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TAJUK PROJEK :

Saya : GIGIH PRIYANDOKO
(HURUF BESAR)

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LIST OF OUTCOME

SHORT GRANT RDU140358

TITLE : DESIGN AND DEVELOPMENT OF SIX DEGREES OF FREEDOM ARTICULATED ROBOT ARM FOR PAINTING

LEADER : DR. GIGIH PRIYANDOKO

STAFF ID : 1486

1. Conference and Publication

    a) K. Yusuf, Y. P. Asmara and M. Safuan, Development of Control System for Three Degree of Freedom (3DOF) Articulated Robot, *ICMER 2015*, published in SCOPUS indexed Journal

    b) MSH Achmad, G Priyandoko, R Rosli, MR Daud, Tele-Operated Mobile Robot for 3D Visual Inspection Utilizing Distributed Operating System Platform, *International Journal of Vehicle Structures & Systems* 9 (3), 190-194.

    c) G Priyandoko, TY Ming, MSH Achmad, Mapping of unknown industrial plant using ROS-based navigation mobile robot, *IOP Conference Series: Materials Science and Engineering* 257 (1), 012088.

    d) MSH Achmad, G Priyandoko, Telepresence Mobile Robot for Industrial Plant Inspection Utilizing Distribute Operating System Platform, *International Conference on Mechanical Manufacturing and Process Plant Engineering*, 23-24 November, 2016, Kuala Lumpur.

2. Exhibition

    a) CITREX 2017, UMP, Bronze Medal
    b) ICE-CINNO Communitising Innovative Computing 2016, UMP, Bronze Medal.

UMP/RMC/LA-2/07

RESEARCH MANAGEMENT CENTRE

PRELIMINARY IP SCREENING & TECHNOLOGY ASSESSMENT FORM

(To be completed by Project Leader submission of Final Report to RMC or whenever IP protection arrangement is required)

1. PROJECT TITLE IDENTIFICATION :

DESIGN AND DEVELOPMENT OF SIX DEGREES OF FREEDOM ARTICULATED ROBOT ARM FOR PAINTING

Vote No: RDU140358

2. PROJEK LEADER :

Name : Dr. Gigih Priyandoko

Address :
Faculty of Mechanical Engineering, Universiti Malaysia Pahang

Tel : 09-424 6219 Fax : 09-424 2202 E-mail: gigih@ump.edu.my

3. DIRECT OUTPUT OF PROJECT *(Please tick where applicable)*

Scientific Research	Applied Research	Product/ Process Development
☐ Algorithm	☐ Method/Technique	☐ Product/Component
☐ Structure	☑ / Demonstration/Prototype	☐ Process
☐ Data		☐ Software
☐ Other, please specify	☐ Other, please Specify	☐ Other, please specify
____________________	____________________	____________________
____________________	____________________	____________________
____________________	____________________	____________________
____________________	____________________	____________________

4. INTELLECTUAL PROPERRTY *(Please tick where applicable)*

☑ / Not patentable	☐ Inventor technology champion
☐ Patent search required	☐ Inventor team player
☐ Paten search completed and clean	☐ Monograph available
☐ Invention remains confidential	☐ Industrial partner identified
☐ No publications pending	☐ Patent Pending
☐ No prior claims to the technology	☐ Technology protected by patents pending

5. LIST OF EQUIPMENT BOUGHT USING THIS VOT

No	Item	Serial No	Location
1	Kinect Fusion Scanner	FKM1000-PB105(R)-1606-0006-00001	Lab. Vibration

6. STATEMENT OF ACCOUNT

a) APPROVED FUNDING RM : 36,800.00

b) TOTAL SPENDING RM : 33,246.13

c) BALANCE RM : 3,553.87

7. TECHNICAL DESCRIPTION AND PERSPECTIVE

Please tick an executive summary of the new technology product, process, etc., describing how it works. Include brief analysis that competitive technology and signals the one that it may replace. Identify potential technology user group and the strategic means for exploitation.

a) Technology Description

A six degrees of freedom articulated robot is a machine that would offer the opportunity to reduce human exposure to hazardous environments in a painting process.

b) Market Potential

c) Commercialisation Strategies

8. RESEARCH PERFORMANCE EVALUATION

a) CHAIRMAN OF FACULTY RESEARCH COMMITTEE

	Excellent	Very Good	Good	Satisfactory	Fair	Weak
Research Status	☐	☐	☐	☐	☐	☐
Spending	☐	☐	☐	☐	☐	☐
Overall Status	☐	☐	☐	☐	☐	☐

Comment/Recommendations :

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…………………………………… **Name :** ……………………………...

Signature and stamp **Date :** ………………………………

b) RMC EVALUATION

	Excellent	Very Good	Good	Satisfactory	Fair	Weak
Research Status	☐	☐	☐	☐	☐	☐
Spending	☐	☐	☐	☐	☐	☐
Overall Status	☐	☐	☐	☐	☐	☐

Comments :

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Recommendations :

☐ Needs further research

☐ Patent application recommended

☐ Market without patent

☐ No tangible product. Report to be filed as reference

……………………………………
Signature and Stamp of Director
Research Management Centre

Nama : ……………………………..
Date : ………………………………

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PUSAT PENGURUSAN PENYELIDIKAN
BORANG PENYERAHAN PERALATAN YANG MENGGUNAKAN PERUNTUKAN VOT PROJEK PENYELIDIKAN

A. BUTIRAN PENYELIDIK

Nama Penyelidik : Gigih Priyandoko
Tajuk Projek : DESIGN AND DEVELOPMENT OF SIX DEGREES OF FREEDOM ARTICULATED ROBOT ARM FOR PAINTING
No Vot Projek : RDU140358
Fakulti : FKM
No. Tel/hp : 01110727461

B. BUTIRAN SERAHAN PERALATAN

Bil	Peralatan	No. Tag	Harga
1.	Kinect Fusion Scanner	FKM1000-PB105(R)-1606-0006-00001	RM 1,280.00

*** Jika ruang tidak mencukupi, sila guna lampiran mengikut format di atas**

C. PENGAKUAN PENYELIDIK

Saya dengan ini menyerahkan peralatan yang telah dibeli dengan menggunakan peruntukan vot projek penyelidikan RDU140358 kepada , Fakulti Kejuruteraan Mekanikal pada 12/12/2017 berikutan projek penyelidikan ini telah selesai dijalankan.

____
Tandatangan & Cop Ketua Penyelidik

Disahkan Oleh
Pengerusi J/Kuasa Penyelidikan Fakulti

____
Tandatangan & Cop

DESIGN AND DEVELOPMENT OF SIX DEGREES OF FREEDOM ARTICULATED ROBOT ARM FOR PAINTING

GIGIH PRIYANDOKO
FADHLUR RAHMAN BIN MOHD ROMLAY
ROSMAZI BIN ROSLI
AT-TASNEEM BINTI MOHD AMIN

RESEARCH VOTE

RDU140358

MECHANICAL ENGINEERING FACULTY

2017

ACKNOWLEDGEMENTS

Praise be to ALLAH s.w.t the Almighty on whom we ask for help and guidance by completing this report. Then we would like to express our appreciation to Research Management Centre (RMC) for their financial support, by which we could performed the research until its completion.

Next, my gratitude goes to all laboratories technician and FKM staffs as they were also contribute to my progress of project. From providing the raw materials, guiding in machine instructions and claiming for project grant, those are such unforgettable help and I appreciate that. Not to forget to all research member who help me during the process, contributing ideas and man power makes me feel confident to finish the project flawlessly.

Finally, I am in forever indebted to my family especially my wife for relentless emotional, technical and financial support as I needed along the journey of this project. There is nothing more to say in expressing my appreciation towards anybody who together with me to take a leap of faith in believing my ability to complete the research.

ABSTRACT

A three six of freedom (6DOF) articulated robot is a machine that would offer the opportunity to reduce or eliminate human exposure to difficult and hazardous environments in a painting process. This research is about to design and develop 6 DOF articulated robot arm to perform the painting process. Development of 6 degrees of freedom articulated painting robot is starting from the designing process, fabrication process and analysis for dynamic characteristics. Besides that another objectives of the project are to develop the control system of 6 DOF articulated robot and to generate the trajectory motion of the articulated robot in the flat surface. The parts of robots are base, arms and end effector. The robot moves in term of rotation of every joint. The performance of the robot is measured using dynamic characteristics such as the velocity, the acceleration and torque produced. The Lagrange Newton formulation is derived to obtain the velocity, acceleration and torque, while the structural analysis is conducted using finite element method. To sum up, the performance of the robot is determined by the dynamic characteristics and compare between the experimental value and theoretical value. A control system of 6 DOF and the trajectory motion of the end effector on a flat surface have been generated to perform the painting process. By using the inverse kinematics equation, the end effector coordinates needs to be assigns appropriately to generate the joint angles for each links of the articulated robot. So far, the result shows that the articulated robot is able to move on the flat surface by using the flat trajectory motion of the robot. Each coordinate of the end effector generated the joint angle of each links by using the inverse kinematics equation. The angular velocity of each links has been simultaneous to perform the painting process on the flat surface.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF SYMBOLS

Angular Acceleration

Angular Velocity

a Linear Acceleration

v Linear Velocity

Torque

l Length

t Time

m Mass

θ Angle

LIST OF ABBREVIATIONS

3D	Three Dimension
FKM	Faculty of Mechanical Engineering
MIG	Metal Inert Gas
SCARA	Selective Compliance Assembly Robot Arm

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Recently the development of service robot becomes popular due to the fact that the society needs robots to relax human from tedious and dangerous jobs. In the millennia era, the technology already grew rapidly than we were expecting yesterday. Everything needs to be done in a fast and efficient. For that purpose, the variation of robotic applications has created so many machinery tools to enhance the performance of workers in completing tasks especially in the automotive industries. Regardless the initial cost to fabricate the robot and develop the control system, the advantages that come may wipe the sceptical thought. It is undeniable that robot contributed a lot in the industries such as the assembly line and painting shop.

With the increasing of customer demands, human are no longer capable to cope with the work load. Commercial and industrial robots are in widespread use, performing jobs more cheaply or with greater accuracy and reliability human. They are also employed for jobs that are too dirty, dangerous or boring to suitable for humans. Robots are widely used in manufacturing, assembly and packing, earth and space exploration, surgery, weaponry, laboratory research and mass production of consumer and industrial goods. Painting is classically done by humans and generally requires exhaustive physical efforts and involves exposure to dangerous chemicals which can seriously impair the vision, respiratory system and general health (Abdellatif, 2013). The automated painting had been realized successfully in the automotive industry to paint millions of cars in the assembly lines. This industry uses spray painting and the robotic system is fixed in the assembly line. The domestic painting robots should be different in the sense that robots should have mobility so that it can move to paint the fixed walls (Abdellatif, 2013).

As robotic technology develops and becomes cheaper domestic robot for cleaning or moving the lawn are available, along with robotic toys for children of all ages. Different types of robot were designed with complex mechanism to fulfil each type of tasks given. Robot is more practical since it has no limitation like human such as getting tired and makes error. Unlike human, robot can perform very accurate and precise operation under critical and dangerous condition (Stengel & Systems 2011).

An articulated robot is a machine with rotary joints (e.g. a gripper robot for assembly operation). Articulated robots can create a reach range from simple jointed mechanism to systems with 10 or more interacting joints. It imitated the human being arm. Different with the usual robot, articulated robot is efficient in using the motor. The concept of articulated robot is a gigantic phenomenon on these days where the application of articulated robot itself has covered about 90% of the industries facilities. The wide range application of articulated robot has improved the productivity of production since it is proven that articulated robot can execute precise operation within its workspace, under condition.

1.2 PROBLEM STATEMENTS

This project is about developing six degrees of freedom articulated painting robot by taking into consideration the suitable dimensions, the material selection for the parts, calculating the torque produced to rotate the arm and DC geared motor as the power source at every joint. The problem arises on how to measure the performance of the robotic arm. Instead of the mechanical specification of the robot, dynamic characteristic of the robot is suggested as the parameter to measure the performance of the robot in terms of velocity, acceleration and torque.

The problem matter is that on how to obtain the dynamic characteristics of the robot itself. Formulation need to be derived based on the concept of kinetic energy and potential energy (Euler Lagrange) which resulting in the derivation of equation of motion to obtain the velocity, acceleration and torque at each degree of freedom. To compare with the theoretical calculation of dynamic characteristics, experimental result is collected using time frame technique based on the actual final product of painting robot movement.

