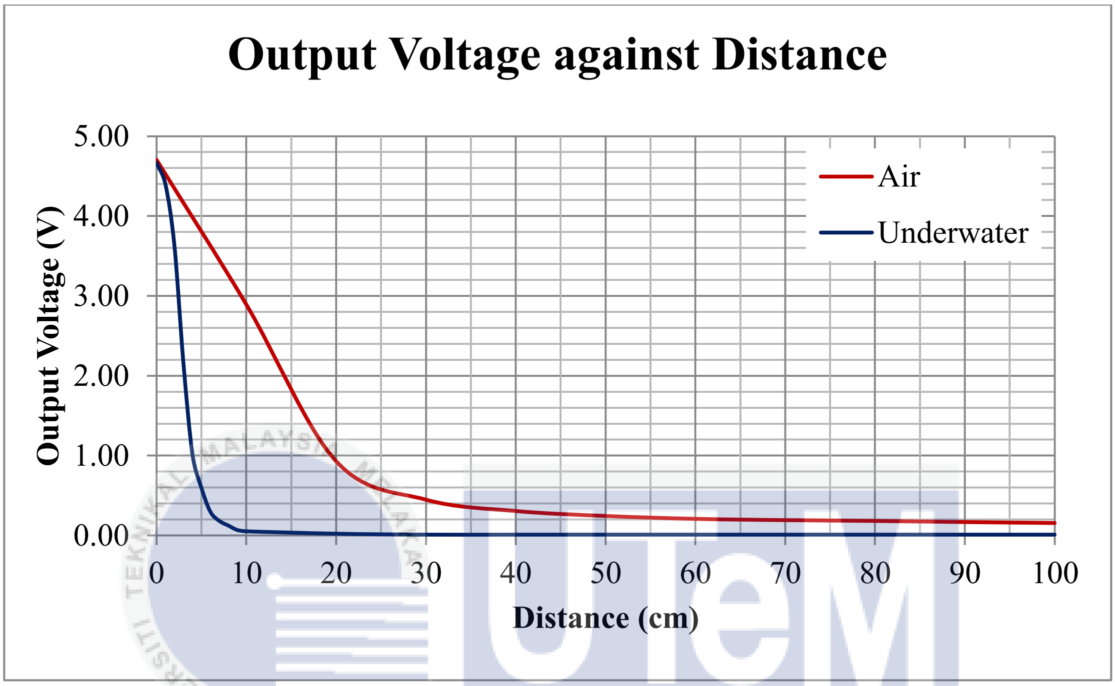

Figure 4.12: Analysis on Output Voltages of Infrared Sensor for Distance Measurement in Air and Underwater Environment

Figure 4.12 shows the analysis on output voltages of infrared sensor for distance measurement in both air and underwater environment. Output voltage of Infrared sensor is taken reading from multimeter in distance measurement.

In air environment, the highest reading of sensor was recorded which is 4.704V at the distance of 0cm from the sensor. As the obstacle moved away from the sensor, the sensor reading was sharply decreased from 4.704V to 0.930V in distance measurement from 0cm to 20cm. For distance measurement from 20cm to 100cm, the sensor reading is decreased exponentially from 0.930V to 0.156V. Based on the graph, assumption has been made that the distance range of Infrared sensor which can detect obstacle effectively is from 0cm to 40cm.

In underwater environment, the highest reading of sensor was recorded which is 4.666V at the distance of 0cm from the sensor. As the obstacle moved away from the sensor, the sensor reading was sharply decreased from 4.666V to 1.018V in distance measurement from 0cm to 4cm. For distance measurement from 4cm to 30cm, the sensor reading is decreased exponentially from 1.018V to 0.010V. For distance measurement from 30cm, the sensor reading remained constant at 0.010V. Based on the graph, assumption has been made that the distance range of Infrared sensor which can detect obstacle effectively is from 0cm to 10cm.

Light intensity detected by the receiver is higher when obstacle is nearer and lower when obstacle is farther from the sensor. In underwater environment, attenuation of light intensity occurs when light travels. Hence, sensor reading in underwater environment degrades more steeply and exponentially as compared in air, due to high absorption rate of Infrared light in water. This finding matched with the finding in Journal 2.3.1.

Besides, the results obtained may be different when the experiment is conducted in different brightness of environment such as brighter room and dimmer room. However, the experiment for different brightness of environment is not covered in the scope.

Analysis Findings

1. In air, effective range: X <= 40 cm.
2. In underwater, effective range: X <= 10 cm. Infrared sensor is not suitable for range detection.

Calculations for Mean and Standard Deviation

For example, distance at 50cm in air environment:-

$$Mean, \mu = \frac{V_1 + V_2 + V_3 + V_4 + V_5}{5} = \frac{0.240 + 0.240 + 0.250 + 0.250 + 0.240}{5} = 0.244\ V$$

$$Standard\ Deviation, \sigma = \sqrt{\frac{(V_1 - \mu)^2 + (V_2 - \mu)^2 + (V_3 - \mu)^2 + (V_4 - \mu)^2 + (V_5 - \mu)^2}{5}}$$

$$\sigma = \sqrt{\frac{(0.240 - 0.244)^2 + (0.240 - 0.244)^2 + (0.250 - 0.244)^2 + (0.250 - 0.244)^2 + (0.240 - 0.244)^2}{5}}$$

$$\sigma = 0.005\ V$$

For consistency, standard deviation for every distance has been calculated. The highest standard deviation is 0.012 V at distance of 2cm in underwater environment. Most of the distances have standard deviation in between 0.004 V and 0.005 V. Since all standard deviations are very near to 0, it can be deduced that all data collected in the experiment are consistent.

4.3.5 Experiment 5: Light Detection of Blue LED with Different Light Wavelengths

Tables have been tabulated for results of this experiment and attached in Appendix H.

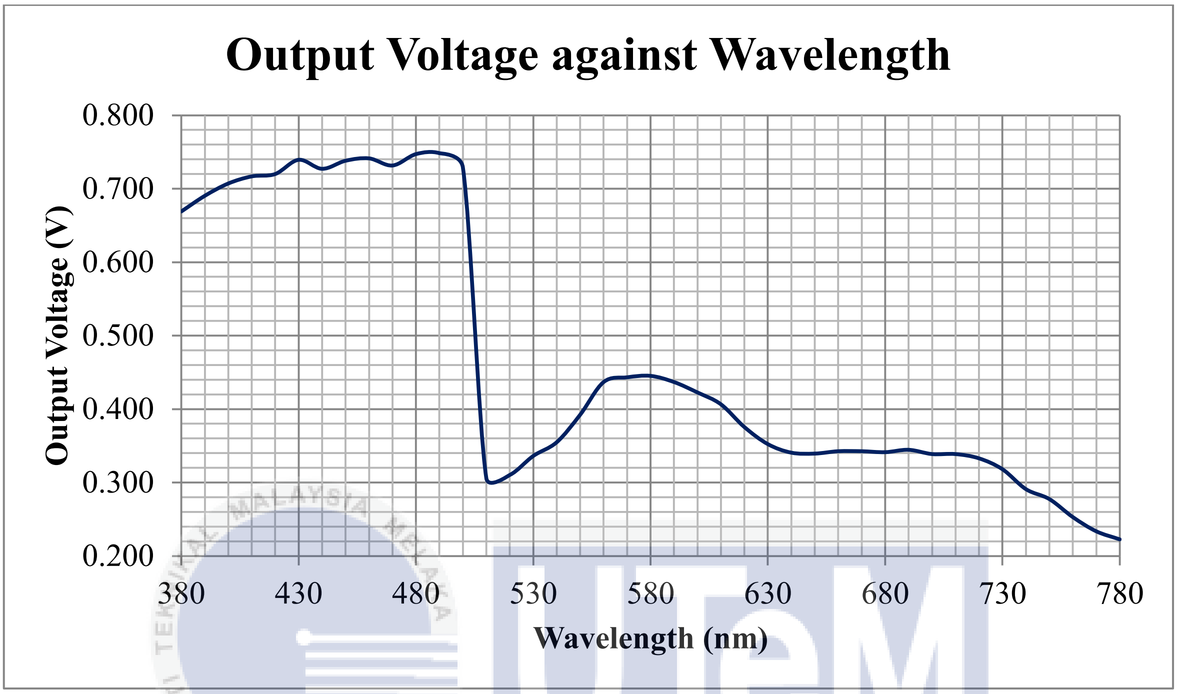

Figure 4.13: Analysis on the Functionality of Blue LED with Different Wavelengths

Figure 4.13 shows analysis on the functionality of blue LED as a spectrally selective photodetector with presence of different wavelengths of light. At wavelengths of interval between 380 nm and 500 cm, the graph was gradually increasing with an output voltage peak of 0.748 V at 490 nm. Beyond wavelengths at 500 nm, the output voltage was decreased sharply and recorded with a small output voltage peak of 0.445 V at 580 nm. After wavelength at 710 nm, the graph was decreasing slowly. The minimum output voltage is 0.223 V at 780 nm.

As summary, blue LED is a spectrally selective photodetector. It is sensitive to light wavelengths from 380 nm to 500 nm. This finding matched with the finding in Journal 2.2.1. Although the wavelengths were limited in a range from 380 nm to 780 nm, the graph tends to decrease if extended beyond this range. The purpose of testing blue LED is because the blue or violet lights have lower absorption coefficient in water as mentioned in Journal 2.3.1. By utilising blue light emitter, blue light can travels farther in water.

