FAKULTI KEJURUTERAAN ELEKTRIK

SMALL SIZED ANIMATRONICS ROBOT MECHANICAL CONSTRUCTION

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DEGREE OF BACHELOR OF MECHATRONIC ENGINEERING

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APPROVAL

I hereby declare that I have read through this report entitle "**Design and Development of Small Size Animatronics Robot Mechanical Construction**" and found that it has comply the partial fulfilment for awarding the degree of Bachelor of Mechatronics Engineering.

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DESIGN AND DEVELOPMENT OF SMALL SIZE ANIMATRONICS ROBOT MECHANICAL CONSTRUCTION

NG WEI YU

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

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2016

I declare that this report entitles "**Design and Development of Small Size Animatronics Robot Mechanical Construction**" 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 : NG WEI YU

Date : ....

To my beloved mother and father

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ABSTRACT

Over the last decade, bioinspired legged robots or animatronics robots have become increasingly agile. Legged robot has been applied in many applications due to its high adaptability and stability. However, legged robots tend to be cheaper if compare to mobile robot due to their legged counterparts. Animal characteristic are applied in the design of legged robot due to its flexibility and mobility moving on uneven terrain. Thus, many research study has been done to study the mechanical construction of an animatronics robot. The objective of this study is to develop the mechanical part of robot that has ability to move on uneven terrain. The performance of animatronics robot is studied in terms of validity and repeatability. The designed robot is fabricated and modelled using SolidWorks software. SolidWorks is chosen as the modelling method for the robot since it provides many function tools on design and analysis of robot. Furthermore, many experiments have been carry out in this research to study and analysis the performance and the stability of the designed robot. Experiment using Matlab simulation is done to analyse the trajectory path of Theo Jansen mechanism. Furthermore, real time experiment is carried out to study the actual trajectory path of Theo Jansen mechanism on robot hardware. Then, result is collected in table to aid for discussion. At last, the simulation result and actual result is compared and discussed in graphical method since it is very pertinent to test and determine the validity and limitation of designed robot.

ABSTRAK

Marcapada ini, robot berkaki bioinspired atau animatronics robot telah menjadi semakin laris. Robot berkaki telah digunakan dalam banyak aplikasi kerana penyesuaian yang tinggi dan kestabilan. Walau bagaimanapun, robot berkaki cenderung untuk menjadi lebih murah jika dibandingkan dengan robot mudah alih kerana rangka-rangka berkaki mereka. Ciri-ciri haiwan digunakan dalam reka bentuk robot berkaki kerana fleksibiliti dan mobiliti yang bergerak di kawasan yang tidak rata. Oleh itu, banyak kajian penyelidikan yang telah dilakukan untuk mengkaji pembinaan mekanikal robot animatronics. Objektif kajian ini adalah untuk membina bahagian mekanikal robot yang mempunyai keupayaan untuk bergerak di kawasan yang tidak rata. Prestasi animatronics robot dikaji dari segi kesahan dan kebolehulangan. Robot yang direka akan dimodelkan menggunakan perisian SolidWorks. SolidWorks dipilih sebagai kaedah pemodelan untuk robot kerana ia menyediakan banyak peralatan fungsi kepada reka bentuk dan analisis robot. Tambahan pula, banyak eksperimen telah menjalankan kajian ini untuk mengkaji dan analisis prestasi dan kestabilan robot yang direka. Eksperimen menggunakan simulasi Matlab dilakukan untuk menganalisis jalan trajektori mekanisme Theo Jansen. Tambahan pula, eksperimen perkakasan robot semasa dijalankan untuk mengkaji jalan trajektori sebenar mekanisme Theo Jansen pada perkakasan robot. Kemudian, hasil yang dikumpul dalam jadual untuk digunakan dalam perbincangan. Akhirnya, hasil simulasi dan keputusan sebenar dibandingkan dan dibincangkan dalam kaedah grafik kerana ia adalah sangat penting untuk menguji dan menentukan kesahihan dan had robot direka.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

According to the review, many walking robot or animatronics robot has been deployed in high risk tasks and applications due to the high reliability and adaptability. Animal locomotion with varied gait pattern are great interest to researchers but designing this kind of robot need to account many criteria such as performance, function and manoeuvrability. For example, these kind of robots is applicable in office building for helping people in carrying things, or walking in dangerous, hazardous places where human cannot simply access. [1] Therefore, researchers tend to develop legged robot with biological or animatronics characteristic so that it has the ability to move through irregular, abrupt terrain and show their significant versatility and manoeuvrability over wheeled robots. Since, legged robots have higher potential to transverse certain type of terrain with more efficient and stable manner. Nowadays, there are many outstanding research projects such as Asimo from Honda, Bigdog and Wildcat from Boston dynamics have been proposed in many fields according to its function. These legged robots can be used as investigation robot and detection robot to be implement in accident area such as collapsed building, bombing area, and other purpose according to applications needs. This greatly ensure the safety of rescue squad as the building may unsafe for people to enter due to poor footing.

In US, a robotic pack mule has been developed for US troops as a leg up on terrain condition and even for military vehicles as shown in figure 1.1. This mechanized legged robot capable of carrying all the gear soldiers and marines might need in combat. Marc Raibert, the president of Boston Dynamics also confidently said that the robotic pack mules might be use by combat troops by embedded with a Marine squad for an operational exercise. [2]

Figure 1.1: Robotic pack mule

1.2 Problem Statement

Bioinspired legged robots or animatronics robots have become increasingly agile. Wheels are much easier to construct and control. Legs have distinct advantages over wheels due to the adapting principle and mechanism. [3] Wheeled robots face a major disadvantage with short instant elevation changes. Movement such as climbing stairs or steep jagged rock piles become a big problem for wheel vehicles thus many researchers tends to find many alternative solutions to solve this kind of problem. While climbing stairs, the robot need to ascend and traverse natural slopes with many different slopes on terrain with variation of degree and climb over small obstacles in rough terrain. The uneven surface slopes can be up to 50 degrees until 75 degrees and difficult for wheeled robot to travel. [4] Moreover, the slope degree for stairs can be up to 90 degrees which is impossible for wheeled robot to travel. Besides, ordinary vehicles unable to move smoothly on the mountains roads or other difficulties and this may cause the limitation in transportation work. Since, the floor is covered with portions of the building collapsed and even the entrances are blocked with obstacles. This make the building unsafe for people to enter due to the poor footing in building. Then, the rescue squad unable to investigate from the area of origin to aid for the rescue mission. Moreover, a small size robot is pertinent to ensure that the area of movement can be expand and more task can be carry out. Therefore, the main problem we need to solve is about the short elevation of legged robot to improve its flexibility and ability to travel along different kind of surfaces and spaces.

Hence, a further research and discussion need to be made in order to develop the legged robot application especially in Malaysia. In details, we need to study what kind of mechanism have greater ability of movement such as degree of elevation and depression. In addition, we also need to consider the problem may encounter when it is travelling around different kind of surfaces. Therefore, different kind of design is needed to fulfil different kind of target and achieved a better result.

1.3 Objective

The main intention of the small size animatronics robot mechanical construction is to design and develop the mechanical part of a device that has the ability to move along uneven or rough terrain. By comparing of the design from many researchers, it will give an opportunity in choosing the best design to use in various applications. However, many data analysis and performance test need to be carry out throughout the project to make sure that the project is applicable in daily life. This project embarks on the objectives as shown below:

1. To design and develop the mechanical part of robot that has an ability travel on small area.
2. To fabricate and analyse the designed robot using SolidWorks and Matlab modelling method.
3. To evaluate the performance of animatronics robot in term of validity and accuracy.

1.4 Project Scope

The research limitation in this project defines the range of data measurement and also evaluation parameters when conducting or designing the prototype of hardware to achieve the objectives as mentioned in previous subchapter. The main focus of this project is on the design and fabrication the mechanical parts of a small size animatronic robot followed by suitable analysis and performance test using proper method. The scopes of the project are listed below:

1. Come out with three feasible designs of small size animatronics robot.
2. Study the mechanical construction use to drive the mechanism of legged robot.
3. Determine the parameters that will affect the characteristics and performance of animatronics robot.
4. Identify the suitable types of actuator needed to actuate the animatronics robot.
5. Analyse the design of animatronics robot using Solidworks and Matlab simulation software.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter explains a brief overview about my project which is small size animatronics robot mechanical construction. After studying all of the literatures, the various types of mechanism and designs are described and analysed based on researchers' findings.

2.2 Animatronics robot

First and foremost, what is animatronics robot? Animatronics refers to a robotic device or machine that able to imitate a human or an animal to make an inanimate object to "life". [1] Animatronics robot that look and operate like us could be very useful in a modern society since it has a high reliability and adaptability and able to be deploy in high risk task. Hence, animatronics robot is typically designed to be as realistic as possible to be applicable in real life. The framework figure such as skeleton, joints, shoulder, palm and even claws need to be design using motors, and actuators act as the "muscles" of the robot. After connecting all of the circuit and wires the robot will acts like a real person with "nervous system". In addition, a small size animatronics robot or microbots are capable to explore harsh environment which are too narrow or dangerous for people or larger robot to explore. As such, microbots is very useful in applications such as survivors rescue mission, exploration of mine cave, or any suitable applications. The mechanical construction of robot must consider all of the criteria and characteristics of small size animatronics in order to fulfil the project requirement.

2.3 Criteria of legged robot

There are many criteria has been discussed for the construction of robot such as types of mechanism, degree of freedom, types of actuator, type of materials selection, software used, controller used and also number of legs for the robot. Lastly, the benefits of legged robot are discussed.

2.3.1 Linkage mechanism

Based on the papers, the two most effective leg mechanisms are Joe Klann's mechanism which resembles a spider leg and Theo Jansen's mechanism which resembles a human leg. Jansen's linkage mechanism designed by kinetic sculptor to simulate a smooth walking motion and Klann linkage mechanism provides many benefits in more advanced walking vehicles. [5] However, a mechanical spider using Klann mechanism is chosen since it has more advantages than Jansen mechanism. Klann mechanism is simpler and less complicated with lesser linkage for movement. The mechanism is a six-bar linkage with one degree-of-freedom mechanism on each leg that constructed from six links and seven joints. These six linkages are connected to two shafts, with three linkages space equally divided on each side of the frame.

Moreover, Theo Jansen's mechanism is 8 bar linkages with one degree of freedom on each leg. The 8 bar linkages are a combination of 4 bar linkage and two 3 bar linkages. [1] Moreover, Hrones-Nelson and Theo Jansen mechanism are compared due to the similarity of their designs which are both comprised solely of rigid triangular bodies attached to four-bar linkages. Theo Jansen mechanism comprised of two four bar linkages attached to each other in series with only one of the linkages driven by the shaft and crank.

Besides that, four bar chain leg mechanism is also one of the mechanism to construct legged robot. The mechanism has 5 linkages per legs. Four bar chain mechanism can be used to modified form as a locomotion element. [6] The basic structure of this mechanism consists mainly of torso frame and legs which are attached to it. Besides, kinematic modelling of quadruped robot consists of two sections that are direct kinematics and reverse kinematics. At last, a two bar chain mechanism can be applied in the development of a biomimetic quadruped robot. [2] Due to enormous complexity in the mechanical structure of biological systems and multiple degrees of freedom in each leg, the designed robot is simpler by reducing number of legs or degrees of freedom. [2] There are many similar types of quadruped robot but has short comings in the ability of carrying a load unless the controller is separate from the machine as it used up a lot of space. In conclusion, four-legged configuration are much simpler than six-legged ones but insufficient in stability. On the contrary, the simplification of the design can improve its stability of the robot. The comparison of linkage mechanism of legged robot is listed in table 2.1.

Table 2.1: Comparison of linkage mechanism

Article	Author	Mechanism	Number of linkages	Degree of Freedom (DOF)
Mechanical Spider Using Klann Mechanism [5]	U. Vanitha	Joe Klann's mechanism	Six linkages per legs	One DOF per legs
Modelling and Fabrication of Quadruped Robot Based on the Theo Jansen's Mechanism by using MATLAB [1]	M. Balaji, B. Bapiraju	Theo Jansen's mechanism	Eight linkages per legs	One DOF per legs
Design, Analysis and Fabrication of Quadruped Robot with Four Bar Chain Leg Mechanism [6]	Sachin Oak, VaibhavNarwane	Four bar chain leg mechanism	Five linkages per legs	Two DOF per legs
Design and Finite Element Analysis of Mechanical Spider [7]	Urvil P Patel	Joe Klann's mechanism	Six linkages per legs	One DOF for four legs
Development of a Biomimetic Quadruped Robot [2]	Thanhtam Ho, Sunghac Choi, Sangyoon Lee	Two bar chain mechanism	2 linkages per legs	One DOF for two legs

2.3.2 Fabrication and modelling method

Based on the research, Theo Jansen mechanism comprised of two four bar linkages attached to each other in series with only one of the linkages driven by the shaft and crank. A four-legged robot made by using Theo Jansen's mechanism and the composed of the mechanism is model by using MATLAB and linear motions are observed on the graph for the Theo Jansen based quadruped robot. For the modelling and fabrication of product, the linkage lengths were taken directly from Theo Jansen's book "The Great Pretender". [1] The fabrication involves many complicated processes like cutting of material, selection of motor, drilling of centre rod, fixing motor and final finishing work. The analysis of the robot performance is done by using the AutoCAD software and MATLAB software. The analysis of trajectory leg movement is done by simulation of mechanism using MATLAB to record the X and Y position of end effector. The coordinate system of its legs path is then recorded and tabulated in table form.

For analysis and fabrication of quadruped robot with four bar chain leg mechanism, the robot was first design and develop using CAD model software to ensure overall dimensions of robot are fixed. [6] A table of joint angles for the hips and knees is then tabulated as results of experiment. Further discussion is made to study the different exist each of the joint angles. The different of angles are because of restriction to servomotor revolution and mounting arrangement on quadruped.

For Joe Klann mechanism spider robot, the frames and links are made of aluminium as aluminium is light and strong material to reduce the weight of device and able to withstand the force on it. [7] For gears and pinions are made of nylon material. The electrical motor is connected to frame and pinions is then connected at the shaft of electric motor. All the links and final assembly is then modelled by using Creo parametric 3D CAD software. When power is supplied, rotation motion of crank and gears is transferred to a connecting arm causing an accurate reciprocating movement. For analysis sections, author carry out static structural analysis, gravitational acceleration analysis and modal analysis to determine its vibration characteristic. Ansys workbench software is used by author to study the finite element deformation and stress in the body. [7] The fabrication of robot has many advantages such as high efficiency, low construction cost, less maintenance, and capable of carrying heavy loads. However, there are a few limitations for this design like high power source, limited speed and smoothness of motion.

At last, acrylic material is used to fabricate quadruped since it is light and rigid body. The fabricated parts are then assembled by using bolts, nuts, carbon rods and carbon pipes. Numerous experiment is done by the author to study the robot performance and efficiency. For example, experiment on effect of frequency on the velocity, effect of angle on velocity and also payload experiments. According to the research findings, bounding motion has a superior ability in terms of the locomotion velocity and payload. [2] Though the prototype yet to be improved such that the could be perform better while carrying circuit and battery. Furthermore, ADAMS software can be used as the mechanism simulation software. [2] Numerous experiment is done by the software to study the robot performance and efficiency. For example, experiment on effect of frequency on the velocity, effect of angle on velocity and also payload experiments. The comparison of fabrication and modelling method of legged robot is listed in table 2.2.

Table 2.2: Comparison of material and modelling method

Article	Author	Material	Modeling Method
Mechanical Spider Using Klann Mechanism [5]	U. Vanitha	Steel	Solid Works
Modelling and Fabrication of Quadruped Robot Based on the Theo Jansen's Mechanism by using MATLAB [1]	M. Balaji, B. Bapiraju	Sheet metal plate	Autocad, MATLAB
Design, Analysis and Fabrication of Quadruped Robot with Four Bar Chain Leg Mechanism [6]	Sachin Oak, VaibhavNarwane	PVC foam sheet (Sunboard)	CAD model, UG NX 7.5 Siemens software
Design and Finite Element Analysis of Mechanical Spider [7]	Urvil P Patel	Aluminium	Creo parametric 3D CAD software, Ansys workbench
Development of a Biomimetic Quadruped Robot [2]	Thanhtam Ho, Sunghac Choi, Sangyoon Lee	Acrylic material	ADAMs software, CAD model

2.3.3 Types of actuator and controller

There are many types of actuator can be used to drive the robot but the most common actuators are direct current motor and servo motor. For Joe Klann mechanism, it does not require microprocessor control or large amount of actuator mechanisms. It just need a simple direct current Motor to drive the gear and linkages of the mechanism. The electrical motor is connected to frame and pinions is then connected at the shaft of electric motor. When power is supplied, rotation motion of crank and gears is transferred to a connecting arm causing an accurate reciprocating movement. Rotating motion of the crank will drive into the motion of foot similar to animal walking. However, the microprocessor not compulsory to be used in this product since Klann mechanism just required a gear motor with relatively high torque, power and speed to drive the mechanism. A 4-Channel Relay Driver Module is suggested may be chosen to drives the loads from 5v to 12v if using microprocessor. [5] However, there are a few limitations for this design like high power source, limited speed and smoothness of motion

For four bar chain leg mechanism, the hardware components such as actuator, control system and power source was then assembled on the robot for operation. The actuator used is Futaba S3305 servomotors and the controller is Arduino controller. Software includes Arduino programming software is then developed for trot and pace gait locomotion separately. As conclusion, four bar chain leg mechanism developed in this product requires actuation only at two joints out of five joints and the maximum mean speed of foots are able to attain throughout the research.

On the other hand, biomimetic quadruped robot used two pieces of Lightweight Piezoceramic Composite Curve Actuator (LIPCA) on the up limbs and each leg has only one joint. [2] In order the simplify the mechanism, one LIPCA actuates two legs which the motion is driven by means of crank. So, two LIPCA are required to actuate 4 legs. Though the prototype yet to be improved such that the could be perform better while carrying circuit and battery. The comparison of actuator and controller of legged robot is listed in table 2.3.

Table 2.3: Comparison of actuator and controller

Article	Author	Actuator	Controller
Mechanical Spider Using Klann Mechanism [5]	U. Vanitha	DC motor	Simple electric circuit
Modelling and Fabrication of Quadruped Robot Based on the Theo Jansen's Mechanism by using MATLAB [1]	M. Balaji, B. Bapiraju	DC motor	AT89c52 microcontroller
Design, Analysis and Fabrication of Quadruped Robot with Four Bar Chain Leg Mechanism [6]	Sachin Oak, VaibhavNarwane	Futaba S3305 servomotor	Arduino Controller
Design and Finite Element Analysis of Mechanical Spider [7]	Urvil P Patel	DC motor	Simple electric circuit
Development of a Biomimetic Quadruped Robot [2]	Thanhtam Ho, Sunghac Choi, Sangyoon Lee	Lightweight Piezoceramic Composite Curve Actuator	Electric circuit with high power supply

2.4 Benefits of legged robot

The main function of legged robot is to replace the function of wheel to overcome the difficulty of travelling on uneven terrain. [5] Hence, legged robot tends to find many alternative solutions to solve uneven terrain problem and found out that animal and human legs which are proven to work more effective on this terrain with greater efficiency. As such, travelling along uneven terrain such as mountains roads become possible by using six leg mechanical spider.

The mechanical spider is very useful in hazardous material handling, clearing minefields or secures an area without putting anyone in risk. Besides that, legged off-road vehicle exhibit better mobility while moving on rough terrain. Theo Jansen's mechanism is gaining widespread of popularity among legged robotics community due to its scalable design, energy efficiency, low payload to machine load ratio, bio inspired locomotion and deterministic foot trajectory. [1]Moreover, a legged robot that able to travel on smooth hard surfaces and mountain roads with capability of carrying heavy load on its platform. In addition, the robot can be applicable for military purpose like placing a bomb detector in machines so that bomb can be easily detected without harmful to humans. [7] It also can be used as heavy tanker machines to carry military goods.