Moreover, the kinematics and dynamic of the robot need to be considered to determine the structure operation and joint angle for controlling the suitable actuator. This is because to reach the end effector of the articulated robot, the forward kinematics and the angular velocity of the links need to be determined. Without using a suitable software and equipment, it will produce a lot of complication during the development of control system. Therefore, an ideal control system of the articulated painting robot need to be developed in order to control the robot to perform the painting process.

In the painting process, there are various types of surfaces such as flat surface and curve surface. In the curve surface, the trajectory motion of the painting robot should not be difficulty to the controller. But if in the flat surface, the end effector position will face some difficulty to make sure the surface will having complete painting process. Therefore, the trajectory motion of the painting process for the articulated robot need to be generate to make sure the robot are convenient for painting process at any types surface.

1.3 PROJECT OBJECTIVES

The objectives of this project are;

i. To develop a six degrees of freedom articulated painting robotic arm
ii. To investigate the dynamic characteristics of the a three degree of freedom articulated painting robot system by Euler Lagrange formulation and compare with time frame experimental value.
iii. To develop control system of the six degrees of freedom articulated robot.
iv. To generate the trajectory motion of the 3 DOF articulated robot.

1.4 PROJECT SCOPE

1.4.1 Development Process

Development process is covering the scope starting from sketching the robot arms to get the rough image of the design. Then, the drawing is translated into 3D drawing with actual dimensions of the parts. For the fabrication process, most of the machining process with the use of tools and machines is involved such as cutting, shearing, bending, welding and drilling. After that, the testing is conducted by installing motor on each joint to rotate each arm with desired angle of rotation. Then, the performance is measure using dynamic characteristics concept which following Euler Lagrange Formulation for theoretical result which will be compared with experimental result.

In the development of control system for six degrees of freedom (6 DOF) static articulated robot for painting process, the rotation angle from the base of the articulated robot is will be 180 degrees because of the painting process will be held in front of the robot. The type of control system that has been developed for the articulated robot was a close loop control system which uses encoder to control the rotation of the motor during the painting process. The formulation of forward kinematics and inverse kinematics will be considered on the three links which are base link, lower arm link and upper arm link. The actuator used in this research is DC geared motor to manipulate the links of the robot because the capability to withstand high torque operations.

1.5 PROJECT HYPOTHESIS

Dynamic characteristics of six degrees of freedom articulated painting robot is measured using Euler Lagrange Formulation in term of velocity, acceleration and torque and compared with experimental result. The control system of the articulated painting robot is developed by using a formulation of forward and inverse kinematic equation. In addition, the control system of the articulated robot able to perform the painting process at a flat surface by using the suitable software and DC geared motor. Result expected to be equal between theoretical and experimental result. The result may vary due to different variables in both formulas.

1.6 REPORT ORGANIZATION

This thesis sums up all the data and process regarding the development of three degree of freedom articulated painting robot. Chapter 2 discussed about the type of robot in market, specifically on articulated painting robot and the design consideration. There is also about the concept of dynamic characteristics of robot as the performance measurement. Chapter 3 is regarding the method on design and fabricate the robot including the derivation of dynamic characteristics equations. After that, all the results such as final product and calculation are shown in Chapter 4. To conclude all, Chapter 5 is written as the summary of the project.

CHAPTER 2

LITERATURE REVIEW

2.1 MOTION DEFINING ROBOT

Below are the summary of the type of robot based on the motion defining system.

Table 2.1: Summary of motion defining robot

Robot	**Joints**		**Coordinates**
Cartesian	Prismatic waist	x	Advantages :
	Prismatic shoulder	y	• Linear motion in 3D
	Prismatic elbow	z	• Simple kinematic model
			• Strong structure
			• Easy to visualize
			Disadvantages :
			• Required large volume
			• Smaller workspace than robot volume
			• Unable to reach areas under objects
Cylindrical	Revolute waist	θ	
	Prismatic shoulder	z	
	Prismatic elbow	r	

Spherical	Revolute waist	θ
	Revolute shoulder	ø
	Prismatic elbow	r
Articulated	Revolute shoulder	θ_1
	Revolute waist	θ_2
	Prismatic elbow	θ_3

Advantages :

- Simple kinematic model
- Easy to visualize
- Easy access to cavity space
- Suitable with hydraulic

  uses Disadvantages :

- Limited work space Advantages :
- Covers a large volume
- Easy to bend down to pick

Disadvantages :

- Complex kinematic
- Difficult to visualize Advantages :
- Maximum flexibility
- Cover large space
- Easy revolute joints
- Suits electric motor Disadvantages :
- Complex kinematics
- Less rigid at full reach

Source: Bright Hub Engineering, 2015

2.2 DESIGN CONSIDERATION

The design selection for a robot must be done, by considering all the factors such as the accuracy, the energy consumption, the cost etc. After all, there's perfect combination of factors in one robot. So, we need to look back at the main purpose of the development of the robot and try to focus the design which one can achieve the main objective of the robot's development. Nowadays, robot's there are so many technologies that being integrated with a robot to enhance its current performance and make it multipurpose. The commonly integrated technologies are the sensor system (infrared sensor, visionary sensor, and acoustical sensor), welding tools, painting tools, gripper and many more. To control the movement of the robot, a control system (software and hardware) is needed, such as the DC geared motor and encoders for the hardware and Arduino for the software as it function to create the coding of the program (Anak Japar 2010).

However, the limiting factor is that robots are limited to their work envelops thus we need to increase their coverage space. This mission can be accomplished by positioning axes which can be programmed to gain optimum working space coverage. The main things that need to be considered to optimize the performance of the robot are the design of base, arms, joints, the selection of suitable motors, and the end effector (Nabeel et al. 2013).

2.2.1 Joints And Links

In a robotic parts, the connection of difference joints is called as links, and the integration of two or more link is called joints (Willinams 2011);

i. **Rotational type joint.** Usually called as R-joint. This joint allow the joints to create a movement in form of a rotary motion along the axis, which is vertical to the arm axis.

Figure 2.1: Rotational joint.

Source: (Robot Basics 2015)

ii. **Twisting type joint.** Known as V –Joint. This joint produce *twisting motion* between the output and input link. The output link axis will be vertical to the rotational axis. The output link rotates according to the input link.

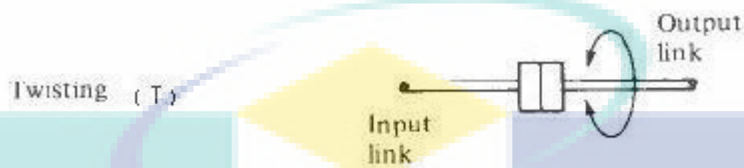

Figure 2.2: Twisting joint

Source: (Robot Basics 2015)

iii. **Linear type joint.** Named as L –Joint. Made to perform both translational and sliding type of movements. The examples of application that use this joint are telescoping mechanism and piston. The two links should be in *parallel axes* to create the linear movement.

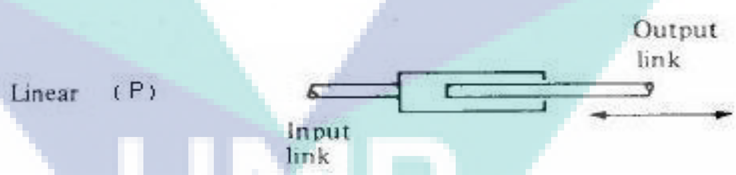

Figure 2.3: Linear joint

Source: (Robot Basics 2015)

iv. **Revolving type joint.** Revolving joint is generally called as V –Joint. This time, the output link axis is *90°*tothe rotational axis, and the input link is *parallel* to the rotational axes. Same like twisting joint, the output link rotates about the input link.

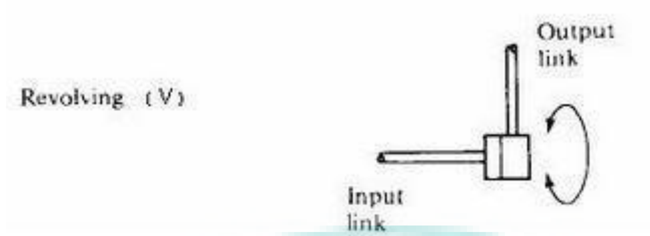

Figure 2.4: Revolve joint

Source: (Robot Basics 2015)

The main purpose of a link is to secure a fixed connection between the joints from one end to another end. The most commonly used link configurations are show below.

v. **Type 1.** It is two parallel revolute joints without twisting between the axes; whereas the axes of the joints are in parallel position.

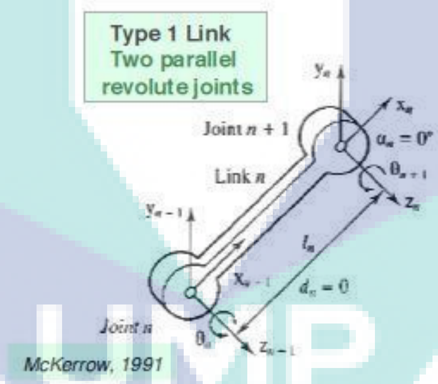

Figure 2.5: Type 1 link

Source: (McKerrow 1991)

vi. **Type 2.** For the second type, an extra degree is the angles that exist between the joint axes if the joints were coincident and similar to a rotation around the X axis. Thus, the type 2 link is a combination of one degree of translation and two degree of rotation.

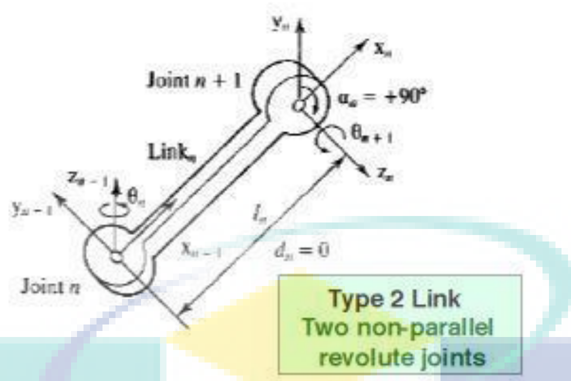

Figure 2 .6: Type 2 link

Source: (McKerrow 1991)

vii. **Type 3.** The second type of revolute joint is added. If the joint in the type 1 is rotated perpendicularly about the Y axis so that the Z axis is collinear with the center line of the link, type 3 link is produced.

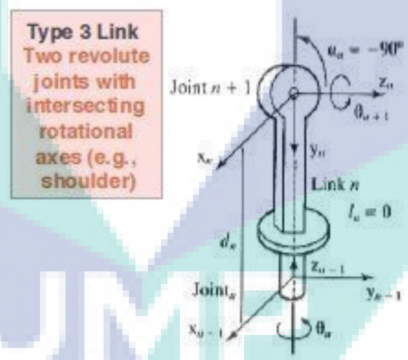

Figure 2.7: Type 3 link

Source: (Robot Basics, 2015)

2.2.2 Robot End-Effectors

Generally, end-effectors are the tools installed at the end tip of the robot arm that act as a 'hand', s hand to. The imitate end-effector is rarely human designed together with the robotic arm since manufacturer will install the end-effector to the robot based on the tasks of the robot itself. Means, for painting robot, manufacturer will attach a spray gun to the last wrist joint and for typical assembly robot, they will attach a gripper instead, as examples (Wallén 2008).

i. **Grippers.** The most common end-effectors in market. Imitating human hand with a thumb and fingers to allow the robot to grasp things.

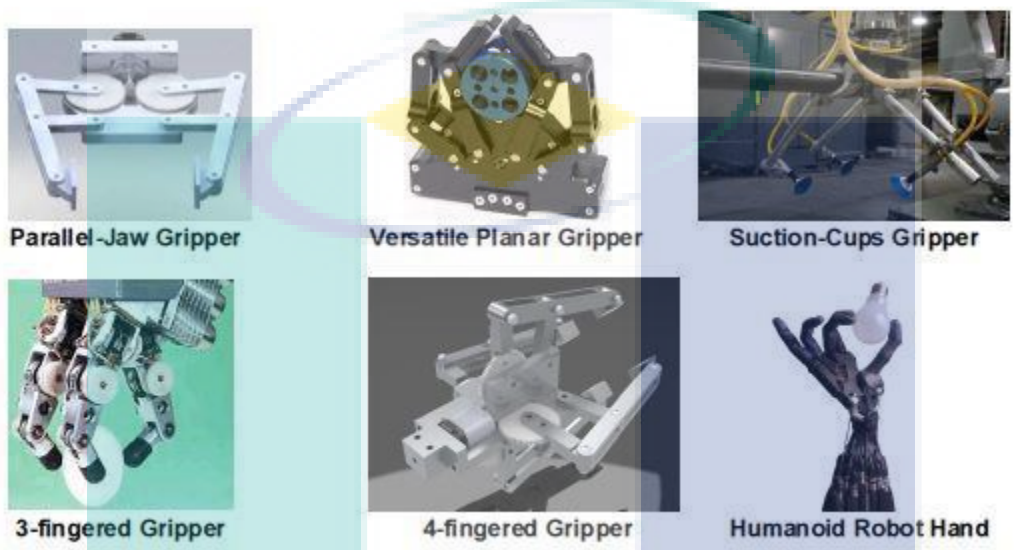

Figure 2.8: Grippers available on market

Source: (Hi Tech Automation, 2015)

ii. **Machine tools.** To do common machining tasks such as drilling, grinding, milling, cutting and sanders.