Analysis Finding

1. Blue LED is sensitive to light wavelength from 380 nm to 500 nm (spectrally selective photodetector). [matched with Journal 2.2.1]

Calculations for Mean and Standard Deviation

For example, output voltage in wavelength at 460 nm:-

$$Mean, \mu = \frac{V_1 + V_2 + V_3 + V_4 + V_5}{5} = \frac{0.752 + 0.748 + 0.745 + 0.742 + 0.719}{5} = 0.741\ V$$

$$Standard\ Deviation, \sigma = \sqrt{\frac{(V_1 - \mu)^2 + (V_2 - \mu)^2 + (V_3 - \mu)^2 + (V_4 - \mu)^2 + (V_5 - \mu)^2}{5}}$$

$$\sigma = \sqrt{\frac{(0.752 - 0.741)^2 + (0.748 - 0.741)^2 + (0.745 - 0.741)^2 + (0.742 - 0.741)^2 + (0.719 - 0.741)^2}{5}}$$

$$\sigma = 0.011\ V$$

For consistency, standard deviation for every distance has been calculated. The highest standard deviation in the results is 0.011 V for wavelength at 460 nm. Since all standard deviations are near to 0 V, it can be deduced that all data collected in the experiment are quite consistent.

4.3.6 Experiment 6: Distance Measurement of Laser Sensor in Air and Underwater Environment

Tables have been tabulated for results of this experiment and attached in Appendix I.

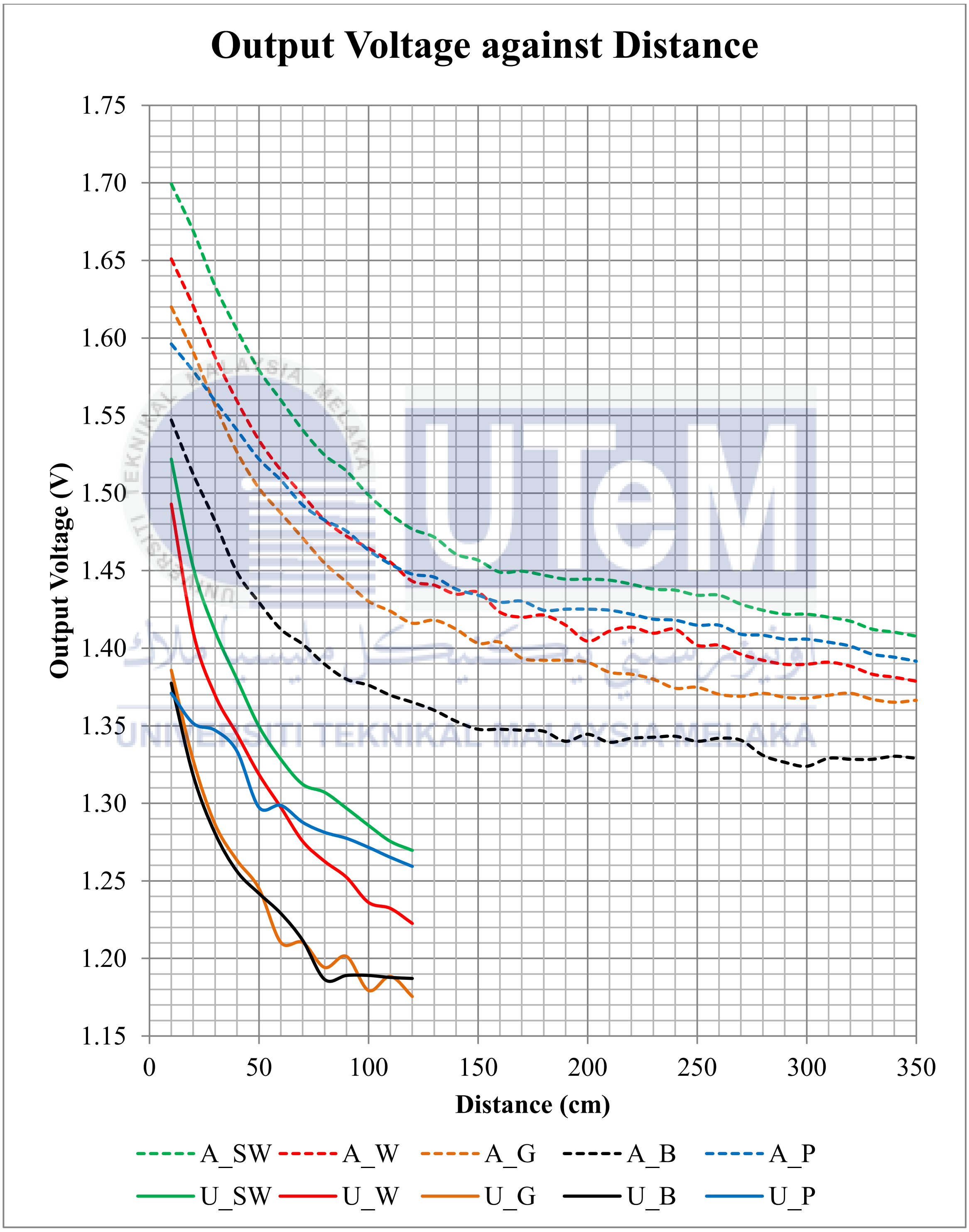

Figure 4.14: Analysis on Output Voltages of Laser Sensor for Distance Measurement of 5 Obstacles with Different Colours in Air and Underwater Environment

Table 4.2 shows the description of abbreviations from legend in Figure 4.14.

Table 4.2: Description of Abbreviations from Legend in Figure 4.14

Abbr.	Description	Abbr.	Description
A_SW	Shiny white paper in air environment	U_SW	Shiny white paper in underwater environment
A_W	White paper in air environment	U_W	White paper in underwater environment
A_G	Grey paper in air environment	U_G	Grey paper in underwater environment
A_B	Black paper in air environment	U_B	Black paper in underwater environment
A_P	Perspex in air environment	U_P	Perspex in underwater environment

In Figure 4.14, there are 10 graphs showing the results from Laser sensor's readings for distance measurements of 5 obstacles with different colours, in air and underwater environment. The obstacles were shiny white paper, white paper, grey paper, black paper and transparent Perspex. All graphs obtained are exponentially decreasing. Based on the graphs obtained, all distance measurements in air environment have higher output voltage from Laser sensor. In contrast, all distance measurements in underwater environment have lower output voltage.

In air environment, the patterns of all graphs are quite similar, only the laser beam intensities from reflection are in different levels. For example at the distance of 10cm, 1.670V, 1.651V, 1.620V were output voltages for shiny white paper, white paper and grey paper respectively. However, output voltage from sensor reading with transparent Perspex was lower than expectation. For example at distance of 10cm, the output voltage with transparent Perspex was 1.596V, which was lower than others except black paper. For grey paper, the output voltage oscillated between 1.366V and 1.370V in distance measurement from 260cm to 350cm. For black paper, the graph showed steepest decreasing in distance measurement from 10cm to 150cm, but the output voltage fluctuated between 1.324V and 1.347V in distance measurement from 150cm to 350cm. Based on the graph with black paper, assumption has been made that the distance range of Laser sensor which can detect obstacle effectively is up to 150cm.

In underwater environment, output voltages have been taken at the distances from 10cm to 120cm due to the limited size of the pool. Graphs with shiny white paper and white paper were quite robust and have similar pattern, but the graph with white paper was decreasing steeper compared to shiny white paper. For example at distance of 10cm, the output voltages of shiny white paper and white paper were 1.522V and 1.493V respectively. At distance of 120cm, the output voltages of shiny white paper and white paper were 1.270V and 1.223V respectively. On the other hand, graphs with grey paper, black paper and transparent Perspex were fluctuated significantly. Similar to air environment, output voltage from sensor reading with transparent Perspex was lower than expectation. For example at distance of 10cm, the output voltage with transparent Perspex was 1.371V, which was lower than others. For grey paper and black paper, the output voltages and graph patterns were similar in distance measurement from 10cm to 50cm. For example at distance of 10cm, output voltages with grey paper and black paper were 1.386V and 1.377V respectively. At distance of 50cm, output voltages with grey paper and black paper were 1.245V and 1.242V respectively. However, graph with grey paper showed fluctuation in distance measurement from 50cm to 120cm. On the contrary, output voltage with black paper was the lowest which is 1.186V at distance of 80cm, increase slightly and tends to keep constant at the distance from 80 to 120cm. Based on the graph with black paper, assumption has been made that the distance range of Laser sensor which can detect obstacle effectively is up to 80cm.

Basically, there are 2 types of light reflection occur on a surface, which are specular reflection and diffuse reflection. Let's take account the 405nm Laser light is an incident ray because it is collimated. Specular reflection can be explained as mirror-like light reflection which a surface reflects an incident ray from single incoming direction into single outgoing direction. In other word, an outgoing incident ray with same intensity is reflected into same direction from a surface if the incoming incident ray is perpendicular to the surface. In contrast, diffuse reflection is light reflection which a surface reflects an incident ray from single incoming direction into many outgoing directions. In this case, scattered formed of outgoing incident ray are reflected into all direction if there is incoming incident ray. Light reflection is influenced by the characteristics of material surfaces; even a mixture of specular and diffuse reflections can be exhibited. Hence, assumption can be made that white paper tends to reflect light diffusely, whereas shiny white paper tends to exhibit a mixture of light reflection. On the contrary, the transparent

Perspex tends to exhibit specular reflection like mirror, even though most of the Laser light passed through it. A surface colour's brightness exhibit the absorption of light on the surface. The more light is absorbed, the darker the surface is observed. Therefore, output voltage with black paper was lower than grey paper because greater absorption of light occurred on black surface.

