SIX LEGGED ROBOT WALKING GAITS

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

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

Faculty of Electrical Engineering
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2015

I declare that this report entitle "Six Legged Robot Walking Gaits" is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :…………………………………………………….

Name : Looi Siew Chin

Date :

To my beloved mother and father

ACKNOWLEDGEMENT

This final year report is made possible through the help and big support from everyone including my supervisor, family and friends.

First and foremost, I would like to thank my supervisor, Dr. Ahmad Zaki bin Haji Shukor for supervised me throughout the whole project. His guidance and advices helped me all the time in doing the project. I also would like to thank to the panels. Finally, I sincerely thank my parents, family, and friends, who provide me advices and supports. The product of this report would not be possible without all of them.

ABSTRACT

Legged robots are used in many applications as they suitable to travel on both even and uneven surface. Six legged robot or hexapod managed to perform well in uneven surface such as space or area after earthquake had happen as it is statically stable in term of its body structure. Six legged robot can walking with different types of gaits and results the different performances of the robot. It is found that six legged robot can perform different task with different algorithms. In order to analyse the effect of different gaits to performance of six legged robot, a single task which is line following is assigned to the robot. In this project, the objectives are to implement line following behaviour to a six legged robot with tripod and wave gaits, analyse the speed of the robot and measure the error from deviation of robot from the line when the robot is moving followed the line. To achieve the objectives in this project, a six legged robot with total of 18 degree of freedom is used. In order to conduct the analysis, the line following algorithm is applied to the robot. Experiments such as the time taken to complete the path to measure speed and the measurement of error deviation between centre of robot and line are carried out to validate the performance of the proposed line following algorithm applied to the robot. By implementing the walking gaits to the robot, the movement of robot"s legs in performing tripod gait and wave gait are observed. Based on the structure of robot, it is found out that joint angles for a single leg should be about 50˚ to allow the robot stand in stable position. The line following behaviour is implemented successfully to the robot by insert the line following circuit. All experimental results are justified with the proposed methodology.

ABSTRAK

Robot berkaki digunakan dalam banyak aplikasi kerana ia sesuai untuk perjalanan di permukaan yang rata atau tidak rata. Robot berkaki enam atau hexapod berjaya menunjukkan prestasi yang baik pada permukaan yang tidak rata dari segi ruang atau kawasan selepas berlaku gempa bumi kerana ia adalah stabil dari segi struktur badannya. Robot berkaki enam boleh berjalan dengan pelbagai gaya berjalan dan menghasilkan prestasi robot yang berbeza. Robot berkaki enam didapati boleh melakukan pelbagai tugas berdasarkan algoritma yang berbeza. Untuk menganalisis kesan gaya berjalan yang berbeza terhadap robot berkaki enam, sebuah tugasan iaitu robot bergerak mengikut garisan telah diberikan kepada robot. Dalam projek ini, objektif adalah untuk melaksanakan kaedah mengikut garisan terhadap robot berkaki enam dengan gaya berjalan tripod dan gaya berjalan gelombang, menganalisis kelajuan robot dan mengukur ralat sisihan antara pusat robot dan garisan apabila robot bergerak mengikut garisan. Demi mencapai objektif dalam projek ini, robot berkaki enam yang mempunyi sebanyak 18 darjah kebebasan telah digunakan. Untuk menjalankan analisis, algoritma bergerak mengikut garisan telah dilaksanakan pada robot tersebut. Eksperimen seperti pengukuran kelajuan robot daripada kiraan masa untuk robot dalam menyelesaikan perjalanan dan pengukuran ralat sisihan antara pusat robot dan garisan telah dijalankan untuk mengesahkan prestasi robot terhadap algoritma bergerak mengikut garisan yang dicadangkan. Dengan melaksanakan gaya berjalan yang berbeza terhadap robot, pergerakan kaki robot dalam gaya berjalan tripod dan gaya berjalan gelombang dapat diperhatikan. Dengan melaksanakan gaya berjalan ke atas robot, pergerakan kaki robot dalam melaksanakan gaya berjalan tripod dan gaya berjalan gelombang dapat dipatuhi. Berdasarkan struktur robot, sudut robot berdiri dalam kedudukan stabil didapati pada sudut 50˚. Robot dapat berjalan mengikut garisan selepas memasukkan litar berkaitan dengan algoritma bergerak mengikut garis. Semua keputusan eksperimen adalah diwajarkan dengan kaedah kajian yang dicadangkan.

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LIST OF ABBREVIATIONS

PWM	-	Pulse width modulation
DOF	-	Degree of freedom
m	-	meter
mm	-	millimetre
Nm	-	Newton per meter
L	-	Length
W	-	Width
H	-	Height
V	-	Volt
g	-	grams
kg/cm	-	kilograms per centimetre
ms	-	milliseconds
cm	-	centimetre
IR	-	infrared
LED	-	light-emitting diode
LDR	-	light-dependent resistor
ADC	-	analog to digital conversion

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

In this chapter, motivation, problem statement, objective and the scope of the project will be presented.

1.1 Motivation

Legged robots have more advantages compared to wheeled robots. Legged robots are suitable for both even and uneven surfaces, while wheeled robots are designed to operate in even surface. Legged robots also help human in exploring the animal locomotion such as study of inserts‟ locomotion from the construction of hexapod robot. Legged robots also manage to avoid obstacles by step over them while wheeled robots only manage to take another path to avoid the obstacles [1]. For legged robot, the stability is increased as the number of legs of robot is increased. Six legged robot also known as hexapod is a robot that is statically stable and can walk in unstructured terrain. According to [1], the hexapod robot concept is used in rescue job where it used to find the earthquake survivors. The hexapod robot designed or also known as Dynamic Autonomous Sprawled Hexapod (DASH) is inspired by structure of cockroach was designed to survive in unstable condition. DASH able to climb between the fallen buildings after earthquake to find survivors as a camera is mounted on the body of robot [1].

Figure 1.1: DASH with wings [1]

Figure 1.1 shows the latest design of DASH which wings are applied on the hexapod robot. The hexapod structure enables DASH to move in uneven terrain and launches the feet on a stable position when descending from a high position [1].

It has different walking gaits that gave it an advantage in performing different kind of applications. However, different walking gaits can formed different locomotions of hexapod although it is performing a same task. Hence, the walking gaits analysis of a hexapod in completing a task is crucial to maintain the well performance of hexapod although different gaits are applied.

1.2 Problem statement

Hexapod has six legs where each leg is actuated by 3 position-controlled servomotors and the control of six legs become complex. Gait planning must be considered well as gait is important to robot locomotion. Based on the previous study, most of the previous researches are done analysis on a single type of walking gait. The analysis are normally done by apply the same type of walking gait in performing different tasks. However, different tasks required different experimental setup and workplace. This is hard to analyse the effect of walking gait to the performance of robot as each of the tasks assigned to the hexapod is carried out in different environment and the variables compared are different. Hence, this project proposed a single task which is the line following task is assigned to hexapod robot. Two types of walking gaits which are tripod gait and wave gait will be implemented to the robot. Since the experimental setup for both walking gaits are same, hence the effect of different walking gaits to the performance of robot can be analyse and compare. Different walking gaits results the change in performance of a hexapod in term of speed of robot to complete the task and accuracy of the body of robot relative to the line while moving.

1.3 Objectives

The objectives for conducting this project are:

1) To implement line following behaviour to the hexapod with tripod gait and wave gait.
2) To analyse the speed and measure the errors from deviation of centre of robot from the line in performing line following task with tripod gait and wave gait.

1.4 Scope

In this project, the six legged robot used in this project has 18 degree of freedom. Each degree of freedom represented by a servo motor with torque value of 2.2kg/cm. The hexapod is designed to perform line following task with two types walking gaits. Two types of walking gaits of hexapod involved in this project are wave gait and tripod gait. The walking surface is on flat surface due to the limitation of degree of freedom on legs and assumption of no leg slipping is made while the robot is moving. In line following task, the robot is set to follow black line with the width of 2.5cm and 8.5cm in a white area. All analysis done on the hexapod is based on one cycle to complete the whole walking line path start from the „START" point and end when the robot reaches „END" point.

CHAPTER 2

LITERATURE REVIEW

This chapter presents about some basic principles and theories involved in the project and review of previous works about the design of six legged robot and the method to analyse its performance as well as some designs of line following robot and method to analyse its performance.

2.1 Theory and basic principle of six legged robot

In this section, the basic principles such as the shape of body and leg structure of six legged robot and types of walking gaits that involved in six legged robot are discussed. The theory involved in analysis of six legged robot will presented in this section as well.

2.1.1 Study of six legged robot

Six legged robot or hexapod robot can be divided into two categories which are rectangular hexapod and hexagonal hexapod. Rectangular hexapod has a rectangular body with two groups of three legs that arranged symmetrically along the two sides of body. Hexagonal hexapod has a hexagonal or circular body with the six legs are placed evenly along the body. The rectangular hexapod is less stable as compared with the hexagonal type [3].

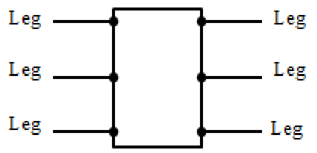


Figure 2.1: The placement of legs for rectangular hexapod [3]

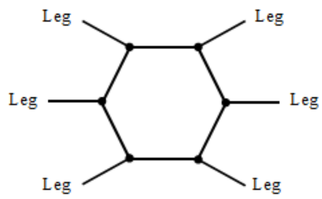


Figure 2.2: The placement of legs for hexagonal hexapod [3]

The construction of the hexapod is inspired by the body structure of insect. There are four main segments for general insect‟s leg which is coxa, femur, tibia and tarsus. From the leg structure of insect, hexapod is created with each leg has 3 degree of freedom.

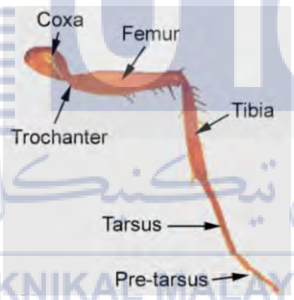


Figure 2.3: Structure of leg for ant [4]

2.1.2 Type of walking gaits for six legged robot

Six legged robot has different types of walking patterns which known as gaits. The types of gaits are classified according to the movement and the number of legs supported the body. The hexapod is considered as statically stable as long as at least three legs are in contact with ground.

2.1.2.1 Tripod gait

Tripod gait is considered as the most well-known gait for a hexapod. In this type of gait, three legs remained on the ground to support while another three legs are lift up and swing to move forward [5].

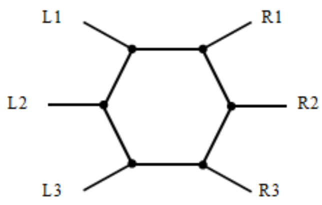


Figure 2.4: The leg arrangement for a hexagonal hexapod

Based on Figure 2.4, when the hexapod is moving forward, L1, L3 and R2 will lift up and swing towards forward, while L2, R1 and R3 will remain on ground and push the body to forward. Another leg configuration can be L2, R1 and R3 raised and swing forward, L1, L3 and R2 remained on ground and push forward.

2.1.2.2 Wave gait

Wave gait is considered as the most stable type of walking gait in hexapod. All legs on one side will move forward, followed by the opposite side. For the walking mechanism, one leg will only lift up on each time, while the other five remained on the ground. Based on Figure 2.5, the robot moves forward by raises up L3, swing forward L3 and put down L3, followed by L2, L1, R3, R2, R1. This type of walking mechanism is based on the movement of an insect to move forward [6].

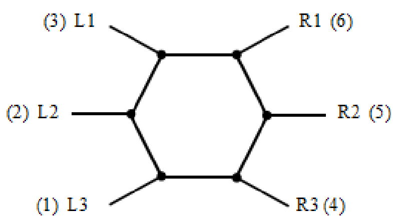


Figure 2.5: The moving sequence of legs in wave gait

2.1.3 Theory involved in analysis of six legged robot

This part describes about the term that used in analysis part of robot.

2.1.3.1 Degree of Freedom

Degree of freedom (DOF) is important in the study of robotics. Degree of freedom can be referred as the ability of an object to move in a single direction independently. The number of degree of freedom is normally known as the number of component required to create motion. The motion generated can be divided into two types which are translational and rotational degree of freedom [7].

2.1.3.2 Stability

Stability is crucial in movement of robot. It can be divided into two types which are static (stand without falling) and dynamic (moving without falling) [8]. Static stability defined as the robot is stable when no motion of robot is required. A robot needs to have a minimum of four legs to achieve static stability. The static stability can be achieved by the mechanical design of the robot which is the structure of the robot itself. Dynamic stability is achieved by control of robot such as the movement of legs of robot [9].

2.1.3.3 Duty factor

Gait can be classified according to its duty factor, β. The duty factor is in range of 0 to 1 and it can be defined as the ratio between leg stand duration and the cycle time [10].

$$\beta = \frac{T_{st}}{T_{st} + T_{sw}} \tag{2.1}$$

where, T_{st} = Duration of foot is standing on ground

T_{sw} = Duration of foot is swinging on air ($T_{sw} + T_{st}$ = total cycle time)

2.1.3.4 Kinematics

Kinematics is the study of motion of object without consider the forces acting on it. There are two types of kinematics which are forward kinematics and inverse kinematics. Forward kinematics is used to determine the position and orientation of the end-effector from all known joint variable. Inverse kinematics is used to calculate the joint angles from the given desired position and orientation. In this project, inverse kinematics is used in order to locate the legs of robot on the desired position.

The formula for link transformation:

$$ {}^{i-1}_{\ i}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & \alpha_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1} d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.2} $$

2.2 Previous related work

This section consists of two parts: review of previous works about six legged robot and review of previous works about line following robot. In the first part, review of previous work is analysed based on the design of hexapod robot, control algorithm, method of modeling for hexapod and the types of analysis involved. In the second part, review of previous work on line following robot is analysed based on the sensor used, line following algorithm as well as the method of analysis involved.

2.2.1 Previous works of six legged robot

2.2.1.1 Design of hexapod robot

According to [11], the hexapod is designed to perform wall following task by using fuzzy controller. Infrared distance sensor is used to measure the distance between wall and robot. The type of gait used in this project is tripod gait.

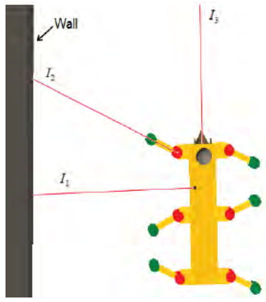


Figure 2.6: Design of hexapod with wall following behaviour [11]

Figure 2.6 shows the placement of three infrared distance sensors on the hexapod robot.

In [12] and [13], line following behaviour is assigned to the hexapod. In [12], based on the design of robot, the line sensor is mounted to the bottom part of robot. The sensors sent digital output to the fuzzy controller to start the line following mode. When the sensors sensed the presence of line, the line following mode is start and generate the servo angles for left and right legs.

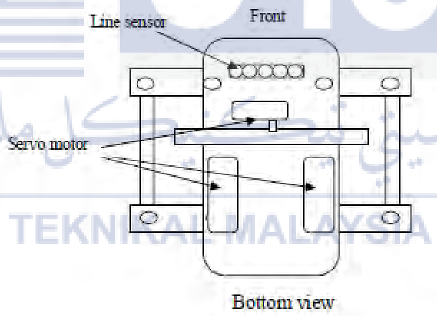


Figure 2.7: Construction of line following hexapod robot [12]

Hexapod robot in [13] used position based controller and image based controller in performing the line following task and tripod gait is applied to the robot.

In [14], [15] and [16], the hexapod used in analysis has a total of 18 DOF. According to [14], a 18 DOF hexapod is designed by using DC motor that supports multiple gaits. Each leg consists of three DC motors and the six legs arranged in circular shape in order the robot can move in omnidirectional.

