DESIGN AND DEVELOPMENT OF COOPERATIVE CONTROLLED TWO ROBOTS FOR PIPELINE INSPECTION

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DESIGN AND DEVELOPMENT OF COOPERATIVE CONTROLLED TWO ROBOTS FOR PIPELINE INSPECTION

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DECLARATION

I declare that this thesis entitled "Design And Development of Cooperative Controlled Two Robots For Pipeline Inspection" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

Name : LAW KOK WAH

Date : 19 June 2019

APPROVAL

I hereby declare that I have checked this report entitled "Design And Development of Cooperative Controlled Two Robots For Pipeline Inspection" and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Mechatronics Engineering with Honours

Signature :
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Supervisor Name :
....

Date :
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DEDICATIONS

To my beloved mother and father

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ABSTRACT

Pipeline explosion is the most dreadful incident in the oil and gas industry which cause a huge number of fatality and financial loss every year. The existing pipeline inspection robots is costly and the efficiency and flexibility of the single robot system is low in case the pipeline have 2 ways such as T-branch. Therefore, the affordable cooperative controlled two robots for pipeline inspection are developed where the robots are applicable for the horizontal pipeline which used to transport air or gas. This project also aims to evaluate the performance of the developed mobile robots and develop the communication between the mobile robots. A simple structure wheeled type robot has good performance in T-branch accessibility is stated. Besides, Bluetooth module is the most common tools to develop the communication between the multi robot system due to its ease to use and can communicate with other Bluetooth enabled devices. Few experiments such as performance of mobile robot on various type of surfaces, tracking object using ultrasonic sensor, leader-follower approach and tracking control of mobile robot are designed to evaluate the performance and communication between the mobile robots. A PVC pipe with T-branch is built to verify the mobile robots in T-branch accessibility. Through the experiment, the mobile robot is successfully pass through the pipeline with various type of surfaces. The speed, efficiency and accuracy are also evaluated through the experiment. The master and slave robot are able to perform forward, backward, turning left and right movement without having communication loss or disconnected in the PVC pipe.

ABSTRAK

Letupan saluran paip adalah kejadian paling mengerikan dalam industri minyak dan gas yang menyebabkan banyak kematian dan kerugian kewangan setiap tahun. Robot pemeriksaan saluran paip yang sedia ada di pasaran adalah mahal dan kecekapan serta fleksibiliti sistem robot tunggal adalah rendah sekiranya saluran paip mempunyai 2 arah seperti T-cawangan. Oleh itu, dua robot yang dikawal dengan koperatif dan harga berpatutan untuk pemeriksaan saluran paip dicadangkan di mana robot itu boleh digunakan untuk saluran paip mendatar yang digunakan untuk mengangkut udara atau gas. Projek ini juga bertujuan untuk menilai prestasi robot mudah alih yang dibina dan membangunkan komunikasi antara robot mudah alih. Robot jenis beroda mempunyai prestasi yang baik dalam akses T-cawangan dipilih. Selain itu, modul Bluetooth adalah alat yang paling biasa untuk membangunkan komunikasi di antara sistem multi robot kerana ia mudah digunakan dan boleh berkomunikasi dengan peranti berkemampuan Bluetooth yang lain. Beberapa eksperimen seperti prestasi robot bergerak pada pelbagai jenis permukaan, objek penjejakan menggunakan pengesan ultrasonik, pendekatan pemimpin-pengikut dan kawalan penjejakan robot bergerak telah direka untuk menilai prestasi dan komunikasi antara robot mudah alih. Paip PVC dengan T-cawangan telah dibina untuk mengesahkan robot mudah alih dalam pengaksesan T-cawangan. Melalui eksperimen, robot mudah alih berjaya melalui saluran paip dengan pelbagai jenis permukaan. Prestasi seperti kelajuan, kecekapan dan ketepatan juga telah dinilai melalui eksperimen. Robot pemimpin dan pengikut dapat melakukan gerakan ke depan, ke belakang, mengubah gerakan kiri dan kanan tanpa kehilangan komunikasi atau terputus di dalam paip PVC.

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LIST OF SYMBOLS AND ABBREVIATIONS

IPE	-	Impacting people and environment
AI	-	Artificial Intelligent
MRS	-	Multi Robot System
USV	-	Unmmaned Surface Vehicle
UAV	-	Unmmaned Aerial Vehicle
HRI	-	Human Robot Interaction
ILI	-	In-line Inspction
MFL	-	Magenetic Flux Leakage
PIR	-	Pipeline Inspection Robot
CCD	-	Charge Coupled Device
CMOS	-	Complementary Metal Oxide Semiconductor
DC	-	Direct Current
IDE	-	Integrated Development Environment
Mbps	-	Megabytes per second
RPM	-	Rotations per minute
PVC	-	Polyvinylchloride
RC	-	Remote control
RMSE	-	Root Mean Square Error
AT	-	Attention Command
PWM	-	Pulse Width Modulation

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Mobile robot is an integration of different type of physical and computational components which are controlled automatically to solve the task given by human being. Basically, the mobile robots are designed and used in three major type of environment which are air, land and underwater. Mobile robots are widely used in industrial plant to solve the task which can’t be solve by human being. Normally, the tasks are dangerous work and the environment is inaccessible by human being.

Pipeline inspection is one of the dangerous work that can be solved by the mobile robots. The purpose of pipeline is used for the movement in transporting the liquids and gases from one place to another place. Basically, the pipeline is used to transport the natural gas, fuel oils and drinkable water. The transporting activities are carry out every day. After a period of time, the pipes are exposed to the chance of break, leak or crack due to the rusting, pressure and aging [1]. These defects can cause the time to complete the transportation become longer. As a result, the business activities of the company will be effected and decelerate and it is a serious impact to the oil and gas industry. This is the main reason that pipeline inspection needed to carry out frequently to reduce the chance of incidents happen.

1.2 Motivation

The serious pipeline incident such as pipeline explosion which will cause fatality or injury due to corrosion failure, equipment failure, incorrect operation, material pipe failure and others incident causes [2]. In recent years, the case of pipeline incidents has been decreased due to the latest technology of pipeline inspection. However there are some case of pipeline incidents happen due to the weakness of the technology. Pipeline incidents cause destruction in terms of economy and fatality. Table 1.1 shows the total number of pipeline incidents that impact the people and environment (IPE) that occur in worldwide from 2013 to 2017 [2].

Table 1.1: Total number of IPE case by cause (2013-2017)

Total IPE incidents by cause (2013-2017)	
Factor	**Total Case**
Corrosion Defeat	168
Equipment Defeat	105
Material Pipe/ Weld Defeat	61
Mistaken Operations	60
Excavation incidents	47
Natural Force incidents	30
Other Causes	26
Outside Force incidents	23
Total	**520**

Based on Table 1.1, there are total 520 cases of IPE incidents that happen in the world. In other words, it is almost 100 cases of IPE incidents are happen every year. Main causes of the IPE incidents are corrosion and equipment failures.

Recently, a natural gas pipeline explosion has been happened in southeast New Mexico at 20 August 2018. The explosion has caused fatality which five adults and five children are killed in the incidents [3]. Besides, the explosion also caused two people in critical injury. The 30 inch pipeline exploded and left a crater about 86 feet long, 46 feet wide and 20 feet deep [3]. The investigator of the incidents said that the explosion could have been happened because of some leakage of the pipeline and ignited by anything.

In terms of percentage of occurs, Malaysia is considered as a country with low percentage of pipeline incidents occurred. However, this should not be ignored because there is a pipeline incident that has been happened in Miri Sarawak at 11 Jun 2014. A pipeline explosion ripped apart a section of the Sabah-Sarawak interstate gas pipeline located in between Lawas town and Long Sukang in the northernmost district of Sarawak [4]. Although there are no fatality in the incident, but the incident causes a temporary business activity shut down. A RM4 billion project that owned by Petronas is shut down for a period of time [4]. The investigator of the incidents said that there must be some serious faults to have ignited the explosion.

In conclusion, an efficient mobile robots is needed in the field of pipeline inspection due to pipeline incidents bring a big impact to human being and environment. Although occurrence of pipeline incidents in Malaysia is less than other countries, however Malaysia should have an effective pipeline inspection robot to reduce or avoid the chance of pipeline incidents happening.

1.3 Problem Statement

The current technology for pipeline inspection robot is very advanced. With this current technology, many pipeline explosion incident can be avoid. The pipeline inspection robot that developed by the JETTY Robot company can even maintenance or repair the pipe which is defect [5]. However, these extremely advanced pipeline inspection robot is not been ordinary to the others country especially Malaysia because of its high cost. One fully equipped pipeline inspection robot costs around 20,000 - 35,000 dollars [6]. Therefore, an affordable pipeline inspection robot with high efficiency should be develop to meet the demand of the countries which have low percentage of pipeline explosion incident.

Next, efficiency is one of the main concerns of a pipeline inspection robot. In current technology, humans are not only need a robot that can perform the physical task but also chasing the high efficiency of the robot to solve the task in a shorter time. However, the evolution of the robotics field has been focused on the single robot systems which consume more time in solving a task compared to multi robot system. The move from single robot system to multi robot system is very important to develop a new era of technology. Multi robot system brings many benefits over single robot system in terms of efficiency, completion of time, and flexibility. Basically, a pipeline inspection robot is move slowly along the pipeline to check and monitor along the pipe. The robot need extra time especially the pipeline have a two ways like T branches. Therefore, the speed and accuracy of the mobile robot must be considered to improve the time efficiency of the pipeline inspection robot so that the inspection work can solved in a shortest time.

Besides, flexibility of the robots also is a main concern issue. In current technology, most of the multi robot system perform the homogeneous action mechanism. Homogeneous action mechanism means that a team of follower robots follow exactly the task that have done by the leader robot. The flexibility of the robots are low if compared to the heterogeneous action mechanism robot. There is a slightly different between two mechanisms. Both mechanism consist of a main robot but the slave robot in heterogeneous action mechanism can perform different task with the master robot. Some pipeline have a two ways like T branches pipeline. In this case, heterogeneous action mechanism robot can perform well by perform the pipeline inspection simultaneously but different direction. Thus, flexibility of the robots must be considered to improve the efficiency of the pipeline inspection process.

In summary, this research will focus on developing a communication system between two mobile robots to perform the pipeline inspection with high efficiency and flexibility with the aid of low cost cooperative controlled robots.

1.4 Objectives

In this project, there are three objectives going to achieve:

1. To develop two affordable mobile robots that are cooperative controlled for pipeline inspection.

2. To evaluate the performance of the mobile robots in terms of speed, accuracy and efficiency.

3. To develop a communication system between the ‘master and slave’ robots by using the Bluetooth module for real time data transmission.

1.5 Scope

1. The robots consist of ultrasonic sensors, infrared sensors, Bluetooth module and the Arduino Uno board as the controller.

2. The size of the robots is 19cm x 13cm x 12cm.

3. There are two of the cooperative controlled robots is developed.

4. The mobile robots are applicable for the pipe where the diameter of the pipe is in the range of 20cm to 30cm.

5. The pipe is set up in horizontal.

6. The distance of the pipe to the junction is fixed to 2m.

7. The robots consists of camera which is specialized for data monitoring only. Robots are performed the task of live streaming in the pipe and capture image without image processing.

8. The mobile robots are applicable for the pipes which use to transport air or gas.

1.6 Summary

Overall, there are 4 subtopics are discussed which are motivation of the project, problem statement, objectives and scope of the research. The objectives of this project is to design two affordable mobile robots that are cooperative controlled for pipeline inspection by using a camera to monitor the environment of the pipeline. Besides, this project also aims to develop a communication system between the master-slave robots by using the Bluetooth module for real time data transmission. Last but not least, to evaluate the performance of the pipeline inspection robots in terms of efficiency, speed and accuracy. The next chapter will discuss and summarizes the findings on previous journal related to the project.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the theoretical background which related to this project such as theories on multi robot system and pipeline inspection are presented. Many previous journals, conference papers and articles which related to this project are studied and analyzed. A summary table is then constructed to summarize the findings based on few specific criteria.

2.2 Cooperative Controlled Robots

The phrase cooperative controlled robots also defined as multi robot system (MRS). MRS means a group of two or more mobile robots working together as a team to solve the tasks in the same environment [7]. Actually multi robots system is not a new technology. Since the late 1980s, researchers have been inspired to design and construct a set of robots which can working together to solve certain tasks [7]. At the beginning, researchers are motivated by observed the natural behavior of a swarm of ants and bees. From the observations, researchers are studied how a group of organism can working together to solve the problems. These early studies is important in contribution to develop the multi robot system nowadays. The studies also led to multi robot system being applied in different field such as surveillance, rescue, exploration, coordinate navigation, cooperative manipulation and among others [7]. The description of the application of MRS is summarize in Table 2.1.

Table 2.1: Description of application of MRS [7]

Application	Description
Surveillance, Search and Rescue	For this application, MRS is used to rescue the victims from natural and technological disaster. For example, with the development of Unmanned Surface Vehicle (USV) and Unmanned Aerial Vehicles (UAV), victims from the Fukushima nuclear accidents 2011 can be rescued. By sending the USV and UAV, the location of victims can be known by using image processing.
Foraging and Flocking	The task of foraging and flocking also called as swarm robotics. For the task of foraging, it use the concept of often decentralized to allow the robots to solve the task by minimum interference between them. For foraging, robots are applied in cleaning up the risky waste by transport the waste and return back to main station. For flocking task, robots are needed to move in straight line and follow the direction. The robots also needed to avoid the obstacles during the process.
Formation and Exploration	For formation application, it is complicated because the robots need to avoid the obstacles and maintain the formation at the same time. In exploration application, the group of robots will distributed to different direction of environment to navigate and explore the environment completely. Communication range between the robots and battery life are the main concern issues in this application.
Cooperative Manipulation	For cooperative manipulation, basically it is same with the foraging application. The difference between them is in traditional cooperative manipulation, communication is absent in this system. The robots used is pre-programmed and they will follow the pre-programmed path to reach the object and transport it.
Team Heterogeneity	Heterogeneity in multi robot system is important to enables the group of robots to perform heterogeneous action to solve the complex task more efficiency. Human robot interaction (HRI) is involved in this application and acted as a commander to supervise and give command to the group of robots.

2.3 Communication in Multi Robot System

Multi robot system can solve the complex task effectively and efficiency that cannot be achieved by single robot system. However, communication system between the team of robots is a big and main challenge to develop an effective multi robot system. Generally, communication is defined as a relationship and connection between the emitter and receiver. The signal is produced by the emitter and interpreted by the receiver [8]. By develop the communication between the robots, the robots can share real time location, status of the environment and sensor information among others in the system [8]. Basically, communication in multi robot system can be classified to two types. The two types of communication are implicit communication and explicit communication [9].

In robotic field, explicit communication refers direct exchange information among the group of robots. The process of exchange information can be made in the form of either unicast or broadcast intentional messages [10]. Explicit communication usually requires a communication modules channel or languages such as WIFI, Bluetooth, Xbee, synthesized speech and voice recognition software [11]. Explicit communication is a good strategy. It is because when a danger or obstacles is detected, fast reaction can be made and related action to overcome the problems can be taken. Most of the multi robot system nowadays are using this mechanism.

On the other hand, implicit communication refers to the way of robot to get signal or information about other robots through the environment. Implicit communication also known as stigmergy which is predominant in organism of insects. This type of mechanism requires to install or insert different type of sensors on the robots. Implicit communication can be classified to two categories which are active implicit communication and passive implicit communication [10]. Active implicit communication means that robots communicate by observe the information left by other robots in the environment. For example, the mobile robots can leave footprint or traits during the exploration. So that other robots that recognize the changes of the environment can get the information.

This type of action is similar to ants leaving the scent trails when searching food [10]. For passive implicit communication, robots are communicate among others by sense the change of environment using the sensors. For example, robots need to observe and analyze the signal and information such as position and direction of others robots by processing the received data in order to communicate with each other [10]. A compute of advantages and disadvantages of the both communication mechanism as shown in Table 2.2.

Table 2.2: Advantages and disadvantages of both communication mechanism [10]

	Advantages	**Disadvantages**
Implicit Communication	Stability and fault tolerance are better	Information obtained not completely reliable
Explicit Communication	High accuracy	System performance decreases as the number of robots increase due to the communication load of system increases

There are few factors that will affect the communication in multi robots system. There are information density, channel bandwidth, channel security, channel reliability, channel efficiency and channel traffic as shown in Table 2.3.

Table 2.3: Factors that affect the communication in MRS [10]

Factor	**Description**
Information density	The exchanged information between robots have to reduce to the desire bandwidth which is fixed to the network channel.
Channel bandwidth	Total of communication throughout can be achieved by deciding the bandwidth of the channel.
Channel security	By using encryption algorithms, unintended interception during the process of exchanged information between robots can be avoid.
Channel reliability	Channel reliability is related to the channel noise. It is expressed by the ratio of received error free bits to the number of transmitted bits.

Channel efficiency	The channel efficiency is expressed by the total number of bits exchanged to the total power required to receive the signal.
Channel traffic	The available bandwidth is affected by the number of robots that competing for a channel to exchange information.

2.4 Pipeline Inspection

Nowadays oil and gas pipeline have become the main bone of national economy for a country. The transportable flammable oil and gas inside the pipeline can lead to explosion due to the leak, crack or corrosion of the pipeline. Although pipeline is the most reliable transport equipment for the oil and gas, but still many cases of pipeline explosion happen every year. The explosion of pipeline can lead to fatality and financial loss for the related company. Therefore pipeline inspection is needed to carry out frequently to avoid the happening of pipeline incidents.

Pipeline inspection is classified to two testing which are destructive testing and non-destructive testing [12]. Basically destructive testing is carried out by using hydrostatic pressure method while non-destructive testing is using the in-line inspection (ILI) tools such as ultrasonic wave method, intelligent pigging, 3-dimensional laser profile, and magnetostriction inspection [13].

The destructive testing applied the hydrostatic pressure to the pipeline to check whether the pipeline achieve the minimum requirement of safety standard operation. First, to carry out destructive testing, pressure taps are used to pressurize the water [12]. Then the pressure taps are placed along the pipeline with a preset distance. The purpose of placing the pressure tap along the pipeline is to monitor the pressure change of the pipeline. There are some electronic device that will sends the signals back to the base station to check the trends of pressure change. There will a deviation from the desired pressure if there is a leak occur in the pipeline [12]. So that operator can know the location of leaking part of the pipeline.

The first technique of non-destructive testing is ultrasonic wave testing. Ultrasonic wave testing is carried out by applied the low frequency guided waves to the pipeline [13].

This method can use to detect the corrosion, erosion and material loss in the pipelines. The working theory of ultrasonic wave testing is clamped a unit of piezoelectric transducer around the pipeline [13]. After that, ultrasound is sent in one direction of the pipeline and then follow by the other direction. The signal achieved is in graphical where the horizontal axis represents the length of the pipe and the vertical axis represents the level of corrosion. Ultrasonic wave testing is suitable for the pipeline that diameter is more than 50mm and thickness more than 40mm [13].

The second technique of non-destructive testing is intelligent pigging method. Most of the intelligent pigging use a magnetic flux leakage (MFL) method but some also applied the ultrasound to do the inspection [14]. The device that used in this method is called 'pigs'. Pigs have the same size with the pipeline diameter where the pig will travel along the pipeline to record the related data. To use the magnetic flux leakage method, magnets is used or driving electric current into the surface of pipeline so that a strong magnetic field can be developed in the pipeline [15]. Defect area of the pipeline cannot withstand the magnetic flux as much as the undamaged area. Then it will lead to a leakage of magnetic flux at the defect area of the pipe wall. The pigs can know the damage area by detect the leakage of the magnetic flux using the sensor that installed on the body [15]. Figure 2.1 shows the device that used in intelligent pigging method.

Figure 2.1: Pigs device that used in intelligent pigging method [14]

The third technique of non-destructing testing is three dimensional (3D) laser profile measurement. This technique is a high accuracy method to measure the corrosion depth of the pipeline [13]. The related software program can generate the report on site which can analysis the corrosion mapping and element analysis. The laser beam scanner that used in this technique records a number of 69,000 measurements per second [13]. Before the 3D laser technique is carried out, the surface of the pipeline must be cleaned to remove all the contaminants or dirt which will affect the accuracy of the measurements. The advantage of 3D laser technique is that the laser beam has high accessibility. Laser beam can access the places such as curved surfaces, nozzles and bends surface which are difficult to access by the mechanical tools [13]. Besides that, the analysis report also allow the maintenance team to determine the best repair method. Furthermore, the analysis report will show the level corrosion of the surface pipeline by using the color depth scale [13].

The fourth technique of non-destructing testing is magnetostriction inspection. In recent year, many researcher focus on magnetostriction due to its faster inspection and crack identification of pipelines. Magnetostriction is one of the characteristic of ferromagnetic material [16]. The ultrasonic wave inside ferromagnetic material can be generated and received by using the theory of magnetostriction effect and its reverse effect [16]. Magnetostriction sensor can transmit and sense the ultrasonic waves to detect the crack, corrosion and leak of the pipeline even the air gap between the inspection probe and pipeline is large [16].

As a summary, there are few aspects to be considered to choose an appropriate pipeline inspection method [12]:

- Speed
- Reliability
- Sensitivity which refer to the probability of detection
- Selectivity which refer to which method suitable to detect the particular defect

2.5 Pipeline Inspection Robot

In recent decades, pipeline inspection robots are widely used in the field of oil and gas industry. In-pipe inspection robots (IPIR) are used to inspect the cracks, erosion, and leakage of pipeline due to many factors such as corrosion, aging of pipeline, overheating and others [17]. In order to develop an in-pipe inspection robot, there are many criteria need to be considered such as mobility, size and shape adaptability, flexibility and others [18]. The in-pipe inspection robots that widely used in the industry nowadays are wheel type, caterpillar type and non-wheel type [18]. These robots are developed based on the industry requirement to adapt the specific environment or application. Table 2.4 shows the classification of the in-pipe inspection robot.

Table 2.4: Classification of in-pipe inspection robot [18]

In-pipe Inspection Robot	Wheel Type Robot	Simple Structure Type
		Wall Press Type
		Screw Drive Type
	Caterpillar Type Robot	Simple Structure Type
		Wall Press Type
	Non-wheel Type Robot	Walking Type
		Inchworm Type
		Snake Type

2.5.1 Wheel Type Robot

Wheel type robot with simple structure with single locomotion is similar to the normal mobile robot. It has simple structure of body and its wheels are directly mounted to the motors. Wheel type robot is capable to achieve the desired direction of motion by using the microcontroller with motor driver system [19]. Besides that, wheel type robot also capable to travel the sharp intersections pipeline like T-junction pipeline by having the enough space for the front and rear wheels to rotate [19]. Figure 2.2 shows the wheel type robot with simple structure.

