I hereby declare that I have read through this report entitle “Leader Follower Robot” and found that it has comply the partial fulfillment for awarding the degree of Bachelor of Mechatronics Engineering

Signature : ……………………………………

Supervisor’s Name : ……………………………………

Date : ……………………………………

LEADER FOLLOWER ROBOT

LAU WHY CHUONG

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

Faculty of Electrical Engineering (FKE)

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

JUNE 2015

I declare that this report entitle "**Leader Follower Robot**" 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 : ……………………………………

Date : ……………………………………

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ABSTRACT

Nowadays, human capacity is limited in a lot of field especially in industry field which some of the tasks is dangerous or impossible. However, cooperation of robots with each other can overcome this kind of problem. The key elements is the ability of robot to follow other robot and concerned on the following tasks of the mobile robot. However, problems that will occur include the accuracy of tracking robot when the leader is moving, distance of avoidance collision between leader and follower robot, capability to avoid obstacle and the ability of the follower to follow the trajectory. In this project, the objectives are to design leader follower robot, determine the sensitivity of sensors used, perform ability of an obstacle avoidance by follower robot, and perform validation test of follower based on leader's trajectory. For the methodology, there are some important components chosen for the mobile robot configuration. The Ultrasonic Sensor HC-SR04, Infrared Sensor Sharp GP2Y0A21, Arduino Uno function as microcontroller, two DC gear motor, 2 Amp Motor Driver Shield L298P and aluminum chassis as the main base for the follower robot are chosen. The first experiment is to determine the sensitivity of the sensor and avoid obstacle or collision between leader robot using IR sensor while the second experiment is to carry out the sensitivity of ultrasonic sensor to track the robot. The third experiment, carried out to analysis angle of turning of the mobile robot. In last experiment, the results show the analysis of trajectories for straight line, S-shape, U-shape and Zigzag for both with and without obstacles. As conclusion, the follower robot can performed the following task and obstacles avoidance.

ABSTRAK

Pada masa kini, kapasiti manusia adalah terhad dalam banyak bidang terutamanya dalam bidang industri mengandungi tugasan yang berbahaya dan mustahil dijalankan oleh manusia. Walau bagaimanapun, kerjasama robot dengan satu sama lain boleh mengatasi masalah ini. Unsur yang terutama ialah keupayaan robot mengikuti robot lain dan mementingkan bahawa tugasan mengikuti robot tersebut. Walau bagaimanapun, masalah yang akan berlaku termasuk ketepatan robot apabila pemimpin yang sedang bergerak, jarak mengelakkan perlanggaran antara pemimpin dan pengikut robot, keupayaan pengesanan untuk mengelakkan halangan dan keupayaan pengikut robot mengikut trajektori. Dalam projek ini, objektif adalah untuk mereka bentuk robot pemimpin pengikut, menentukan sensitiviti sensor digunakan, melaksanakan keupayaan pengelakan halangan oleh pengikut robot dan menjalankan ujian pengesahan pengikut berdasarkan trajektori pemimpin. Untuk kaedah ini, terdapat beberapa komponen penting yang dipilih untuk konfigurasi pengikut robot. Ultrasonic Sensor HC-SR04, Infrared Sensor Sharp GP2Y0A21, Arduino Uno fungsi sebagai pengawal mikro, dua DC motor gear, 2 Amp Motor Driver Shield L298P dan aluminium chassis sebagai asas utama untuk robot pengikut telah dipilih. Eskperimen pertama adalah untuk menentukan kepekaan sensor dan mengelakkan halangan atau perlanggaran antara robot pemimpin dengan menggunakan infrared sensor manakala eskperimen kedua adalah untuk menjalankan sensitiviti sensor ultrasonik untuk mengesan robot. Eskperimen ketiga, dijalankan untuk menganalisis sudut beralih oleh pengikut robot. Dalam eksperimen terakhir, keputusan menunjukkan analisis trajektori untuk garisan lurus, S-bentuk, bentuk U dan kesenian untuk kedua-dua yang ada halangan dan tanpa halangan. Kesimpulannya, robot pengikut boleh menjalankan tugasan untuk mengikut robot pemimpin dan dapat mengelakkan halangan.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

Nowadays, mobile robots are becoming more heavily used in environments especially in industry field where human involvement is limited, dangerous or impossible. Different levels of complexity of the robots are built to perform multiple tasks that are required. These robots perform in more dangerous and strenuous human tasks and lead to greater efficiency and accuracy, saving both time and resources [1].

Robots are best at performing the same job every time repeatedly. Such jobs are programmed and the performance is reliable and consistent. Humans usually will get worn out from repetitive jobs and suffer from repetitive motion injuries. Human's tiredness and error will lead to fatal accidents and drop the performance of the tasks.

AME BC and PDAC have collected information on fatal incidents in mineral exploration by searching information from exploration companies working in Canada. The Figure 1 illustrates the data of fatalities in mineral exploration in Canada from 1980-2012. These data is clearly incomplete and misleading. The graph shows that there were 91 fatalities cases in mineral exploration in Canada since 1980. With the passage of time, the current trend is no clear indication. There are only 10 cases of the past 33 years including year 2010 which had zero fatalities. The higher numbers of fatal incidents is year 2011 since year 1980. The data shows that industry has not managed to make a significantly safer way for exploration although increased safety awareness over time. This fact is a challenge for all concerned to take action [2].

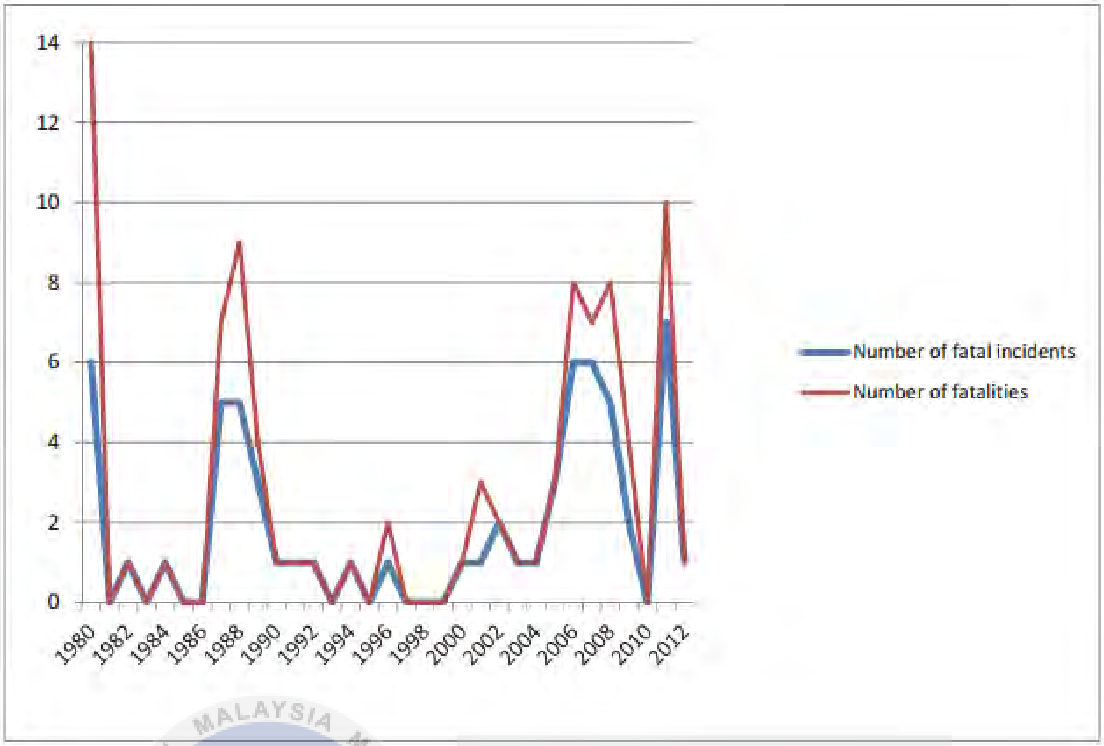

Figure 1.1: Fatalities in Mineral Exploration in Canada 1980 – 2012 [2]

To overcome this problem, robots are required to cooperate with each other to replace human tasks. One of the key elements for the multiple robots to work together is the ability of robot to follow other robot. This element leads to study of leader and follower behavior.

1.2 Problem Statement

Nowadays, robotic technologies have become very important since many industries are trying to improve their performance. This technology has developed many years to make sure an excellent impact. Recently, the robots have been invented to help peoples running their daily life to get the better life.

The main task for the concept of leader follower robot is the following tasks. The following task is important for the mobile robot since the target can be static or dynamic object. However, there are many problems occur when designing a robot to perform a following task. These problems include the accuracy of tracking the robot when the leader is moving, the distance to avoid collisions between leader and follower and the capability to avoid the obstacles. Besides, the response time of the follower when the moment the leader is moving.

1.3 Objectives

1. To design leader follower robot.
2. To determine the sensitivity of sensors used.
3. To implement the concept of an obstacle avoidance and collision avoidance with leader.
4. To perform validation test of follower based on leader's trajectory.

1.4 Scope

1. To implement the ultrasonic sensors and infrared sensors.
2. The collision avoidance with only one leader.
3. The leader and follower robot are run on flat floor.
4. Able to avoid a small size obstacle.
5. The robot are able to turn left, right, forward and reverse.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter review some of the robots that were built to perform the task following. The advantages and disadvantages for each of the robot are also included in the review.

2.2 Coordinated Control of Mobile Robots Based On Artificial Vision

According to [3], in this project, is a coordinated control strategy of multiple robots based on artificial vision to measure the relative position between them, in order to achieve and maintain the specified formation. A leader robot is given that moves about an unknown trajectory and unknown speed. In order to maintain the robots with certain distance between the leader, a controller is designed by using visual information about the position of the leader robot. At equilibrium point, the control system is proved to be stable which achievement of the navigation objective. Experimental results with a leader robot and a follower robot, are included to show the performance based on the vision control system.

Odometric sensors, sonar sensors, gyros, laser and vision and its fusion are commonly used for robot localization and environmental modelling. Vision used because of its ability to capture information. The leader has a pattern mounted on the back, which is observed by the follower robots in order to obtain information about their relative position information to the leader. This is used to control their positions, in order to achieve the specified information. To obtain the visual information, by looking ahead camera mounted on each follower robot. Geometric descriptions of the mobile robot are calculated for the robot position, orientation angle, angular velocities and distance between two driven wheels.

The image of four pattern marks square of know side length that mounted on the leader will be captured by the camera. The image's height of the horizontal median of this square is coinciding with height of the image's camera centre. The location of the leader and the relative position between the leader and a follower robots can be calculated from the image captured by vision system.

Experiments were carried out with two Pioneer 2DX Mobile Robots which has its own control system. The vision system includes a frame grabber PXC200 that allows capturing the images from a camera SONY EV-D30 mounted on the follower robot. These images are transmitted from the follower robot to a Pentium II-400 MHz PC, in charge of processing the images and of calculating the corresponding control actions. From this image, the centroids of the four projected pattern's marks are calculated and used to compute the variables needed by the controller. Finally, the computed control actions are sent by a transmitter to the follower robot.

However, this method has the limitation that the leader robot mounted with pattern's mark need to be made to coincide with the height of the image's camera centre. The image will not transmit by the follower robot if the centroid of each mark is not capture. The follower robot also could not avoid obstacle if there is obstacle in between the leader and follower robot. The cost will be expensive due to complex hardware need to be implemented.

Figure 2.1: Pioneer 2DX Mobile Robots [3]

2.3 A distributed multi-robot sensing system using an infrared location system

According to [4], in this project, the distributed multi-robot sensing system using the infrared location system. The relative positions are estimated using intensity and bearing measurements of the received infrared signals. Fusing the position estimated among robots to obtain the relative orientations. The location system enables a group of robots to perform distributed and cooperative environment sensing by maintaining a given formation while the group measures distributions of light and magnetic field. In the experiments, a group of three robots moves and collects spatial information (i.e. illuminance and compass heading) from the given environment. The information is stored into grid maps and illustrated in the figures presenting illuminance and compass heading.

The infrared location system enables the robots to maintain given formation while sensing the environment. The relative position can be estimated without data transmission between robots. However, the relative orientation needs the data transmission. Estimation of the radial and angular coordinates, respectively, of the other robots in polar coordinates are using intensity and bearing measurements of the signals received. Each robot can be identified through different frequencies in the received signals.

The components are upward pointing emitter, rotating receiver and two microcontrollers to perform position estimation and rotation speed control of the receiver. A conical mirror is used to reflect the signal from emitter sideways into unified zone. Rotating receiving mechanism called beam collector is used to collect the signals from other robots. Signals are received through a small aperture in the beam collector and reflected to the receiver using a mirror. Scanning the surroundings at a constant rotation speed is realized using a DC motor, Hall-effect-sensors and discrete PID controller.

Figure 2.2: Block diagram of the infrared location system [4]

One microcontroller estimates the position of detected and identified robot using an intensity of the received signal and a bearing of the beam collector. The other controls the speed of the beam collector using a discrete PID controller. The microcontrollers exchange information containing a bearing of the beam collector to be used in position estimation and a modulation frequency setup which defines the identification frequency of the robot.

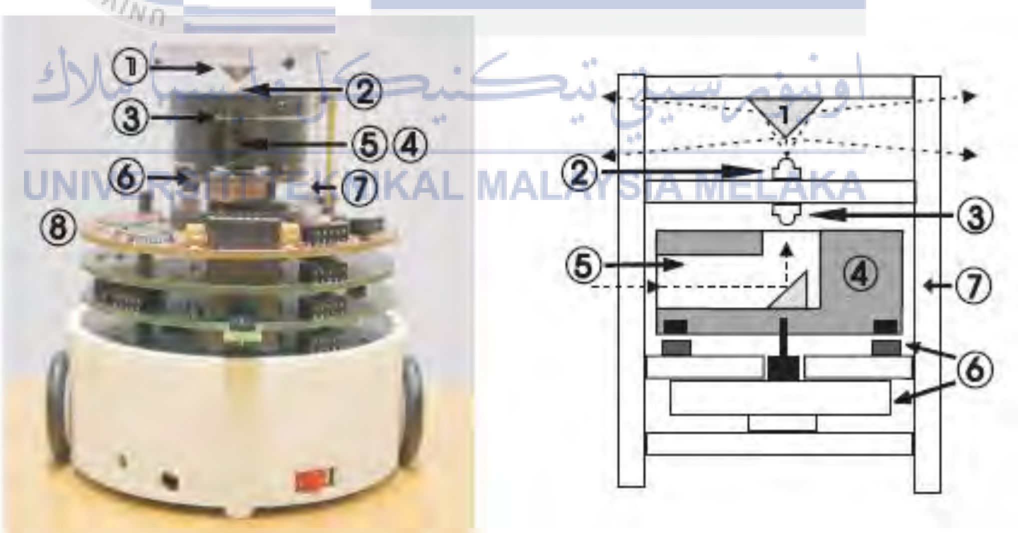

Figure 2.3: The actual system and the illustration of mechanics [4]

There are limitations of this for following behaviour. The measurement range of the location system is limited. Standard deviation for radial coordinate is relative to the distance between a position estimating and a target robot giving the best estimates when only the target is near. Noises in the infrared location system and irregular ground will result in position error. The accuracy of the infrared location system and the leader's odometry will affect the accuracy of the spatial measurements in coordinates. However, there is advantage using infrared sensor method which is low cost compare to vision system. The accuracy of detection for collision avoidance is better that using vision system.

2.4 Low Cost Sensing For Autonomous Car Driving In Highways

According to [5], this project, a car like robot equipped with a system called HANS able to following the road, performing trajectories and safe manner. Besides that, also can keep the safe distance between leader and follower and perform the avoiding obstacles. The experiment was conducted to test the system in both simulation and in a laboratory environment. As a result, these autonomous robots can perform the leader follower behaviour. It is assumed that there are no others car driving faster than HANS vehicle which mean no cars will appear from behind.

HANS using a low resolution web camera located in the centre of the mobile robot behind the rear view mirror and a set of sixteen ultrasonic sensors. The camera functions as a vision system to detect the objects that nearby. It used to detect the side lines that bound the traffic lanes, position and orientation of the robot and distance between robots.

The sixteen ultrasonic sensors are discretized into an occupancy grid as shown in Figure 4. This strategy used to filter the effect that will influence by sonar reflexions. Each of the sonar cones is divided into a number of zones and defined by its distance to the centre of the robot. Each cone or cell, the number of measurement that fell in it is recorded in the occupancy grid. The zone with the highest number of measurements are defined as occupied by an obstacle. Sonars also used to detect the emergency stop.

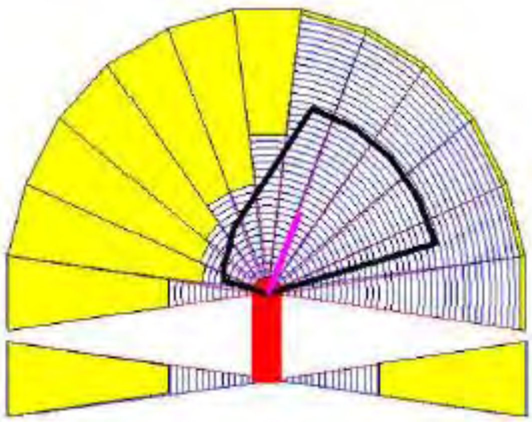

Figure 2.4: Occupancy grid for the sonar data [5]

In this project, the cost is expensive due to use of many ultrasonic sensors. Besides that, the camera is using low resolution web. The low visibility due to light reflection and occlusion due to other vehicles in the road are the common problem.

2.5 The X80 Robot

According to [6], this project presents a control strategy that responds to the requirement of the leader following task. The X80 Robot have two discrete PID controllers, located at each wheel's motor and the data used by the controllers was transmitted from the infrared sensors. When one of the infrared sensors loses the object, an algorithm was conceived to provide the inputs for the controllers. A faulty infrared sensor was detected by using a fault detection scheme that using the information of another sonar sensor. A result of an implementation on the X80 mobile robot was presented.

The robot also has 4 infrared sensors and 4 sonar sensors to perform the following task. It is used to pursuit the direct position of leader robot. The image of the X80 Robot is shown in Figure 5 and the position of each sensor are arranged as shown in Figure 6 respectively. The following task is heavily depending on the infrared sensors only. The measurement of distance return by infrared sensors is checking by the other 3 sonar sensors. The controller used motor to control the angular speed of the two wheels. The linear speed, orientation variation speed and the distance between robots are calculated.