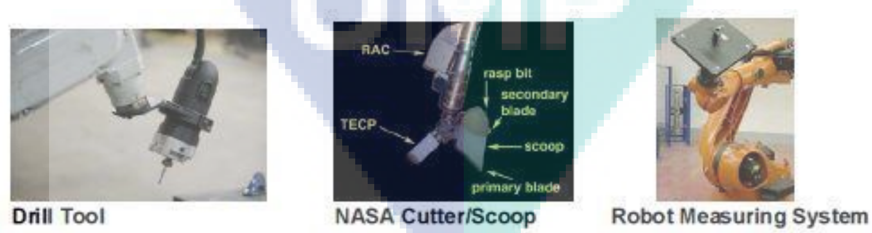

Figure 2.9: Common type of machining tools

Source: (Hi Tech Automation, 2015)

iii. **Spray painting tools.** For painting robot, automatic sprayer is a useful tool for spraying especially in automotive industries.

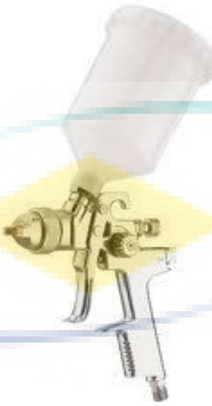

Figure 2.10: Painting spray as end effector

Source: (Hi Tech Automation, 2015)

2.3 TORQUE AND DC GEARED MOTOR

Torque is defined as the measuring of rotating force of an object. As the point the rotation is called the pivot point.

Figure 2.11: Definition of torque

Source: (The Guelph Physics Department, 2015)

The concept of torque can be found at every joint that has a rotation which driven by a DC geared motor. As for the DC geared motor itself, it is available with different specification which suits for specific task and purposes. For the one that used in robot, low RPM DC geared motor will produce high torque to rotate the arms and vice versa.

2.4 PAINTING ROBOT

To design a three degrees of freedom articulated painting robot, manufacturer will need to face two questions which are, does a painting robot truly suits the application of painting ? If that's so, by what means the r including the operation and overall ries of design painting technique that being applied in the industries nowadays (Aris et al. 2007).

i. Manual painting. An operator with an air-gun painting spray.

ii. Automated painting station. Spray guns attached fixed to stationary arms or systems such as rotated guns, multiple axis positioners or reciprocators.

iii. Painting Robot. Basically a six axes programmable robot which capable of sophisticated arm and complex wrist motion. Attached together with a spray gun on its wrist and acts like an end effector.

It is known that robot provides more flexibility compared to automated systems. Painting robot provide high consistency, better productivity, increased labours safety, less power consumption and minimizes the use of paint thus save cost. There are a few parameters that also need to be considered to achieve consistent quality of painting such as air & fluid pressure, flow rate, specific gravity, viscosity, appropriate temperature. To meet those criteria, engineers have come up with a new design of painting robot which already take into account all the important factor as it is also to fulfil the demand of the industries especially in the automotive sector (Diao et al. 2009).

2.4.1 Trajectory Planning For Painting Robot

Since the purpose of painting itself is to provide finishing on the surface, thus the painting technique must be perfect to produce uniform coating on the surface. The uniformity of painting thickness contributes a lot to the quality of the product. Here comes the trajectory planning. The objective of trajectory planning is to find the optimum trajectory that result in minimum variation on the surface of the painted body. Till the present day, the most used trajectory methods are;

i. Teaching method
ii. Automated trajectory method

The teaching method is pretty lame and conservative because it is really time consuming and the thickness of the paint i with the automatic trajectory, it is done automatically, controlled by programmed which is time efficient and reduce paint waste but still can achieve optimum result (Potkonjak et al. 2000).

An Automatic Trajectory Planning System (ATPS) has been developed for a spray painting robot. The mechanism is based on approximating the original free form surface as a small plane. But still, achieving uniformity in painting trajectory is a total challenge research and it still continue to these days. One way to optimize the painting quality is the spatial gun path and direction, and the velocity need to be programmed based on the local geometry of the free form surface (Chen et al. 2002)

2.5 DYNAMIC CHARATERISTICS OF ROBOTIC ARMS

Dynamic characteristics of robotic arms are defined as the performance measure of the robotic arms. Two main factors important in dynamic characteristics are the forces and motion. Forces is usually divided whether internal forces of external forces. The motion comes from external forces, while motion itself is known as the trajectory which consists of positioning, velocity, acceleration of some points in the system. In robotic terms, dynamic characteristics related to the relationship (Patel& George 2013).

i. *Forward dynamics*. Where the forces given to the robot and resulting in motion.
ii. *Inverse dynamics*. Measure the generalized force that produce motion trajectory.

In the other words, dynamic behaviour of certain robotic system is the time rate of robot configuration change in relation to the joint torque at every degree of freedom by the motorized actuator. As the result of equation of motions relationship, it governed the dynamic response of each linkage for the robotic arms to the torque at the joint. Methods such as Newton Euler and Euler Lagrange are used to study the characteristics of dynamic of the robotic systems (Kosuge and Furuta 1985).

2.5.1 Newton Euler Formulation

In order to move an end effector to perform a task, the control program plans a trajectory by converting the desired hand movement into a time sequence of joints motions. For this trajectory plan, it finds the net forces and torques acting on each link using the Newton Euler formulations. From these, the control program formulates the required joint torques using the static balance equations derived. The Newton Euler equations relate forces and torques to the velocities and accelerations of the centroids of the links by taking into account the masses, length, positions and inertias of the links (Nikravesh & Chung 1982).

Consider an isolated link (link n) with forces and torques acting upon it. A centroid frame is placed at the centre of mass, a frame which is fixed to the link and moves with respect to a stationary reference frame. Refers to Equation 2.1 and 2.2, the forces and torques acting on the link cause it to move, in accordance with the following relations (Clarke 2000).

$$f_n = \frac{dP_n}{dt} = \text{ force applied to link n} \tag{2.1}$$

$$\tau_n = \frac{dL_n}{dt} = \text{torque about the centroid of link n} \tag{2.2}$$

$$I_{xx} = \int (y^2 + z^2) dm = \int (y^2 + z^2) \rho dV = \iiint (y^2 + z^2) \rho dx\, dydz \tag{2.3}$$

$$I_{xy} = \int xydm \tag{2.4}$$

$$I_{xy} = I_{yx} \tag{2.5}$$

To include the dynamics by adding the dynamic terms for the forces and torques due to motion in Equation 2.6 and 2.7.

$$ {}^R_0f_n = {}^R_0f_{n-1.n} - {}^R_0f_{n.n+1} + m_n {}^R_0g = m_n {}^R_0g_n \tag{2.6} $$

$$ {}^R_0\tau_n = {}^R_0\tau_{n-1.n} - {}^R_0\tau_{n.n+1} - {}^R_0c_{n-1,n} \times {}^R_0f_{n-1,n} + {}^R_0c_{n,n} \times {}^R_0f_{n,n+1} $$

$$ = I_n {}^R_0\alpha_n + {}^R_0\omega_n \times I_n {}^R_0\omega_n \tag{2.7} $$

Where ${}^R_0c_{n,n}$ is the distance from frame n to the centroid of link n as seen from the reference's frame.

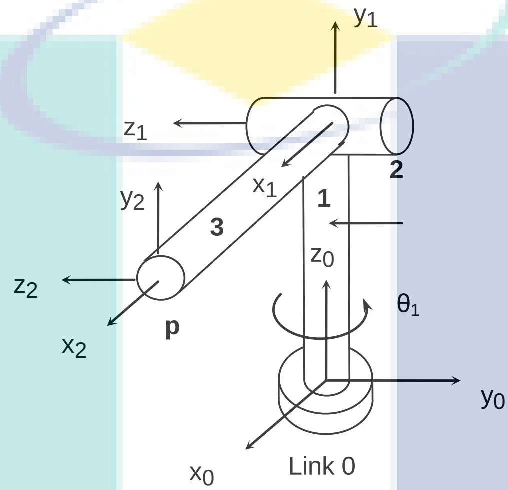

Figure 2.12: Type 2 two link manipulator

Source: (McKerrow 1991)

As the static case, the net force and torque are zero when the forces and torque on the link are balanced. For example, a robot moving in free space has a torque balance. For example a robot moving in free space has a torque balance when the actuator torques match the torques due to inertia and gravitation. If an external force or torque is applied to the tip of the robot additional actuator torques are required to regain torque balance (McKerrow 1991).

In case of a revolute joint, the z axis component of the torque at the joint is the torque the actuator has to supply and in the case of a prismatic joint, the z axis force at the joint is the force the actuator has to supply. By rearranging Equation 2.6 and 2.7, we obtain equations for the situation where the actuator torque and force balance all the applied torques and forces.

$$
{}^R_0\tau_{n-1,n} = {}^R_0\tau_{n,n+1} + {}^R_0c_{n=1.n} \times m_n\,{}^R_0a_n + {}^R_0p_{n-1,n} \times {}^R_0f_{n,n+1}
$$
$$
-{}^R_0c_{n-1,n} \times m_n\,{}^R_0g + I_n\,{}^R_0\alpha_n + {}^R_0\omega_n \times I_n\,{}^R_0\omega_n \qquad (2.8)
$$

2.5.2 Euler Lagrange Formulation

The Lagrange formulation describes the dynamic behavior of a robot in terms of the work done by and energy stored in the system. The robot is treated as a black box that has an energy balance. The constraint forces are eliminated during the formulation other equations. As with Newton Euler dynamics, the closed from equations can be derived in any coordinate system (McKerrow 1991).

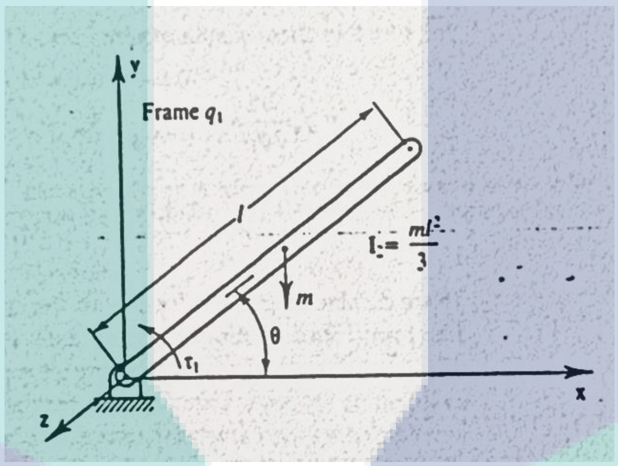

Figure 2.13: Uniform slender rod

Source: (McKerrow 1991)

To illustrate Euler Lagrange formulation, the model is based on the uniform slender rod rotating about a fixed axis.

$$
x,y,z = x,y,z(q) \qquad (2.9)
$$

Virtual displacement in Cartesian coordinates can be described in terms of virtual displacements if the generalized coordinates.

$$\delta_x \delta_y \delta_z = \frac{\partial_x}{\partial_{q1}} \frac{\partial_y}{\partial_{q1}} \frac{\partial_z}{\partial_{q1}} (\delta_{q1}) \tag{2.10}$$

Substituting these displacement into D'Alembert

$$\delta W = f_x \frac{\partial_x}{\partial_{q1}} \delta_{q1} + f_y \frac{\partial_y}{\partial_{q1}} \delta_{q1} + f_z \frac{\partial_z}{\partial_{q1}} \delta_{q1} = m \left(a_x \frac{\partial_x}{\partial_{q1}} + a_y \frac{\partial_y}{\partial_{q1}} + a_z \frac{\partial_z}{\partial_{q1}} \right) \tag{2.11}$$

These displacements conform with the constraint of motion in one degree of freedom: rotation about the joint axis. Hence, the virtual work for a virtual displacement conforms with the constrain. As δ_{q1} can be given an arbitrarily small value without violating the constrain and the constraint is smooth, the work done by the force of constraint is zero. Thus the force of constraint is eliminated from the equation.