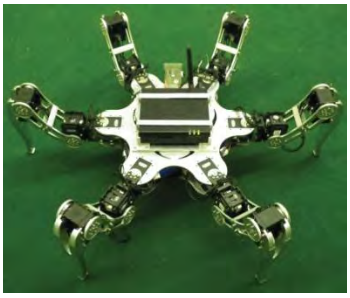


Figure 2.8: 18 DOF hexapod used in [14]

In [15] and [16], each leg of hexapod consists of 3 servo motors and a single type of gait which is tripod gait is implemented to the hexapod robot.

2.2.1.2 Controller algorithm of hexapod robot

In [11], fuzzy controller is used to receive the data from infrared distance sensor and control the swing angle of left and right middle legs to make turn based on the inputs.

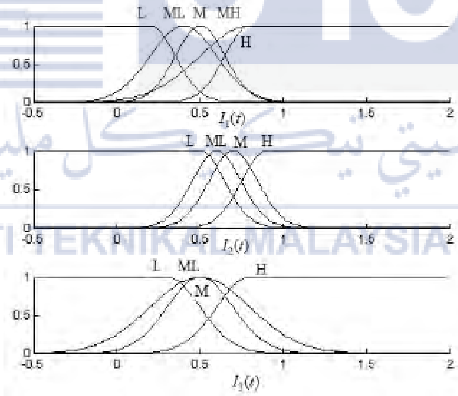


Figure 2.9: Fuzzy sets for each of three inputs [11]

The forward moving of hexapod is controlled by a finite state machine. In this finite state machine, six states are set to ensure the hexapod robot balance on ground and make sure at least three out of six legs of hexapod are on ground when moving.

According to [17], the gait analysis of the hexapod is by using fuzzy reward reinforcement learning. In reinforcement learning algorithm, Q-learning is used to enable the robot learns to walk forward. In reinforcement learning, rules fixed that walking in straight line get better reward. Q-learning does not require model environment and all the values are stored in Q-matrix. The learning starts when all the legs are lifted and the values of joint will sent to the hexapod simulator. Fuzzy reward system is implemented to update the status of Q and the process is repeated until the learning process is completed. The algorithm is applied in the simulator environment and the dynamic model of hexapod is moving to the desired position. In [20], the hexapod is using reinforcement learning to learn the walking gait on unstructured terrain.

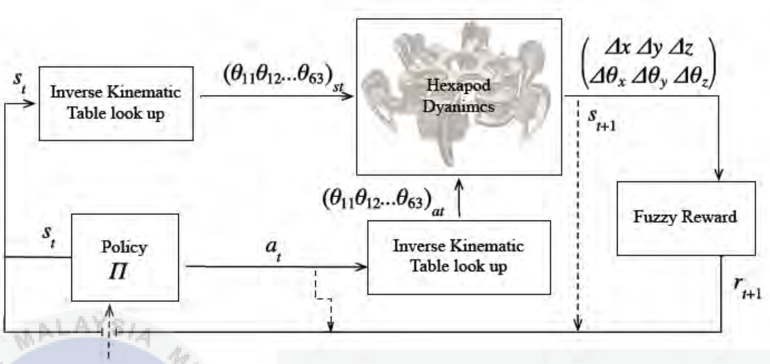


Figure 2.10: Schematic of reinforcement learning algorithm for hexapod [17]

In [15], the hexapod is controlled by using microcontroller called DSP TMS320. The controller design is based on the differential kinematic algorithm where the end-effector for a single leg can track the path that designed.

In [16], the hexapod uses FPGA in control the servomotors by assign PWM to each servomotor. Based on the PWM, each servo motor can be programmed to reach desired position and create the walking gait.

2.2.1.3 Method of modeling for hexapod

In [15] and [19], forward kinematic is used to design the mathematic modeling for a single leg of hexapod. In this case, the Denavit Hartenberg notation (DH parameter) is used to determine the coordinates of leg. By using DH parameter, the homogeneous transformation matrix is obtained as shown in equation (2.3) and (2.4).

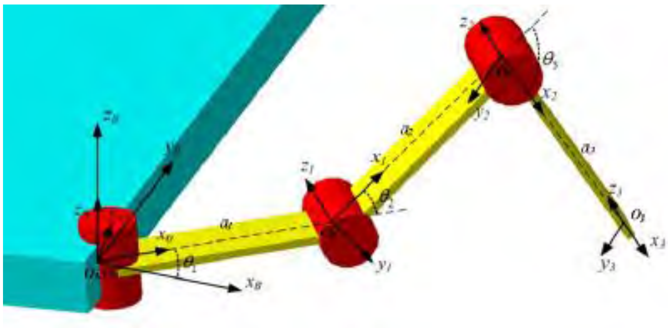


Figure 2.11: Configuration of single leg [14]

$$ {}^{0}_{3}T = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T \tag{2.3}$$

$$ {}^{0}_{3}T = \begin{bmatrix} c_1c_{23} & -c_1s_{23} & s_1 & c_1(a_1 + a_2c_2 + a_3c_{23}) \\ s_1c_{23} & -s_1s_{23} & -c_1 & s_1(a_1 + a_2c_2 + a_3c_{23}) \\ s_{23} & c_{23} & 0 & a_3s_{23} + a_2s_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.4}$$

In [20], Denavit-Hartenberg algorithm is used to create the model of robot in Matlab environment. In this research, the position of centre of mass of leg is found by using DH transformation. The position of centre of mass for the leg can be calculated by using equation (2.5).

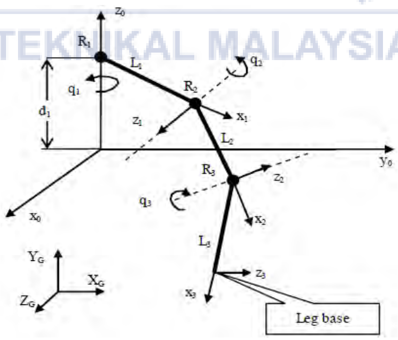


Figure 2.12: Coordinate frame of kinematics for a single leg [20]

$$ x_g = \frac{\sum_{i=1}^{3} x_i m_{li}}{\sum_{i=1}^{3} m_{li}}, y_g = \frac{\sum_{i=1}^{3} y_i m_{li}}{\sum_{i=1}^{3} m_{li}}, z_g = \frac{\sum_{i=1}^{3} z_i m_{li}}{\sum_{i=1}^{3} m_{li}} \tag{2.5}$$

where m_{li} = mass of link i

2.2.1.4 Analysis on performance of hexapod

In [14], [18], [19], [20] and [21], analysis done on the performance of hexapod is in term of stability. In [14], Inertial Measurement Unit (IMU) is attached to robot to measure its stability when performing different types of gaits. In [18], the stability of the hexapod is analysed by remove single leg of hexapod. In this research, the ability of the hexapod in walking without 1 leg is analysed and the observations are categorised into stable condition, marginally stable condition and unstable condition. [19] and [20] proposed the turning angle of servo motors or maximum reachable area for each legs of hexapod in determine the stability. Based on the results obtained, it is proved that tripod gait is statically stable as the centre of robot body is inside the stability polygon. In [21], a virtual hexapod robot is controlled by using Matlab to measure the stability of robot for a certain leg configuration. Two types of analysis are carried out to measure the stability of hexapod. The first one is free fall analysis where the robot left to fall from a height that beyond the extension of leg, while transitory analysis is the analysis when the robot went through two static routines.

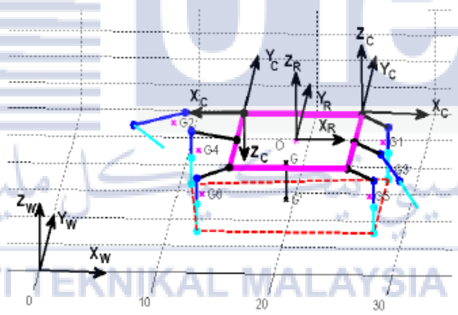


Figure 2.13: Virtual model of hexapod in Matlab [21]

[14], [15] and [16] analyse the performance of hexapod robot by analyse the output of actuator used with the applied gaits. In [14], the torque readings of each leg are recorded and shown in its Graphical User Interface (GUI). From the torque reading, the movement of leg in perform the tripod gait can be observed as shown in Figure 2.14.

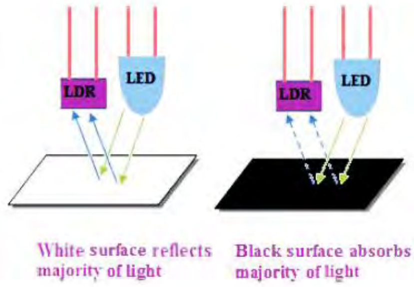


Figure 2.15: Arrangement of sensor [24]

2.2.2.2 Line following algorithm

In [22] and [24], the line path is black in colour and the ground colour is white. In [23], the line path is white colour and the ground colour is black. The robot used eight infrared sensors and placed it on bottom of robot to detect the line and the position of each sensor is shown in Figure 2.16 [22].

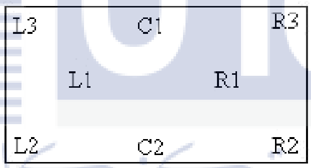


Figure 2.16: Position of sensors [22]

Sensors L1, L2 and L3 indicate left position, C1 and C2 sensors indicate central position while sensors R1, R2 and R3 indicate right position and sensors L1, L2 and L3 indicate left position.

In [23], five IR sensors are used to detect the light. All the sensors are arranged in series as shown in Figure 2.17.

Sensor1	Sensor2	Sensor3	Sensor4	Sensor5
LeftMost	Left	middle	right	rightMost

Figure 2.17: Arrangement of sensors [23]

According to Figure 2.17, if Sensor 1 or combination of Sensor 2 and Sensor 3 detect the line, the robot will rotate left. If Sensor 2 or Sensor 3 or Sensor 4 detect the line, the robot will move straight. If combination of Sensor 3 and Sensor 4 or Sensor 5 detect the line, the robot will rotate right.

In [24], the value of sensor is produced by using resistance of sensors and voltage divider. Two pairs of sensors are used in the control algorithm. The line following algorithm can divided into 4 parts:

a) When $V_1<V_{Ref}$ and $V_2<V_{Ref}$, the robot will stop.
b) When $V_1<V_{Ref}$ and $V_2>V_{Ref}$, the robot will rotate right.
c) When $V_1>V_{Ref}$ and $V_2<V_{Ref}$, the robot will rotate left.
d) When $V_1>V_{Ref}$ and $V_2>V_{Ref}$, the robot will move forward.

2.2.2.3 Method to analyse performance of line following robot

In [22], the robot is tested with different curve and cycle with different angles as shown in Figure 2.18. In [24], the robot is tested with different turning angle and discovered that robot able to perform well with minimum turning angle of 110˚.

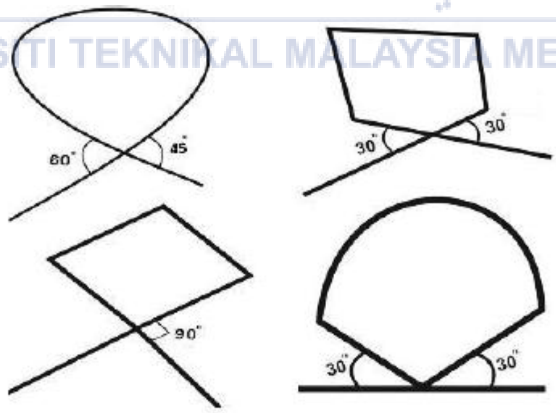


Figure 2.19: Different curve and cycle [22]

According to [23], ADC value of all sensors against cycle number are measured and shown in graph form. Besides that, the PWM of both left and right motors against cycle are observed as well.

2.3 Summary

Table 2.1 shows the comparison on the design of hexapod robot, control algorithm, method of modeling and the respective way of analysis from the previous related works.

Table 2.1: Comparison of the types of design of hexapod and the performance test

Title	**Design of hexapod**				**Controller algorithm**	**Method of modeling**	**Analysis on performance of hexapod**
	DOF of robot	**Actuator**	**Sensor**	**Type of gait**			
Hexapod robot wall-following control using a fuzzy controller [11]	12	Servo motors	Infrared distance sensor	Tripod gait	Fuzzy controller	-	Output of actuator to verify the implementation of gait to robot (position of leg for robot when perform wall following task)
Line and wall follower hexapod robot [12]	6	Servo motors	Line sensor	Free gait	Fuzzy logic controller	-	Movement of hexapod
Inertial navigation and visual line following for a dynamical hexapod robot [13]	6	Servo motors	Visual sensor and on board inertia	Tripod gait	Inertia-guided controller	-	Speed of robot in perform walking, jogging and running

The development of a remote controlled, omnidirectional six legged walker with feedback [14]	18	DC motors with encoders	-	Tripod and wave gaits	FIT-PC2	-	1) Output of actuator to verify the implementation of gait to robot (torque reading of DC motor) 2) Stability
Path tracking controller design of hexapod robot for omni-directional gaits [15]	18	Servo motors	-	Tripod gait	Path tracking controller	Denavit Hartenberg notation	Output of actuator to verify the implementation of gait to robot (joint angle of each leg)
PWM controller design of a hexapod robot using FPGA [16]	18	Servo motors	-	Tripod gait	FPGA controller	-	Output of actuator to verify the implementation of gait to robot (PWM for each servo motor)
Gait analysis of a six-legged walking robot using fuzzy reward reinforcement learning [17]	18	Servo motors	-	Free gait	Fuzzy reward and reinforcement study	-	Movement of robot

Analysis and evaluation of the stability of a biologically inspired, leg loss tolerant gait for six- and eight-legged walking [18]	18	-	-	Wave gait	Cruse‟s mechanism (all six legs is inter-related and when a leg is lost, another leg will actuate to cover the loss of leg)	-	1) Movement of robot 2) Stability
Tripod gaits planning and kinematics analysis of a hexapod robot [19]	18	Servo motors	-	Tripod gait	Kinematic control	Denavit Hartenberg notation	Turning angle of servo motors and maximum reachable area for each legs of hexapod
Model of the signal processing and decision making process of hexapods with static-stable walking [20]	-	Servo motors	-	Acyclic gait	Fuzzy reinforcement learning	-	Maximum reachable area for each legs of hexapod
Hexapod robot. virtual models for preliminary studies [21]	18	-	-	Free gait	In Matlab environment and Arduino Duemilanove	Denavit Hartenberg algorithm	Stability

Table 2.2 shows the comparison on the design of line following robot in term of its type of sensor used and line following algorithm as well as the method to analyse the performance of robot.

Table 2.2: Comparison of line following robot and the performance test

Title	**Type of sensor used**	**Line following algorithm**			**Analysis on performance of robot**
		Colour of line	**Amount of sensors used**	**Control algorithm**	
A Line Follower Robot from design to Implementation: Technical issues and problems [22]	IR sensors	Black	8 sensors	3 sensors indicated left, 2 sensors indicated central, 3 sensors indicated right	Different curve with different angles
Line Follower Robot: Fabrication and accuracy measurement by data acquisition [23]	IR sensors	White	5 sensors	S1 or S2&S3 detect line – left S2 or S3 or S4 detect line – straight S3&S4 or S5 detect line – right	ADC value of sensors and PWM of motors
Implementation Of Autonomous Line Follower Robot [24]	LED and LDR	Black	2 pairs	$V_1<V_{Ref}$ & $V_2<V_{Ref}$ – stop $V_1<V_{Ref}$ & $V_2>V_{Ref}$ – right $V_1>V_{Ref}$ & $V_2<V_{Ref}$ – left $V_1>V_{Ref}$ & $V_2>V_{Ref}$ – forward	Different turning angles

Based on Table 2.1, it shows that most of the six legged robot is designed to have total of 18 DOF with 3 DOF on each leg. This is because the construction of six legged robot is based on the insect‟s locomotion and most of the insects have three DOF for their single leg structure. Servo motors are commonly used in six legged robot to create the movement as its position can be controlled by angles. Based on Table 2.1, two types of walking gaits which are tripod gait and wave gait are commonly used in analysis of gaits. Free gait or acyclic gait is not suitable to use as the movement of legs are not fixed as the legs move randomly. Table 2.1 also shows that fuzzy control is commonly used in control the hexapod as it applied fuzzy rule that can interpreted by human and fuzzy can be designed without knowing the mathematical models of the robot. The modeling of robot is commonly use Denavit Hartenberg notation as it can be used to determine the coordinates of the end effector of robot based on joint angles or determine the joint angles based on the position of end effector of robot. For the analysis of performance of robot, stability and movement of robot are the most common parameters used to analyse.