Figure 2.2: Wheel type robot with simple structure

Wheeled press type robot with driver system are capable to travel complex pipeline condition such as pipeline with branches, uneven surface, and diameter change pipeline [17]. Wheeled wall pressed robot are high efficiency than other type of wall pressed robots such as caterpillar wall pressed robots due to its high speed mobility [17]. Basically, wheeled wall pressed robots consist of at least three wheel chain with folding mechanism. The folding mechanism applied the spring mechanism so that the robot can adapt the changing diameter id the pipeline [17]. For four wheel chain wheeled wall pressed robots, the wheel chain is installed parallel with folding mechanism and 180˚ apart so that all the four wheels can directly contact to the wall of pipeline [17]. Figure 2.3 shows the wheeled wall pressed robot with four wheel chain.

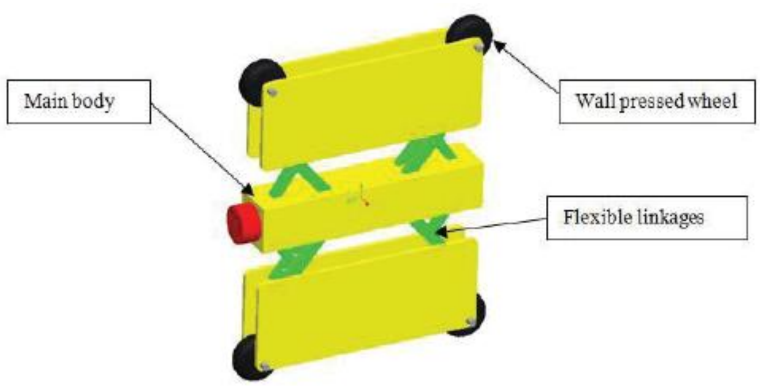


Figure 2.3: Wheeled wall pressed robot with four wheel chain [17]

Wheeled wall pressed with screw type robot combine three degree of freedom in one robot. The advantages of this type of robot is the wheel features in the robot reduce the friction between the screw and the pipe wall [17]. Generally, this type of robot requires rotor and stator to perform the motion. Rotor is used to compose the three wheels in various angle [18]. The rotor is directly mounted with motor so that it can converts the rotational energy of motor to translational energy of robot. On the other hand, stator consists of three straight wheels which use to eliminate the reaction force from the rotation of rotor so that the stability of the robot can be maintained [18]. Figure 2.4 shows the wheeled wall pressed with screw type robot.

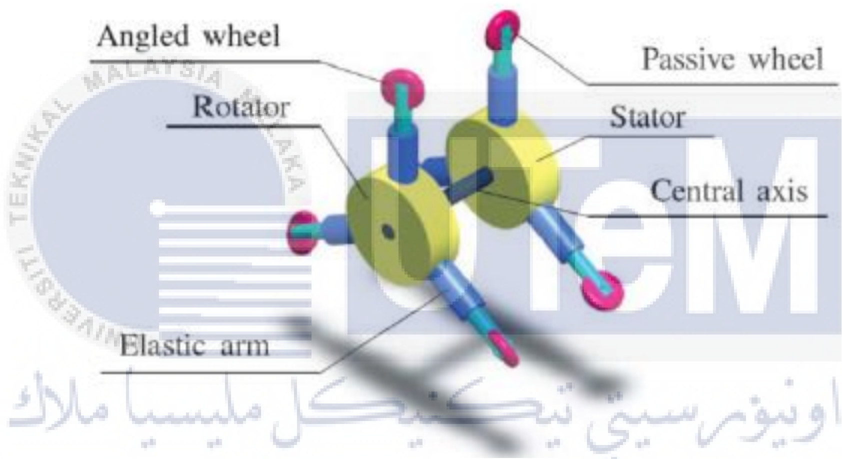


Figure 2.4: Wheeled wall pressed robot with screw type robot [17]

2.5.2 Caterpillar Type Robot

Caterpillar type robot with simple structure has similar mechanism with the wheel type robot with simple structure. The main difference between them is caterpillar type robot has the wheels which bounded with belt to increase the friction between the wheels and pipe wall [19]. This mechanism is to allow the robots to move on uneven surface in the pipeline. By the way, this robot cannot climb vertical and inclined pipelines [19]. Figure 2.5 shows the caterpillar type robot with simple structure.

Figure 2.5: Caterpillar type robot with simple structure

Caterpillar wall pressed type robot basically is combined caterpillar simple structure system with wall pressed system. This combined mechanism allows the robots to move in various diameter of pipelines, move smoothly on curvature and rugged surface of pipeline [17]. The caterpillar wall pressed type robot that widely used in industry generally consists of three main parts which are main body, flexible linkage mechanism and caterpillar wheel. Caterpillar wheels have a good feature that it supply enough traction force for robots to move forward and backward. Flexible linkage mechanism play the role as wall pressed system to allow the wheels directly contact to the wall of pipeline [19]. Figure 2.6 shows the structure of caterpillar wall pressed type robot.

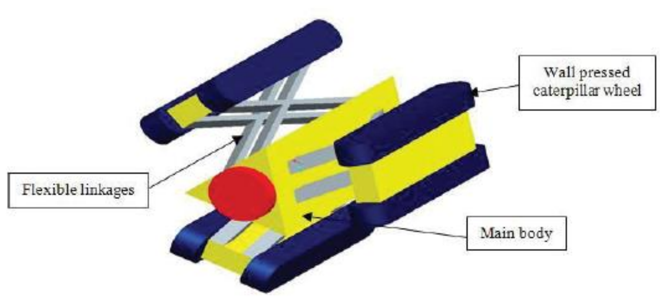


Figure 2.6: Structure of caterpillar wall pressed type robot [17]

2.5.3 Non-wheel Type Robot

Walking leg robot is one of the non-wheel type robot. A perfect walking leg robot consists two sets of four legs which are pushed against the pipe wall. The walking legs are attached to the main body of robot with the revolving joint [20]. These legs consists of knee joint like human leg which making the leg flexible. These developed legs allow the robot to move over almost all shape and surfaces of pipeline. Walking leg robot can travel the extremely complex environment such as vertical pipes, curvature surfaces, T-junction pipelines, and others without slipping [20]. The overall performance of the waking leg robot is relatively high compare to others type of in-pipe inspection robot. The disadvantages of this robot is require more motors to drive the leg. Therefore, more energy is consumed and the process of development is much more complicated [19]. Figure 2.7 shows the simulation of walking type robot with two set of four legs.

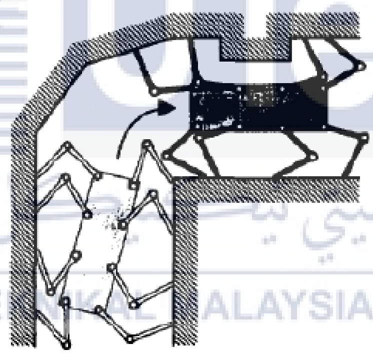


Figure 2.7: Simulation of walking type robot with two set of four legs [19]

Inchworm type robot is another type of non-wheel type robot. Inchworm type robot is a robot which make its body area that equipped with moving mechanisms to create friction force with the surface of pipe wall [19]. Basically, inchworm type module consists of two clamper module which are upper clamper module and lower clamper module and an extensor module. The inchworm type robot moving along the pipeline by repeatedly clamping the bottom part against the wall and extending the body forward, clamping the upper part and then retract the bottom part towards the front [20]. Inchworm type robot is adaptable in various environment especially the vertical pipe. Figure 2.8 shows the structure of inchworm type robot.

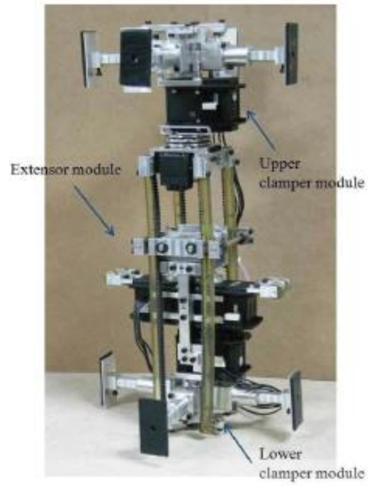


Figure 2.8: Structure of inchworm type robot [20]

Snake type robot also called as serpentine robot have many articulated active modules along its body. The body of snake type robot is divided to seven identical segments. Each segment is driven by a pair of antagonistic muscles or also called as flexor and extensor [19]. The moving theory of snake type robot is by using the propulsive force [19]. To move forward, snake type robot use the propulsive force from the low friction along the vertical direction to the high friction along the horizontal direction [19]. Figure 2.9 shows the structure of snake type robot.

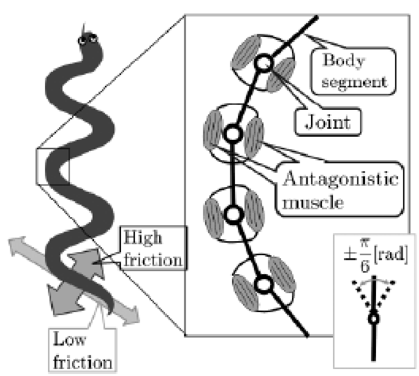


Figure 2.9: Structure of snake type robot [19]

2.6 Table Comparison of Cooperative Controlled Robots

Table 2.5: Comparison of cooperative controlled robots from previous studied journals and papers

Journal / Criteria	**Mobile Robots for Cooperative Autonomous Navigation** [21]	**Investigation of Homogeneous Multi Robots Communication** [22]	**Multi Robot Communication and Target Tracking System** [23]	**Multi Robot System for Real Time Sensing and Monitoring** [24]	**Multi Robot Cooperative Wireless Communication Control System** [25]	**Wireless Network for Mobile Robot Applications** [26]
Type of microcontroller	Atmel ATmega 2560	PIC16F877A	Atmel ATmega 2560	Atmel ATmega 2560	Atmel ATmega 2560	Atmel ATmega 2560
Communication Module	WIFI module ESP8266	Bluetooth Module	CC2500 Serial Communication Module	Bluetooth, Xbee and WIFI Module	Xbee Communication Module	WIFI module ESP8266
Programming Language	Python Programming	C Programming	C++ Programming	Python Programming	Python Programming	Python Programming
Sensor Used	Infrared Sensor	N/A	Ultrasonic Sensor, Sharp Distance Sensor and Infrared Sensor	Ultrasonic Sensor	N/A	Ultrasonic Sensor
Number of mobile robots involved	2	2	2	3	3	3
Type of mechanism	Leader-follower robots	Leader-follower robots	Leader-follower robots	1 master with 2 slave robots	1 master with 2 slave robots	1 master with 2 slave robots

In this section, comparison of cooperative controlled robots from previous journal and papers are summarized. Based on the Table 2.5, all the papers consists of microcontroller which play an important role to develop the cooperative controlled robots. [21], [23] , [24], [25], and [26] use Atmel ATmega chip as the microcontroller while [22] uses PIC16F877A as the microcontroller for the research. For the language which used to program the microcontroller, [21], [24], [25], and [26] applied python as the programming languages. While [22] and [23] use C and C++ languages, respectively.

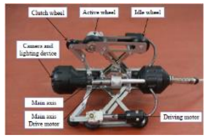
All of the papers shown in Table 2.5 involve the communication module which perform the explicit communication between the robots. For [21] and [26], WIFI module ESP8266 is used for their communication module. While [22] and [25] used Bluetooth module and Xbee communication module, respectively. Besides, [23] used CC2500 serial communication module while [24] used up three communication modules which are Bluetooth, WIFI and Xbee.

For the number of mobile robots involved in the system, [21], [22], and [23] involved two robots in their system while [24], [25] and [26] involved three mobile robots. The robots in the system are perform either homogeneous action (Leader-Follower) or heterogeneous action (Master-Slave). [21], [22], and [23] perform their robots in homogeneous action while [24], [25] and [26] perform in heterogeneous action.

Basically, the robots that developed by the papers are performed some task to show that the robots are cooperative controlled. The task such as obstacles avoidance, target tracking and navigation need the assist of sensors to perform well. Based on the Table 2.5, [24] and [26] consist of ultrasonic sensor while [21] consists of infrared sensor. In this case, [23] used up the most sensors such as ultrasonic sensor, sharp distance sensor an infrared sensor. But, [22] and [25] are not consist any sensors in their robots.

2.7 Table Comparison of In-pipe Inspection robot (IPIR)

Table 2.6: Comparison of in-pipe inspection robot from previous studied journals and papers

Criteria \ Journal	**A Pipeline Inspection Robot With Linkage Type Mechanical Clutch** [27]	**Design and Motion Planning of a Two-Module Collaborative Indoor PIR** [28]	**Development and Controller Design of Wheeled-Type Inspection Robot** [29]	**Development of In-pipe Robot for Passing through Bent and Brach Pipes** [30]	**FAMPER: A Fully Autonomous Mobile Robot for Pipeline Exploration** [31]
Type of mechanism	Wheeled Wall Pressed Type	Caterpillar Wall pressed Type	Wheeled Simple Structure Type	Screw Drive Type	Caterpillar Wall Pressed Type
Controller used	ATmega 128	ATmega 128, ATmega 8	ATmega 8	PIC16F88	PIC16LF88
Camera module	Micro CMOS Camera	Micro CMOS Camera	VIJE IP-2000 PTW	N/A	RF-CCD Camera
Weight (kg)	0.189	N/A	11.0	0.7	N/A
Size and Shape Adaptability	Yes	Yes	No	Yes	Yes
Vertical Mobility	Yes	Yes	No	Yes	Yes
T-joint Accessibility	No	Yes	Yes	Yes	Yes
Overall Design					

In this section, comparison of in-pipe inspection robot from previous journals and papers are summarized. For the controller that used up to develop the pipeline inspection robot, [27] and [29] used ATmega 128 and ATmega 8 respectively while [28] used both ATmega 128 and ATmega 8. On the other hand, [30] and [31] used PIC16F88 and PIC16LF88, respectively as stated in Table 2.6.

For the type of mechanism of the robots that developed by the papers above, most of the pipeline inspection robots are wall pressed type such as wheeled and caterpillar wall pressed mechanism except the [30] used the screw drive type mechanism. For the camera module that involved in development of pipeline inspection robot for monitoring purpose, both [27] and [28] used the same camera module which is Micro CMOS Camera. While [29] and [31] used VIJE IP-2000 PTW and RF-CCD Camera respectively. [28] and [31] have no mention their robot's weight whereas [27] and [30] have the light weight of robot which both not exceed 1kg.

In term of performance of the robots, almost all the robots that developed by the papers except [29] are vertical mobility and size and shape adaptability which means that robots can climb the vertical pipeline and working in various size and shape of pipeline. For T-branch accessibility, almost of the robots have the ability except [27].

2.8 Critical Literature Review

Based on the comparison of cooperative controlled robots and in-pipe inspection robot from previous studied papers listed in Table 2.5 and Table 2.6, each system or robots contain its pros and cons. In this part, the pros and cons of each system or robot will be discussed to pick the desired setup which is suitable for this research.

For the cooperative controlled robots, Atmel ATmega 2560 is the most common microcontroller which used by the previous study. It is because Atmel ATmega 2560 considered as a new technology if compared to PIC16F877A. Atmel ATmega 2560 can program in C++ languages or Python languages which give more opinion for user to choose to write the coding. For the type of mechanism of the robots, most of the previous choose to develop the robots which can perform heterogeneous action. It is because heterogeneity of the robots are very important in order to solve the task efficiency. In previous study, most of them involved three robots. Although three robots can solve the task more effectively, but on the other hand, system performance decreases as the number of robots increase due to the communication load of system increases. In order to perform the obstacles avoidance task, ultrasonic sensor and infrared sensor are most commonly used. It is because the sensors are cheap and the performance of the sensor are satisfy to perform the obstacles avoidance. For the communication module, Bluetooth module and WIFI module are the most common module that used by the previous study. Bluetooth module is cheap and it can communicate with any kind of Bluetooth enabled devices. Whereas WIFI module have a longer distance coverage but it is high power demand device. Hence if the requirement distance is not far, Bluetooth module is the best choice to use to develop the robots.

For the in-pipe inspection robots, wall pressed type is the most common mechanism that developed by the previous study. It is because wall pressed robots have the high performance such as size and shape adaptability, vertical mobility and T-joint accessibility. But on the hand, wall pressed robot have the complex structure and the cost development is relatively high if compared to the wheeled simple structure robot. For the pipeline construction, most of the pipeline are developed in horizontal style. Hence, wheeled simple structure robot which is high steerable and low cost development is suitable used to inspect the pipeline. For the camera used to monitoring the pipeline, most of the previous study used the Micro CMOS camera. CMOS sensors are extraordinary high frame rates, strong image quality and high sensitivity if compared to CCD sensors.

2.9 Summary

In a nutshell, this chapter presents all the theoretical background which are related to this research project. Besides, the pros and cons of previous studied papers also have been discussed in this chapter. In next chapter, the setup to be used in this project based on the studied papers and designed experiments will be discuss in order to achieve the objectives of this research project.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, all the methods that used to achieve the objectives of the project that stated in Chapter 1 are discussed and presented. Thus, this chapter is divided to three parts which are hardware development, program development and experiment setup. Besides, the procedure and list of apparatus and material for each conducted experiment are shown in this chapter.

3.2 Overall Process Chart of Project

A flow chart that shows the overall progress of the project is created as Figure 3.1 to ensure the project to be well organized. A Gantt chart also constructed as shown in Appendix A for proper schedule purpose. The whole research project can be divided into several parts. Introduction part includes the objectives, problem statements, motivation and scope of the project. The literature review includes the theoretical background about the cooperative controlled robots and pipeline inspection robot and evaluation of the robots that developed in previous studied research paper. The hardware development consists of selection of material and equipment as well as sensor to develop the cooperative controlled robots. Next, software development includes the programming for the overall multi robot system. The experiment setup describes the integration of hardware and software with detailed procedures to achieve the objectives of the project. Data collection and analysis is carried out after the conducted experiments to evaluate the performance of the robots. Lastly, conclusion is done to summarize the project.

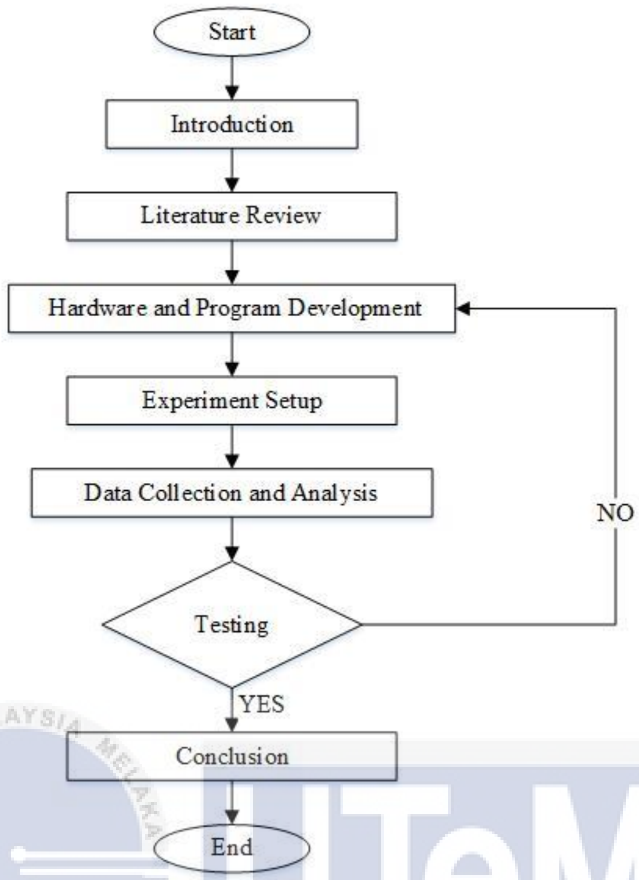


Figure 3.1: Overall progress chart of the project

3.3 Cooperative Controlled Robots Design

The selection of hardware and software are done after comparing the pros and cons of each system form previous studied journal that have discussed in Chapter 2. The illustration of the cooperative controlled robots system is shown in Figure 3.2.

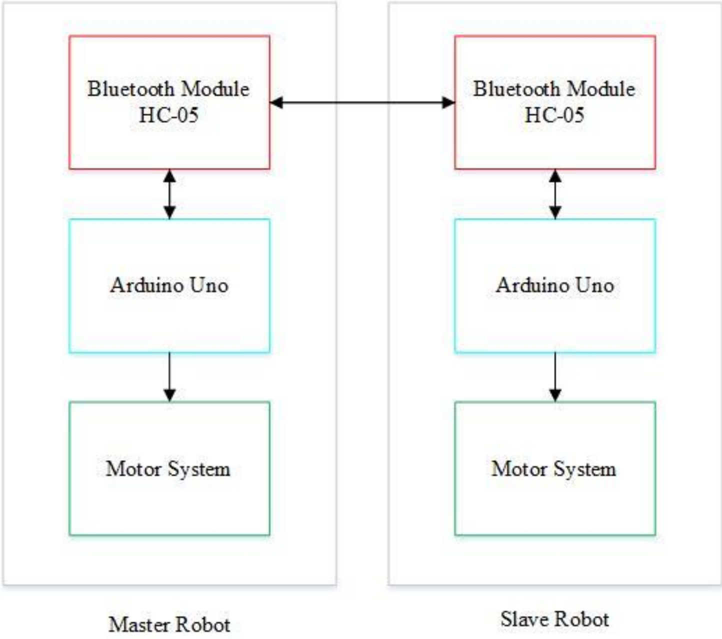


Figure 3.2: Illustration of the cooperative controlled robot system

Based on Figure 3.2, the controller chosen to develop the cooperative controlled robots is Arduino Uno due to its number of input and output (I/O) pins is sufficient to build a simple mobile robots which is cooperative controlled. Next, Bluetooth module is chosen to act as a communication channel between the robots to perform real time data transmission due to its ease of use and low power consumption. For the motor system, DC gear motor is chosen because its ability of reduce speed and increase torque at the same time.

3.4 Hardware Development

In this project, the hardware involved to develop the cooperative controlled robots for pipeline inspection can divided to six parts which are controller, motion, sensory system, communication, monitoring and power management.