2.5 Summary of literature review

Based on the literature review findings, each article has present about the types of mechanism, number of legs, degree of freedom, types of actuator, material selection, modelling method and the controller use for development of device. By referring all of the comparison tables, many information is obtained to assist in development of small size animatronics robot. In the development of animatronics robot, the device developed later should apply Theo Jansen's mechanism since the number of links involved is less than the other mechanism and it is less costly. Besides, the robot is able to operate by using one degree of freedom on each leg which save up a lot of energy consumption. Theo Jansen's mechanism has been proven as an effective leg mechanism to travel in uneven terrain which is very useful for future applications. By constructing a robot with four legs is stable enough to maintain the balance and withstand the force of whole robot. Then, the design is modelling by using Solid Works Software based on the second article (Quadruped Robot Based on the Theo Jansen's Mechanism) as mentioned above. Servo motor are used as an actuator system for the device since a rotation force with high torque and power is required to drive to whole mechanism. For research purpose, a low complexity of fabrication is preferable because it save up a lot budget and the fabricated prototype will become simpler. Moreover, Arduino controller is chosen to control the operation of the device since it is more common and easier to configure. The motor speed will be control by using Arduino microcontroller and motor driver with suitable programming method.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter discussed about project methodology that are carried out in this research. Project methodology is defined as procedure or technique to achieve the research goals. In this chapter, the means of conducting experiments to achieve the research objectives will be discussed. Throughout this chapter, it is focusing on comparing three different designs of small size animatronics robot in terms of different mechanism used.

3.2 Overview of research

The research project is initiated with the study of the concept review of the animatronics robot that has been proposed nowadays. Firstly, motivation is set to understand the response of a product and its marketing situation. Next, identification of the problems is very essential while doing a project. As the problem statements are listed out clearly for solving purposes. Then, objectives and scope should be set up to be achieved at the end of the project. Besides, limitations and constraints of researching an animatronics robot are defined while setting the scopes of the project. Figure 3.1 shows the research methodology.

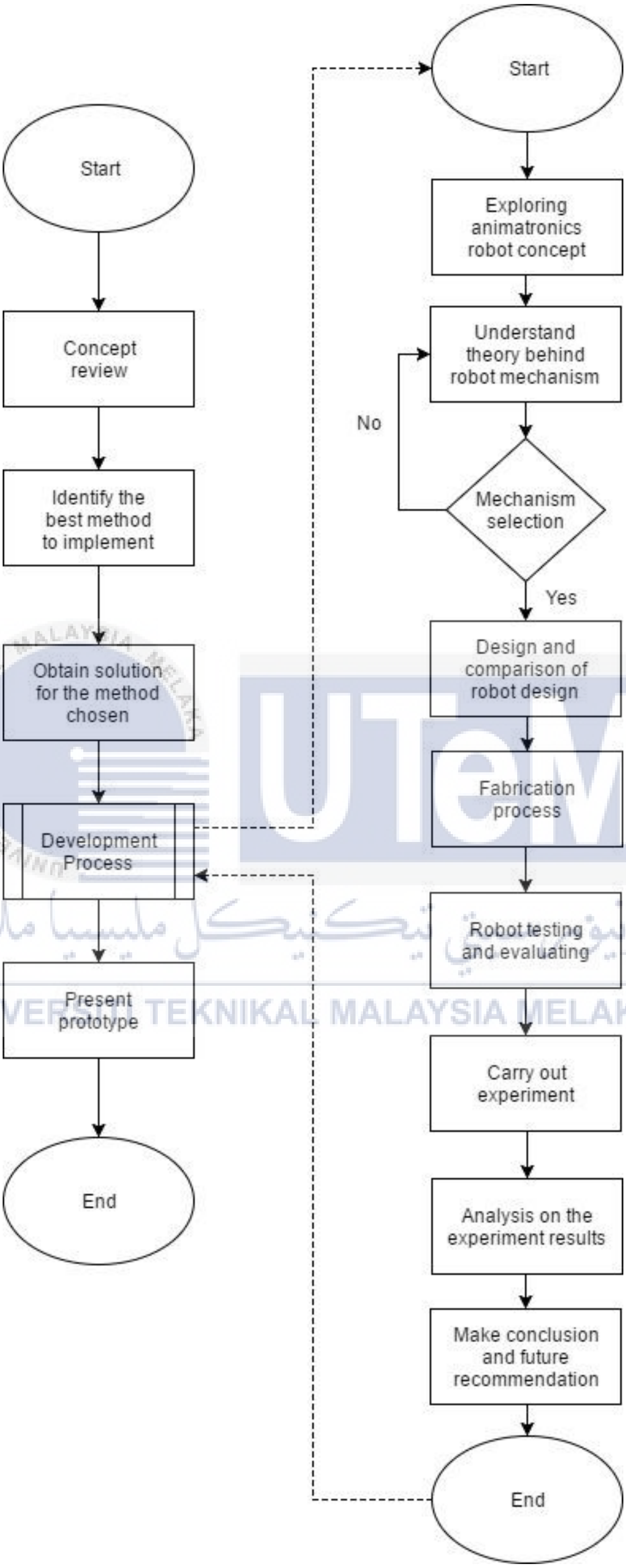


Figure 3.1: Research flowchart

3.3 Design Methodology

3.3.1 Animatronics Design concept

The robot constructed consist of animal walking behaviour since this project is about mechanical construction of an animatronics robot. There are many locomotion types in nature can be applied for quadruped robots, among which walking, running and bounding are the most general locomotion. The robot constructed is based on the locomotion of horse which consists of four legs. According to research done by Muybridge, all four legged animals walk with a fixed pattern of motion which is hind left, front left, hind right and front right. Figure 3.2 above shows the cycle of a walking horse in normal ways. [8]

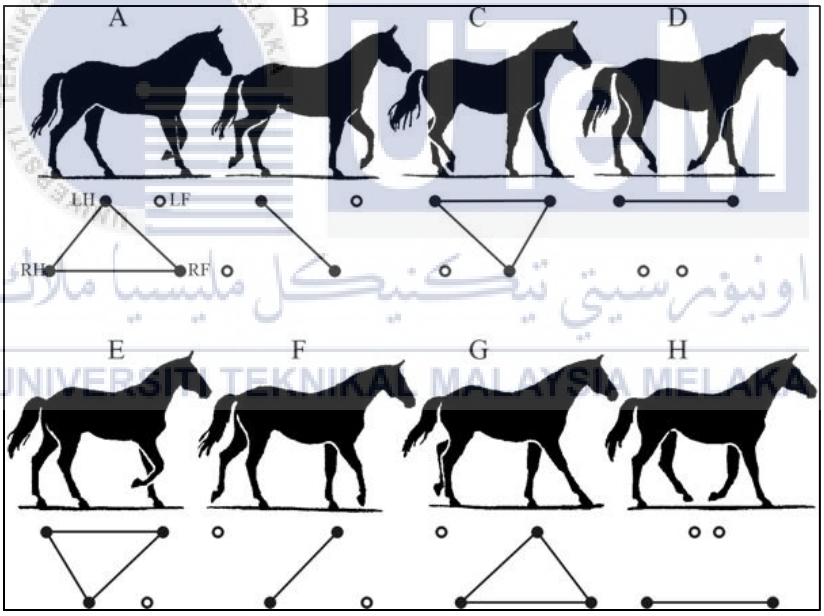


Figure 3.2: Normal cycle of walking horse

Most horses possess 4 natural gaits of movement which are walk, trot, canter and gallop. Firstly, the walk motion is a natural 4-beat movement where the horse always has two or three hooves on the ground. This gait is the slowest gait but it also the steadiest and most comfortable gait if compare to others. The second gait is the trot which is a 2-beat movement. The horse springs from one diagonal to the other and all legs are off the ground in between these springs. This gait is more comfortable for the rider to rise up and down and this means that it is easier for loading and unloading of object. The third gait is canter which is a 3-beat movement where this gait has a period of suspension after each stride. Lastly, the gallop is a 4-beat movement gait where it is similar to canter but the horse's legs move one at a time. Hence, trot gait is chosen as the locomotion movement of quadruped since it is simpler with higher stability and capable of carrying object on the body of robot. [9] Figure 3.3 below shows the beat movement of all gaits mentioned above.

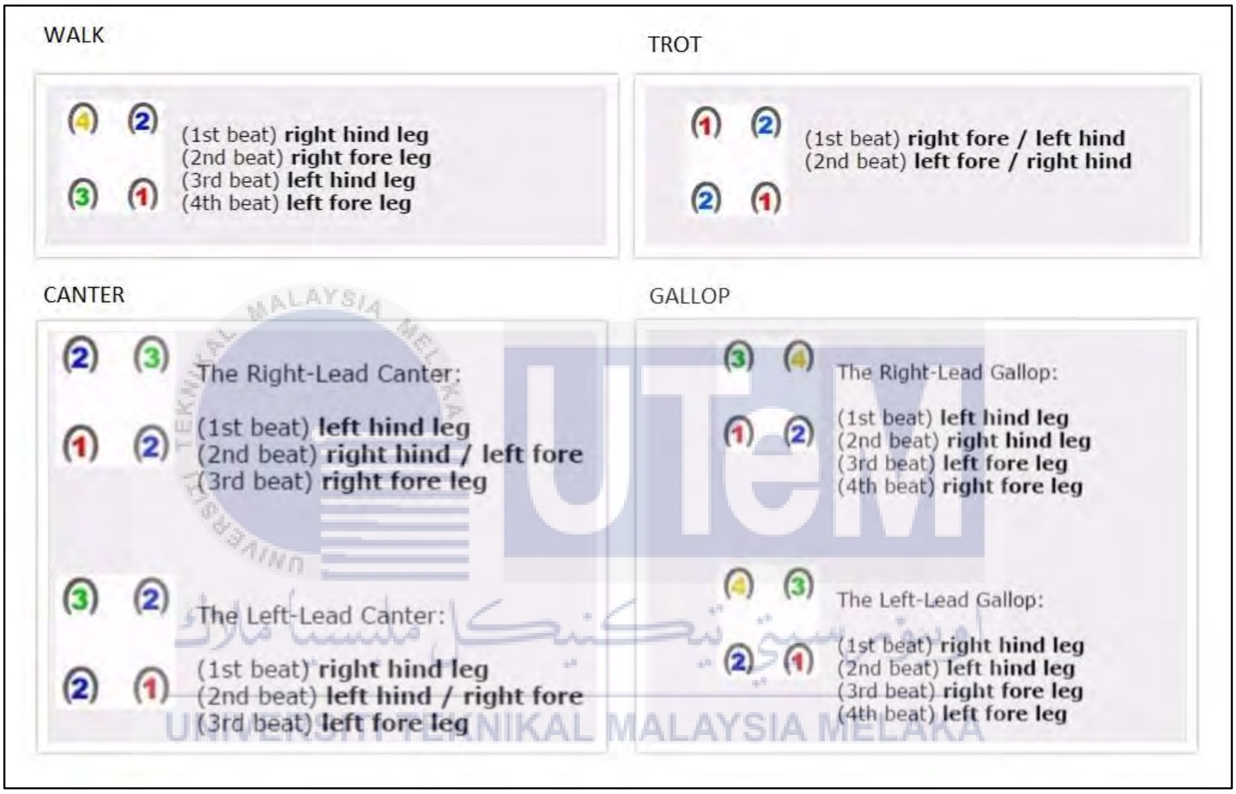


Figure 3.3: Beat movement of gaits for horse

3.3.2 Linkage design mechanism

For Theo Jansen mechanism, it is comprised of two four bar linkages attached to each other in series with only one of the four bar linkages driven by the crank. Figure 3.4 above show the linkages combination for of this mechanism with four bar mechanisms and two couplers connected by a parallel mechanism. Besides, the four bar linkages share one hinge in common and are separated by a rigid triangular structure on one side. [10] This mechanism belongs to the “8-bar mechanism” category because it contains 8 rigid bodies (5 line elements, two triangles, and the ground element). One of the links is designated the “crank” and its motion is controlled by a motor. Lastly, the linkage lengths can refer directly from Theo Jansen’s book “The Great Pretender” [1] but need to undergo suitable types of scaling to suit for the size of designed robot.

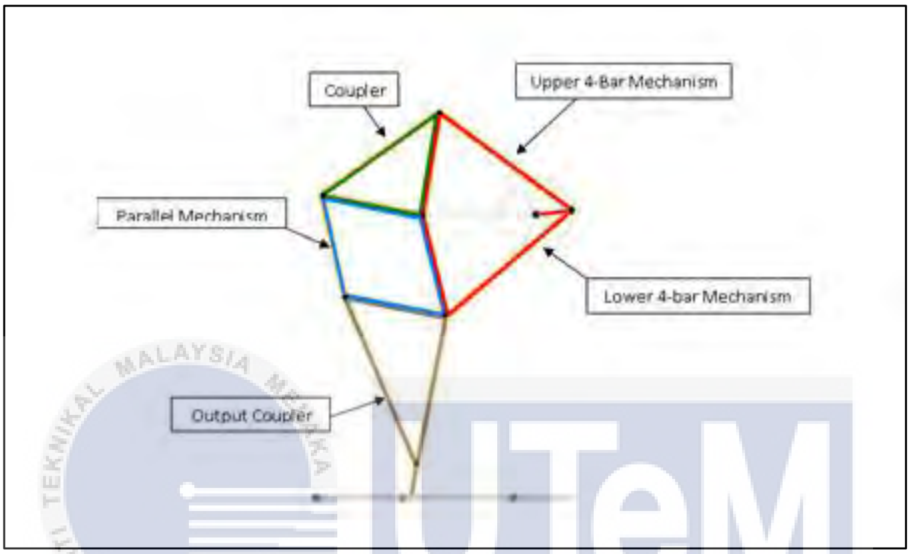


Figure 3.4: Theo Jansen mechanism

3.3.3 Three Initial Design of Animatronics Robot

Figure 3.5 shows the robot the first design of the horse robot. The mechanism used in this robot is Theo Jansen mechanism which consist only two degrees of freedom. Servo motor is used as the actuator to drive mechanism since it does not require any external motor driver to power up the actuator. Besides that, the base of the robot is smaller if compare to others since the controller and power supply is placed in portrait position which saves up a lot of space. This is very important to reduce the weight of the robot and increase the efficiency of the robot. There is only a single shaft connected between crank and the linkages mechanism. The rotating motion of the crank will then drive the mechanism into motion that creates movement of the robot. Hence, this method greatly reduces the complexity and cost of designing the robot. As such, the most important benefit of this mechanism is small base size, light weight, low cost, and most importantly it is easy to operate.

Figure 3.5: Animatronics robot design 1

Figure 3.6 shows the robot the second design of the horse robot. The mechanism used in this robot is also Theo Jansen mechanism. Most of the design are same as the first design except for the linkages design. The size of linkages of Theo Jansen mechanism is smaller and thinner which can reduce the manufacturing cost. The width and length of the linkages is shorter and thinner to increase the speed of the mechanism. Moreover, there are an additional horse head added to the mechanism to improve its animal behaviour. The movement of head linkages is drive by the same crank motion. There is only a single shaft connected between crank and the linkages mechanism. The rotating motion of the crank will then drive the mechanism into motion that creates movement of the robot. Therefore, this design of linkages can create more speed to the motion but it also reduce the stability of robot since the strength of mechanism is reduced.

Figure 3.6: Animatronics robot design 2

Figure 3.7 is the third design of the robot, the mechanism used is also Theo Jansen mechanism. The linkages of mechanism are the same as design one but with smaller size of linkages at each leg and additional gears to drive the mechanism. As additional gears into the robot will create a motion with higher torque and higher stability. Furthermore, the distance between legs and actuation gear increase to increase the overall surface area of contact between robot and ground. By increasing the surface area of contact can greatly increase the stability of robot as its main function is to walk on uneven surface. Hence, this robot is the most desire design since it is more stable, less cost, higher torque produced with simple mechanical construction.

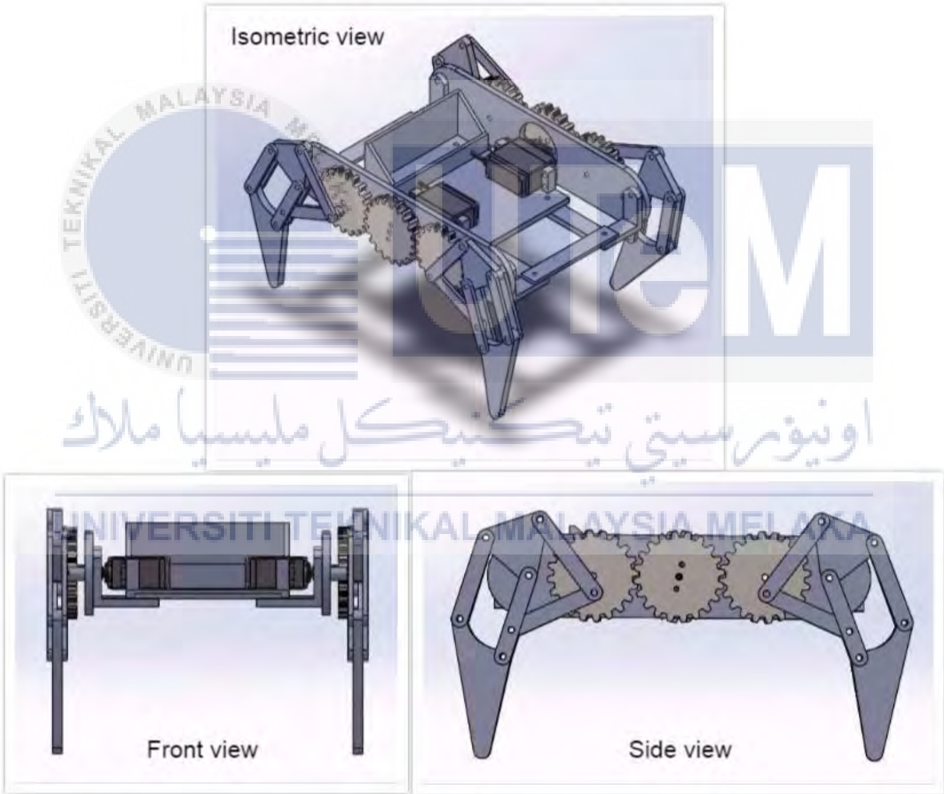


Figure 3.7: Animatronics robot design 3

3.4 Fabrication Process

After chosen the most suitable, the complete SolidWorks files including the design for all of the parts are sent for fabrication. Before fabrication, the robot is simulated in order to know the capability of the strength and safety level of materials via SolidWorks software. SolidWorks part files given to the fabricator must have proper dimension and with correct format in order for the machine to function well and fabricate a product with correct dimension. As a computer aided design (CAD) file is needed for the 3D printer to fabricate into an existing object.

3.4.1 Fabrication material

Poly Lactic Acid (PLA) plastic is selected as material to fabricate the robot since it is more suitable and more light weight to be used in developing the robot based on study from journal and conference paper. Besides, it is a biodegradable plastic which is environmental friendly. The bed temperature range of this material is about 20-55℃ which is very suitable with normal room temperature and extruder temperature is 180-220℃ . PLA is useful in a broad range of printing applications, has the virtue of being both odorless and low-warp, and does not require a heated bed. PLA filament is also one of the more ecofriendly 3D printer materials available. PLA is the material using by the 3D printer in faculty laboratory nowadays as shown in figure 3.8. It is best used for making durable parts that need to withstand high temperature and variation of color. [11]

Figure 3.8: Poly Lactic Acid (PLA) plastic

3.4.2 Fabrication technique

Figure 3.9 above shows a MakaerPi which is a common 3D printer which is used in the fakulty laboratory nowadays. It is a type of 3D printer that places layers of material to create an object. The 3D printer reads every slice of 2D images and proceeds to create the object by blending each layer together with no sign of the layering visible and resulting a one three-dimensional object. This fabrication technique is expanding nowadays which may soon start an industry that everything has the possibility to be manufacture.