Figure 2.5: The X80 Robot [6]

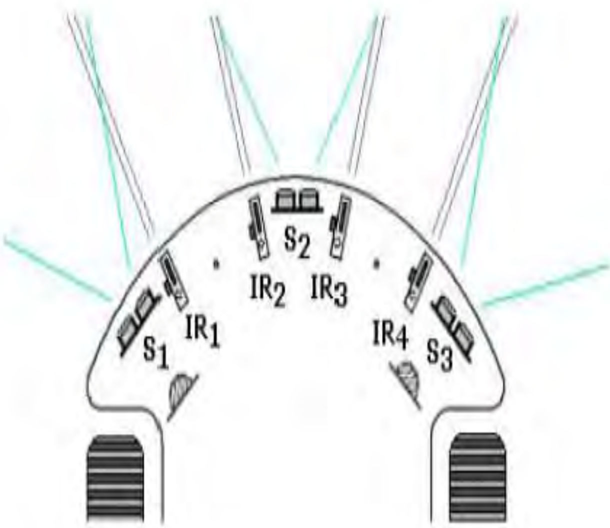

Figure 2.6: IR sensors on X80 Robot

The limitation of the robot is the response of the robot is not fast enough then the follower robots can be lost. The follower will lost the target if the environment space full with the obstacles. Another limitation is that the follower robot needs to stop during when leader is turning direction. Despite its limitation, the X80 robot can follow the leader robot at low speed in free space.

2.6 Vision-based Navigation of Mobile Robot with Obstacle Avoidance by Single Camera Vision and Ultrasonic Sensing

According to [7], this project describes a vision-based navigation method for an autonomous mobile robot, YAMABICO robot, which can perform the obstacles avoidance. In this method, model-based vision system is used for self-localization of the robots and non-stop navigation is achieved through retroactive position correction system. By combination of these two systems, the direction of safe passage can be calculated in the presence of obstacles.

First, the robot will renders an expectation image to estimate the location. Next, extract both model edges for expectation image and camera image and compare through an extended Kalman Filter. Navigate with dead reckoning, meaning that the robot will update its position. The wheel encoders will supply the information to the system. Stationary obstacles are avoided with single-camera vision and moving obstacles are detected with ultrasonic sensors.

The advantage of this method is the view angles of two sensors systems are nearly identical 60 degrees. The ultrasonic sensors can detect obstacles with range of 50cm from robot. Vision sensor detects stationary obstacles at ranges far exceeding 50cm.

Figure 2.7: YAMABICO robot [7]

2.7 Comparison

2.7.1 Overall Criteria

Table 2.1: Comparison of overall criteria

Criteria	Robots				
	Pioneer 2DX Mobile Robot	Distributed Multi-Robot	HANS Robots	X80 Robot	YAMABICO Robot
Sensor	camera	infrared, Hall-effect sensor	low resolution web camera, ultrasonic sensor	Motion sensor, infrared sensor, ultrasonic sensor, camera	vision sensor, ultrasonic sensor
Actuator	motor	DC motor	motor	motor	motor
Controller	-	PID controller	-	WiRobot controller	-
Accuracy of tracking	Low	best estimates when the target is near	low due to low resolution web camera	High	High
Collision avoidance	Low	High	High	High	depends obviously on the visual contrast between the obstacle

2.7.2 Specific Criteria: Sensor

Table 2.2: Comparison of sensor used

Journal	Robots	sensor	Accuracy of tracking	Cost	Directivity	Remark
1	Pioneer 2DX Mobile Robot	camera	low	High	Wide angle	-
2	Distributed Multi-Robot	infrared, Hall-effect sensor	best estimates when the target is near	Low	approximate 15˚ for infrared	for infrared: Vulnerable to changes in ambient light.
3	HANS Robots	low resolution web camera, ultrasonic sensor	low due to low resolution web camera	Low	approximate 30˚ for ultraosnic sensor	for ultrasonic: Work in any lighting conditions.
4	X80 Robot	Motion sensor, infrared sensor, ultrasonic sensor, camera	High	High	Wide angle	-
5	YAMABICO Robot	vision sensor, ultrasonic sensor	High	High	Wide angle	-

2.8 Conclusion

Various methods were developed to perform the task following. The advantages and disadvantages of robots reviewed are discussed in Literature Review. These reviews provide some guidance and knowledge in selecting suitable components. In this project, the most important components that will lead to success for following behaviour and collision avoidance are the ultrasonic sensor and infrared sensor. In conclusion, the ultrasonic sensor and infrared sensor are chosen to be implemented in the project.

The reason of choosing ultrasonic sensor is because it is unaffected by lighting condition of surrounding environment compared to vision sensor. It can perform well under different lighting condition. Besides, the cost of the ultrasonic sensor is much lower compared to vision sensor. The infrared sensor is used to perform the obstacle avoidance. This component is helpful for this project since the robot need to avoid the collision with obstacles around the surrounding.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Previous chapter focuses on the past studies and research related to concept of following task. This chapter will discusses about the methods and techniques used in this project. The following section includes the project planning, components selected, testing and evaluating, procedures and others. The flow of this project will be explained clearly in this chapter.

3.2 Description of the work

3.2.1 Project Flow Chart and Methodology

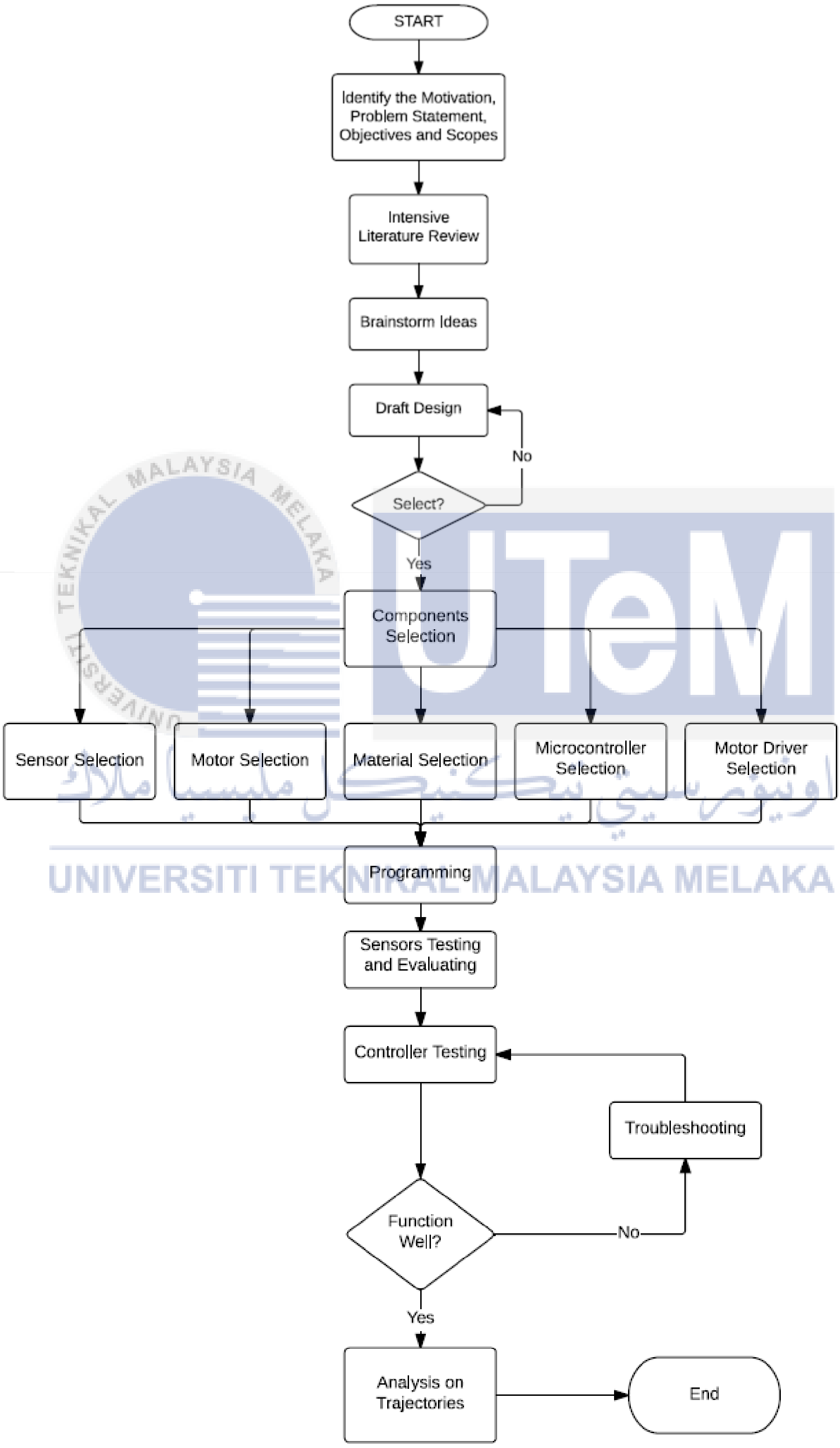

Figure 3.1: Overview of the whole project

The first step to be done is to identify the motivation and problem statement. Next, clearly set up the objectives that need to be achieve in this project as well as the scope which defining the limitation and constraints of the project which is following task. Then, brain storming the ideas and came out with different draft design of follower robot. After compared the designs, the most suitable design will be chosen based on the advantages. Besides, the selection of components are also be considered before proceed to next step which is testing and evaluating. The experiments are done for each part of components and data are collected to do analyzing and interpreting. Once all the structure is constructed, all the components are integrated into the follower robot to start moving. Every step is tested and troubleshooting until it functions well. Last, the result, analysis and discussion are done. Data is collected from Serial Monitor in Arduino Uno.

3.3 Components Selected

3.3.1 Sensor

The main tasks for the concept of leader follower robot are the following tasks. In order for the follower robot to follow the leader robot, the Ultrasonic Sensor HC-SR04 is used to help the follower robot to detect the leader robot. The ultrasonic sensor ranging provides 2cm – 400cm non-contact measurement function. The module includes ultrasonic transmitters, receiver and control circuit. The sensor is tested in Arduino serial monitor. The Figure 3.8 shows the setup of the ultrasonic sensor on mobile robot.

The basic principle of work:

1. Using IO trigger for at least 10µs high level signal.
2. The module automatically sends eight 49 kHz and detect whether there is a pulse signal back.
3. If the signal back, through high level, time of high output 10 duration is the time from sending ultrasonic to returning.

   Test distance = (high level time X velocity of sound (340m/s)/2) [8]

Figure 3.2: Ultrasonic Sensor HC-SR04 [9].

Electric Parameter [8]

Working Voltage	DC 5 V
Working Current	15mA
Working Frequency	40Hz
Max Range	4m
Min Range	2cm
Measuring Angle	15 degree
Trigger Input Signal	10uS TTL pulse
Echo Output Signal	Input TTL lever signal and the range in proportion
Dimension	45*20*15mm

Another sensor selected is the Infrared Sensor Sharp GP2Y0A21 which functions as the collision avoidance between the leader and the follower and avoids the obstacles surrounding the area. The infrared sensors will implement on the follower robot which will measure the distance between the leader robot. The interfacing is very simple with most microcontrollers; the only analog output from the Sharp GP2Y0A21 sensor can be connected to an analog-to-digital converter for taking distance measurements. The sensor is tested and the value is read on Arduino serial monitor. The Figure 3.9 shows the setup of infrared sensors on mobile robot.

Figure 3.3: Infrared Sensor Sharp GP2Y0A21 [10].

Specification as follow:

- Distance measuring range: 10 to 80cm (4" to 32")
- Operating voltage: 4.5V to 5.5V
- Output type: Analog voltage
- Average power consumption : 35 mA
- Peak power consumption : about 200 mA
- Output voltage differential over distance range: 1.9V
- Maximum allowable Angle : > 40 °
- The frequency of updates/cycle : 25 Hz/40 ms

3.3.2 Microcontroller

Arduino is an open-source computing platform based on a simple microcontroller board and can control easily by developing the software and coding for the board. It can be used for developing the interactive objects and can taking physical inputs and outputs. The Arduino software can be downloaded free from internet and able to communicate with software running on computer [11]. Besides, Arduino board are low cost than other microcontroller and it provides a simple and clear programming environment which suitable for beginners. In this project, Arduino Uno is selected as microcontroller. The Figure 3.11 shows the Arduino Uno setup on the mobile robot.

Figure 3.4: Arduino Uno [11].

3.3.3 Motor

Table 3.1: Comparison between DC, Stepper and Servo Motor

Types of Motor	Rotation (Clockwise or Counterclockwise direction)	Speed	Accuracy of Rotation	Application
DC motor	360°	Fast	-	Anything that need high RPM
Stepper Motor	Rotate few degree in one times	Slow	Accurate within limited angle	Position Control
Servo Motor	i. Standard Servo - 120° to 180° ii. Continues Servo - 360°	Fast	Precise	Robotic Arms / Legs

From Table 3.1, DC motor is chosen as the torque-speed characteristics are achievable with different configurations and the speed can be smoothly. The different speeds for wheels are used to achieve rotation and similar motor speed cause to straight motion. Besides, DC motor performs higher speed compared to stepper motor. In this project, Micro Metal Gearmotor is chosen and total of two DC gear motor are needed. The Figure 3.11 shows the setup of DC gear motor on mobile robot.

Table 3.2: Product specification from its datasheet [13].

Gear ratio	Free-run RPM	Free-run Current	Stall Current	Stall Torque*(oz-in/kg-cm)	Weight(oz-in)
150:1	85	40mA	360mA	15/1.1	0.35/10

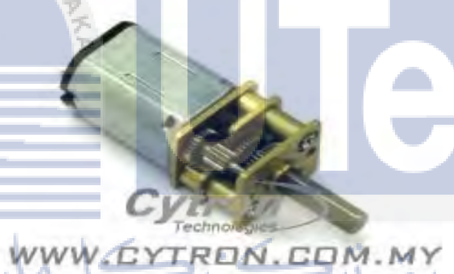

Figure 3.5: Micro Metal Gearmotor [12].

3.3.4 Material

In this project, the aluminium chassis is chosen as the main base for the follower robot. The reasons that choose aluminium as the most suitable base material is because aluminium has a higher strength to weight ratio. Besides, aluminium is resistant to rust. Oxidized layer will be formed which acts as a protective coating against will rust. Moreover, the aluminium is harder than Perspex. If there is any collision between the leader robot and obstacles, the extent of damage on robot will reduce a lot. Hence, the aluminium chassis will be selected to be the base for the follower robot. The Figure 3.10 shows the setup of the aluminium chassis as base of mobile robot.

Figure 3.6: Aluminium Chassis [14].

3.3.5 Motor Driver

For the motor driver, the 2Amp Motor Driver Shield is chosen for this project. It uses L298P chip which allow control of two 5 - 26V DC brush motors with maximum of 2A current each channel. The speed control can be achieved from conventional PWM which can be obtained from Arduino's PWM output pin 5 and 6. The enable or disable of motor driver is controlled by Arduino pin 4 and pin 7. The control mode can be configured from jumpers and also program. The reason choose this motor driver is because this shield can be directly stacked onto standard Arduino UNO [15]. The Figure 3.11 shows the motor driver shield setup.

Figure 3.7: 2Amp Motor Driver Shield [15].

3.4 Prototype of Follower Robot

After all the materials and components were completely integrated, the follower robot was completely assembled. There are three ultrasonic sensors that function as tracking leader while the three infrared sensors to perform the obstacles avoidance. The ultrasonic sensors was setup in second layer while the infrared sensors was in first layer of the mobile robot. The Arduino Uno as the microcontroller and motor driver shield to control the motor speed. The motor driver shield will attached on the Arduino Uno. There were some others parts included the aluminium chassis, dc gear motor, battery, breadboard, wire jumpers and others auxiliary materials. The top view, front view, side view and back view of the mobile robot were shown in Figure 3.8, Figure 3.9, Figure 3.10 and Figure 3.11 respectively.

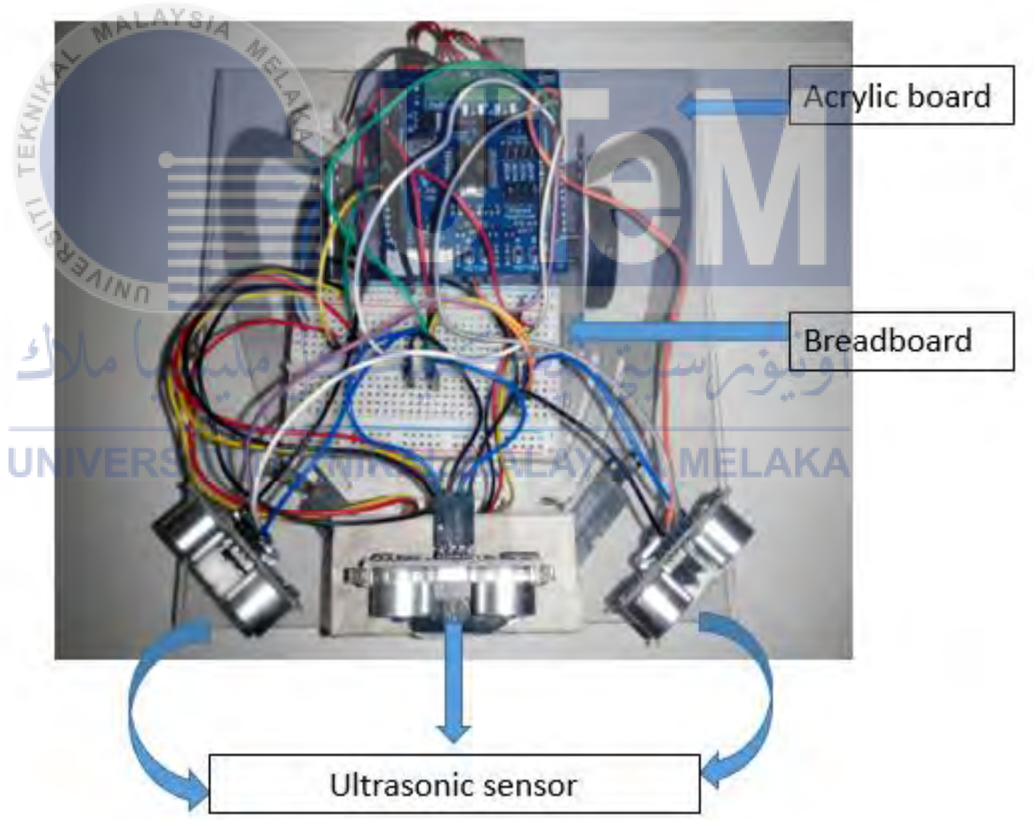

Figure 3.8: Top view of mobile robot.