3.4.1 Controller

3.4.1.1 Arduino Uno

Arduino is an open-source programming platform that produced microcontroller board for building a program to control the physical devices.

Arduino platform is chosen in this project because Arduino provides an integrated development environment (IDE) based on a simple programming languages. Besides, Arduino platform also have many open source libraries that are very convenient for user to develop a project. Due to no image processing is needed in this project, therefore this 8-bit microcontroller board is sufficient and suitable with this project. In addition, Arduino microcontroller is cost effective if compare to other microcontroller.

In choosing the microcontroller for this project, there are a few aspects that need to be considered as listed on Table 3.1. Table 3.1 listed out the specification of Arduino Uno for further understanding. The objectives of this project is to develop the robots which are cooperative controlled to perform pipeline inspection. Since the projects are focus on the communication system between the robots by using Bluetooth module, therefore the demand for higher flash memory and number of input/output pins are not that high. Therefore, Arduino Uno is chosen to use in this project.

Table 3.1: Specification of Arduino Uno [32]

Type of controller / **Specification**	**Arduino Uno** 
Microcontroller	ATmega 328
Operating voltage	5V
Digital I/O pins	14
Analog input pins	6
Flash memory	32KB
SRAM	2KB
Clock speed	16MHz

3.4.1.2 L298P Motor Shield

In this project, power that deliver to the motor must be sufficient in order to develop the mobile robots which can moving inside the pipeline. Therefore, L298P motor shield is chosen as shown in Figure 3.3 to extend the capabilities of Arduino Uno board by stacking the shield on top of the board. The capabilities of L298P are depending on the electronic circuit which is built on the shield. L298P shield is a motor driver electronic circuit base on L298P chip that can drive two DC motors simultaneously. It can drive current up to 2A for each motor [33]. The shield that chosen consists of features such as buzzer, two-ways Bluetooth interface, digital and analog pins and led indicators for forward and backward changing direction.

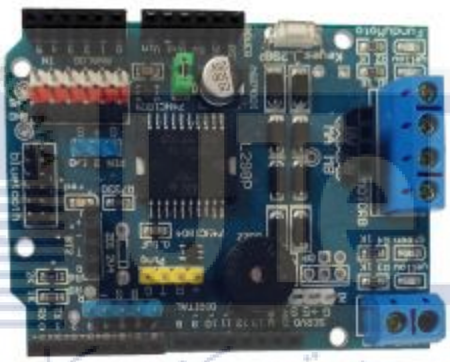


Figure 3.3: L298P Motor Shield

3.4.2 Communication

3.4.2.1 Bluetooth Module

In this project, communication between the mobile robots is the most important elements in order to develop the cooperative controlled robots. There are many types of wireless communication module such as Zigbee, Bluetooth and WIFI. In the Chapter 2, most of the past studied journals used the Bluetooth as the communication module. Bluetooth module has the default baud rate of 38400 but also support the other baud rates such as 9600, 19200, 57600,115200,230400 and 460800 [34]. Bluetooth module as shown in Figure 3.4 is chosen in this project because of its ease of use and low power consumption. Besides, the data rate of Bluetooth module is high which is around 3Mbps. In addition, Bluetooth module has the 2.4 GHz radio frequency which ensures worldwide operability.

Figure 3.4: Bluetooth module HC-05

3.4.3 Sensory System

3.4.3.1 Ultrasonic Sensor

In this project, one of the objectives is to evaluate the performance of the developed mobile robots. To achieve the objective, experiment such as obstacles avoidance is needed to carry out in order to evaluate the performance of the robots. Ultrasonic sensor as shown in Figure 3.5 is used to conduct the obstacles avoidance experiment. An ultrasonic sensor is an instrument that used to measure the distance to an object by using ultrasonic sound waves. Ultrasonic sensor is chosen because it is reliable in any bright or dark environment. Besides, ultrasonic sensor is resistant to mist and dirt and can detect the complex shape and transparent objects [35]. The working principle of ultrasonic sensor is using a transducer to send and receive ultrasonic pulse from the object. The distance can be calculated with the following formula:

$$Distance,\ L = \tfrac{1}{2} \times T \times C \qquad (3.1)$$

where L is the distance, T is the time between the emission and reception, and C is the sonic speed which is equal to 331m/s.

Figure 3.5: Ultrasonic sensor

3.4.3.2 Infrared Sensor

In order to evaluate the performance of the mobile robots, line-following task is a good experiment to make sure the mobile robots perform well in the pipeline. Infrared sensor as shown in Figure 3.6 is the best choice of instrument to conduct the line-following experiment. Infrared sensor is the most popular sensor among the previous discussed journals due to its low cost and ease to use. Infrared sensor is used to detect certain criteria of its surroundings. The working principle of infrared sensor is by emitting and detecting the infrared radiation. The infrared waves have wavelength between 0.75 µm and 1000 µm. Infrared sensor has the features such as faster response time, low power consumption, and provides good stability over time [36].

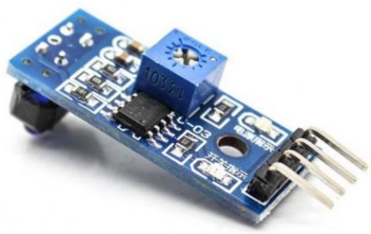


Figure 3.6: Infrared sensor

3.4.4 Monitoring

3.4.4.1 Mini WIFI Camera

To perform the environment monitoring inside the pipeline, mini WIFI camera is chosen due to its light weight. The dimension of the camera is 8mm x 8mm. The camera has the features such as 120˚ wide angle, night vision with infrared, and 1080P high definition image. The camera as shown in Figure 3.7 is equipped with WIFI interface. By using the WIFI interface, pipeline monitoring can be done by using mobile phone which is very convenient. Besides, mini WIFI camera is using the CMOS sensor which have better light sensitivity than other sensors.

Figure 3.7: Mini WIFI Camera

3.4.5 Motion

3.4.5.1 DC Gear Motor

In this project, direct current (DC) gear motor is choose for motion control. DC gear motor as shown in Figure 3.8 has a gear assembly attached to the motor. The speed of motor is counted in terms of rotations of the shaft per minute (RPM). DC gear motor have generate higher torque by reducing the speed. The gearbox's ability which reduce the speed but increase the force at the same time is suitable to use in this project. During the inspection in the pipeline, the mobile robots should move slowly to monitoring the environment of pipeline.

Figure 3.8: DC Gear Motor

3.4.5.2 Servo motor

In order to monitoring the environment of pipeline and perform obstacles avoidance, servo motor is used for the movements of the camera and ultrasonic sensor. Camera and ultrasonic sensor which are attached to the rotary part of the servo motor can change the direction of sensory or monitoring area by using the servo mechanism. The Tower Pro SG90 servo motor as shown in Figure 3.9 is tiny and light weight but produce high output power. The servo motor also can rotate approximately 180 degrees which is sufficient for the monitoring purpose.

Figure 3.9: Tower Pro SG90 Servo Motor

3.4.6 Power Management

3.4.6.1 Lithium Battery

In multi robot system application, every mobile robot must have a sufficient battery power to complete a time consuming task. Therefore, two lithium ion rechargeable battery with 3.7V each as shown in Figure 3.10 is chosen for powering all the system. The BRC 18650 battery has 4000mAh and has the advantages such as low self-discharge, low maintenance, and high energy density. By using external charger, battery can be charged when required.

Figure 3.10: Lithium ion BRC 18650 Battery

3.5 Program Development

In this project, the software that involved to develop the cooperative controlled robots is the programming platform. Programming platform is a software platform that included all the necessary components such as application programming interfaces and libraries required by programmers and developers to compile, debug and execute language-specific applications.

3.5.1 Arduino IDE

The Arduino integrated development environment (IDE) as shown in Figure 3.11 is a programming platform application for Windows, Mac, and Linux that is written in the programming languages C and C++. It is used to write and upload programs to Arduino board. Arduino IDE is highly-rated by users due to its ease of used. It is also capable of performing complex processes with the easily access contributed libraries. It is beneficial for the beginner as well as advanced users to develop a project.

ARDUINO IDE

Figure 3.11: Arduino IDE Programming Software

3.6 Design and Assembly of Master-Slave Robot

All the hardware parts that listed at hardware development are installed and assemble on a chassis which act as the main base for the mobile robots. Figure 3.12 shows the chassis used in this project. The chassis is made by aluminum which is rust resistance and can withstand the weight of other hardware components. All the hardware components such as ultrasonic sensor, DC gear motor and servo motor are assemble on the chassis by using screw and nut. The top view, front view, side view and back view of the assembled robot are shown in Figure 3.13, Figure 3.14, Figure 3.15, and Figure 3.16, respectively.

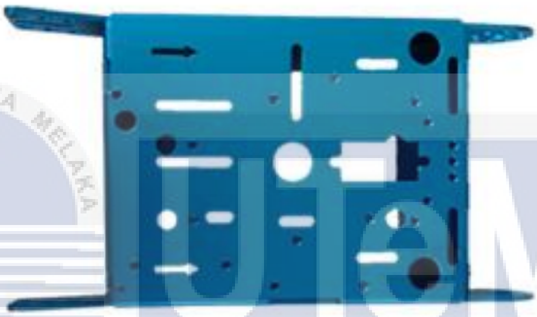


Figure 3.12: Aluminum Chassis

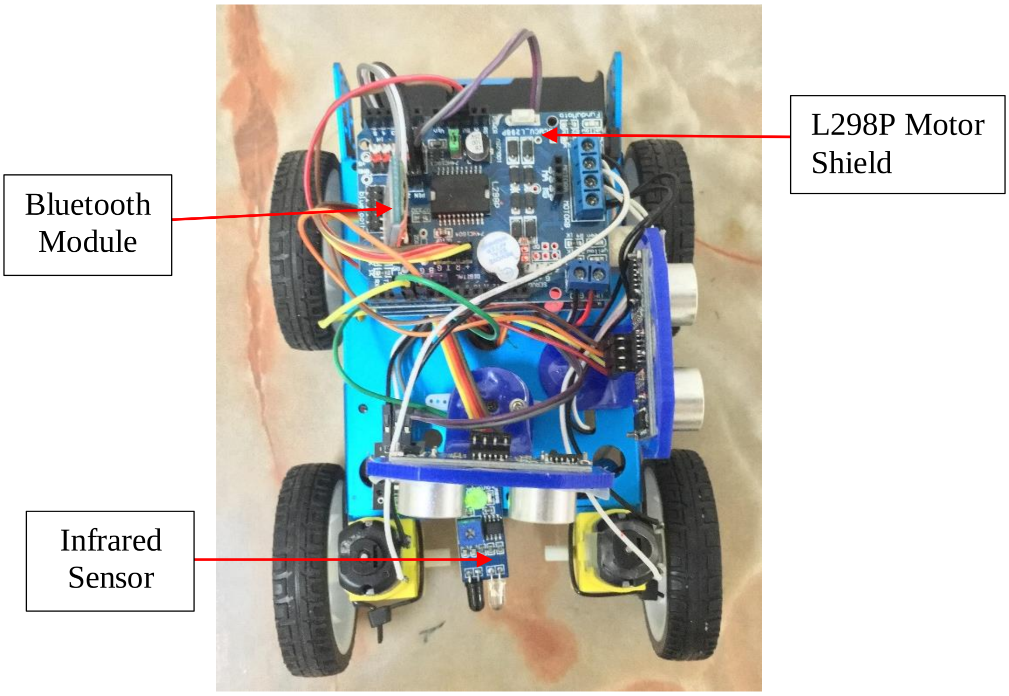


Figure 3.13: Top view of mobile robot

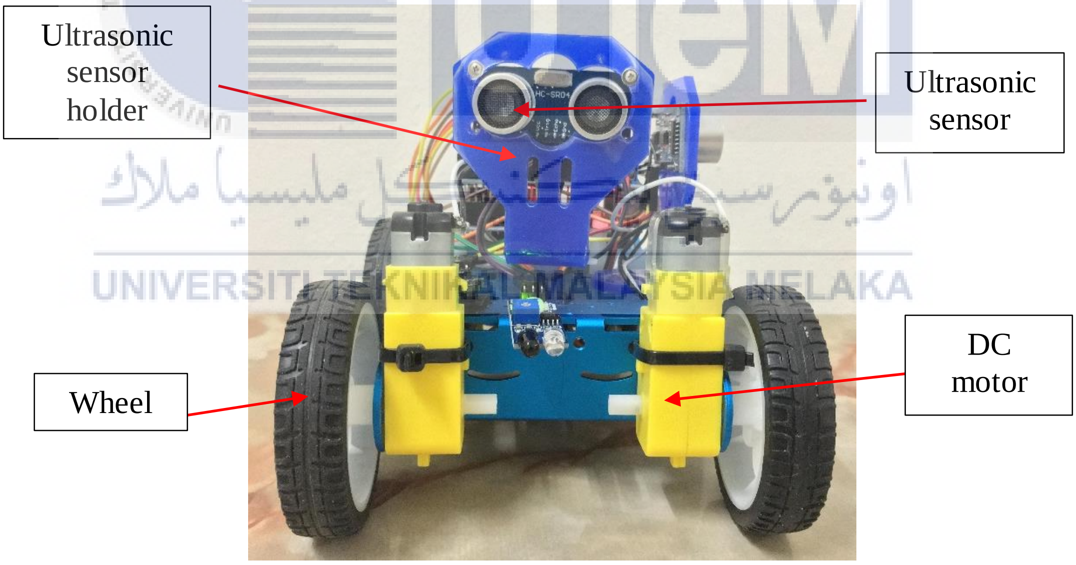


Figure 3.14: Front view of mobile robot

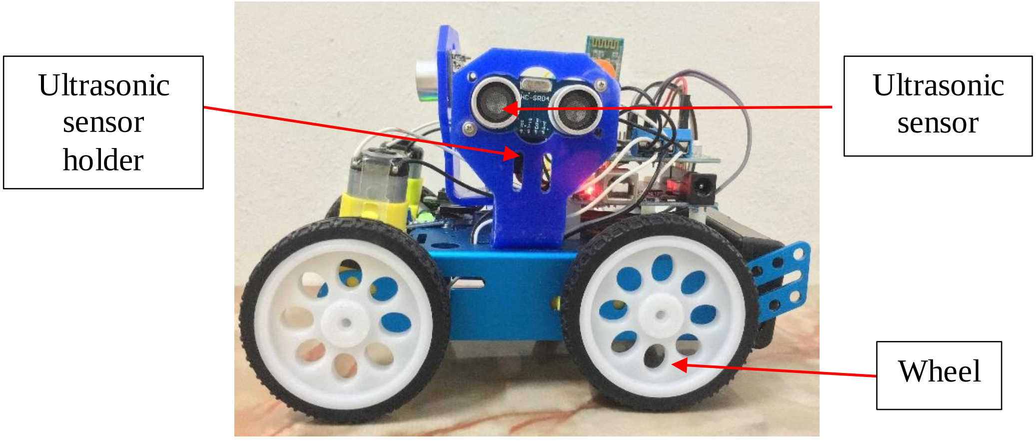


Figure 3.15: Side view of mobile robot

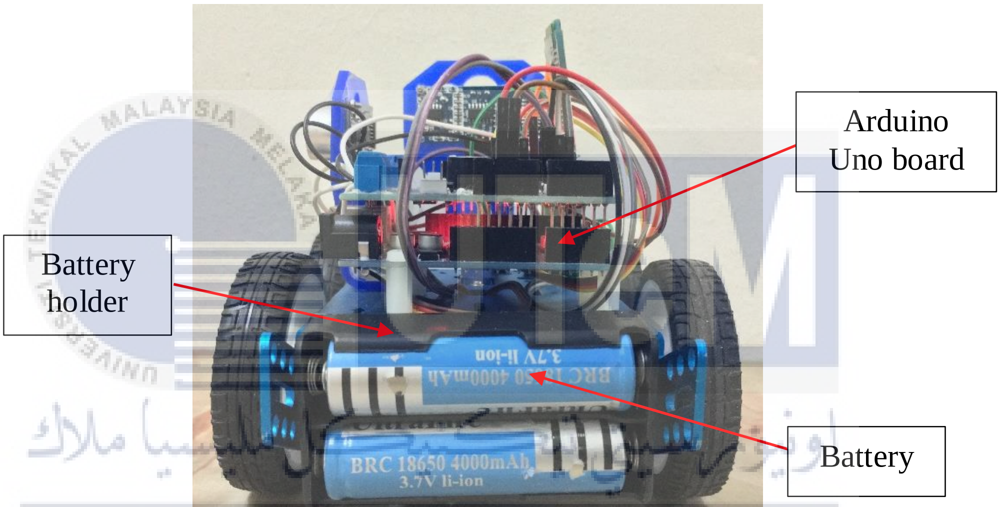


Figure 3.16: Back view of mobile robot

Each of the sensors or electrical components has their own 5V and ground pin configuration, respectively. Therefore, the 5V and ground pin of the sensors is connect to the microcontroller by using the female to female jumper wire. In this project, L298P motor shield is used to extend the capability of the Arduino Uno by stacking the shield on the top of the Arduino Uno board. Therefore all the sensors and electrical components are directly connect to the shield instead of the Arduino Uno. Table 3.2 shows the pin configuration connection between the electrical components and shield.

Table 3.2: Pin configuration connection between the electrical components and shield.

Sensors/ Electrical Components	L298P Motor Shield
DC Gear Motor	
Live wire (Black)	Terminal 1
Neutral Wire (White)	Terminal 2
Push Button	
Ground	Ground
5V	5V
Signal	Signal
Bluetooth Module	
RX	R
TX	T
Ground	Ground
5V	5V
Ultrasonic Sensor	
5V	5V
Trig	R
Echo	T
Ground	Ground
Infrared Sensor	
Ground	Ground
5V	5V
A0	Analog Input Signal
Servo Motor	
Ground (Brown)	Ground
5V (Red)	5V
Signal (Yellow)	9
Battery Holder	
Live Wire (Red)	VMS
Neutral wire (Black)	Ground

3.7 Flowchart of the Cooperative Controlled Robot System

The overall flowchart of the cooperative controlled robot system for pipeline inspection as shown in Figure 3.17. First, when both of the power source of master and slave robots is turned on, microcontroller and Bluetooth module will be initialize for both master and slave robot. Master robot will then run first and follow by slave robot. Both the camera that equipped by the master and slave robot will turn on and start the live streaming of the environment of the pipeline. When the master robot detects the obstacles by using the ultrasonic sensor, it will stop and at the same time, master robot will send the command to the slave robot about the obstacles in front. Slave robot receives the command and perform the same action of the master robot. If the master robot detects the obstacles for 3 times, it will reverse back to the base station and at the same time, master robot will send the command to slave robot to reverse back to base station. If there are no obstacles in front, master robot will continues move until it detects the T branch of the pipeline. When the master robot detect the T branch, it will stop and turns right. It will runs again and send the command to the slave robot about the T branch in front. Slave robot receive the command and stop at the front of T branch. Slave robot will then turn left and runs again.

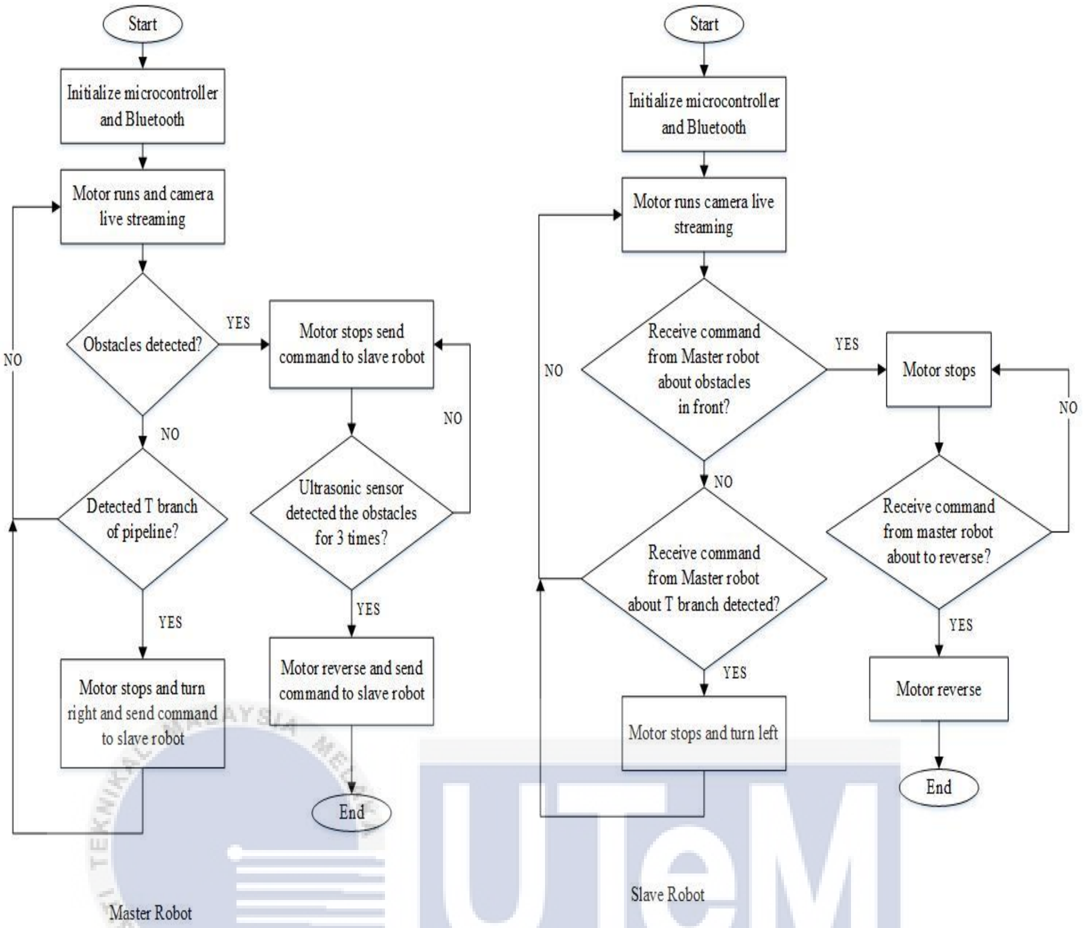


Figure 3.17: Flowchart of the cooperative controlled robots system

3.8 Experiment Setup

The three main objectives of this project are mapped to a few experiments to provide a brief on how to achieve the objectives. They are summed up as shown in Table 3.3. A detailed explanation on each experiment is presented by listing out the materials and apparatus, hardware setup and the procedures. The experiments are stated as below.