As summary, 405nm Laser light is attenuated in underwater for any distance as compared to air. This finding matched with the findings in Journal 2.3.1. Next, the brighter colour the surface of obstacle, the greater the reflection. For example, shiny white paper reflected the Laser beam with highest intensity, followed by white paper, grey paper and black paper. The transparent Perspex can only reflect certain intensity of the laser beam from near to far distance. In other word, the transparent Perspex is less manipulated by distance adjustment. In this case, it can be deduced that the Laser sensor is hard to determine distance for transparent obstacle.

Analysis Findings

1. In air, effective range: X <= 150 cm.
2. In underwater, effective range: X <= 80 cm. Laser sensor is suitable for short range detection.
3. As compared to air, 405nm Laser light is attenuated in underwater for any distance. [matched with Journal 2.3.1]
4. The brighter colour the surface of obstacle, the greater the reflection. Laser sensor hard to determine distance for transparent obstacle.

Calculations for Mean and Standard Deviation

For example, distance at 10cm for grey paper in air environment:-

$$Mean, \mu = \frac{V_1 + V_2 + V_3 + V_4 + V_5}{5} = \frac{1.635 + 1.623 + 1.616 + 1.613 + 1.613}{5} = 1.620\ V$$

$$Standard\ Deviation, \sigma = \sqrt{\frac{(V_1-\mu)^2 + (V_2-\mu)^2 + (V_3-\mu)^2 + (V_4-\mu)^2 + (V_5-\mu)^2}{5}}$$

$$\sigma = \sqrt{\frac{(1.635-1.620)^2 + (1.623-1.620)^2 + (1.616-1.620)^2 + (1.613-1.620)^2 + (1.613-1.620)^2}{5}}$$

$$\sigma = 0.009\ V$$

For consistency, standard deviation for every distance has been calculated. In air environment, the highest standard deviation is 0.009 V at distance of 10cm with grey paper. Most of the distances have standard deviation in less than 0.005 V.

On the other hand, the highest standard deviation in underwater environment is 0.042 V at distance of 80cm with black paper. All distances with shiny white paper, white paper and transparent Perspex have standard deviation less than 0.008 V. Next, distances with grey paper have standard deviations from 0.004 V to 0.028 V. Distances with black paper have standard deviation in between 0.004 V to 0.042 V.

The trend is most of the standard deviation in underwater environment are higher as compared to air environment. Most probably this is because there were some parallax errors when adjusting the distance of the obstacle. Since all standard deviations are less than 0.05 V, it can be deduced that all data collected in the experiment are quite consistent.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

In conclusion, this Final Year Project is completed successfully. All objectives of this Final Year Project have been achieved. In other word, desired outcome has been yielded.

First, plenty of journal and conference papers have been studied. Best of 5 papers has been chosen for literature reviews. 3 of them are related to design and construction of AUVs. 1 paper is about light detection of Light Emitting Diode (LED) as photodiode. The last paper is related to absorption spectrum of light in pure water.

Next, the prototype has been designed in CAD Drawing using SolidWorks software which illustrates the mechanical designs. The embedded system in the prototype has been figured out and suitable components have been selected. At the same time, the algorithms for obstacle avoidance mechanism and depth control mechanism have been created as well. After that, the prototype has been started to develop.

During prototype development, several experiments have been conducted. Experiment 1 and 2 has been conducted to test the functionality of the Raspberry Pi and DC motor. Analysis in Experiment 2 shows DC brushless motor will be damaged in salt water if it is not waterproof. Hence, the prototype activity has been scoped in tap water pools only. Next, Experiment 5 has been conducted to test the functionality of blue LED to detect lights with different wavelengths. Analysis has been done and showed that blue LED is sensitive to lights with wavelength from 380 nm to 500 nm. In addition, Experiment 3, 4 and 6 have been conducted to test the functionality of ultrasonic, infrared and laser sensors in air and underwater environment. Analysis in these 3 experiments shows that there were significant attenuations in performance of each sensor in different environment. Fortunately, Laser sensor gave better results in the experiment because it can detect obstacle at desired distance which is up to 80cm in underwater environment. Therefore, it has been selected as the sensor of the embedded system of the prototype. Standard deviation and root-mean-squared error has been calculated for all results to examine the accuracy. As a result, all data collected in the experiments were considered accurate. Laser sensor which comprises 405 nm Laser dot module as emitter and blue LED as detector perhaps is the most efficient light dependent sensor for underwater.

For future works, controller in embedded system can be designed improve the robustness and stability of the prototype. For example, fuzzy logic controller can be introduced into current obstacle avoidance and depth control algorithm.

Next, fabrication of the prototype can be performed based on mechanical and electrical configuration of the current prototype. Fabricated prototype is believed to have better endurance and longer life span than current prototype. Besides, results obtained by fabricated prototype may be more precise. This is because the hull of the prototype and components such as Laser sensors can be precisely produced. For example, the fabricated hull can deliver better hydrodynamic. Another example, 4 Laser sensors may be showing same output voltage in same obstacle distance if they were fabricated.

It is suggested to the conduct experiment in completely dark condition to test the performance of Laser sensor with a longer distance in air and underwater environment. Hypothesis has been made that Laser sensor can detect obstacle from a distance of a few meters from the sensor in completely dark environment. This is because the Laser is collimated as it travels. This will be useful if it is true because the Laser sensor can be used in underwater exploration in deep sea water where sunlight is attenuated as it travels further down from the sea surface.

Since the Laser sensor is focusable, it is recommended to adjust the focus point of the Laser sensor to diverge the Laser beam to increase the projection angle of the Laser. This may be useful to overcome the problem that obstacle might missed the Laser beam.

It is believed that while going through numerous experiments and analysis, a number of findings regarding obstacle avoidance mechanism of AUV by using Laser sensor can be achieved.

REFERENCES

[1] B. K. Sahu and S. Member, "The State of Art of Autonomous Underwater Vehicles in Current and Future Decades," *Automation, Control, Energy and Systems (ACES)*, 2014 First International Conference, pp. 1-6, Feb. 2014.

[2] R. B. Wynn, V. a. I. Huvenne, T. P. Le Bas, B. J. Murton, D. P. Connelly, B. J. Bett, H. a. Ruhl, K. J. Morris, J. Peakall, D. R. Parsons, E. J. Sumner, S. E. Darby, R. M. Dorrell, and J. E. Hunt, "Autonomous Underwater Vehicles (AUVs): Their past, present and future contributions to the advancement of marine geoscience," *Mar. Geol.*, vol. 352, pp. 451–468, Jun. 2014.

[3] K. Alam, T. Ray, and S. G. Anavatti, "A brief taxonomy of autonomous underwater vehicle design literature," *Ocean Eng.*, vol. 88, pp. 627–630, Sep. 2014.

[4] M. Tang, Z. Zhang, and Y. Xing, "Analysis of New Developments and Key Technologies of Autonomous Underwater Vehicle in Marine Survey," *Procedia Environ. Sci.*, vol. 10, pp. 1992–1997, 2011.

[5] K. K. A. David, R. R. Vicerra, A. A. Bandala, L. A. G. Lim, and E. P. Dadios, "Unmanned Underwater Vehicle Navigation and Collision Avoidance Using Fuzzy Logic," *System Integration (SII), 2013 IEEE/SICE International Symposium*, pp. 126-131, Dec. 2013.

[6] "MH370 search: Bluefin-21 continues on seventh mission - Nation | The Star Online." [Online]. Available: http://www.thestar.com.my/News/Nation/2014/04/19/MH370-Bluefin-continue-search/. [Accessed: 15-Dec-2014].

[7] S. Araki and K. Ishii, "Development of glider type small AUV Seabird," *Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies, 2007*. pp.320-325, 17-20 April 2007

[8] C. Osterloh, T. Pionteck, and E. Maehle, "MONSUN II : A small and inexpensive AUV for underwater swarms," *Robotics; Proceedings of ROBOTIK 2012*; 7th German Conference. pp.1-6, 21-22 May 2012

[9] M. Hildebrandt, C. Gaudig, L. Christensen, S. Natarajan, P. Paranhos, and J. Albiez, "Two years of experiments with the AUV dagon - a versatile vehicle for high precision visual mapping and algorithm evaluation," *2012 IEEE/OES Auton. Underw. Veh.*, pp. 1–9, Sep. 2012.

[10] S. A. Watson and P. N. Green, “A De-Coupled Vertical Controller for Micro-Autonomous Underwater Vehicles (μAUVs) ,” *Mechatronics and Automation (ICMA), 2011 International Conference.* pp.561-566, 7-10 Aug. 2011

[11] “Iver 3 Nano - AUVAC.” [Online]. Available: http://auvac.org/configurations/view/260. [Accessed: 15-Dec-2014].

[13] S. G. Castro, J. G. Agudelo, and A. Arbós, “Design and Construction of the GUANAY-II Autonomous Underwater Vehicle," *OCEANS, 2011 IEEE - Spain*, pp. 1-6, June 2011.