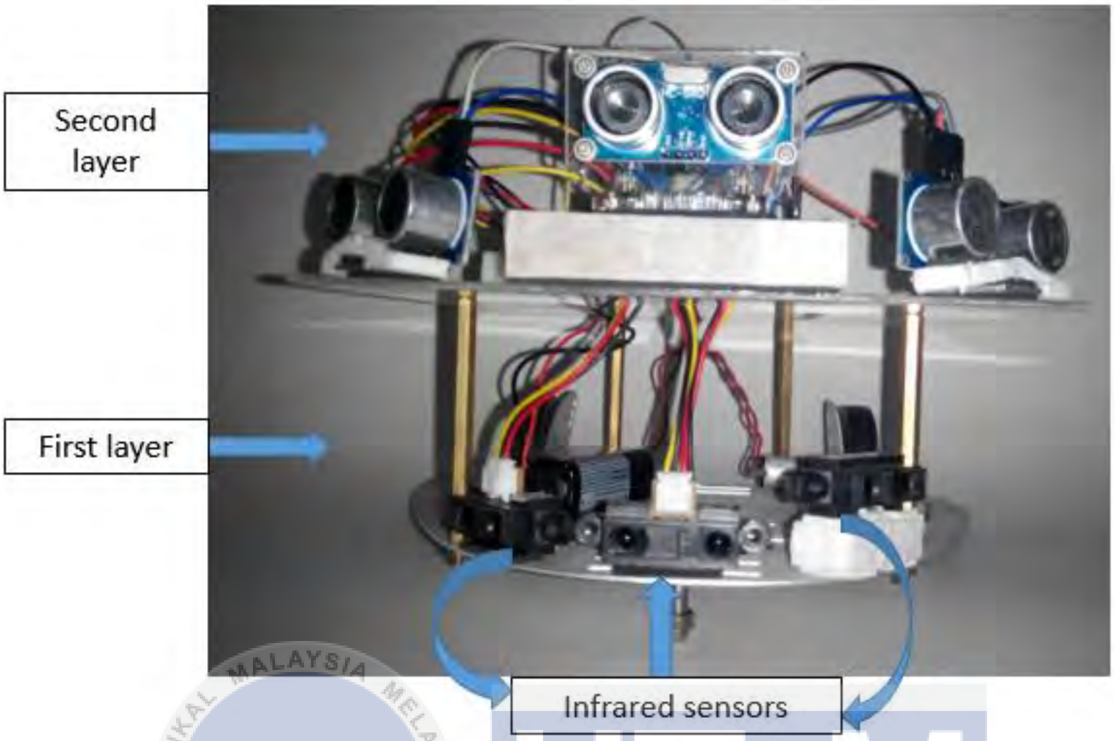

Figure 3.9: Front view of mobile robot.

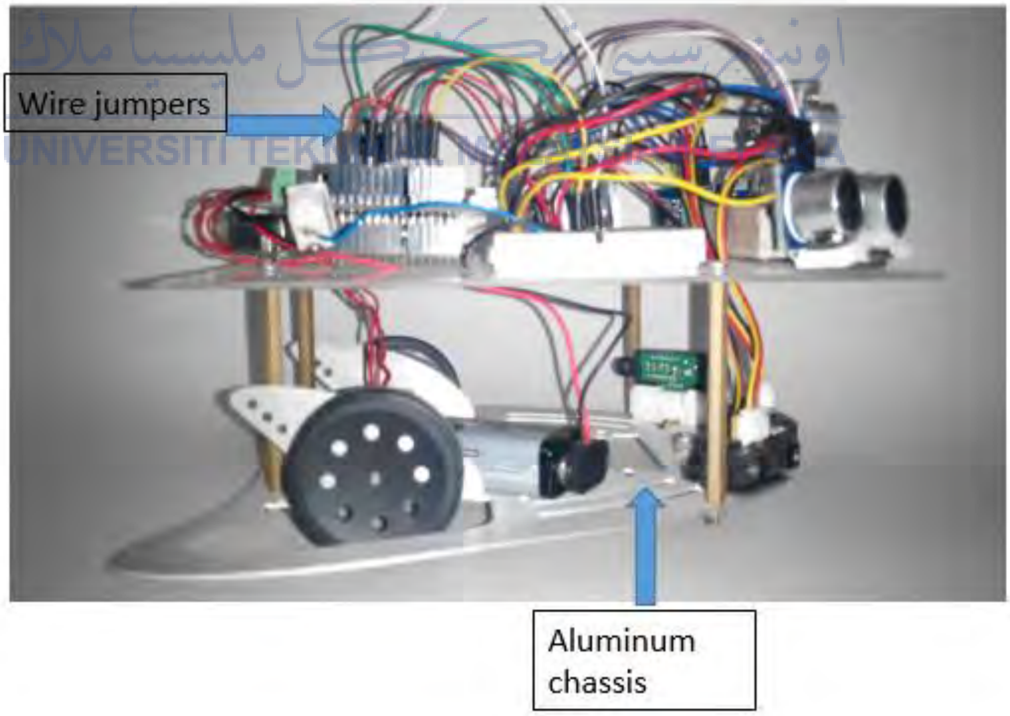

Figure 3.10: Side view of mobile robot.

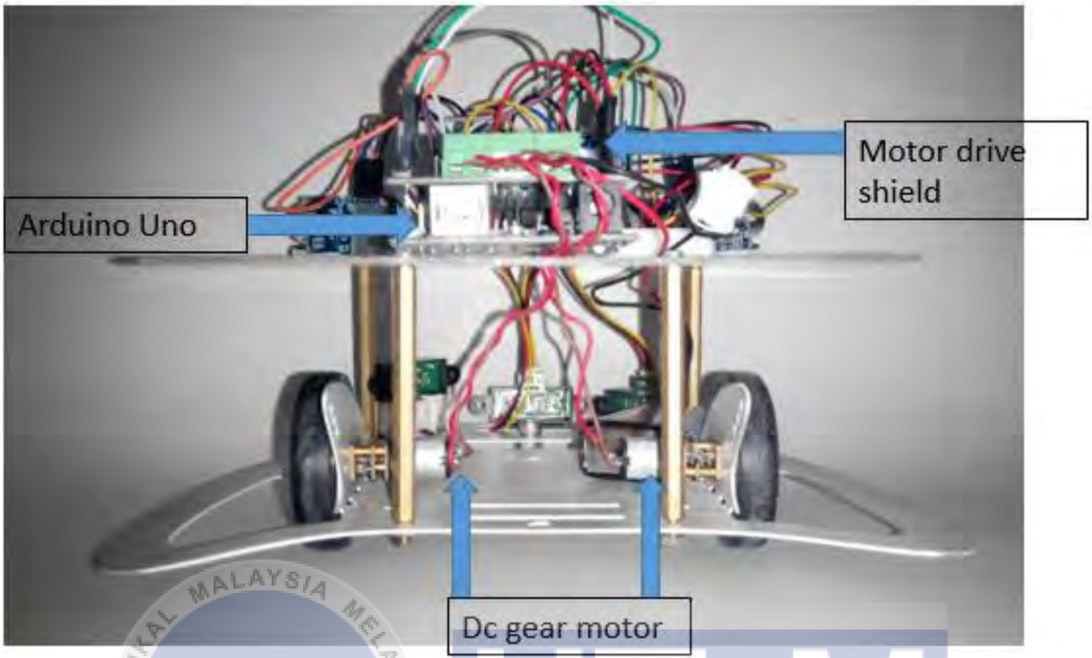

Figure 3.11: Back view of mobile robot.

3.5 Experiment Setup

In this section, four different experiments were carried out on the components selected to achieve all the objectives that have been stated in previous chapter. The experiments included the infrared sensor experiment, ultrasonic sensor experiment, angle turning of mobile robot trajectory and validate the tracking control of follower robot for moving leader robot.

3.5.1 Experiment 1: Object Detection Using Infrared Sensor

Two experiments were carried out where first experiment was to determine the sensitivity of each of the IR sensors by measured the voltage output with different distance of the object from the IR sensor. Second experiment was to obtain the detection angle of three IR sensors by placed the sensors along the U-shape.

Figure 3.12 shows the experimental setup for sensitivity of infrared sensors. The experiment was conducted to determine the sensitivity of the infrared sensor by placed an object with different distance away from the sensor. The object was positioned directly in front of the infrared sensor where the range that tested was in between 0cm -100cm. the program was uploaded to the Arduino Uno to run the programming. Different distance of the object from the infrared sensor had shown different output voltage of the infrared sensor. The data was recorded from Arduino Serial Monitor. The experiment was repeated with different distance of the object distance for IR sensor 2 and IR sensor. The results were recorded and tabulated.

Figure 3.13 shows the experimental setup for angle detection of infrared sensors. This experiment was conducted to determine the angle of detection for infrared sensor by positioned an obstacle with distance of 10cm away from the infrared sensors. Three infrared sensors were tested together by setting the front sensor at 90 ^{0}, while left and right sensor at 45^0 away from the front sensor. The coding was uploaded to Arduino Uno to run the programming. The data was recorded from the Arduino Serial Monitor. The experiment was repeated with different angle for the position of the object. The results were recorded and tabulated.

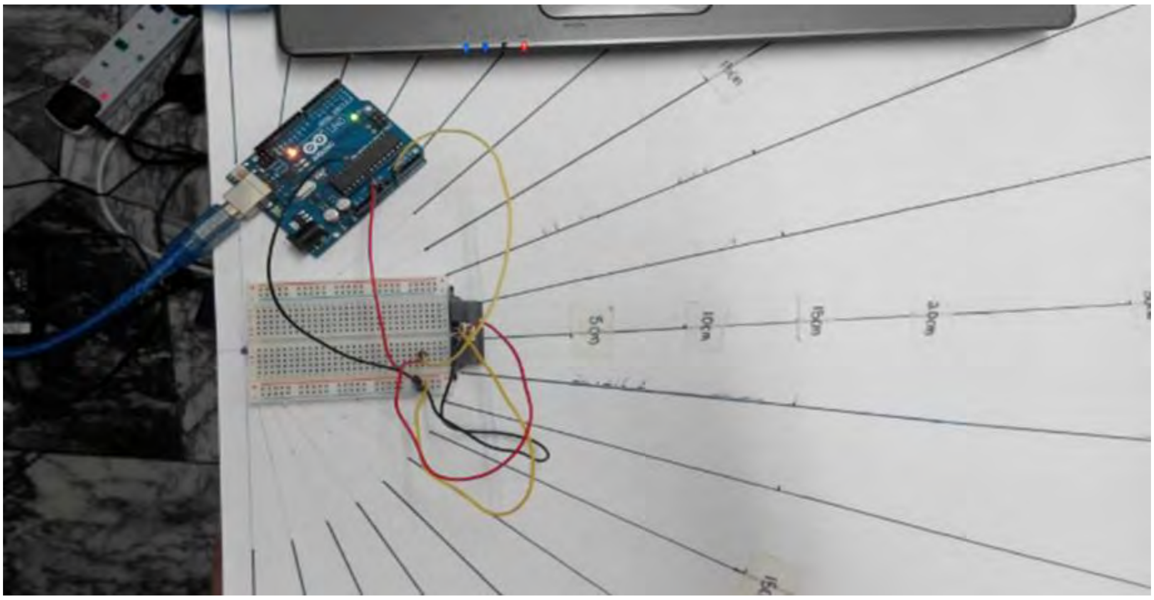

Figure 3.12: The experimental setup for sensitivity test.

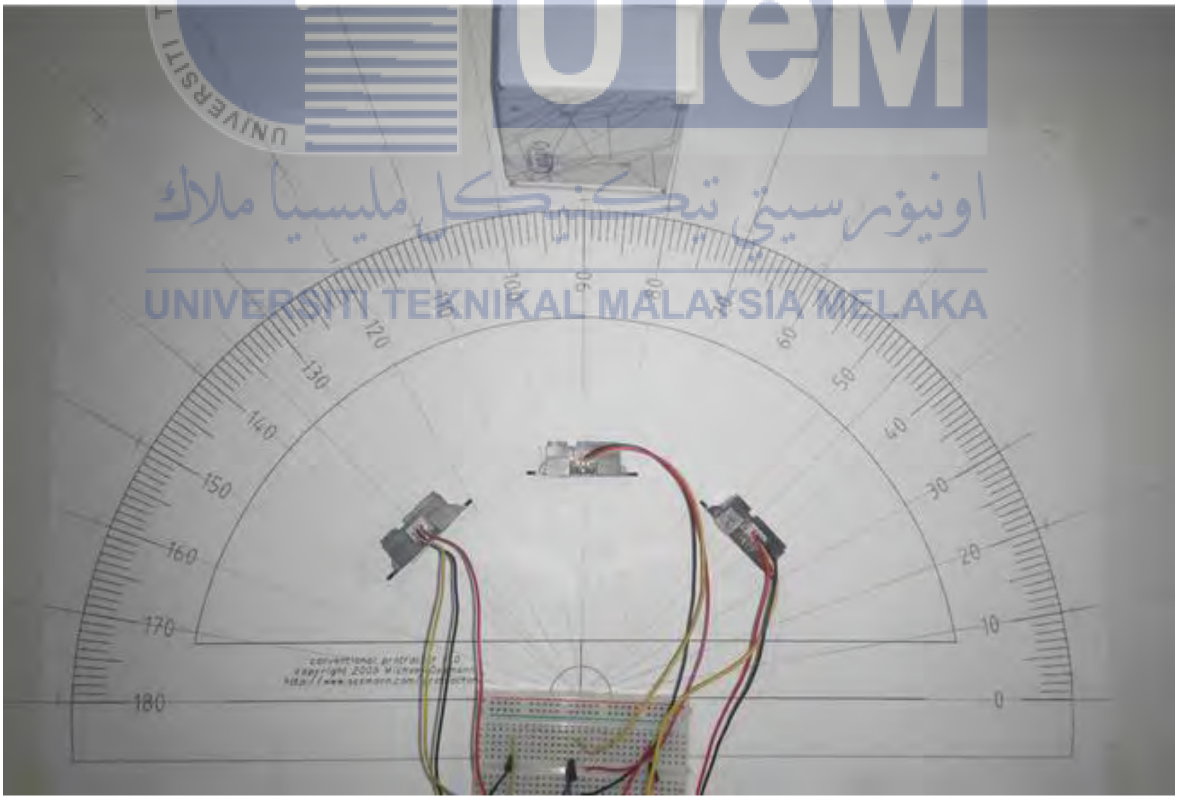

Figure 3.13: The experimental setup for angle detection.

3.5.2 Experiment 2: Tracking Object using Ultrasonic Sensor

The experiment was conducted to determine the effective angle of the ultrasonic sensor can be detect by placed an object with different angles from the ultrasonic sensor. The object was positioned in front of the ultrasonic sensor while the range of angle tested was in range of 0^0 to 180^0. The distance were tested from ultrasonic sensor was 10cm, 20cm, 30cm and 40 cm. The experimental setup to determine the effective angles was shown in Figure 3.14. An object was positioned in different distances and angles had shown different results. The results were recorded and tabulated.

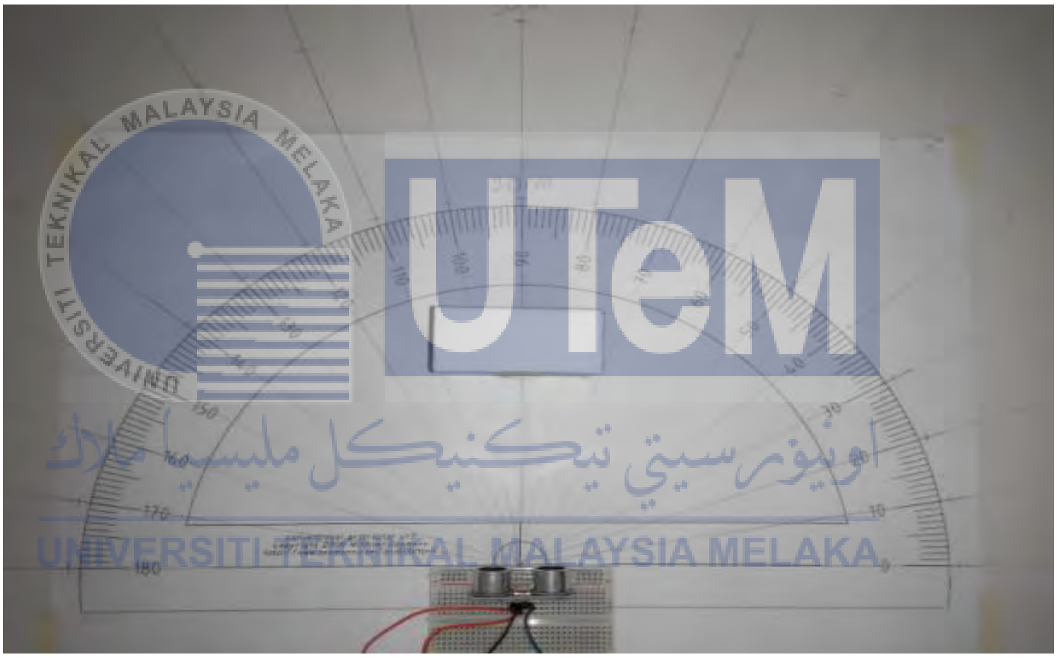

Figure 3.14: The experimental setup for determine effective angles of ultrasonic sensor.

3.5.3 Experiment 3: Mobile Robot Turning Trajectory

In this experiment was to determine the angle of turning trajectory of the two wheels mobile robot using Pulse Width Modulation (PWM) with Length of time (delay). There were two experiment, first experiment, turning direction to right side and left side. For turning direction to right side, inside the program, the duty cycles for left and right motor was set to fixed variables which equal to 255 duty cycles and 0 duty cycles respectively. Second experiment, for turning direction to left side, inside the program, the left and right duty cycles will set as 0 duty cycles and 255 duty cycles respectively. Manipulated and responding variables were length of time (delay) and angles for both part experiments. The experiment was repeated with different length of time. There will be a needle implemented to the mobile robot to point the angle. The experiment setup to turn right side was as shows in Figure 3.15 while Figure 3.16 shows for turning left side. The results were recorded and tabulated.