1. Experiment 1: Performance of mobile robots on various type of surfaces

2. Experiment 2: Tracking object using ultrasonic sensor

3. Experiment 3: Leader-Follower approach

4. Experiment 4: Performance of the master and slave robot in various type of trajectories

Table 3.3: Mapping of experiments and objectives

Experiments \ Objectives	Objective 1	Objective 2	Objective 3
Experiment 1	✓	✓	
Experiment 2		✓	
Experiment 3	✓	✓	✓
Experiment 4	✓	✓	✓

3.8.1 Experiment 1: Performance of mobile robot in pipeline

Objective:

To analyze the moving smoothness and observe the vision of camera of the mobile robot on various type of surfaces in the pipeline.

Parameter:

Manipulated variable: Type of surfaces

Responding variable: Time taken for the mobile robot to pass through the PVC pipe.

Equipment:

1. Sand
2. Soil
3. Small stones
4. Oil
5. PVC pipe
6. Mobile robot
7. Stop watch

Procedure:

1. Various type of surfaces such as sand, soil, small stones and oil are prepared as shown in Figure 3.18. The reason that the stated surfaces are chosen is due to the aging of the pipeline in the real life. Aging of the pipeline and the chemical reaction will cause the pipeline become as uneven surfaces such as small stones and sand.
2. The mobile robot is programmed to move through the PVC pipe with normal condition as shown in Figure 3.19 .
3. When the mobile robot is passing through the pipe, time is recorded by using stop watch and at the same time video is recorded.
4. Observed the movement of the mobile robot when it passing through the PVC pipe.
5. After that, small stones is poured into the PVC pipe as shown in Figure 3.20.
6. The steps of 3 and 4 are repeated to record the time and observe the movement of robot in the pipe.

7. The steps are repeated by changing the surfaces of sand, soil and oil as shown in Figure 3.21 to Figure 3.23.
8. The data collected that time taken for mobile robot to pass through the pipe with various type of surfaces is plotted.

Figure 3.18: Various type of surfaces

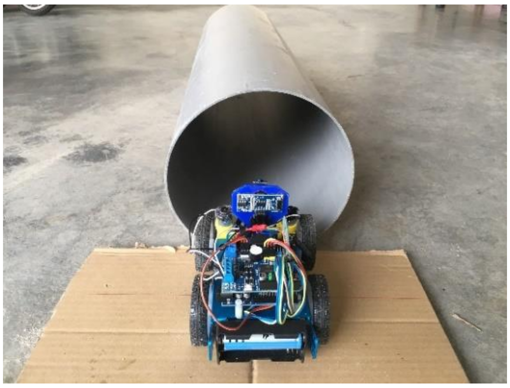


Figure 3.19: Normal condition of pipe

Figure 3.20: Set up of pipe with small stones

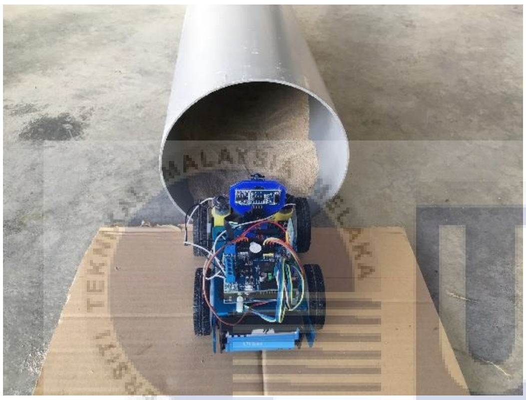


Figure 3.21: Set up of pipe with sand

Figure 3.22: Set up of pipe with soil

Figure 3.23: Set up of pipe with oil

3.8.2 Experiment 2: Tracking object using ultrasonic sensor

Objectives:

To determine the effective angle of the ultrasonic sensor in detecting an object that placed at different angle.

Parameter:

Manipulated variable: Angle and distance of the object placed

Responding variable: Distance detection of the ultrasonic sensor

Equipment:

1. Arduino Uno
2. Breadboard
3. Ultrasonic sensor
4. Mahjong paper
5. Obstacle
6. Ruler

Procedure:

1. A big scale protractor is print on an A4 paper.
2. The distance of 10cm, 20cm, 30cm, and 40cm from the ultrasonic sensor is measured and marked. 40cm is chosen as the maximum distance to test is due to the 40cm distance giving a sufficient place and time for the mobile robot to make decision to turn direction.
3. The ultrasonic sensor is programmed to measure the distance of the obstacle and print at serial monitor.
4. First, the obstacle is placed on the marked distance of 10cm by 90˚ as shown in Figure 3.24.
5. Then, the obstacle is placed to various position of angle from 0˚ to 180˚.
6. Record the distance that measured by the ultrasonic sensor from 0˚ to 180˚ of 10cm.
7. Repeat the steps by placing the obstacle to the distance of 20cm, 30cm, and 40cm from the ultrasonic sensor as shown in Figure 3.25, Figure 3.26, and Figure 3.27.

8. The data of average distance measured by the ultrasonic sensor versus angle is plotted.

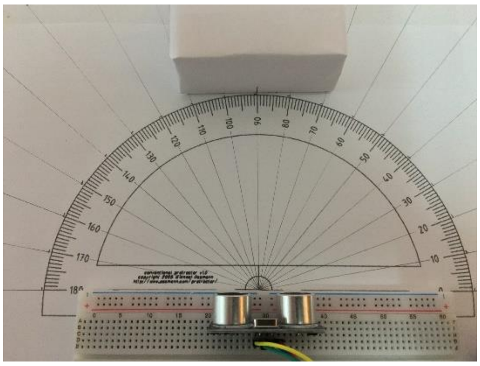


Figure 3.24: Obstacle 10cm far from the ultrasonic sensor

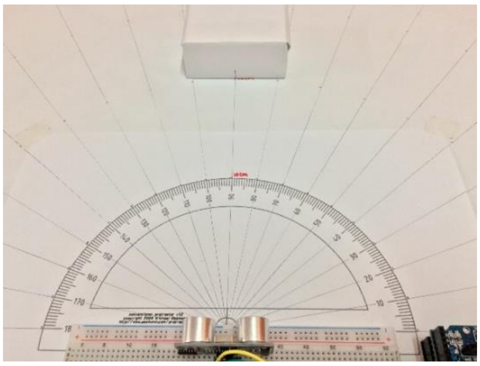


Figure 3.25: Obstacle 20cm far from the ultrasonic sensor

Figure 3.26: Obstacle 30cm far from the ultrasonic sensor

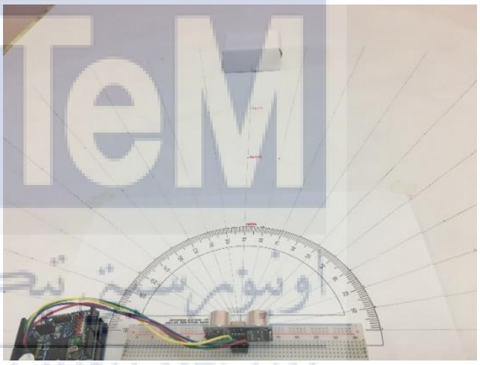


Figure 3.27: Obstacle 40cm far from the ultrasonic sensor

3.8.3 Experiment 3: Leader-Follower approach

Objective:

To develop a communication and determine the efficiency of the communication between the master and slave robot

Parameter:

Manipulated variable: Time setting for the mobile robots to move

Responding variable: Distance travelled by the mobile robots

Equipment:

1. Mobile robot
2. Mahjong paper
3. Breadboard
4. Measuring tape

Procedure:

1. Two Bluetooth module HC-05 is set up as master and slave role by using the Attention (AT) commands in serial monitor. AT commands is used to change the default setting of the Bluetooth module.
2. The set up process for the master and slave Bluetooth module are shown in Figure 3.28 to Figure 3.31.
3. The Bluetooth modules are then inserted to the Bluetooth interface on the Arduino Uno board.
4. The master mobile robot is programmed to move and stop at 0.5s and at the same time it will send the command to the slave mobile robot.
5. The slave robot is programmed to follow the command of master robot.
6. The master and slave robot are placed at the same beginning point as shown in Figure 3.32 before the robots move.
7. When both of the robots stop, measure and record the distance travelled by both robots by using measuring tape.
8. The step is repeated by changing the time of movement of the robots by 1.0s, 1,5s, 2.0s, 2.5s, 3.0s, 3.5s, 4.0s, 4.5s, 5.0s, and 5.5s. The range of 0.5s to 5.5s

is chosen to do the testing is due to the mobile robot still can move in straight line in the range of time.

9. The speed and difference of distance travelled by both robots are calculated based on the data collected.
10. The graphs of average distance travelled by both robots over time and speed of both robots over time are plotted.

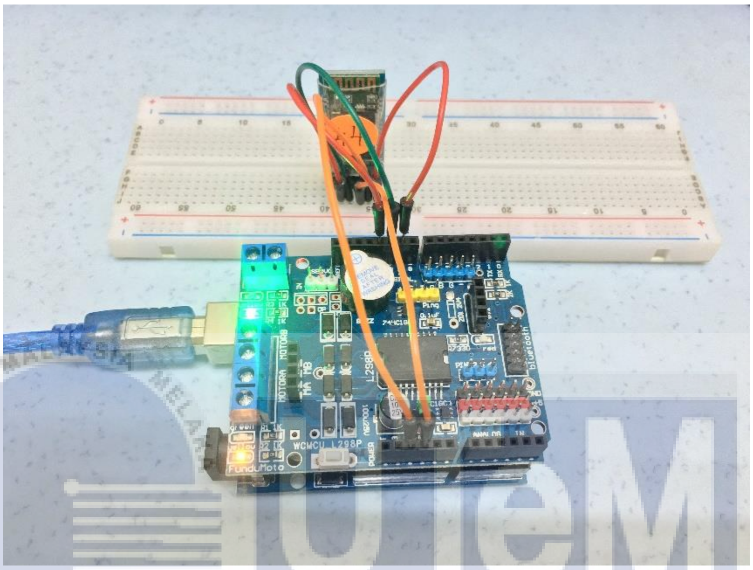


Figure 3.28: Master Bluetooth module setup

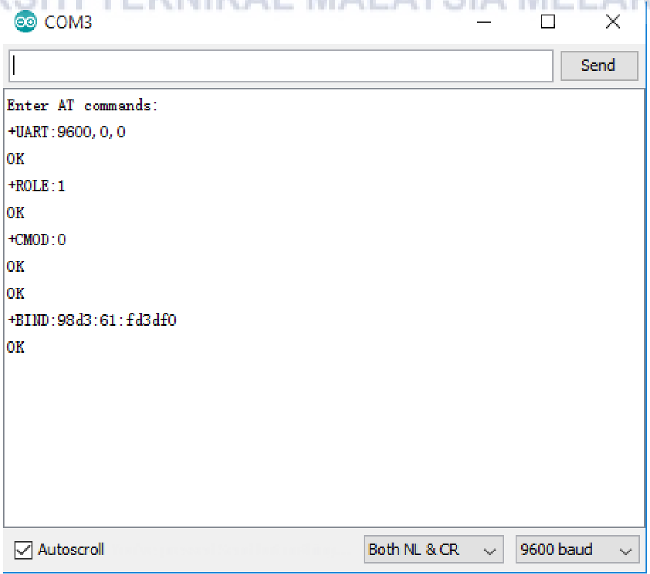


Figure 3.29: Setting in AT command of master Bluetooth module

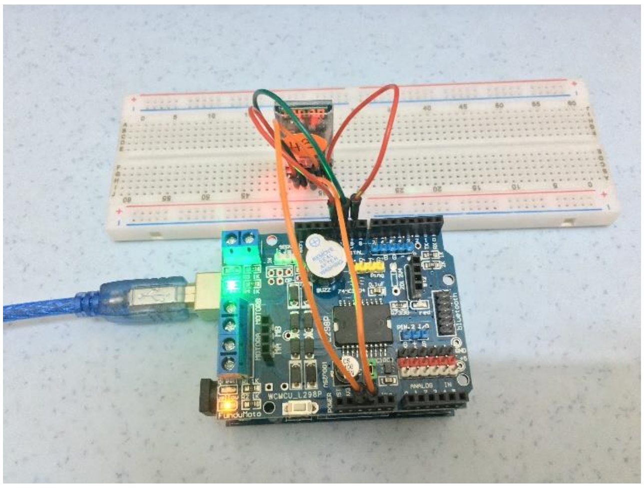


Figure 3.30: Slave Bluetooth module setup

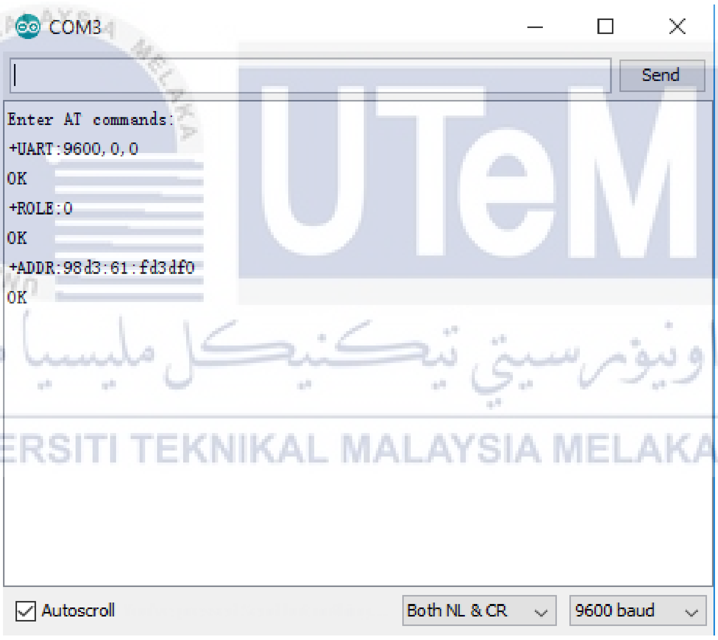


Figure 3.31: Setting in AT command of slave Bluetooth module

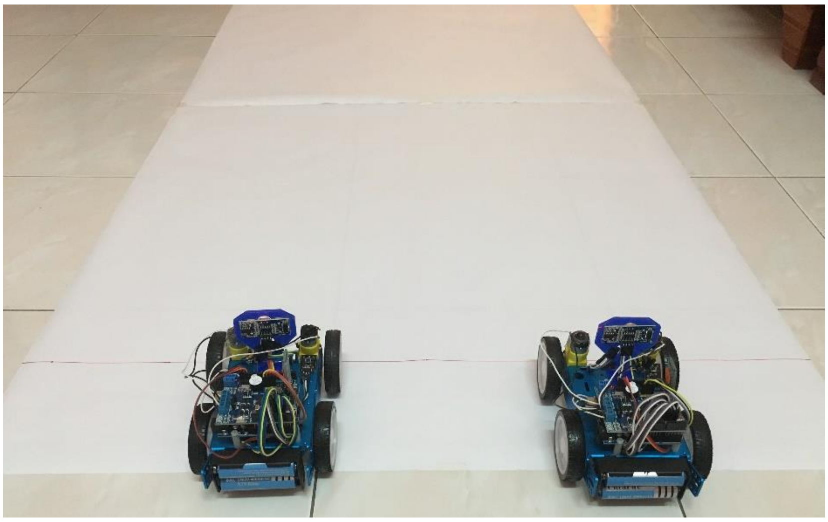


Figure 3.32: Same startup point of master and slave robot

3.8.4 Experiment 4: Performance of the master and slave robot in various type of trajectories

Objective:

To validate the accuracy of the slave robot in following the command of master robot

Parameter:

Manipulated variable: Various type of trajectories

Responding variable: The X and Y-axis that draw out by the master and slave robot

Equipment:

1. Mahjong paper
2. Marker pen
3. Mobile robots
4. Measuring tape

Procedure:

1. First, the master robot is programmed to move in straight line and at the same time, it will send the command to the slave robot.
2. The slave robot is programmed to accumulate the command from master robot for 4 seconds and perform the action after 4 seconds.
3. Both robots are installed with marker pen to draw out the trajectories when the robots are moving.
4. The steps is repeated by changing the trajectories to U-shape and S-shape.
5. For every trajectories, an obstacle is involved to validate whether the slave robot able to avoid the obstacle and at the same time follow the trajectory of master robot.
6. The experiments are repeated for three times for each trajectory and the best trajectory is plot in graphical form.
7. The deviation of the trajectory of slave robot from master robot is observed.
8. The root mean square error (RMSE) and standard deviation are calculated based on the data collected.

3.9 Summary

As a summary, based on the methodology that has been discussed in this chapter, the stages to complete this project has been done accordingly. This chapter provides a detailed plan so that the project can be complete on time to achieve the objectives of the project. In this chapter, the information about the hardware and components used to develop the mobile robots as well as the clear experiment setup have been discussed. All the data collected in the experiments are analyzed in next chapter.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter discuss how to analyse the performance of the mobile robots from the data obtained. All the results obtained from the conducted experiments listed in chapter 3 are recorded in either table or graph form for better understanding towards the parameters being measured from each experiment.

4.2 Experiment 1: Performance of mobile robot on various type of surfaces

Table 4.1 shows the observation results of the performance of mobile robot on various type of surfaces. Figure 4.1 shows the time taken of mobile robot in travelling various type of surfaces. The mobile robot was successfully move and pass through the PVC pipe. Time for the mobile robot to pass through the pipe has reflected the smoothness of the motion of mobile robot on various type of surfaces. The mobile robot consume the least time which is 2.92s in average when passing through the PVC pipe with normal condition. On contrast, the mobile robot spent the longest time which is 4.46s in average when passing through the PVC pipe with the surfaces of small stones. This is because the uneven surface of the small stones cause the slipping which will affect the wheels of the robot in making a proper contact with the surface. The performances of the mobile robot on the surfaces of sand, soil and oil are almost the same which spent within 3s to pass through the PVC pipe. The smoothness of the mobile robot in moving on various type of surfaces is very important because it will affect the monitoring process of the camera in the pipeline or even the image processing process in the future work.

Table 4.1: Observation results of the performance of mobile robot on various type of surfaces

Type of surfaces	**Performance of the robot**	**Time (s)**			
		Trial 1	**Trial 2**	**Trial 3**	**Average**
Normal	Success and smooth	2.92	3.00	2.85	2.92
Sand	Success but not smooth	4.09	3.72	3.91	3.91
Soil	Success but not smooth	3.77	3.62	3.51	3.63
Small stone	Success but very not smooth	4.39	4.47	4.51	4.46
Oil	Success and smooth	3.03	3.16	3.24	3.14

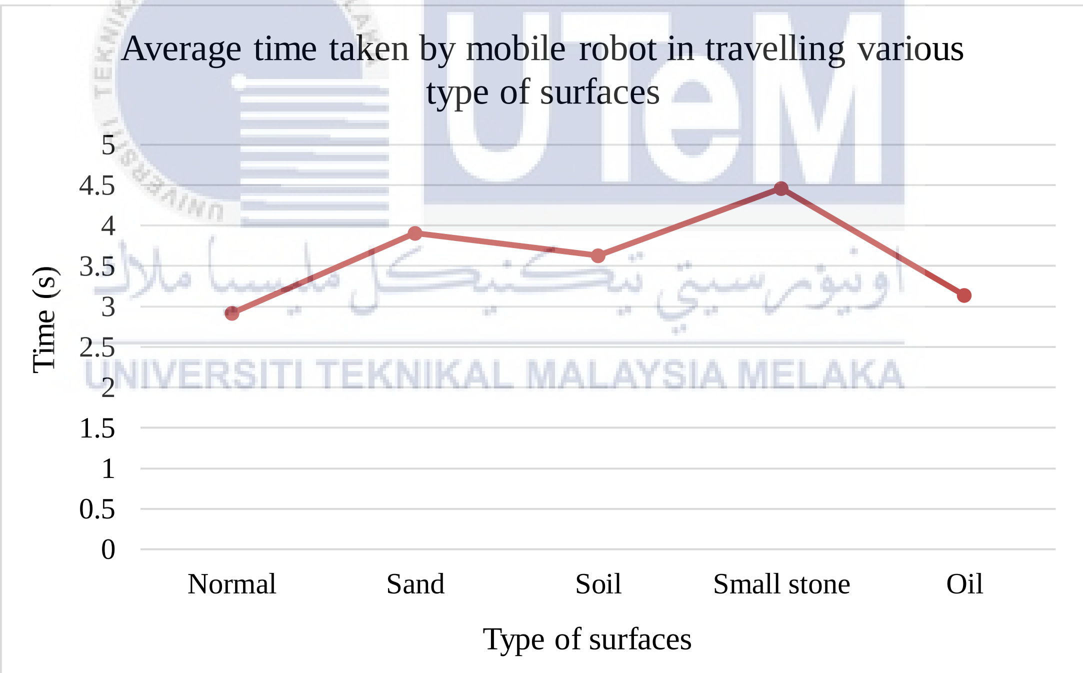


Figure 4.1: Time taken of mobile robot in travelling various type of surfaces

4.3 Experiment 2: Tracking object using ultrasonic sensor

Table 4.2 shows the data collected for the effective angle of ultrasonic sensor in detecting an object. Figure 4.2 shows the graphical form angle against average distance from ultrasonic sensor. From the Table 4.2 and Figure 4.2, the object that placed at the distance of 10cm and 20cm had the same angles of detection by ultrasonic sensor which is from 70˚ to 110˚. However, the object that placed at 30cm and 40cm had the same angles of detection by ultrasonic sensor which is only from 80˚ to 110˚. The 0cm states that the ultrasonic sensor is unable to detect the object at certain angles. This results is validate by the specification of the ultrasonic sensor which stated that the effective angles of detection are within 30˚ although the detectable distance if from 0cm to 400cm. In this experiment, the data collected shown that when the object is placed at 30cm and 40cm, the ultrasonic sensor unable to receive the reflected signal wave from the object at 70˚. The distance will affect the effective angles that able detect by the ultrasonic sensor. The graph is plotted based on the data collected. As conclusion, the coding can be develop according to the distance between mobile robots and the obstacle with effective angles to be track.