[14] C. Barngrover, R. Kastner, T. Denewiler, and G. Mills, “The Stingray AUV : A Small And Cost-Effective Solution for Ecological Monitoring,” *OCEANS 2011*, pp. 1-8, 2011.

[15] R. Stojanovic and D. Karadaglic, “An Optical Sensing Approach Based On Light Emitting Diodes,” *J. Phys. Conf. Ser.*, vol. 76, p. 012054, Jul. 2007.

[16] Robin M. Pope and Edward S. Fry, "Absorption spectrum (380–700 nm) of pure water. II. Integrating cavity measurements," Appl. Opt. 36, 8710-8723, 1997.

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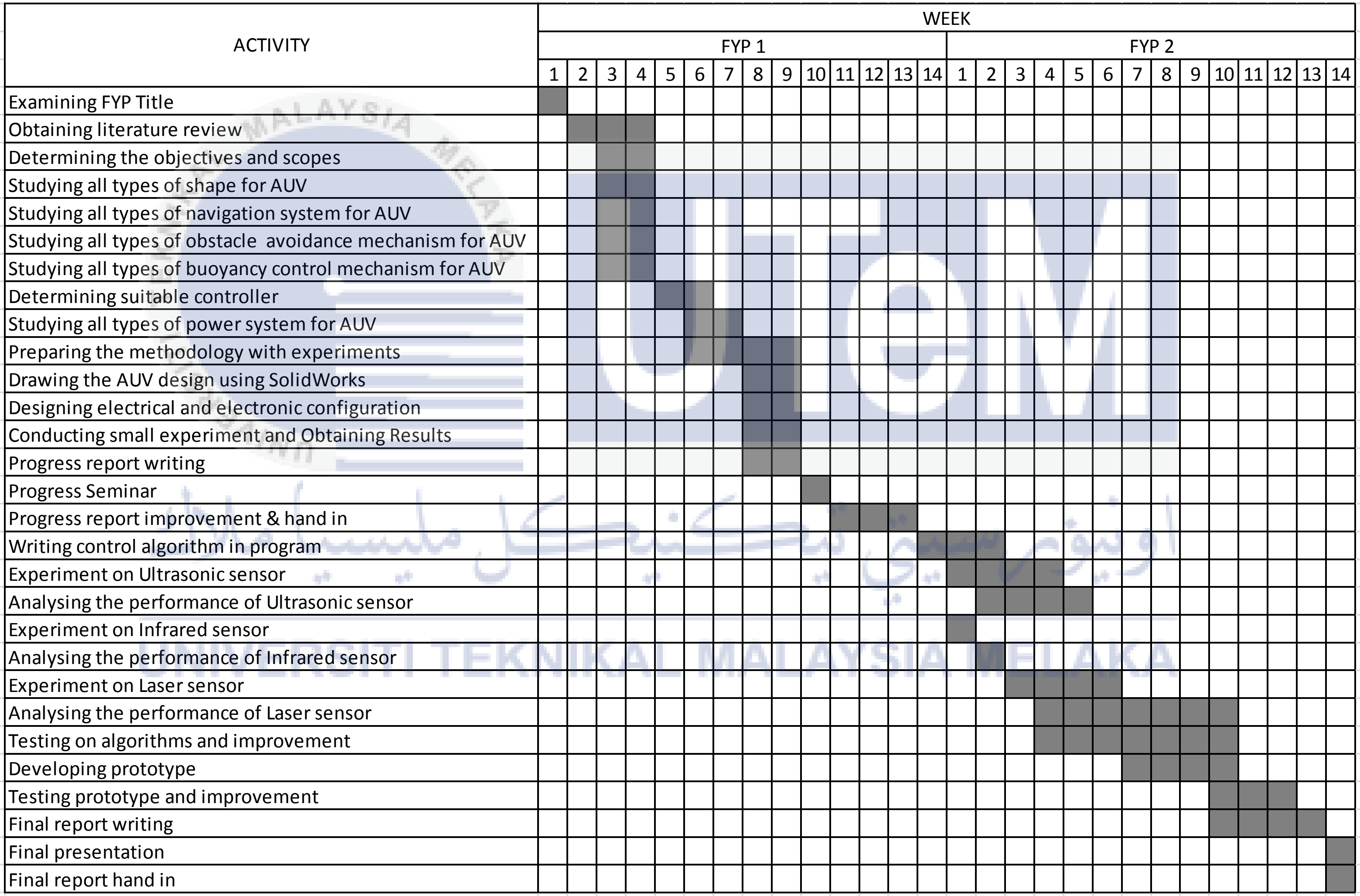
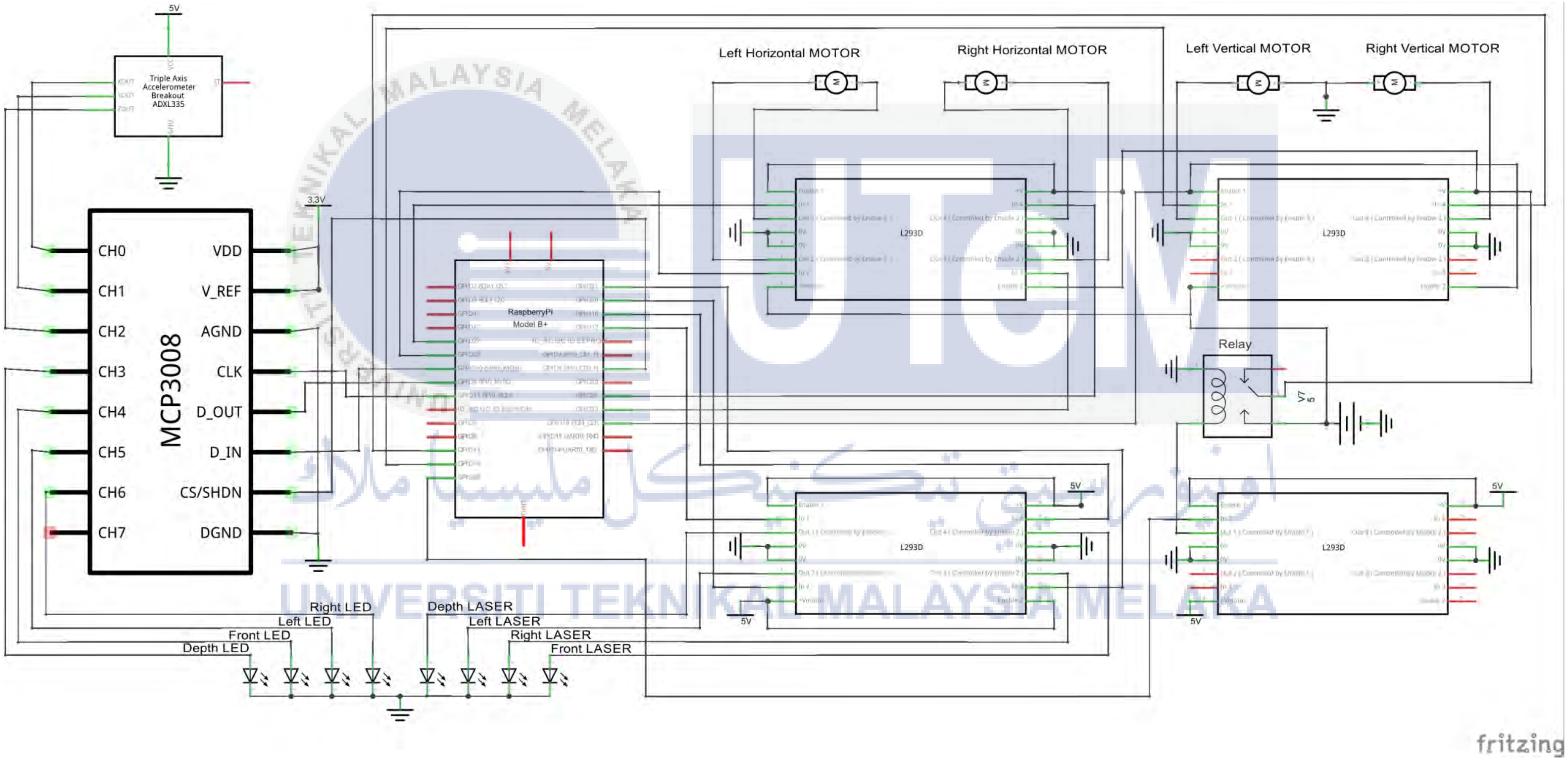
APPENDIX A