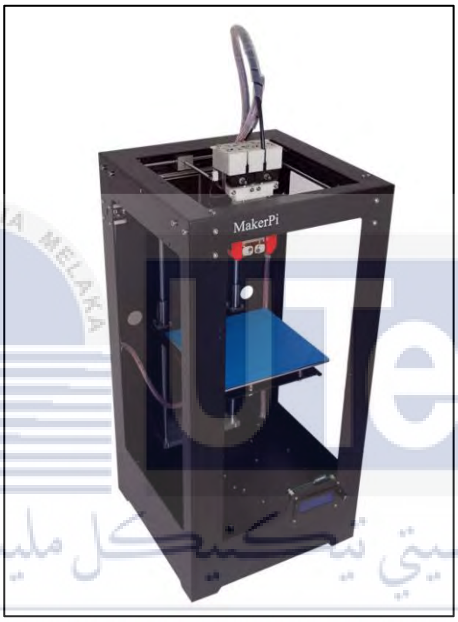


Figure 3.9: MakerPi M2030 Metal Frame 3D printer

3.4.3 Software interface

There are many types of CAD software can be used as an interface software between 3D printer and computer such as SolidWorks, Autodesk Inventor and Rhino as shown in figure 3.10. [12] SolidWorks software is used as the software interface since it is more common and easier to configure. The part files store in the SolidWorks will store in SLDPRT format and need to convert into STL format in order for the 3D printer to fabricate it. There are two main setting to consider for every CAD program which are chordal deviation and angle control. Chordal deviation will determine the maximum distance between surface of original design with the surface of STL triangle created and angle control is the allowable deviation between adjacent triangles.

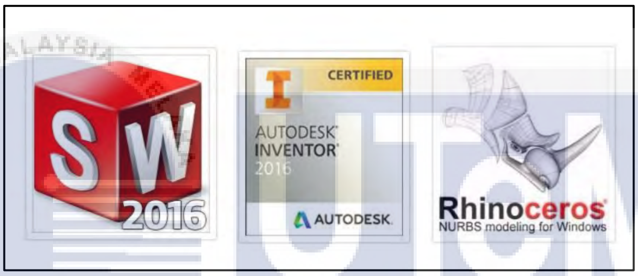


Figure 3.10: CAD software for 3D printer

The STL file generated by the CAD software is then put into CURA software for the 3D printer to simulate the size of printing model and capability to print. CURA will translate the STL file into a format that the 3D printer can handle. The fabrication time and weight of product will be calculated and display in the software as shown in figure above.

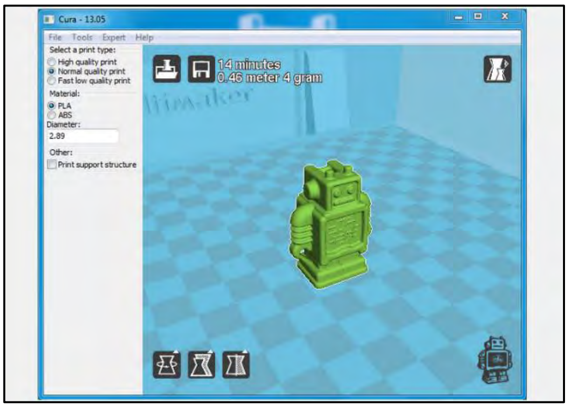


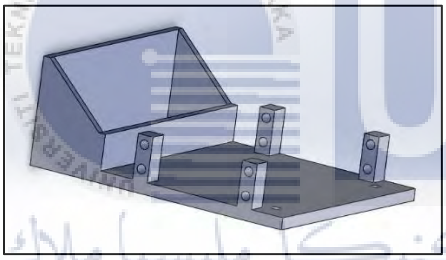
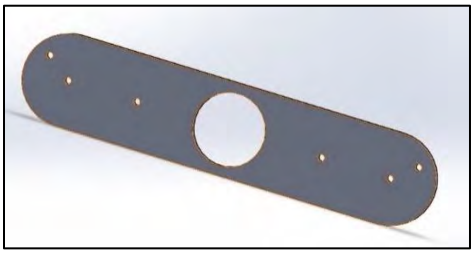
Figure 3.11: Interface in CURA software

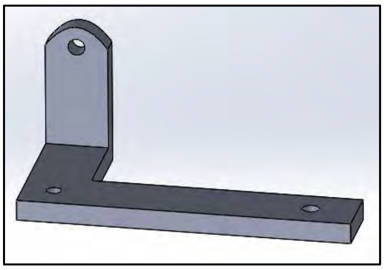
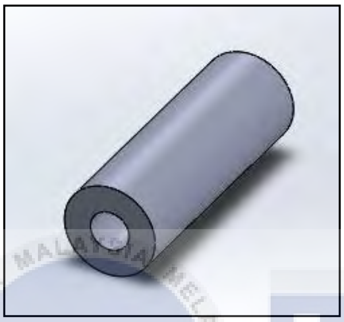
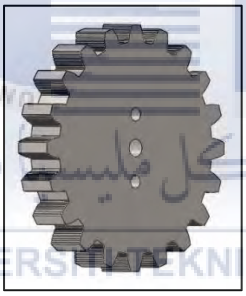
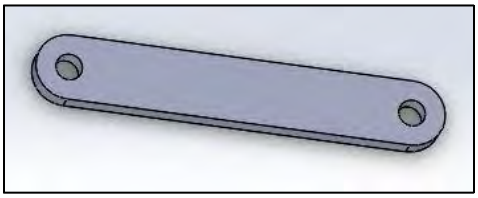
3.5 Hardware Development

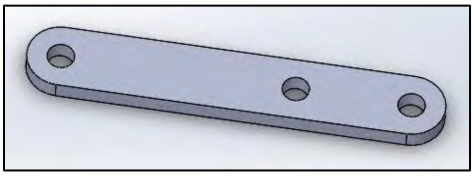
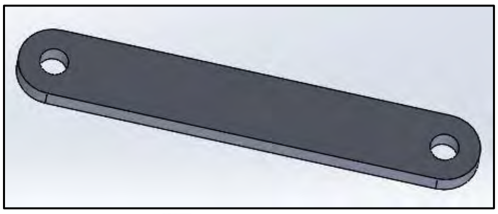
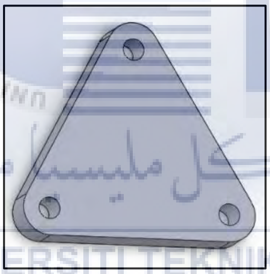
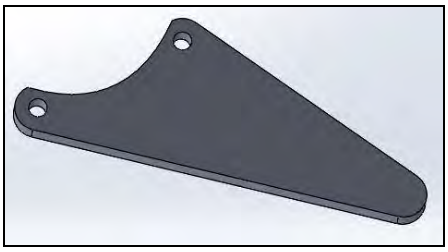
3.5.1 Parts of animatronics robot

The design of parts of animatronics robot is done by using SolidWorks 2016 software. The robot is designed according to the horse leg behaviour. The sequence of movement of robot is trot gait which is a natural 4-beat movement where the horse always has two or three hooves on the ground. Table 3.1 shows the parts of robot that need to be designed in order to complete the whole robot construction.

Table 3.1: Parts of animatronics robot

No.	Parts	Description
1	Robot base 	The main structure of the robot where the servo motor, controller and power supply battery are place on it.
2	Support bar 	A support bar that connects the linkage mechanism with the motor base.

3	Base connector 	A connector use to fix the support between support bar and robot base.
4	Connector tube 	A connector use to fix the support between support bar and robot base.
5	50mm diameter gear 	Gear that use to drive the linkage mechanism. Gear that connect with the shaft of motor to provide motion of mechanism.
6	Linkage 1 	Linkage use to construct Theo Jansen mechanism. It is used to connect upper triangle with lower triangle.

7	Linkage 2 	Linkage use to construct Theo Jansen mechanism. It is used to connect upper triangle with lower triangle.
8	Linkage 3 	One of the linkage on Theo Jansen mechanism. It is used to connect the linkages with the crank shaft.
9	Linkage triangle 	The upper triangle linkage for Theo Jansen mechanism.
10	Leg base 	The lower triangle linkage for Theo Jansen mechanism which is also act as the leg base of the robot.

3.5.2 Construction of Animatronics Robot

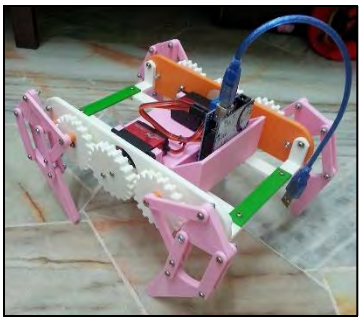
For the hardware, there are many criteria that need to be consider such as the number of legs of robot, degree of freedom of robot, actuator used, mechanism used in robot design, material of robot body, modelling method and controller used to control robot.

For the construction of robot, each of the linkages dimension must be precise and accurate to ensure the working principle of Theo Jansen mechanism. The distance between each parts of the robot must be calculated accurately and precisely to make sure parts can be mate together successfully as shown in table 3.2. In addition, it is pertinent to include tolerance into the holes fabricated as the instalment of screws and nuts is very sensitive to this criterion. The tolerance is one millimetre for a fabricated hole. Thus, the animatronics robot is consisted of four legs with two degrees of freedom. The actuator chosen is JX PDI-6221MG 360-degree metal servo motor. Moreover, the material of the robot body is made up of ABS or PLA thermoplastic. Lastly, the power sources include four 1.5 volt batteries to power servomotors and a 9 volt battery to power up Arduino controller board.

Table 3.2: Parts of animatronics robot

Steps of construction	Explanation
1. 	Servo motor is installed on the robot base of robot by using four M3 screws and nuts on each motor.

2.. 	The base connector is then installed on the robot base to connect base with the support bar.
3. 	The linkages are installed using M3 screws and nuts with washers connected between each linkage to reduce the friction on it.
4. 	After all the linkages is successfully installed the Theo Jansen mechanism is formed by using 8 linkages per legs.
5. 	The linkage formed is then connected on gears and the support bar to drive the mechanism movement.

6. 	After four legs are connected on the support bar, the support bars are combine with the robot base using base connector.
7. 	Now is the part for the connection between servo motor and the gears. The driving gears is first screwed on the shaft of servo motor.
8. 	The driving gear then installed on the servo motor completed the connection gears. The teeth must be properly mate to ensure the smoothness of mechanism.
9. 	The complete hardware assembly of animatronics robot.

3.5.3 Gear and linkage mechanism

Figure 3.12 shows the construction of linkages for a single leg. The robot need four of these legs to complete the robot. The lower triangle is used as a robot leg base and shape can be designed according the robot usage and function.

Figure 3.12: Single leg linkages mechanism

Based on figure 3.13, the gear at the center is connected directly to the shaft of servo motor to provide rotation motion for the linkages mechanism. Then, the rotation motion will drive the gears beside to rotate. The rotation of the gears will create a torque to drive the linkage mechanism since the linkage is connected to the gears by using a shaft. As a result, the rotation motion at the center gear will drive the motion mechanism of linkage and create movement on the robot.

Figure 3.13: Gear and linkage construction

3.5.4 Installation of Servo motor

Every servo motor used has its specific dimension and need to be consider seriously to ensure that the motor is properly installed on the robot base. After considering all the criteria of the motor, a robot base designed according to the motor dimension. This is very pertinent to make sure that the hole extruded on the base fit with the motor hole. Then, the motor is installed on the base by using M3 nut and screw as shown in figure 3.14.

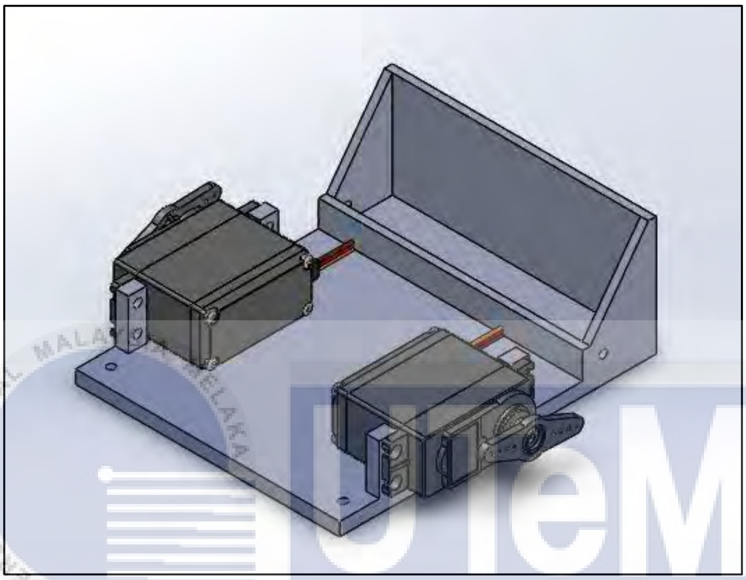


Figure 3.14: Servo motor and robot base

The diameter of the motor hole, base extruded hole and the diameter of M3 screw must be the same in order to complete the instalment perfectly. The screw is then tightened up with a nut to complete the instalment of motor and base as shown in figure 3.15.

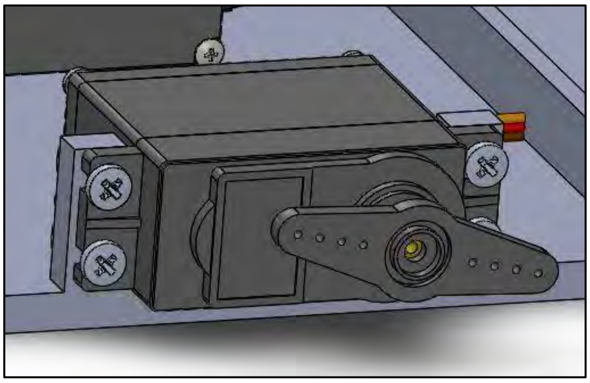


Figure 3.15: Instalment of motor with screw and nut

Table 3.3 shows the key features and specifications of 6221MG servo motor. This is suitable to be used since the stall torque is high enough for Theo Jansen mechanism as the stall torque is only 17.25 kg.cm. The output voltage for Arduino UNO is about 4.9 volt which suitable operating voltage for this motor. Then, metal gears have higher capability to bear the force exerted on it. The servo motor can be purchased with 180 or 360-degree rotation according for the robotic applications.

Figure 3.16: JX PDI-6221MG 360-degree servo motor

Table 3.3: Specification of JX PDI-6221MG servomotor

Operating Speed	4.8V: 0.18sec/60° 6.0V: 0.16sec/60°
Stall Torque	4.8V: 17.25kg.cm(239.55oz/in) 6.0V: 20.32kg-cm (281.89 oz/in)
Operation Voltage	4.8 - 7.2 Volts
Gear Type	All Metal Gears

3.5.5 Installation of controller board

There is a special apartment for the controller to place on it as show in figure 3.17. Since the robot is requires a power supply to power up the controller and actuator a space for the battery is needed also. Therefore, the power supply is place beside the controller to power it up. The power supply is placed just beside the controller since the controller is the only component need to be powered up. Arduino UNO R3 is chosen as the controller for the robot since it is the best microcontroller to get started with electronics and coding. Since, the mainly focus on the mechanical construction so controlling using Arduino Uno is enough to fulfil the condition. Figure 3.18 shows the Arduino UNO controller which is commonly used in simple robot nowadays.

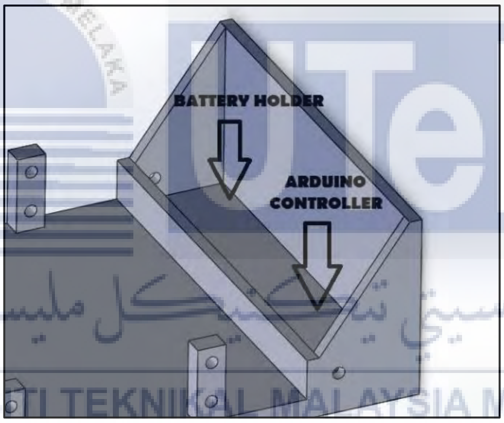


Figure 3.17: Installment of controller board and power supply

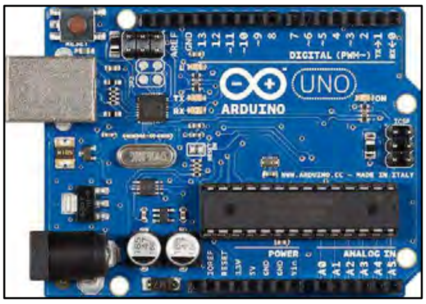


Figure 3.18: Arduino UNO R3

As servo motor needs a lot of power to operate as the efficiency is very low. It is important to realize the required voltage and current to drive the servo motor. Arduino Motor Control Shield L293D is installed on controller board in order for PDI-6221MG servo motor to operate since the stall torque of the motor is very high and the current rated is about 1 A to produce an output rotation. Therefore, the motor shield with current rated of 1.2 A are needed to operate the motor. Table 3.4 shows the key features and specifications of Arduino Motor Control Shield L293D.

Figure 3.19: Arduino Motor Control Shield L293D

Table 3.4: Arduino Motor Control Shield L293D

Current Rated	0.6 A – 1.2 A
Motor driver chips	2
Number of motor support	4 DC motors, 2 servo motors
Voltage drives	4.5 V – 16 V

3.6 Experiment

There are total of three experiments are carried out to study and analysed the animatronics robot performance which are structural analysis, trajectory planning study and gait analysis. It is necessary to carry out many experiment to determine the performance of robot since the robot is a fabrication work that all parts are being assemble together to operate.

3.6.1 Experiment 1: Structural analysis of robot

The three designed robot will be analyse by using Cosmos Works Finite Elements Analysis (FEA) software which is available in SolidWorks analysis tools. Many tests such as stress test, strain test and determination of centre of gravity will be carry out to predict the overall performance of the animatronics robot. Moreover, the overall dimension of the three designed robot will also be showing in this section to aid for analysis purpose.

Centre of mass analysis

The centre of mass is the equivalent center of gravity for a collection mass of bearing particles. It can be calculated by averaging the position of each particle and divide by its mass as shown in equations.

$$x_{cm} = \frac{\sum_i m_i x_i}{\sum_i m_i} \tag{3.1}$$

$$x_{cm} = \frac{1}{M}\int x\, dm \tag{3.2}$$

Where equation 4.1 is for discrete masses of object and equation 4.2 is used for continuous mass distribution object. For legged robot, the position of center of mass (COM) is pertinent since it can be used to estimate the stability of robot. When the COM is outside the support area of the robot body it has a risk of falling over and cause the robot become unstable. In particular, the animatronics robot should have COM slightly in front of the robot to make the robot in a direction of moving forward to aid for the robot movement. [13] Hence, determination of center of gravity is very important for an animatronics robot since it can increase the stability and balancing of a robot.

Stress, strain and displacement analysis

Stress and strain are defined on the basic of a simple uniaxial tension test. Stress is defined as force of resistance offered by a body against the deformation. Equation 4.2 shows the equation of stress which is used to express the loading in terms of force applied to a certain cross-sectional area of an object. Equation 4.3 shows the equation of strain where it shows the response of a system to an applied stress. In engineering fields, strain is defined as the amount of deformation in direction of applied force divided by the initial length of the material. It is very pertinent to determine the stress and strain limit of a material or structure since elastic deformation and the plastic deformation may occur as the material is loaded beyond its elastic limit. [14]

$$Stress, \sigma = \frac{F}{A_o} \tag{3.3}$$

$$Strain = \frac{\Delta L}{L_o} \tag{3.4}$$

Where F is the force exerted on object, A_o stands for cross sectional area, ΔL stands for the elongation of the object and L_o is the original length of the object.

3.6.2 Experiment 2: Path trajectory planning study

This section explains about the trajectory movement of the desire animatronics robot and to study Theo Jansen mechanism. The path of the legs movements is analysed by using MATLAB simulation software as shown in figure 4.1. After that, the coordinate system of the robot leg path data is collected in a table with related variable like joint angle, horizontal displacement, vertical displacement. The study focused on one of the legs of robot only since the linkages length and design for every leg is the same. For every degree of rotation of driving crank, the path for end point of leg base are identify and store the result data in coordinate system form.