To derive a relationship between virtual work and kinetic energy, the expressions is obtain to relate the derivative of the Cartesian coordinate to generalize coordinates.

$$\frac{dx}{dt} = v_x = \frac{\partial x}{\partial q_1} \delta q_1 \tag{2.12}$$

First derivative

$$\frac{\partial v_x}{\partial q_1} = \frac{\partial}{\partial q_1} \left(\frac{\partial x}{\partial q_1} \right) \dot{q_1} \tag{2.13}$$

Second derivative:

$$\frac{d}{dt} \left(\frac{\partial x}{\partial q_1} \right) = \frac{\partial v_x}{\partial q_1} = \frac{\partial}{\partial q_1} \left(\frac{\partial x}{\partial q_q} \right) \dot{q_1} \tag{2.14}$$

$$\frac{\partial v_x}{\partial q_1} = \frac{\partial \dot{x_1}}{\partial \dot{q_1}} \tag{2.15}$$

For acceleration equation:

$$\frac{d}{dt} \left(v_x \frac{dx}{dq_1} \right) = a_x \frac{dx}{dq_1} + v_x \frac{d}{dt} \left(\frac{dx}{dq_1} \right) \tag{2.16}$$

Substitute Equation 2.14 and 2.15 into 2.16:

$$a_x \frac{dx}{dq_1} = \frac{d}{dt}\left(v_x \frac{\partial v_x}{\partial q_1}\right) - \left(v_x \frac{\partial v_x}{\partial q_1}\right) = \frac{d}{dt}\left(\frac{\partial\left(\frac{v_x^2}{2}\right)}{d\dot{q}_1}\right) - \frac{\partial\left(\frac{v_x^2}{2}\right)}{dq_1} \tag{2.17}$$

Finally, substitute Equation 2.17 into Equation 2.11 to obtain the relationship between virtual work and kinetic energy.

$$\delta W_{q1} = \left\{\frac{d}{dt}\left[\frac{\partial}{\partial \dot{q}_1} m \frac{(v_x^2+v_y^2+v_z^2)}{2}\right] - \frac{\partial}{\partial q_1} m \frac{(v_x^2+v_y^2+v_z^2)}{2}\right\} \delta q_1$$

$$\left[\frac{d}{dt}\left(\frac{\partial K}{\partial \dot{q}_1}\right) - \frac{\partial K}{\partial q_1}\right] = \left(f_x \frac{\partial x}{\partial q_1} + f_y \frac{\partial y}{\partial q_1} + f_z \frac{\partial z}{\partial q_1}\right) \delta q_1 \tag{2.18}$$

By this, a single rotating link, the generalized coordinate is the joint angle and Equation 2.18 is reduce to Lagrange equation

$$\frac{d}{dt}\left(\frac{\partial K}{\partial \omega}\right) - \frac{\partial K}{\partial \theta} = \left(f_x \frac{\partial x}{\partial \theta} + f_y \frac{\partial y}{\partial \theta} + f_z \frac{\partial z}{\partial \theta}\right) = F \tag{2.19}$$

The kinetic energy of body moving with translation and rotation:

$$K = \frac{m}{2}\left(\frac{1}{2}\omega\right)^2 + \frac{1}{2}\left(\frac{mL^2}{12}\right)\omega^2 = \frac{1}{6} mL^2 \omega^2 \tag{2.20}$$

$$\frac{\partial K}{\partial \omega} = \frac{1}{3} mL^2 \omega \tag{2.21}$$

$$\tau = \frac{d}{dt}\left(\frac{1}{3} mL^2 \omega\right) = \frac{1}{3} mL^2 \alpha \tag{2.22}$$

2.6 TYPE OF CONTROL SYSTEM

A control system is a device, or set of devices that able to manage, command, directs or regulated the behaviour of other devices or systems. In addition, the control system also is an interconnection of components in forming a system configuration that will provide a desired system response (Dorf and Bishop, 2001). There are basically two types of control systems which are open loop system and closed loop system. Both the systems are trying to maintain a variable at a predetermined value. The control systems incorporate measurement systems, but a pure measurement system the output from a parameter whose value is not necessarily displayed to the user (Omirou, 2012).

2.6.1 Open Loop Control System

The open loop control system does not use feedback in order to determine the output has achieved the desired goal of the input. The system of open loop systems is controlled by a signal which is at a pre-set value. The pre-set value is considered that the required control is achievable without measuring the system output on the parameter which is set to control. Even though other factors render into the system is incorrect, the pre –set value

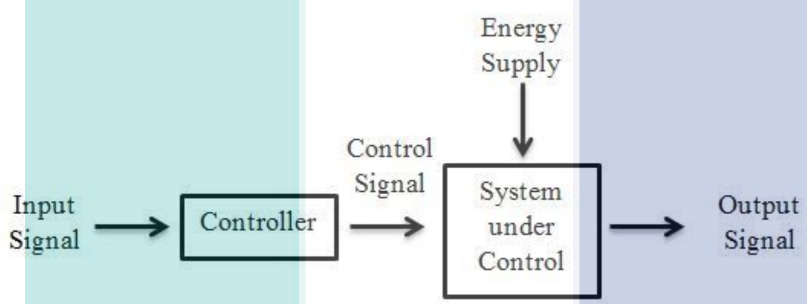

Figure 2.14: Flow Diagram of Open Loop Control System

Source: Sotiris Omirou, 2012

Figure 2.1 shows the flow diagram of the open loop control system. Open loop controls systems are in general have a simple design and inexpensive cost, but they require frequent operator intervention and can be inefficient. The pre –set value required a high level of skill to set it correctly.

2.6.2 Closed Loop Control System

A closed loop control system measures the value of the parameters that have been control of the output and compare the result with the desired value. The closed loop system will continuously operate through the application of feedback devices based on the feedback provided until the desired output was achieved. Therefore, a closed loop system always needs a sensor to monitor the output and compare with the expected result.

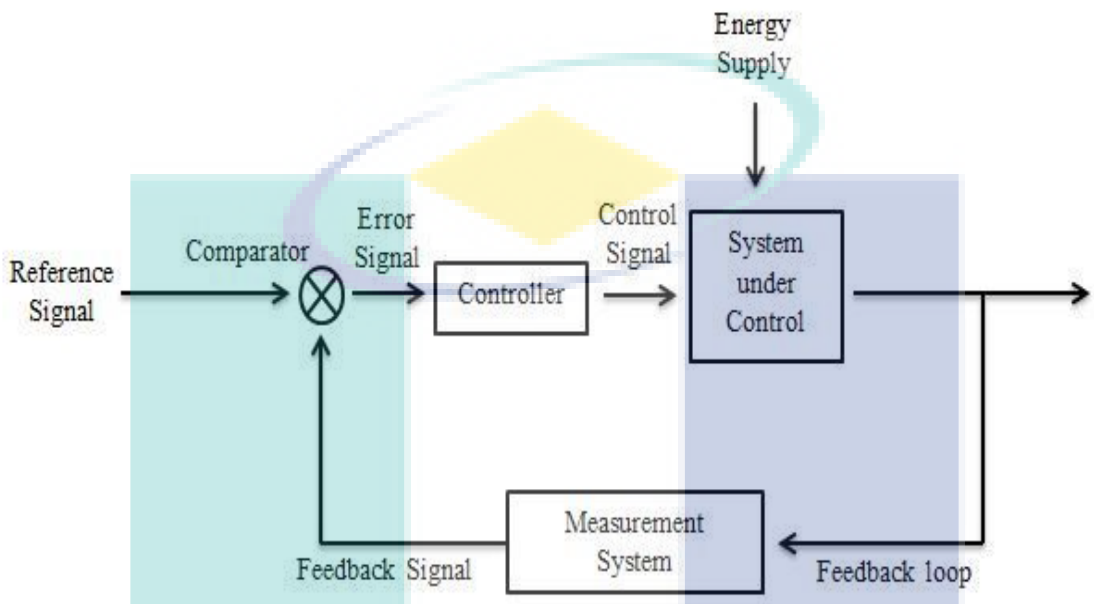

Figure 2.15: Flow Diagram of a Closed Loop Control System

Source: Sotiris Omirou, 2012

Figure 2.2 shows the flow diagram of the open loop control system. The term of feedback is used to refer to a situation in which two or more dynamical systems are connected together such that each system influences the other and their dynamics are thus strongly coupled (Astrom, 2006). The advantages of closed loop system are convenience and the simplicity of determining an optimum operating condition that allows decreasing the flow rate to the minimum value that will make the desired output achieved. Another advantage of the closed loop control system is that it is able to adjust the output automatically by feeding the output signal back to the input. The error signals that be generated by the system will adjust the output when the load changes.

2.7 TRANSFORMATION MATRIX

Through the vector addition or subtraction method, the transformation of an object from previous location to a new location in a Cartesian coordinate axes can be done. If the object structure is complex structure, the vector addition of and subtraction method will be more complicated in achieving the new coordinate of an object. This problem has been overcome through the introducing of a method where a new coordinate frame was defined with respect to a reference coordinate frame in which the base of the static robot manipulator was assigned as the reference point (Mckerrow, 1991). The complication suffers in transforming the object in Cartesian space can be reducing by implementing the relative coordinate frame method. Besides that, it is easy to apply matrix in calculation of the transformation.

$$A = \begin{bmatrix} 3 \times 3\ ROTATION & 3 \times 1\ TRANSLATION \\ 0 & 1 \end{bmatrix} \quad (2.1)$$

The 4 X 4 matrices in the equation 2.1 shows the object transformation in a three dimensional was determined where the rotation component is define in 3 X 3 matrix with the translational is define in 3 X 1 matrix (Ridzwan, 2014). The rotation transforms defined more complicated and complex compare to the translation transformation. The rotation of the object has been restricted about z –axis only on the process of assigning the coordinate frame in order to define the rotation transform. The transformation of the robot manipulator was restricted to four transform listed in the convention method (Ridzwan, 2014):

i. The rotation about the z –axis through the joint angle, Ө

ii. The translation along the z –axis through the offset between the joint axis, d

iii. The translation along the x –axis through the distance between the joint axis, l

iv. The rotation about the x axis through

$$A = \begin{bmatrix} cos\emptyset & -sin\emptyset cosa & sinsin\emptyset a & lcos\emptyset \\ sin\emptyset & cos\emptyset cosa & -cos\emptyset sina & lsin\emptyset \\ 0 & sina & cosa & d \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2.2)$$

Equation 2.2 shows the general A matrix for the each link of the articulated robot. The positions of the end effectors that are refer to the base which is determine by the transformation matrix of the robot are simplified in the above equation.

2.8 THE FORWARD KINEMATICS ALGORITHM

The forward kinematic analysis are define that the location and pose of the end of manipulator in a given references coordinate system can be worked out by the geometry parameter of the links and the variables of the joints in a robot (M. Dahari, 2011). Forward kinematics is also a calculation of the position and orientation of the end effector in terms of the joint variable. A robot mechanism need to use a suitable kinematics model in order to get forward kinematic in a systematic manner. There are steps to use the forward kinematics algorithm in order to obtain the forward transformation equation (McKerrow, 1991).

- Set the manipulator to zero position.

  This step must be done correctly and precisely because errors can be defined on the forward kinematics equation if the zero position was set in the wrong position.

- Assign the coordinate frame to each link.

  On the respective link need to be assign the coordinate frame after the zero position has been set correctly.

- Collect the link parameters.

  The link parameter need to be collect to obtain the forward kinematics including the general parameter which depends on the type of link installed.

- Define the A matrices for each link.

  To obtain the respective A matrix for each link, all the link parameter need to be substituted into the equation of object transformation. A matrix is matrix that defines the homogenous transformation happen between the two links.

- Multiply all the A matrices (Manipulator Transformation Matrix).

  The manipulator transformation matrix has been formulated by multiplying all the A matrices after each of the A matrices for the links have been through the derivation process.

- Equate the manipulator transformation matrix to the general transformation matrix.

  The manipulator transformation matrix is equated against the general transformation matrix in equation 2.3 to obtain the end effectors coordinates.

- Obtain the joint coordinates.

$$\textbf{\textit{General Tranformation matrix}} = \begin{bmatrix} 1 & 0 & 0 & P_X \\ 0 & 1 & 0 & P_Y \\ 0 & 0 & 1 & P_Z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.3}$$

2.9 THE INVERSE KINEMATICS

The inverse kinematics analysis is the opposite of the forward kinematics where the corresponding variable for each joints can be found by the given location requirement of the end of manipulator at the references coordinate system (M. Dahari, 2011). The analysis can be performing by multiplying each of the inverse matrices and equalizing the corresponding elements of the equal matrices of both ends. In order to place the arm at the required position and orientation, the value of each joint should be determine by the inverse kinematic solutions. There are four stages of algorithms that can be done to develop the inverse kinematics equation (McKerrow, 1991).