Gantt Chart of FYP



APPENDIX B

Schematic Diagram of Circuit Design



APPENDIX C

Costing of Procurement for Prototype Development

Material/Component	Unit	Price/Unit (RM)	Price (RM)	Procurement Reference
Raspberry Pi Model B+	1	131.00	131.00	Purchased at http://my.element14.com/raspberry-pi/raspberry-modb-8gb-usd/raspberry-pi-model-b-8gb-noobs/dp/2431427
405nm 20mW Laser Dot Module	4	30.50	122.00	Purchased at http://www.ebay.com/itm/New-industrial-Blue-Violet-Focusable-Laser-Dot-Module-405nm-20mW-12x45mm-3V-5V-/171470473611?pt=LH_DefaultDomain_0&hash=item27ec6fc98b
Xiaomi 10400mAh Power Bank	2	36.00	72.00	Purchased at http://www.mi.com/my/mipowerbank10400/
L293D Motor Driver	4	11.50	46.00	Applied from FKE Store
Adafruit Miniature Wi-Fi Module	1	42.00	42.00	Purchased at http://my.element14.com/adafruit-industries/814/miniature-wifi-module-raspberry/dp/2301652
3-Axis Accelerometer	1	36.50	36.50	Purchased at http://www.cytron.com.my/p-sn-adxl335-cy
Mitsumi M31E-1 DC Brushless Motor	4	7.00	28.00	Applied from FKE Store
Half-Sized Breadboard	2	8.00	16.00	Purchased at Component Shop
Nylon Propeller Blade	4	2.50	10.00	Purchasedathttp://detail.tmall.com/item.htm?id=41197041120&spm=a220o.1000855.0.0.30ESQ3
0.5Kg Dumbbell	2	5.00	10.00	Purchased at Fitness Shop
2-Liter Plastic Tumbler	1	8.50	8.50	Purchased at Family Store Supermarket
Microchip MCP 3008 ADC	1	7.50	7.50	Purchased at http://my.element14.com/microchip/mcp3008-i-p/10bit-adc-2-7v-8ch-spi-16dip/dp/1627174
5mm Clear Blue LED	4	1.00	4.00	Purchased at Component Shop
Rounded Transparent Perspex	4	1.00	4.00	Purchased at Mr. DIY Shop
Faber-Castell 30cm Hard Plastic Ruler	1	3.00	3.00	Purchased at Stationary Shop
3VDC 5-Pins Relay	1	2.00	2.00	Purchased at Component Shop
		Total Cost	**542.50**	

APPENDIX D

Coding for Prototype Based on Algorithms

1

```
#include <stdio.h>
#include <stdlib.h>
#include <stdint.h>
#include <wiringPi.h>
#include <mcp3004.h>

#define BASE 100
#define SPI_CHAN 0

int main (void)
{
wiringPiSetup () ;
mcp3004Setup (BASE, SPI_CHAN) ;
pinMode (1, PWM_OUTPUT) ;
pinMode (2, OUTPUT) ;
pinMode (3, OUTPUT) ;
pinMode (4, OUTPUT) ;
pinMode (5, OUTPUT) ;
pinMode (23, OUTPUT) ;
pinMode (24, OUTPUT) ;
pinMode (25, OUTPUT) ;
pinMode (26, OUTPUT) ;
pinMode (27, OUTPUT) ;
pinMode (28, OUTPUT) ;
pinMode (29, OUTPUT) ;

int count ;
int y ;
int depth ;
int front ;
int left ;
int right ;
```

2

```
printf ("Inputs:\n") ;

digitalWrite (25, HIGH) ;
delay (10000) ;

for (count = 1 ; count < 501 ; ++count)
{
y = analogRead (BASE + 1) ;

digitalWrite (27, HIGH) ;
delay (100) ;
front = analogRead (BASE + 4) ;
digitalWrite (27, LOW) ;

digitalWrite (28, HIGH) ;
delay (100) ;
left  = analogRead (BASE + 5) ;
digitalWrite (28, LOW) ;

digitalWrite (29, HIGH) ;
delay (100) ;
right = analogRead (BASE + 6) ;
digitalWrite (29, LOW) ;

if (front > 500)
{
digitalWrite (2, LOW) ;
digitalWrite (3, LOW) ;
digitalWrite (4, LOW) ;
digitalWrite (5, LOW) ;
delay (20) ;

digitalWrite (2, LOW) ;
```

3

```
digitalWrite (3, HIGH) ;
digitalWrite (4, LOW) ;
digitalWrite (5, HIGH) ;
delay (200) ;
}
else if (front > 400 && front <= 500)
{
digitalWrite (2, LOW) ;
digitalWrite (3, LOW) ;
digitalWrite (4, LOW) ;
digitalWrite (5, LOW) ;
delay (20) ;
if (left >= right)
{
digitalWrite (2, HIGH) ;
digitalWrite (3, LOW) ;
digitalWrite (4, LOW) ;
digitalWrite (5, HIGH) ;
delay (200) ;
}
else
{
digitalWrite (2, LOW) ;
digitalWrite (3, HIGH) ;
digitalWrite (4, HIGH) ;
digitalWrite (5, LOW) ;
delay (200) ;
}
digitalWrite (2, LOW) ;
digitalWrite (3, LOW) ;
digitalWrite (4, LOW) ;
digitalWrite (5, LOW) ;
delay (20) ;
```

4

```
}

else
{
if (left > 500)
{
digitalWrite (2, HIGH) ;
digitalWrite (3, LOW) ;
digitalWrite (4, LOW) ;
digitalWrite (5, LOW) ;
delay (200) ;
}
else if (right > 500)
{
digitalWrite (2, LOW) ;
digitalWrite (3, LOW) ;
digitalWrite (4, HIGH) ;
digitalWrite (5, LOW) ;
delay (200) ;
}
else
{
digitalWrite (2, HIGH) ;
digitalWrite (3, LOW) ;
digitalWrite (4, HIGH) ;
digitalWrite (5, LOW) ;
delay (200) ;
}
}

if (depth < 450)
{
digitalWrite (26, HIGH) ;
```

5

```
delay (100) ;
depth = analogRead (BASE + 3) ;
digitalWrite (26, LOW) ;

if (depth < 400)
{
pwmWrite (1, 800) ;
}

else
{
pwmWrite (1, 600) ;
}

digitalWrite (23, HIGH) ;
digitalWrite (24, HIGH) ;
}

else
{
depth = analogRead (BASE + 3) ;
digitalWrite (23, LOW) ;
digitalWrite (24, LOW) ;
}

printf      ("%5d%5d%5d%5d%5d%5d\n",
count, y, depth, front, left, right) ;
}

pwmWrite (1, 0) ;
digitalWrite (2, LOW) ;
digitalWrite (3, LOW) ;
digitalWrite (4, LOW) ;
```

6

```
digitalWrite (5, LOW) ;
digitalWrite (23, LOW) ;
digitalWrite (24, LOW) ;
digitalWrite (25, LOW) ;
digitalWrite (26, LOW) ;
digitalWrite (27, LOW) ;
digitalWrite (28, LOW) ;
digitalWrite (29, LOW) ;

return 0 ;
}
```

APPENDIX E

Results for Experiment 1: Controlling DC Brushless Motor

Time (s)	Output Voltages (V)
0	0.00
2	0.08
4	0.20
6	0.52
8	3.12
10	3.86
12	3.28
14	2.41
16	0.93
18	0.07
20	0.00
22	-0.10
24	-0.31
26	-1.95
28	-3.37
30	-3.88
32	-3.42
34	-2.82
36	-1.77
38	-0.10
40	0.00

APPENDIX F

Results for Experiment 3: Distance Measurement of Ultrasonic Sensor in Air and Underwater Environment

1. Distance Measurement of Ultrasonic Sensor in Air

Distance (cm)	Desired Voltage (V)	Measured Output Voltage (V)							
		1st	2nd	3rd	4th	5th	Mean	Std. Dev.	RMS Error
10	0.100	0.210	0.210	0.210	0.210	0.210	0.210	0.000	0.110
20	0.200	0.190	0.190	0.190	0.190	0.190	0.190	0.000	0.010
30	0.300	0.270	0.270	0.270	0.270	0.270	0.270	0.000	0.030
40	0.400	0.370	0.370	0.370	0.370	0.370	0.370	0.000	0.030
50	0.500	0.470	0.470	0.470	0.470	0.470	0.470	0.000	0.030
60	0.600	0.570	0.570	0.570	0.570	0.570	0.570	0.000	0.030
70	0.700	0.660	0.660	0.660	0.660	0.660	0.660	0.000	0.040
80	0.800	0.770	0.760	0.760	0.760	0.760	0.762	0.004	0.038
90	0.900	0.860	0.860	0.860	0.860	0.860	0.860	0.000	0.040
100	1.000	0.960	0.960	0.960	0.960	0.960	0.960	0.000	0.040
110	1.100	1.050	1.060	1.050	1.050	1.050	1.052	0.004	0.048
120	1.200	1.150	1.150	1.150	1.150	1.150	1.150	0.000	0.050
130	1.300	1.250	1.250	1.250	1.250	1.250	1.250	0.000	0.050
140	1.400	1.350	1.350	1.350	1.350	1.350	1.350	0.000	0.050
150	1.500	1.450	1.450	1.450	1.450	1.450	1.450	0.000	0.050
160	1.600	1.550	1.550	1.550	1.550	1.550	1.550	0.000	0.050
170	1.700	1.650	1.650	1.650	1.650	1.650	1.650	0.000	0.050
180	1.800	1.750	1.750	1.740	1.750	1.750	1.748	0.004	0.052
190	1.900	1.840	1.840	1.840	1.840	1.840	1.840	0.000	0.060
200	2.000	1.940	1.940	1.940	1.940	1.940	1.940	0.000	0.060
210	2.100	2.040	2.040	2.040	2.040	2.040	2.040	0.000	0.060
220	2.200	2.140	2.140	2.140	2.140	2.140	2.140	0.000	0.060
230	2.300	2.240	2.240	2.240	2.230	2.240	2.238	0.004	0.062
240	2.400	2.330	2.330	2.330	2.330	2.330	2.330	0.000	0.070
250	2.500	2.440	2.430	2.430	2.440	2.430	2.434	0.005	0.066
260	2.600	2.530	2.540	2.530	2.530	2.530	2.532	0.004	0.068
270	2.700	2.630	2.630	2.630	2.630	2.630	2.630	0.000	0.070
280	2.800	2.730	2.730	2.730	2.730	2.730	2.730	0.000	0.070
290	2.900	2.840	2.830	2.830	2.830	2.830	2.832	0.004	0.068
300	3.000	2.930	2.930	2.930	2.930	2.930	2.930	0.000	0.070
310	3.100	3.030	3.030	3.030	3.030	3.030	3.030	0.000	0.070
320	3.200	3.130	3.130	3.130	3.120	3.130	3.128	0.004	0.072
330	3.300	3.230	3.230	3.230	3.230	3.220	3.228	0.004	0.072
340	3.400	5.980	5.980	5.980	5.980	5.980	5.980	0.000	2.580
350	3.500	5.980	5.980	5.980	5.980	5.980	5.980	0.000	2.480