Based on Table 2.2, it shows that most common sensor used in line detection is IR sensor as LDR sensor requires comparator to compare the analogue signal. Most of the line following path is black in colour and the ground is white colour. Besides that, more than 3 sensors is used in line detection to provide the more accurate detection. For the line following algorithm, if IR sensors are used, the central sensor functions as indicator for robot to move forward, while left sensors and right sensors are indicators for the robot to turn left and right respectively. If LDR sensors are used, the voltage across the LDR sensors will be compared and output made based on the comparison of voltage level. For the analysis of performance of line following algorithm, different turning angles is the most common parameter used to analyse.

2.4 Conclusion

In summary, the basic principles such as the background study of six legged robot and some theory involved in analysis are presented in this chapter. Several previous works are analysed and the comparison of all design of six legged robot is shown in Table 2.1 while Table 2.2 shows the comparison of different line following algorithm. Based on Table 2.1 and Table 2.2, the results from comparison are discussed and evaluated.

CHAPTER 3

METHODOLOGY

In this chapter, the methodology to achieve the objectives of the project is discussed. This chapter covers about implementation of line following behaviour to the six legged robot with two types of gaits and method to perform the analysis on its performance. Figure 3.1 shows the overall methodology to achieve the objectives of project.

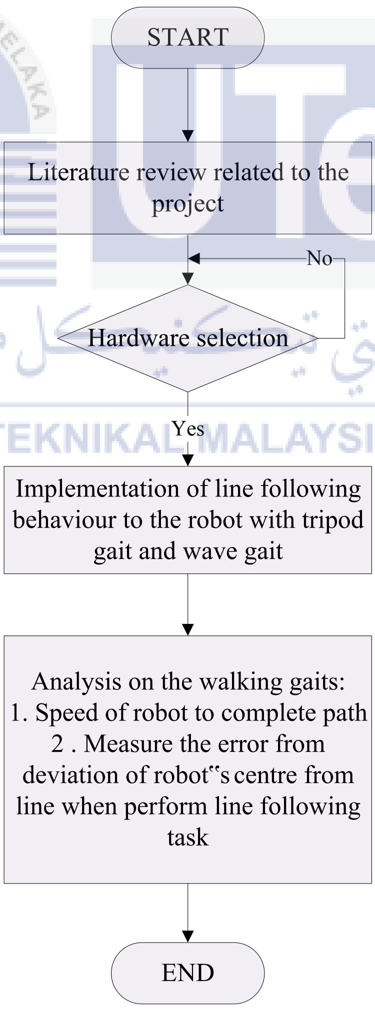


Figure 3.1: Flow chart for methodology (overall)

3.1 Project methodology to achieve first objective

This section discuss about the project methodology to achieve the first objective which is to implement line following behaviour to hexapod with tripod gait and wave gait.

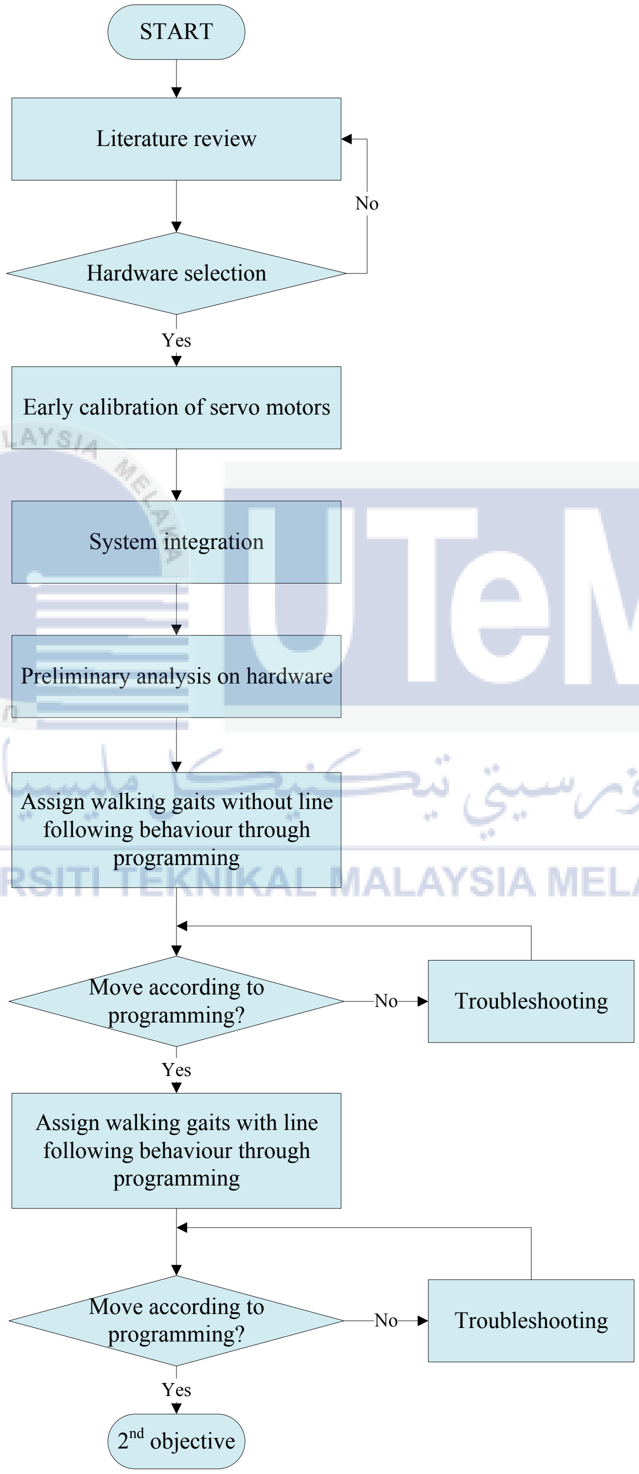


Figure 3.2: Project methodology flowchart to achieve objective 1

3.1.1 Hardware selection

This part discussed about the selection of hardware and the results for the hardware selection.

3.1.1.1 Comparison different design of hexapod hardware

Table 3.1: Comparison different design of hexapod hardware

Design of hexapod	**Design 1 [25]**	**Design 2 [26]**	**Design 3 [27]**	**Design 4 [28]**
Shape of hexapod	Rectangular	Hexagonal	Hexagonal	Rectangular
Degree of freedom	6	12	18	18
Actuator	6 DC motors	12 heavy duty servo motors	18 9g servos	18 Hitec 645MG servos
Controller	Advanced Motion Controls DZRALTE-020L080	EZ-B v4 WiFi Robot Controller	Full arduino based Servotor32 robot controller	BotBoarduino + SSC-32 Servo Controller
Advantages	> Small in size > Simple to control as the trajectories of legs are fixed	> Able to move in different direction > Able to perform various type of gaits	> No external microcontroller is needed > Able to perform various type of gaits	> Able to move in different direction > Able to perform various type of gaits

Based on Table 3.1, six legged robot with 18 DOF is selected as it is most similar to insect‟s leg structure (coxa, femur and tibia). Hexagonal shape type hexapod has structure of all the six legs arranged radially and allowed the robot to move in omnidirection. Based on these two criteria, Design 3 hexapod is chosen as it is hexagonal in shape with 18 DOF. Its controller is a servo controller that consists of Arduino chip, so the programs can write in Arduino format and execute without additional microcontroller, and servo motors are used to allow the generation of different walking gaits. Besides that, small size of servo motors and medium torque value results the weight of robot is lighter and more smooth in walking.

3.1.1.2 Hardware used in project

Figure 3.3: Six legged robot used in project

Figure 3.3 shows the robot of Design 3 is selected based on the results of comparison. It has total of 18 DOF with 3 DOF on each leg. The material for body construction is acrylic material. The controller used is a full Arduino based Servotor32 controller which can control up to 32 servo motors [27]. Hence, the program can written in Arduino environment.

Figure 3.4: Servotor32 controller

Specification for Servotor32 controller: [29]

a) Atmega32u4 Processor @16mhz

b) 32 servo pins

c) Ultrasonic distance sensing module plug

d) Slot for bluetooth-serial converter

e) 8 extra analog inputs

f) 14 digital I/O pins

The servo motors used for the selected hardware design is a 9g mini servo motors. The connection of servo motor is shown in Figure 3.5. The red wire is connected to power supply, which is 5V, brown wire is connected to ground, and the orange wire is connected to the signal which is the output of the Servotor32.

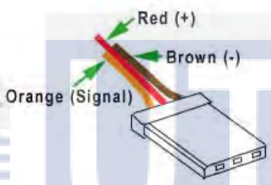


Figure 3.5: Connection of servo motor [30]

Table 3.2: Specifications of servo motor used [31]

Specifications	Value / unit
Dimension (LxWxH)	22 x 12 x 22 mm
Weight	9 g
Stall torque at 4.8V	2.2 kg/cm
Operating voltage	4 to 6V
Operating speed at 4.8V (no load)	247.65 mm
Material	Carbon fiber gears

Figure 3.7 shows the structure of hexapod before assembly. The parts are later attached with 3 servo motors to form a leg of the robot as shown in Figure 3.8.

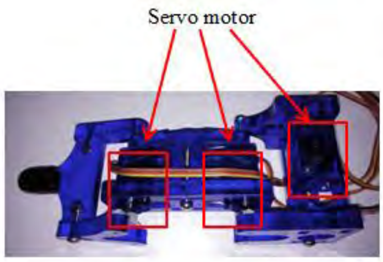


Figure 3.8: Leg of robot

After all the six legs are finish assembled, the legs are attached to the body of robot. When the structure of robot is done, Servotor32 controller is attached to the robot. Before insert the programming to controller, driver for Servotor32 controller is required to install to power the controller.

3.1.3.2 Construction of robot with line following behaviour

The line following circuit is added to the six legged robot to allow it to perform line following task. Figure 3.9 shows the block diagram for the line following circuit that consists of input and output parts.

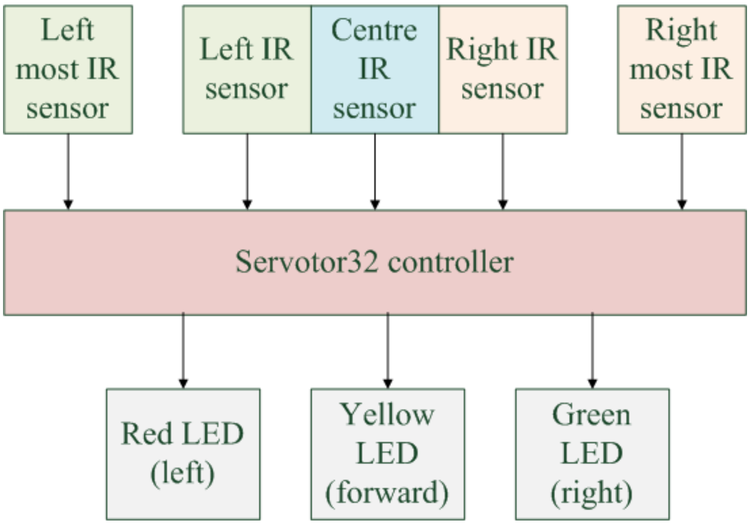


Figure 3.9: Block diagram of line following task

In the circuit design, the input part consists of five IR sensors that attached on the base of the six legged robot as shown in Figure 3.10. The IR sensors use to detect the presence of line and send its outputs to Servotor32 controller. The output part consists of three different colour of LEDs that indicate the direction of robot moves according to the line following algorithm.

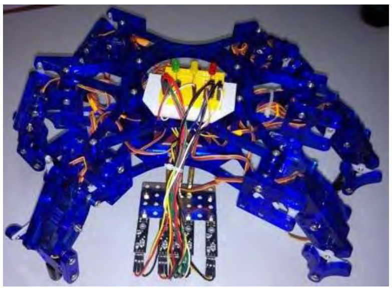


Figure 3.10: Six legged robot after implemented line following circuit

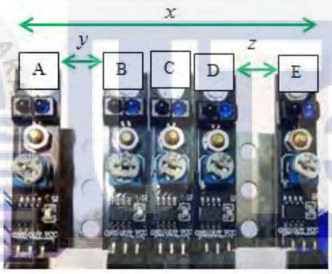


Figure 3.11: Position of IR sensors

The IR sensors selected to use in this project produces digital signal: HIGH (detect black surface) and LOW (detect white surface). The base to attach the IR sensors has a width, *x* of 7cm which is the same width with the base of robot. The IR sensors are placed on the front of robot, which is 8cm from the centre of robot. Both distance between sensor A and sensor B, *y* and distance between sensor D and sensor E, *z* are same, which is 1cm. A is the left most IR sensor, B is the left IR sensor, C is the centre IR sensor, D is the right sensor and E is the right most sensor.

3.1.4 Preliminary analysis on hardware

The preliminary analysis of hardware is about the inverse kinematics and the size of moveable area of the leg of robot before the line following behaviour is implemented to the robot.

3.1.4.1 Inverse kinematics

Based on the hardware, the calculation of inverse kinematics for a single leg can be obtained.

The rotations of servo motors are crucial to ensure smooth walking gaits for robot. Hence, joint angles are required to determine to rotate the servo motors rotate to the desired position. Inverse kinematics is used in determine the joint angles as the desired position and orientation of the legs are known. Figure 3.12 shows the leg structure of six legged robot when it is in standby position.

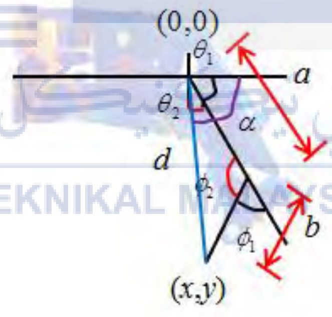


Figure 3.12: Leg structure of robot

Calculation of joint angles for single leg:

θ_1: Angle of knee

ϕ_1: Angle of ankle

a = distance of joint from knee to ankle = 50mm,

b = distance of joint from ankle until the point touch ground = 54mm

d = resultant distance of a and b

(x,y) = desired position

To calculate d,

$$d = \sqrt{x^2 + y^2} \tag{3.1}$$

From Figure 3.12,

$$\phi_1 = 180° - \phi_2 \tag{3.2}$$

By using cosine rule,

$$\cos\phi_2 = \frac{a^2 + b^2 - d^2}{2ab} \tag{3.3}$$

$$\sin\phi_2 = \sqrt{1 - \cos^2\phi_2} \tag{3.4}$$

Let $D = \cos\phi_2$,

$$\sin\phi_2 = \pm\sqrt{1 - D^2} \tag{3.5}$$

To obtain ϕ_2,

(3.5) / (3.3),

$$\tan\phi_2 = \frac{\pm\sqrt{1 - D^2}}{D} \tag{3.6}$$

$$\phi_2 = \tan^{-1}\frac{\pm\sqrt{1 - D^2}}{D} \tag{3.7}$$

To obtain ϕ_1,

Sub. (3.7) into (3.2),

$$\phi_1 = 180° - \tan^{-1}\frac{\pm\sqrt{1 - D^2}}{D} \tag{3.8}$$

From Figure 3.12,

$$\theta_1 = \alpha - \theta_2 \tag{3.9}$$

To obtain α,

$$\alpha = \tan^{-1}\frac{y}{x} \tag{3.10}$$

To calculate θ_2,

$$\tan\theta_2 = \frac{b\sin\phi_1}{a + b\cos\phi_1} \tag{3.11}$$

$$\theta_2 = \tan^{-1}\frac{54\sin\phi_1}{50 + 54\cos\phi_1} \tag{3.12}$$

To obtain θ_1,

Sub. (3.9) and (3.12) into (3.9),

$$\theta_1 = \tan^{-1}\frac{y}{x} - \tan^{-1}\frac{54\sin\phi_1}{50+54\cos\phi_1} \tag{3.13}$$

3.1.4.2 Size of moveable area of leg

The size or area that the leg able to move is needed to determine before the programming is implemented to the robot to avoid the collision between a leg with another leg of robot when moving. Each leg has a moveable area in loop shape of maximum radius. In this case, a leg is used to analyse as the structure for the remaining five legs are the same.