- Stage 1

  The manipulator transformation matrix has been equated to the general transformation matrix.

- Stage 2

  The elements in the matrices have been determined to be classified in three different paths in the stage 3.

- Stage 3
  - Path 1: Element with only one joint variable
  - Path 2: Pair of element of providing one joint variable when divided.
  - Path 3: Element that can be specified through trigonometry.

- Stage 4

  Last but not least, the equation of inverse kinematic has been solving.

CHAPTER 3

METHODOLOGY

3.1 PROPOSED DESIGN OF PAINTING ROBOT

To make sure the painting robot works flawlessly, the combination between the mechanical and electrical system must be paired to create movement mechanism of the painting robot. The DC geared motor must be attached precisely at the joint of the painting robot to rotate the arm and eventually translate the rotation into the movement of the painting robot and it must be placed at the right place to make sure the rotation is smooth. Whereas the mechanical part are the base, the arms and end effector need to be designed by considering the purpose of the robot to paint within its reach area.

Basically, the gearing mechanism proposed gears are very useful to change the direct but still can be designed for different angles. Compared to direct gearing transmission, bevel gear is on the winning side because obviously it is possible to change the rotation angle. Besides, the gear ratio can be changed so that the torque and rotational drive power can be varies such as high RPM with low torque or low RPM with high torque which suits the need of the painting robot itself.

The material selection is focused on light weight material but strong enough to support the load of the painting robot. Hollow mild steel with the thickness of 1mm is selected for the arms because mild steel is strong and easy for machining and welding process compared to aluminium. Moreover, mild steel is cheaper compare to aluminium. For the base, same material is used but it is circular hollow mild steel.

3.1.1 Design Consideration

The design must be first drawn into sketches before being translated into technical drawing using CAD software. There will be a few sketches of robot design as it is the early idea of the robot concept and need to be evaluated before the technical drawing is drew. Once the design is confirmed, technical drawing will be drawn using SolidWork 2014 for better view and simulation such as the degrees of freedom of the robot. If there is any error spotted, the correction can be directly made and run again the simulation.

Below are the general steps to complete the design;

i. **Sketch process**. Sketching is a process to bring up the idea into drawing without any specific dimensions. There is just the type of joint of the arms, base and end effector.

ii. **CAD software: SolidWork 2014**. The drawing is made part by part so that it could be easy to define the dimensions of the part. The dimensions used is the actual dimension.

iii. **Assembling.** After all parts have been drew, it will need to be assembled to see if the parts fit to each other and to simulate how the robot will work.

iv. **Stress analysis.** To see whether the design is strong enough to sustain the load given, a stress analysis is done using SolidWork 2014.

3.2 PAINTING ROBOT DESIGN

3.2.1 Basic Parts Drawing

The parts of the painting robot arms should have advantage of easy for machining, lightweight and low cost. The overall design materials was using mild steel plate, rectangular hollow mild steel and circular mild steel with the dimensions that are decided to achieve the specified reach area. The main process to attach the plate is by welding and at the joint, a combination of gear transmission is used. The basic parts are the end effector, the arms (arm 1 and arm 2) and the base.

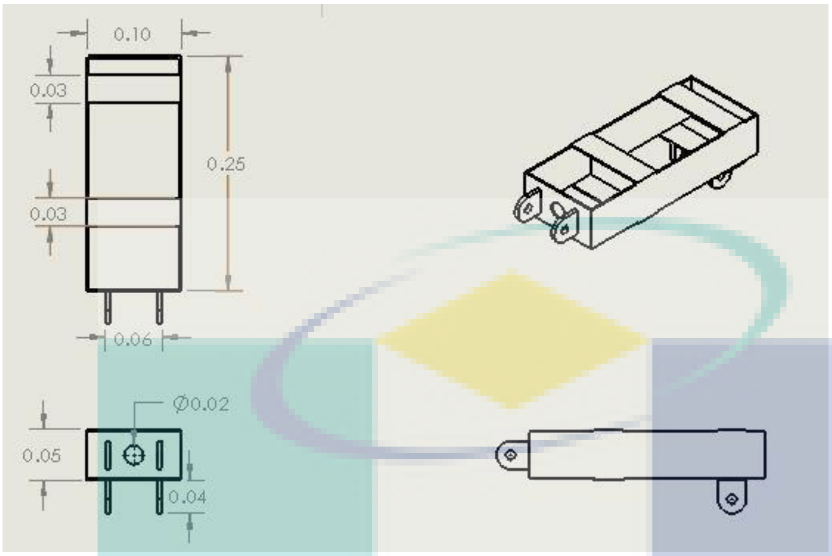

Figure 3.1: Technical drawing of arm 1

The used of mild steel plate in designing the arms is because by fabricate the rectangular shape; it is easier for cutting process and welding process. Besides that, the dimension marking is more accurate on rectangular shape thus producing precise dimensions of the arm. The design for the 1st and 2nd arm is the same but with different length for better weight distribution and reduces weight.

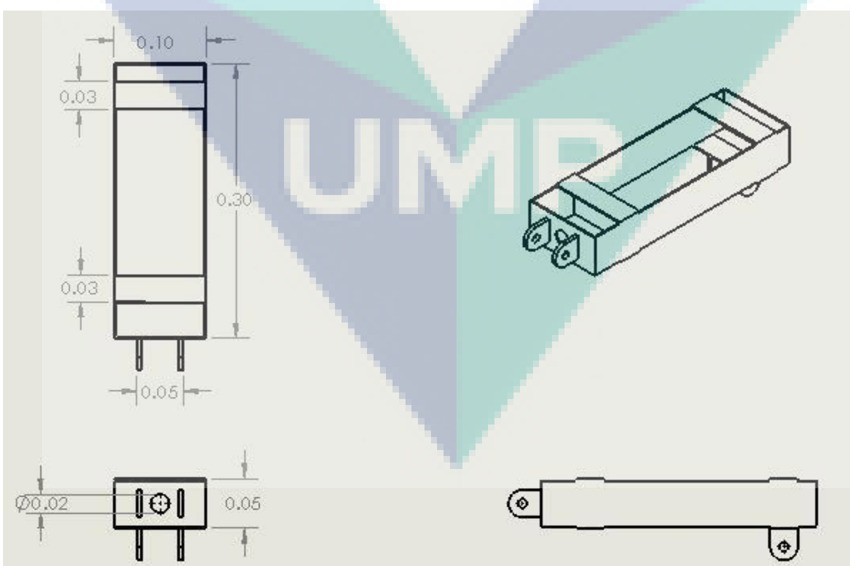

Figure 3.2: Technical drawing of arm 2

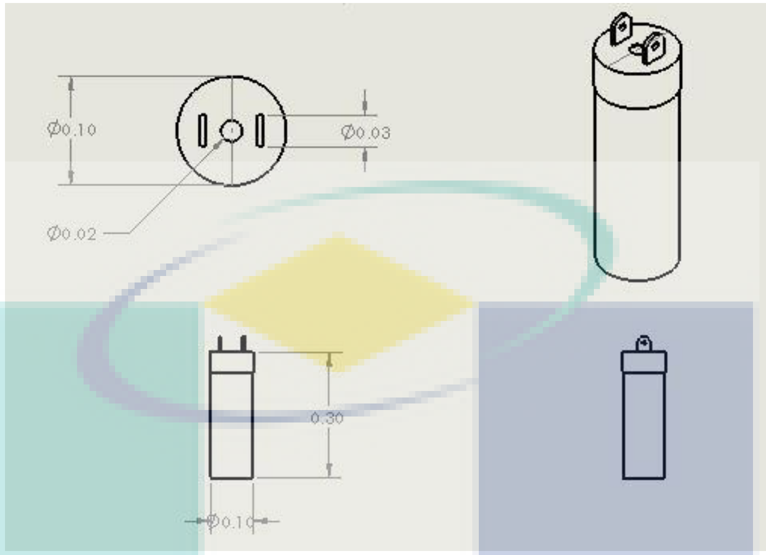

Figure 3.3: Technical drawing of cylinder base

Cylinder for base is made of stainless steel cylinder. Inside the cylinder is an inner gear which acts as the gearing mechanism to rotate the whole structure when assembled. At the top part is the cap which there is a mounting for gear and also motor. The cylinder is divided into three parts which is top, middle and bottom. Top is for motor installation area, middle is for the body and the bottom is for inner gear installation and motor for base.

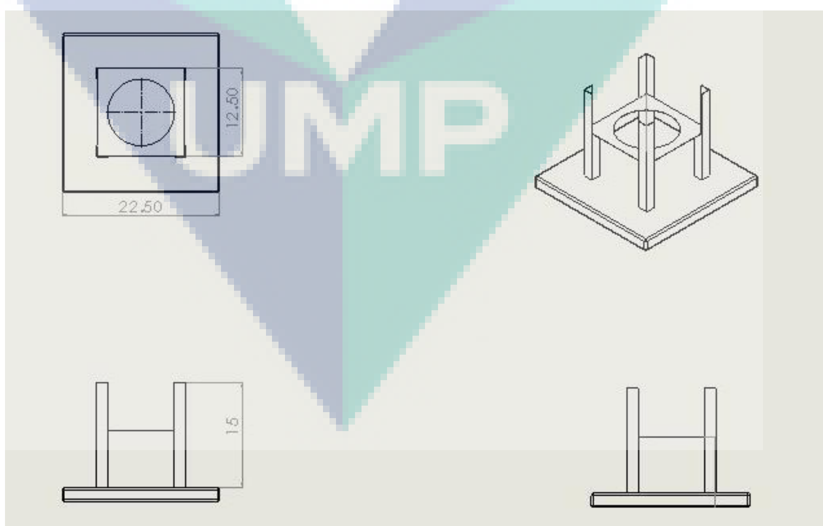

Figure 3.4: Technical drawing of base

As for the base, it is made up of rectangular hollow steel. Square shape base is chose as it provides more stability and rigid structure. There is bracket at the middle which is to hold the bearing and cylinder base.

3.2.2 Full Assembly Drawing

As mentioned earlier, all the parts being drew using SolidWork 2014. For overall view, the parts are assembled together like the actual design to illustrate the actual function of the arms and the rotation of joints. The full assembled parts including end effector, arm 1, arm 2, cylinder base and the base.

The end effector is a type of paint spray nozzle that attach to the very end of the arm 1. As it attach to the gearing system, the end effector can move up and down. For the arms, the design are identical to each other but with different length for better weight distribution which will reduce the torque at the top part of the robot thus make the rotation of arms is stable. There are plates that welded at the top part of the arms as a truss to make the design is more rigid and able to support the load.

Cylinder base is fabricated from circular mechanism between the arm and the base which provide 270̊ rotation.

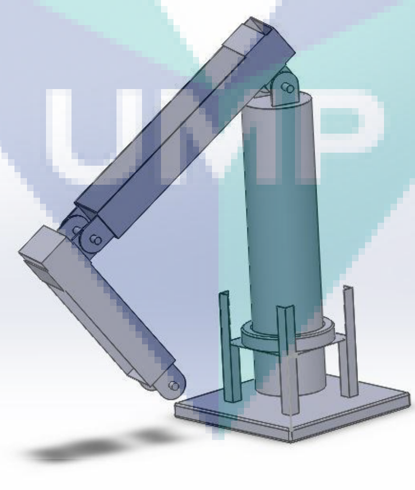

Figure 3.5: Final drawing

3.3 GEARING MECHANISM

Gear is used to transmit the power from one link to another link by means of rotation system. Nowadays, there are a lot of gearing transmission mechanism developed to suits varies type of tasks. Watches, car engines, wind turbine and many more. For such application in robotics joints, the common type of gearing transmission mechanism used is bevel gears transmission and direct gear transmission.

Direct gearing transmission is the simplest type of transmission because it use two gears positioned direct to each other and each connected to respective shafts to transmit the force. It is easy to install but quite space consuming because for the selected painting robot design, using such gear may need an external gearing operation because inner part of the joints is small.