2. Distance Measurement of Ultrasonic Sensor in Underwater

Distance (cm)	Desired Voltage (V)	Measured Output Voltage (V)							
		1st	2nd	3rd	4th	5th	Mean	Std. Dev.	RMS Error
10	0.023	0.196	0.196	0.196	0.196	0.196	0.196	0.000	0.172
20	0.047	0.196	0.196	0.196	0.196	0.196	0.196	0.000	0.149
30	0.070	0.196	0.196	0.196	0.196	0.196	0.196	0.000	0.126
40	0.093	0.196	0.196	0.196	0.196	0.196	0.196	0.000	0.102
50	0.116	0.196	0.196	0.196	0.196	0.196	0.196	0.000	0.079
60	0.140	0.196	0.196	0.196	0.196	0.196	0.196	0.000	0.056
70	0.163	0.196	0.196	0.196	0.196	0.196	0.196	0.000	0.033
80	0.186	0.196	0.198	0.198	0.196	0.198	0.197	0.001	0.011
90	0.209	0.198	0.198	0.198	0.198	0.198	0.198	0.000	0.012
100	0.233	0.198	0.200	0.200	0.200	0.200	0.200	0.001	0.033
110	0.256	0.200	0.203	0.203	0.203	0.203	0.202	0.001	0.054
120	0.279	0.203	0.205	0.205	0.205	0.205	0.204	0.001	0.075
130	0.303	0.205	0.207	0.207	0.207	0.207	0.207	0.001	0.096
140	0.326	0.207	0.209	0.209	0.209	0.209	0.209	0.001	0.117
150	0.349	0.209	0.212	0.212	0.212	0.212	0.211	0.001	0.138
160	0.372	0.212	0.214	0.214	0.214	0.214	0.214	0.001	0.159
170	0.396	0.214	0.216	0.216	0.216	0.216	0.216	0.001	0.180
180	0.419	0.216	0.219	0.219	0.219	0.219	0.218	0.001	0.201

APPENDIX G

Results for Experiment 4: Distance Measurement of Infrared Sensor in Air and Underwater Environment

1. Distance Measurement of Infrared Sensor in Air

Distance (cm)	Measured Output Voltage(V)						
	1st	2nd	3rd	4th	5th	Mean	Std. Dev.
0	4.700	4.710	4.700	4.710	4.700	4.704	0.005
10	2.890	2.890	2.890	2.890	2.900	2.892	0.004
20	0.930	0.940	0.930	0.920	0.930	0.930	0.006
30	0.440	0.450	0.450	0.450	0.450	0.448	0.004
40	0.310	0.310	0.300	0.310	0.300	0.306	0.005
50	0.240	0.240	0.250	0.250	0.240	0.244	0.005
60	0.200	0.210	0.210	0.210	0.210	0.208	0.004
70	0.190	0.190	0.190	0.200	0.190	0.192	0.004
80	0.180	0.180	0.180	0.180	0.190	0.182	0.004
90	0.160	0.170	0.170	0.170	0.170	0.168	0.004
100	0.160	0.150	0.150	0.160	0.160	0.156	0.005

2. Distance Measurement of Infrared Sensor in Underwater

Distance (cm)	Measured Output Voltage(V)						
	1st	2nd	3rd	4th	5th	Mean	Std. Dev.
0	4.670	4.670	4.660	4.670	4.660	4.666	0.005
1	4.390	4.400	4.400	4.390	4.390	4.394	0.005
2	3.630	3.600	3.620	3.630	3.630	3.622	0.012
3	2.150	2.160	2.150	2.150	2.160	2.154	0.005
4	1.020	1.010	1.020	1.020	1.020	1.018	0.004
5	0.590	0.610	0.600	0.590	0.590	0.596	0.008
6	0.300	0.290	0.300	0.300	0.290	0.296	0.005
7	0.180	0.190	0.180	0.180	0.180	0.182	0.004
8	0.120	0.130	0.130	0.120	0.120	0.124	0.005
9	0.070	0.060	0.070	0.070	0.070	0.068	0.004
10	0.050	0.040	0.050	0.060	0.060	0.052	0.007
20	0.020	0.020	0.030	0.020	0.020	0.022	0.004
30	0.010	0.010	0.010	0.010	0.010	0.010	0.000
40	0.010	0.010	0.010	0.010	0.010	0.010	0.000
50	0.010	0.010	0.010	0.010	0.010	0.010	0.000
60	0.010	0.010	0.010	0.010	0.010	0.010	0.000
70	0.010	0.010	0.010	0.010	0.010	0.010	0.000
80	0.010	0.010	0.010	0.010	0.010	0.010	0.000
90	0.010	0.010	0.010	0.010	0.010	0.010	0.000
100	0.010	0.010	0.010	0.010	0.010	0.010	0.000

APPENDIX H

Results for Experiment 5: Light Detection of Blue LED with Different Light Wavelengths

Wavelength (nm)	Measured Output Voltage (V)						
	1st	2nd	3rd	4th	5th	Mean	Std. Dev.
380	0.674	0.671	0.668	0.665	0.668	0.669	0.003
390	0.694	0.684	0.687	0.690	0.697	0.690	0.005
400	0.713	0.706	0.703	0.706	0.706	0.707	0.003
410	0.713	0.716	0.719	0.723	0.713	0.717	0.004
420	0.723	0.719	0.719	0.716	0.723	0.720	0.002
430	0.742	0.739	0.739	0.742	0.735	0.739	0.002
440	0.726	0.723	0.739	0.723	0.726	0.727	0.006
450	0.729	0.735	0.739	0.742	0.745	0.738	0.006
460	0.752	0.748	0.745	0.742	0.719	0.741	0.011
470	0.735	0.735	0.732	0.726	0.729	0.732	0.004
480	0.748	0.748	0.748	0.745	0.745	0.747	0.002
490	0.745	0.752	0.748	0.752	0.745	0.748	0.003
500	0.735	0.716	0.723	0.739	0.732	0.729	0.008
510	0.310	0.306	0.306	0.303	0.303	0.306	0.002
520	0.316	0.310	0.306	0.303	0.316	0.310	0.005
530	0.339	0.339	0.335	0.332	0.335	0.336	0.002
540	0.355	0.355	0.355	0.355	0.355	0.355	0.000
550	0.394	0.390	0.390	0.394	0.394	0.392	0.002
560	0.432	0.442	0.442	0.429	0.439	0.437	0.005
570	0.452	0.445	0.442	0.439	0.439	0.443	0.005
580	0.452	0.445	0.445	0.442	0.442	0.445	0.004
590	0.435	0.435	0.435	0.439	0.439	0.437	0.002
600	0.432	0.419	0.416	0.413	0.432	0.423	0.008
610	0.406	0.410	0.406	0.410	0.400	0.406	0.004
620	0.371	0.384	0.387	0.365	0.371	0.375	0.009
630	0.348	0.348	0.358	0.352	0.355	0.352	0.004
640	0.332	0.335	0.348	0.355	0.332	0.341	0.009
650	0.329	0.335	0.348	0.332	0.352	0.339	0.009
660	0.352	0.348	0.332	0.335	0.345	0.343	0.007
670	0.348	0.348	0.345	0.335	0.335	0.343	0.006
680	0.339	0.332	0.335	0.348	0.352	0.341	0.007
690	0.329	0.342	0.348	0.352	0.352	0.345	0.009
700	0.329	0.348	0.342	0.335	0.339	0.339	0.006
710	0.335	0.329	0.348	0.352	0.329	0.339	0.010
720	0.326	0.339	0.342	0.332	0.326	0.333	0.007
730	0.329	0.319	0.316	0.310	0.316	0.318	0.006
740	0.290	0.281	0.297	0.297	0.290	0.291	0.006

750	0.287	0.274	0.271	0.281	0.274	0.277	0.006
760	0.248	0.252	0.258	0.258	0.248	0.253	0.004
770	0.229	0.235	0.239	0.235	0.229	0.234	0.004
780	0.219	0.219	0.226	0.226	0.223	0.223	0.003
White	0.768	0.768	0.758	0.768	0.768	0.766	0.004
Black	0.142	0.139	0.132	0.135	0.142	0.138	0.004

APPENDIX I

Results for Experiment 6: Distance Measurement of Laser Sensor in Air and Underwater Environment