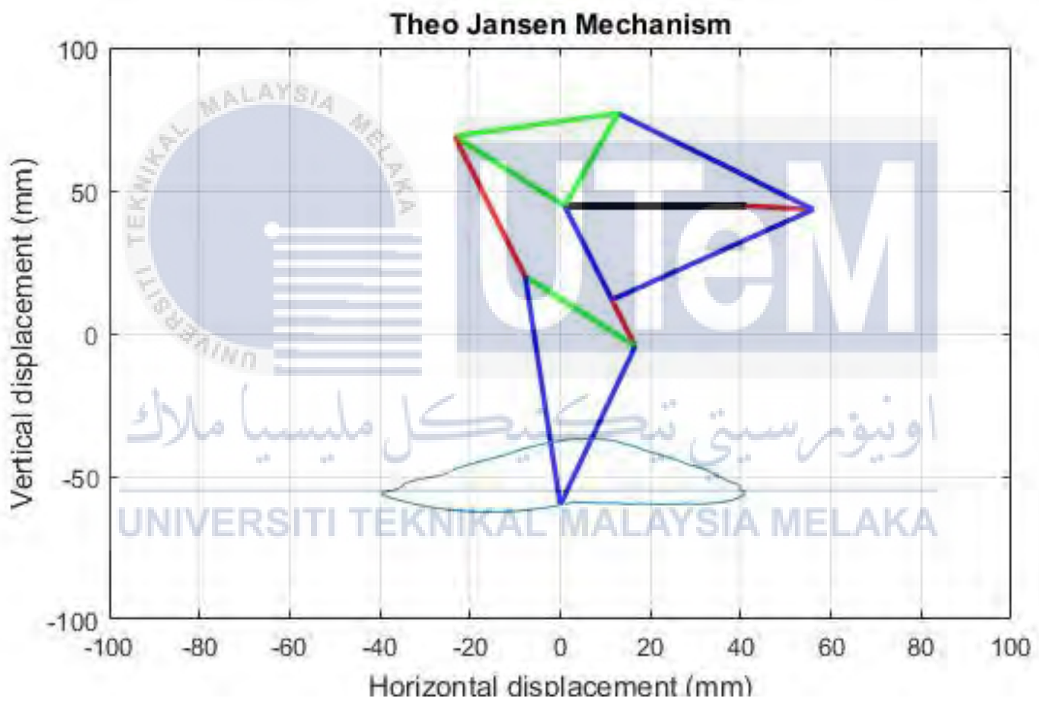


Figure 3.20: Matlab simulation

For Matlab simulation, the coding of Theo Jansen mechanism must be developed first to do the analysis. Firstly, the variables of the linkages must be declared first in order to simulate the linkages movement. The length for each linkage must be declare according to the actual design of the prototype as shown in figure 4.2. The mechanical linkages are then brought into many function and equation to start the coding.

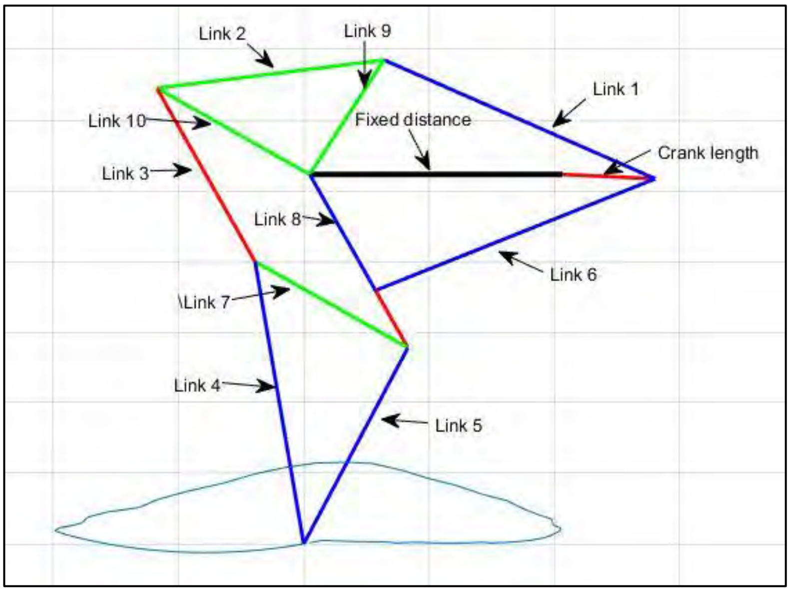


Figure 3.21: Theo Jansen mechanism linkages

$$\text{crank\_x} = 41.288 \tag{3.5}$$

$$\text{pin\_x} = \text{crank\_x} - (40.33/1) \tag{3.6}$$

$$\text{node\_1\_x} = \text{pin\_x} \tag{3.7}$$

$$\text{node\_2\_x} = \text{pin\_x} - \text{link\_9} \tag{3.8}$$

$$\text{link\_8\_t} = 3/4*\text{pi} \tag{3.9}$$

The length of the legs, the distance between the crank and the pivot, and the angle of crank are the values needed to be run in the coding. The crank angle at certain degree is important to find the end point of the leg base. After all the variables are declared, equation 4.4 shows the starting position of the link then equation 4.5 state that the length between crank pivot and the linkage fixed point. The end point at the fixed point is state in equation 4.6 as node 1 Then nodes need to be determine form the starting position. Equation 4.7 is used to state the length from the fixed point to the end of link 9. Then equation 4.8 is used to shows the angle of rotation of the specific link. Different theta must be declared for different position of nodes.

$$\text{for } t=0:0.1:1*2*\text{pi} \tag{3.10}$$

$$\text{node\_1\_x} = \text{pin\_x} + \text{link\_9}*\cos(\text{link\_9\_t}) \tag{3.11}$$

dist_tmp = sqrt((node_0_x-node_1_x)^2+(node_0_y-node_1_y)^2) (3.12)

plot([node_3_x node_6_x], [node_3_y node_6_y],'b','linewidth', 2) (3.13)

x(end+1) = node_6_x (3.14)

plot(x,y) (3.15)

While running simulation, many for loop is used to simulate Theo Jansen linkage movement. Equation 4.9 is used to set the degree of rotation of the crank. Then equation 4.10 and 4.11 is used to shows the movement of link 9 by calculating the angle and temporary distance in the simulation. The for loop repeat six times to develop the movement of six nodes in the mechanism. Moreover, equation 4.12 is used to plot out link 5 in the simulation graph. Each of the linkages need to be plot by using corresponding nodes to shows the linkage motion in the graph. Lastly, equation 4.13 and 4.14 are used to plot the path movement of the end point at leg base.

3.6.3 Experiment 3: Real time hardware experiment

Figure 3.22 shows the overview design of the robot where the position of controller, servo motors, gears and linkages can be shown in the figure. Each of the legs consist of 5 parts and assembled together to form a Theo Jansen linkage mechanism. The linkage motion is drove by a gear and shaft where the torque is produced by the center gear that connect directly to servo motor.

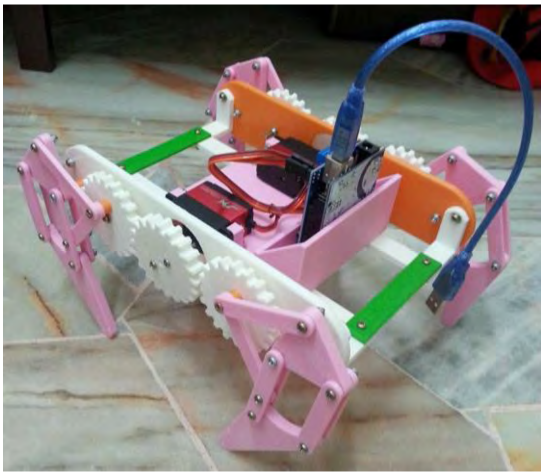


Figure 3.22: Complete hardware design of animatronics robot

During experiment, the robot is slanted to carry out the experiment as shown in figure 3.23. Firstly, a pencil is connected at the leg base to draw out the path motion at the leg base. Then, the crank angel is set to 40 degrees to collect the path movement result. The result is taken for every 40 degrees of crank angel moved. As such, a complete cycle of path movement is obtained will nine data of X and Y coordinates collected. The result is then tabulated in table form and imported into Matlab software to compare with the simulation result. The experiment repeated for 8 times to obtain a repeatability test result for the path trajectory at the end effector. The results is then calculated and tabulated in table form to obtain the average position for each crank angel applied.

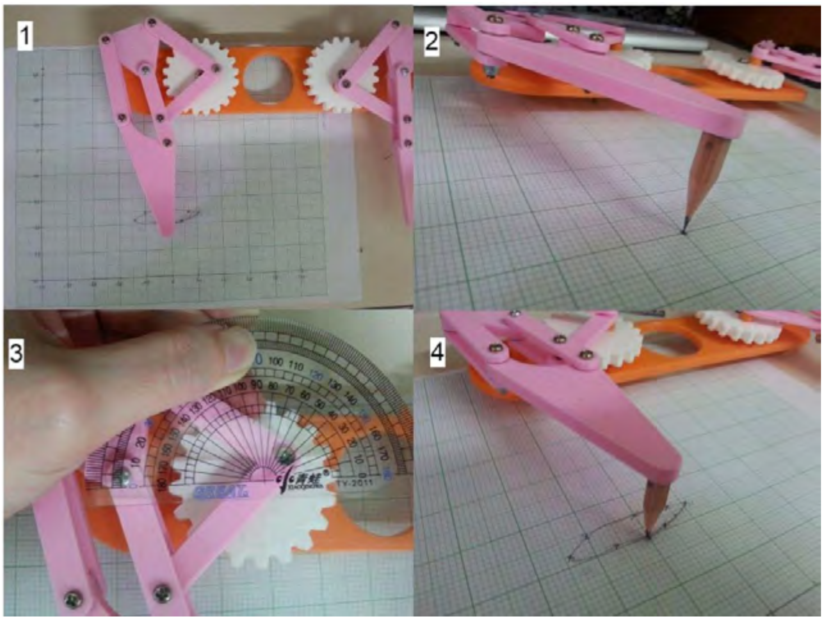


Figure 3.23: Data collecting procedure

Furthermore, an accuracy test is carried out by calculating the percentage of error. However, the calculation of percentage of error only carry out on some of the angle due to the limitation on the hardware.

$$\text{Error} = \text{measured value} - \text{actual value} \tag{3.16}$$

$$\text{Percentage error} = \frac{error}{actual\ value} \times 100\% \tag{3.17}$$

where the actual value is the value get from Matlab simulation and the measured value is the value of the hardware.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Experiment 1: Structural Analysis of robot

4.1.1 Centre of mass analysis

Design 1 center of mass analysis

The blue circle in figure 4.1 indicate the position of centre of mass located on robot design 1. The location of the centre of mass is measured with respect to the origin as shown in figure above with distance of X-axis = 49.41mm, Y-axis = 19.67mm, and Z-axis = 87.42mm.

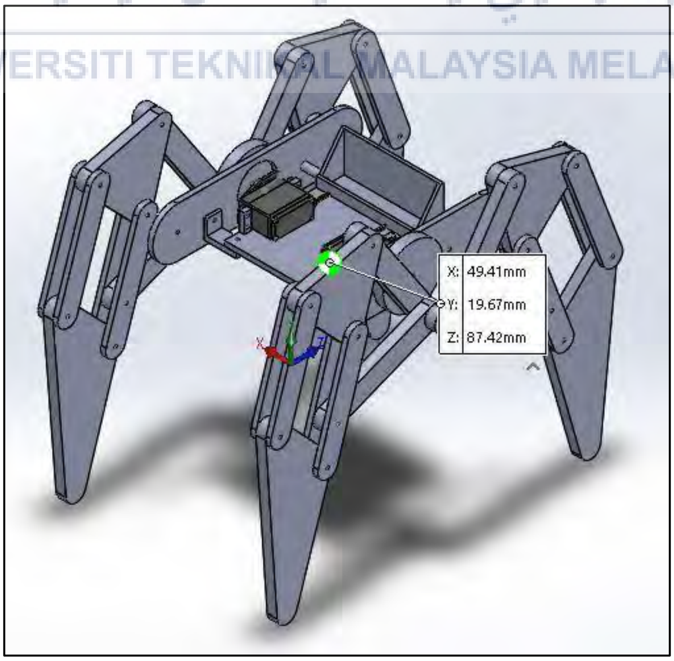


Figure 4.1: Centre of mass for design 1

Figure 4.2 shows the position of centre of mass with different types of view which are top view, front view, and side view. The length shows in the figure above are measured in unit millimetres.mm. The centre of mass is very pertinent to determine the overall stability of a legged robot.

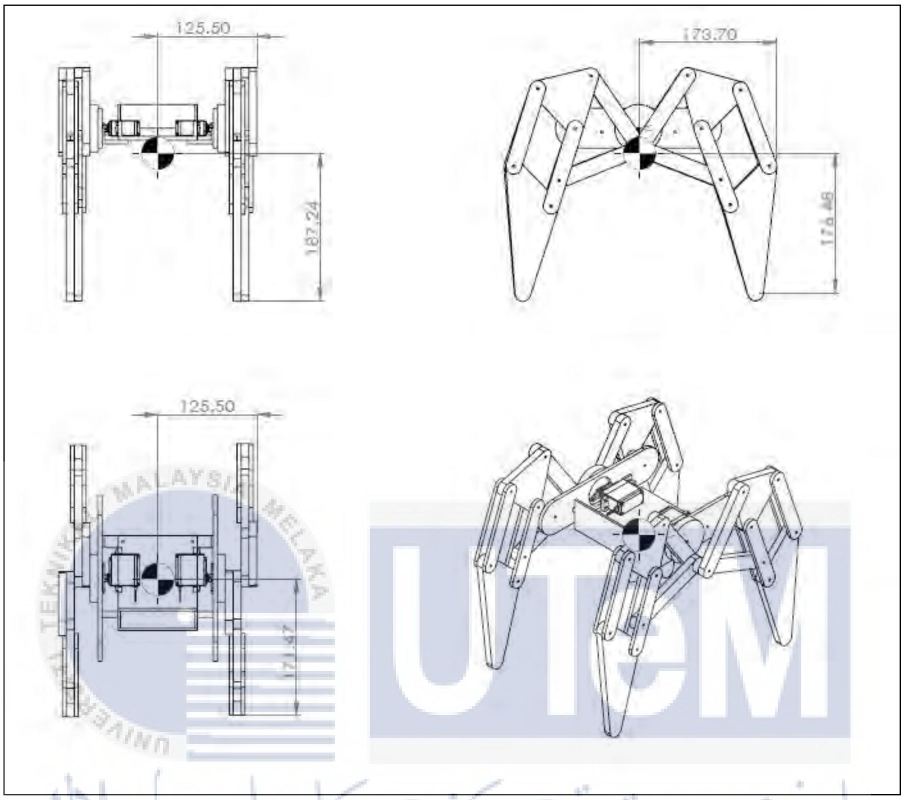


Figure 4.2: Design 1 centre of mass view

Figure 4.3 shows data for robot mass, volume, moments of inertia can also be obtained by generating the mass properties feature in SolidWorks software.

```
Mass properties of Theo Design 1 assem
    Configuration: Default
    Coordinate system: -- default --

Mass = 1153.02 grams

Volume = 1150371.15 cubic millimeters

Surface area = 412972.77  square millimeters

Center of mass: ( millimeters )
     X = 49.41
     Y = 19.67
     Z = 87.42

Principal axes of inertia and principal moments of inertia: ( grams *  square millimeters )
Taken at the center of mass.
     Ix = (-0.47,  0.00,  0.88)      Px = 15274553.73
     Iy = ( 0.88,  0.00,  0.47)      Py = 16521422.35
     Iz = ( 0.00,  1.00,  0.00)      Pz = 21999085.82

Moments of inertia: ( grams *  square millimeters )
Taken at the center of mass and aligned with the output coordinate system.
     Lxx = 16242836.57      Lxy = -1027.96        Lxz = -519373.46
     Lyx = -1027.96         Lyy = 21999066.29     Lyz = 11221.21
     Lzx = -519373.46       Lzy = 11221.21        Lzz = 15553159.05

Moments of inertia: ( grams *  square millimeters )
Taken at the output coordinate system.
     Ixx = 25501204.05      Ixy = 1119691.73      Ixz = 4461354.82
     Iyx = 1119691.73       Iyy = 33626418.60     Iyz = 1994066.14
     Izx = 4461354.82       Izy = 1994066.14      Izz = 18814468.54
```


Figure 4.3: Mass properties for design 1

Design 2 center of mass analysis

The yellow circle in figure 4.4 indicate the position of centre of mass located on robot design 2. The location of the centre of mass is measured with respect to the origin as shown in figure 4.4 with distance of X-axis = 49.42mm, Y-axis = 47.17mm, and Z-axis = 87.86mm.

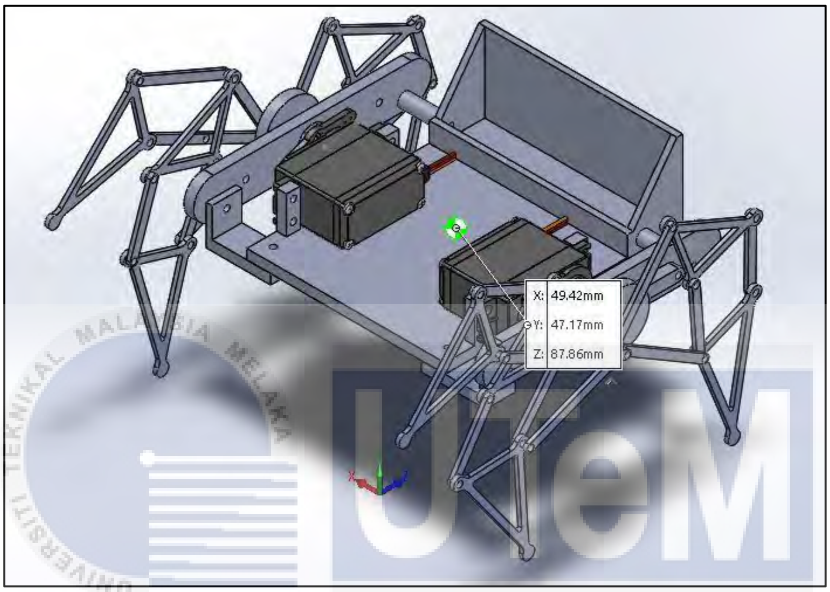


Figure 4.4: Centre of mass for design 2

Figure 4.5 shows the position of centre of mass with different types of view which are top view, front view, and side view. The length shows in the figure above are measured in unit millimetres.mm. The centre of mass is very pertinent to determine the overall stability of a legged robot.