Table 4.2: Effective angles of ultrasonic sensor

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

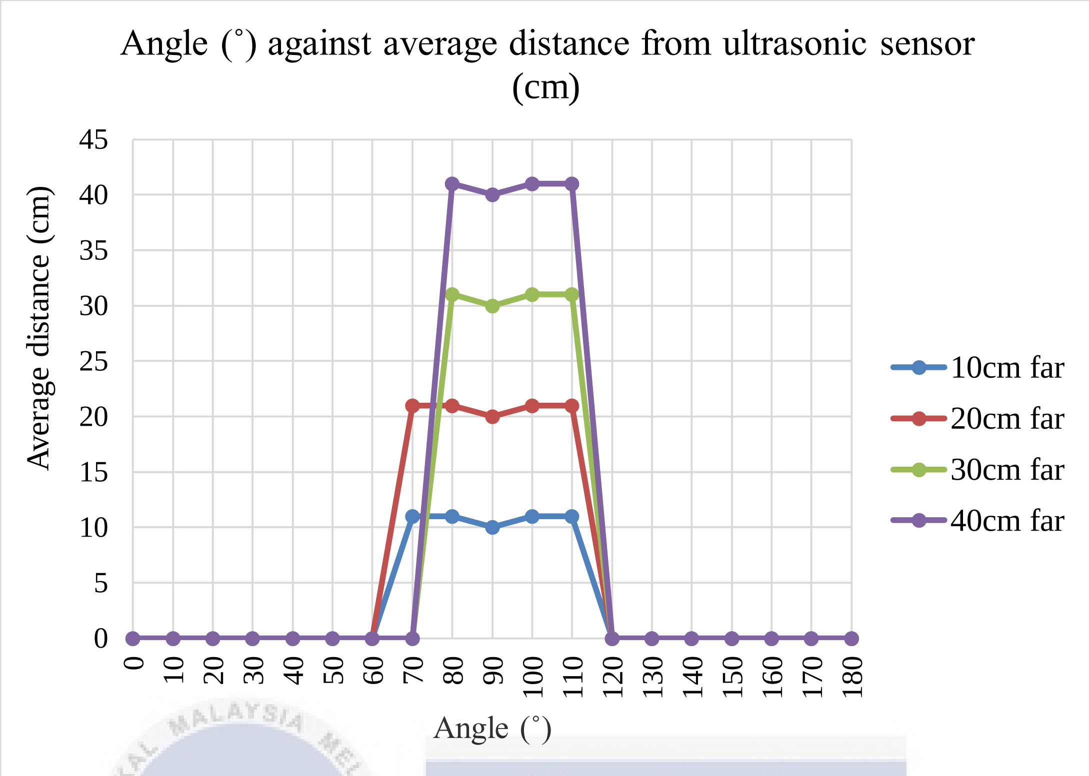


Figure 4.2: Graph of angle against average distance from ultrasonic sensor

4.4 Experiment 3: Leader-Follower approach

Table 4.3 shows the speed and average distance travelled by the master and slave robot in different period of time. For further analysis, the data collected have been plotted in graphical form as shown in Figure 4.3 and Figure 4.4 for better analysis. Figure 4.3 shows the average distance travelled by the master and slave robot over time. It is clearly seen that increasing the time will increase the distance travelled and the difference of distance travelled by both robots is linearly constant throughout the experiment. The graph also shows the efficiency of performance of the robot system through wireless communication. The average difference of distance travelled by both robots is within the acceptable range which is 0.033m, hence it can interpreted that there is no data loss during the transmitting and receiving process between the robots. The efficiency of the robot system is good, meaning that the response of slave robot to the commands of master robot is immediate. Lastly, speed time graph as shown in Figure 4.4 is plotted to check the variation of speeds of both master and slave robot for respective time. For master robot, it is moderately constant at about 0.34 m/s in average while the slave robot is about 0.33 m/s in average regardless the time. As a conclusion, a robust communication is successfully developed between the master and slave robot by using the Bluetooth module. This communication technique can be applied in the case of pipeline inspection by using multi robot system.

Table 4.3: Data collected for master and slave robot over time

Time (s)	Average Distance Travelled (m)		Distance Travelled Difference (m)	Speed (m/s)	
	Master	Slave		Master	Slave
0.5	0.145	0.135	0.010	0.290	0.270
1.0	0.305	0.303	0.002	0.305	0.303
1.5	0.520	0.485	0.035	0.347	0.323
2.0	0.722	0.695	0.027	0.361	0.348
2.5	0.862	0.841	0.021	0.345	0.336
3.0	1.038	0.998	0.040	0.346	0.333
3.5	1.202	1.194	0.008	0.343	0.341
4.0	1.395	1.355	0.040	0.349	0.339
4.5	1.592	1.534	0.058	0.353	0.341
5.0	1.703	1.664	0.039	0.341	0.333
5.5	1.830	1.752	0.078	0.333	0.319
		Average	0.033	0.338	0.326

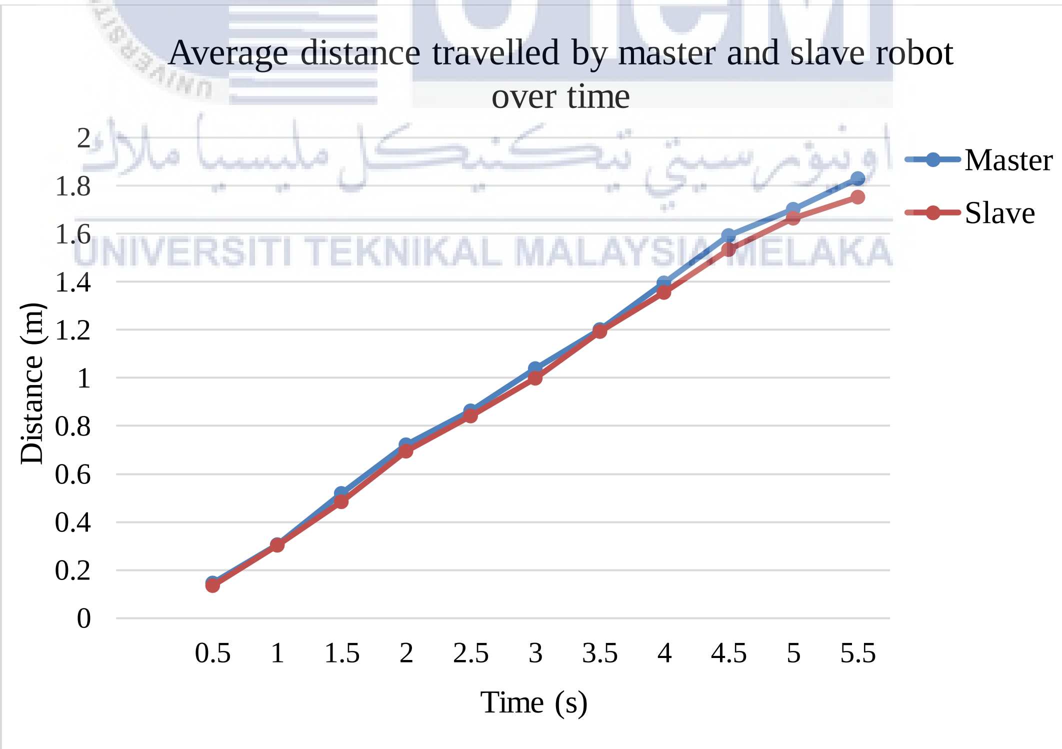


Figure 4.3: Average distance travelled by master and slave robot over time

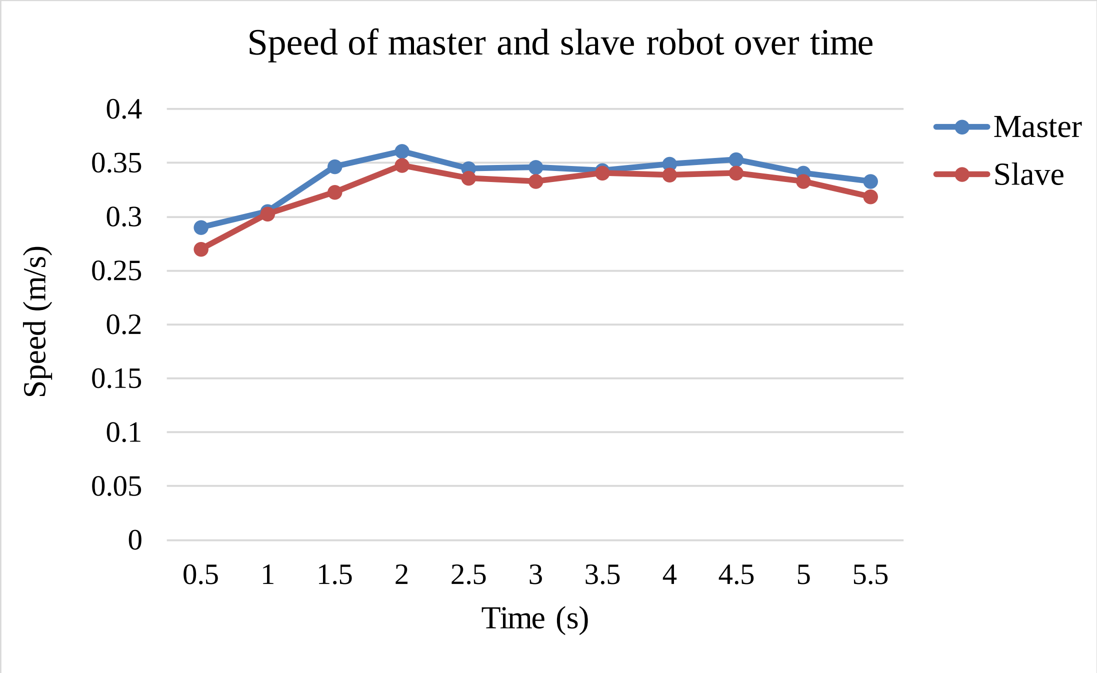


Figure 4.4: Speed of master and slave robot over time

4.5 Experiment 4: Performance of the master and slave robot in various type of trajectories

Table 4.4 shows the summarize data of root mean square error for all the trajectories both for with and without obstacles. By comparing the root mean square error, the smallest root mean square error or the best trial for every trajectory are plotted in graphical form. The example of tabulating the standard deviation and root mean square error is shown in Appendix B.

Table 4.4: Summarize data of root mean square error for all the trajectories

No.	Type of Trajectory	RMSE		
		Trial 1	Trial 2	Trial 3
1	Straight line	2.76	1.04	1.68
2	Straight line with obstacle	7.30	3.39	4.20
3	U-shape	3.97	4.98	7.89
4	U-shape with obstacle	7.28	5.97	6.94
5	S-shape	1.93	1.66	2.32
6	S-shape with obstacle	2.88	4.65	1.69

4.5.1 Straight Line Trajectory

Figure 4.5 shows the experiment setup of trajectory in straight line. Figure 4.6 and Figure 4.7 show the general view and zoom in view of graphical form in straight line trajectory by master and slave robot. Based on the data collected, the RMSE of the first trial is 2.76, second trial is 1.04 and third trial is 1.68. The second trial is the best and chosen among the trials, this is because the RMSE shown the smallest error. Besides, the standard deviation range fall in between 0.29 to 2.30. From the graph shown, the slave robot slightly deviate about 1cm of Y-axis from the master's trajectory from the beginning. However, this is only a very small error which the highest deviation error is only 1.7cm from the master's trajectory. Due to the efficiency is different for every motor, both robots cannot perform the absolutely straight line motion. As a conclusion, the slave robot was able to follow the commands from the master robot and move in straight line.

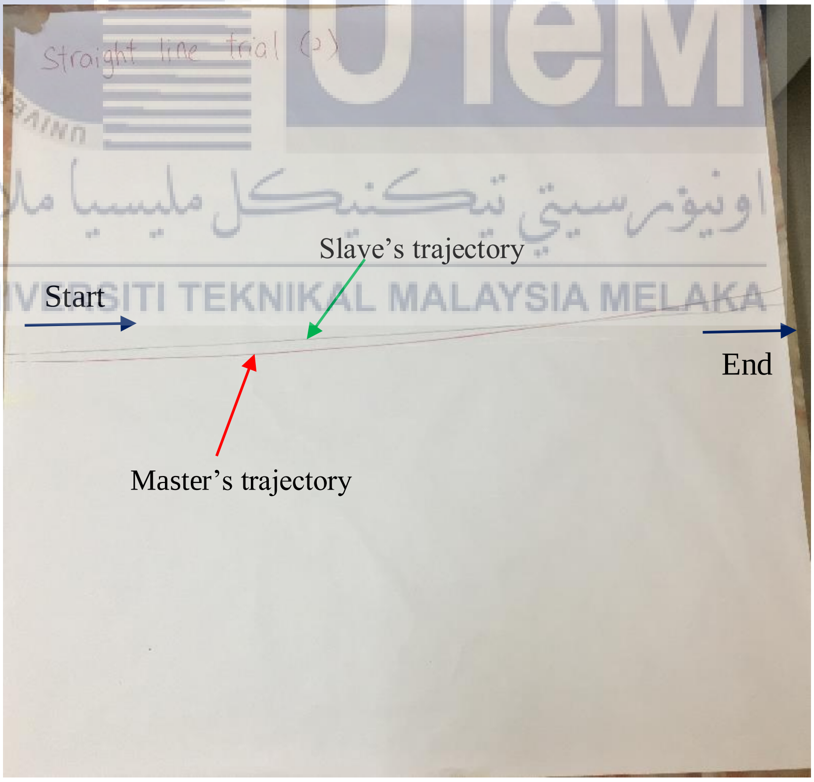


Figure 4.5: Trajectory in straight line

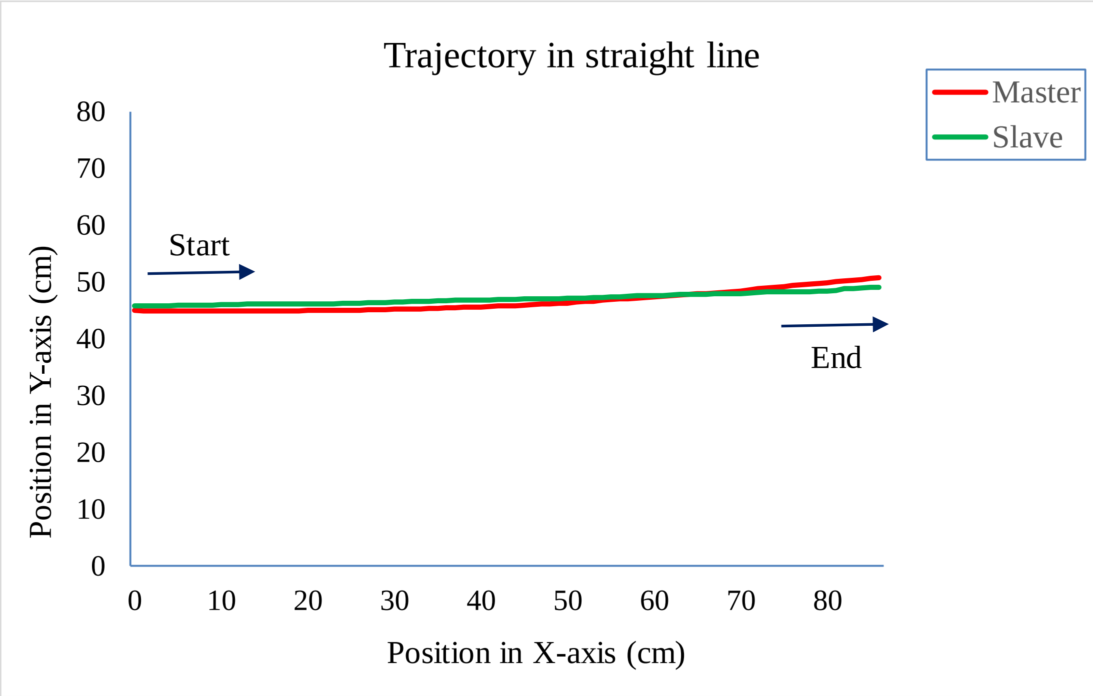


Figure 4.6: General view of graphical form of trajectory in straight line

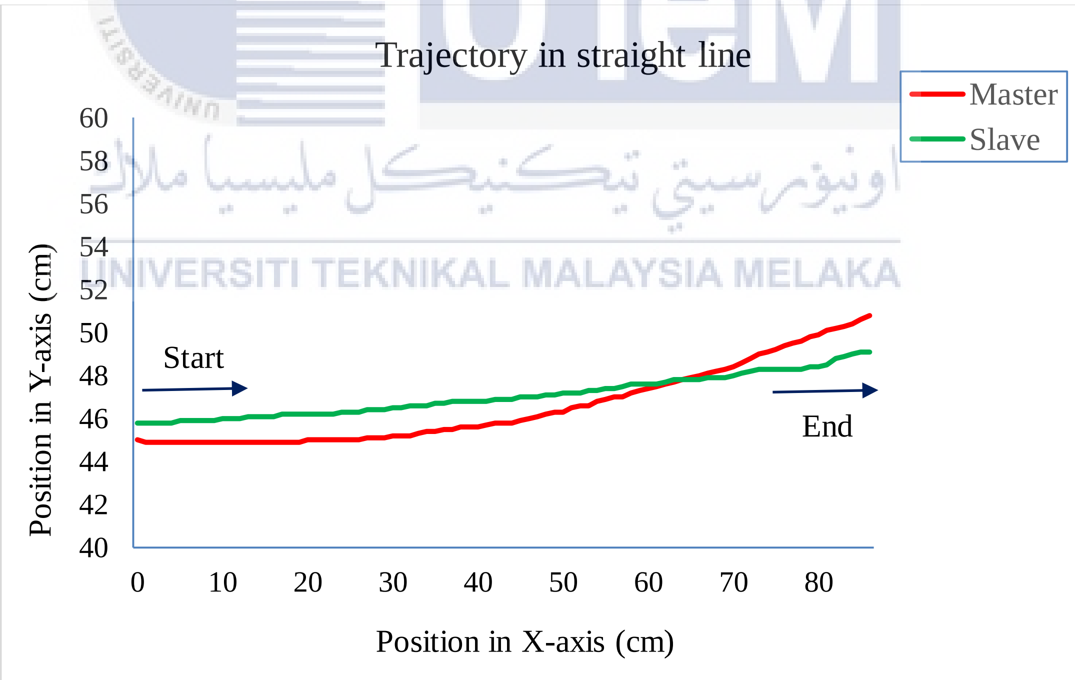


Figure 4.7: Zoom in view of graphical form in straight line trajectory

4.5.2 Straight Line Trajectory with Obstacle

Figure 4.8 shows the experiment setup of trajectory in straight line with obstacle. Figure 4.9 and Figure 4.10 show the general and zoom in view of graphical form of trajectory in straight line with obstacles. Based on the data collected, the RMSE for the three trials are equal to 7.30, 3.39 and 4.20 respectively. The second trial is the best and chosen among the trials, this is because the RMSE shown the smallest error. Besides, the standard deviation for the trials are fall in between range of 0.21 to 12.29. In this experiment, an obstacle was involved as shown in Figure 4.8. From the graph shown, the master robot supposed to move in straight line but there are obstacle involved. So, the master robot was turn direction to avoid the obstacle and after that it move in straight line again. At the same time, the master robot is sending the commands to the slave robot so that it can perform the same actions. The slave robot accumulated the commands from the master robot for 5s. After 5s, it will only perform the action so that the turning points for the both robots are the same. The slave robot was able to avoid the obstacle and move in straight line again. However, both robots are started to have a large deviation after 56cm in X-axis position. This is because the efficiency of the motors will cause the difference of the angle of turning of the motors. The largest deviation of the slave robot is 9.3cm away from the master's trajectory. As a conclusion, the slave robot was successfully to avoid the obstacle and follow the commands of the master robot.