According to [32],

r_{max} = radius for maximum reachable area of robot‟s leg

r_{min} = radius for minimum reachable area of robot‟s leg

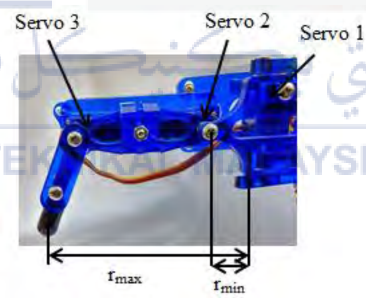


Figure 3.13: The maximum and minimum radius for reachable area of robot‟s leg

The measurements for the radius for both minimum and maximum reachable area are shown in Figure 3.13. r_{max} is measured from the centre of Servo 1 to the part of the leg that touches the ground, r_{min} is measured from the centre of Servo 1 to centre of Servo 2. The actual moveable area of leg is fall in the region between minimum and maximum reachable area.

3.1.5 Programming for six legged robot

In this part, the programming for the robot can be divided into 2 parts where first part is the implementation of tripod gait and wave gait to the robot to observe the movement of robot correspond to the assigned gaits. The second part of the programming is to implement the line following algorithm together with the assigned gaits to allow the robot has line following behaviour.

3.1.5.1 Gait generator

To generate the position and motion of the six legged robot, “PoMoCo – Position and Motion Controller Software” is used. In this project, PoMoCo software provides a Python environment to program the movement of the robot‟s legs and produces the position to turn for each servo motor involved after execute the program.

Calculation of rotation angle from position of servos to turn:

$$\theta = 180\left[\frac{\theta_p - 600}{1800}\right] - 90 \tag{3.14}$$

where, $\theta =$ rotation angle of servos in range of -90˚ to 90˚

$\theta_p =$ position of servos to turn

Table 3.3: Calculation of rotation angle of servo motor from the position to turn

Position of servos to turn	600	1500	2400
Rotation angle of servo	-90˚	0˚	+90˚
Rotation of servo motor	90˚ counter clockwise (maximum displacement to counter clockwise direction)	Centre	90˚ clockwise (maximum displacement to clockwise direction)

3.1.5.2 Implementation of walking gaits to robot with line following behaviour

After the line following circuit is applied on the robot, the line following algorithm is designed as shown in Table 3.4.

Table 3.4: Line following algorithm

IR sensor					Output
Left most (1)	Left (2)	Centre (3)	Right (4)	Right most (5)	
1	/	/	/	0	Rotate left
0	1	0	0	0	
0	0	1	0	0	Move straight
0	1	1	0	0	
0	0	1	1	0	
0	/	/	/	1	Rotate right
0	0	0	1	0	
1	1	1	1	1	Stop
0	0	0	0	0	Reset

Based on Table 3.4, „1‟ indicates the IR sensor detect the line (black) and gives output as HIGH, „0‟ indicates the IR sensor does not detect the line (white surface) and produces LOW output and „/‟ indicates the condition where the outputs of IR sensors can be either HIGH or LOW.

3.2 Project methodology for Final Year Project to achieve second objective

This section discuss about the project methodology to achieve the second objective which is to analyse the performance of robot in performing line following task with different gaits.

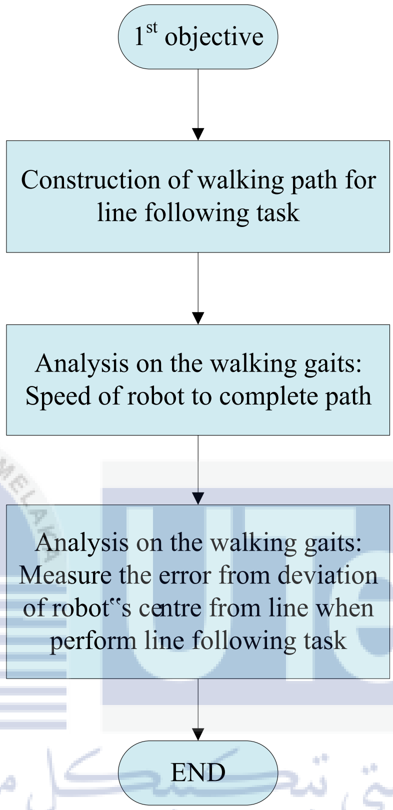


Figure 3.14: Project methodology flowchart to achieve second objective

3.2.1 Construction of walking path for line following task

In order to perform the analysis, different line following paths which are straight line path and three different paths with different turning angles are designed for the robot as shown in Figure 3.15 and Figure 3.16.

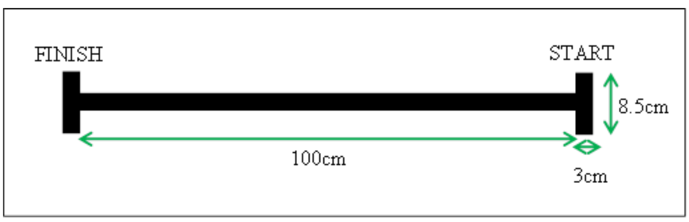


Figure 3.15: Straight line path for robot

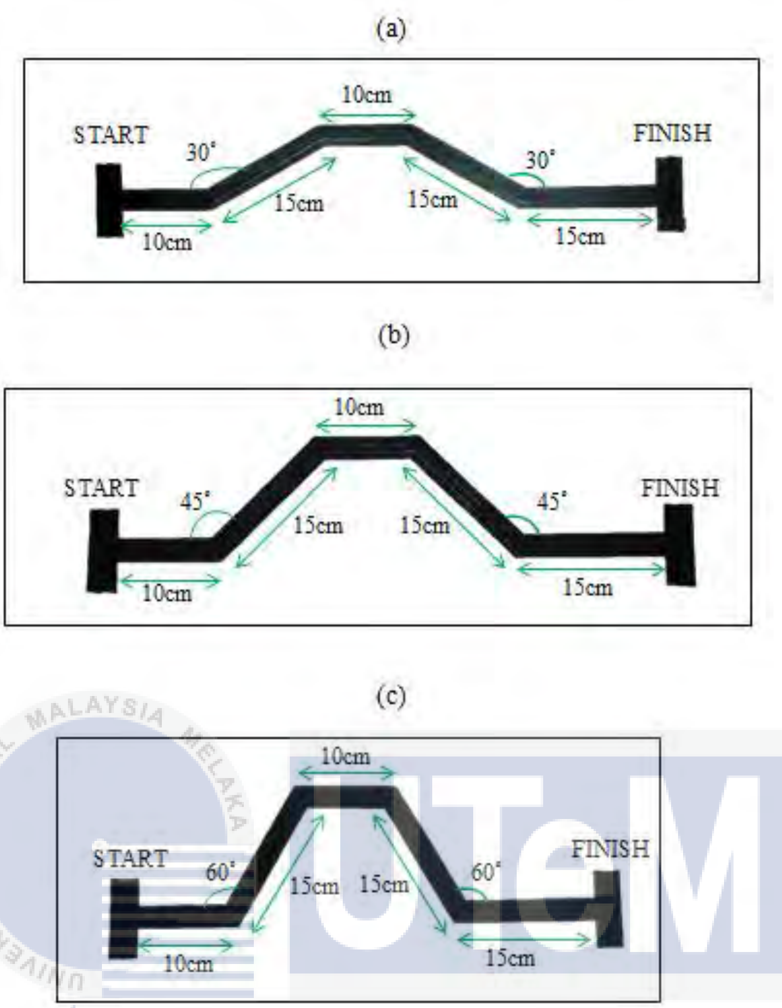


Figure 3.16: (a) Path with turning angle of 30˚, (b) Path with turning angle of 45˚, (c) Path with turning angle of 60˚

3.2.2 Analysis on speed of robot to complete line following task with tripod and wave gaits

This analysis is done to measure the time taken for the hexapod to complete the walking path for one cycle. Since the walking path for both gaits are the same, indirectly the speed of robot can be obtained. The analysis of the speed is conducted to analyse the performance of tripod and wave gait in moving straight and turning in term of the speed.

For the moving straight analysis, the robot is required to complete a 100cm straight line path. For the turning analysis, the length of path is 65cm and 3 turning angles are tested which are 30˚, 45˚ and 60˚. The time is started to take when robot is started moving from "START" point and stop when the robot is reached "END" point. To reduce the error, each experiment is carried out for five times and the average value is calculated. The results obtained are recorded in Table 3.5 and Table 3.6.

Table 3.5: Results for time taken to complete 1 cycle (move straight)

Types of walking gaits	Time taken to complete one cycle, t (s)					
	t_1	t_2	t_3	t_4	t_5	t_{ave}
Tripod gait						
Wave gait						

Table 3.6: Results for time taken to complete 1 cycle (turning at different angles)

Turning angle	Time taken to complete one cycle, t (s)											
	Tripod gait						Wave gait					
	t_1	t_2	t_3	t_4	t_5	t_{ave}	t_1	t_2	t_3	t_4	t_5	t_{ave}
30˚												
45˚												
60˚												

By using equation (3.15), the speed of robot, v can be calculated.

$$v = \frac{s}{t_{ave}} \tag{3.15}$$

where, s = total distance of the walking path, t_{ave} = average time taken to complete path

3.2.3 Analysis on measurement of errors from deviation of centre of robot from the line in performing line following task with tripod and wave gaits

This analysis is carried out to examine the performance of robot in term of measuring error when it is performing the line following task for both straight line path and turning path. The errors are measured from deviation of centre of robot from the line.

To measure the error, an LDR circuit is designed as shown in Figure 3.17 and attached to the base of robot.

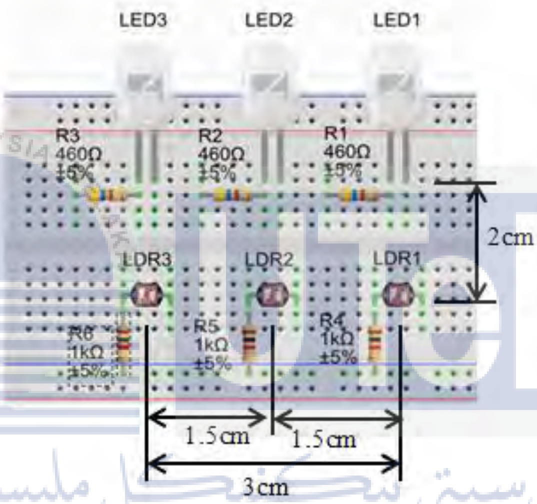


Figure 3.17: LDR circuit

The LDR circuit is connected and the LDR values can be read from Arduino serial monitor. Each LDR is illuminated with a super bright LED light to allow LDR to differentiate the white colour ground and black colour path. LDR 1 represented the left most boundary of line, LDR 2 represented as the centre and LDR 3 represented as the right most boundary of line. The algorithm as shown in Table 3.7 and Table 3.8 are used to analyse the result when conducting the analysis. The algorithm is based on the comparison of LDR values between LDR 1, LDR 2 and LDR 3.

Table 3.7: Algorithm of LDR circuit in differentiate the error (centre of robot fall on line)

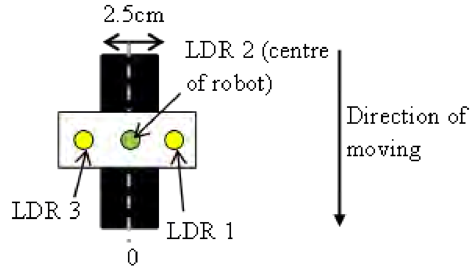
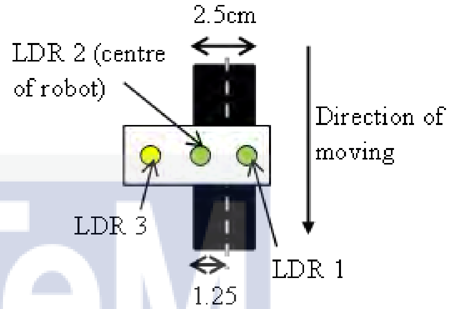
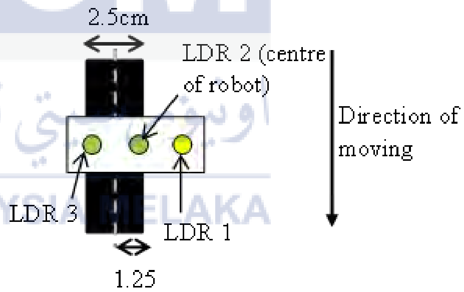
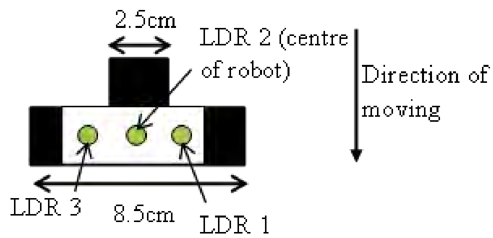
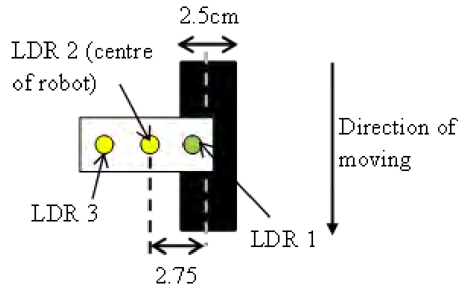
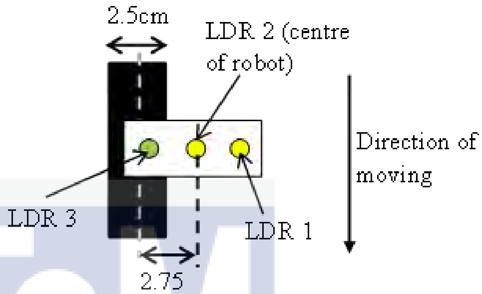
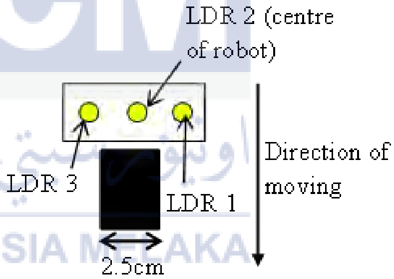
LDR value			Position of robot on/from line	Range of error from deviation of centre of robot from line, x	Illustration of position of centre of robot to line
LDR 1	LDR 2	LDR 3			
high	low	high	Centre of robot on centre of line	0	 Figure 3.18: Centre on line
low	low	high	Centre of robot on right side of line	$0<x<1.25$	 Figure 3.19: Centre on line
high	low	low	Centre of robot on left side of line	$-1.25<x<0$	 Figure 3.20: Centre on line
low	low	low	Centre of robot on line (robot in static position)	-	 Figure 3.21: Centre on line

Table 3.8: Algorithm of LDR circuit in differentiate the error (centre of robot out from line)

LDR			Presence of line from centre of robot	Range of error from deviation of centre of robot from line, x	Illustration of position of centre of robot to line
LDR 1	LDR 2	LDR 3			
low	high	high	Centre of robot on right side (out from line)	$1.25<x<2.75$	 Figure 3.22: Centre out from line
high	high	low	Centre of robot on left side (out from line)	$-2.75<x<-1.25$	 Figure 3.23: Centre out from line
high	high	high	Centre of robot out from line (robot in static position)	-	 Figure 3.24: Centre out from line

Based on the range of error from deviation of centre of robot from centre of line, a diagram of position of centre of robot with respect to line is plotted and the results obtained recorded in Table 3.9.