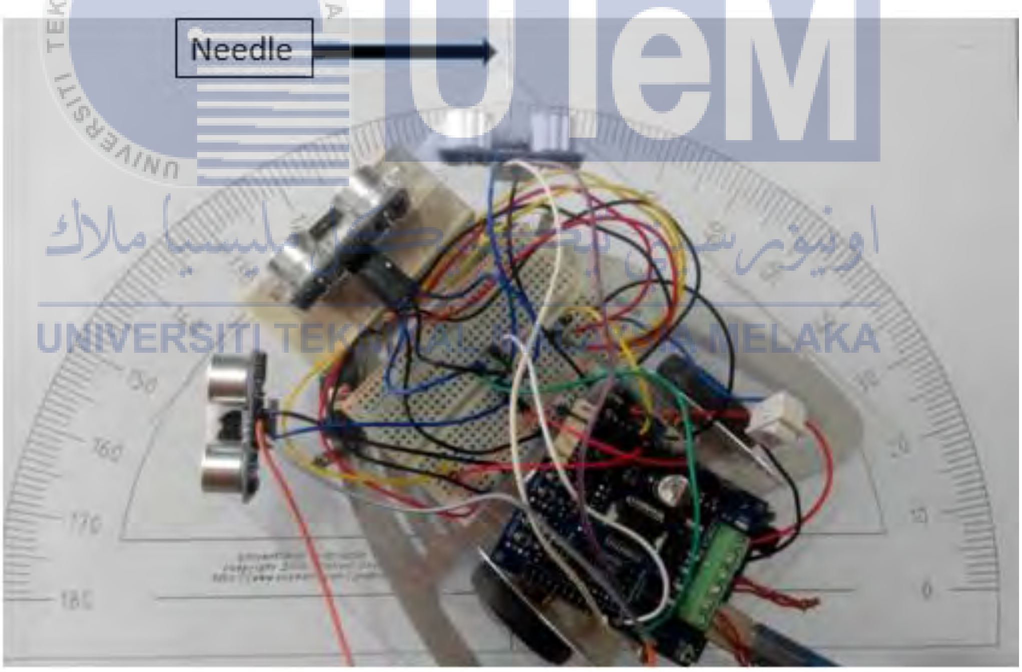

Figure 3.15: The experimental setup for turning right side.

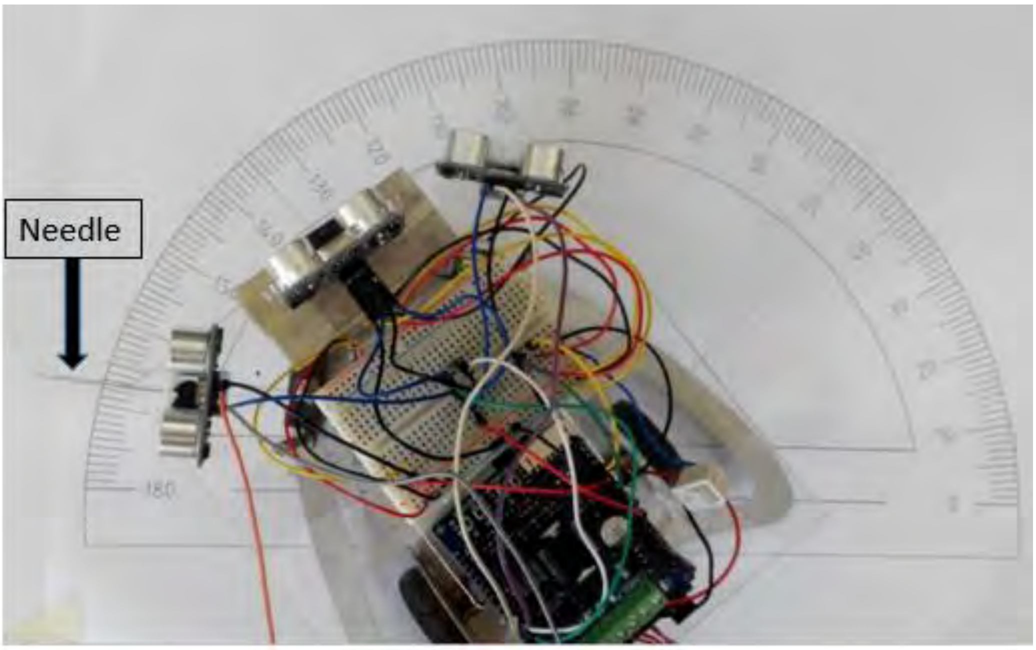

Figure 3.16: The experimental setup for turning left side.

3.5.4 Experiment 4: Tracking Control of Follower Robot for Moving Leader Robot

In this experiment, there were four type of trajectories was carried out to perform the travelling of the follower robot's trajectory and able to avoid small obstacles. The experiment was performed indoor experimental condition. All the experiments were carried out on the mah-jong paper. Four type of trajectories included straight line, S-shape, U-shape and Zigzag trajectory. For every trajectory, two small obstacles were involved to validate the follower robot able to avoid the obstacles. The straight line, S-shape and U-shape trajectories experiments were done on 1m x 1m mah-jong paper while the Zigzag trajectory on 1m x 2m mah-jong paper. The experiments were repeated for three times for every trajectories and the best trajectory was plotted in graphical form. The data was recorded and tabulated. All the real situation photos and graphical form of the trajectories were shown in Chapter 4. The table's data also contained error and average error for y-axis, root mean square error (RMSE) for three trials and standard deviation for both trajectories with and without obstacles.

CHAPTER 4

RESULTS, ANALYSIS AND DISCUSSION

4.1 Results

4.1.1 Experiment 1: Object Detection Using Infrared Sensor

4.1.1.1 Sensitivity of Infrared Sensor

Table 4.1 shows data collected for sensitivity of infrared sensors and Figure 4.1 shows the graphical form of sensitivity of infrared sensors when object at different distance. From the Table 4.1 and Figure 4.1, the output voltage for each of the infrared sensor was decreased as the object was positioned far away from the infrared sensor except the distance at 0cm and 80cm – 100 cm. This is because the infrared sensor's specification stated that the range are only available in between 5cm - 80cm. The voltage suddenly increased more than 1V at 0cm and 80cm - 100cm will indicated as Not Available voltage value. The higher output voltage are 3.11V, 3.09V and 3.11V at distance 5cm respectively for three infrared sensors. While the lowest voltage value is 0,49V for all the three infrared sensor at distance of 80cm. The graph was plotted according to the data collected. The experiment shown that the sensitivity detection of the three infrared sensors were approximately the same results. As conclusion, the output voltage value will decreasing as the further the distance of the object from the infrared sensor.

Table 4.1: Sensitivity of infrared sensors.

Object distance from sensor (cm)	IR sensor 1 (voltage, V)	IR sensor 2 (voltage, V)	IR sensor 3 (voltage, V)
0	1.61 (N/A)	1.56 (N/A)	1.63 (N/A)
5	3.11	3.09	3.11
10	2.40	2.36	2.42
15	1.68	1.65	1.74
20	1.32	1.28	1.47
25	1.09	1.07	1.10
30	0.94	0.93	0.95
35	0.84	0.87	0.86
40	0.76	0.81	0.79
45	0.68	0.80	0.72
50	0.65	0.78	0.64
55	0.62	0.74	0.60
60	0.55	0.66	0.56
65	0.54	0.58	0.53
70	0.50	0.54	0.51
75	0.50	0.50	0.51
80	0.49	0.49	0.49
85	1.35 (N/A)	1.36 (N/A)	1.34 (N/A)
90	1.31 (N/A)	1.33 (N/A)	1.32 (N/A)
95	1.32 (N/A)	1.31 (N/A)	1.31 (N/A)
100	1.32 (N/A)	1.31 (N/A)	1.32 (N/A)

Graph:

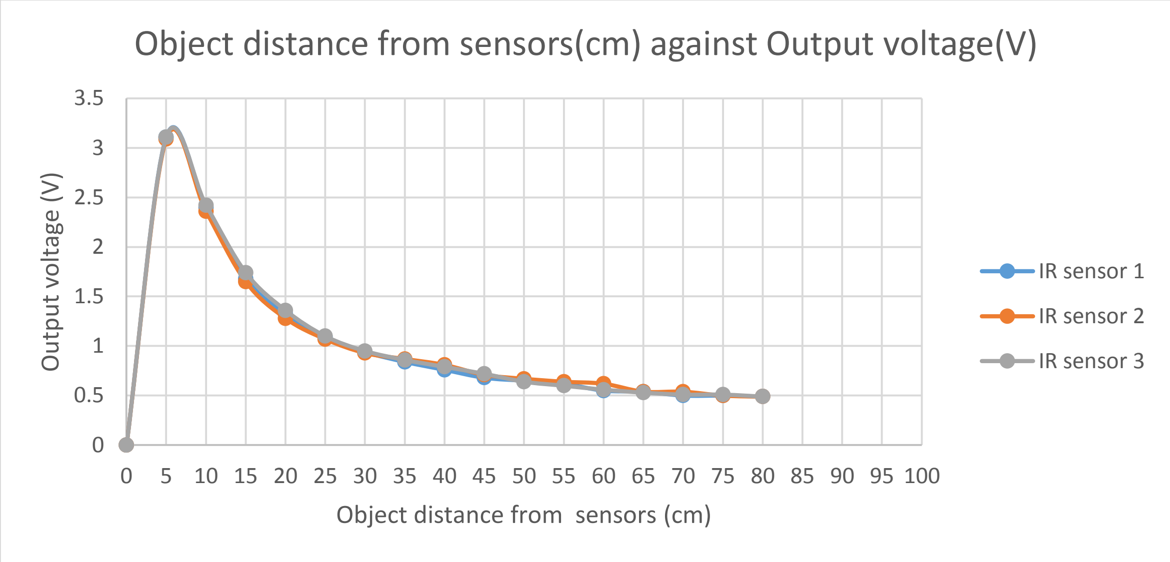

Figure 4.1: Graph of sensitivity of the IR sensor when object at different distance.

4.1.1.2 Detection Angle of Infrared Sensor

Table 4.2 shows the angle of detection by the infrared sensors and Figure 4.2 shows the graphical form of angle against voltage. From the Figure 4.2, the graph shows that only front sensor was able to detect the object from 90^0 to 100^0 while the left and right sensor unable to detect it. When the object at 40^0 to 50^0, the only that can detected the object was the right side infrared sensor. For left side infrared sensor, the range of angle detection is in between 130^0 to 140^0, while the front and right side not able to detect the object. The results show that is because the angle of transmit the signal by the infrared sensor is very small. In this project, the infrared sensors were used to perform the obstacles avoidance. From the data collected, the coding can be set to avoid the obstacles when the obstacles is 10cm away from the mobile robot.

Table 4.2: Angle of detection by the infrared sensors.

Angle (^{0})	IR sensor 1 (Left)		IR sensor 2 (Front)		IR sensor 3 (Right)	
	Voltage, V	Detection	Voltage, V	Detection	Voltage, V	Detection
0	0	No	0	No	0	No
10	0	No	0	No	0	No
20	0	No	0	No	0	No
30	0	No	0	No	0	No
40	0	No	0	No	2.41	Yes
50	0	No	0	No	2.41	Yes
60	0	No	0	No	0	No
70	0	No	0	No	0	No
80	0	No	0	No	0	No
90	0	No	2.4	Yes	0	No
100	0	No	2.4	Yes	0	No
110	0	No	0	No	0	No
120	0	No	0	No	0	No
130	2.43	Yes	0	No	0	No
140	2.42	Yes	0	No	0	No
150	0	No	0	No	0	No
160	0	No	0	No	0	No
170	0	No	0	No	0	No
180	0	No	0	No	0	No

Graph:

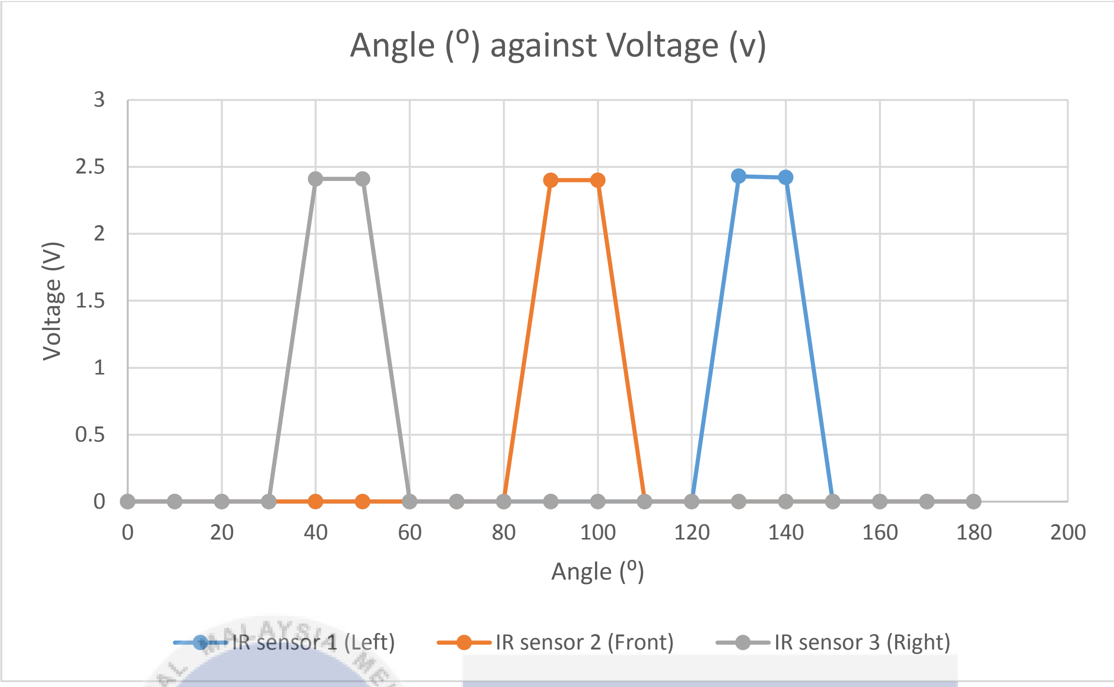

Figure 4.2: Graph of angle against voltage.

4.1.2 Experiment 2: Tracking Object Using Ultrasonic Sensor

Table 4.3 shows the data collected for effective angles of ultrasonic sensors and Figure 4.3 shows the graphical form angle against average distance from ultrasonic sensor. From the Table 4.3 and Figure 4.3, the object placed at 10cm and 20cm had the same angles detection by the ultrasonic sensor which from 70^0 to 110^0. However, the object placed at 30cm and 40cm had the same angles detection by ultrasonic sensor which from 80^0 to 100^0. The 0cm indicated that the object was undetectable by the ultrasonic with different angles. This is because the ultrasonic sensor's specification stated that the effective angles of detection are within 30^0 although the distance can be measure from 0cm to 400cm. In this experiment, the data collected shown that when the object placed at 30cm and 40cm, the ultrasonic sensor unable to receive the reflected signal wave from the object at 70^0 and 110^0. The distance will affect the effective angles that able detect by ultrasonic sensor. The graph was plotted according to the data collected. As conclusion, the coding can be develop according to the distance between follower robot and leader robot with effective angles to be track.

Table 4.3: Effective angles of ultrasonic sensor.

Angle(^{0})	Average distance of an object placing from ultrasonic sensor(cm)								Standard Deviation
	10	Detection	20	Detection	30	Detection	40	Detection	
0	0	No	0	No	0	No	0	No	0
10	0	No	0	No	0	No	0	No	0
20	0	No	0	No	0	No	0	No	0
30	0	No	0	No	0	No	0	No	0
40	0	No	0	No	0	No	0	No	0
50	0	No	0	No	0	No	0	No	0
60	0	No	0	No	0	No	0	No	0
70	11	Yes	21	Yes	0	No	0	No	0
80	11	Yes	21	Yes	31	Yes	41	Yes	0
90	10	Yes	20	Yes	30	Yes	40	Yes	0
100	11	Yes	21	Yes	31	Yes	41	Yes	0
110	11	Yes	21	Yes	0	No	0	No	0
120	0	No	0	No	0	No	0	No	0
130	0	No	0	No	0	No	0	No	0
140	0	No	0	No	0	No	0	No	0
150	0	No	0	No	0	No	0	No	0
160	0	No	0	No	0	No	0	No	0
170	0	No	0	No	0	No	0	No	0
180	0	No	0	No	0	No	0	No	0

Graph:

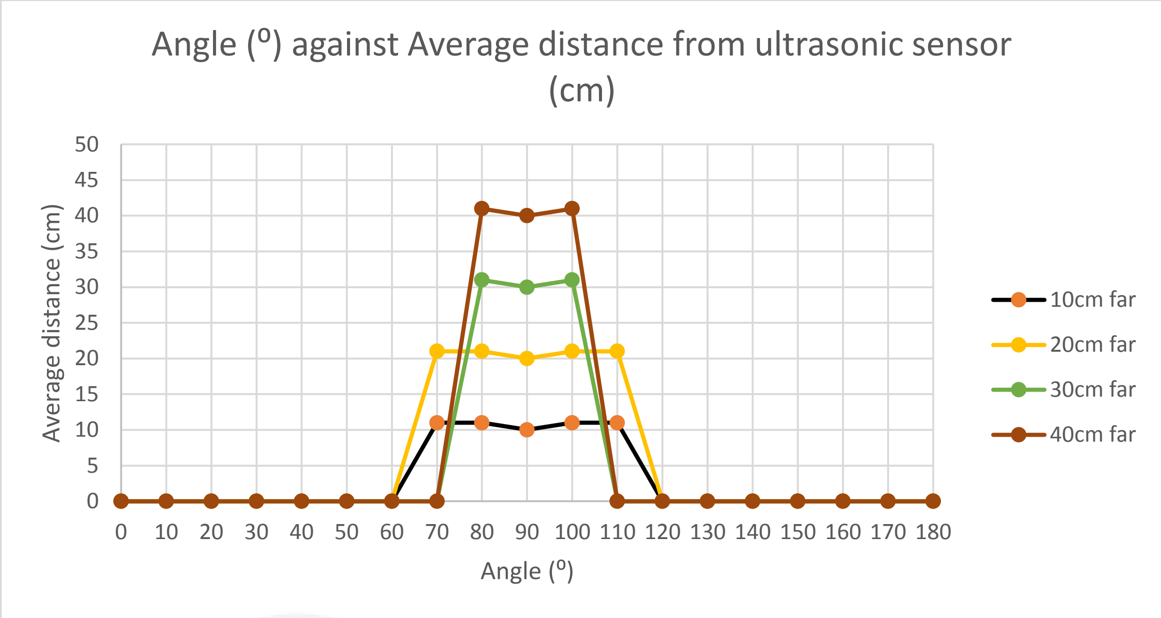

Figure 4.3: Graph of angle against average distance from ultrasonic sensor.

4.1.3 Experiment 3: Mobile Robot Turning Trajectory

4.1.3.1 Turning direction to right side

Table 4.4 shows the right side angles obtained with different time and Figure 4.4 shows the graph of average angle against length of time. From the Table 4.4 and Figure 4.4, the data shown that the average angles detected by the ultrasonic sensor was increased as the length of time increased. In this experiment, the left and right duty cycles was set as 255 duty cycles and 0 duty cycles respectively. The manipulated variable is length of time and responding variable is angle of turning. The length of time that tested was in range of 100ms to 1000ms. In order to let mobile robot turn to 45^0 to the right side, the length of time has to set in between range of 500ms to 600ms. This is because when the leader was turned to right side, the front ultrasonic sensor can detect it and follower robot was able to turn to right side. After turned, the right ultrasonic sensor able to track the leader robot and move forward. From the table above, the standard deviation was also calculated. The range fall in between 0 to 0.58. The lower the value of standard deviation, the more accurate the result. At time of 300ms, 700ms and 900ms, the standard deviation value was 0, while the others were 0.58. The data collected was plotted in graphical form.