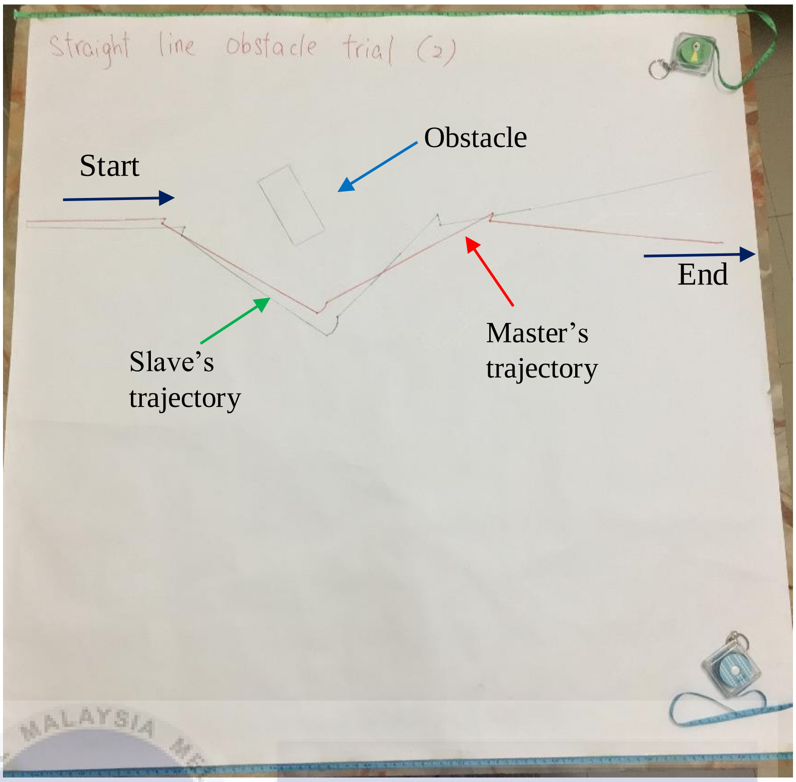


Figure 4.8: Trajectory in straight line with obstacle

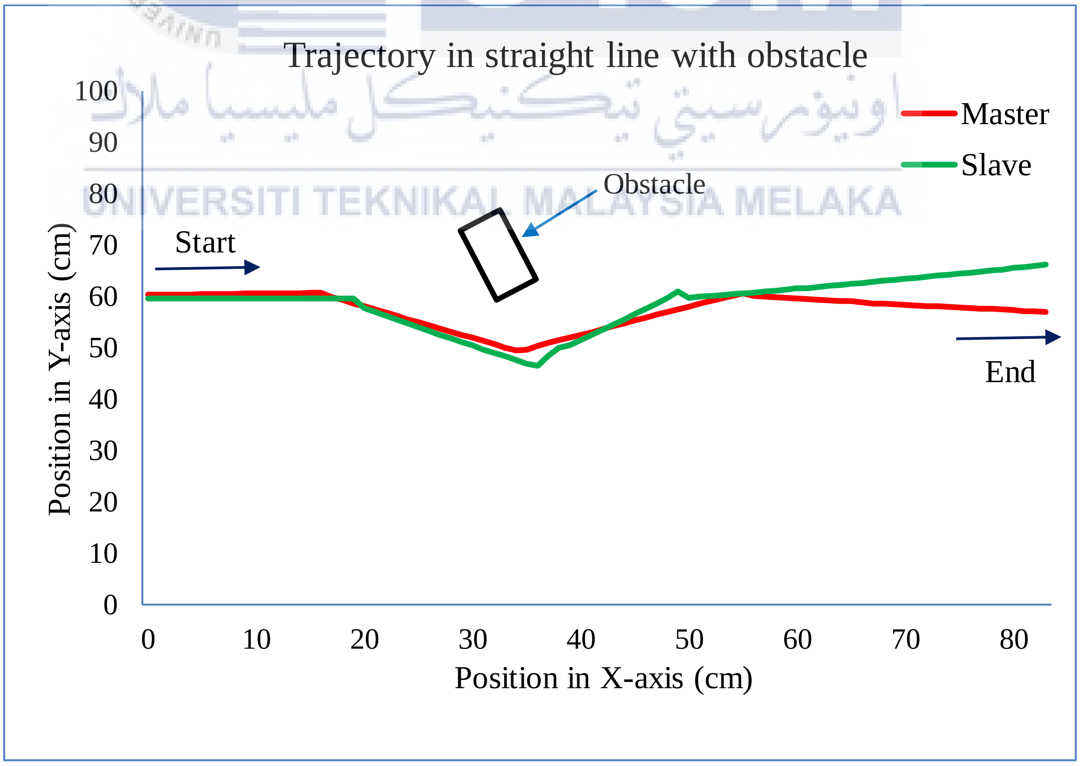


Figure 4.9: General view of graphical form of trajectory in straight line with obstacle

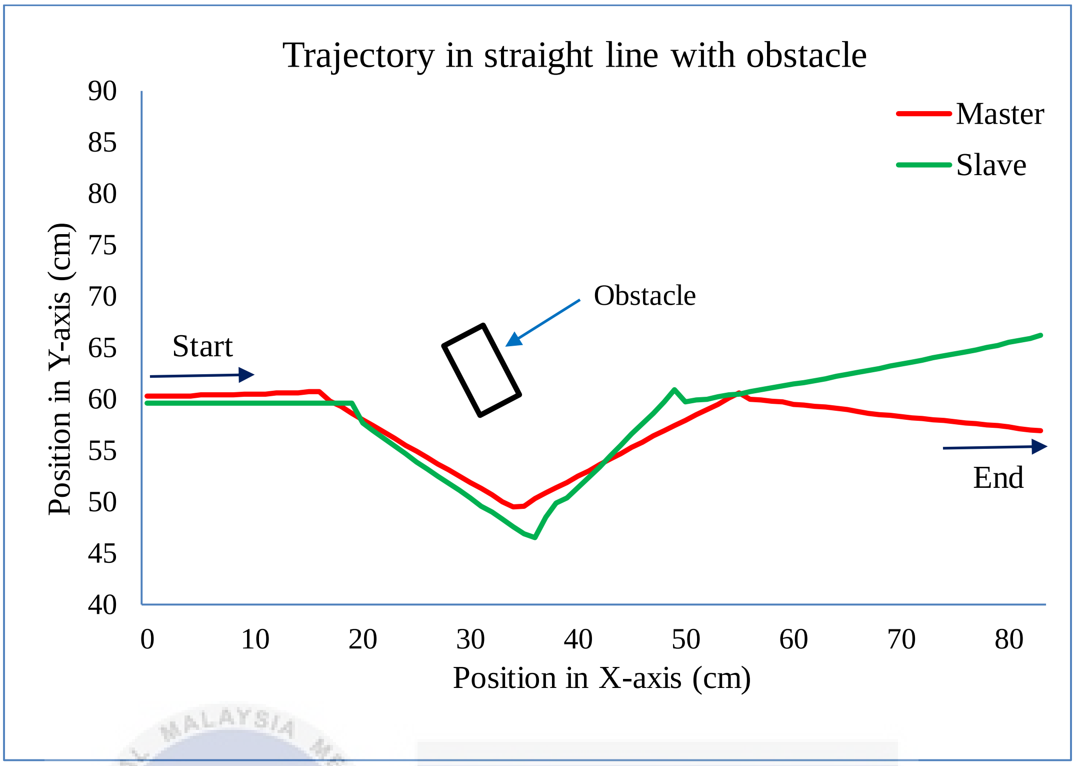


Figure 4.10: Zoom in view of graphical form of trajectory in straight line with obstacle

4.5.3 U-shape Trajectory

Figure 4.11 shows the experiment setup of the trajectory in U-shape by the master and slave robot while Figure 4.12 shows the graphical form of the trajectory. Based on the data collected, RMSE for the three trials are 3.97, 4.98, and 7.89 respectively. First trial are the best compare to another two trials as the RMSE are the smallest. The standard deviation fall in a range of 0 to 15.68 in this trajectory. Observed from the graph, at the beginning, the slave robot was able to follow the same trajectory of master robot. However, from the U-turning point, the slave robot start deviate from the master's trajectory until the end of the trajectory. This is because the angle of turning is not absolutely the same for both robots. While the angle of turning can be affected by the efficiency of the motors and the friction between the wheel and the mahjong paper. The largest deviation of the slave robot is 11.8cm away from the master's trajectory. As a conclusion, although the accuracy of the slave robot in following the trajectory of master robot is not that high, but it still able to follow the commands from master robot and move in U-shape trajectory.

Figure 4.11: Trajectory in U-shape

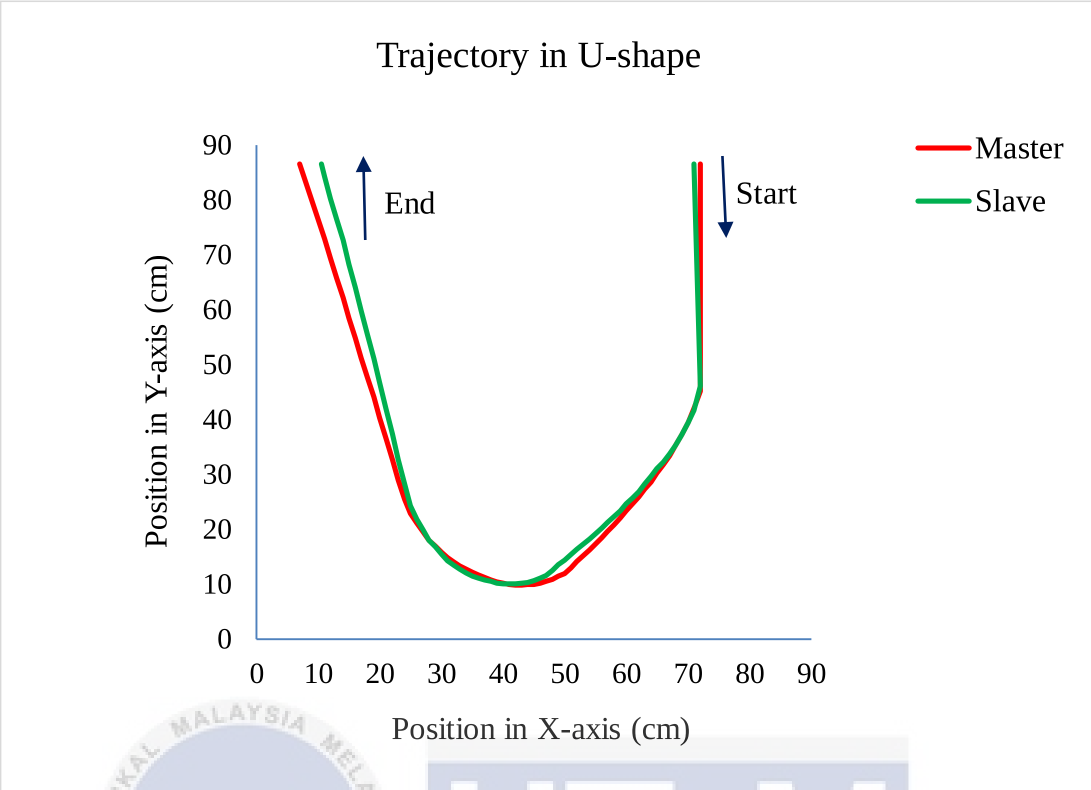


Figure 4.12: Graphical form of trajectory in U-shape

4.5.4 U-shape Trajectory with Obstacle

Figure 4.13 shows the experiment setup of the trajectory in U-shape with obstacle while Figure 4.14 shows the graphical form of the U-shape trajectory with obstacle. From the data collected, RMSE for the three trials are 7.28, 5.97, and 6.94 respectively. Second trial are the best compare to another two trials as the RMSE are the smallest. The standard deviation fall in a range of 0 to 17.65 in this trajectory. The value of RMSE are large is due to the mobile robots performed the obstacle avoidance which need the turning of direction. The angle of turning is not consistent for both master and slave robot cause the big value of RMSE. Observed from the graph, at the beginning, the slave robot was still able to follow the same trajectory of master robot. After performed the action or commands from the master robot to avoid the obstacle in front, the slave robot was started deviate from the master trajectory until the end of the trajectory. As a conclusion, the slave robot was able to perform the obstacle avoidance and follow the commands from master robot to move in U-shape trajectory.

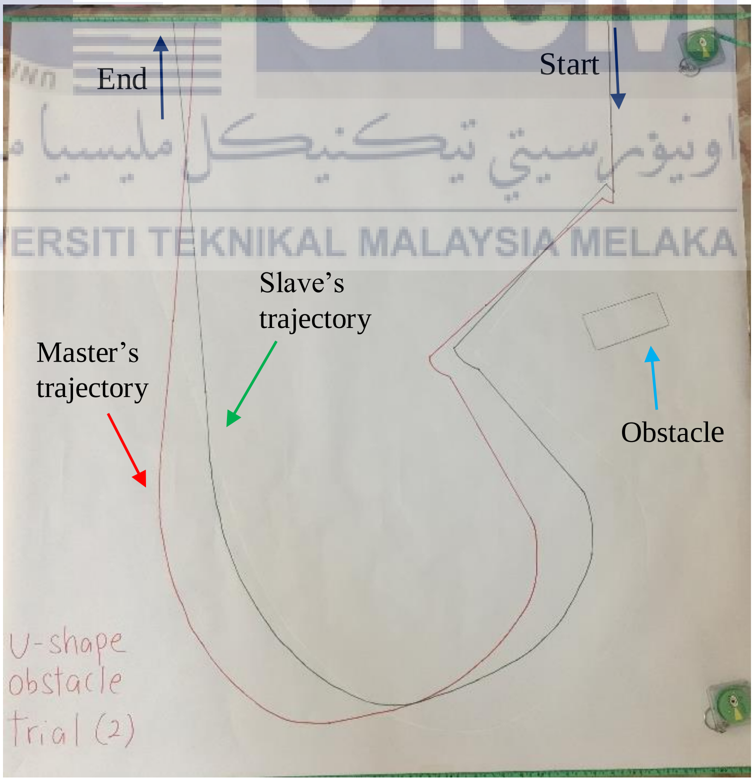


Figure 4.13: Trajectory in U-shape with obstacle

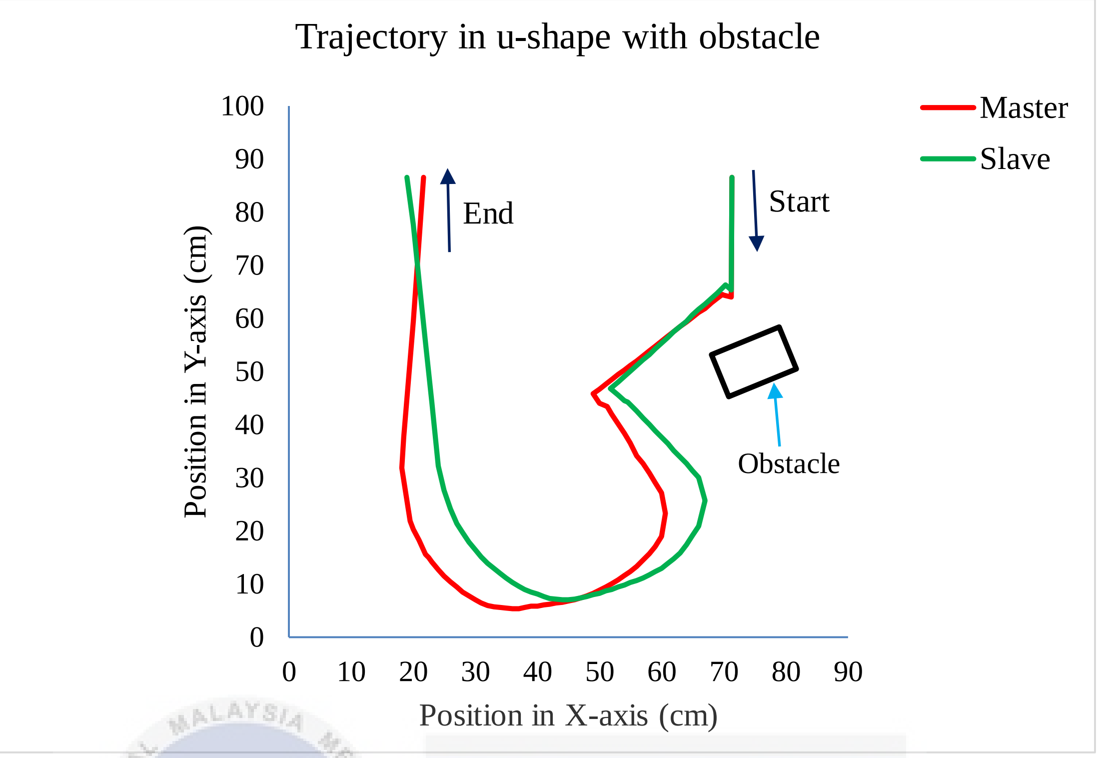


Figure 4.14: Graphical form of trajectory in U-shape with obstacle

4.5.5 S-shape Trajectory

Figure 4.15 shows the experiment setup of trajectory in S-shape while Figure 4.16 shows the graphical form of trajectory in S-shape by the master and slave robot. Based on the data collected, RMSE for the three trials are 1.93, 1.66 and 2.32 respectively. Second trial are the best compare to another two trials as the RMSE are the smallest. The standard deviation fall in a range of 0.15 to 9.15 while the largest deviation from the master's trajectory is 5cm. The smaller the standard deviation value, the higher the accuracy of the slave robot in following the trajectory of the master robot. Observed from the graph, at the beginning, the slave robot was still able to follow the same trajectory of master robot. This is because the angle of turning of the mobile robots are controlled by the length of time and the Pulse Width Modulation (PWM) value for both left and right motor. It is very difficult to make sure the angle of turning to be the same for both mobile robots. As a conclusion, the slave robot was able to follow the commands from master robot to perform the trajectory in S-shape.

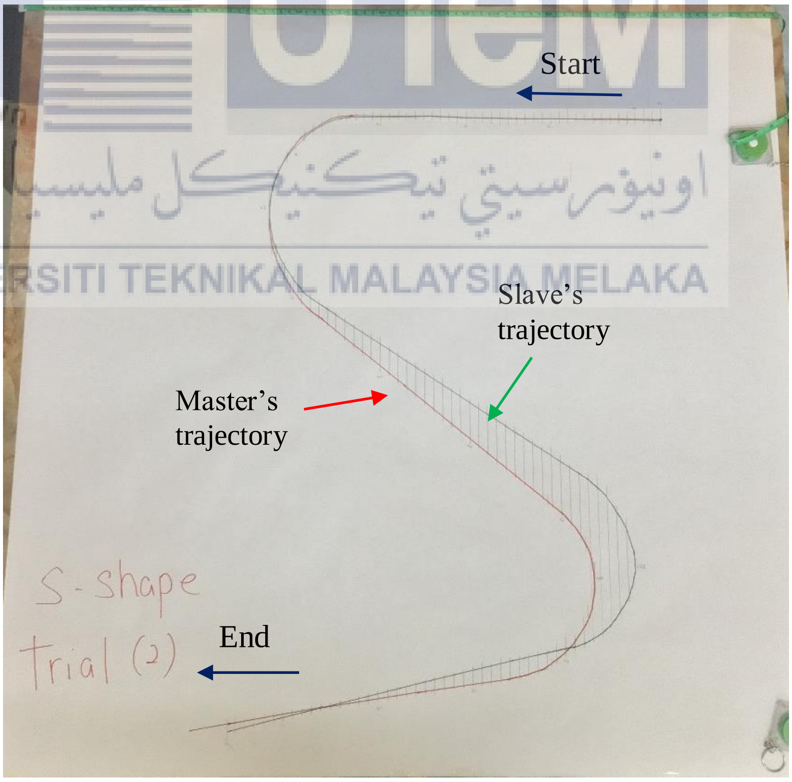


Figure 4.15: Trajectory in S-shape

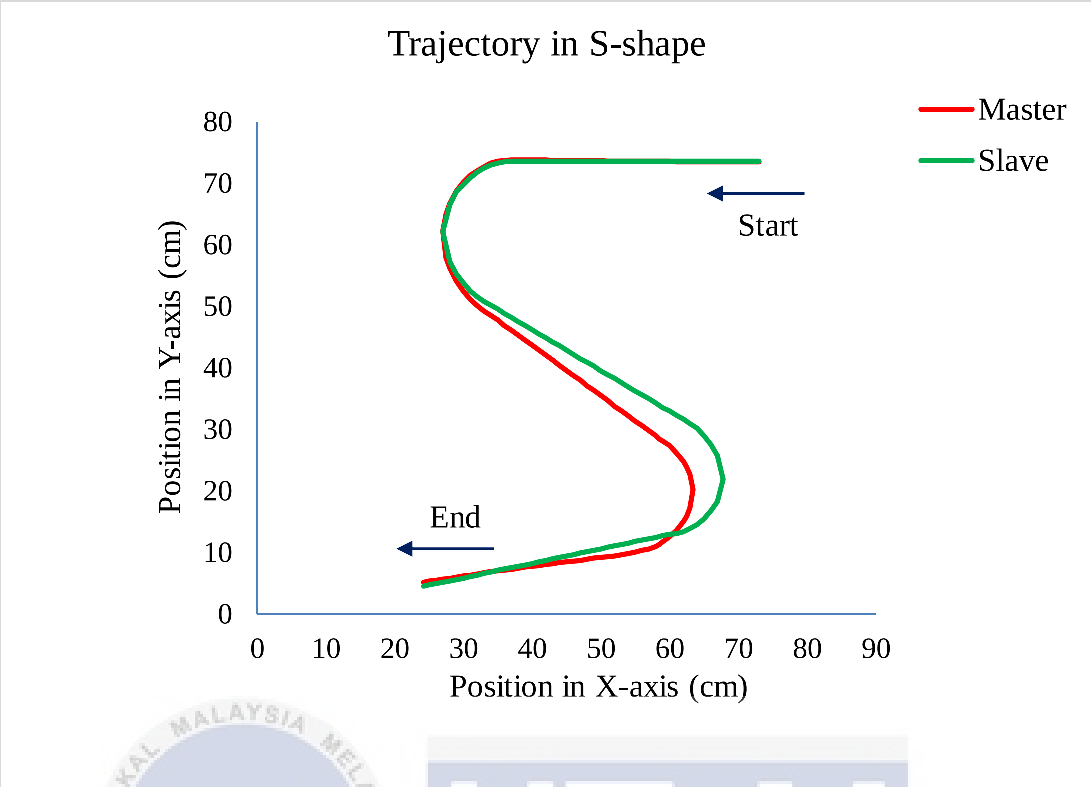


Figure 4.16: Graphical form of trajectory in S-shape

4.5.6 S-shape Trajectory with Obstacle

Figure 4.17 shows the experiment setup of trajectory in S-shape with obstacle while Figure 4.18 shows the graphical form of trajectory in S-shape with obstacle by the master and slave robot. Based on the data collected, RMSE for the three trials are 2.88, 4.65 and 1.69 respectively. Third trial are the best compare to another two trials as the RMSE are the smallest. The standard deviation fall in a range of 0.21 to 6.75 while the largest deviation from the master's trajectory is 4.2cm. Observed from the graph, at the beginning, the trajectory of the slave robot was approximately the same to the trajectory of the master robot. After avoid the obstacle and continue to S-shape trajectory, the slave robot start deviate from the master trajectory. This is because the angle of turning is affected by efficiency of the motors and the friction between the wheels and mahjong paper. It is very difficult to make sure the angle of turning to be the same for both mobile robots. As a conclusion, the slave robot was able to perform obstacles avoidance and follow the commands from master robot to move in S-shape trajectory.