Table 3.9: Number of occurrence of centre of robot at different location on or out from line

Position	Inside line			Out from line		Start / End
	Left	Centre	Right	Left	Right	
Number of occurrence of centre of robot, n						
Percentage of error occurred, P (out from line)						

By using equation (3.16), the percentage of errors (centre of robot is lies out from the line), P can be calculated

$$P = \frac{n_{out(left)} + n_{out(right)}}{n_{in(left)} + n_{in(centre)} + n_{in(right)}} \tag{3.16}$$

where $n_{out(left)}$ = Number of occurrence of centre of robot at outside of line (left)

$n_{out(right)}$ = Number of occurrence of centre of robot at outside of line (right)

$n_{in(left)}$ = Number of occurrence of centre of robot in line (left)

$n_{in(centre)}$ = Number of occurrence of centre of robot in line (centre)

$n_{in(right)}$ = Number of occurrence of centre of robot in line (right)

3.3 Conclusion

In summary, this project is started with the selection of hardware to choose the most suitable hardware design, actuator and controller to use. After the hardware selection, some preliminary analysis such as finding the size of moveable area of robot‟s leg and inverse kinematics are done on the robot. The project is proceeded with the implementation of line following behaviour to the robot with tripod and wave gaits and analysis on the performance of the robot to achieve the objectives.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter covers about the results of each of the achieved objectives and data obtained from the methodology will be discuss in this chapter as well.

4.1 Preliminary analysis on hardware

This section is about the analysis on the six legged robot which covers about the inverse kinematics that used to find the joint angles and size of moveable area of leg. The preliminary analysis is done to determine the limitation of robot before the implementation of walking gaits.

4.1.1 Inverse kinematics

The inverse kinematics is used to calculate joint angle at knee and ankle on a single leg to allow the robot to stand in stable condition.

The variable used in calculation of angle of knee and angle of ankle:

θ_1: Angle of knee

ϕ_1: Angle of ankle

a = distance of joint from knee to ankle = 50mm,

b = distance of joint from ankle until the point touch ground = 54mm

d = resultant distance of a and b

(x,y) = desired position

Before find the joint angle, the position of the end-effector of leg is determined.

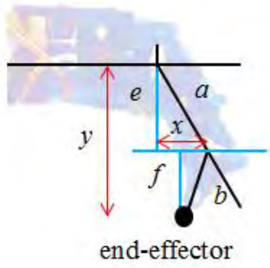


Figure 4.1: Joint variable on a single leg

To obtain the most stable position, the position of end-effector of leg is chosen at the centre of joint length from knee to ankle, x = 25mm.

To calculate y,

$$e = \sqrt{a^2 - x^2} \tag{4.1}$$

$$e = \sqrt{50^2 - 25^2} = 43.3mm$$

$$f = \sqrt{b^2 - x^2} \tag{4.2}$$

$$f = \sqrt{54^2 - 25^2} = 47.86mm$$

$$y = e + f = 43.3 + 47.86 = 91.16mm \tag{4.3}$$

To enable the robot to stand in stable condition, position of end-effector of leg,

x = 25 mm, y = 91.16 mm

Using equation (3.1),

$$d = \sqrt{25^2 + 91.16^2}$$

$$d = 94.5259mm$$

Using equation (3.3),

$$\cos\phi_2 = \frac{50^2 + 54^2 - 94.5259^2}{2(50)(54)}$$

$$\cos\phi_2 = -0.6517$$

To obtain ϕ_1, equation (3.8) is used,

$$\phi_1 = 180° - \tan^{-1}\frac{\pm\sqrt{1-(-0.6517)^2}}{-0.6517}$$

$$\phi_1 = 49.33°$$

$$\phi_1 \approx 50°$$

To obtain θ_1,

Sub. $\phi_1 = 49.33°$ into equation (3.13),

$$\theta_1 = \tan^{-1}\frac{91.16}{25} - \tan^{-1}\frac{54\sin 49.33°}{50+54\cos 49.44°}$$

$$\theta_1 = 48.97°$$

$$\theta_1 \approx 50°$$

Hence, to achieve the stable standing position, both angle for knee and angle for ankle should be rotate 50˚.

4.1.2 Size of moveable area of leg

The measurement of radius for both maximum and minimum reachable area of robot‟s leg are taken.

Radius for maximum reachable area of robot‟s leg, r_{max} = 9cm

Radius for minimum reachable area of robot‟s leg, r_{min} = 3cm

P and Q = actual moveable area of leg to avoid collision

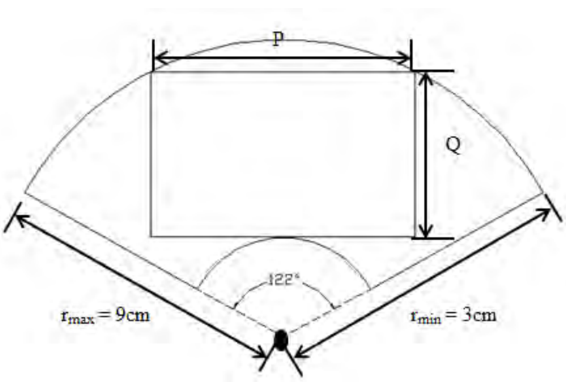


Figure 4.2: Size of moveable area of leg

By measuring the region between radius for maximum reachable area and radius for minimum reachable area, it is found that the actual moveable area of leg to avoid collision is $40cm^2$ (mark as rectangular region in Figure 4.2) with P = 8cm and Q = 5cm.

4.2 Implementation of tripod and wave gaits to six legged robot

Two types of walking gaits are implemented to the six legged robot, which are tripod gait and wave gait. The walking patterns of the robot are described and shown in this section.

4.2.1 Tripod gait

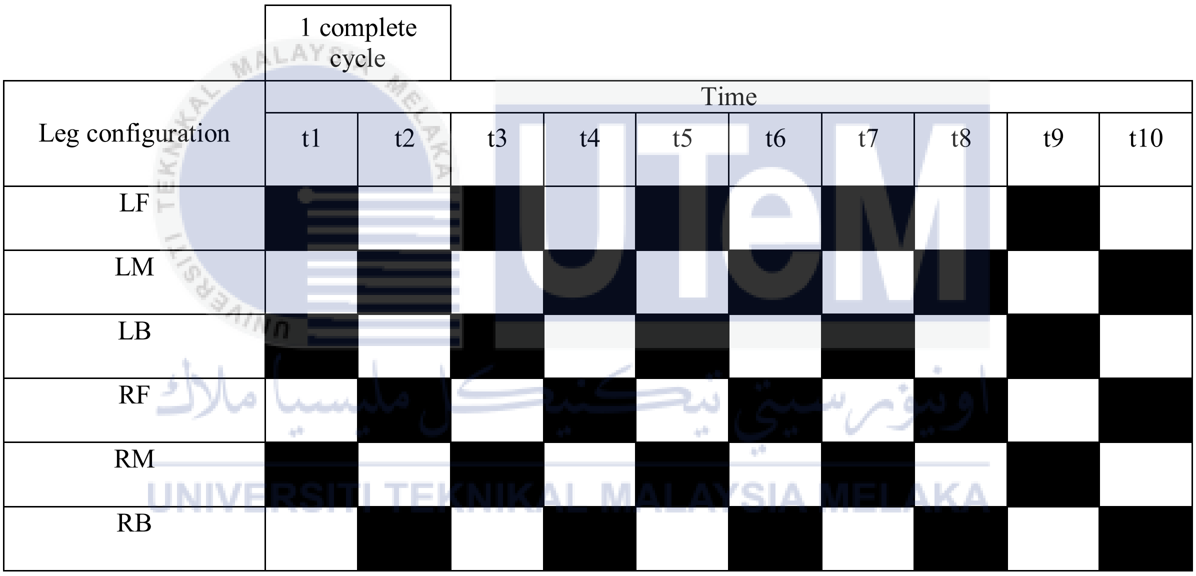


Figure 4.3: Movement of legs in tripod gait

Figure 4.3 shows the movement of legs of six legged robot when perform the tripod gait. The black colour indicated leg lift up from ground and white colour indicated leg in contact with ground. It is shown that the tripod 1 is made up by left front leg (LF), left back leg (LB) and right middle leg (RM). The tripod 2 is made up by right front leg (RF), right back leg (RB) and left middle leg (LM). For the first period, tripod 1 is lifted up, while tripod 2 is stayed on the ground. It is followed by tripod 2 lifted up and tripod 1 stayed on the ground for the second period. This is considered as one complete cycle for tripod gait.

By using equation (2.1),

$$\beta = \frac{6}{12} = 0.5$$

The duty factor of tripod gait is 0.5.

4.2.2 Wave gait

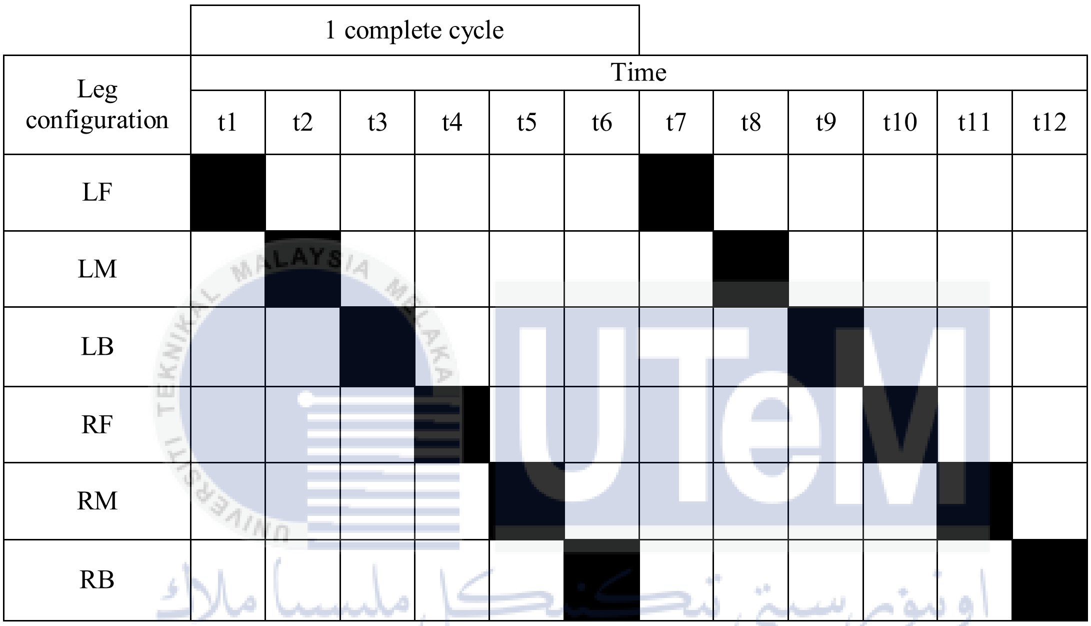


Figure 4.4: Movement of legs in wave gait

Figure 4.4 shows the movement of legs of six legged robot when perform the wave gait. The black colour indicated leg lift up from ground and white colour indicated leg in contact with ground. It is shown that for each period, only a leg is lifted up and the other five legs are in contact with ground. All the legs on left side are lifted up, followed by the legs on right side. The wave gait is started with left front leg (LF) lifted up, followed by left middle leg (LM), left back leg (LB), right front leg (RF), right middle leg (RM) and right back leg (RB). The complete cycle of wave gait is considered after all six legs had lifted up one by one.

By using equation (2.1),

$$\beta = \frac{30}{36} = 0.83$$

The duty factor of tripod gait is 0.83.

4.3 Analysis on speed of robot to complete line following task with tripod and wave gaits

This analysis is done to analyse the performance in term of speed of walking gaits in completing the line following task (moving straight and turning at different angles).

4.3.1 Move straight

Table 4.1 shows the time taken for the six legged robot to complete a 100cm straight line path for 5 times and the average values are calculated.

Table 4.1: Results for time taken to complete 1 cycle (move straight)

Types of walking gaits	Time taken to complete one cycle, t (s)					
	t_1	t_2	t_3	t_4	t_5	t_{ave}
Tripod gait	30.0	32.0	37.2	36.9	33.2	33.86
Wave gait	64.5	71.1	68.7	69.5	66.7	68.10

The speed of robot in performing tripod gait, $v1$

$$v1 = \frac{100}{33.86} = 2.95 cm/s$$

The speed of robot in performing wave gait, $v2$

$$v2 = \frac{100}{68.10} = 1.47 cm/s$$

From the values obtained from the experiments, the average time taken of robot in finishing the path for tripod and wave gaits are calculated. Robot with tripod gait takes shorter time, 33.86s in completing the path than wave gait, 68.10s. By using equation (3.15), the speed of robot are calculated and it is found that speed of robot in completing the straight line path by using tripod gait (2.95cm/s) is faster than by using wave gait (1.47cm/s)

4.3.2 Turning at different angles

Table 4.2 shows the time taken for the six legged robot to complete different turning angle path for 5 times and the average values are calculated.