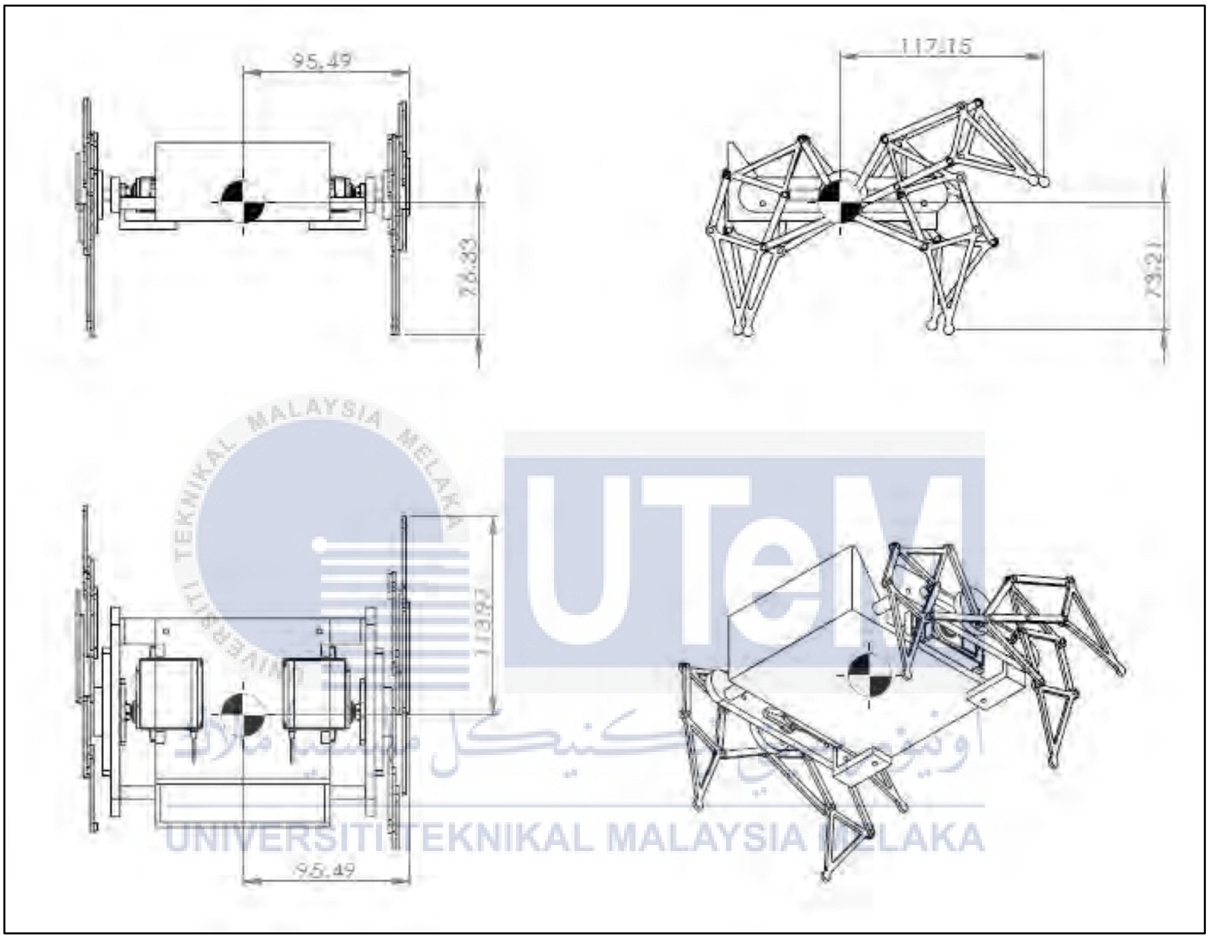


Figure 4.5: Design 2 centre of mass view

Figure 4.6 shows data for robot mass, volume, moments of inertia of the robot. The data can be obtained by generating the mass properties feature in SolidWorks software.

```
Mass properties of Robot Base completed assem
    Configuration: Default
    Coordinate system: -- default --

Mass = 199.77 grams

Volume = 197114.79 cubic millimeters

Surface area = 114773.46  square millimeters

Center of mass: ( millimeters )
     X = 49.42
     Y = 47.17
     Z = 87.86

Principal axes of inertia and principal moments of inertia: ( grams *  square millimeters )
Taken at the center of mass.
      Ix = ( 1.00,  0.00,  0.01)      Px = 268369.69
      Iy = ( 0.01, -0.02, -1.00)      Py = 561168.14
      Iz = ( 0.00,  1.00, -0.02)      Pz = 775251.35

Moments of inertia: ( grams *  square millimeters )
Taken at the center of mass and aligned with the output coordinate system.
     Lxx = 268412.13          Lxy = -84.39             Lxz = 3524.97
     Lyx = -84.39             Lyy = 775181.19          Lyz = 3874.04
     Lzx = 3524.97            Lzy = 3874.04            Lzz = 561195.86

Moments of inertia: ( grams *  square millimeters )
Taken at the output coordinate system.
     Ixx = 2254875.20         Ixy = 465603.82          Ixz = 870994.40
     Iyx = 465603.82          Iyy = 2805223.45         Iyz = 831703.57
     Izx = 870994.40          Izy = 831703.57          Izz = 1493591.27
```


Figure 4.6: Mass properties for design 1

Design 3 center of mass analysis

The blue circle in figure 4.7 indicate the position of centre of mass located on robot design 3. The location of the centre of mass is measured with respect to the origin as shown in figure above with distance of X-axis = 51.57mm, Y-axis = 31.22mm, and Z-axis = 94.06mm.

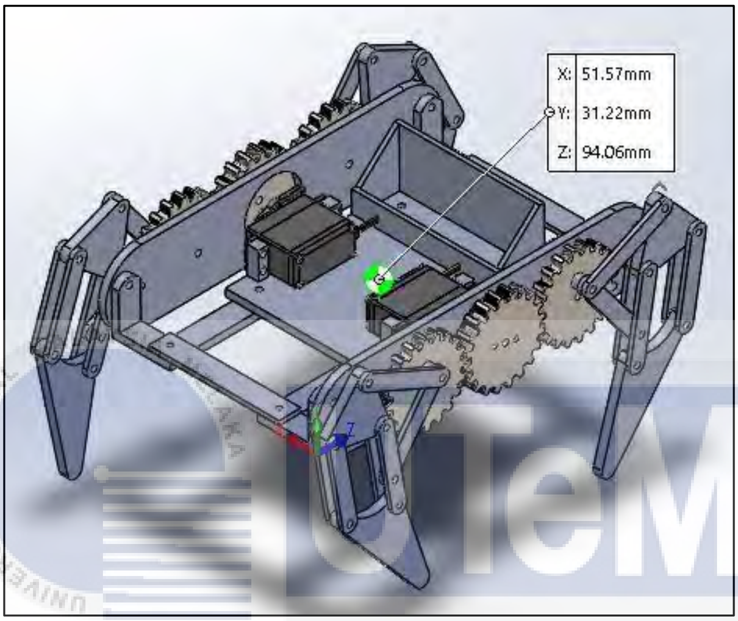


Figure 4.7: Centre of mass for design 3

Figure 4.8 shows the position of centre of mass with different types of view which are top view, front view, and side view. The length shows in the figure above are measured in unit millimetres.mm. The centre of mass is very pertinent to determine the overall stability of a legged robot.

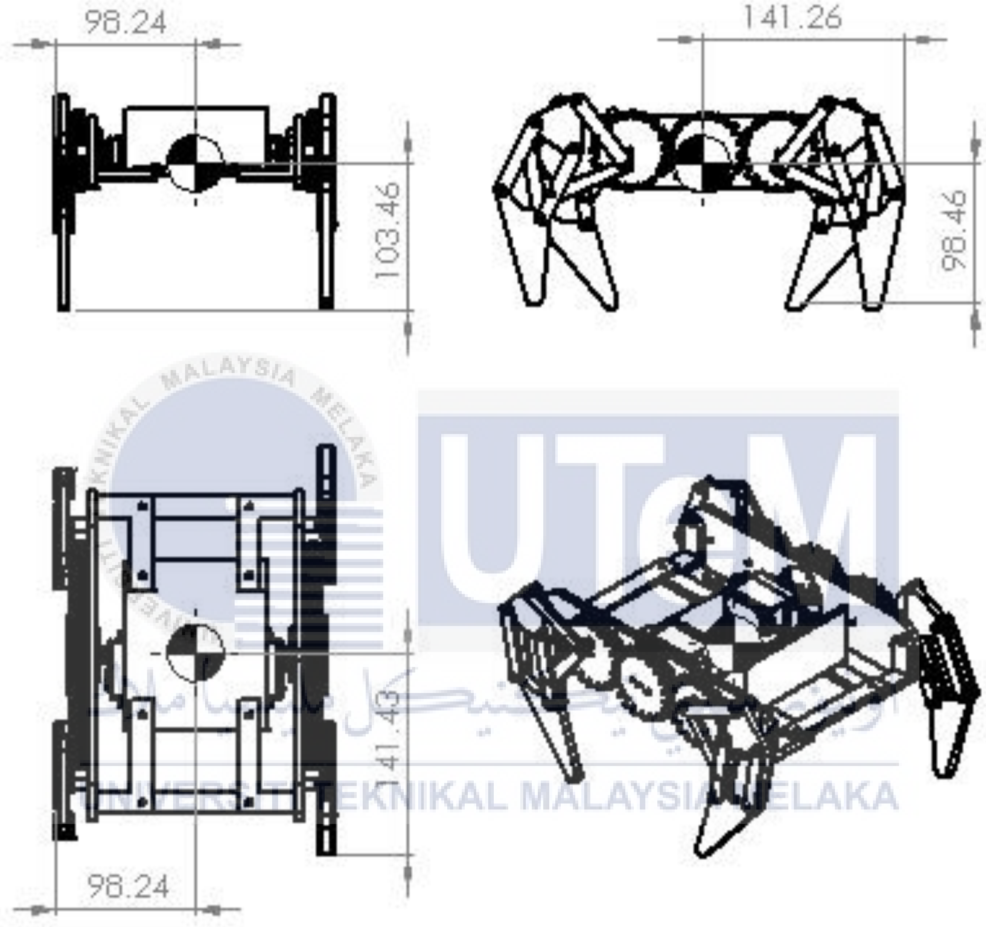


Figure 4.8: Design 3 centre of mass view

Figure 4.9 shows data for robot mass, volume, moments of inertia can also be obtained by generating the mass properties feature in SolidWorks software.

Mass properties of Design 4 complete assembly
Configuration: Default
Coordinate system: -- default --

Mass = 497.01 grams

Volume = 494353.56 cubic millimeters

Surface area = 255224.50 square millimeters

Center of mass: (millimeters)
X = 51.57
Y = 31.22
Z = 94.06

Principal axes of inertia and principal moments of inertia: (grams * square millimeters)
Taken at the center of mass.

Ix = (1.00, 0.01, 0.06)	Px = 2561925.81
Iy = (0.06, -0.01, -1.00)	Py = 2701984.78
Iz = (-0.01, 1.00, -0.01)	Pz = 4744991.40

Moments of inertia: (grams * square millimeters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 2562661.22	Lxy = 22806.00	Lxz = 8016.14
Lyx = 22806.00	Lyy = 4744314.17	Lyz = 30028.41
Lzx = 8016.14	Lzy = 30028.41	Lzz = 2701926.59

Moments of inertia: (grams * square millimeters)
Taken at the output coordinate system.

Ixx = 7444092.56	Ixy = 823065.91	Ixz = 2418946.31
Iyx = 823065.91	Iyy = 10463245.37	Iyz = 1489518.65
Izx = 2418946.31	Izy = 1489518.65	Izz = 4508323.47

Figure 4.9: Mass properties for design 3

4.1.2 Stress, strain and displacement analysis

For stress analysis, a force of 9.81 N is apply on the support bar as the weight of the robot is about 1 kg. The stress analysis is mainly focused on the gears by applying torque of 1.7 Nm or 17.25 kg.cm on the driving gears. The material for the parts is all ABS plastic which is very similar to material of PLA plastic.

Design 1 Stress, strain, displacement analysis

According to figure 4.10, the stress analysis is acceptable since the colour of the crank are mostly green colour which is within the safety limit. The red colour indicates the range stress value which is too high which is beyond the elastic limit and elastic deformation may occur.

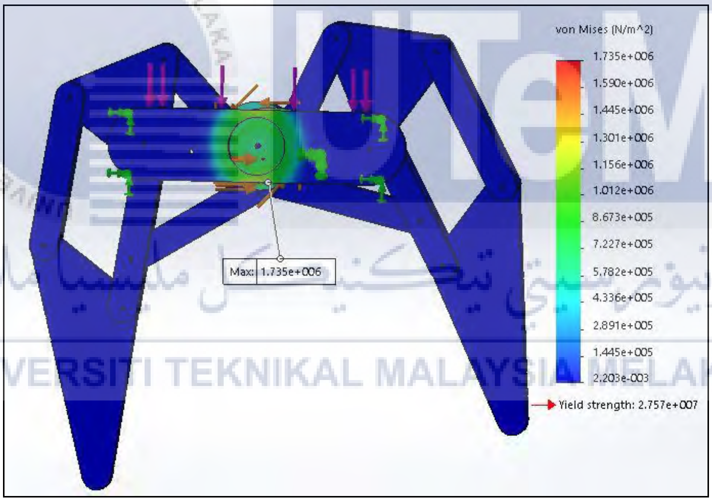


Figure 4.10: Stress analysis for design 1

According to figure 4.11, the strain analysis for design 1 is acceptable since the colour of the crank are mostly green and blue colour which is within the safety limit. There is a small portion of red area region on the support bar but this will not cause any serious problem since the portion is too small to affect the whole linkages.

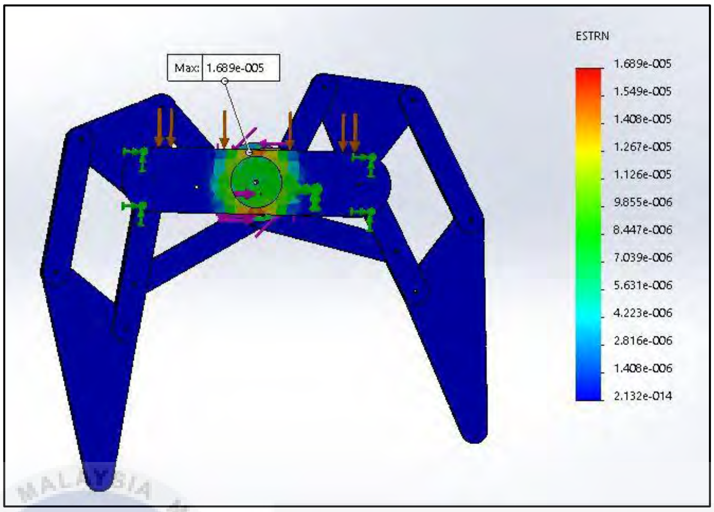


Figure 4.11: Strain analysis for design 1

Figure 4.12 shows the displacement analysis for robot design 1. The red colour indicated the area where the displacement occur is the most. This analysis shows the parts or area where the displacement occurs the most for linkage design 1.

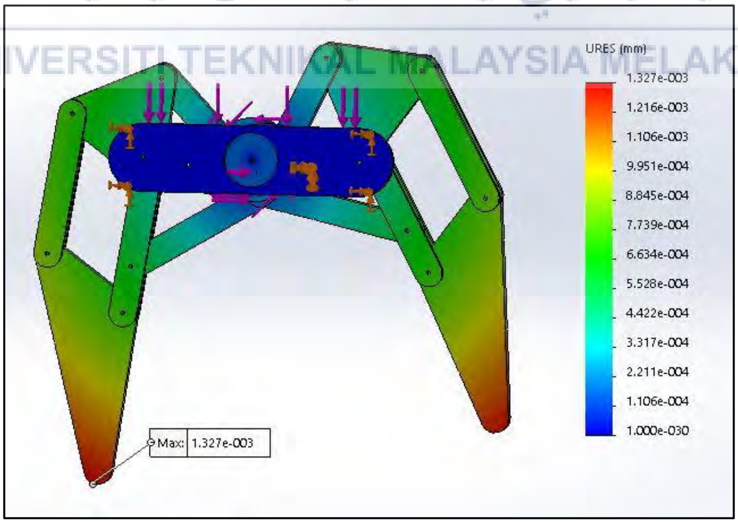


Figure 4.12: Displacement analysis for design 1

Design 2 Stress, strain, displacement analysis

According to figure 4.13, the stress analysis is acceptable since the colour of the crank are mostly green colour which is within the safety limit. The red colour indicates the range stress value which is too high which is beyond the elastic limit and elastic deformation may occur.

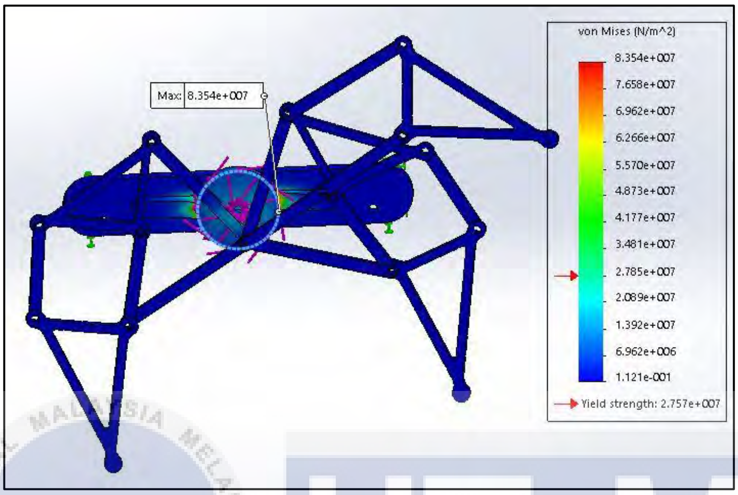


Figure 4.13: Stress analysis for design 2

According to figure 4.14, the strain analysis for design 1 is acceptable since the colour of the crank are mostly green and blue colour which is within the safety limit. The orange arrows indicate the direction of torque applied.

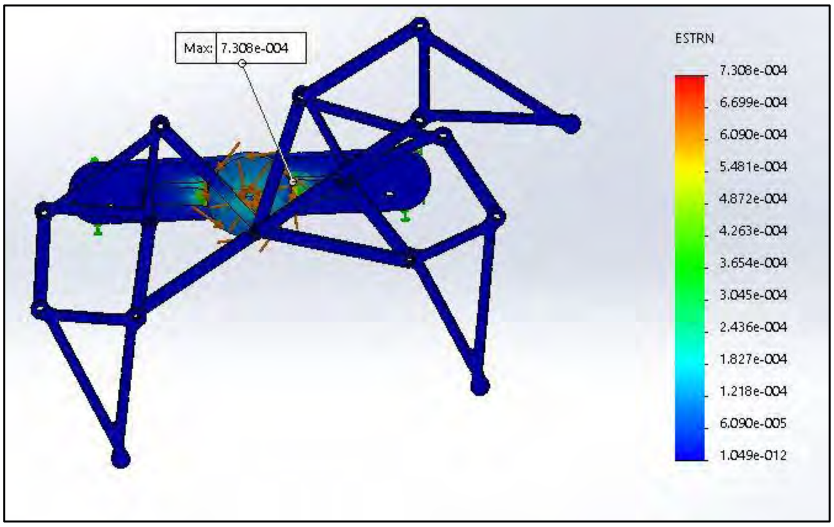


Figure 4.14: Strain analysis for design 2

Figure 4.15 shows the displacement analysis for robot design 2. The red colour indicated the area where the displacement occur is the most. This analysis shows the parts or area where the displacement occurs the most for linkage design 2 which is the head of the horse.

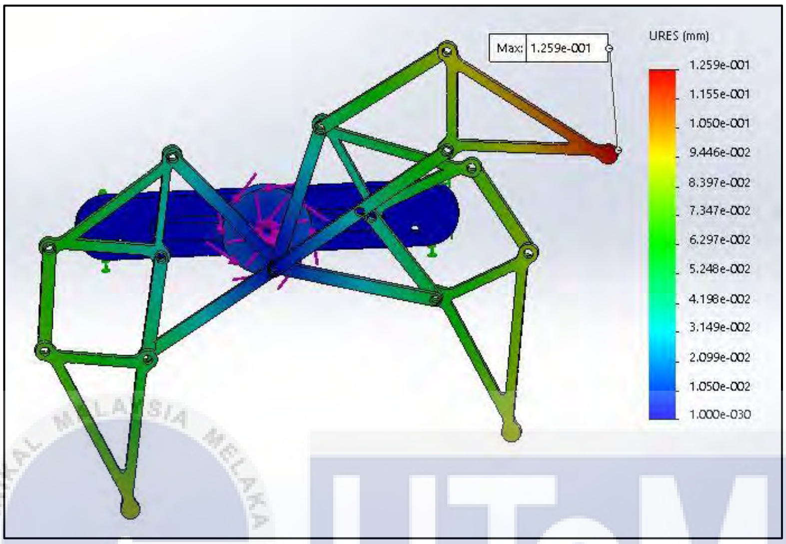


Figure 4.15: Displacement analysis on design 2

Design 3 Stress, strain, displacement analysis

According to figure 4.16, the stress analysis is acceptable since the colour of the crank are mostly green colour which is within the safety limit. The red colour indicates the range stress value which is too high which is beyond the elastic limit and elastic deformation may occur.