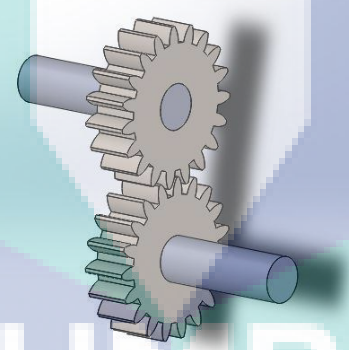

Figure 3.6: Direct gear transmission

Different with bevel gear transmission, it is more practical for the robotic joint because even the mechanism is a little more complex compared to direct gearing transmission, but it can be installed inside the arm, direct to the joint. Thus it is better to be used at the painting robot arm.

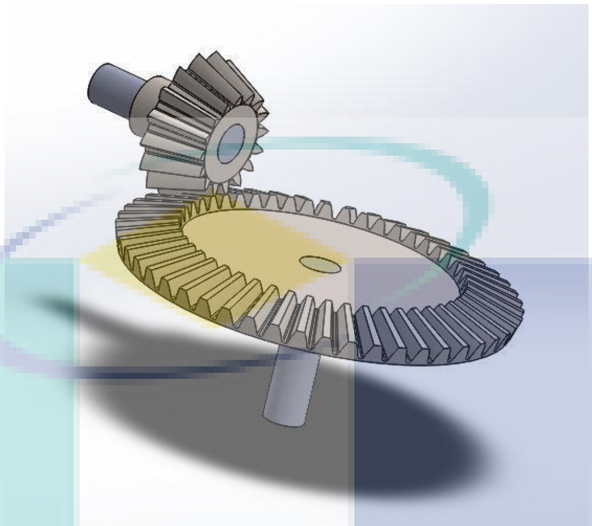

Figure 3.7: Bevel gear transmission

3.4 FABRICATION PROCESS PLANNING

The fabrication process is the important process where all the parts is going to be fabricate by means of common machining process. It starts by measuring the dimension of the raw materials until the finishing process.

i. Dimension measuring process

After the raw material is taken from the store, the first thing to do is measuring the actual dimension of the robot parts on the raw materials. For the arms, square hollow mild steel and for the base is the circular hollow mild steel. Specific length is measured by measuring tape and rulers.

ii. Cutting process

After the dimension being measured and marked on the raw materials, the next process is cutting. The main parts such as base and arms, floor cutter are used. To make sure the parts is still under the actual dimensions; tolerance has been made just in case error is occurred during cutting process.

iii. Assembling process

To attach the parts together, some of it need to be attached using welding process. Starting by marking the area that needs to be welded, then tap welding is done to hold still the both part. After that, full welding is done to strengthen the connection between two parts.

iv. Finishing

After all process is done and robot is already fabricated, coating process need to be done to protect the surface of the robot and of course to improve the appearance itself. Any bur at the edge of the arms is grinded to avoid any hazard to the user. After that, coating process is conducted by spraying the whole robot with aerosol painting spray to avoid rusting.

3.5 DYNAMIC CHARACTERISTIC MEASUREMENT

The dynamic characteristic is one of the measurements to measure the actual performance of the robotic arm instead of its mechanical specification. Instead of statics analysis, dynamic analysis is also important to verify whether the structure can perform well during under movement such as rotation and so on.

One of the ways is by deriving the Euler Lagrange formulation from the robot dimension to obtain the equation of motion which velocity, acceleration and torque can be obtained.

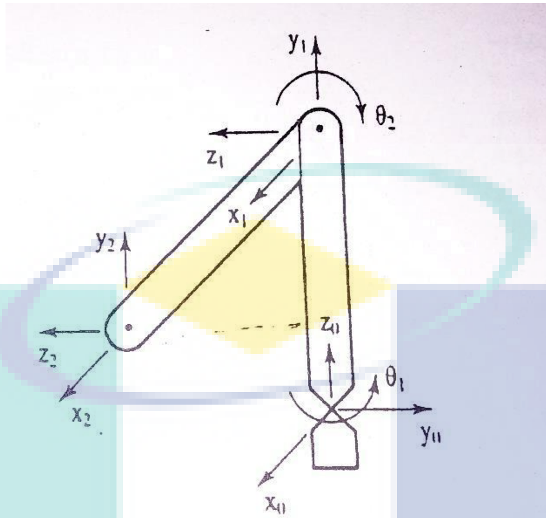

Figure 3.8: Free body diagram of type 2 two link manipulator

Source: (McKerrow 1991)

Velocities at centre mass of link;

$$v_{base} = \begin{bmatrix} -l_2 s_1 c_1 & -l_2 s_2 c_1 \\ l_2 c_1 c_2 & -l_2 s_1 s_2 \\ 0 & l_2 c_2 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} \tag{3.4}$$

$$\omega_{base} = \begin{bmatrix} s_2 \dot{\theta}_1 \\ c_2 \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} \tag{3.5}$$

Total energy :

$$K_1 = \frac{1}{2} m \dot{\theta}_1^2 = 0 \tag{3.6}$$

$$K_2 = \frac{1}{2} m l_2^2 \left(c_2^2 \dot{\theta}_1^2 + \dot{\theta}_2^2 \right) \tag{3.7}$$

$$U_1 = mgl_1 \tag{3.8}$$

$$U_2 = mgl_2\left(c_2^2\theta_1^2 + \dot{\theta}_2^2\right) \tag{3.9}$$

$$L = \frac{1}{2}ml_2^2\left(c_2^2\theta_1^2 + \dot{\theta}_2^2\right) \tag{3.10}$$

The final Euler Lagrange equation:

$$\frac{\partial L}{\partial \theta_1} = -ml_2^2 s_2 c_2 \dot{\theta}_1^2 - mgl_1 - mgl_2(1 + s_2) \tag{3.11}$$

$$\tau_{base} = ml_2^2(c_1^2\dot{\theta}_1^2 - 2s_2c_2) \tag{3.12}$$

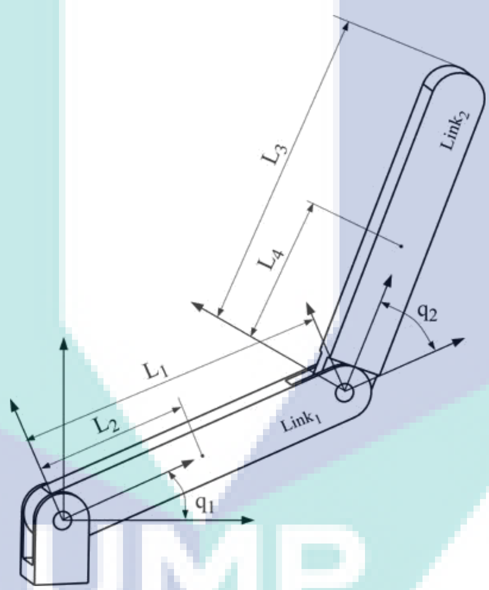

Figure 3.9: Free body diagram of arm 1 and arm 2

Source: (Nikravesh & Chung 1982)

Velocities at centre mass of link;

$$x_D = -l_1 s_1 \dot{\theta}_1 - 0.25 l_2 s_{12}\left(\dot{\theta}_1 + \dot{\theta}_2\right) \tag{3.13}$$

$$y_D = -l_1 c_1 \dot{\theta}_1 + 0.25 l_2 c_{12}\left(\dot{\theta}_1 + \dot{\theta}_2\right) \tag{3.14}$$

Total velocity;

$$V_D^2 = \dot{x}_D^2 + \dot{y}_D^2 \tag{3.15}$$

Total kinetic energy:

$$K = \dot{\theta}^2\left(\frac{1}{6}m_1 l_1^2 + \frac{1}{6}m_2 l_2^2 + \frac{1}{2}m_2 l_1^2 + \frac{1}{2}m_2 l_1 l_2 c_2\right) + \dot{\theta}_2^2\left(\frac{1}{6}m_2 l_2^2\right)$$

$$+\dot{\theta}_1\dot{\theta}_2\left(\frac{1}{3}m_2 l_2^2 + \frac{1}{2}m_2 l_1 l_2 c_c\right) \tag{3.16}$$

Total potential energy:

$$P = \frac{m_1 g l_1}{2}s_1 + m_2 g\left(l_1 s_1 + \frac{l_2}{2}s_{12}\right) \tag{3.17}$$

The final Euler Lagrange equation:

$$L = \left[\dot{\theta}^2\left(\frac{1}{6}m_1 l_1^2 + +\frac{1}{6}m_2 l_2^2 + \frac{1}{2}m_2 l_1^2 + \frac{1}{2}m_2 l_1 l_2 c_2\right)\right.$$

$$\left.+\dot{\theta}_1\dot{\theta}_2\left(\frac{1}{3}m_2 l_2^2 + \frac{1}{2}m_2 l_1 l_2 c_2\right)\right]$$

$$-\left[\frac{m_1 g l_1}{2}s_1 + m_2 g\left(l_1 s_1 + \frac{l_2}{2}s_{12}\right)\right] \tag{3.18}$$

Derivation from Euler Lagrange to find Torque:

$$\frac{\partial L}{\partial \theta_1} = \left(\frac{1}{2}m_1 + m_2\right)g l_1 c_1 + \frac{1}{2}m_2 g l_2 c_{12} \tag{3.19}$$

$$\tau_1 = \left(\frac{1}{3}m_1 l^2 + \frac{1}{2}m_2 l^2 c_2\right)\ddot{\theta}_1 + \left(\frac{1}{3}m_1 l^2\right)\ddot{\theta}_2 + \left(\frac{1}{2}m_2 l^2 c_2\right)$$

$$+\left(\frac{1}{2}m_2l^2s_2\right)\dot{\theta}_2^2+(m_2l^2s_2)\dot{\theta}_1\dot{\theta}_2+\left(\frac{1}{2}m_1lgc_1\right)+\left(\frac{1}{2}m_2lgc_{12}\right)$$

$$+m_2lgc_1 \qquad (3.20)$$

$$\frac{\partial L}{\partial \theta_2}=(m_1l_1l_2s_2)\dot{\theta}_1\dot{\theta}_2+\frac{1}{2}m_2gl_2c_{12} \qquad (3.21)$$

$$\tau_2=\left(\frac{1}{3}m_1l^2+\frac{1}{2}m_2l^2c_2\right)\ddot{\theta}_1+\left(\frac{1}{3}m_1l^2\right)\ddot{\theta}_2+\left(\frac{1}{2}m_2l^2c_2\right)$$

$$+\left(\frac{1}{2}m_2lgc_{12}\right) \qquad (3.22)$$

3.6 TRAJECTORY MOTION CALCULATION

In the trajectory motion of calculation, trigonometric function has been used to determine the location of the end effector articulated robot in a straight line. The radiuses for the end effector are same at the initial state and the final state of the trajectory motion. Figure 3.19 shows the Comparison between the normal motion and flat trajectory motion of articulated robot.

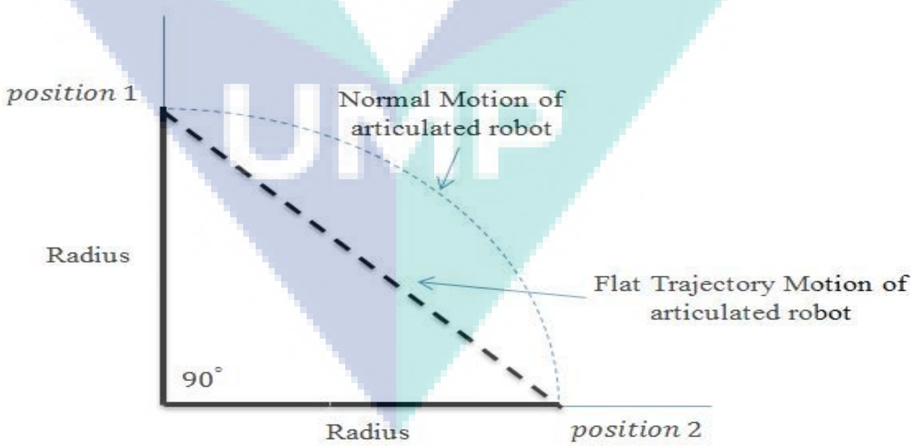

Figure 3.10: Comparison between the normal motion and flat trajectory motion

Coordinate position 1: (x_1, y_1, z_1)

Coordinate position 2: (x_2, y_2, z_2)

Then, we need to determine the gradient of the straight line to gain the linear equation of the trajectory motion.

$$gradient, m = \frac{(y_2 - y_1)}{(x_2 - x_1)}$$

Hence, we substitute the gradient of the straight line into the linear equation as follows:

$$y = mx + y_{intercept} \tag{3.21}$$

Therefore, the coordinate of the end effector in the straight line is achievable by obtain the value of X coordinate and substitute into the equation. For the Z coordinate, the value of the z coordinate will be constant in order to produce a straight line in the flat surface.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 DEVELOPMENT PROCESS

Development process is started from the design process itself. After the design is finalize, fabrication process starts. The robot has three basic parts which are the base, the arms, and end effector. Bevel gears, inner gear, spur gears, and bearing also used in the fabrication process. A rectangular hollow stainless steel is used for the base with the dimension of 250 mm x 250 mm x 15 mm. For the arms, mild steel with thickness of 3 mm is used. The first arm has a dimension of 350mm x 80mm x 50mm. The second arm has a dimension of 250mm x 80mm x 50mm. The end effector is the mechanical part that only need to be assemble at the end tip of second arm.