1. Shiny White Paper in Air

Distance (cm)	Measured Output Voltage (V)						
	1st	2nd	3rd	4th	5th	Mean	Std. Dev.
10	1.703	1.700	1.700	1.697	1.697	1.699	0.002
20	1.674	1.668	1.668	1.668	1.668	1.669	0.003
30	1.639	1.632	1.632	1.632	1.632	1.634	0.003
40	1.613	1.606	1.603	1.600	1.603	1.605	0.004
50	1.581	1.577	1.577	1.581	1.581	1.579	0.002
60	1.561	1.561	1.558	1.561	1.558	1.560	0.002
70	1.539	1.542	1.542	1.539	1.542	1.541	0.002
80	1.526	1.526	1.523	1.526	1.523	1.525	0.002
90	1.516	1.516	1.513	1.513	1.513	1.514	0.002
100	1.503	1.500	1.500	1.497	1.494	1.499	0.003
110	1.487	1.490	1.484	1.484	1.487	1.486	0.002
120	1.481	1.474	1.477	1.474	1.477	1.477	0.002
130	1.474	1.474	1.471	1.468	1.471	1.472	0.002
140	1.468	1.461	1.461	1.455	1.458	1.461	0.004
150	1.458	1.458	1.458	1.452	1.458	1.457	0.003
160	1.452	1.448	1.445	1.448	1.452	1.449	0.002
170	1.452	1.448	1.448	1.452	1.448	1.450	0.002
180	1.445	1.448	1.452	1.442	1.448	1.447	0.003
190	1.445	1.445	1.442	1.445	1.445	1.445	0.001
200	1.442	1.445	1.442	1.445	1.448	1.445	0.002
210	1.439	1.439	1.439	1.448	1.455	1.444	0.007
220	1.439	1.442	1.439	1.445	1.442	1.441	0.002
230	1.439	1.432	1.435	1.439	1.445	1.438	0.004
240	1.435	1.439	1.432	1.439	1.442	1.437	0.003
250	1.439	1.429	1.429	1.439	1.435	1.434	0.004
260	1.435	1.439	1.435	1.432	1.429	1.434	0.003
270	1.429	1.432	1.432	1.423	1.426	1.428	0.004
280	1.423	1.426	1.429	1.419	1.426	1.425	0.003
290	1.419	1.423	1.419	1.423	1.426	1.422	0.002
300	1.423	1.423	1.423	1.419	1.423	1.422	0.001
310	1.416	1.416	1.429	1.419	1.419	1.420	0.005
320	1.413	1.416	1.419	1.419	1.419	1.417	0.003
330	1.416	1.413	1.410	1.413	1.410	1.412	0.002
340	1.413	1.413	1.410	1.410	1.406	1.410	0.002
350	1.410	1.410	1.406	1.403	1.410	1.408	0.003

2. White Paper in Air

Distance (cm)	Measured Output Voltage (V)						
	1st	2nd	3rd	4th	5th	Mean	Std. Dev.
10	1.655	1.652	1.652	1.648	1.648	1.651	0.002
20	1.626	1.619	1.619	1.619	1.619	1.621	0.003
30	1.590	1.587	1.587	1.587	1.587	1.588	0.001
40	1.565	1.561	1.558	1.555	1.558	1.559	0.003
50	1.535	1.532	1.532	1.535	1.535	1.534	0.002
60	1.516	1.516	1.513	1.516	1.513	1.515	0.002
70	1.497	1.500	1.500	1.497	1.500	1.499	0.002
80	1.484	1.484	1.481	1.484	1.481	1.483	0.002
90	1.474	1.474	1.471	1.471	1.471	1.472	0.002
100	1.465	1.461	1.468	1.465	1.465	1.465	0.002
110	1.455	1.452	1.455	1.458	1.458	1.455	0.002
120	1.445	1.448	1.442	1.435	1.445	1.443	0.004
130	1.442	1.442	1.439	1.439	1.442	1.441	0.002
140	1.442	1.435	1.435	1.429	1.432	1.435	0.004
150	1.439	1.432	1.432	1.439	1.439	1.436	0.003
160	1.426	1.423	1.419	1.423	1.426	1.423	0.002
170	1.416	1.423	1.423	1.416	1.423	1.420	0.003
180	1.419	1.423	1.426	1.416	1.423	1.421	0.003
190	1.406	1.413	1.416	1.419	1.419	1.415	0.005
200	1.410	1.403	1.403	1.403	1.403	1.405	0.003
210	1.406	1.406	1.406	1.416	1.419	1.411	0.006
220	1.413	1.410	1.416	1.413	1.416	1.414	0.002
230	1.419	1.400	1.410	1.410	1.410	1.410	0.006
240	1.426	1.416	1.403	1.406	1.410	1.412	0.008
250	1.406	1.397	1.397	1.406	1.403	1.402	0.004
260	1.403	1.406	1.403	1.400	1.397	1.402	0.003
270	1.397	1.400	1.400	1.390	1.394	1.396	0.004
280	1.390	1.394	1.397	1.387	1.394	1.392	0.003
290	1.387	1.390	1.387	1.390	1.394	1.390	0.002
300	1.390	1.390	1.390	1.387	1.390	1.390	0.001
310	1.387	1.387	1.400	1.390	1.390	1.391	0.005
320	1.384	1.387	1.390	1.390	1.390	1.388	0.003
330	1.387	1.384	1.381	1.384	1.381	1.383	0.002
340	1.384	1.384	1.381	1.381	1.377	1.381	0.002
350	1.381	1.381	1.377	1.374	1.381	1.379	0.003

3. Grey Paper in Air

Distance (cm)	Measured Output Voltage (V)						
	1st	2nd	3rd	4th	5th	Mean	Std. Dev.
10	1.635	1.623	1.616	1.613	1.613	1.620	0.009
20	1.600	1.594	1.590	1.587	1.584	1.591	0.006
30	1.561	1.558	1.555	1.555	1.555	1.557	0.003
40	1.529	1.526	1.529	1.526	1.523	1.526	0.002
50	1.506	1.506	1.503	1.503	1.497	1.503	0.004
60	1.487	1.487	1.484	1.490	1.487	1.487	0.002
70	1.474	1.474	1.471	1.468	1.468	1.471	0.003
80	1.458	1.455	1.452	1.455	1.455	1.455	0.002
90	1.442	1.442	1.442	1.445	1.442	1.443	0.001
100	1.429	1.429	1.435	1.426	1.432	1.430	0.003
110	1.426	1.429	1.426	1.419	1.419	1.424	0.004
120	1.419	1.419	1.419	1.416	1.406	1.416	0.005
130	1.416	1.419	1.413	1.419	1.423	1.418	0.003
140	1.410	1.413	1.416	1.410	1.413	1.412	0.002
150	1.403	1.403	1.403	1.403	1.403	1.403	0.000
160	1.400	1.413	1.400	1.400	1.406	1.404	0.005
170	1.390	1.394	1.394	1.397	1.394	1.394	0.002
180	1.387	1.390	1.394	1.397	1.394	1.392	0.003
190	1.390	1.394	1.390	1.394	1.394	1.392	0.002
200	1.390	1.394	1.387	1.390	1.394	1.391	0.002
210	1.384	1.381	1.384	1.387	1.387	1.385	0.002
220	1.387	1.384	1.381	1.381	1.384	1.383	0.002
230	1.381	1.377	1.387	1.381	1.374	1.380	0.004
240	1.371	1.371	1.377	1.377	1.374	1.374	0.003
250	1.368	1.377	1.377	1.381	1.371	1.375	0.005
260	1.368	1.374	1.371	1.371	1.368	1.370	0.002
270	1.374	1.371	1.368	1.365	1.368	1.369	0.003
280	1.371	1.371	1.368	1.374	1.371	1.371	0.002
290	1.365	1.371	1.374	1.368	1.365	1.368	0.004
300	1.365	1.374	1.365	1.371	1.365	1.368	0.004
310	1.371	1.368	1.371	1.368	1.371	1.370	0.002
320	1.371	1.374	1.365	1.374	1.371	1.371	0.004
330	1.365	1.368	1.371	1.368	1.365	1.367	0.002
340	1.365	1.365	1.368	1.365	1.365	1.365	0.001
350	1.368	1.371	1.368	1.365	1.361	1.366	0.003

4. Black Paper in Air

Distance (cm)	Measured Output Voltage (V)						
	1st	2nd	3rd	4th	5th	Mean	Std. Dev.
10	1.552	1.548	1.545	1.545	1.545	1.547	0.003
20	1.516	1.513	1.513	1.510	1.510	1.512	0.002
30	1.484	1.481	1.484	1.481	1.481	1.482	0.002
40	1.448	1.448	1.445	1.452	1.452	1.449	0.002
50	1.429	1.432	1.429	1.429	1.429	1.430	0.001
60	1.410	1.413	1.416	1.413	1.410	1.412	0.002
70	1.403	1.403	1.403	1.403	1.400	1.403	0.001
80	1.390	1.387	1.387	1.390	1.394	1.390	0.002
90	1.381	1.381	1.377	1.381	1.381	1.380	0.001
100	1.374	1.377	1.377	1.377	1.374	1.376	0.002
110	1.371	1.371	1.368	1.371	1.368	1.370	0.002
120	1.365	1.365	1.365	1.365	1.368	1.365	0.001
130	1.358	1.361	1.361	1.361	1.358	1.360	0.002
140	1.352	1.352	1.352	1.358	1.352	1.353	0.003
150	1.352	1.345	1.348	1.348	1.345	1.348	0.002
160	1.348	1.348	1.348	1.345	1.348	1.348	0.001
170	1.345	1.345	1.348	1.345	1.352	1.347	0.003
180	1.342	1.345	1.348	1.348	1.348	1.346	0.003
190	1.345	1.335	1.339	1.342	1.339	1.340	0.003
200	1.342	1.339	1.352	1.345	1.345	1.345	0.004
210	1.339	1.342	1.339	1.339	1.339	1.339	0.001
220	1.342	1.342	1.342	1.342	1.342	1.342	0.000
230	1.339	1.345	1.342	1.345	1.342	1.343	0.002
240	1.342	1.348	1.345	1.339	1.342	1.343	0.003
250	1.339	1.339	1.342	1.339	1.342	1.340	0.002
260	1.339	1.345	1.339	1.345	1.342	1.342	0.003
270	1.345	1.342	1.342	1.339	1.335	1.341	0.003
280	1.329	1.329	1.332	1.332	1.332	1.331	0.002
290	1.326	1.326	1.326	1.323	1.332	1.326	0.003
300	1.323	1.326	1.323	1.326	1.323	1.324	0.002
310	1.329	1.326	1.332	1.326	1.332	1.329	0.003
320	1.329	1.329	1.329	1.326	1.329	1.328	0.001
330	1.329	1.329	1.329	1.326	1.329	1.328	0.001
340	1.329	1.332	1.332	1.329	1.329	1.330	0.002
350	1.326	1.329	1.329	1.329	1.332	1.329	0.002