Table 4.2: Results for time taken to complete 1 cycle (turning at different angles)

Turning angle	Time taken to complete one cycle, t (s)											
	Tripod gait						Wave gait					
	t_1	t_2	t_3	t_4	t_5	t_{ave}	t_1	t_2	t_3	t_4	t_5	t_{ave}
30˚	41.9	42.8	44.4	42.9	45.6	43.52	54.5	54.3	53.7	49.5	48.1	52.02
45˚	49.1	47.6	38.9	47.3	51.5	46.88	58.6	49.2	55.3	49.8	59.2	54.42
60˚	59.8	62.8	54.4	60.8	56.3	58.82	62.5	59.5	59.2	58.2	57.2	59.32

The speed of robot in performing tripod gait, $v1$

For turning angle = 30˚,

$$v1_{30} = \frac{10+15+10+15+15}{43.52} = \frac{65}{43.52} = 1.49cm/s$$

For turning angle = 45˚,

$$v1_{45} = \frac{10+15+10+15+15}{46.88} = \frac{65}{46.88} = 1.39cm/s$$

For turning angle = 60˚,

$$v1_{60} = \frac{10+15+10+15+15}{58.82} = \frac{65}{58.82} = 1.11cm/s$$

The speed of robot in performing wave gait, $v2$

For turning angle = 30˚,

$$v2_{30} = \frac{10+15+10+15+15}{52.02} = \frac{65}{52.02} = 1.25cm/s$$

For turning angle = 45˚,

$$v2_{45} = \frac{10+15+10+15+15}{54.42} = \frac{65}{54.42} = 1.19cm/s$$

For turning angle = 60˚,

$$v2_{60} = \frac{10+15+10+15+15}{59.32} = \frac{65}{59.32} = 1.10cm/s$$

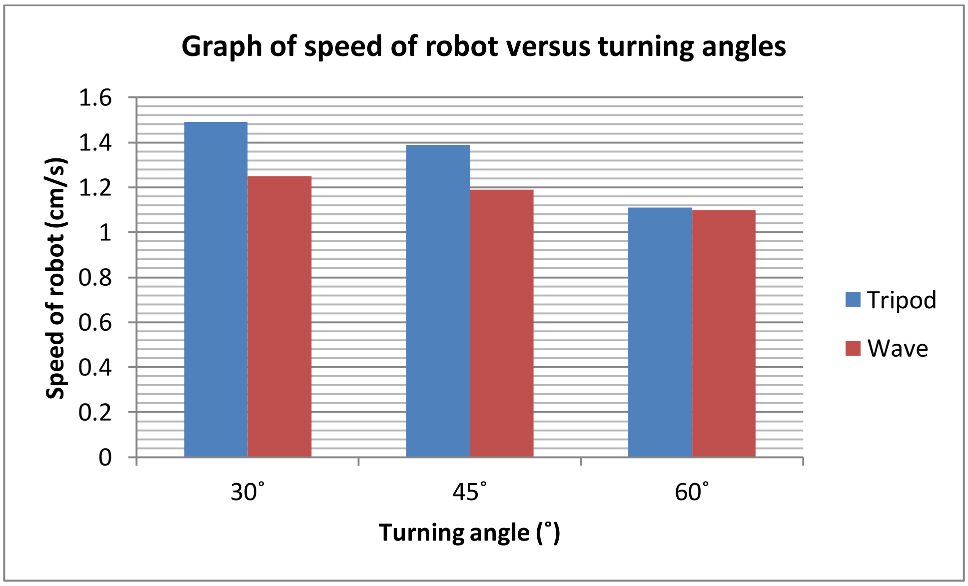


Figure 4.5: Graph of speed of robot in completing the path versus turning angle for tripod and wave gaits

According to Figure 4.5, by compare speed of robot to finish all different turning angles line path, the speed of robot in completing the line path by using tripod gait is faster than by using wave gait. For tripod gait, robot able to finish the turning path with turning angle of 30˚ faster as compared to turning angles 45˚ and 60˚. For wave gait, robot also able to finish the turning path with angle of 30˚ faster than another two turning angles.

4.3.3 Summary of result obtained in analysis of speed

In summary, for the experiments done on analyse the speed of robot on completing the task with tripod and wave gait, it is found that tripod gait allows the robot to move faster than by using wave gait for both moving straight and turning motion. This can be explain from the duty factor of tripod gait, which is 0.5 is smaller than wave gait, which is 0.83, the movement of tripod gait are walked with two tripods in one time compared to movement in wave gait which move only a single leg in a single time. The complete cycle of tripod gait only required two steps as compared to wave gait that required a total of 6 steps to complete a cycle, results the step size of movement in tripod gait is larger and able to reach the END point in shorter time. Hence, the speed of robot in moving with tripod gait is faster. For the turning motion, robot able to finish the path with smaller turning angle faster compared to higher turning angle for both gaits. As the robot is programmed to turn 10˚ for every turning motion, when the robot reaches small turning angle, for example 30˚, it manages to pass the desired angle in three rotations compared to other larger turning angles. In the turning path experiment, the speed of robot with tripod gait is faster than wave gait in finish turning path. This is because tripod gait able to perform forward motion as well while turning left or right, unlike wave gait that only rotate without moving forward while turning.

4.4 Analysis on measurement of errors from deviation of centre of robot from the line in performing line following task with tripod and wave gaits

This analysis is done to measure the errors from deviation of centre of robot from the line when it is perform line following task. In measuring the error, LDR circuit is attached on the base of robot instead of attach a camera to the robot. This is because the attachment of LDR is lighter compared by using camera which will add heavy load on the robot and affected the performance of robot. Hence, LDR circuit is used to measure the error by comparing the different LDR values and providing the results in range value of errors, as well as without affecting the movement of robot.

4.4.1 Move straight

4.4.1.1 Tripod gait

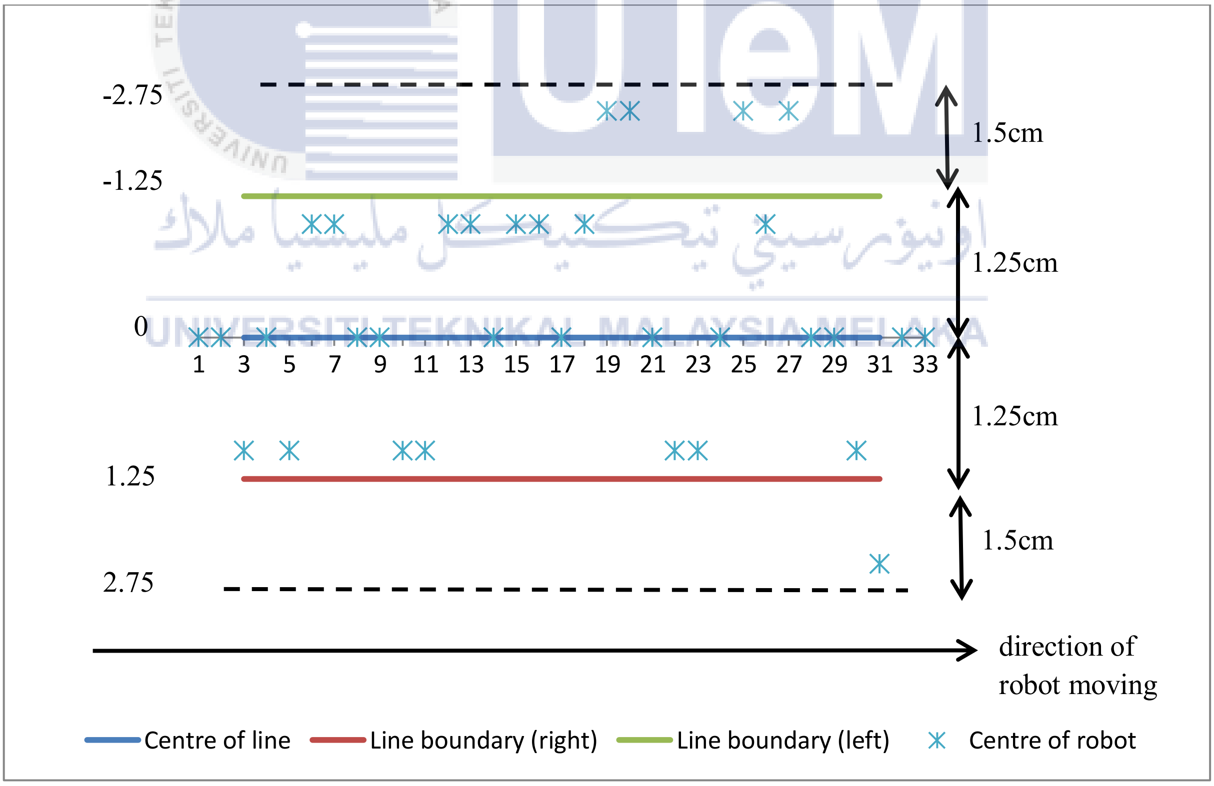


Figure 4.6: The position of centre of robot with respect to line (tripod gait)

Table 4.3: Number of occurrence of centre of robot at different location on or out from line (tripod gait)

Position	Inside line			Out from line		Start / End
	Left	Centre	Right	Left	Right	
Number of occurrence of centre of robot, *n*	8	9	7	4	1	4
Percentage of error occurred, *P* (out from line)	17.24%					

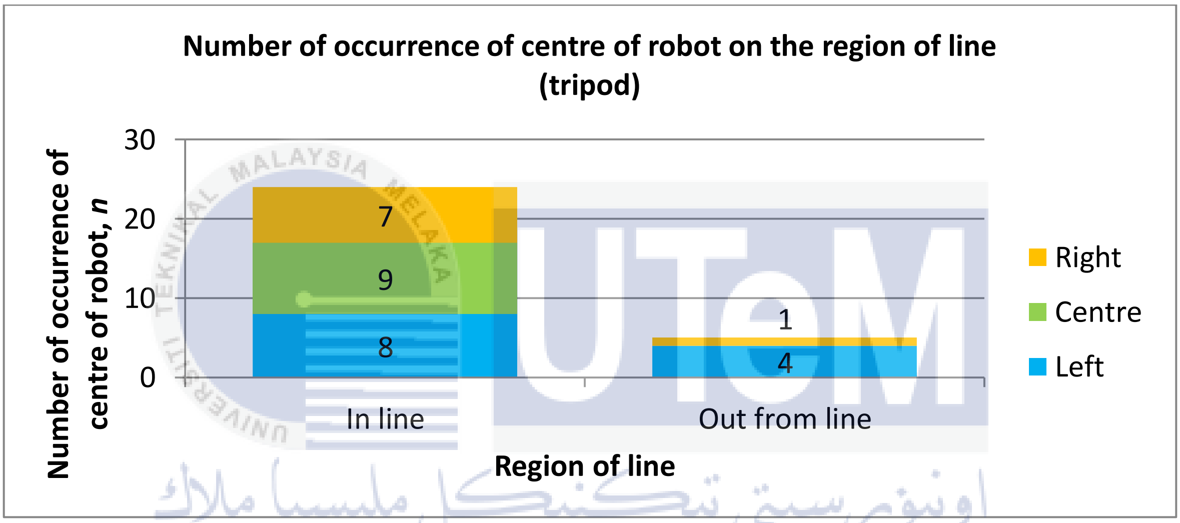


Figure 4.7: Number of occurrence of centre of robot on the region of line (tripod)

Figure 4.6 and Figure 4.7 show the position of centre of robot with respect to the line when it is moving straight with tripod gait. From Figure 4.7, it can be seen that the errors mostly occurred on the left boundary of line as compared to the right boundary region. This errors will occurred as the robot is moving forward by its tripod legs 1 which consists of left front legs, right middle legs and left back legs, hence, the robot will intend to move to left when it started to move. Overall, the percentage of centre of robot lies out from line when complete the path is 17.24%.

4.4.1.2 Wave gait

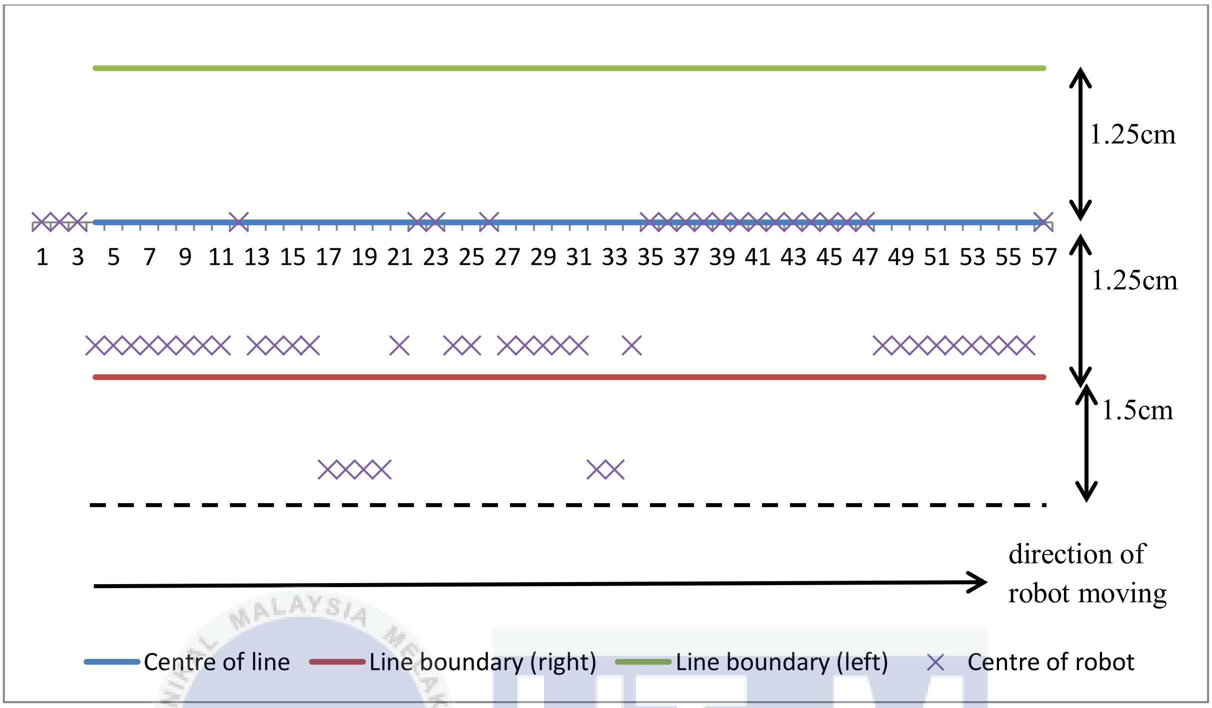


Figure 4.8: The position of centre of robot with respect to line (wave gait)

Table 4.4: Number of occurrence of centre of robot at different location on or from line (wave gait)

Position	Inside line			Out from line		Start / End
	Left	Centre	Right	Left	Right	
Number of occurrence of centre of robot, n	0	18	30	0	6	3
Percentage of error occurred, P (out from line)	11.11%					

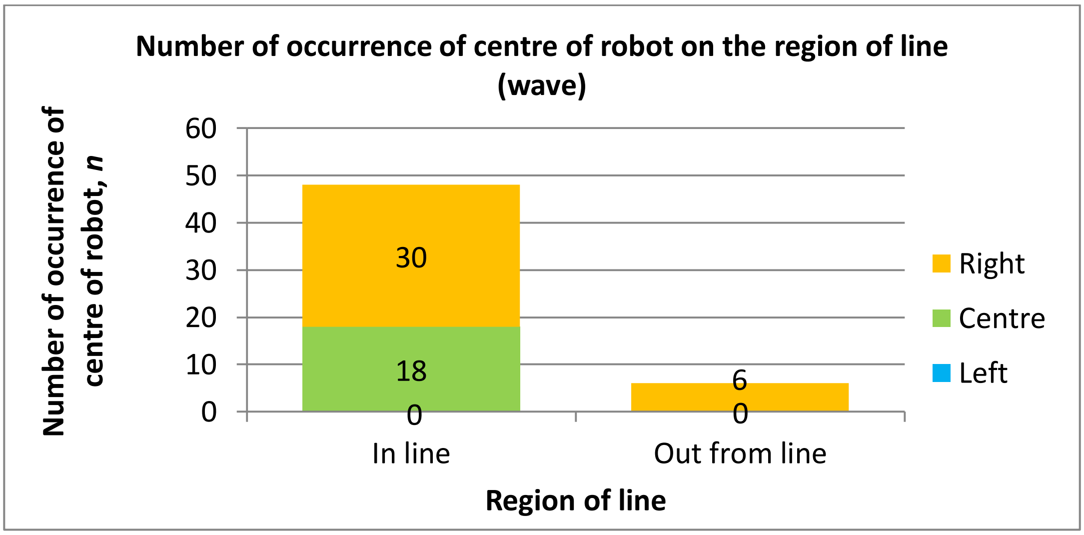


Figure 4.9: Number of occurrence of centre of robot on the region of line (wave)

Figure 4.8 and Figure 4.9 show the position of centre of robot with respect to the line when it is moving straight with wave gait. From Figure 4.8 and Figure 4.9, it can be seen that most of the errors are fall on the right region of the line and none of the centre of robot is fall on the left region. The errors are caused by the movement of wave gait where wave gait provides a stable movement when the robot is moving. It only lifts a single leg in each time, the other five legs that stand on the ground create a stable structure and hard to move the robot to change direction. Besides that, the step size in wave gait is small, hence the robot able to move straight without creating a big movement. Overall, the percentage of centre of robot lies out from line when complete the path is 11.11%.