Table 4.4: Right side angles obtained with different time

Length of time, Delay/ms	Angle(^{0}) reading 1	reading 2	reading 3	Average angle(^{0})	Standard Deviation
100	8.00	9.00	8.00	8.67	0.58
200	19.00	19.00	18.00	18.67	0.58
300	25.00	25.00	25.00	25.00	0.00
400	37.00	36.00	37.00	36.67	0.58
500	42.00	41.00	42.00	41.67	0.58
600	50.00	51.00	50.00	50.33	0.58
700	60.00	60.00	60.00	60.00	0.00
800	67.00	67.00	68.00	67.33	0.58
900	77.00	77.00	77.00	77.00	0.00
1000	87.00	88.00	87.00	87.33	0.58

Graph:

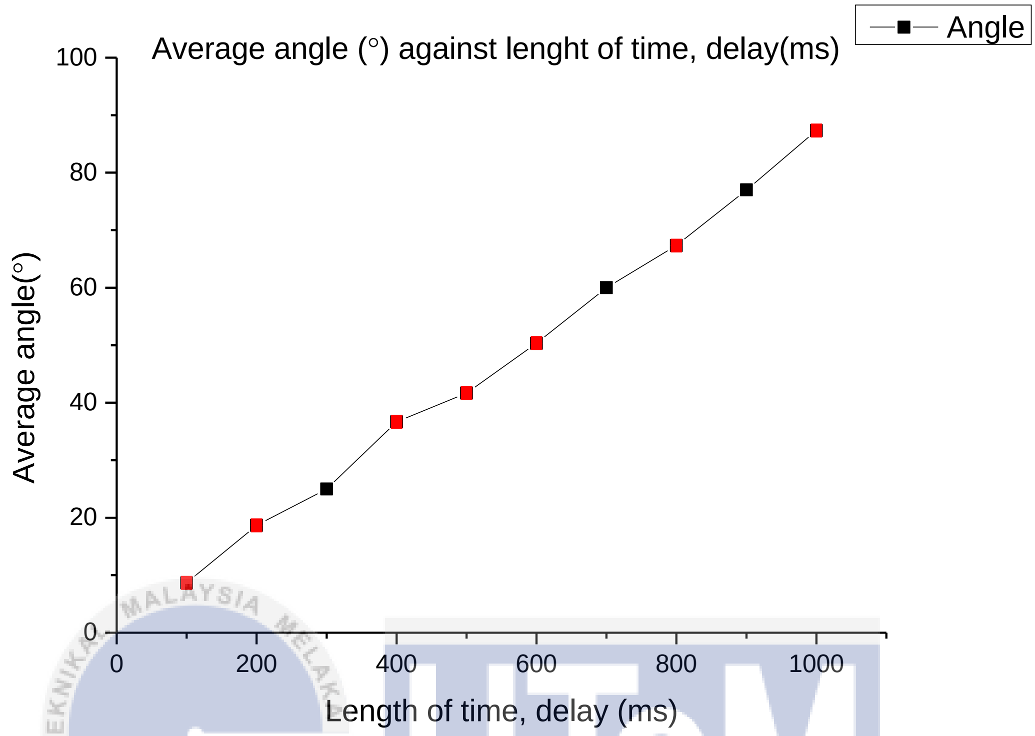

Figure 4.4: Graph of average angle against length of time for turning right side.

4.1.3.2 Turning direction to left side

Table 4.5 shows the left side angles obtained with different time and Figure 4.5 shows the graph of average angle against length of time. In this experiment, the left and right duty cycles set as 0 duty cycle and 255 duty cycles respectively. The manipulated variable is length of time and responding variable is angle of turning. When an object was placed at left side, the result shows that the average angles detected by the ultrasonic sensor was increased as the length of time increased. The length of time that tested was in range of 100ms to 1000ms. In order to let mobile robot turn to 45^0 left side, the length of time has to set in between range of 500ms to 600ms. This is because when the leader was turned to right side, the left ultrasonic sensor can detect it and follower robot was able to turn to left side. After turned, the front ultrasonic sensor able to track the leader robot and move forward. From the table above, the standard deviation was also calculated. The range fall in between 0 to 1.15. The lower the value of standard deviation, the more accurate the result. The lowest standard deviation value was 0 at time 700ms, while the highest was 1.15 at time 600ms and 800ms.

Table 4.5: Left side angles obtained with different time

Length of time, Delay/ms	Angle(^{0})			Average angle(^{0})	Standard Deviation
	reading 1	reading 2	reading 3		
100	7.00	8.00	8.00	7.67	0.58
200	19.00	18.00	19.00	18.67	0.58
300	26.00	24.00	25.00	25.00	1.00
400	34.00	35.00	36.00	35.00	1.00
500	40.00	41.00	40.00	40.33	0.58
600	49.00	51.00	51.00	50.33	1.15
700	55.00	55.00	55.00	55.00	0.00
800	67.00	65.00	67.00	66.33	1.15
900	80.00	79.00	78.00	79.00	1.00
1000	85.00	86.00	86.00	85.67	0.58

Graph:

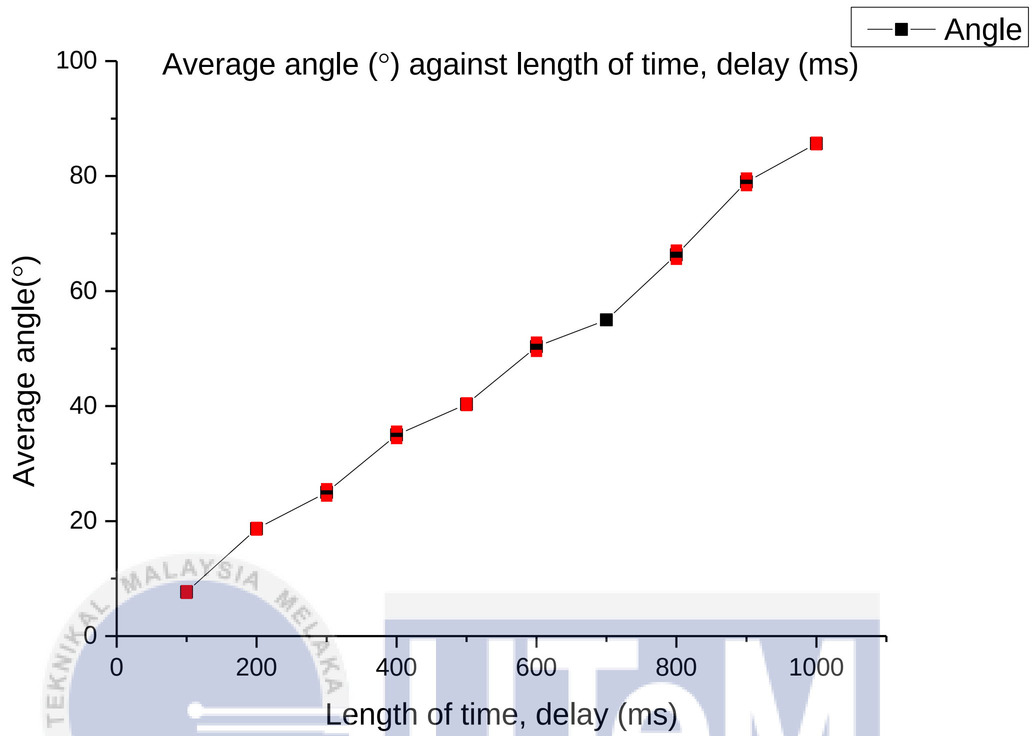

Figure 4.5: Graph of average angle against length of time for turning left side.

4.1.4 Experiment 4: Tracking Control of Follower Robot for Moving Leader Robot

In this section, the results was collected and plotted in graphical form for all the trajectories. Table 4.6 shows the summarize data of root mean square error for all the trajectories both for with and without obstacles.

Table 4.6: Summarize data of root mean square error for all the trajectories.

No.	Type of Trajectory	RMSE		
		Trail 1	Trial 2	Trial 3
1	Straight line	0.83	0.73	0.90
2	Straight line with obstacles	2.11	2.13	2.16
3	S-shape	5.09	6.03	10.96
4	s-shape with obstacles	5.81	6.08	5.99
5	U-shape	7.57	7.63	7.74
6	U-shape with obstacles	16.18	18.27	16.63
7	Zigzag	9.88	9.99	10.17
8	Zigzag with obstacles	5.89	5.62	5.71

4.1.4.1 Straight Line Trajectory

Figure 4.6 shows the experiment setup of trajectory in straight line. Figure 4.7 and Figure 4.8 show the general view and zoom in view of graphical form in straight line trajectory by leader and follower robot. Based on the data collected, the RMSE of the first trial is 0.83, second trial is 0.73 and third trial is 0.90. The second trial is best and chosen among the trials, this is because the RMSE shown the smallest error. Besides, the standard deviation range fall in between 0 to 1.18. From the graph shown, the follower robot slightly deviate from the leader's trajectory after 20cm in X-axis position. However, this is only a very small error which the highest deviation error is only 1cm from the leader's trajectory. As conclusion, the follower robot was still able to move in straight line.

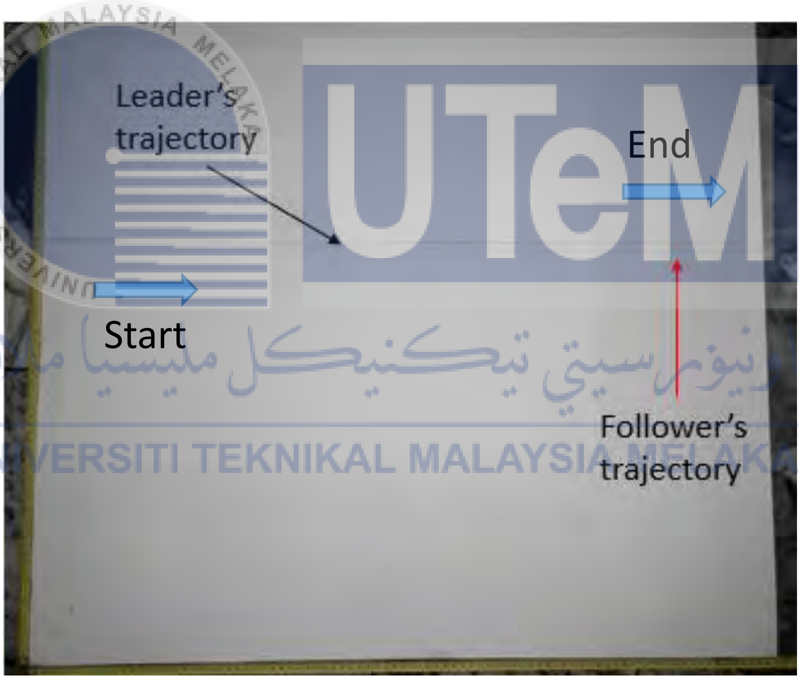

Figure 4.6: Trajectory in straight line.

Graph:

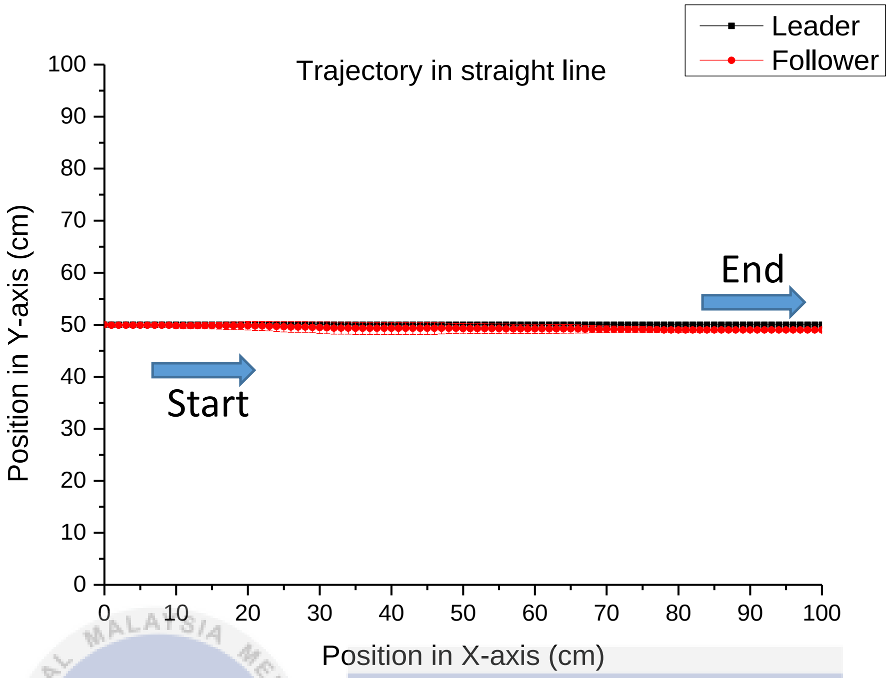

Figure 4.7: General view of graphical form of trajectory in straight line.

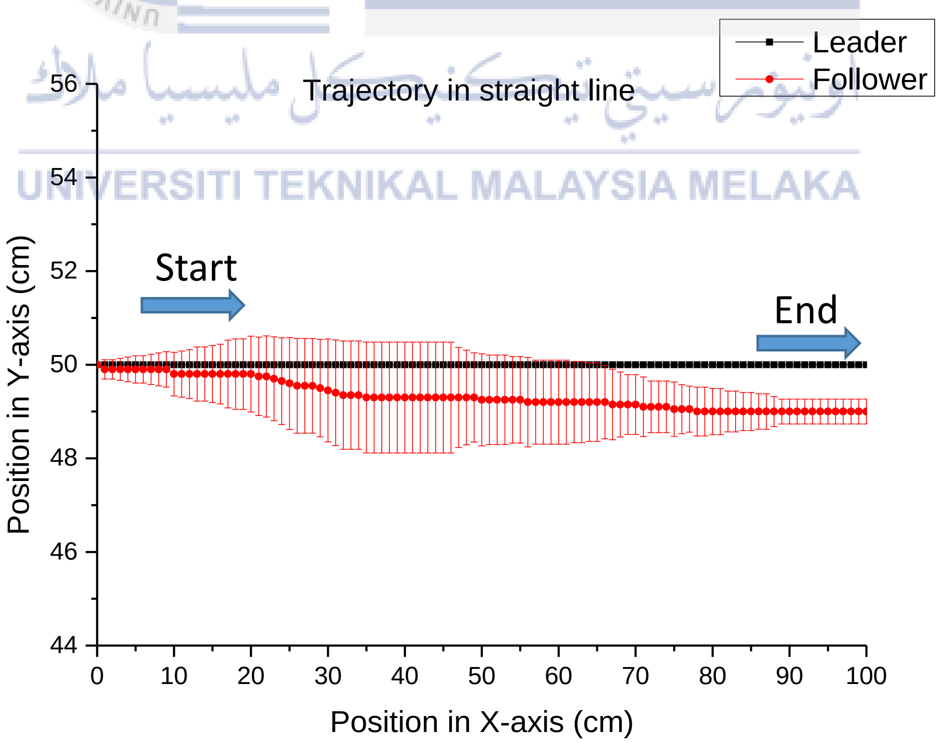

Figure 4.8: Zoom in view of graphical form in straight line trajectory.

4.1.4.2 Straight Line Trajectory With Obstacles

Figure 9 shows the experiment setup of trajectory in straight line with obstacles. Figure 4.10 and Figure 4.11 show the general and zoom in view of graphical form of trajectory in straight line with obstacles. Based on the data collected from the three trials, the smallest error was chosen which RMSE equal to 2.11 while the others two equal to 2.12 and 2.16. Besides, the standard deviation for the trials are fall in between range of 0 to 1.24. In this experiment, two small obstacles were involved as shown in Figure 4.13. From the graph shown, the follower robot suppose move in straight line but there were obstacles involved. However, the follower robot was able to avoid the obstacles and tracked the leader again. The largest deviation of the follower robot is 5.55cm away from the leader's trajectory. As conclusion, the follower robot was able to perform obstacles avoidance and tracked the leader again.

Figure 4.9: Trajectory in straight line with obstacles.

Graph:

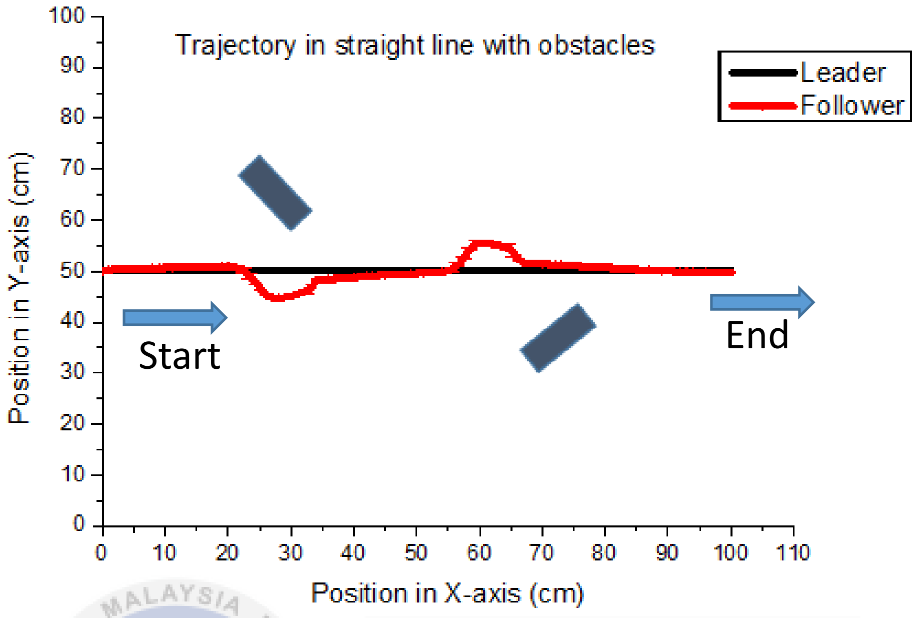

Figure 4.10: General view of graphical form of trajectory in straight line with obstacles.