4.1.1 Robot Model

The final product of robotic arm is the assembly of all parts which consists of base, arm 1 and arm 2. Since the analysis has been done earlier on the design, the suitable type of materials and dimension had been decided. After taken into account all the criteria needed, the final detailing of the robot is represented as the final product as shown in figure 4.1.

All the parts are fabricated detachable so that it will be easy for maintenance and installation of motors. The parts that can be detached is the arm 1, arm 2, the base, motors, drive gears, and shafts. At the base cylinder, it can be detach into three parts since the inner gear need to be welded inside the cylinder at the bottom part. As for the upper part, motor is mounted at the cylinder cap. Some parts are welded permanently to make sure the structure is strong enough to sustain the load during static and during the robot moves by rotation.

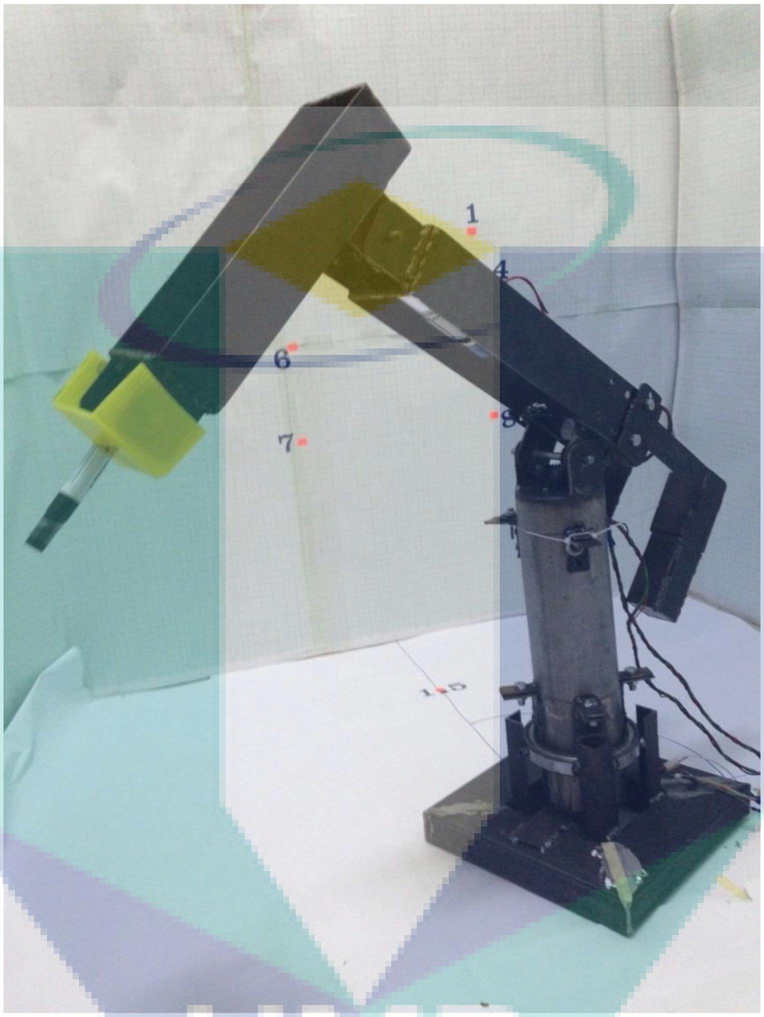

Figure 4.1: Full assembly of robot

4.1.2 Base Fabrication

Base design is very important to make sure the overall structure is stable enough to support the load of the whole body. The design of based is inspired by the design of gate frame. A rectangular hollow stainless steel is used for the base. The dimension is 250 mm x 250 mm. The process started by cut four pieces of stainless steel with length of 250 mm. At both end for every piece, a45°inward cutting is done so that the four pieces of stainless steel can be attached to form a square base. The intersection between every piece is welded to make sure it does not rip apart after full assembly is done.

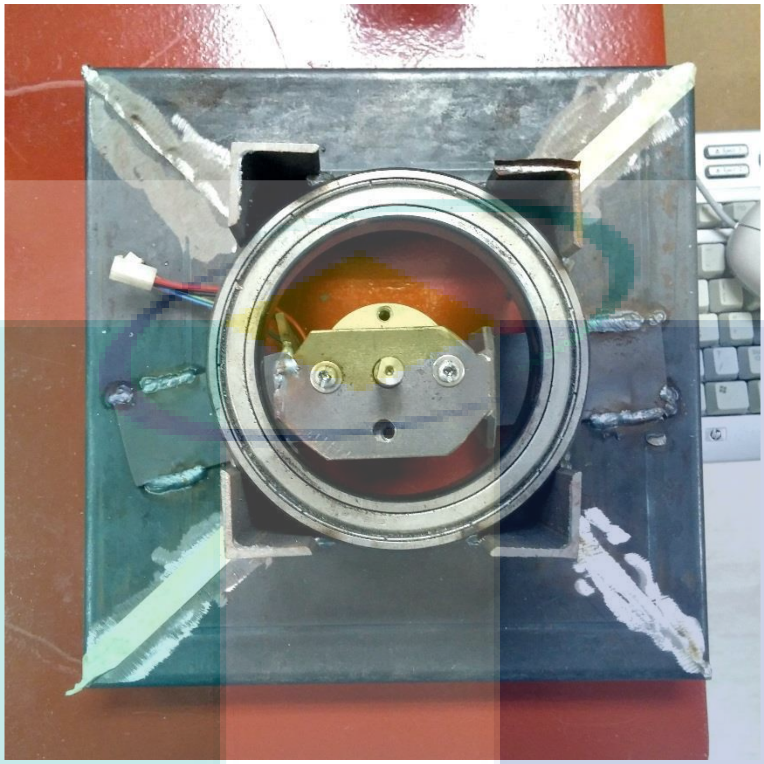

Figure 4.2: Base structure with bearing

As for the bearing, it works as the stopper that holds the base cylinder from touching the ground level. L-shaped mild steel is used as the bracket that holds the bearing. The bearing bracket is first welded at the box base. Then the bearing is welded at the bracket so that it will remain stationary at the designated level. For the motor bracket, it is also welded on the box base with the same purpose, to make sure minimize the vibration effect when the motor powered up.

4.1.3 Gearing Mechanism

To rotate the cylinder base, inner gearing system is used with the combination of steel spur gear. Different with the concept of planetary gearing system which use sun gear, planet gear and ring gear, the inner gearing system use direct gearing with the center gear. This is to make sure the force is transferred directly with less friction loss.

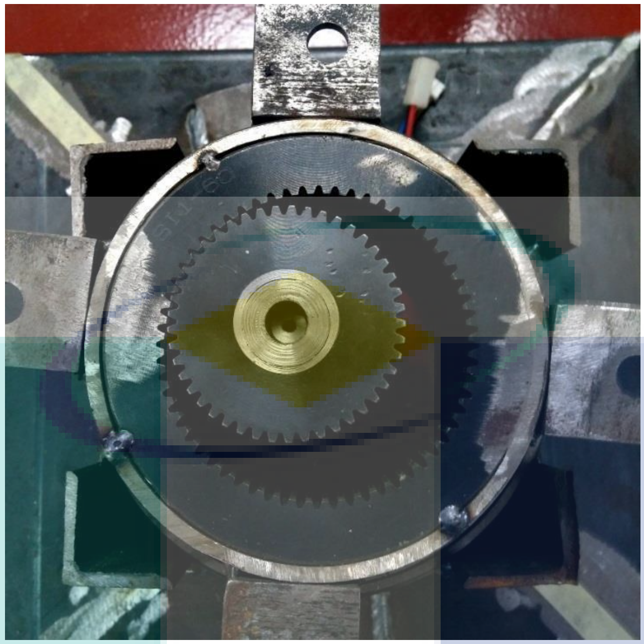

Figure 4.3: Base structure with inner gear and spur gear

The spur gear is mounted of the motor shaft with jammed nut. Inner gear with diameter of 95mm is placed inside the cylinder. The inner gear is welded permanently of the inner part of the cylinder so that as the motor rotate along with the spur gear, the inner gear can rotate together thus rotate the whole structure. The inner gear has 60 teeth and the spur gear has 45 teeth which make the ratio is 0.75.

For the gearing system at the joint, bevel gear system is used in the situation where a force is need to be transferred in other direction. The axes of the two gears is intersects in 90° position.

The drive gear is mounted fixed on the motor shaft using jammed nut. While for the driven gear, it is welded permanently on the bracket of the arm so that as the drive gear rotate the driven gear, the corresponding arm can be rotated as well. Drive gear has 30 teeth and driven gear has 20 teeth which make the ratio is 3:2. The shaft is not attached permanently so that the assembly of the arms can be set off anytime needed.

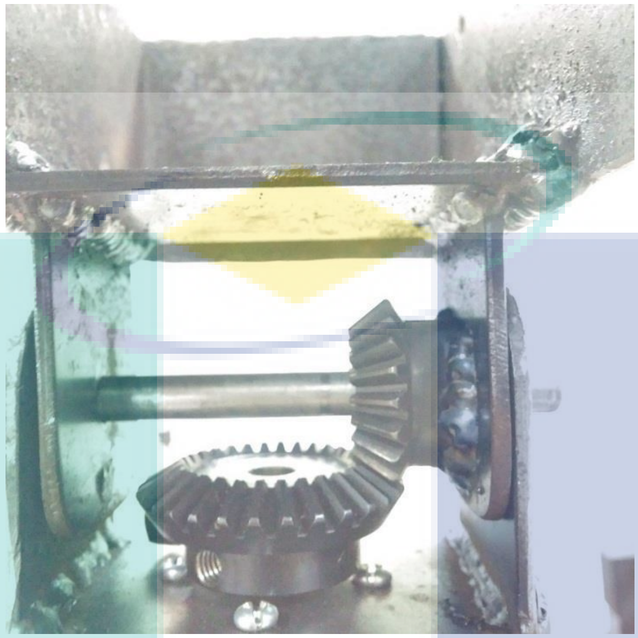

Figure 4.4: Bevel gear configuration

4.1.4 Arms Fabrication

The fabrication process of arm 1 and arm 2 are the same because the design is alike. The things that different is the dimensions. The material chose is mild steel plate with 3 mm thickness. The dimension of arm 1 is 350 mm x 80 mm x 50 mm. Two plate is cut into the dimensions. Each plate is bend into C shape then welded together to form an arm with rectangular shape. Same step is done for the arm 2 but with different dimension, 250 mm x 80 mm x 50mm. At each arm, two sets of bracket is welded for the mounting of gearing system.

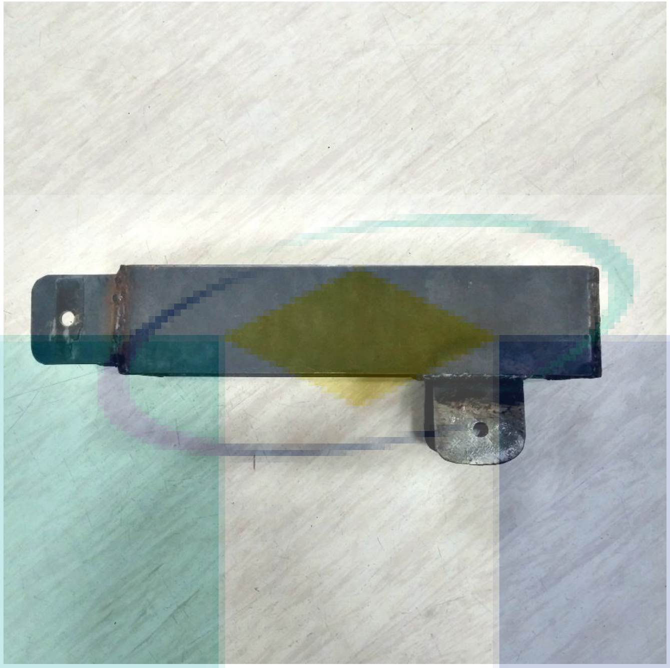

Figure 4.5: Arm 1 structure

Figure 4.6: Arm 2 structure

4.2 DYNAMIC CHARACTERISTICS CALCULATION

To measure the performance of the robot during in motion, Euler Lagrange formulation approach is used to define the velocity, acceleration and the torque acquired at each degree of freedom. It describes the dynamic behaviour of a robot in terms of the work done by and energy stored in the system. The robot is treated as a black box that has an energy balance. The constraint forces are eliminated during the formulation of the equations. As with Newton Euler dynamics, the closed form equations can be derived in any coordinated system.