4.4.2 Turning at different angles

4.4.2.1 Tripod gait

For turning angle = 30˚,

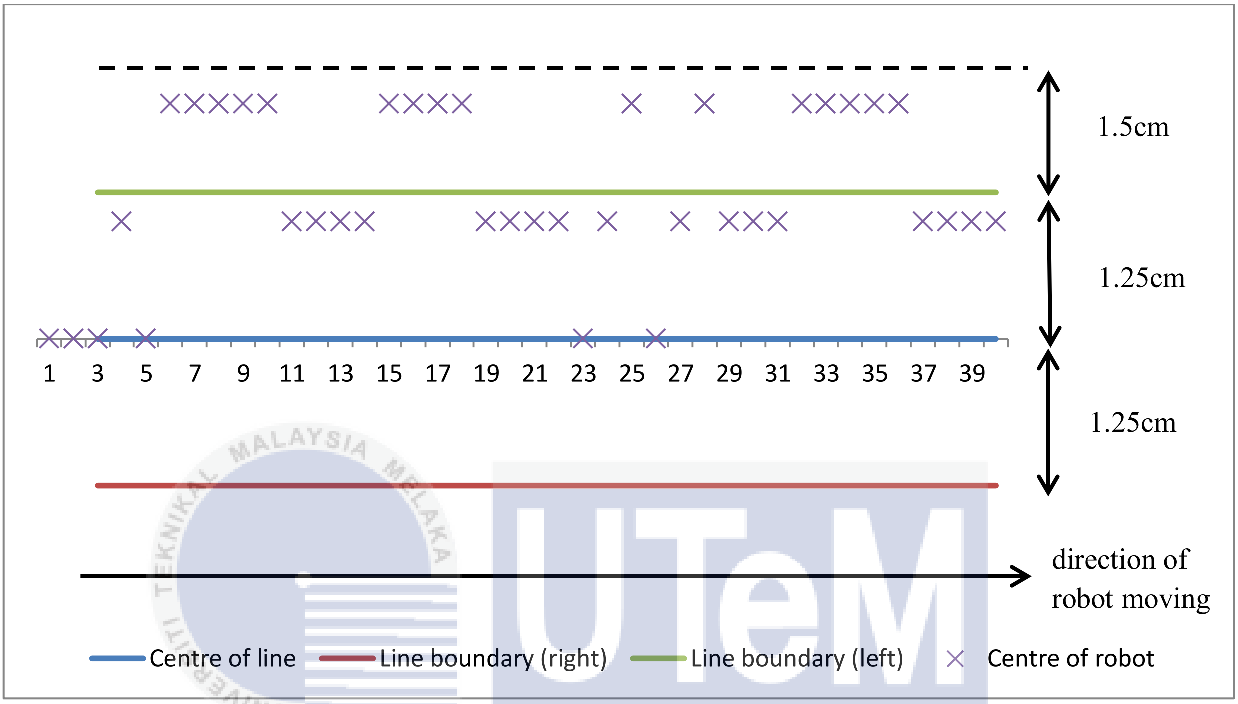


Figure 4.10: The position of centre of robot with respect to line (turning angle = 30˚)

Table 4.5: Number of occurrence of centre of robot at different location on or from line (turning angle of 30˚)

Position	Inside line			Out from line		Start / End
	Left	Centre	Right	Left	Right	
Number of occurrence of centre of robot, *n*	18	4	0	16	0	2
Percentage of error occurred, *P* (out from line)	42.11%					

According to Table 4.5, most of the centre of robot is lies on the left region and none of the centre of robot is lies on right region. The percentage of centre of robot lies out from line is 42.11%.

For turning angle = 45˚,

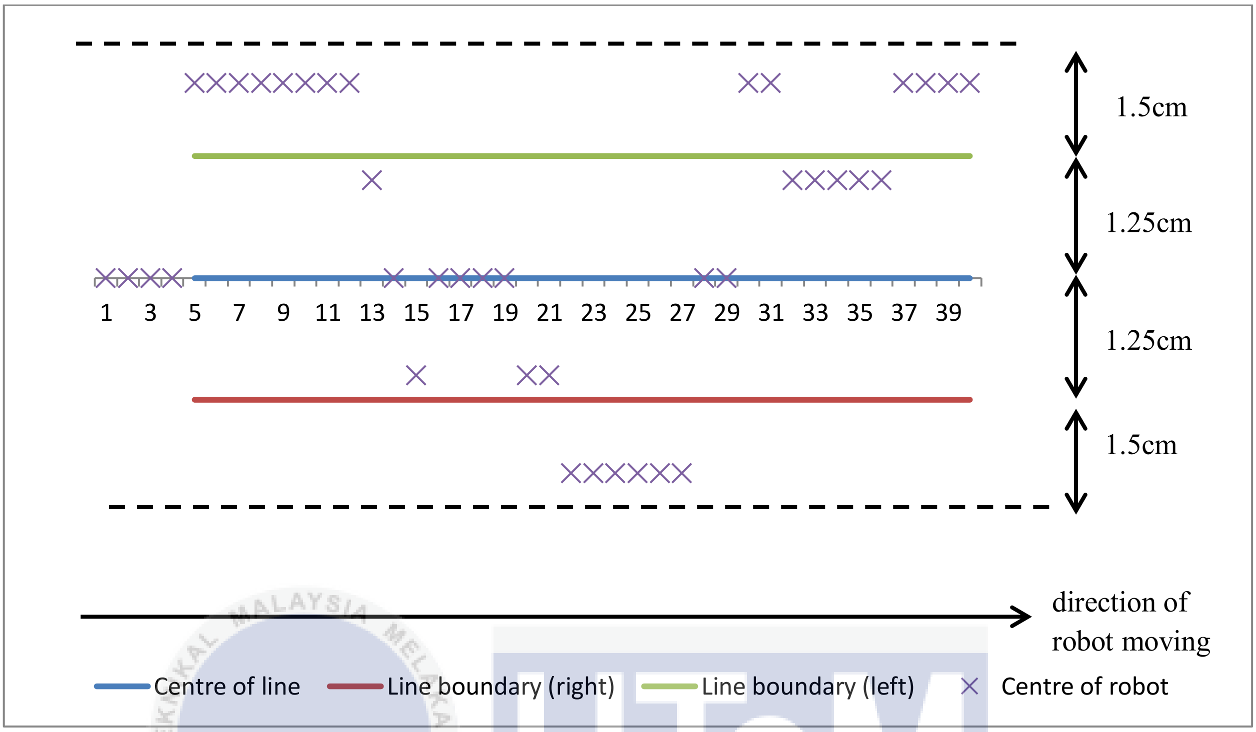


Figure 4.11: The position of centre of robot with respect to line (turning angle = 45˚)

Table 4.6: Number of occurrence of centre of robot at different location on or from line (turning angle of 45˚)

Position	Inside line			Out from line		Start / End
	Left	Centre	Right	Left	Right	
Number of occurrence of centre of robot, n	6	7	3	14	6	4
Percentage of error occurred, P (out from line)	55.56%					

According to Table 4.6, most of the centre of robot is lies on the left region. The percentage of centre of robot lies out from line is 55.56%.

For turning angle = 60˚,

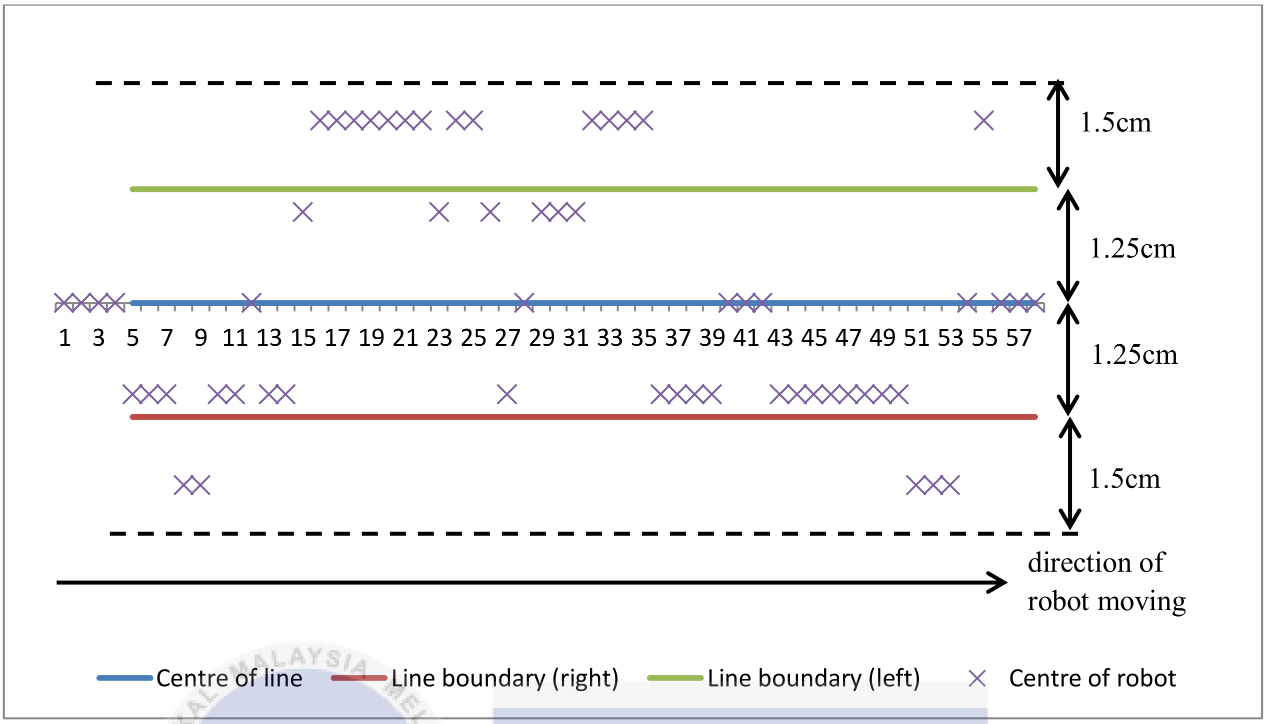


Figure 4.12: The position of centre of robot with respect to line (turning angle = 60˚)

Table 4.7: Number of occurrence of centre of robot at different location on or from line (turning angle of 60˚)

Position	Inside line			Out from line		Start / End
	Left	Centre	Right	Left	Right	
Number of occurrence of centre of robot, *n*	6	9	20	13	5	4
Percentage of error occurred, *P* (out from line)	33.96%					

According to Table 4.7, most of the centre of robot is lies on the right region and the percentage of centre of robot lies out from line is 33.96%.

As compared with three different angles, it is found out that tripod gait can perform well for larger turning angles which are 60˚ as the percentage of error occurred is 33.96%. For smaller turning angles of 30˚ and 45˚, most the readings shows centre of robot is fall on the left region of the line as the robot is turning to left.

4.4.2.2 Wave gait

For turning angle = 30˚,

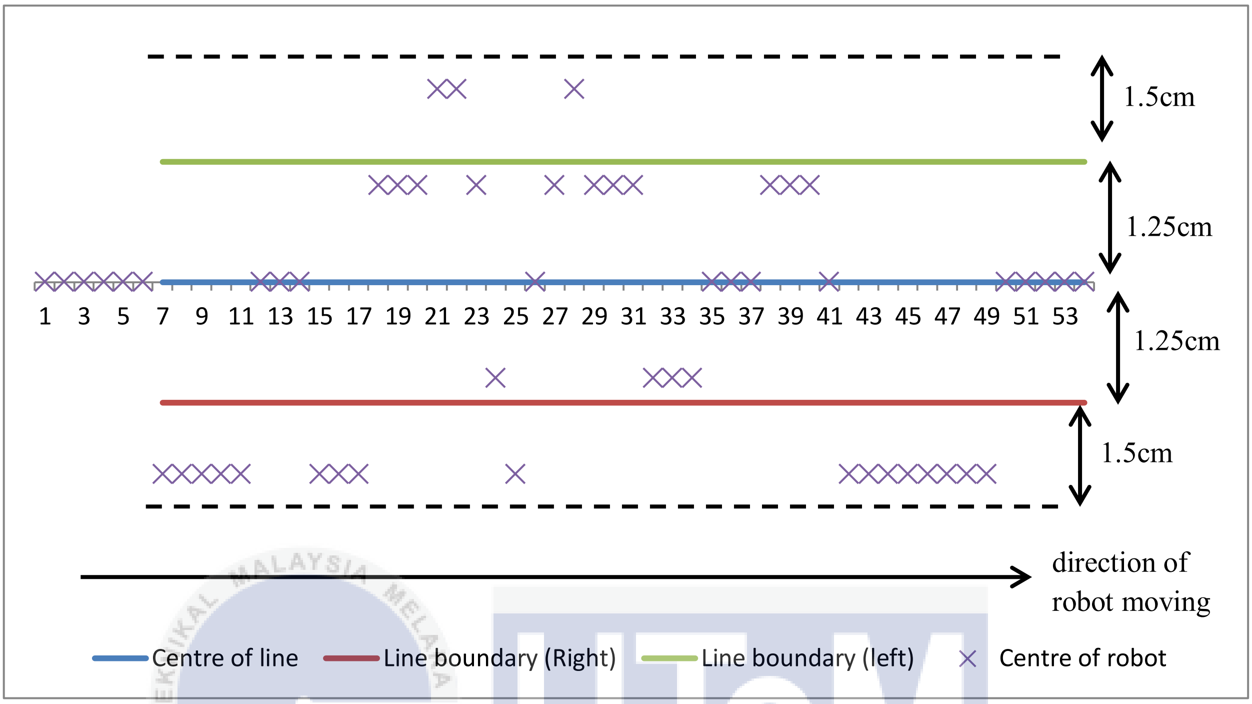


Figure 4.13: The position of centre of robot with respect to line (turning angle = 30˚)

Table 4.8: Number of occurrence of centre of robot at different location on or from line (turning angle of 30˚)

Position	Inside line			Out from line		Start / End
	Left	Centre	Right	Left	Right	
Number of occurrence of centre of robot, *n*	11	13	4	3	17	6
Percentage of error occurred, *P* (out from line)	41.67%					

According to Table 4.8, most of the centre of robot is lies on the right region and the percentage of centre of robot lies out from line is 41.67%.