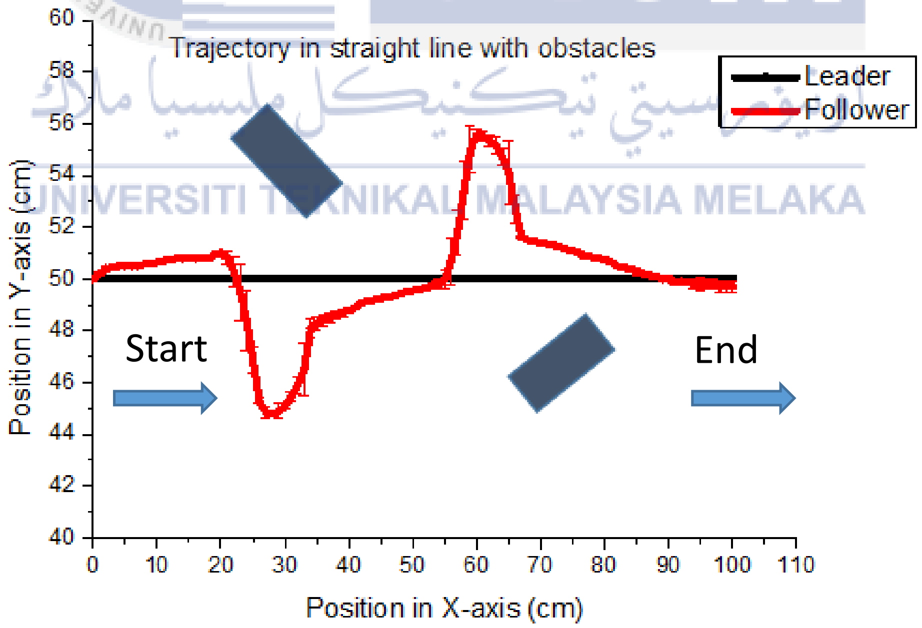

Figure 4.11: Zoom in view of graphical form of trajectory in straight line with obstacles.

4.1.4.3 S-shape Trajectory

Figure 4.12 shows the experiment setup of trajectory in S-shape. Figure 4.13 shows the graphical form of trajectory in S-shape by the leader and follower robot. Based on the data collected, RMSE for first, second and third trials are 5.09, 6.03 and 10.96 respectively. The data shown the RMSE for this experiment are large is because the follower robot unable exactly followed the same points as the leader's trajectory. Definitely, the best trajectory will be the smallest RMSE which is 5.09 and the graph was plotted as in Figure 4.17. The standard deviation fall in between range of 0 to 8.32 and the largest deviation from the leader's trajectory is approximate in range of 45cm to 60cm of position in X-axis. The smaller the standard deviation value, the better the results. From the graph plotted, the follower's trajectory are not smooth as leader's trajectory especially in curve line. This is because the angle of turning of the mobile robot are controlled by the length of time and the PWM value for both left and right motor. The length of time was set as 500ms while the motor speed are depend on which direction of turn. As conclusion, the follower robot was able to perform the trajectory in S-shape.

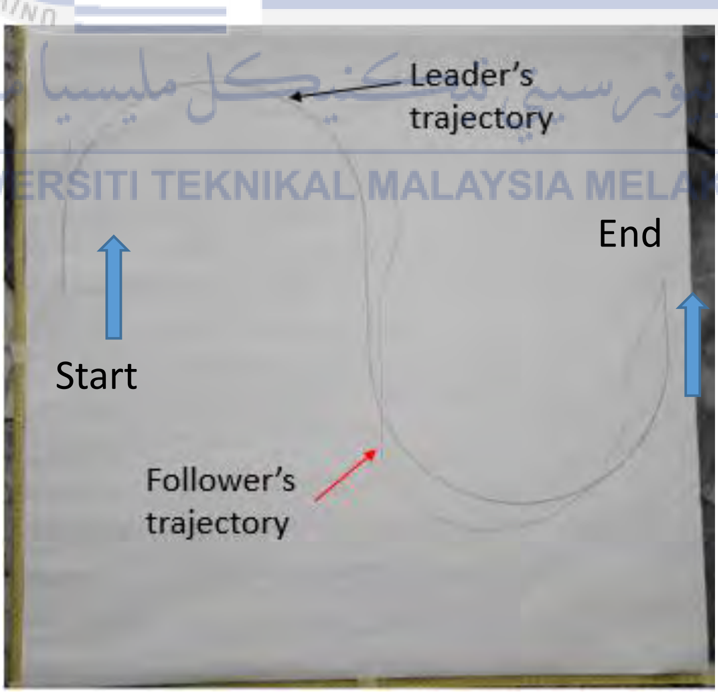

Figure 4.12: Trajectory in S-shape

Graph:

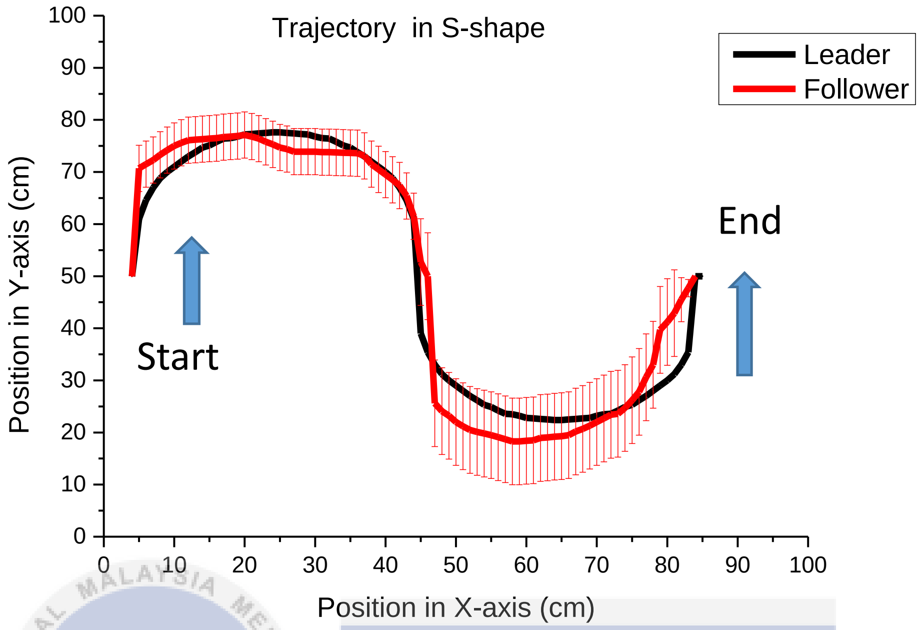

Figure 4.13: Graphical form of trajectory in S-shape.

4.1.4.4 S-shape Trajectory With Obstacles

Figure 4.14 shows the experiment setup of trajectory in S-shape with obstacles while Figure 4.15 shows the graphical form. Based on the data collected, the graph plotted by choosing the best trajectory of the follower robot which the smallest RMSE is 5.81 while another two RMSE are 6.08 and 5.99. Large value of RMSE is because this experiment was to determine the performance of the obstacles avoidance of the follower robot. Definitely, the trajectory will have large different compare to leader's trajectory. For the standard deviation, the value are in between range of 0 to 1.40 for this experiment. From the graph plotted, the follower robot avoided the first obstacle which detected by front infrared sensor and it will stop for 1000ms then turned to right side. After that, the follower robot continue tracked the leader robot and followed until the second obstacle. The follower robot managed to avoid the second obstacle which detected by the right infrared sensor and make it to turn left side. As conclusion, the follower robot was able to perform obstacles avoidance.

Figure 4.14: Trajectory in S-shape with obstacles.

Graph:

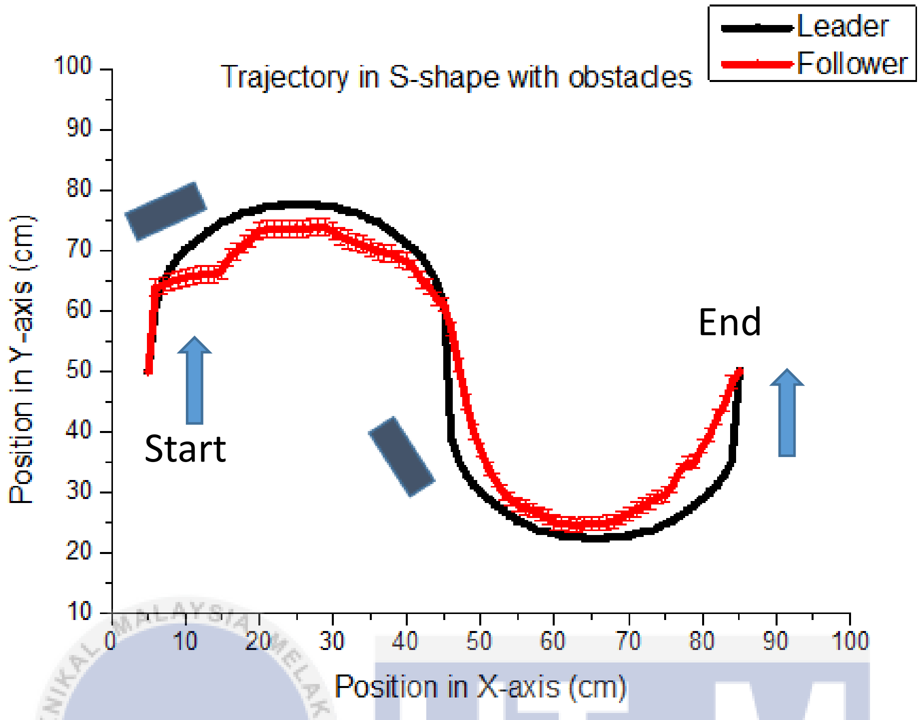

Figure 4.15: Graphical form of trajectory in S-shape with obstacles.

4.1.4.5 U-shape Trajectory

Figure 4.16 shows the experiment setup of the trajectory in U-shape by the leader and follower robot while Figure 4.17 shows the graphical form. Based on the data collected, RMSE for the first trial is 7.57, second trial is 7.63 and third trial is 7.74. First trial are the best compare to another two trials as the RMSE are the smallest. The value of the RMSE are large is because when the follower robot turned direction to left or right, the mobile robot unable to move in significant curve line which caused the trajectory were not approximate to leader's trajectory. The standard deviation fall in between range of 0 to 2.48 in this trajectory. Observed from the graph, at the beginning, the follower robot able followed almost the same trajectory of leader. However, at the curve line, the mobile robot start deviate from the leader's trajectory. Then, the follower tracked the leader until the end of the trajectory. As a conclusion, although the mobile robot unable to move in curve line, it still able to move in U-shape trajectory.

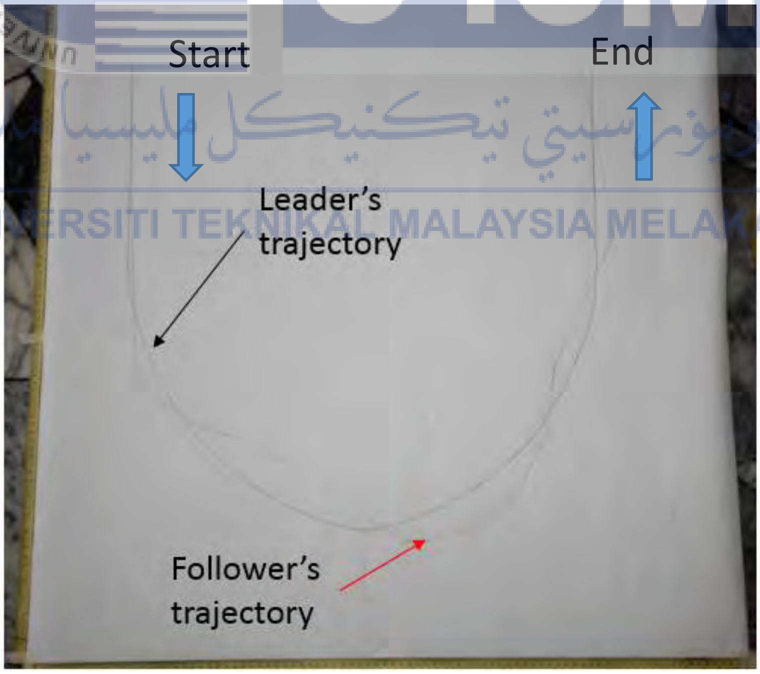

Figure 4.16: Trajectory in U-shape.

Graph:

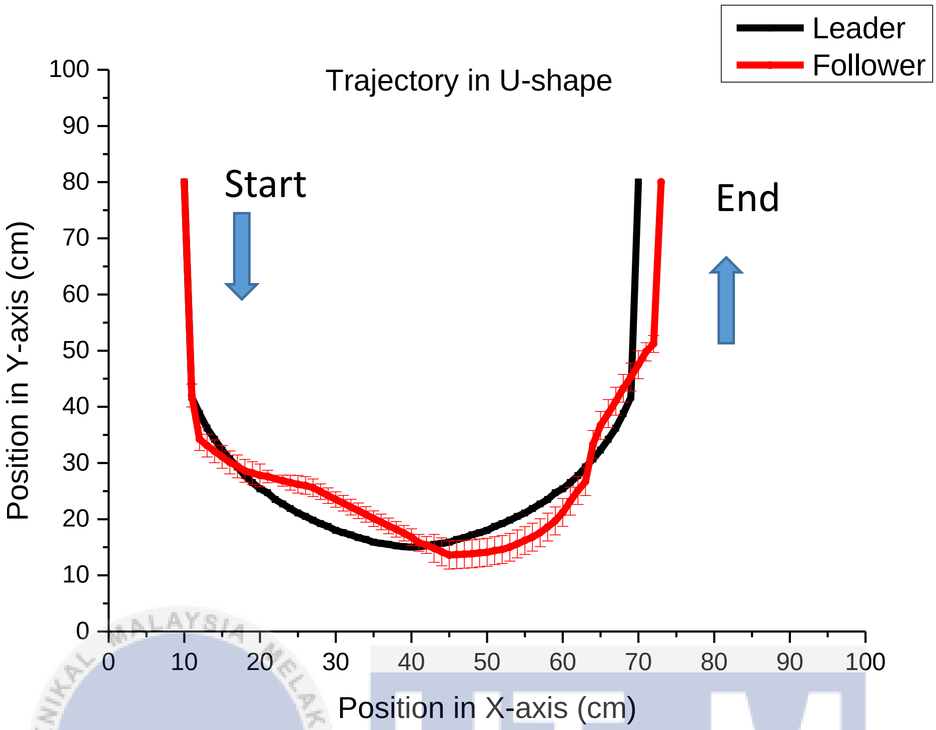

Figure 4.17: Graphical form of trajectory in U-shape.

4.1.4.6 U-shape Trajectory With Obstacles

Figure 4.18 shows the experiment setup of the trajectory in U-shape with obstacles while Figure 4.19 shown graphical form of the U-shape trajectory with obstacles. From the data collected, the best results among three trials are the first trial which had RMSE equal to 16.18, while another two RMSE are 18.27 and 16.63 for second and third trial respectively. The value of RMSE are large is due to the mobile robot performed the obstacles avoidance which caused the large different between the leader's trajectory. The standard deviation is in between range of 0 to 2.15. When the follower robot detected the first obstacle, the left infrared sensor triggered to avoid the obstacle and turned to right side. Then the mobile robot continued to track the leader until the second obstacle. When the mobile robot meet the second obstacle, the right infrared sensor detected the obstacle and turned the mobile robot to left side and continued tracked leader to the end. As conclusion, the follower robot was able to perform the obstacles avoidance and followed the leader in U-shape trajectory.

Figure 4.18: Trajectory in U-shape with obstacles.

Graph:

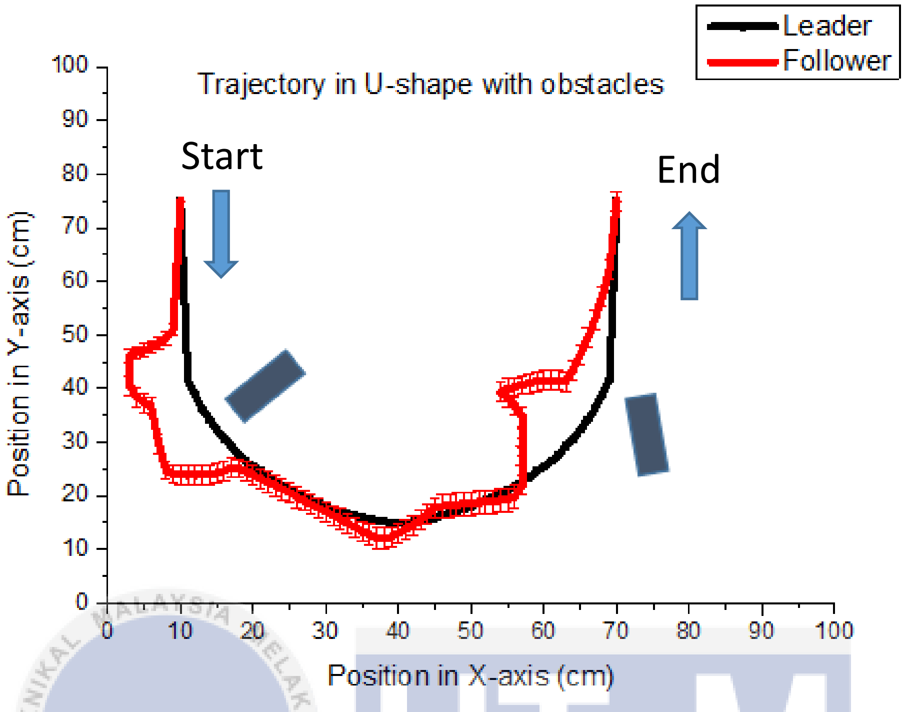

Figure 4.19: Graphical form of trajectory in U-shape with obstacles.

4.1.4.7 Zigzag Trajectory

The Figure 4.20 shows the experiment setup of trajectory in Zigzag and Figure 4.21 shows the graphical form of trajectory in Zigzag. In this experiment, the trajectory was done on the size of 1m x 2m so that the graph can be plotted in bigger size. Based on the data collected, the RMSE for first, second and third trials are 9.88, 9.99 and 10.17 respectively. The value of the RMSE are large is because of the turning angle of the mobile robot caused it deviate from leader's trajectory and difficult to follow back the original path way. Whenever the first turning direction, there will be a large different compare to leader's trajectory as well as the next turning direction until completing the trajectory. The standard deviation value for this experiment are fall in between 0 to 0.26. At the beginning, the follower robot move in straight line until the first turning direction which turned to left side. No others way, the mobile robot have to turn in large angle to follow back the leader's trajectory as well as the second, third and fourth turning. There is no problem for the mobile robot to move in straight line. As a conclusion, the follower robot managed to move in Zigzag trajectory.