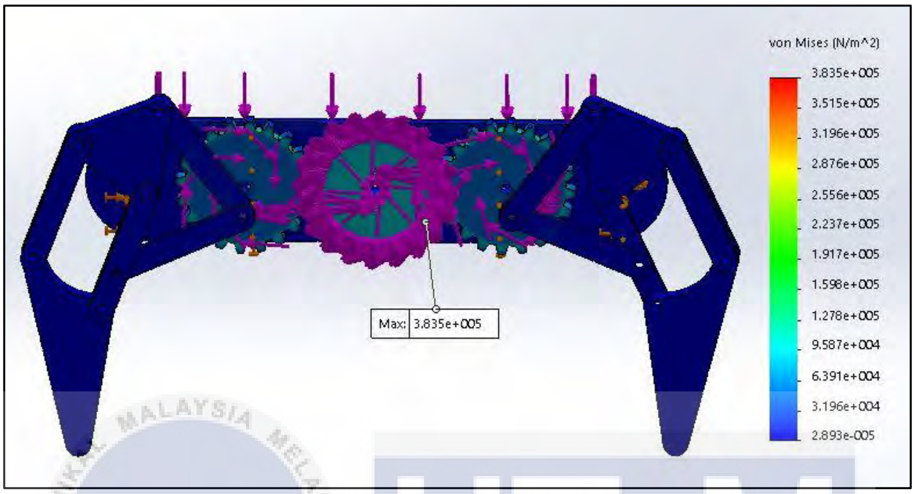


Figure 4.16: Stress analysis for design 3

According to figure 4.17, the strain analysis for design 3 is acceptable since the colour of the crank are mostly green and blue colour which is within the safety limit. There is a small portion of red area region on the support bar but this will not cause any serious problem since the portion is too small to affect the whole linkages.

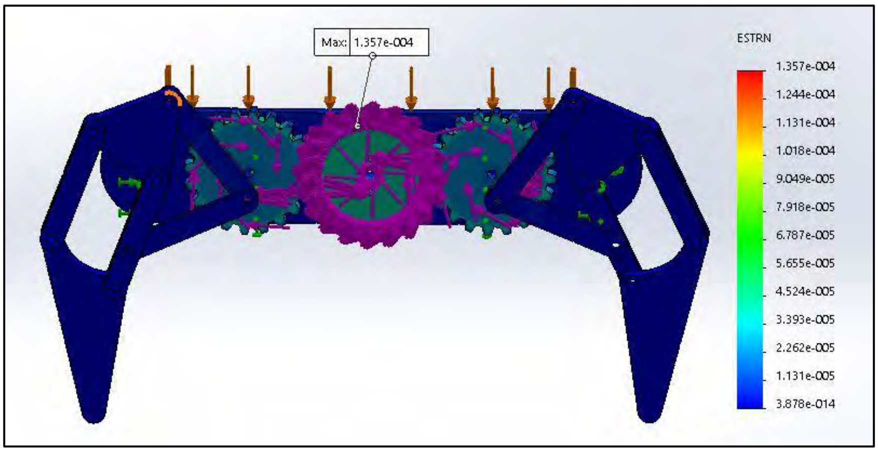


Figure 4.17: Strain analysis for design 3

Figure 4.18 shows the displacement analysis for robot design 3. The red colour indicated the area where the displacement occur is the most. This analysis shows the parts or area where the displacement occurs the most for linkage design 3.

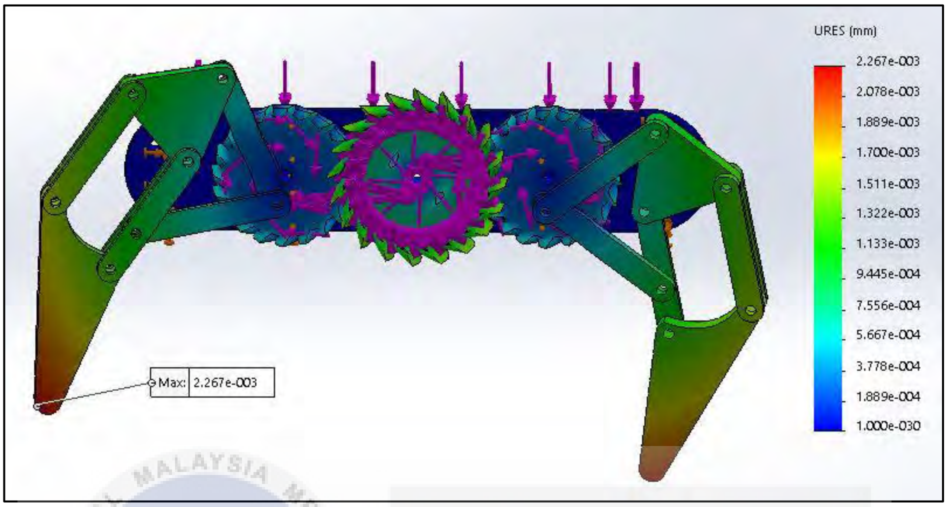


Figure 4.18: Displacement analysis on design 3

4.1.3 Summary of structural analysis

In conclusion, robot design three is chosen as the desire robot to be fabricated since the robot is more stable and more reliable compare to the others as the height of the robot is lower with smaller dimension of linkages mechanism. Furthermore, the additional gears into the linkage mechanism can increase the torque generated by the motor to drive the mechanism. Moreover, the surface area of contact between the legs and the ground is bigger compared to the others.

4.2 Experiment 2: Path trajectory planning study

The result is then collected in Matlab software as shown in table 4.1. The results are obtained by crank angle rotate and resulting different horizontal displacement and vertical displacement. There are 63 data collected where the crank angle is set on 0 rad and starting point of the path is 0 on x-axis and -60 on the y-axis. the maximum horizontal displacement and maximum vertical displacement can be calculated by using equation:

$$\text{Maximum displacement} = \text{maximum value} - \text{minimum value} \qquad (4.15)$$

where the values are all in unit millimetres. According to table 4.1, the maximum horizontal displacement is 80.66mm where the maximum vertical displacement is 25.56mm.

Table 4.1: Simulation data result

Crank Angle (rad)	Horizontal displacement (mm)	Vertical displacement (mm)
0	0.98	-59.68
0.1	1.95	-59.34
0.2	2.91	-58.97
0.3	6.11	-59.21
0.4	9.31	-59.34
0.5	12.53	-59.36
0.6	14.82	-59.71
0.7	18.06	-59.53
0.8	20.38	-59.70
0.9	22.70	-59.77
1	26.17	-59.70
1.1	28.49	-59.54
1.2	29.86	-59.73
1.3	32.36	-59.59
1.4	34.80	-59.24
1.5	36.08	-59.00
1.6	38.42	-58.27
1.7	38.64	-58.10
1.8	39.84	-57.27
1.9	40.93	-56.17
2	40.92	-55.43
2.1	39.82	-54.67

2.2	39.58	-52.96
2.3	37.29	-51.64
2.4	34.93	-49.92
2.5	32.55	-47.80
2.6	28.35	-45.86
2.7	24.27	-43.40
2.8	19.57	-41.30
2.9	15.98	-39.29
3	10.93	-37.21
3.1	6.86	-36.88
3.2	1.96	-37.09
3.3	-3.18	-38.43
3.4	-7.79	-40.17
3.5	-12.94	-42.85
3.6	-18.32	-44.99
3.7	-23.19	-47.34
3.8	-26.30	-49.68
3.9	-31.32	-50.96
4	-34.43	-52.38
4.1	-35.50	-54.11
4.2	-37.29	-54.91
4.3	-39.00	-55.43
4.4	-39.73	-56.19
4.5	-38.11	-57.30
4.6	-36.24	-58.16
4.7	-33.37	-59.31
4.8	-31.42	-59.98
4.9	-28.45	-60.83
5	-25.44	-61.51
5.1	-23.41	-61.86
5.2	-20.34	-62.23
5.3	-18.29	-62.38
5.4	-16.23	-62.44
5.5	-13.14	-62.38
5.6	-11.08	-62.24
5.7	-9.04	-62.02
5.8	-7.00	-61.71
5.9	-4.98	-61.32
6	-3.97	-61.10
6.1	-1.97	-60.59
6.2	0.00	-60.00

4.3 Experiment 3: Real time hardware experiment

For hardware data collection, the experiment is set for one complete rotation of the crank and this will bring to one complete cycle of leg path. Due to the hardware limitation, the crank angle was initially set on 0 degree and then the angle will keep on increasing by 40 degrees or 0.70 rad only. The steps repeat until it reaches 360 degree or 6.3 rad which will show one complete rotation of path movement. Each of the crank angle data is repeated for eight times to reduce the random error occur on data collecting. The result of the experiment is then tabulated in table 4.2 below. After calculations, the maximum horizontal displacement is 51 mm and the maximum vertical displacement is 11 mm only.

Table 4.2: Hardware experiment average result

Crank Angle (rad)	Horizontal displacement (mm)		Vertical displacement (mm)	
	Position	Average	Position	Average
0	0.0	0.00	-60.00	-60.00
	0.0		-60.00	
	0.0		-60.00	
	0.0		-60.00	
	0.0		-60.00	
	0.0		-60.00	
	0.0		-60.00	
	0.0		-60.00	
0.7	8.3	7.94	-60.50	-58.00
	9.4		-59.50	
	7.2		-60.00	
	8.3		-59.00	
	7.0		-55.00	
	8.0		-58.50	
	8.3		-56.00	
	7.0		-55.50	
1.4	22.0	21.96	-52.50	-51.90
	21.6		-54.50	
	22.5		-51.00	
	23.2		-55.50	
	23.1		-48.20	
	21.6		-50.00	
	21.1		-52.50	
	20.6		-51.00	
2.1	13.0	13.53	-49.00	-51.15
	14.6		-49.50	
	13.9		-53.50	
	13.3		-52.00	
	15.0		-54.20	
	12.8		-49.50	
	11.9		-49.00	
	13.7		-52.50	
2.8	0.1	0.06	-49.50	-49.13
	-0.4		-46.50	
	0.0		-49.50	
	0.3		-48.50	
	0.2		-51.00	
	-0.4		-52.00	
	0.4		-47.00	
	0.3		-49.00	
3.5	-16.3	-16.46	-51.00	-49.94
	-16.6		-49.50	
	-15.3		-53.00	
	-17.0		-48.00	
	-17.5		-47.00	
	-18.0		-52.00	
	-15.4		-50.00	
	-15.6		-49.00	
	-30.0		-58.90	

4.2	-30.0	-29.00	-58.90	-56.91
	-27.0		-59.00	
	-29.0		-55.90	
	-31.0		-57.80	
	-28.0		-59.50	
	-27.5		-55.20	
	-29.5		-51.50	
	-30.0		-57.50	
4.9	-22.5	-21.09	-59.50	-59.04
	-22.0		-48.50	
	-21.5		-55.00	
	-20.9		-62.30	
	-20.0		-63.00	
	-20.3		-64.00	
	-20.5		-61.50	
	-21.0		-58.50	
5.6	-12.5	-12.65	-60.50	-59.88
	-14.0		-61.00	
	-11.0		-58.00	
	-12.2		-62.00	
	-13.5		-57.00	
	-13.9		-58.50	
	-12.1		-60.50	
	-12.0		-61.50	
6.3	0.0	0.05	-58.50	-60.25
	-0.1		-62.00	
	0.3		-57.00	
	-0.2		-62.50	
	0.5		-62.50	
	0.2		-57.50	
	-0.4		-65.50	
	0.1		-56.50	

Table 4.3 shows data collected for the calculation of accuracy test. However, the calculation of percentage of error only carry out on some of the angle due to the limitation on the hardware.

$$\text{Error} = \text{measured value} - \text{actual value} \quad (3.16)$$

$$\text{Percentage error} = \frac{error}{actual\ value} \times 100\% \quad (3.17)$$

where the actual value is the value get from Matlab simulation and the measured value is the value get from the hardware.

Table 4.3: Data of measured value vs actual value

Crank Angle (rad)	Horizontal displacement (mm)		Vertical displacement (mm)	
	Measured value	Actual value	Measured value	Actual value
0.7	7.94	18.06	-58.00	-59.53
1.4	21.96	34.80	-51.90	-59.24
2.1	13.53	39.82	-51.15	-54.67
2.8	0.06	19.57	-49.13	-41.30
3.5	-16.46	-12.94	-49.94	-42.85
4.2	-29.00	-37.29	-56.91	-54.91
4.9	-21.09	-28.45	-59.04	-60.83
5.6	-12.65	-11.08	-59.88	-62.24
6.3	0.05	0.00	-60.25	-60.00

Table 4.4 shows the percentage of error calculated. The highest percentage of error for horizontal displacement occur at 2.8 rad or 160 degrees which is 99.7 %. For vertical displacement, it occurs at 2.8 rad also which is 18.96%. On the other hand, the lowest percentage of error occurs at 5.6 rad for horizontal displacement and 0.7 rad for vertical displacement.

Table 4.4: Percentage of error

Crank Angle (rad)	Percentage of error (%)	
	Horizontal displacement	Vertical displacement
0.7	-56.04	-2.57
1.4	-36.90	-12.39
2.1	-66.02	-6.44
2.8	-99.69	18.96
3.5	27.20	16.55
4.2	-22.23	3.64
4.9	-25.87	-2.94
5.6	14.17	-3.79

4.4 Result and discussion for Experiment 2 and 3

The graph of horizontal displacement versus vertical displacement is plot to compare the result obtained from simulation with the result from actual hardware as shown in figure 4.3. The trajectory path obtained from the hardware is smaller compare to the theoretical simulation path. The maximum horizontal displacement on the actual path is 51 mm and 80.66 mm for simulation path. The vertical displacement of actual path is only 11 mm and 25.56 mm for simulation path.

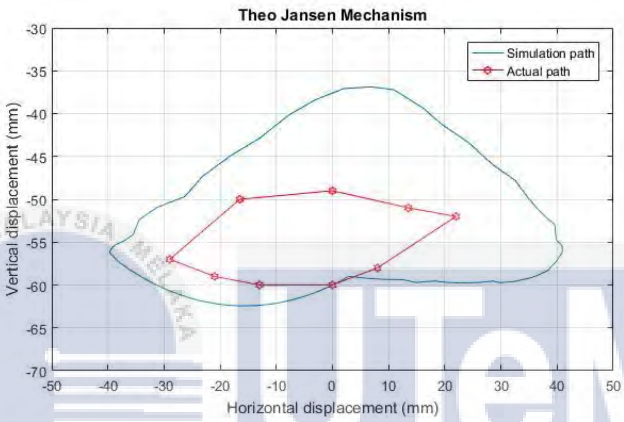


Figure 4.19: Trajectory path result comparison

Besides, the graph of horizontal displacement versus crank angel is plotted to analysis the effect of angel applied on the trajectory path. According to figure 4.4, the horizontal displacement on the actual robot is clearly shorter compare to the simulation result. The maximum displacement achieved when the crank angel is 1.4 rad for actual result and 1.9 rad for simulation result. Then, the minimum displacement is achieved when the crank angel is 4.2 rad for actual result and 4.4 rad for simulation result.

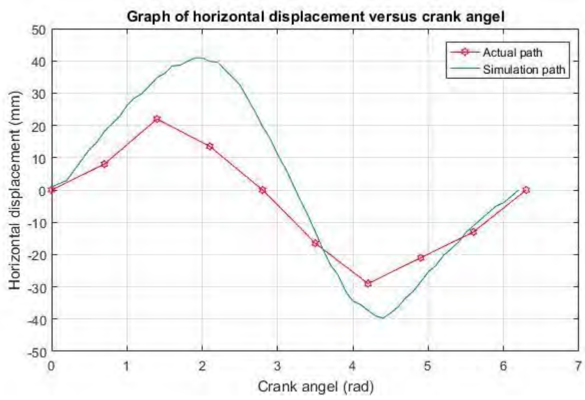


Figure 4.20: Horizontal displacement result comparison

Furthermore, the graph of vertical displacement versus crank angel is plotted to analysis the effect of angel applied on the trajectory path. Based on figure 4.5, the vertical displacement traveled on actual robot is clearly shorter compare to the simulation result. The maximum displacement achieved when the crank angel is 2.8 rad for actual result and 3.1 rad for simulation result.

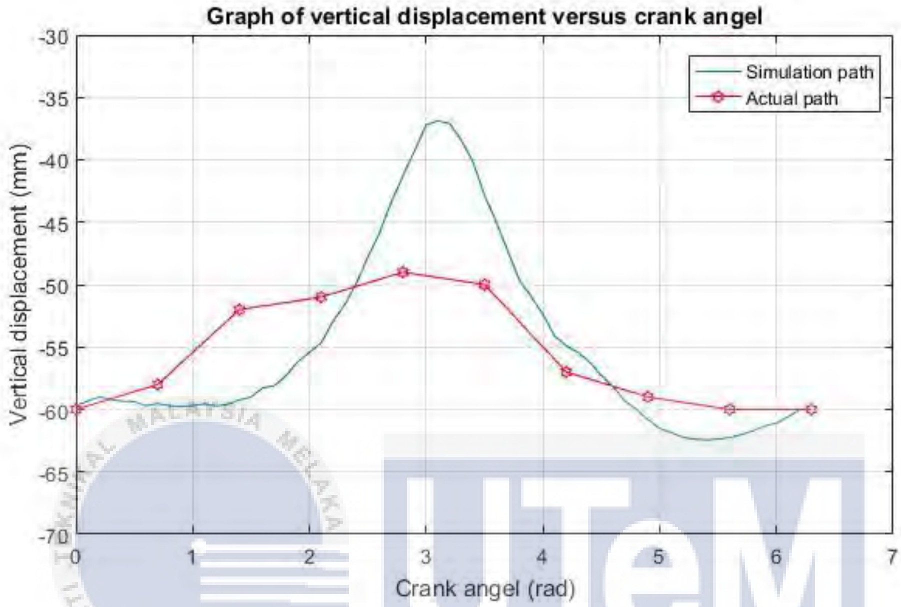


Figure 4.21: Vertical displacement data comparison

The systematic errors affected the measurements of hardware and cause the inaccurate data obtained on the result. [15] This type of error is due to the imperfect personal technique and bias of the observer thus greatly reduce the accuracy of data and effect the precision of measurement.

Besides that, there are many issues that cause the inaccurate result obtain on the hardware. Backslash error in the gears is one of the major problems since it causes the lost motion between the input and output shaft. This makes the efficiency of gears difficult to achieve with inaccurate positioning in the hardware parts. [16] As such, the precision of the gears will reduce and lead to the ineffective linkages movement on robot legs. It also may cause overheating and tooth damage on gears. Moreover, gravitational force is one of the issues as the actuator need to compensate the gravitational force in order to produce the robot motion. [17] Since, the unbalance forces produced may exert a higher force on one of the legs and destroyed the smooth motion of linkage movement.

CHAPTER 5

CONCLUSION AND FUTURE RESEARCH

5.1 Conclusion

In conclusion, the design and development of small size animatronics robot is very challenging and complicated at the same time. The objectives of this research have been achieved. Since, the designed robot able to travel on uneven terrain with legged mechanism of the robot. There are many specifications that need to be consider in order to design an animatronics robot. The criteria such as animatronics concept, actuator, fabrication material and also the mechanism of robot need to be consider for the robot. After that, many experiment can be carry out to test the performance and capability of the designed robot. Furthermore, many analyses have been made to realise the stability and performance of the robots. The analysis made by using SolidWorks is very important to increase the reliability of designed robot. As a result, robot design three is chosen as the robot to be fabricated since it is more stable and higher capability of movement. Since the surface area of contact with ground is bigger compare to design 1 and 2 and the additional of gears can improve the torque produced from the actuator. For the experiment of trajectory path, the highest accuracy of the hardware achieved when the crank angle is 0.7 rad for vertical displacement and 5.6 rad for horizontal displacement. However, the most inaccurate result is recorded at crank angel of 2.8 rad which is 99.69% and 18.96% percentage of error. As such, Theo Jansen mechanism is difficult to achieved an accurate trajectory path at the end effector due to its complex linkages mechanism and other unexpected factors.

Furthermore, students are encouraged to strengthen the knowledge on SolidWorks software in order to complete this project. Since, the design and fabrication of hardware requires great amount of knowledge while running analysis in order to analyse the robot. For the robot design, the size of the robot can become smaller by modifying the support frame bar. As the support bar become smaller, the distance between gear and linkages and be decrease to reduce the size of robot. Besides that, the actuation system can be replaced by any other actuator like direct current motor to produce a higher speed of rotation motion although the torque may decrease. The increase of rotation at crank or gear can definitely speed up the movement of robot.