For turning angle = 45˚,

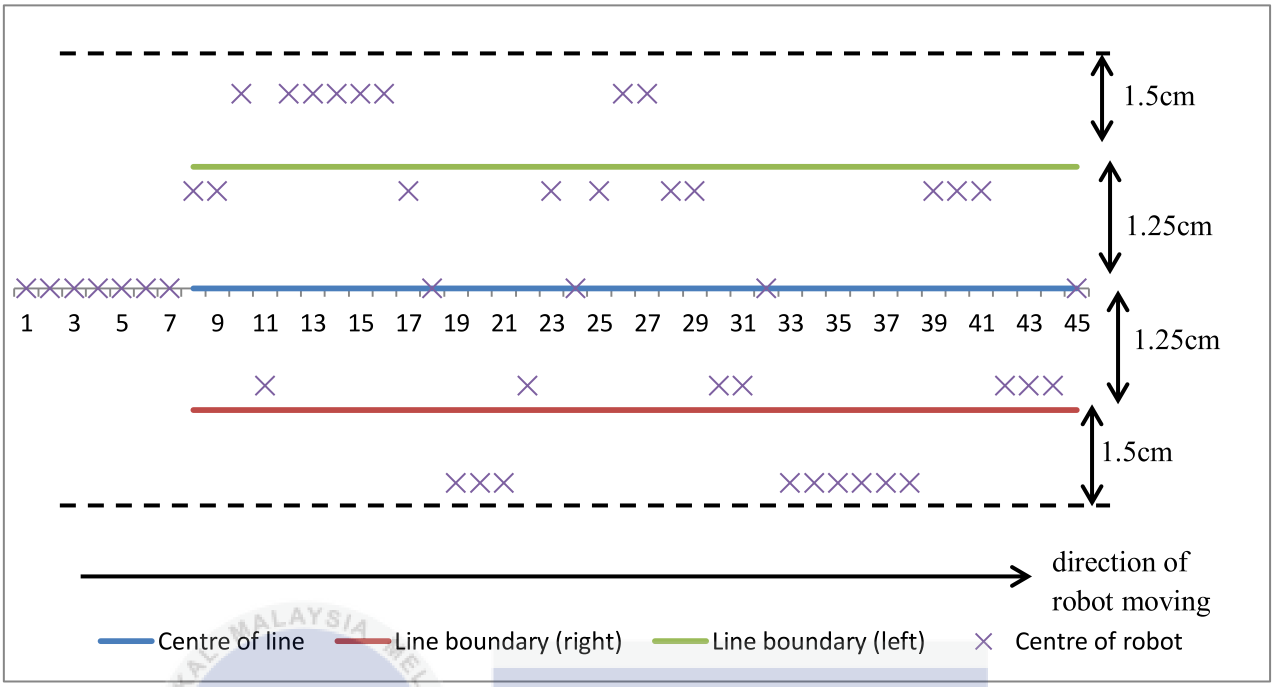


Figure 4.14: The position of centre of robot with respect to line (turning angle = 45˚)

Table 4.9: Number of occurrence of centre of robot at different location on or from line (turning angle of 45˚)

Position	Inside line			Out from line		Start / End
	Left	Centre	Right	Left	Right	
Number of occurrence of centre of robot, *n*	10	4	7	8	9	7
Percentage of error occurred, *P* (out from line)	44.73%					

According to Table 4.9, the percentage of centre of robot lies out from line is 44.73%.

For turning angle = 60˚,

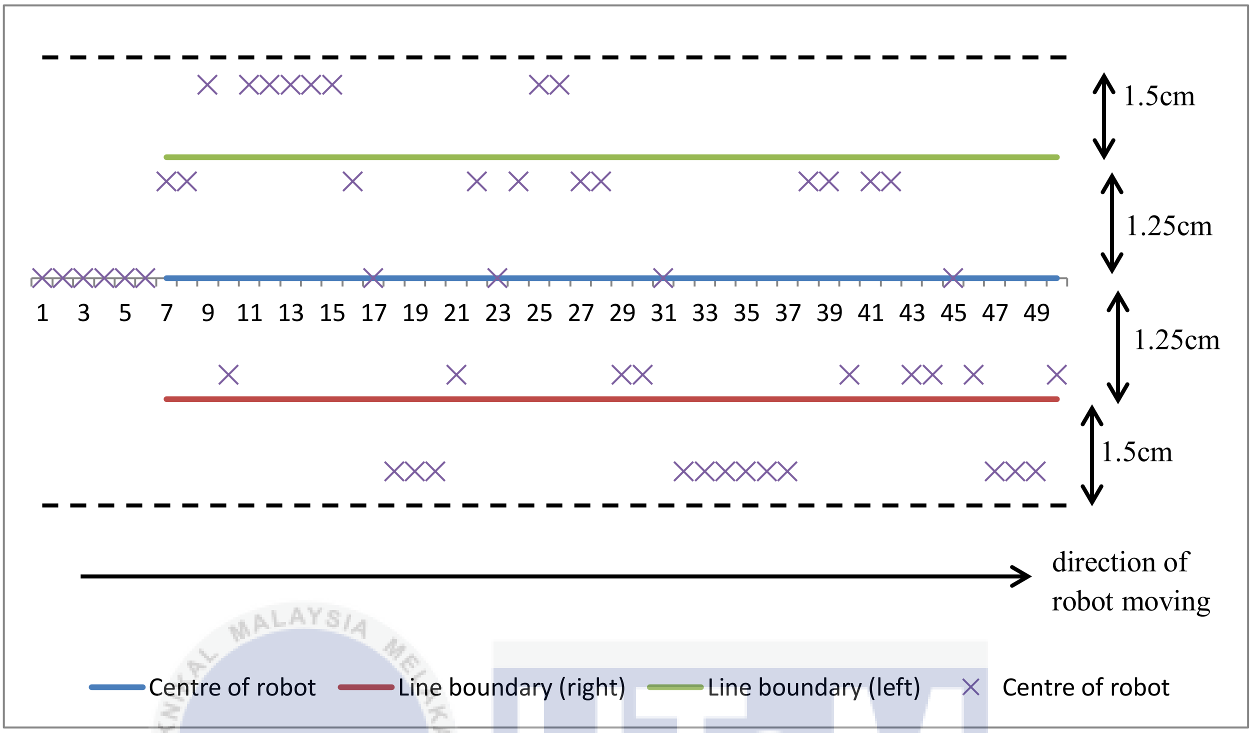


Figure 4.15: The position of centre of robot with respect to line (turning angle = 60˚)

Table 4.10: Number of occurrence of centre of robot at different location on or from line (turning angle of 60˚)

Position	Inside line			Out from line		Start / End
	Left	Centre	Right	Left	Right	
Number of occurrence of centre of robot, *n*	11	4	9	8	12	6
Percentage of error occurred, *P* (out from line)	45.45%					

According to Table 4.10, the percentage of centre of robot lies out from line is 45.45%.

As compared with three different angles, it is found out that wave gait is suitable for small angle turning, 30˚ as the percentage of centre of robot lies out from line is 41.67% and most of the centre of robot for turning angle of 30˚ is fall on centre of line region as compared to another two bigger turning angles, 45˚ and 60˚.

4.4.3 Summary of result obtained in analysis of measurement of errors from deviation of centre of robot from the line

In summary, as compared wave gait and tripod gait in completing the straight line path, it is found that wave gait able to perform well as it shows less percentage of centre of robot lies out from line which is 11.11% compared to tripod gait, 17.24%. This is because wait gait is stable in moving and slow when moving, results the robot only change slightly the direction when moving.

In perform turning gait, it shows that tripod gait suitable for larger turning angle while wave gait is suitable for smaller turning angle. This is because the robot is programmed to turn 10˚ for both gaits (turning motion), when the robot reaches small turning angle, for example 30˚, wave gait has the smaller step size manages to pass the desired angle in three rotations compared to other larger turning angles. Tripod gait suitable to turn effectively for larger angle, 60˚ as while the robot perform turning motion, at the same time, it also move forward, results it is hardly to rotate accurately for smaller angles.

Overall, wave gait allows six legged robot to perform less errors when follow the line as compared to tripod gait for both straight line moving and different angles turning.

4.5 Summary

Table 4.11: Summary for analysis of speed and analysis of error measurement

Experiments	Speed of robot (cm/s)		Measurement of errors from deviation of centre of robot to the line (%)	
	Tripod gait	Wave gait	Tripod gait	Wave gait
Straight Line	2.95	1.47	17.24	11.11
Turning angle = 30˚	1.49	1.25	42.11	41.67
Turning angle = 45˚	1.39	1.19	55.56	44.73
Turning angle = 60˚	1.11	1.10	33.96	45.45

Table 4.11 shows the summary for analysis of speed and analysis of error measurement from deviation of centre of robot from the line. Overall, in term of speed, tripod gait enables the robot to move faster than wave gait for both moving straight and turning as the duty factor of tripod gait is less than wave gait. When turning angles increase, the speed of robot to turn also decrease. In term of errors from deviation of centre of robot to the line, wave gait shows better performance than tripod gait where the percentage of centre of robot lies out from line occurred is less compared to tripod gait. Tripod gait suitable for larger turning angle while wave gait suitable for smaller turning angle.

In summary, the results obtained from the proposed methodology are shown. Some analysis is done to the hardware which is to find the joint angle for robot to stand in stable condition by using inverse kinematics and find the size of moveable area of robot‟s legs. By doing the preliminary analysis on the hardware, the limitation of hardware can be discovered. Before the implementation of line following behaviour to the robot, the walking gaits are assigned to robot is to observe the movement of legs in the gaits. After the line following algorithm is applied to the robot, experiments are carried out and from the results obtained, the effect of different walking gaits can be observed.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

This chapter will concludes the whole project of six legged robot walking gaits. The limitation of the project is included in this chapter as well.

5.1 Conclusion

In summary, there are two main objectives in this project which is the implementation of line following behaviour to the six legged robot with tripod and wave gait and to analyse the effect of different walking gaits in performing the line following task. The developed line following algorithm is implemented to the six legged robot that allow it can move and turn following the line. Experiment setup to measure speed and measurement of error from deviation of centre of robot to line are used to analyse the performance of robot in completing the task. From the results obtained from the experiments, tripod gait takes a shorter time than wave gait in finishing the line path, the speed of robot moves in tripod gait is faster than move in wave gait. Besides that, it also found that tripod gait suitable for larger turning angle and wave gait are suitable for smaller turning angle.

Based on the results obtained, in the future research, the robot can be develop to allow it to move on uneven surface as well to investigate its performance of walking gaits. Besides that, there are also some recommendations for the future research, the servo motors used in this project should change to metal gears type as the current type of servo motors are plastic gears which they cannot support high torque and heavy load. Next, other experiments can be done to analyse the effect of different types of walking gaits such as obstacles avoidance test on both even and uneven surfaces.

5.2 Limitation of the project

The limitation in this project is the six legged robot is designed to perform a single task which is line following task. The weight of this six legged robot cannot exceed 1.6kg as it required higher voltage if the weight of robot is increasing. The maximum voltage input can supported by the servo motor is 6V.

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APPENDIX A: Gantt chart for Final Year Project

Task	Semester 1 / 2014																Semester 2 / 2015																							
	Sep				Oct				Nov				Dec				Jan				Feb				Mar				Apr				May				Jun			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1) Initial stage																																								
Project title selection																																								
Planning of project																																								
2) Literature review stage																																								
Study on the six legged robot																																								
Study on the previous research done by others																																								
Study on the specification of the hardware																																								
Study on Python programming language																																								
3) Research introduction stage																																								
Identify the problem statement, objective and scope of project																																								
4) Research methodology stage																																								
Planning for methodology																																								
5) Prototype preparation stage																																								

System integration																																								
Implementation of line following behaviour to robot																																								
Insert programming																																								
6) Analysis and result stage																																								
Result analysis																																								
7) Report writing stage																																								
Final FYP 1 report writing																																								
Final FYP 1 submission																																								
Final FYP 2 report writing																																								
Final FYP 2 report submission																																								
8) Presentation stage																																								
Presentation FYP 1																																								
Presentation FYP 2																																								

APPENDIX B: Program for early calibration of servo motors

```
// Program for early calibration of servos
#include "Servotor32.h" // call the servotor32 Library
Servotor32 hexapod; // create a servotor32 object

/*Servos of left front leg: 16,17,18 (hip, knee, foot)
  Servos of left middle leg: 20,21,22 (hip, knee, foot)
  Servos of left back leg: 24,25,26 (hip, knee, foot)
  Servos of right front leg: 15,14,13 (hip, knee, foot)
  Servos of right middle leg: 11,10,9 (hip, knee, foot)
  Servos of right back leg: 7,6,5 (hip, knee, foot) */

  void blinkled(){    // blink status led
  digitalWrite(STATUS_LED, HIGH);  // set LED on
  hexapod.delay_ms(500); // wait for 500ms
  digitalWrite(STATUS_LED, LOW);  // set LED off
  hexapod.delay_ms(500); // wait 500ms
}

 void setup(){
  hexapod.begin();    // start communicate with controller

  for(int i=0; i<27; i++){         // from pin 0 to pin 27
    hexapod.changeServo(i,1500);      // set the angle for servo equal to 0
  }
}

void loop(){
  blinkled();
}
```

Figure: Program for early calibration of servo motors

APPENDIX C: Schematic diagram for Servotor32

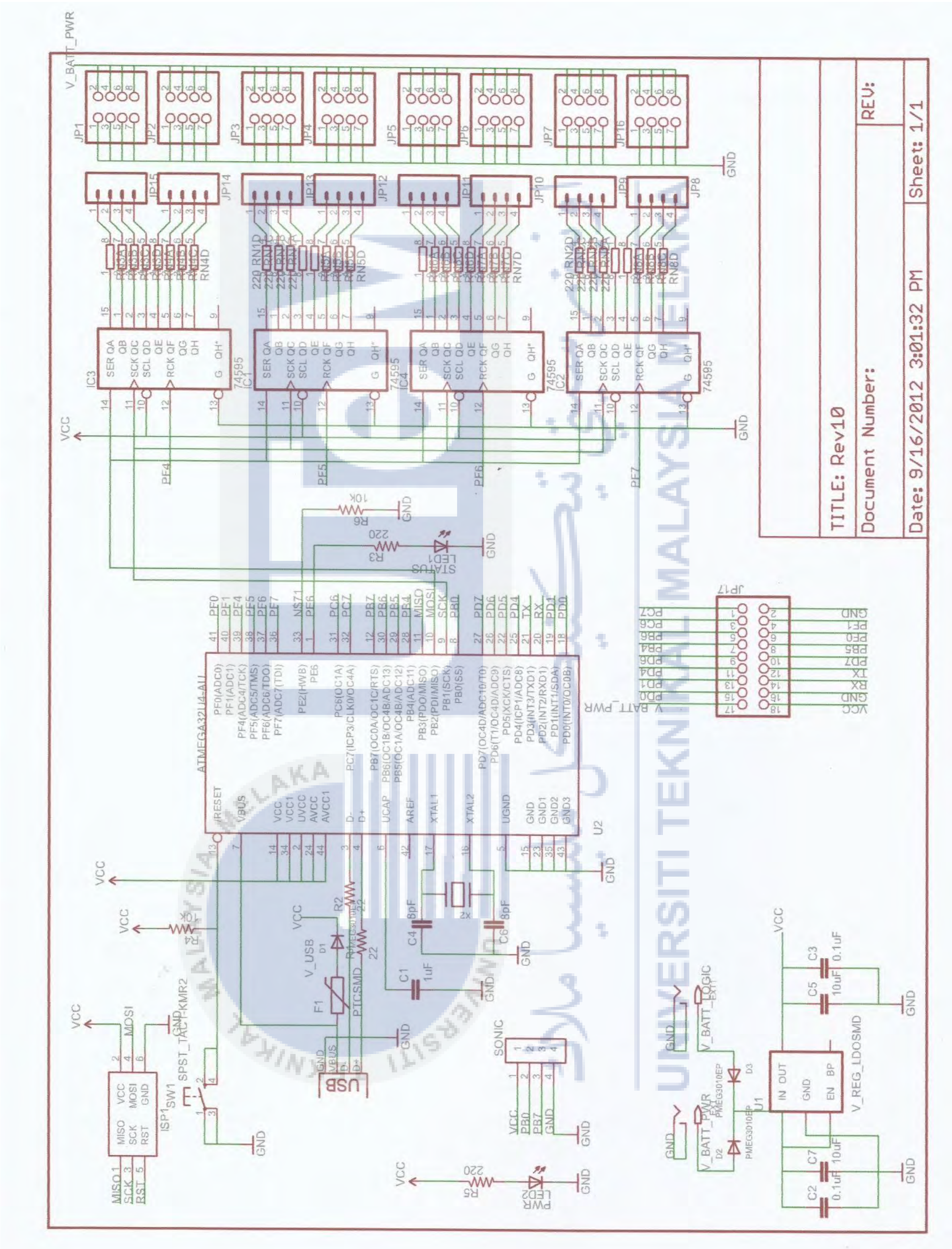

Figure: Schematic diagram for Servotor32 [33]