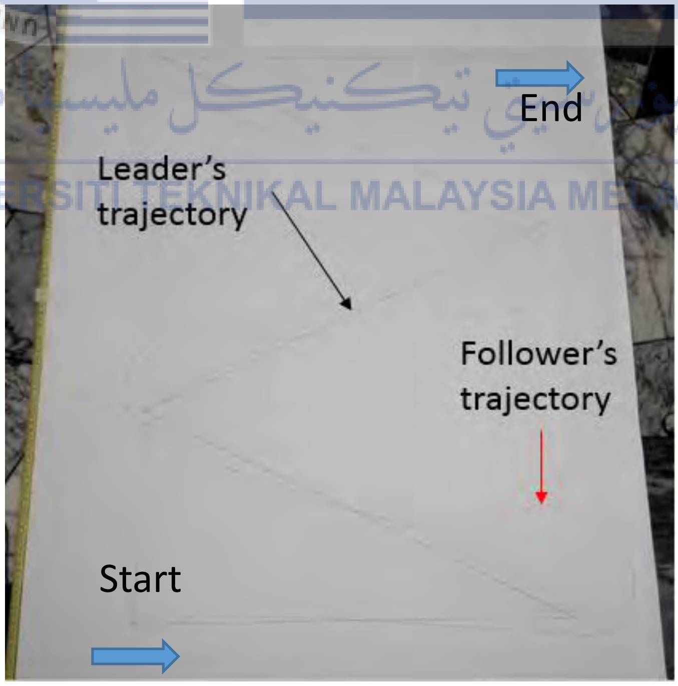

Figure 4.20: Trajectory in Zigzag.

Graph:

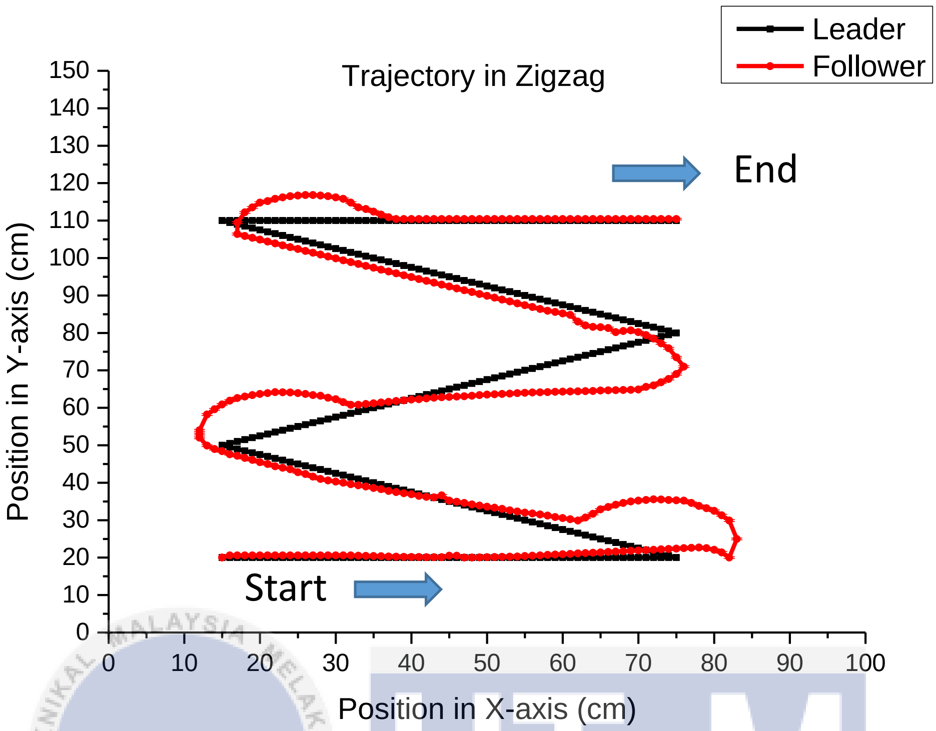

Figure 4.21: Graphical form of trajectory in Zigzag.

4.1.4.8 Zigzag Trajectory With Obstacles

Figure 4.22 and Figure 4.23 show the experiment setup and graphical form of trajectory in Zigzag with obstacles respectively. From the data collected, the value of RMSE for first trial is 5.89, second trial is 5.62 and third trial is 5.71. By comparing the RMSE value, the smallest will be the best result which is second trial. The graph was plotted as in Figure 4.27. By observed the graph, the follower's trajectory performed in that way is due to obstacles avoidance by the mobile robot. When the mobile robot meet the first obstacles, the right infrared sensor detected and moved to left side to avoid it and continued followed the leader. After the large turning angle, the mobile robot meet again the first obstacle which detected by the right infrared sensor and eventually still able to avoid it by moved to left side. The mobile robot continued to move until meet the second obstacle which detected again by right infrared sensor and it moved to left side. Again, after the large turning angle, the right infrared sensor triggered the mobile robot to avoid the second obstacle again. After that, the mobile robot moved straight line until the end. As a conclusion, the follower robot was able to finish followed the leader's trajectory with existing of obstacles.

Figure 4.22: Trajectory in Zigzag with obstacles.

Graph:

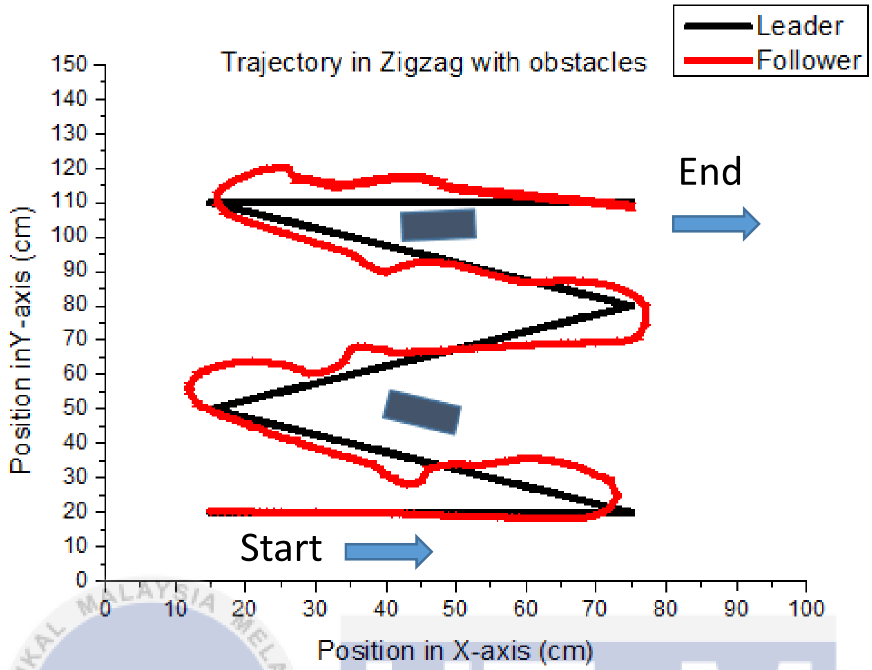

Figure 4.23: Graphical form of trajectory in Zigzag with obstacles.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion and Future Work

In conclusion, the objectives for this project had been achieved by design the leader follower robot. All the way through the experiments on the components chosen, the ultrasonic sensors and infrared sensors were assembled in the best position on the mobile robot to function well on tracking and obstacles avoidance respectively. Besides that, the follower robot successfully follow the leader robot in forward, turn left, turn right and reverse motion. The distance to track leader robot can be set at the coding part, it depends on the distance between leader and follower robot. In this project the distance of follower robot was set in range of 20cm to 30cm away from the leader robot. However, the distance for infrared sensors to perform obstacle avoidance was set the distance as 10cm from the obstacle. Lastly, the follower robot was able to validate the leader's trajectory in straight line, S-shape, U-shape and Zigzag as shown by the results.

In this project, the mechatronic elements had been learned and was applied in this project. The follower robot can performed the following task successfully and all the objectives had been achieved.

For future work, to improve the tracking performance, the vision system was recommended for better result. Vision system can produce the image of the object and send a feedback to the mobile robot via certain software. The map of the trajectories can be visualize by the camera and can give more accurate coordinate. That will be benefit for the graph plotting.

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APPENDICES

Appendix A

Gannt Chart for FYP 1

	FYP 1													
TASK	Week 1	Week	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14
Journal Searching														
Drawing design														
Components selection														
Components testing														
Configuration setup														
Progress Report Writing FYP 1														
Submission of Progress Report														
Presentation of FYP 1														

Gannt Chart for FYP 2

	FYP 2/Week															
TASK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Components Integration																
Programming																
Sensors Testing																
System Troubleshooting																
Analysis on Trajecotries																
Progress Report Writing FYP 2																
Draft Report to Supervisor																
Correction of Final Report																
Submission of Final Report																
FYP 2 Seminar and Demonstration																

Appendix B

Ultrasonic Sensor

User's Manual

May 2013

1.0 INTRODUCTION

The HC-SR04 ultrasonic sensor uses sonar to determine distance to an object like bats or dolphins do. It offers excellent non-contact range detection with high accuracy and stable readings in an easy-to-use package. From 2cm to 400 cm or 1” to 13 feet. It operation is not affected by sunlight or black material like Sharp rangefinders are (although acoustically soft materials like cloth can be difficult to detect). It comes complete with ultrasonic transmitter and receiver module.

Features:

- Power Supply :+5V DC
- Quiescent Current : <2mA
- Working Currnt: 15mA
- Effectual Angle: <15°
- Ranging Distance : 2cm – 400 cm/1" - 13ft
- Resolution : 0.3 cm
- Measuring Angle: 30 degree

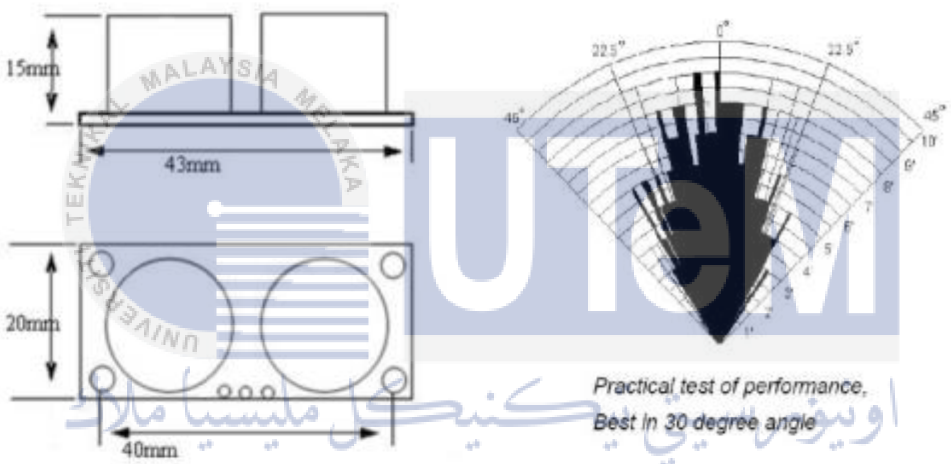
- Trigger Input Pulse width: 10uS
- Dimension: 45mm x 20mm x 15mm

VCC = +5VDC

Trig = Trigger input of Sensor

Echo = Echo output of Sensor

GND = GND



2.0 PRODUCT SPECIFICATION AND LIMITATIONS

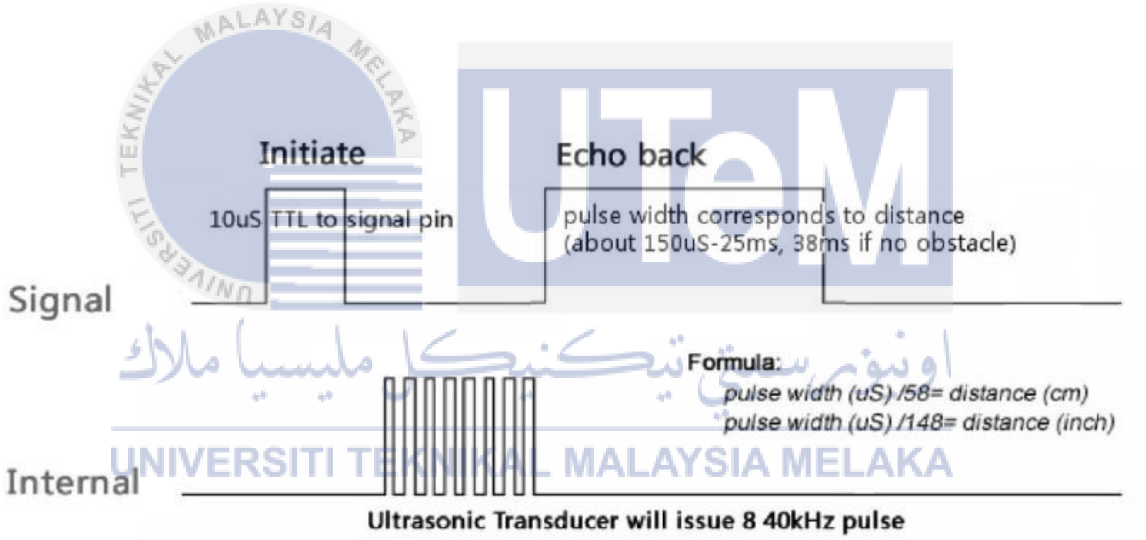
Parameter	Min	Typ.	Max	Unit
Operating Voltage	4.50	5.0	5.5	V
Quiescent Current	1.5	2	2.5	mA
Working Current	10	15	20	mA
Ultrasonic Frequency	-	40	-	kHz

3.0 OPERATION

The timing diagram of HC-SR04 is shown. To start measurement, Trig of SR04 must receive a pulse of high (5V) for at least 10us, this will initiate the sensor will transmit out 8 cycle of ultrasonic burst at 40kHz and wait for the reflected ultrasonic burst. When the sensor detected ultrasonic from receiver, it will set the Echo pin to high (5V) and delay for a period (width) which proportion to distance. To obtain the distance, measure the width (Ton) of Echo pin.

Time = Width of Echo pulse, in uS (micro second)

- Distance in centimeters = Time / 58
- Distance in inches = Time / 148
- Or you can utilize the speed of sound, which is 340m/s



Note:

- Please connect the GND pin first before supplying power to VCC.
- Please make sure the surface of object to be detect should have at least 0.5 meter^2 for better performance.

Appendix C

Infrared Sensor

SHARP

GP2Y0A21YK/GP2Y0D21YK

GP2Y0A21YK/ GP2Y0D21YK

General Purpose Type Distance Measuring Sensors

■ Features

1. Less influence on the color of reflective objects, reflectivity
2. Line-up of distance output/distance judgement type
   Distance output type (analog voltage) : **GP2Y0A21YK**
   Detecting distance : 10 to 80cm
   Distance judgement type : **GP2Y0D21YK**
   Judgement distance : 24cm
   (Adjustable within the range of 10 to 80cm [Optionally available])
3. External control circuit is unnecessary
4. Low cost

■ Applications

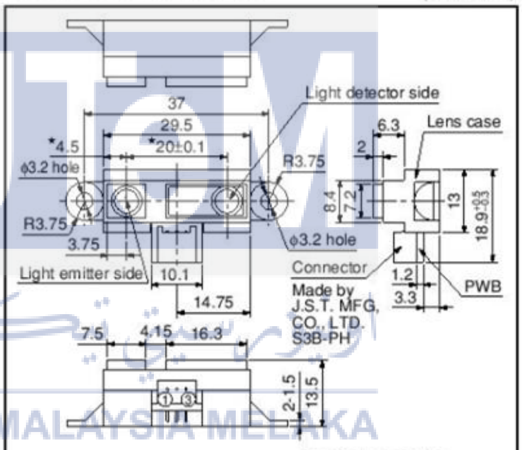
1. TVs
2. Personal computers
3. Cars
4. Copiers

■ Absolute Maximum Ratings (T_a=25°C, V_{CC}=5V)

Parameter	Symbol	Rating	Unit
Supply voltage	V_{CC}	−0.3 to +7	V
Output terminal voltage	V_O	−0.3 to V_{CC} +0.3	V
Operating temperature	T_{opr}	−10 to +60	°C
Storage temperature	T_{stg}	−40 to +70	°C

■ Outline Dimensions

(Unit : mm)



Terminal connection
① V_O
② GND
③ V_{CC}

✤ The dimensions marked * are described the dimensions of lens center position.
✤ Unspecified tolerance : ±0.3mm

Fig.4 Distance Characteristics

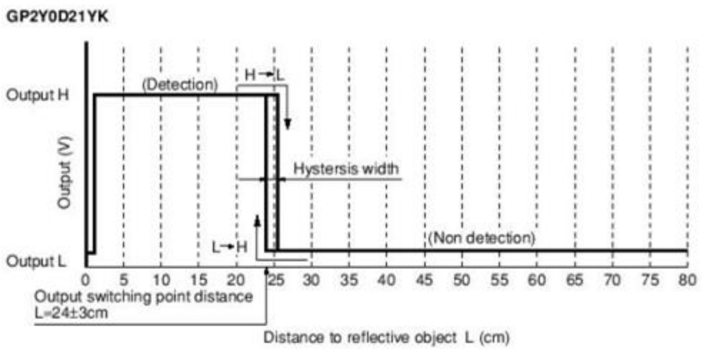
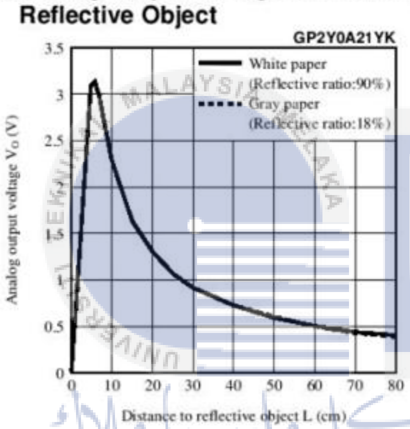