5.2 Future research

Although robot design three is already been fabricated, but there are still ways to improve the mechanical design of the hardware especially ways to reduce backslash error in fabricated parts. Backslash error is a big issue for this robot as the efficiency of gears is decrease due to the lost motion of tooth on gears. Furthermore, the controlling system of the robot should be improved to makes the robot becomes more stable and easier to control. Adding of controller is very important to make sure the robot move by following the desired gait movement in order to maintain its balance. At last, sensors can be added on the robot to increase the functions of robot or even makes the robot become automated. Sensors such as infrared sensor or ultrasonic sensor can be added to make it becomes obstacles avoidance robot.

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APPENDICES (A)

Arduino coding

<u>Code 1:</u>

```
#include <Servo.h>
Servo servo1;
Servo servo2;
void setup()
{
  servo1.attach(9);
  servo2.attach(10);
}
void loop()
{
  servo1.write(0);      // rotate clockwise with full speed
  servo2.write(180);    // rotate anticlockwise direction with full speed
  delay(10000);
}
// 0 means max speed clockwise, 90 means no motion, 180 means max speed counter-clockwise
```


<u>Code 2:</u>

```
#include <Servo.h>
Servo servo1;
Servo servo2;
void setup()
{
  servo1.attach(9);
  servo2.attach(10);
}
void loop()
{
  servo1.writeMicroseconds(500);
  servo2.writeMicroseconds(1000);
}
```

Matlab simulation coding

```
%Theo Jansen Matlab simulation coding
%Max Thrun
%Simulation of Jensen Mechanism

close all            %Clsoes windows
clear all            %Clears all variables
clc                  %Clear command window

%Declare variables

crank_r = 14.87;
link_1 = 55;
link_2 = 34.5;
link_3 = 51.5;
link_4 = 80.5;
link_5 = 58;
link_6 = 55;
link_7 = 34.5;
link_8 = 51.5;
link_82 = 34.5;
link_9 = 34.5;
link_10 = 34.5;
link_11 = 58;%540;

crank_x = 41.288;
crank_y = 44.62;

pin_x = crank_x - (40.33/1);
pin_y = crank_y;

node_1_x = pin_x;
node_1_y = 2;

link_9_t = 0;

link_10_t = pi;
link_11_t = pi;

node_2_x = pin_x - link_9;
node_2_y = pin_y;

link_8_t = 3/4*pi;

node_3_x = pin_x;
node_3_y = pin_y - link_8;

link_7_t = pi;

node_4_x = pin_x - link_7;
```

```
node_4_y = pin_y - link_3;

link_5_t = 3/4*pi;

node_5_y = pin_y - link_8 - link_5;
node_5_x = pin_x;

node_6_y = node_5_y;
node_6_x = node_5_x;

axis([-300 300 -300 300]);
grid on              %Display grid on plot
xlabel('real axis');    %Give the xlabel
ylabel('imag axis');    %Give the ylabel
title('Example 1');     %Give the title of the plot


avi = moviein((8*pi+pi/2)*5);

%Animation
figure(3)

i=0;

x = [];
xnew = [0;8;22;13.50;0;-16.50;-29;-21;-13;0];
y = [];
ynew = [-60;-58;-52;-51;-49;-50;-57;-59;-60;-60];
v = [];
vnew = [0;0.70;1.40;2.10;2.80;3.50;4.20;4.90;5.60;6.30];


for t=0:0.1:1*2*pi;

  i = i + 1;
  node_0_x = crank_x + crank_r*cos(t);
  node_0_y = crank_y + crank_r*sin(t);


  %
  % NODE 1
  %

  dist = 10000000;

  for link_9_t=0:0.02:pi;
    node_1_x = pin_x + link_9*cos(link_9_t);
    node_1_y = pin_y + link_9*sin(link_9_t);

    dist_tmp = sqrt((node_0_x-node_1_x)^2+(node_0_y-node_1_y)^2);
```

```
    diff = abs(dist_tmp - link_1);

    if (diff < dist)
        dist = diff;
        theta = link_9_t;
        %fprintf('New theta: %d  Diff: %d\n', theta, diff);
    end
end

link_9_t = theta;

node_1_x = pin_x + link_9*cos(link_9_t);
node_1_y = pin_y + link_9*sin(link_9_t);


%
% NODE 2
%

dist = 10000000;

for link_10_t=.75*pi:0.02:1.5*pi;
    node_2_x = pin_x + link_10*cos(link_10_t);
    node_2_y = pin_y + link_10*sin(link_10_t);

    dist_tmp = sqrt((node_2_x-node_1_x)^2+(node_2_y-node_1_y)^2);

    diff = abs(dist_tmp - link_2);

    if (diff < dist)
        dist = diff;
        theta = link_10_t;
        %fprintf('New theta: %d  Diff: %d\n', theta, diff);
    end
end

link_10_t = theta;

node_2_x = pin_x + link_10*cos(link_10_t);
node_2_y = pin_y + link_10*sin(link_10_t);

%
% NODE 3
%

 dist = 10000000;

for link_8_t=pi:0.02:2*pi;
```

```
    node_3_x = pin_x + link_8*cos(link_8_t);
    node_3_y = pin_y + link_8*sin(link_8_t);

    node_7_x = pin_x + link_82*cos(link_8_t);
    node_7_y = pin_y + link_82*sin(link_8_t);

    dist_tmp = sqrt((node_0_x-node_7_x)^2+(node_0_y-node_7_y)^2);

    diff = abs(dist_tmp - link_6);

    if (diff < dist)
        dist = diff;
        theta = link_8_t;
    end
end

link_8_t = theta;

node_3_x = pin_x + link_8*cos(link_8_t);
node_3_y = pin_y + link_8*sin(link_8_t);

node_7_x = pin_x + link_82*cos(link_8_t);
node_7_y = pin_y + link_82*sin(link_8_t);

%
% NODE 4
%

dist = 10000000;

for link_7_t=.75*pi:0.02:1.5*pi;
    node_4_x = node_3_x + link_7*cos(link_7_t);
    node_4_y = node_3_y + link_7*sin(link_7_t);

    dist_tmp = sqrt((node_4_x-node_2_x)^2+(node_4_y-node_2_y)^2);

    diff = abs(dist_tmp - link_3);

    if (diff < dist)
        dist = diff;
        theta = link_7_t;
    end
end

link_7_t = theta;

node_4_x = node_3_x + link_7*cos(link_7_t);
node_4_y = node_3_y + link_7*sin(link_7_t);
```

```
%
% NODE 5
%

dist = 10000000;

for link_5_t=pi:0.02:2*pi;
   node_5_x = node_3_x + link_5*cos(link_5_t);
   node_5_y = node_3_y + link_5*sin(link_5_t);

   dist_tmp = sqrt((node_4_x-node_5_x)^2+(node_4_y-node_5_y)^2);

   diff = abs(dist_tmp - link_4);

   if (diff < dist)
      dist = diff;
      theta = link_5_t;
      %fprintf('New theta: %d  Diff: %d\n', theta, diff);
   end
end

link_5_t = theta;

node_5_x = node_3_x + link_5*cos(link_5_t);
node_5_y = node_3_y + link_5*sin(link_5_t);

node_6_x = node_3_x + link_11*cos(link_5_t);
node_6_y = node_3_y + link_11*sin(link_5_t);

x(end+1) = node_6_x;
y(end+1) = node_6_y;
v(end+1) = t;

%
% DRAW
%

plot([crank_x pin_x], [crank_y pin_y],'black','linewidth',3); hold on       % crank to pin
plot([crank_x node_0_x], [crank_y node_0_y],'r','linewidth',2); hold on     % crank

plot([node_0_x node_1_x], [node_0_y node_1_y],'b','linewidth',2);           % link_1
plot([pin_x node_1_x], [pin_y node_1_y],'g','linewidth',2);                 % link_9

plot([pin_x node_2_x], [pin_y node_2_y],'g','linewidth', 2);                % link_10
plot([node_1_x node_2_x], [node_1_y node_2_y],'g','linewidth', 2);          % link_2

plot([node_0_x node_7_x], [node_0_y node_7_y],'b','linewidth',2);           % link_6 new
plot([pin_x node_3_x], [pin_y node_3_y],'r','linewidth',2);                 % link_8
plot([pin_x node_7_x], [pin_y node_7_y],'b','linewidth',2);                 % link_82
```

```
    plot([node_3_x node_4_x], [node_3_y node_4_y],'g','linewidth', 2);         % link_7
    plot([node_2_x node_4_x], [node_2_y node_4_y],'r','linewidth', 2);         % link_3

    plot([node_3_x node_5_x], [node_3_y node_5_y],'r','linewidth', 2);         % link_5
    plot([node_4_x node_5_x], [node_4_y node_5_y],'b','linewidth', 2);         % link_4

    plot([node_3_x node_6_x], [node_3_y node_6_y],'b','linewidth', 2);         % link_5

    plot(x,y);
    %plot(xnew,ynew);

    hold off           %So next plot will erase the current plot
    axis([-100 100 -100 100]);
    grid on              %Display grid on plot
    xlabel('Horizontal displacement (mm)');    %Give the xlabel
    ylabel('Vertical displacement (mm)');    %Give the ylabel
    title('Theo Jansen Mechanism');     %Give the title of the plot
    %pause(10.001)          %Stop execution for 0.1 sec so that the animation can be seen
    avi(i) = getframe(gca);
end

 movie2avi(avi,'jansen.avi','compression','cinepak') % or cinepak, indeo5
```

Trajectory path experiment data collecting graph

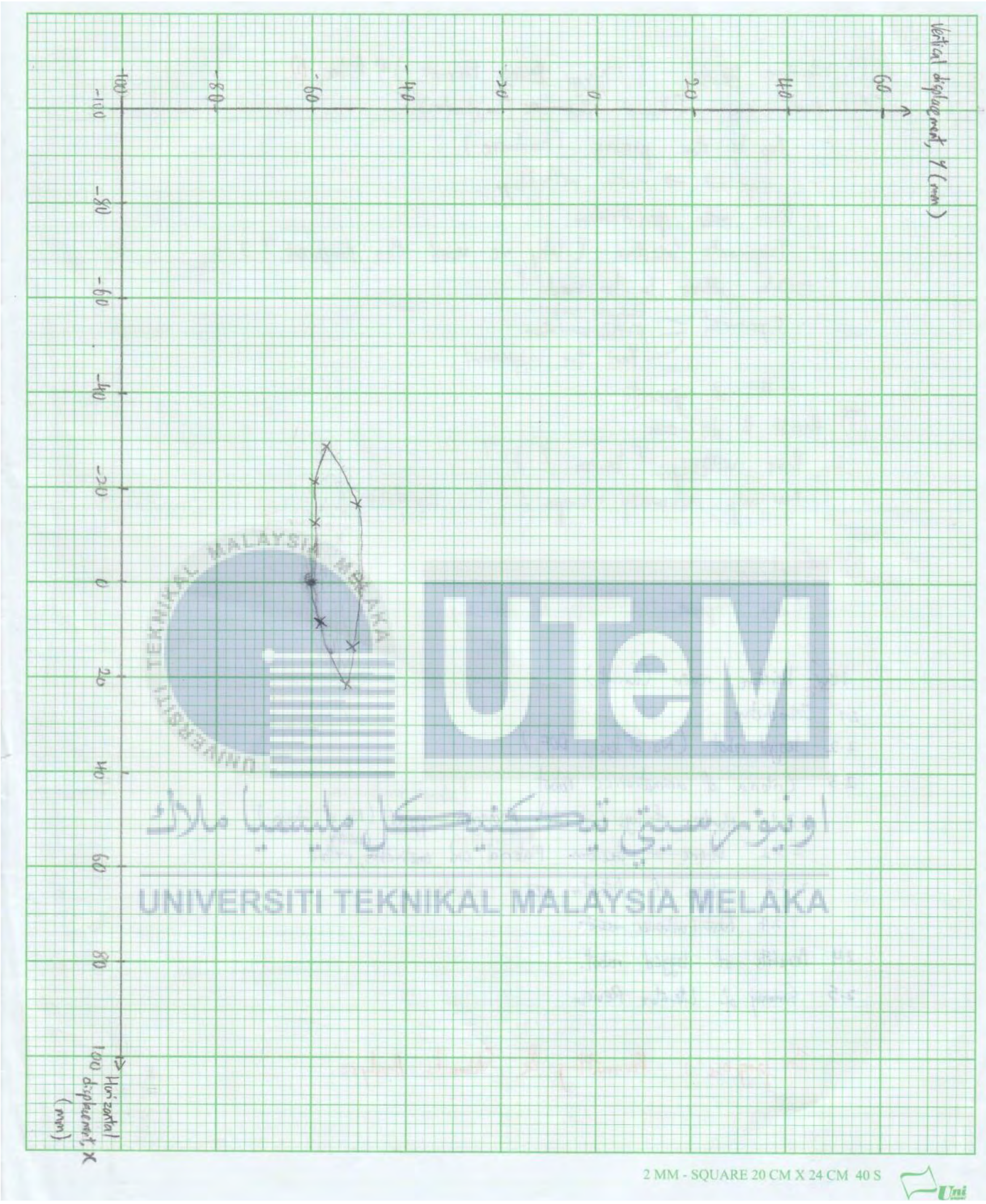

Figure A1: Trajectory path experiment data collecting graph

Gantt chart

Figure A 2: FYP2 gantt chart

FAKULTI KEJURUTERAAN ELEKTRIK

BORANG PENGGUNAAN RAPID PROTYPING SYSTEM

No. Rujukan:

MAKLUMAT PENGGUNA / PERALATAN			
NAMA PENGGUNA: NG WEI YU			TARIKH SIAP PRINT PROJEK:
FAKULTI/JABATAN/UNIT: FKE-BEKM			
NO. STAF/MATRIK: B011310094	TAJUK PROJEK: Animatronics Robot		NO. TEL:017-4149480

BIL	**DESKRIPSI PERALATAN**	**KUANTITI**	**REKOD PENGGUNAAN**
1	uPrint Modelling Base		
2	uPrint P430 ABSplus Modelling Material Cartridges		
3	uPrint P400 SR Soluble Material Cartridges		

PENGESAHAN PENGGUNA		
PELAJAR	**PENYELIA**	**PENGGUNAAN (√)**
	NAMA:	√ PSM /PROJEK DIPLOMA
		PJP
TANDATANGAN:	TANDATANGAN/COP:	PERTANDINGNGAN : ....
TARIKH :	TARIKH :	LAIN-LAIN: ....

PENGESAHAN MAKMAL	
PENYELARAS MAKMAL (KETUA JABATAN / PENOLONG JURUTERA	**JURUTEKNIK MAKMAL**
NAMA:	NAMA:
TANDATANGAN/COP:	TANDATANGAN/COP:
TARIKH :	TARIKH :

PENGESAHAN / KELULUSAN (DEKAN)	
NAMA:	TARIKH :
TANDATANGAN/COP :	

CATATAN :

POSEDUR DAN PERATURAN

Perkhidmatan penggunaan mesin rapid protyping system yang disediakan pada asasnya adalah untuk kegunaan rasmi yang berkaitan dengan pengajaran dan pembelajaran subjek makmal Fakulti Kejuruteraan Elektrik Universiti Teknikal Malaysia Melaka (UTeM). Oleh itu staf dan pelajar harus menggunakannya secara bertanggungjawab dan bercermat cermat berlandaskan undang-undang dan peraturan-peraturan makmal.

Peraturan penggunaan:

a) Setiap produk yang direkabentuk perlulah mendapat kelulusan dan justifikasi ukuran serta bentuk yang tepat;
b) Setiap satu produk hanya dibenarkan sekali sahaja untuk print sebarang kesilapan perlu ditanggung sendiri, pihak makmal tidak akan membenarkan print produk untuk kali kedua.
c) Produk untuk penggunaan peribadi tidak dibenarkan;
d) Pengguna yang mempuyai bajet/geran sendiri digalakkan membeli sendiri material;
e) Kerja-kerja print produk hanya dilakukan pada waktu bekerja sahaja (Diluar waktu berkerja perlulah mendapat kebenaran bertulis dari Dekan).

Figure A 3: Prototyping machine application form

APPENDICES (B)