5. Transparent Perspex in Air

Distance (cm)	Measured Output Voltage (V)						
	1st	2nd	3rd	4th	5th	Mean	Std. Dev.
10	1.600	1.597	1.597	1.594	1.594	1.596	0.002
20	1.584	1.577	1.577	1.577	1.577	1.579	0.003
30	1.565	1.558	1.558	1.558	1.558	1.559	0.003
40	1.548	1.542	1.539	1.535	1.539	1.541	0.004
50	1.523	1.519	1.519	1.523	1.526	1.522	0.002
60	1.510	1.510	1.506	1.510	1.506	1.508	0.002
70	1.490	1.494	1.494	1.490	1.494	1.492	0.002
80	1.484	1.484	1.481	1.484	1.481	1.483	0.002
90	1.477	1.477	1.474	1.474	1.474	1.475	0.002
100	1.468	1.465	1.465	1.461	1.458	1.463	0.003
110	1.455	1.458	1.452	1.452	1.455	1.454	0.002
120	1.452	1.445	1.448	1.445	1.448	1.448	0.002
130	1.448	1.448	1.445	1.442	1.445	1.446	0.002
140	1.445	1.439	1.439	1.432	1.435	1.438	0.004
150	1.435	1.435	1.435	1.429	1.435	1.434	0.003
160	1.432	1.429	1.426	1.429	1.432	1.430	0.002
170	1.432	1.429	1.429	1.432	1.429	1.430	0.002
180	1.423	1.426	1.429	1.419	1.426	1.425	0.003
190	1.426	1.426	1.423	1.426	1.426	1.425	0.001
200	1.423	1.426	1.423	1.426	1.429	1.425	0.002
210	1.419	1.419	1.419	1.429	1.435	1.425	0.007
220	1.419	1.423	1.419	1.426	1.423	1.422	0.002
230	1.419	1.413	1.416	1.419	1.426	1.419	0.004
240	1.416	1.419	1.413	1.419	1.423	1.418	0.003
250	1.419	1.410	1.410	1.419	1.416	1.415	0.004
260	1.416	1.419	1.416	1.413	1.410	1.415	0.003
270	1.410	1.413	1.413	1.403	1.406	1.409	0.004
280	1.406	1.410	1.413	1.403	1.410	1.408	0.003
290	1.403	1.406	1.403	1.406	1.410	1.406	0.002
300	1.406	1.406	1.406	1.403	1.406	1.406	0.001
310	1.400	1.400	1.413	1.403	1.403	1.404	0.005
320	1.397	1.400	1.403	1.403	1.403	1.401	0.003
330	1.400	1.397	1.394	1.397	1.394	1.396	0.002
340	1.397	1.397	1.394	1.394	1.390	1.394	0.002
350	1.394	1.394	1.390	1.387	1.394	1.392	0.003

6. Shiny White Paper in Underwater

Distance (cm)	Measured Output Voltage (V)						
	1st	2nd	3rd	4th	5th	Mean	Std. Dev.
10	1.526	1.516	1.523	1.523	1.523	1.522	0.003
20	1.455	1.458	1.455	1.448	1.445	1.452	0.005
30	1.413	1.406	1.416	1.413	1.406	1.411	0.004
40	1.384	1.387	1.377	1.371	1.381	1.380	0.006
50	1.348	1.348	1.355	1.348	1.348	1.350	0.003
60	1.326	1.339	1.332	1.323	1.323	1.328	0.006
70	1.323	1.310	1.310	1.310	1.310	1.312	0.005
80	1.306	1.310	1.310	1.310	1.300	1.307	0.004
90	1.297	1.294	1.287	1.303	1.303	1.297	0.006
100	1.290	1.290	1.277	1.281	1.290	1.286	0.006
110	1.281	1.271	1.281	1.268	1.277	1.275	0.005
120	1.277	1.268	1.274	1.265	1.265	1.270	0.005

7. White Paper in Underwater

Distance (cm)	Measured Output Voltage (V)						
	1st	2nd	3rd	4th	5th	Mean	Std. Dev.
10	1.500	1.487	1.497	1.490	1.490	1.493	0.005
20	1.413	1.410	1.413	1.400	1.416	1.410	0.006
30	1.368	1.368	1.374	1.365	1.374	1.370	0.004
40	1.352	1.339	1.348	1.345	1.339	1.345	0.005
50	1.319	1.316	1.316	1.316	1.326	1.319	0.004
60	1.294	1.294	1.300	1.303	1.297	1.297	0.004
70	1.274	1.268	1.277	1.284	1.274	1.275	0.005
80	1.268	1.252	1.265	1.258	1.271	1.263	0.007
90	1.245	1.255	1.261	1.245	1.255	1.252	0.006
100	1.235	1.229	1.242	1.239	1.235	1.236	0.004
110	1.223	1.235	1.232	1.239	1.232	1.232	0.005
120	1.223	1.226	1.226	1.226	1.213	1.223	0.005

8. Grey Paper in Underwater

Distance (cm)	Measured Output Voltage (V)						
	1st	2nd	3rd	4th	5th	Mean	Std. Dev.
10	1.394	1.390	1.384	1.381	1.381	1.386	0.005
20	1.335	1.329	1.313	1.332	1.329	1.328	0.008
30	1.294	1.294	1.290	1.277	1.277	1.286	0.007
40	1.261	1.261	1.261	1.261	1.271	1.263	0.004
50	1.261	1.242	1.235	1.245	1.242	1.245	0.009
60	1.184	1.210	1.226	1.216	1.216	1.210	0.014
70	1.194	1.213	1.206	1.213	1.226	1.210	0.010
80	1.155	1.203	1.206	1.200	1.206	1.194	0.020
90	1.177	1.203	1.210	1.200	1.216	1.201	0.013
100	1.129	1.177	1.187	1.190	1.213	1.179	0.028
110	1.152	1.190	1.197	1.206	1.197	1.188	0.019
120	1.139	1.168	1.194	1.187	1.190	1.175	0.020

9. Black Paper in Underwater

Distance (cm)	Measured Output Voltage (V)						
	1st	2nd	3rd	4th	5th	Mean	Std. Dev.
10	1.377	1.381	1.377	1.371	1.381	1.377	0.004
20	1.323	1.319	1.310	1.319	1.319	1.318	0.004
30	1.287	1.277	1.277	1.281	1.281	1.281	0.004
40	1.255	1.265	1.255	1.252	1.255	1.256	0.004
50	1.223	1.252	1.235	1.252	1.248	1.242	0.011
60	1.200	1.232	1.229	1.242	1.242	1.229	0.015
70	1.161	1.223	1.223	1.223	1.229	1.212	0.025
80	1.106	1.181	1.213	1.219	1.213	1.186	0.042
90	1.110	1.190	1.206	1.216	1.223	1.189	0.041
100	1.126	1.187	1.206	1.219	1.206	1.189	0.033
110	1.129	1.187	1.200	1.206	1.216	1.188	0.031
120	1.123	1.177	1.206	1.210	1.219	1.187	0.035

10. Transparent Perspex in Underwater

Distance (cm)	Measured Output Voltage (V)						
	1st	2nd	3rd	4th	5th	Mean	Std. Dev.
10	1.377	1.377	1.371	1.358	1.371	1.371	0.007
20	1.352	1.355	1.352	1.352	1.348	1.352	0.002
30	1.342	1.352	1.352	1.339	1.352	1.347	0.006
40	1.329	1.335	1.332	1.329	1.342	1.334	0.005
50	1.303	1.294	1.290	1.294	1.306	1.297	0.006
60	1.297	1.297	1.303	1.306	1.290	1.299	0.006
70	1.290	1.294	1.287	1.290	1.277	1.288	0.006
80	1.287	1.271	1.290	1.274	1.284	1.281	0.007
90	1.290	1.271	1.274	1.277	1.274	1.277	0.007
100	1.274	1.277	1.268	1.261	1.277	1.272	0.006
110	1.261	1.271	1.271	1.255	1.268	1.265	0.006
120	1.261	1.258	1.268	1.258	1.252	1.259	0.005