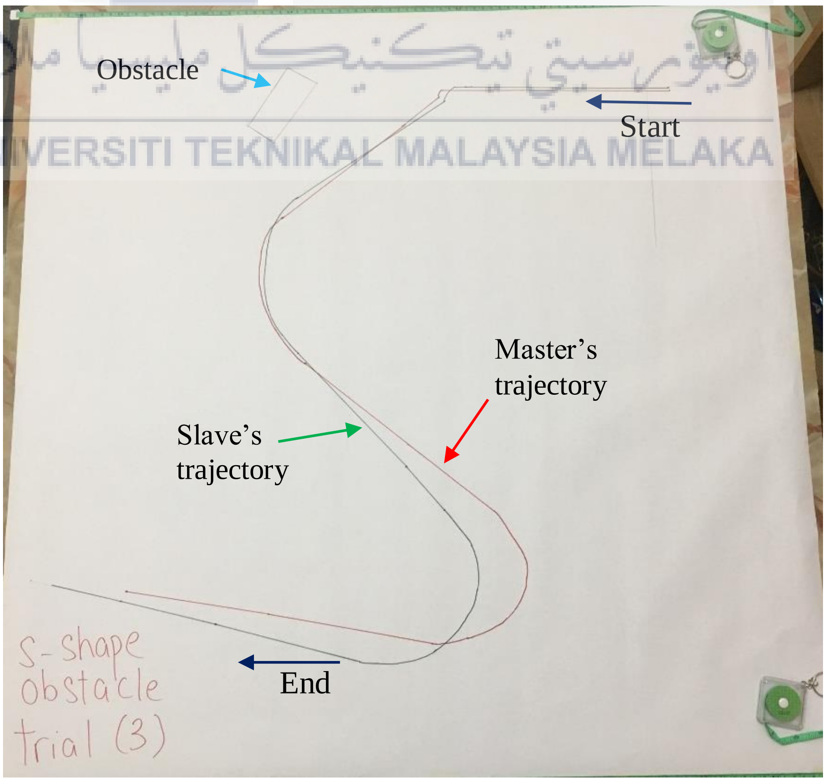


Figure 4.17: Trajectory in S-shape with obstacle

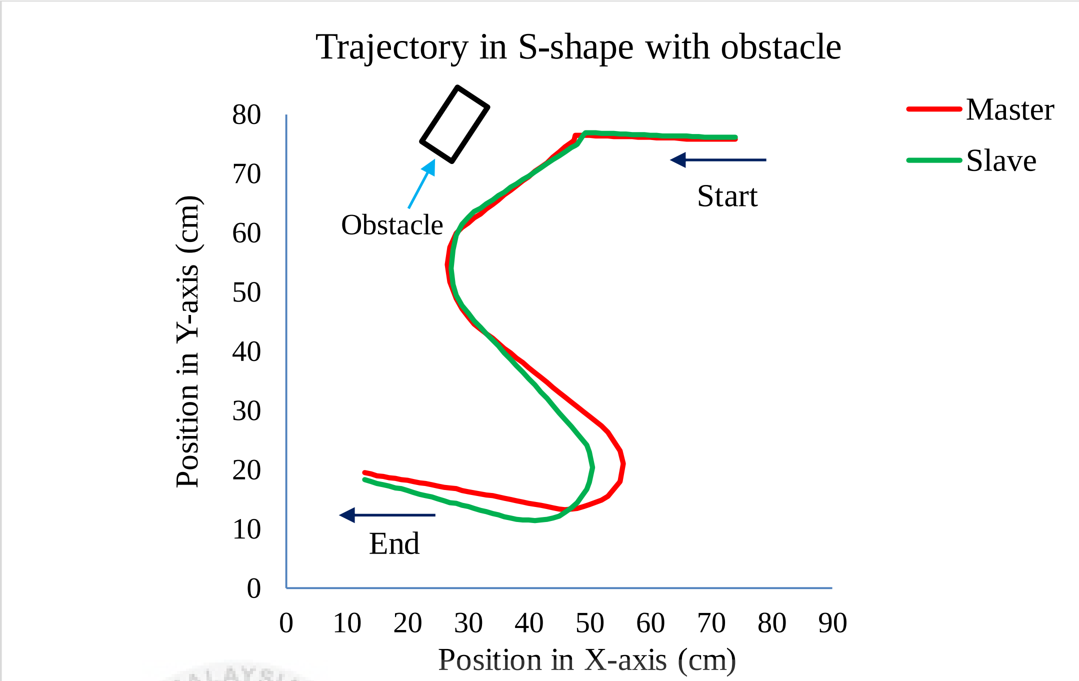


Figure 4.18: Graphical form of trajectory in S-shape with obstacle

4.6 Demonstration of the movement of master and slave robot in the pipeline

4.6.1 Case 1: Without obstacle

Figure 4.19 shows the demonstration of the master and slave robot in the pipeline without obstacle. In this case, there is no obstacle involved for the demonstration. Firstly, when the master robot start to move, it sends the command to the slave robot. The slave robot is moving simultaneously with the master robot. Next, when the master robot reached and detected the T branch of the PVC pipe by using ultrasonic sensor, it send the command to the slave robot to stop for 4s. After that, the master robot is turned right and send the command to the slave robot. Once the slave robot receive the command from the master robot, the serial communication between the master and robot is ended. The slave robot is then become a master role and start to move. The slave robot is turned left when it reached and detected the T branch of the pipe by using ultrasonic sensor. The reason for the slave robot to end the serial communication and change to master role after the master robot turning right is discussed in case 3. As a conclusion, the master and slave robot successfully explore the T shape pipeline without obstacle.

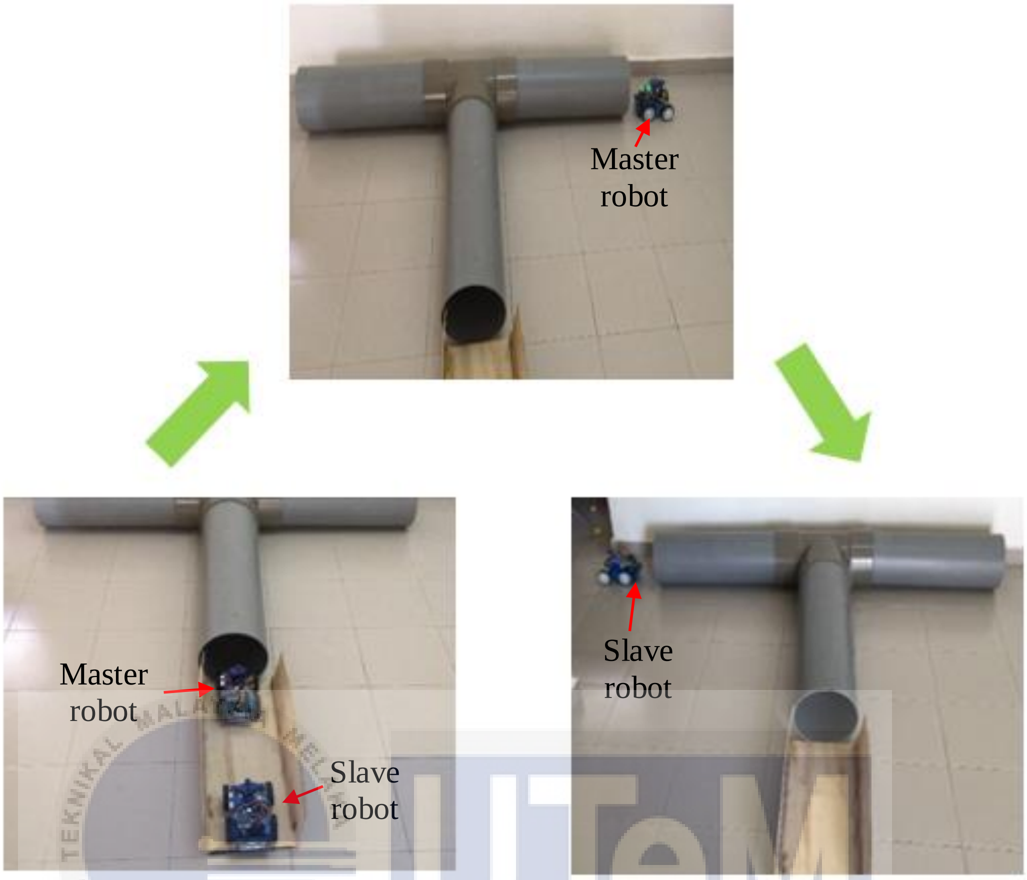


Figure 4.19: Demonstration of the master and slave robot in the pipeline without obstacle

4.6.2 Case 2: With obstacle at the first branch

Figure 4.20 shows the demonstration of the master and slave robot in the pipeline with obstacle at the first branch. Firstly, when the master robot start to move, it sends the command to the slave robot. The slave robot is moving simultaneously with the master robot. In this case, the obstacle is placed at first branch before the master robot reached to the T branch of the pipeline. So, when the master robot detected the obstacle by using the infrared sensor, it stopped for 4s and send the command to the slave robot. Once the slave robot received the command, it reverse to the base station immediately. After 4s, the master robot reverse to the base station. The delay of time for the master robot to reverse back to base station is to avoid the collision with the slave robot. As a conclusion, the master and slave robot successfully explore the pipeline with the obstacle at the first branch.

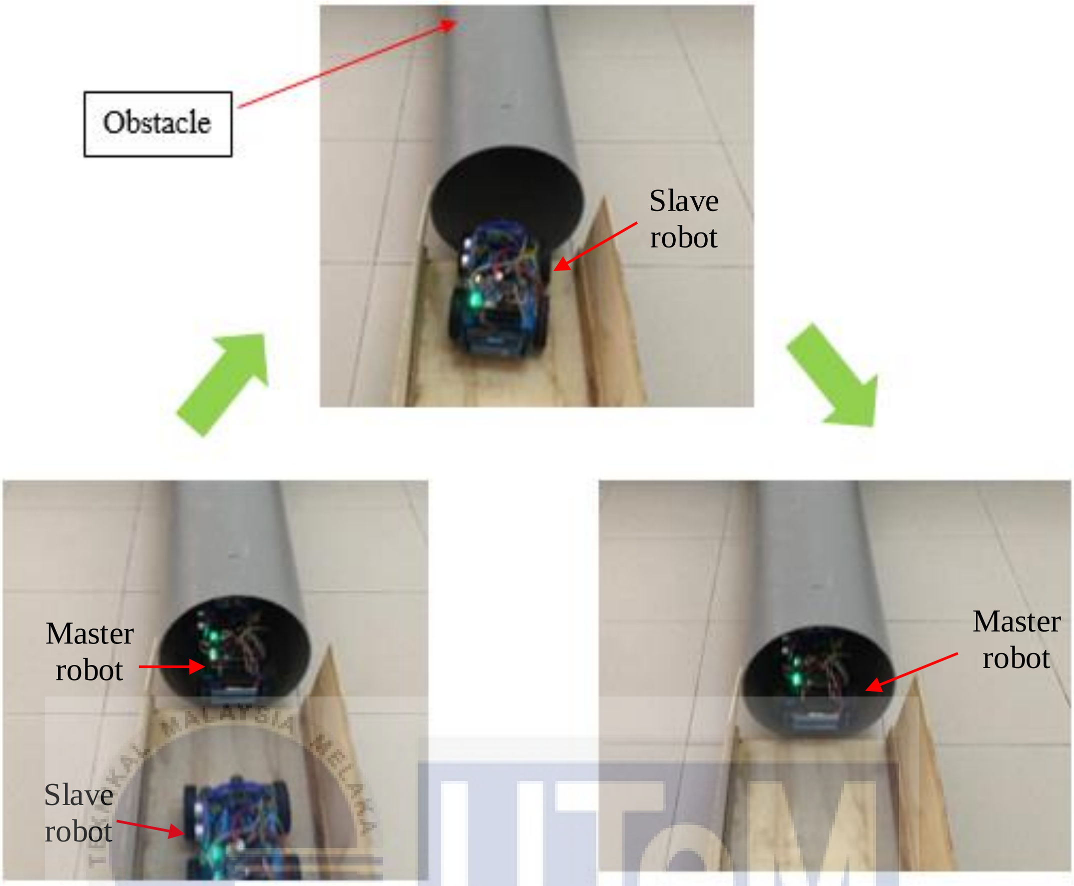


Figure 4.20: Demonstration of the master and slave robot in the pipeline with obstacle at the first branch

4.6.3 Case 3: With obstacle at the second branch

Figure 4.21 shows the demonstration of the master and slave robot in the pipeline with obstacle at the second branch. In this case, the obstacle is placed at the left side before the end of the second branch. Firstly, when the master robot start to move, it sends the command to the slave robot. The slave robot is moving simultaneously with the master robot. Next, when the master robot reached and detected the T branch of the PVC pipe by using ultrasonic sensor, it send the command to the slave robot to stop for 4s. After that, the master robot is turned right and send the command to the slave robot. Once the slave robot receive the command from the master robot, the serial communication between the master and robot is ended. The reason to stop the serial communication is due to the slave robot need to avoid the obstacle when it turned to the left side. The slave robot cannot follow the command of the master robot to move forward due to no obstacle at the right side. The slave robot is then become a master role and start to move. The slave robot is turned left when it reached and detected the T branch of the pipe by using ultrasonic sensor. When the slave robot detected the obstacle by using the infrared sensor, it reversed back to the base station. As a conclusion, the master and slave robot are successfully cooperative controlled to explore the pipeline but at the same time, both robots are successfully avoid the obstacle although the robots at different direction.

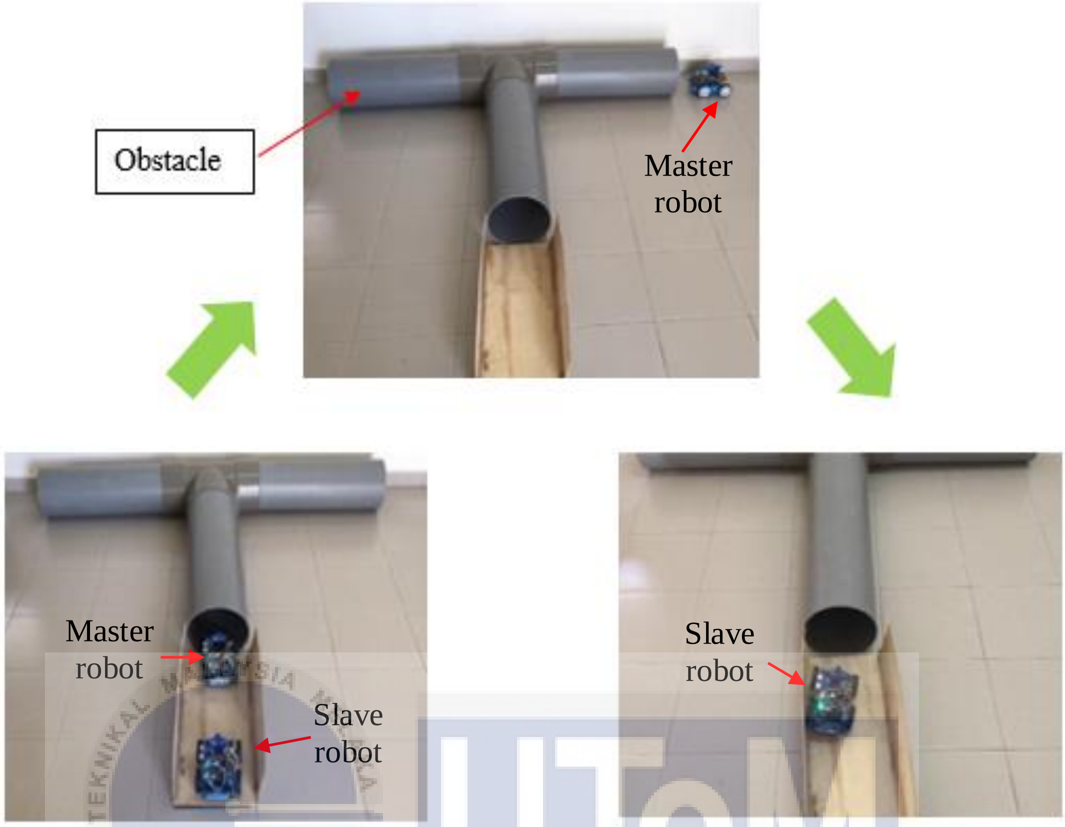


Figure 4.21: Demonstration of the master and slave robot in the pipeline with obstacle at the second branch

4.7 Summary

Analysis and discussion on the outputs obtained from total of 4 conducted experiments are done with proper explanation on presented tables or figures. Throughout the experiments, few issues which can affect the performance of the mobile robots are discussed. Firstly, the smoothness of the motion of mobile robot on various type of surfaces will affect the monitoring process for the pipeline inspection. Secondly, the effective angles of the ultrasonic sensor in detecting an object will affect the mobile robots in performing the obstacle avoidance. Next, the efficiency in data transmitting and receiving between the master robot and slave robot will affect the response time of slave robot to the commands from master robot. Lastly, the accuracy of the slave robot in following the trajectory of the master robot. The mobile robots are able to perform forward, backward, turning left and right movement without having communication loss or disconnected. The master and slave robot are successfully pass through the T branch pipeline by avoid the obstacle. The next chapter concludes the project findings and further improvement suggestion.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

All the objectives are achieved where two affordable mobile robots that are cooperative controlled for pipeline inspection have been successfully developed. The developed mobile robots can move on various type of surfaces such as sand, soil, small stones and oil. The performances of the mobile robot in terms of speed, accuracy and efficiency are evaluated. The speeds of the master and slave robot have been evaluated which is 0.34m/s and 0.33m/s respectively. Besides, the efficiency of the data transmitting and receiving process between the master and slave robot is good, meaning that the response of the slave robot to the commands from the master robot is immediate. Next, the accuracy of the slave robot in following the trajectory of master robot is evaluated by obtaining the RMSE of the trajectory that drawn by the master and slave robot. The slave robot was successfully follow the commands from the master robot to avoid the obstacle and move in straight line, U-shape and S-shape trajectory. Lastly, a communication system between the master and slave robot by using the Bluetooth module for real time data transmission was successfully developed. The master and slave robot are able to communicate in the PVC pipe by using the Bluetooth module. The master robot is able to turn right when detected the T branch and send command to the slave robot to turn left. Besides, both robots can avoid the obstacle in the PVC pipe.

5.2 Future Works

For future development, an image processing system is recommended to develop to process and analyze the image that capture by the camera, so that the defected area of the pipeline can be known. Besides, more slave robots can be developed to explore the branches of the pipeline so that the time to complete the pipeline inspection process can be reduced. Moreover, to improve the obstacle avoidance performance and the collision avoidance between the master and slave robot, the vision system is recommended for better result. Vision system can produce the image of the object and send a feedback to the mobile robot via the software. The map of the trajectories can be visualize by the camera and can give more accurate coordinate. This will be benefit for the graph plotting.

REFERENCES

[1] N. A. Binti Haji Yahya, N. Ashrafi, and A. H. Humod, “Development and Adaptability of In-Pipe Inspection Robots,” *IOSR J. Mech. Civ. Eng.*, vol. 11, no. 4, pp. 01–08, 2014.

[2] Todd, D. (2014). *Pipeline Safety Excellence*. *Natural Resources Canada*. Retrieved from https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/files/pdf/14-0279-PS_expanding_oil_gas_safetly_e.pdf

[3] ABC NEWS. (2018). Pipeline Explosion Kills 10 Campers in N.M. - ABC News. Retrieved November 12, 2018, from https://abcnews.go.com/US/story?id=96090&page=1

[4] StephenThen. (2014). Blast rips Sabah-Sarawak gas pipeline - Nation | The Star Online. Retrieved November 12, 2018, from https://www.thestar.com.my/news/nation/2014/06/11/blast-rips-sabahsarawak-gas-pipeline-no-one-hurt-in-2am-explosion-fire-is-out/

[5] New Technology JettyRobot for Ducts & Pipes Cleaning and Repairs. (2018). Retrieved December 5, 2018, from https://www.jettyrobot.com/technology/

[6] Auto Ptz Motorised Elevator Sewer Pipe Inspection Camera Robot Jt-c300 - Buy Sewer Pipe Inspection Camera,Pipe Inspection Camera,Inspection Camera Product on Alibaba.com. (2018). Retrieved December 5, 2018, from https://www.alibaba.com/product-detail/Auto-PTZ-Motorised-Elevator-Sewer-Pipe_60442886316.html?spm=a2700.7724857.normalList.52.3a095ee8b593Lg

[7] R. N. Darmanin and M. K. Bugeja, “A review on multi-robot systems categorised by application domain,” *2017 25th Mediterr. Conf. Control Autom. MED 2017*, no. July, pp. 701–706, 2017.

[8] Tang, D. D. (2018). Multi-Robot Communication. Retrieved November 6, 2018, from https://www.cpp.edu/~ftang/courses/CS599-DI/notes/Communication.pdf

[9] R. Doriya, S. Mishra, and S. Gupta, “A brief survey and analysis of multi-robot communication and coordination,” *Int. Conf. Comput. Commun. Autom. ICCCA 2015*, pp. 1014–1021, 2015.

[10] Z. Yan, N. Jouandeau, and A. A. Cherif, “A survey and analysis of multi-robot coordination,” *Int. J. Adv. Robot. Syst.*, vol. 10, 2013.

[11] N. Gildert, A. G. Millard, A. Pomfret, and J. Timmis, “The Need for Combining Implicit and Explicit Communication in Cooperative Robotic Systems,” *Front. Robot. AI*, vol. 5, no. June, p. 65, 2018.

[12] C. Maneggia, “Pipeline Inspection Techniques,” 2013.

[13] P. J. Garland, “The Importance of Non-Destructive Testing And Inspection of Pipelines,” *OSG Test.*, pp. 1–10, 2010.

[14] H. R. Vanaei, A. Eslami, and A. Egbewande, “A review on pipeline corrosion, in-line inspection (ILI), and corrosion growth rate models,” *Int. J. Press. Vessel. Pip.*, vol. 149, no. Ili, pp. 43–54, 2017.

[15] S. Navigation *et al.*, “Pipeline Inspection,” *Hydrofest*, vol. 115, no. March, pp. 1–2, 2007.

[16] Q. Feng, R. Li, B. Nie, S. Liu, L. Zhao, and H. Zhang, “Literature review: Theory and application of in-line inspection technologies for oil and gas pipeline girth weld defection,” *Sensors*, vol. 17, no. 1, 2017.

[17] N. S. Roslin, A. Anuar, M. F. A. Jalal, and K. S. M. Sahari, “A review: Hybrid locomotion of in-pipe inspection robot,” *Procedia Eng.*, vol. 41, pp. 1456–1462, 2012.

[18] A. Nayak and S. K. Pradhan, “Design of a new in-pipe inspection robot,” *Procedia Eng.*, vol. 97, pp. 2081–2091, 2014.

[19] M. Han, J. Zhou, X. Chen, and L. Li, “Analysis of In-Pipe Inspection Robot Structure Design,” *2nd Work. Adv. Res. Technol. Ind. Appl. (WARTIA 2016)*, pp. 989–993, 2016.

[20] M. L. Jones, “Real-Time Pipe Inspection Robot Prototype Development,” p. 201, 2008.

[21] A. Bhuiya, A. Mukherjee, and R. K. Barai, “Development of Wi-Fi communication module for ATmega microcontroller based mobile robot for cooperative autonomous navigation,” *2017 IEEE Calcutta Conf. CALCON 2017 - Proc.*, vol. 2018–Janua, pp. 168–172, 2018.

[22] A. H. Ismail *et al.*, “Investigation of homogeneous multi robots communication via Bluetooth,” *ISCAIE 2012 - 2012 IEEE Symp. Comput. Appl. Ind. Electron.*, no. Iscaie, pp. 124–129, 2012.

[23] D. A. Patil, M. Y. Upadhye, F. S. Kazi, and N. M. Singh, “Multi Robot Communication and Target Tracking system with controller design and implementation of SWARM robot using Arduino,” *2015 Int. Conf. Ind. Instrum.*

Control. ICIC 2015, no. Icic, pp. 412–416, 2015.

[24] A. M. Derbas, K. M. Al-Aubidy, M. M. Ali, and A. W. Al-Mutairi, “Multi-robot system for real-time sensing and monitoring,” *2014 15th Int. Work. Res. Educ. Mechatronics, REM 2014*, 2014.