Robot Parts dimension

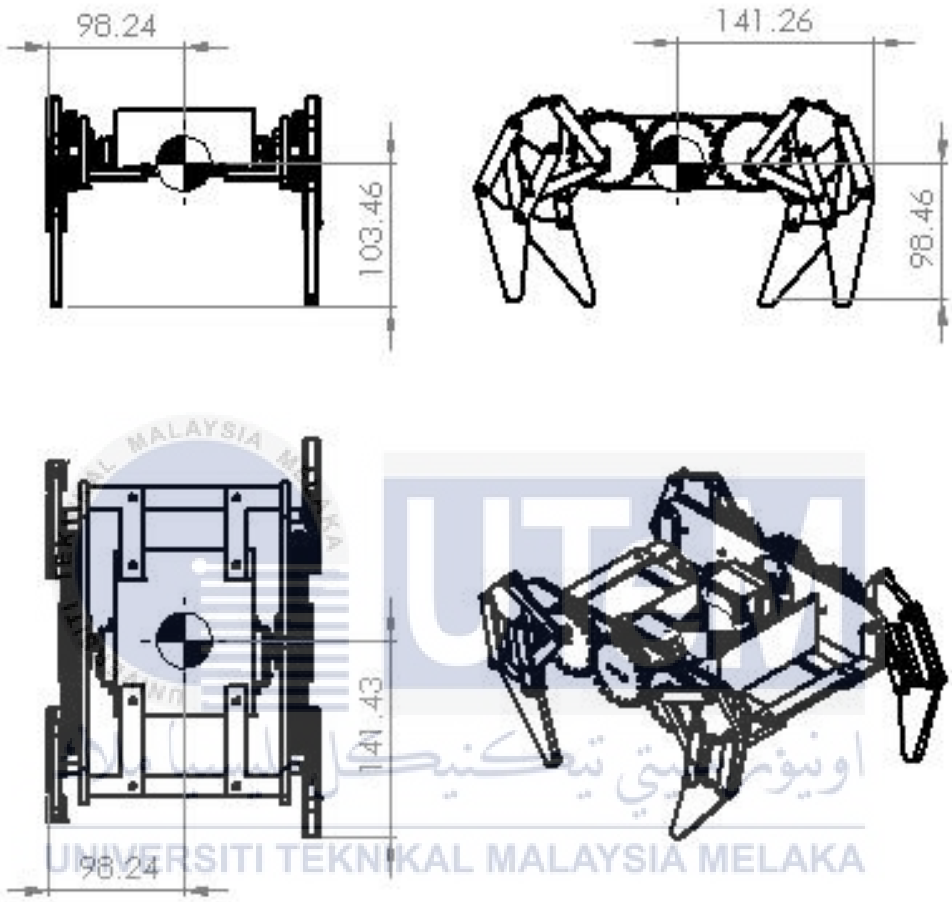

Figure B 1: Full robot dimension

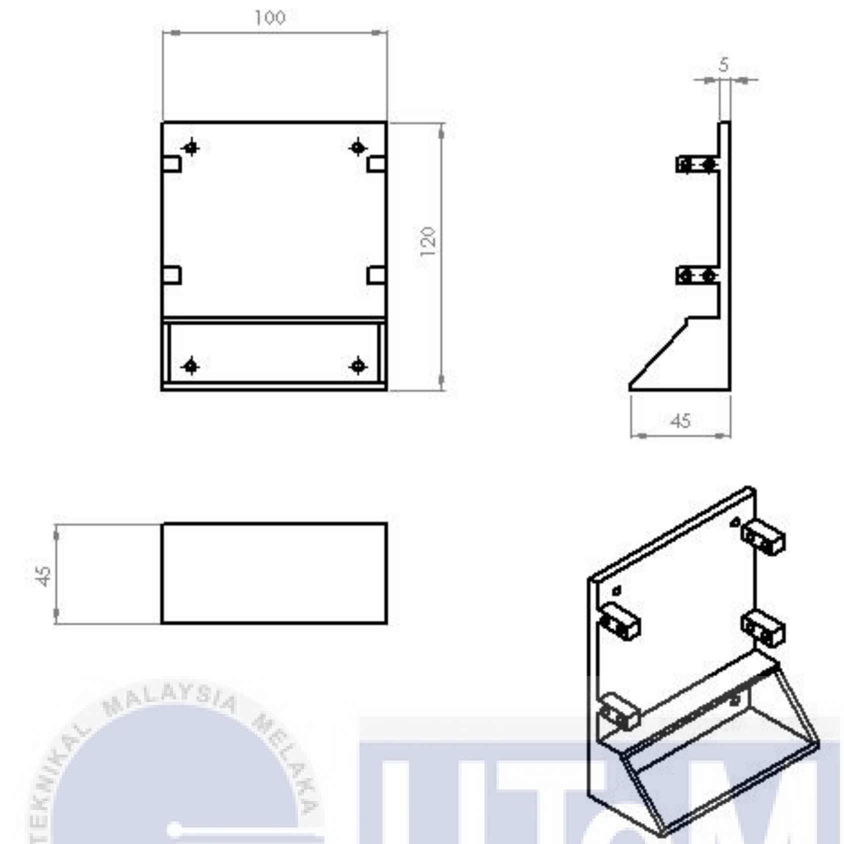

Figure B 2: Robot base dimension

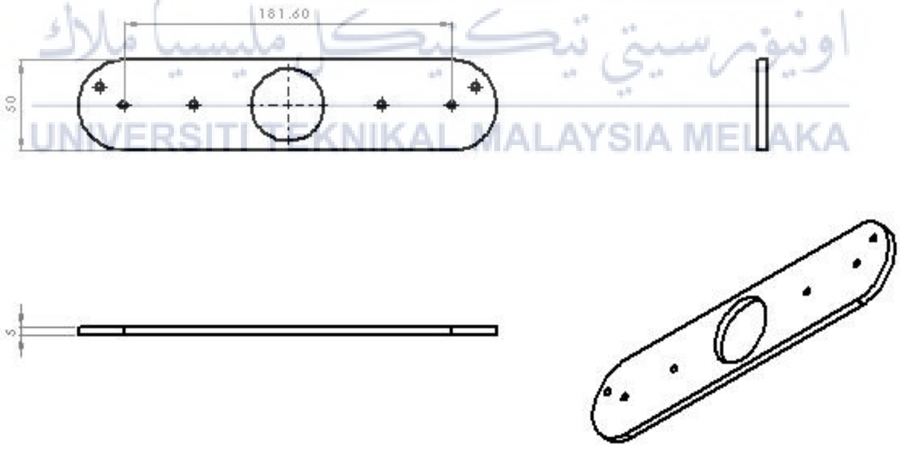

Figure B 3: Support bar dimension

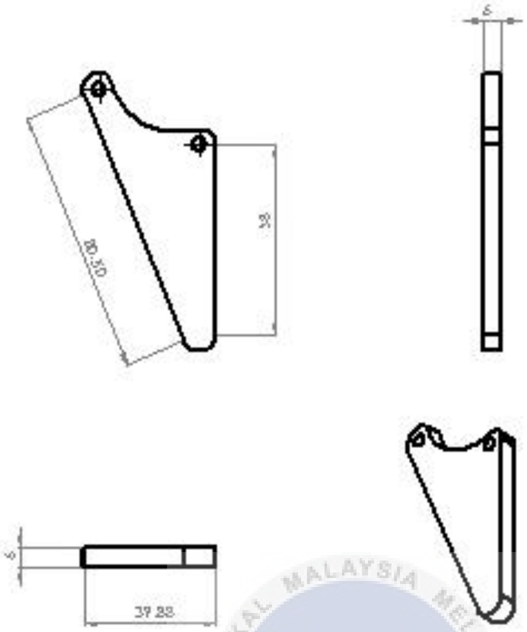

Figure B 4: Leg base dimension

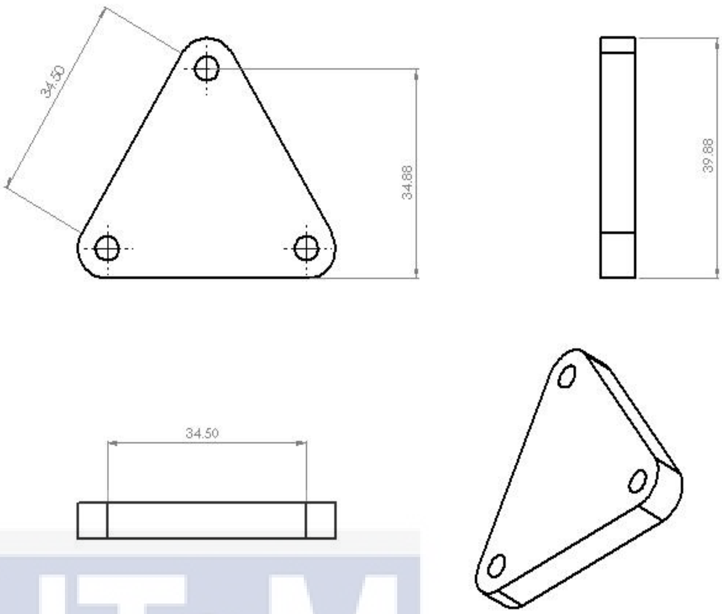

Figure B 5: Linkage triangle dimension

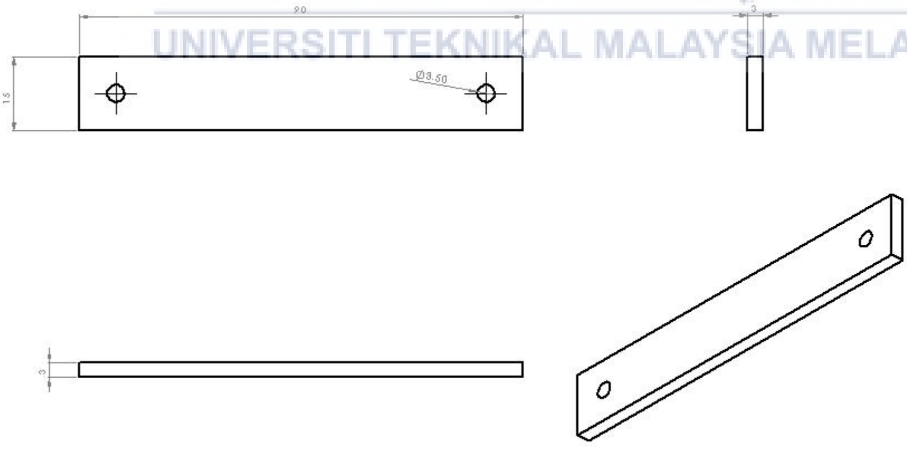

Figure B 6: Connector bar dimension

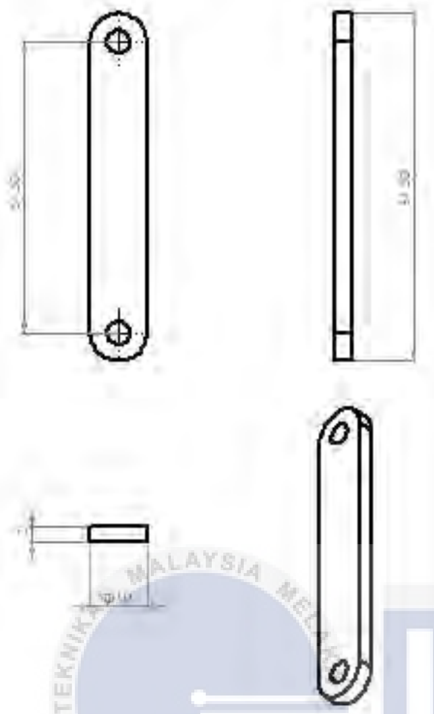

Figure B 9: Link 2 dimension

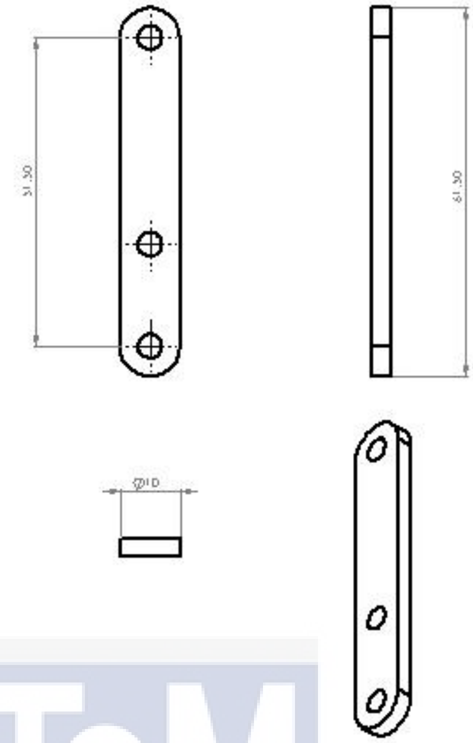

Figure B 8: Link 1 dimension

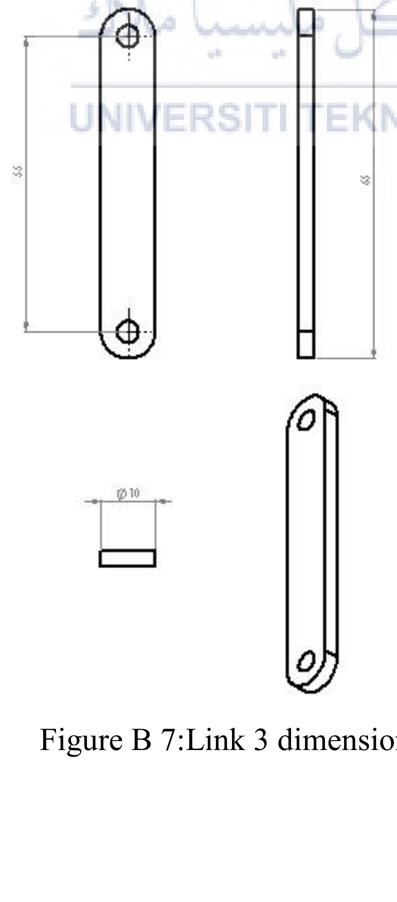

Figure B 7:Link 3 dimension

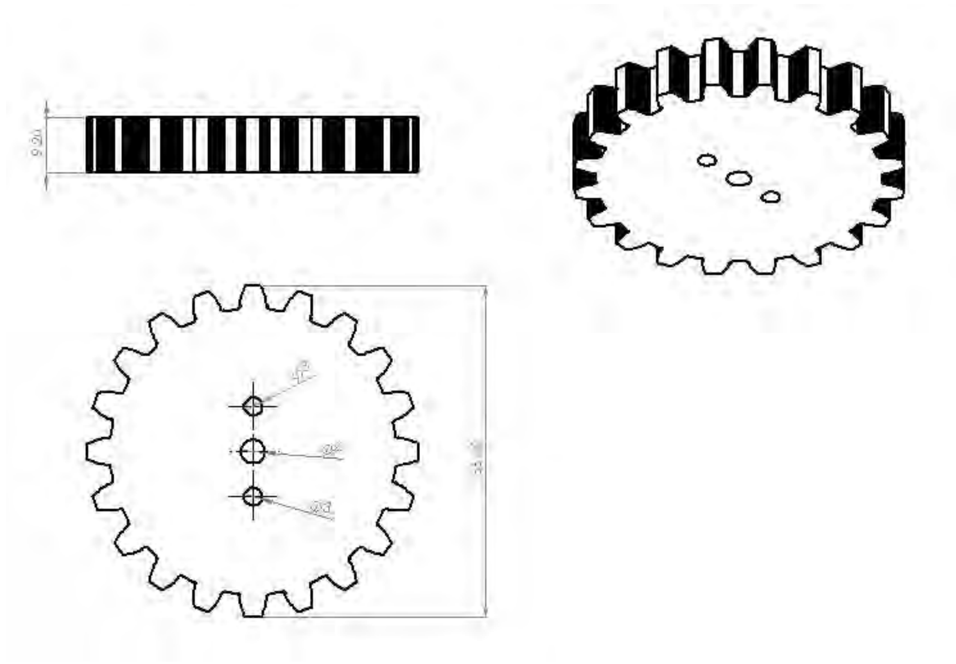

Figure B 10: Gear 1 dimension

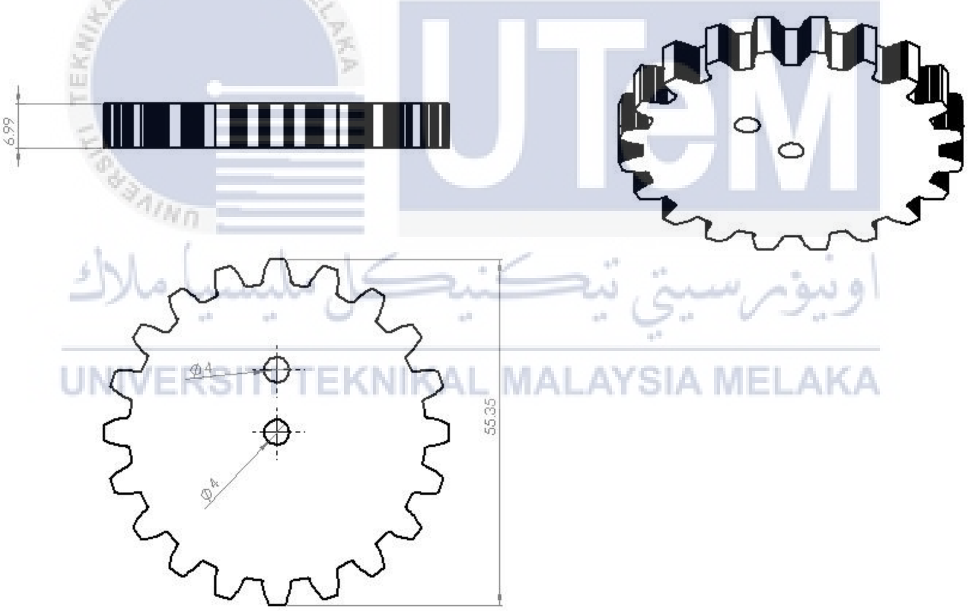

Figure B 11: Gear 2 dimension

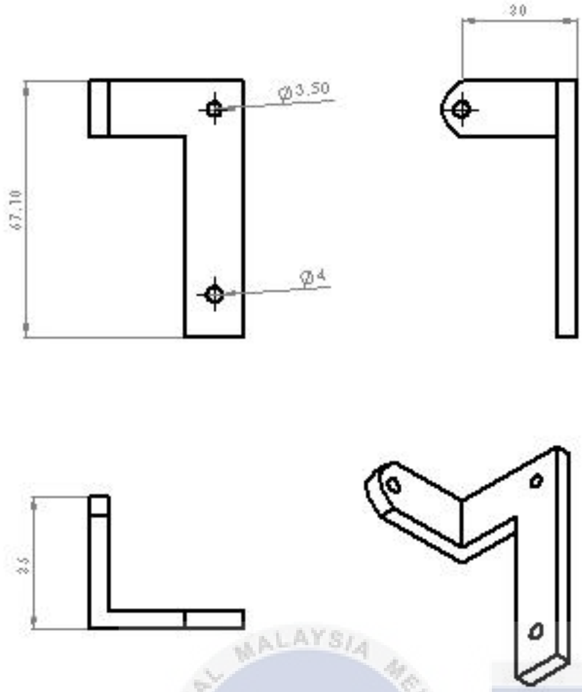

Figure B 13: Base connector 1 dimension

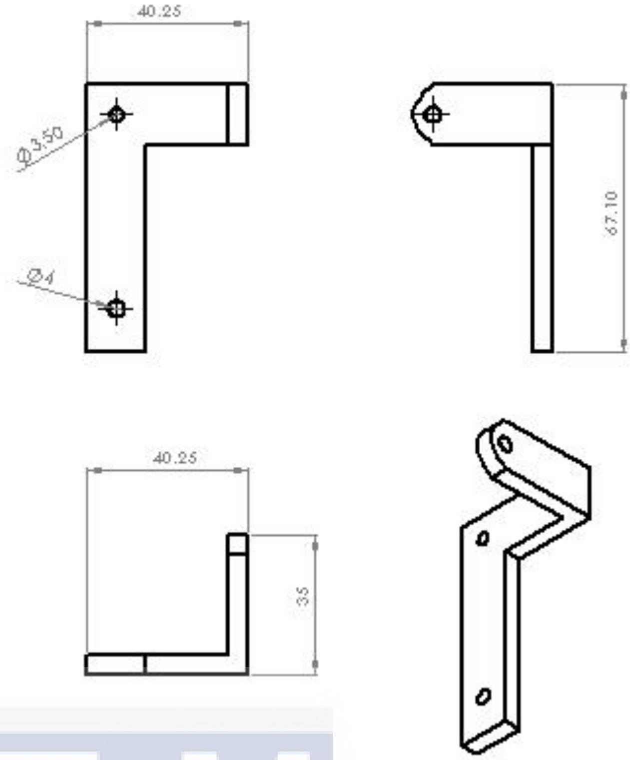

Figure B 12: Base connector 2 dimension

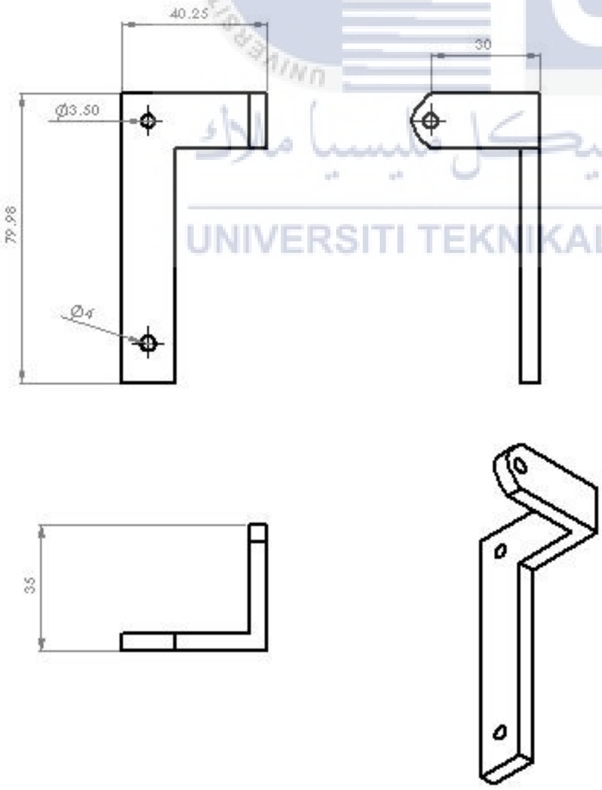

Figure B 15: Base connector 3 dimension

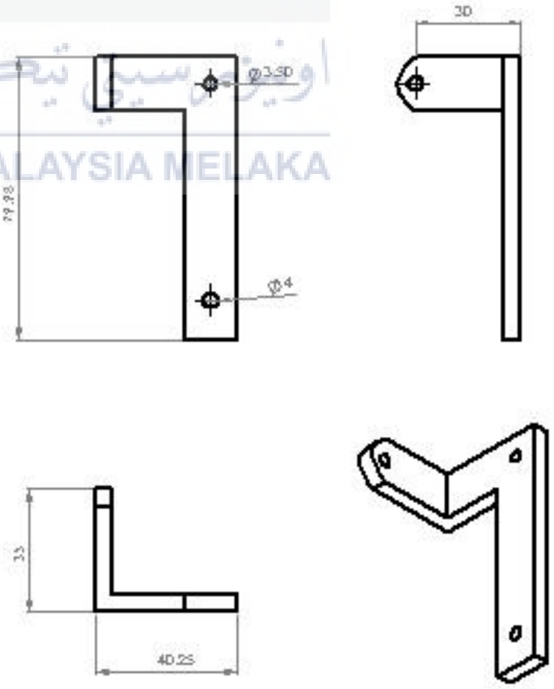

Figure B 14: Base connector 4 dimension