Fig.5 Analog Output Voltage vs. Distance to Reflective Object



Appendix D

Program in Follower Robot

```
#include <NewPing.h>
#include "Shield2AMotor.h"

Shield2AMotor motor(SIGNED_MAGNITUDE);
signed int motor1Speed, motor2Speed;
int THRESHOLD = 300;

int echoPinLeft = 13;
int trigPinLeft = 12;
int echoPinFront = 11;
int trigPinFront = 10;
int echoPinRight = 9;
int trigPinRight = 8;


void setup()
{
 Serial.begin(9600);
 pinMode(trigPinLeft,OUTPUT);
 pinMode(echoPinLeft,INPUT);
 pinMode(trigPinFront,OUTPUT);
 pinMode(echoPinFront,INPUT);
 pinMode(trigPinRight,OUTPUT);
 pinMode(echoPinRight,INPUT);
}

void loop()
{
 int sensorF = analogRead(A0);//front sensor
 int sensorL = analogRead(A1);//left sensor
 int sensorR = analogRead(A2);//right sensor
 Serial.print("IR F: ");
 Serial.print(sensorF);
 Serial.println(" ");
 Serial.print("IR L: ");
 Serial.print(sensorL);
 Serial.println(" ");
```

```
  Serial.print("IR R: ");
  Serial.print(sensorR);
  Serial.println(" ");

  //first read
  long duration, distance;
  digitalWrite(trigPinFront, LOW);
  delayMicroseconds(2);
  digitalWrite(trigPinFront, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPinFront, LOW);
  duration = pulseIn(echoPinFront, HIGH);
  distance = (duration/2) / 29.1;

//Second read
  long duration2, distance2;
  digitalWrite(trigPinLeft, LOW);
  delayMicroseconds(2);
  digitalWrite(trigPinLeft, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPinLeft, LOW);
  duration2 = pulseIn(echoPinLeft, HIGH);
  distance2 = (duration2/2) / 29.1;

//Third read
  long duration3, distance3;
  digitalWrite(trigPinRight, LOW);
  delayMicroseconds(2);
  digitalWrite(trigPinRight, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPinRight, LOW);
  duration3 = pulseIn(echoPinRight, HIGH);
  distance3 = (duration3/2) / 29.1;

   if(distance <15 || distance >40)
   {
    Serial.print("Front: ");
    Serial.print(distance);
    Serial.println("cm  Out of range");
    motor.control(0,0);
   }
   else if(distance >=15 || distance <=40)
   {
    Serial.print("Front: ");
    Serial.print(distance);
    Serial.println("cm  track");
    motor.control(255,255);
    delay(100);
    if(sensorL > THRESHOLD && distance >=15 && distance <=40)
    {
```

```
  Serial.println("turn right");
  motor.control(255,10);
  delay(600);
  motor.control(10,255);
  delay(600);
  motor.control(10,40);
  delay(70);

 }
 if(sensorF > THRESHOLD && distance >=30 && distance <=40)
 {
  Serial.println("stop");
    motor.control(0,0);
    delay(1000);
    Serial.println("reverse");
    motor.control(-255,-255);
    delay(1000);
  motor.control(225,10);//turn right
  delay(700);
 }
 if(sensorR > THRESHOLD && distance >=15 && distance <=40)
 {
  Serial.println("turn left");
  motor.control(10,255);
  delay(600);
  motor.control(255,10);
  delay(600);
  motor.control(40,-40);
  delay(70);
 }
else
 {
  motor.control(255,255);
  delay(500);
 }
}

if(distance2 <10 || distance2 >40)
{
 Serial.print("Left: ");
 Serial.print(distance2);
 Serial.println("cm  Out of range");
 motor.control(0,0);
}
else if(distance2 >=10 || distance2 <=40)
{
 Serial.print("Left: ");
 Serial.print(distance2);
 Serial.println("cm  turn left");
 motor.control(0,255);
```

```
  delay(500);
  motor.control(0,0);
  delay(500);
  if(sensorL > THRESHOLD && distance >=30 && distance <=40)
  {
   Serial.println("turn right");
   motor.control(255,-255);
   delay(500);
  }
 }

 if(distance3 <10 || distance3 >40)
 {
  Serial.print("Right: ");
  Serial.print(distance3);
  Serial.println("cm  Out of range");
  motor.control(0,0);
 }
 else if(distance3 >=10 || distance3 <=40)
 {
  Serial.print("Right: ");
  Serial.print(distance3);
  Serial.println("cm  turn right");
  motor.control(255,0);
  delay(500);
  motor.control(0,0);
  delay(500);
  if(sensorR > THRESHOLD && distance >=30 && distance <=40)
  {
   Serial.println("turn left");
   motor.control(-255,255);
   delay(500);
  }
 }
 if(distance <10 || distance >20)
 {
  Serial.print("Front: ");
  Serial.print(distance);
  Serial.println("cm  Out of range");
  motor.control(0,0);
 }
 else if(distance >=10 || distance <=20)
 {
  Serial.print("Front: ");
  Serial.print(distance);
  Serial.println("cm  reverse");
  motor.control(-255,-255);
  delay(1500);
 }
}
```

Appendix E

Tables

Straight line trajectory

Actual coordinate for Leader, cm		Y-axis for Follower, cm				Error Y-axis for Follower, cm				Standard deviation	Error Squared		
		Trail 1	Trial 2	Trail 3	Average	Error 1	Error 2	Error 3	Average				
XL	YL	YF1	YF2	YF3	YAVG	EY1	EY2	EY3	EAVG		Ey12	Ey22	Ey32
0.00	50.00	50.00	50.00	50.00	50.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.00	50.00	50.20	49.90	50.30	50.13	0.20	-0.10	0.30	0.13	0.21	0.04	0.01	0.09
2.00	50.00	50.20	49.90	50.30	50.13	0.20	-0.10	0.30	0.13	0.21	0.04	0.01	0.09
3.00	50.00	50.25	49.90	50.35	50.17	0.25	-0.10	0.35	0.17	0.24	0.06	0.01	0.12
4.00	50.00	50.30	49.90	50.40	50.20	0.30	-0.10	0.40	0.20	0.26	0.09	0.01	0.16
5.00	50.00	50.35	49.90	50.45	50.23	0.35	-0.10	0.45	0.23	0.29	0.12	0.01	0.20
6.00	50.00	50.35	49.90	50.45	50.23	0.35	-0.10	0.45	0.23	0.29	0.12	0.01	0.20
7.00	50.00	50.40	49.90	50.50	50.27	0.40	-0.10	0.50	0.27	0.32	0.16	0.01	0.25
8.00	50.00	50.45	49.90	50.55	50.30	0.45	-0.10	0.55	0.30	0.35	0.20	0.01	0.30
9.00	50.00	50.50	49.90	50.60	50.33	0.50	-0.10	0.60	0.33	0.38	0.25	0.01	0.36
10.00	50.00	50.55	49.80	50.65	50.33	0.55	-0.20	0.65	0.33	0.46	0.30	0.04	0.42
11.00	50.00	50.60	49.80	50.70	50.37	0.60	-0.20	0.70	0.37	0.49	0.36	0.04	0.49
12.00	50.00	50.65	49.80	50.75	50.40	0.65	-0.20	0.75	0.40	0.52	0.42	0.04	0.56
13.00	50.00	50.75	49.80	50.85	50.47	0.75	-0.20	0.85	0.47	0.58	0.56	0.04	0.72
14.00	50.00	50.75	49.80	50.85	50.47	0.75	-0.20	0.85	0.47	0.58	0.56	0.04	0.72
15.00	50.00	50.80	49.80	50.90	50.50	0.80	-0.20	0.90	0.50	0.61	0.64	0.04	0.81
16.00	50.00	50.85	49.80	50.95	50.53	0.85	-0.20	0.95	0.53	0.64	0.72	0.04	0.90
17.00	50.00	51.00	49.80	51.10	50.63	1.00	-0.20	1.10	0.63	0.72	1.00	0.04	1.21
18.00	50.00	51.05	49.80	51.15	50.67	1.05	-0.20	1.15	0.67	0.75	1.10	0.04	1.32
19.00	50.00	51.05	49.80	51.15	50.67	1.05	-0.20	1.15	0.67	0.75	1.10	0.04	1.32
20.00	50.00	51.15	49.80	51.25	50.73	1.15	-0.20	1.25	0.73	0.81	1.32	0.04	1.56
21.00	50.00	51.15	49.75	51.25	50.72	1.15	-0.25	1.25	0.72	0.84	1.32	0.06	1.56
22.00	50.00	51.20	49.75	51.30	50.75	1.20	-0.25	1.30	0.75	0.87	1.44	0.06	1.69
23.00	50.00	51.20	49.70	51.30	50.73	1.20	-0.30	1.30	0.73	0.90	1.44	0.09	1.69
24.00	50.00	51.20	49.65	51.30	50.72	1.20	-0.35	1.30	0.72	0.93	1.44	0.12	1.69
25.00	50.00	51.25	49.60	51.35	50.73	1.25	-0.40	1.35	0.73	0.98	1.56	0.16	1.82
26.00	50.00	51.25	49.55	51.35	50.72	1.25	-0.45	1.35	0.72	1.01	1.56	0.20	1.82
27.00	50.00	51.25	49.55	51.35	50.72	1.25	-0.45	1.35	0.72	1.01	1.56	0.20	1.82
28.00	50.00	51.25	49.55	51.35	50.72	1.25	-0.45	1.35	0.72	1.01	1.56	0.20	1.82
29.00	50.00	51.25	49.50	51.35	50.70	1.25	-0.50	1.35	0.70	1.04	1.56	0.25	1.82
30.00	50.00	51.30	49.45	51.40	50.72	1.30	-0.55	1.40	0.72	1.10	1.69	0.30	1.96
31.00	50.00	51.30	49.40	51.40	50.70	1.30	-0.60	1.40	0.70	1.13	1.69	0.36	1.96
32.00	50.00	51.30	49.35	51.40	50.68	1.30	-0.65	1.40	0.68	1.16	1.69	0.42	1.96
33.00	50.00	51.30	49.35	51.40	50.68	1.30	-0.65	1.40	0.68	1.16	1.69	0.42	1.96
34.00	50.00	51.30	49.35	51.40	50.68	1.30	-0.65	1.40	0.68	1.16	1.69	0.42	1.96

35.00	50.00	51.30	49.30	51.40	50.67	1.30	-0.70	1.40	0.67	1.18	1.69	0.49	1.96
36.00	50.00	51.30	49.30	51.40	50.67	1.30	-0.70	1.40	0.67	1.18	1.69	0.49	1.96
37.00	50.00	51.30	49.30	51.40	50.67	1.30	-0.70	1.40	0.67	1.18	1.69	0.49	1.96
38.00	50.00	51.30	49.30	51.40	50.67	1.30	-0.70	1.40	0.67	1.18	1.69	0.49	1.96
39.00	50.00	51.30	49.30	51.40	50.67	1.30	-0.70	1.40	0.67	1.18	1.69	0.49	1.96
40.00	50.00	51.30	49.30	51.40	50.67	1.30	-0.70	1.40	0.67	1.18	1.69	0.49	1.96
41.00	50.00	51.30	49.30	51.40	50.67	1.30	-0.70	1.40	0.67	1.18	1.69	0.49	1.96
42.00	50.00	51.30	49.30	51.40	50.67	1.30	-0.70	1.40	0.67	1.18	1.69	0.49	1.96
43.00	50.00	51.30	49.30	51.40	50.67	1.30	-0.70	1.40	0.67	1.18	1.69	0.49	1.96
44.00	50.00	51.30	49.30	51.40	50.67	1.30	-0.70	1.40	0.67	1.18	1.69	0.49	1.96
45.00	50.00	51.30	49.30	51.40	50.67	1.30	-0.70	1.40	0.67	1.18	1.69	0.49	1.96
46.00	50.00	51.30	49.30	51.40	50.67	1.30	-0.70	1.40	0.67	1.18	1.69	0.49	1.96
47.00	50.00	51.10	49.30	51.20	50.53	1.10	-0.70	1.20	0.53	1.07	1.21	0.49	1.44
48.00	50.00	51.00	49.30	51.10	50.47	1.00	-0.70	1.10	0.47	1.01	1.00	0.49	1.21
49.00	50.00	50.90	49.30	51.00	50.40	0.90	-0.70	1.00	0.40	0.95	0.81	0.49	1.00
50.00	50.00	50.90	49.25	51.00	50.38	0.90	-0.75	1.00	0.38	0.98	0.81	0.56	1.00
51.00	50.00	50.85	49.25	50.95	50.35	0.85	-0.75	0.95	0.35	0.95	0.72	0.56	0.90
52.00	50.00	50.85	49.25	50.95	50.35	0.85	-0.75	0.95	0.35	0.95	0.72	0.56	0.90
53.00	50.00	50.85	49.25	50.95	50.35	0.85	-0.75	0.95	0.35	0.95	0.72	0.56	0.90
54.00	50.00	50.80	49.25	50.90	50.32	0.80	-0.75	0.90	0.32	0.93	0.64	0.56	0.81
55.00	50.00	50.80	49.25	50.90	50.32	0.80	-0.75	0.90	0.32	0.93	0.64	0.56	0.81
56.00	50.00	50.80	49.20	50.90	50.30	0.80	-0.80	0.90	0.30	0.95	0.64	0.64	0.81
57.00	50.00	50.70	49.20	50.80	50.23	0.70	-0.80	0.80	0.23	0.90	0.49	0.64	0.64
58.00	50.00	50.70	49.20	50.80	50.23	0.70	-0.80	0.80	0.23	0.90	0.49	0.64	0.64
59.00	50.00	50.70	49.20	50.80	50.23	0.70	-0.80	0.80	0.23	0.90	0.49	0.64	0.64
60.00	50.00	50.70	49.20	50.80	50.23	0.70	-0.80	0.80	0.23	0.90	0.49	0.64	0.64
61.00	50.00	50.70	49.20	50.80	50.23	0.70	-0.80	0.80	0.23	0.90	0.49	0.64	0.64
62.00	50.00	50.65	49.20	50.75	50.20	0.65	-0.80	0.75	0.20	0.87	0.42	0.64	0.56
63.00	50.00	50.65	49.20	50.75	50.20	0.65	-0.80	0.75	0.20	0.87	0.42	0.64	0.56
64.00	50.00	50.60	49.20	50.70	50.17	0.60	-0.80	0.70	0.17	0.84	0.36	0.64	0.49
65.00	50.00	50.60	49.20	50.70	50.17	0.60	-0.80	0.70	0.17	0.84	0.36	0.64	0.49
66.00	50.00	50.50	49.20	50.60	50.10	0.50	-0.80	0.60	0.10	0.78	0.25	0.64	0.36
67.00	50.00	50.40	49.15	50.50	50.02	0.40	-0.85	0.50	0.02	0.75	0.16	0.72	0.25
68.00	50.00	50.30	49.15	50.40	49.95	0.30	-0.85	0.40	-0.05	0.69	0.09	0.72	0.16
69.00	50.00	50.20	49.15	50.30	49.88	0.20	-0.85	0.30	-0.12	0.64	0.04	0.72	0.09
70.00	50.00	50.20	49.15	50.30	49.88	0.20	-0.85	0.30	-0.12	0.64	0.04	0.72	0.09
71.00	50.00	50.15	49.10	50.25	49.83	0.15	-0.90	0.25	-0.17	0.64	0.02	0.81	0.06
72.00	50.00	50.00	49.10	50.10	49.73	0.00	-0.90	0.10	-0.27	0.55	0.00	0.81	0.01
73.00	50.00	50.00	49.10	50.10	49.73	0.00	-0.90	0.10	-0.27	0.55	0.00	0.81	0.01
74.00	50.00	50.00	49.10	50.10	49.73	0.00	-0.90	0.10	-0.27	0.55	0.00	0.81	0.01
75.00	50.00	50.00	49.05	50.10	49.72	0.00	-0.95	0.10	-0.28	0.58	0.00	0.90	0.01
76.00	50.00	49.90	49.05	50.00	49.65	-0.10	-0.95	0.00	-0.35	0.52	0.01	0.90	0.00
77.00	50.00	49.85	49.05	49.95	49.62	-0.15	-0.95	-0.05	-0.38	0.49	0.02	0.90	0.00
78.00	50.00	49.85	49.00	49.95	49.60	-0.15	-1.00	-0.05	-0.40	0.52	0.02	1.00	0.00
79.00	50.00	49.85	49.00	49.95	49.60	-0.15	-1.00	-0.05	-0.40	0.52	0.02	1.00	0.00
80.00	50.00	49.80	49.00	49.90	49.57	-0.20	-1.00	-0.10	-0.43	0.49	0.04	1.00	0.01
81.00	50.00	49.80	49.00	49.90	49.57	-0.20	-1.00	-0.10	-0.43	0.49	0.04	1.00	0.01
82.00	50.00	49.70	49.00	49.80	49.50	-0.30	-1.00	-0.20	-0.50	0.44	0.09	1.00	0.04
83.00	50.00	49.70	49.00	49.80	49.50	-0.30	-1.00	-0.20	-0.50	0.44	0.09	1.00	0.04
84.00	50.00	49.65	49.00	49.75	49.47	-0.35	-1.00	-0.25	-0.53	0.41	0.12	1.00	0.06
85.00	50.00	49.65	49.00	49.75	49.47	-0.35	-1.00	-0.25	-0.53	0.41	0.12	1.00	0.06
86.00	50.00	49.60	49.00	49.70	49.43	-0.40	-1.00	-0.30	-0.57	0.38	0.16	1.00	0.09
87.00	50.00	49.60	49.00	49.70	49.43	-0.40	-1.00	-0.30	-0.57	0.38	0.16	1.00	0.09
88.00	50.00	49.50	49.00	49.60	49.37	-0.50	-1.00	-0.40	-0.63	0.32	0.25	1.00	0.16
89.00	50.00	49.40	49.00	49.50	49.30	-0.60	-1.00	-0.50	-0.70	0.26	0.36	1.00	0.25
90.00	50.00	49.40	49.00	49.50	49.30	-0.60	-1.00	-0.50	-0.70	0.26	0.36	1.00	0.25

91.00	50.00	49.40	49.00	49.50	49.30	-0.60	-1.00	-0.50	-0.70	0.26	0.36	1.00	0.25
92.00	50.00	49.40	49.00	49.50	49.30	-0.60	-1.00	-0.50	-0.70	0.26	0.36	1.00	0.25
93.00	50.00	49.40	49.00	49.50	49.30	-0.60	-1.00	-0.50	-0.70	0.26	0.36	1.00	0.25
94.00	50.00	49.40	49.00	49.50	49.30	-0.60	-1.00	-0.50	-0.70	0.26	0.36	1.00	0.25
95.00	50.00	49.40	49.00	49.50	49.30	-0.60	-1.00	-0.50	-0.70	0.26	0.36	1.00	0.25
96.00	50.00	49.40	49.00	49.50	49.30	-0.60	-1.00	-0.50	-0.70	0.26	0.36	1.00	0.25
97.00	50.00	49.40	49.00	49.50	49.30	-0.60	-1.00	-0.50	-0.70	0.26	0.36	1.00	0.25
98.00	50.00	49.40	49.00	49.50	49.30	-0.60	-1.00	-0.50	-0.70	0.26	0.36	1.00	0.25
99.00	50.00	49.40	49.00	49.50	49.30	-0.60	-1.00	-0.50	-0.70	0.26	0.36	1.00	0.25
100.00	50.00	49.40	49.00	49.50	49.30	-0.60	-1.00	-0.50	-0.70	0.26	0.36	1.00	0.25
										RMSE	0.83	0.73	0.90