[25] S. Guo, X. Li, and J. Guo, “Study on a multi-robot cooperative wireless communication control system for the spherical amphibious robot,” *2016 IEEE Int. Conf. Mechatronics Autom. IEEE ICMA 2016*, pp. 1143–1148, 2016.

[26] R. Kazala, A. Taneva, M. Petrov, and S. Penkov, “Wireless Network for Mobile Robot Applications,” *IFAC-PapersOnLine*, vol. 48, no. 24, pp. 231–236, 2015.

[27] Y. S. Kwon, J. T. Suh, and B. J. Yi, “A linkage type mechanical clutch synthesis for pipeline inspection robot,” *IEEE Int. Conf. Autom. Sci. Eng.*, pp. 618–623, 2012.

[28] Y. S. Kwon and B. J. Yi, “Design and motion planning of a two-module collaborative indoor pipeline inspection robot,” *IEEE Trans. Robot.*, vol. 28, no. 3, pp. 681–696, 2012.

[29] J. Min, Y. D. Setiawan, P. S. Pratama, S. B. Kim, and H. K. Kim, “Development and controller design of wheeled-type pipe inspection robot,” *Proc. 2014 Int. Conf. Adv. Comput. Commun. Informatics, ICACCI 2014*, pp. 789–795, 2014.

[30] A. Kakogawa, T. Nishimura, and S. Ma, “Development of a screw drive in-pipe robot for passing through bent and branch pipes,” *2013 44th Int. Symp. Robot. ISR 2013*, 2013.

[31] J. H. Kim, G. Sharma, and S. S. Iyengar, “FAMPER: A fully autonomous mobile robot for pipeline exploration,” *Proc. IEEE Int. Conf. Ind. Technol.*, no. April, pp. 517–523, 2010.

[32] O. Voltage, A. I. Pins, F. Memory, and C. Speed, “Schematic & Reference Design,” vol. 328, pp. 0–3.

[33] “L298P Motor Shield Parameters,”*Mantech*, 2018.

[34] A. Cotta, N. T. Devidas, and V. K. N. Ekoskar, “Wireless Communication Using Hc-05 Bluetooth Module Interfaced With Arduino,” *Int. J. Sci. Eng. Technol. Res.*, vol. 5, no. 4, pp. 869–872, 2016.

[35] ultrasonic principle | ultrasonic sensors | microsonic. (2018). Retrieved December 6, 2018, from https://www.microsonic.de/en/support/ultrasonic-technology/principle.htm

[36] The Working Principle and Key Applications of Infrared Sensors. (2018).

Retrieved December 6, 2018, from https://www.azosensors.com/article.aspx?ArticleID=339

APPENDICES

APPENDIX A GANTT CHART

No.	Activity	2018/2019 (Semester 1) FYP 1																	Semester Break	2018/2019 (Semester 2) FYP 2																
		1	2	3	4	5	6	7	8	9	Mid-Term Break	10	11	12	13	14	15 Study Week	16 Final Exam Week		1	2	3	4	5	6	7	8	Mid-Term Break	9	10	11	12	13	14	15 Study Week	16 Final Exam Week
	Final Year Project 1																																			
1	Title Registration																																			
2	FYP Talk																																			
3	Discussion with Supervisor																																			
4	Library and Internet Research																																			
5	Hardware and Program Development																																			
6	Design Experiment																																			
7	Preparation Draft Report and Slide																																			
8	Submission Draft Report																																			
9	Presentation of FYP 1																																			
10	Submission Final Draft Report																																			
	Final Year Project 2																																			
11	Complete Hardware and Program Development																																			
12	Complete Designed Experiment																																			
13	Reparation of Final Report and Slide																																			
14	Submission Final Report																																			
15	Presentation of FYP 2																																			

APPENDIX B STRAIGHT LINE TRAJECTORY

1	Straight Line																				
2	Point	Trial 1				Trial 2				Trial 3				Error in Y-axis (cm)				Standard deviation	Error Squared		
3		Master (cm)		Slave (cm)		Master (cm)		Slave (cm)		Master (cm)		Slave (cm)									
4		X_m	Y_m	X_s	Y_s	X_m	Y_m	X_s	Y_s	X_m	Y_m	X_s	Y_s	E_{Y1}	E_{Y2}	E_{Y3}	Average		E_{Y1}^2	E_{Y2}^2	E_{Y3}^2
5	1	0.00	45.80	0.00	46.10	0.00	45.00	0.00	45.80	0.00	45.90	0.00	46.70	0.30	0.80	0.80	0.63	0.29	0.09	0.64	0.64
6	2	1.00	45.80	1.00	46.10	1.00	44.90	1.00	45.80	1.00	45.90	1.00	46.70	0.30	0.90	0.80	0.67	0.32	0.09	0.81	0.64
7	3	2.00	45.80	2.00	46.10	2.00	44.90	2.00	45.80	2.00	45.90	2.00	46.70	0.30	0.90	0.80	0.67	0.32	0.09	0.81	0.64
8	4	3.00	45.80	3.00	46.10	3.00	44.90	3.00	45.80	3.00	45.90	3.00	46.60	0.30	0.90	0.70	0.63	0.31	0.09	0.81	0.49
9	5	4.00	45.80	4.00	46.10	4.00	44.90	4.00	45.80	4.00	45.90	4.00	46.60	0.30	0.90	0.70	0.63	0.31	0.09	0.81	0.49
10	6	5.00	45.80	5.00	46.10	5.00	44.90	5.00	45.90	5.00	45.90	5.00	46.60	0.30	1.00	0.70	0.67	0.35	0.09	1.00	0.49
11	7	6.00	45.80	6.00	46.10	6.00	44.90	6.00	45.90	6.00	45.80	6.00	46.60	0.30	1.00	0.80	0.70	0.36	0.09	1.00	0.64
12	8	7.00	45.80	7.00	46.10	7.00	44.90	7.00	45.90	7.00	45.70	7.00	46.60	0.30	1.00	0.90	0.73	0.38	0.09	1.00	0.81
13	9	8.00	45.80	8.00	46.10	8.00	44.90	8.00	45.90	8.00	45.70	8.00	46.50	0.30	1.00	0.80	0.70	0.36	0.09	1.00	0.64
14	10	9.00	45.80	9.00	46.00	9.00	44.90	9.00	45.90	9.00	45.70	9.00	46.50	0.20	1.00	0.80	0.67	0.42	0.04	1.00	0.64
15	11	10.00	45.80	10.00	46.00	10.00	44.90	10.00	46.00	10.00	45.70	10.00	46.50	0.20	1.10	0.80	0.70	0.46	0.04	1.21	0.64
16	12	11.00	45.80	11.00	46.00	11.00	44.90	11.00	46.00	11.00	45.70	11.00	46.50	0.20	1.10	0.80	0.70	0.46	0.04	1.21	0.64
17	13	12.00	45.80	12.00	45.90	12.00	44.90	12.00	46.00	12.00	45.70	12.00	46.50	0.10	1.10	0.80	0.67	0.51	0.01	1.21	0.64
18	14	13.00	45.80	13.00	45.90	13.00	44.90	13.00	46.10	13.00	45.70	13.00	46.50	0.10	1.20	0.80	0.70	0.56	0.01	1.44	0.64
19	15	14.00	45.80	14.00	45.90	14.00	44.90	14.00	46.10	14.00	45.80	14.00	46.50	0.10	1.20	0.70	0.67	0.55	0.01	1.44	0.49
20	16	15.00	45.80	15.00	45.90	15.00	44.90	15.00	46.10	15.00	45.80	15.00	46.50	0.10	1.20	0.70	0.67	0.55	0.01	1.44	0.49
21	17	16.00	45.80	16.00	45.90	16.00	44.90	16.00	46.10	16.00	45.80	16.00	46.50	0.10	1.20	0.70	0.67	0.55	0.01	1.44	0.49
22	18	17.00	45.80	17.00	45.90	17.00	44.90	17.00	46.20	17.00	45.80	17.00	46.50	0.10	1.30	0.70	0.70	0.60	0.01	1.69	0.49
23	19	18.00	45.80	18.00	45.90	18.00	44.90	18.00	46.20	18.00	45.80	18.00	46.50	0.10	1.30	0.70	0.70	0.60	0.01	1.69	0.49
24	20	19.00	45.90	19.00	45.80	19.00	44.90	19.00	46.20	19.00	45.80	19.00	46.50	-0.10	1.30	0.70	0.63	0.70	0.01	1.69	0.49
25	21	20.00	45.90	20.00	45.80	20.00	45.00	20.00	46.20	20.00	45.90	20.00	46.50	-0.10	1.20	0.60	0.57	0.65	0.01	1.44	0.36
26	22	21.00	45.90	21.00	45.80	21.00	45.00	21.00	46.20	21.00	45.90	21.00	46.50	-0.10	1.20	0.60	0.57	0.65	0.01	1.44	0.36
27	23	22.00	45.90	22.00	45.80	22.00	45.00	22.00	46.20	22.00	45.90	22.00	46.50	-0.10	1.20	0.60	0.57	0.65	0.01	1.44	0.36
28	24	23.00	46.00	23.00	45.80	23.00	45.00	23.00	46.20	23.00	45.90	23.00	46.50	-0.20	1.20	0.60	0.53	0.70	0.04	1.44	0.36
29	25	24.00	46.00	24.00	45.70	24.00	45.00	24.00	46.30	24.00	45.90	24.00	46.50	-0.30	1.30	0.60	0.53	0.80	0.09	1.69	0.36

30	26	25.00	46.10	25.00	45.70	25.00	45.00	25.00	46.30	25.00	46.00	25.00	46.50	-0.40	1.30	0.50	0.47	0.85	0.16	1.69	0.25
31	27	26.00	46.10	26.00	45.70	26.00	45.00	26.00	46.30	26.00	46.00	26.00	46.50	-0.40	1.30	0.50	0.47	0.85	0.16	1.69	0.25
32	28	27.00	46.10	27.00	45.70	27.00	45.10	27.00	46.40	27.00	46.00	27.00	46.50	-0.40	1.30	0.50	0.47	0.85	0.16	1.69	0.25
33	29	28.00	46.20	28.00	45.70	28.00	45.10	28.00	46.40	28.00	46.00	28.00	46.50	-0.50	1.30	0.50	0.43	0.90	0.25	1.69	0.25
34	30	29.00	46.20	29.00	45.70	29.00	45.10	29.00	46.40	29.00	46.00	29.00	46.50	-0.50	1.30	0.50	0.43	0.90	0.25	1.69	0.25
35	31	30.00	46.30	30.00	45.70	30.00	45.20	30.00	46.50	30.00	46.10	30.00	46.50	-0.60	1.30	0.40	0.37	0.95	0.36	1.69	0.16
36	32	31.00	46.30	31.00	45.70	31.00	45.20	31.00	46.50	31.00	46.10	31.00	46.50	-0.60	1.30	0.40	0.37	0.95	0.36	1.69	0.16
37	33	32.00	46.30	32.00	45.70	32.00	45.20	32.00	46.60	32.00	46.10	32.00	46.50	-0.60	1.40	0.40	0.40	1.00	0.36	1.96	0.16
38	34	33.00	46.40	33.00	45.70	33.00	45.30	33.00	46.60	33.00	46.20	33.00	46.50	-0.70	1.30	0.30	0.30	1.00	0.49	1.69	0.09
39	35	34.00	46.40	34.00	45.70	34.00	45.40	34.00	46.60	34.00	46.20	34.00	46.50	-0.70	1.20	0.30	0.27	0.95	0.49	1.44	0.09
40	36	35.00	46.40	35.00	45.70	35.00	45.40	35.00	46.70	35.00	46.30	35.00	46.50	-0.70	1.30	0.20	0.27	1.00	0.49	1.69	0.04
41	37	36.00	46.40	36.00	45.60	36.00	45.50	36.00	46.70	36.00	46.30	36.00	46.50	-0.80	1.20	0.20	0.20	1.00	0.64	1.44	0.04
42	38	37.00	46.50	37.00	45.60	37.00	45.50	37.00	46.80	37.00	46.40	37.00	46.50	-0.90	1.30	0.10	0.17	1.10	0.81	1.69	0.01
43	39	38.00	46.50	38.00	45.60	38.00	45.60	38.00	46.80	38.00	46.50	38.00	46.50	-0.90	1.20	0.00	0.10	1.05	0.81	1.44	0.00
44	40	39.00	46.60	39.00	45.60	39.00	45.60	39.00	46.80	39.00	46.60	39.00	46.50	-1.00	1.20	-0.10	0.03	1.11	1.00	1.44	0.01
45	41	40.00	46.70	40.00	45.60	40.00	45.60	40.00	46.80	40.00	46.60	40.00	46.50	-1.10	1.20	-0.10	0.00	1.15	1.21	1.44	0.01
46	42	41.00	46.70	41.00	45.60	41.00	45.70	41.00	46.80	41.00	46.70	41.00	46.50	-1.10	1.10	-0.20	-0.07	1.11	1.21	1.21	0.04
47	43	42.00	46.80	42.00	45.60	42.00	45.80	42.00	46.90	42.00	46.70	42.00	46.50	-1.20	1.10	-0.20	-0.10	1.15	1.44	1.21	0.04
48	44	43.00	46.90	43.00	45.60	43.00	45.80	43.00	46.90	43.00	46.80	43.00	46.50	-1.30	1.10	-0.30	-0.17	1.21	1.69	1.21	0.09
49	45	44.00	47.00	44.00	45.60	44.00	45.80	44.00	46.90	44.00	46.80	44.00	46.50	-1.40	1.10	-0.30	-0.20	1.25	1.96	1.21	0.09
50	46	45.00	47.10	45.00	45.60	45.00	45.90	45.00	47.00	45.00	46.90	45.00	46.50	-1.50	1.10	-0.40	-0.27	1.31	2.25	1.21	0.16
51	47	46.00	47.20	46.00	45.60	46.00	46.00	46.00	47.00	46.00	47.00	46.00	46.50	-1.60	1.00	-0.50	-0.37	1.31	2.56	1.00	0.25
52	48	47.00	47.30	47.00	45.60	47.00	46.10	47.00	47.00	47.00	47.00	47.00	46.50	-1.70	0.90	-0.50	-0.43	1.30	2.89	0.81	0.25
53	49	48.00	47.40	48.00	45.60	48.00	46.20	48.00	47.10	48.00	47.10	48.00	46.50	-1.80	0.90	-0.60	-0.50	1.35	3.24	0.81	0.36
54	50	49.00	47.50	49.00	45.60	49.00	46.30	49.00	47.10	49.00	47.20	49.00	46.50	-1.90	0.80	-0.70	-0.60	1.35	3.61	0.64	0.49
55	51	50.00	47.60	50.00	45.60	50.00	46.30	50.00	47.20	50.00	47.30	50.00	46.50	-2.00	0.90	-0.80	-0.63	1.46	4.00	0.81	0.64
56	52	51.00	47.70	51.00	45.60	51.00	46.50	51.00	47.20	51.00	47.30	51.00	46.50	-2.10	0.70	-0.80	-0.73	1.40	4.41	0.49	0.64
57	53	52.00	47.80	52.00	45.60	52.00	46.60	52.00	47.20	52.00	47.40	52.00	46.50	-2.20	0.60	-0.90	-0.83	1.40	4.84	0.36	0.81

58	54	53.00	47.90	53.00	45.70	53.00	46.60	53.00	47.30	53.00	47.50	53.00	46.50	-2.20	0.70	-1.00	-0.83	1.46	4.84	0.49	1.00
59	55	54.00	48.00	54.00	45.70	54.00	46.80	54.00	47.30	54.00	47.60	54.00	46.60	-2.30	0.50	-1.00	-0.93	1.40	5.29	0.25	1.00
60	56	55.00	48.10	55.00	45.70	55.00	46.90	55.00	47.40	55.00	47.70	55.00	46.60	-2.40	0.50	-1.10	-1.00	1.45	5.76	0.25	1.21
61	57	56.00	48.20	56.00	45.70	56.00	47.00	56.00	47.40	56.00	47.80	56.00	46.60	-2.50	0.40	-1.20	-1.10	1.45	6.25	0.16	1.44
62	58	57.00	48.30	57.00	45.70	57.00	47.00	57.00	47.50	57.00	47.90	57.00	46.60	-2.60	0.50	-1.30	-1.13	1.56	6.76	0.25	1.69
63	59	58.00	48.40	58.00	45.70	58.00	47.20	58.00	47.60	58.00	47.90	58.00	46.60	-2.70	0.40	-1.30	-1.20	1.55	7.29	0.16	1.69
64	60	59.00	48.50	59.00	45.70	59.00	47.30	59.00	47.60	59.00	48.00	59.00	46.60	-2.80	0.30	-1.40	-1.30	1.55	7.84	0.09	1.96
65	61	60.00	48.60	60.00	45.70	60.00	47.40	60.00	47.60	60.00	48.10	60.00	46.70	-2.90	0.20	-1.40	-1.37	1.55	8.41	0.04	1.96
66	62	61.00	48.70	61.00	45.70	61.00	47.50	61.00	47.60	61.00	48.30	61.00	46.70	-3.00	0.10	-1.60	-1.50	1.55	9.00	0.01	2.56
67	63	62.00	48.80	62.00	45.80	62.00	47.60	62.00	47.70	62.00	48.30	62.00	46.70	-3.00	0.10	-1.60	-1.50	1.55	9.00	0.01	2.56
68	64	63.00	49.00	63.00	45.80	63.00	47.70	63.00	47.80	63.00	48.40	63.00	46.70	-3.20	0.10	-1.70	-1.60	1.65	10.24	0.01	2.89
69	65	64.00	49.10	64.00	45.80	64.00	47.80	64.00	47.80	64.00	48.40	64.00	46.70	-3.30	0.00	-1.70	-1.67	1.65	10.89	0.00	2.89
70	66	65.00	49.20	65.00	45.80	65.00	47.90	65.00	47.80	65.00	48.60	65.00	46.70	-3.40	-0.10	-1.90	-1.80	1.65	11.56	0.01	3.61
71	67	66.00	49.40	66.00	45.80	66.00	48.00	66.00	47.80	66.00	48.70	66.00	46.70	-3.60	-0.20	-2.00	-1.93	1.70	12.96	0.04	4.00
72	68	67.00	49.60	67.00	45.80	67.00	48.10	67.00	47.90	67.00	48.80	67.00	46.70	-3.80	-0.20	-2.10	-2.03	1.80	14.44	0.04	4.41
73	69	68.00	49.70	68.00	45.80	68.00	48.20	68.00	47.90	68.00	48.90	68.00	46.70	-3.90	-0.30	-2.20	-2.13	1.80	15.21	0.09	4.84
74	70	69.00	49.80	69.00	45.80	69.00	48.30	69.00	47.90	69.00	49.00	69.00	46.70	-4.00	-0.40	-2.30	-2.23	1.80	16.00	0.16	5.29
75	71	70.00	50.00	70.00	45.80	70.00	48.40	70.00	48.00	70.00	49.10	70.00	46.70	-4.20	-0.40	-2.40	-2.33	1.90	17.64	0.16	5.76
76	72	71.00	50.10	71.00	45.90	71.00	48.60	71.00	48.10	71.00	49.20	71.00	46.70	-4.20	-0.50	-2.50	-2.40	1.85	17.64	0.25	6.25
77	73	72.00	50.30	72.00	45.90	72.00	48.80	72.00	48.20	72.00	49.30	72.00	46.70	-4.40	-0.60	-2.60	-2.53	1.90	19.36	0.36	6.76
78	74	73.00	50.40	73.00	45.90	73.00	49.00	73.00	48.30	73.00	49.40	73.00	46.80	-4.50	-0.70	-2.60	-2.60	1.90	20.25	0.49	6.76
79	75	74.00	50.50	74.00	45.90	74.00	49.10	74.00	48.30	74.00	49.50	74.00	46.80	-4.60	-0.80	-2.70	-2.70	1.90	21.16	0.64	7.29
80	76	75.00	50.60	75.00	45.90	75.00	49.20	75.00	48.30	75.00	49.70	75.00	46.80	-4.70	-0.90	-2.90	-2.83	1.90	22.09	0.81	8.41
81	77	76.00	50.80	76.00	45.90	76.00	49.40	76.00	48.30	76.00	49.80	76.00	46.90	-4.90	-1.10	-2.90	-2.97	1.90	24.01	1.21	8.41
82	78	77.00	50.90	77.00	46.00	77.00	49.50	77.00	48.30	77.00	49.90	77.00	46.90	-4.90	-1.20	-3.00	-3.03	1.85	24.01	1.44	9.00
83	79	78.00	51.10	78.00	46.00	78.00	49.60	78.00	48.30	78.00	50.00	78.00	46.90	-5.10	-1.30	-3.10	-3.17	1.90	26.01	1.69	9.61
84	80	79.00	51.20	79.00	46.00	79.00	49.80	79.00	48.40	79.00	50.20	79.00	46.90	-5.20	-1.40	-3.30	-3.30	1.90	27.04	1.96	10.89
85	81	80.00	51.30	80.00	46.00	80.00	49.90	80.00	48.40	80.00	50.50	80.00	47.00	-5.30	-1.50	-3.50	-3.43	1.90	28.09	2.25	12.25

86	82	81.00	51.50	81.00	46.00	81.00	50.10	81.00	48.50	81.00	50.50	81.00	47.00	-5.50	-1.60	-3.50	-3.53	1.95	30.25	2.56	12.25
87	83	82.00	51.60	82.00	46.00	82.00	50.20	82.00	48.80	82.00	50.70	82.00	47.00	-5.60	-1.40	-3.70	-3.57	2.10	31.36	1.96	13.69
88	84	83.00	51.80	83.00	46.00	83.00	50.30	83.00	48.90	83.00	50.80	83.00	47.00	-5.80	-1.40	-3.80	-3.67	2.20	33.64	1.96	14.44
89	85	84.00	52.00	84.00	46.00	84.00	50.40	84.00	49.00	84.00	51.00	84.00	47.00	-6.00	-1.40	-4.00	-3.80	2.31	36.00	1.96	16.00
90	86	85.00	52.10	85.00	46.00	85.00	50.60	85.00	49.10	85.00	51.10	85.00	47.10	-6.10	-1.50	-4.00	-3.87	2.30	37.21	2.25	16.00
91	87	86.00	52.30	86.00	46.00	86.00	50.80	86.00	49.10	86.00	51.30	86.00	47.10	-6.30	-1.70	-4.20	-4.07	2.30	39.69	2.89	17.64
92																		RMSE	2.755267	1.043425	1.680551