4.2.1 Base Calculation result

t = 3 seconds to rotate in 90°

Angular velocity (ω_0) : 0.52 rad/s

Angular acceleration (α_0) : 0.17 rad/s^2

Torque, (τ_0) : 0.09 Nm.

4.2.2 Arm 1 Calculation result

t = 5 seconds to rotate in 30°

Angular velocity, (ω_1) : 0.104 rad/s

Angular acceleration (α_1) : 0.02 rad/s^2

Torque (τ_1) : 5.47 Nm

4.2.3 Arm 2 Calculation result

t = 5 seconds to rotate in 20°

Angular velocity ω_2 : 0.07 rad/s

Angular acceleration (α_2) : 0.014 rad/

Torque (τ_2) : 1.79 Nm

4.3 CALCULATION FOR EXPERIMENTAL RESULT

By using time frame technique, the time taken for each rotation by arm is measured using video. For each angle of rotation, time is taken. Then the velocity, acceleration and torque is calculated using formulae.

4.3.1 Base Calculation

Angle, $\theta = 30^{\circ}$ and time, t = 6 seconds

Angular velocities (ω_0) : 0.175 rad/seconds

$V_0 = \omega_0 L_0$ = 0.053 m/s

Angular acceleration (α_0) : 0.029 rad/s^2

Torque (τ_0): 3.56 Nm

Figure 4.7: Arm position at 0°

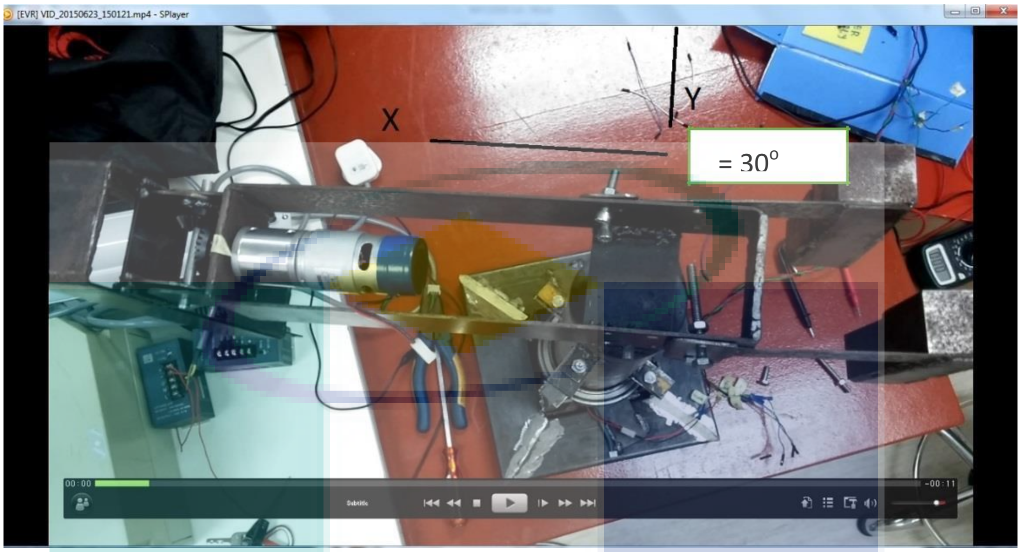

Figure 4.8: Arm position at 30°

4.3.2 Arm 1 Calculation:

Figure 4.9: Arm 1 position at 0°

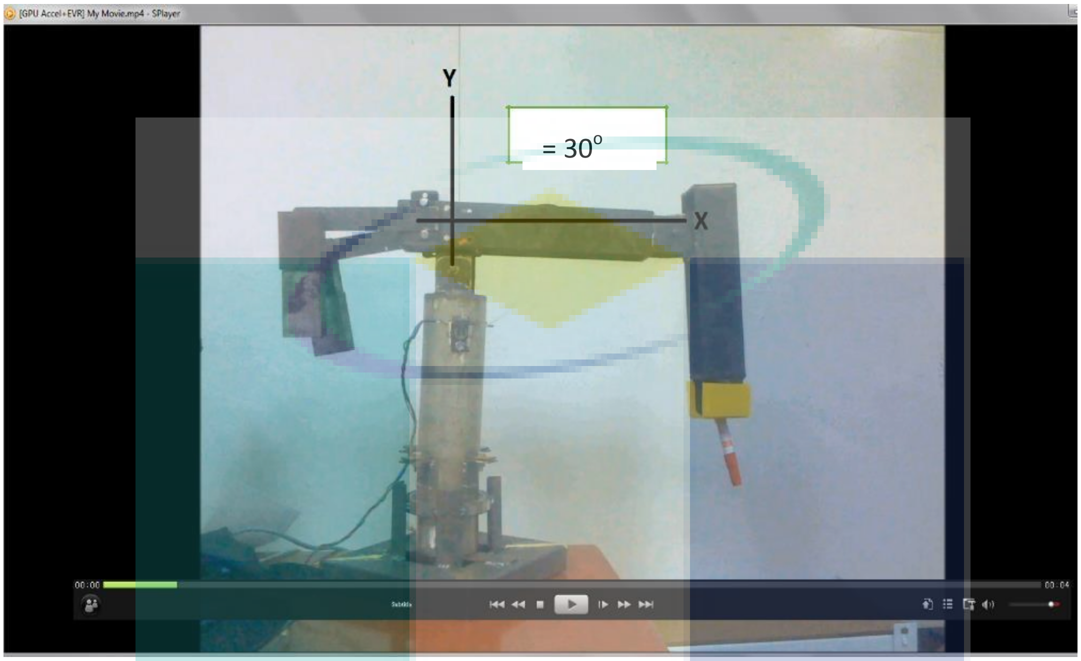

Figure 4.10: Arm 1 position at 30°

Angle, = 30° and time, t = 5 seconds

Angular velocities (ω_1) : =0.2094 rad/s

$V_1 = \omega_1 L_1$ = 0.073 m/s

Angular acceleration (α_1) : 0.03 rad/s^2

Torque (τ_1): 4.28 Nm

4.3.3 Arm 2 Calculation:

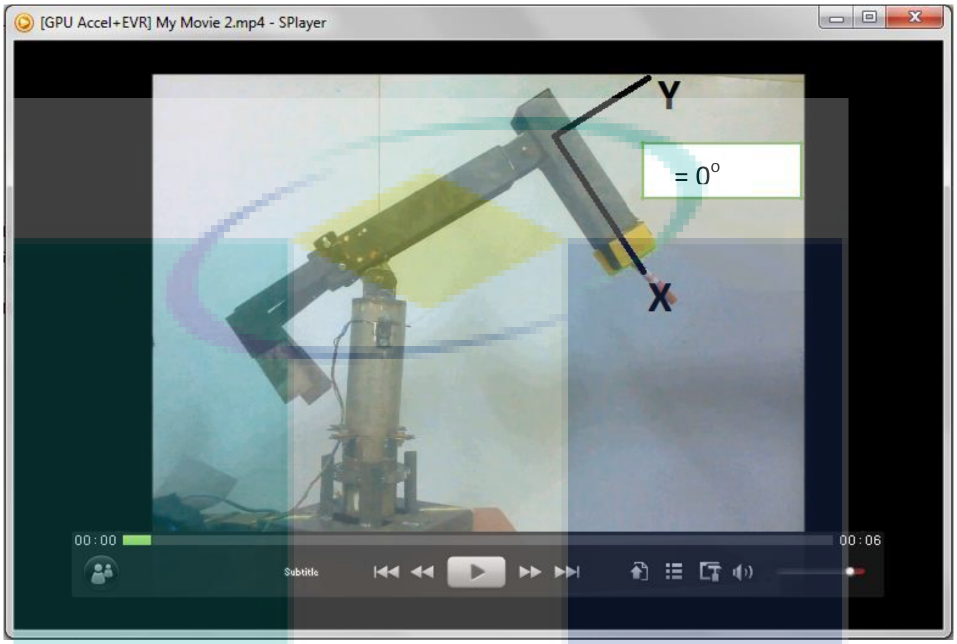

Figure 4.11: Arm position at 0°

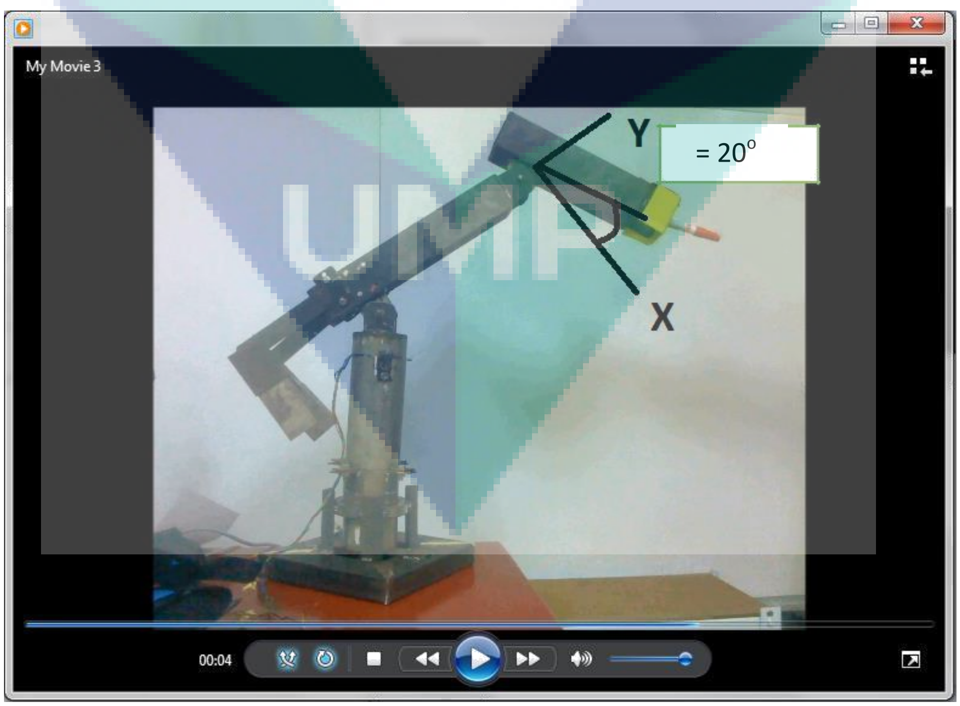

Figure 4.12: Arm position at 20°

Angle, = 20° and t = 4 seconds

Angular velocities (ω_2) : =0.17 rad/s

$V_2 = V_1 + \omega_1 L_2 + \omega_2 L_2 = 0.02$ m/s

Angular acceleration (2) : 0.04 rad/s^2

Torque (τ_2): 3.72 Nm

Table below shows the summary of result between theoretical using Euler Lagrange Formulation with experimental result using time frame.

Table 4.1: Summary of result

Dynamic Charactersitics	Euler Lagrange Formulation		Experimental	
	Arm 1	**Arm 2**	**Arm 1**	**Arm 2**
Anguler Velocity	0.104 rad/s	0.07 rad/s	0.2094 rad/s	0.17 rad/s
Anguler Acceleration	0.02 rad/s^2	0.014 rad/s^2	0.042 rad/s^2	0.04 rad/s^2
Torque	5.47 Nm	1.79 Nm	4.28 Nm	3.75 Nm

4.4 DC MOTOR OUPUT TORQUE

I = current (Ampere)

V = voltage (Volt)

E = efficiency *assume at 50%*

$$\tau_{motor\ 0} = \frac{(900\times10^{-3})\times12\times0.5\times60}{15\times2\pi} = 3.43\ Nm \tag{4.30}$$

$$\tau_{motor\ 1} = \frac{(900\times10^{-3})\times12\times0.5\times60}{10\times2\pi} = 5.16\ Nm \tag{4.31}$$

$$\tau_{motor\ 2} = \frac{(900\times10^{-3})\times12\times0.5\times60}{25\times2\pi} = 2.06\ Nm \tag{4.32}$$

4.5 COUNTERWEIGHT LOAD CALCULATION

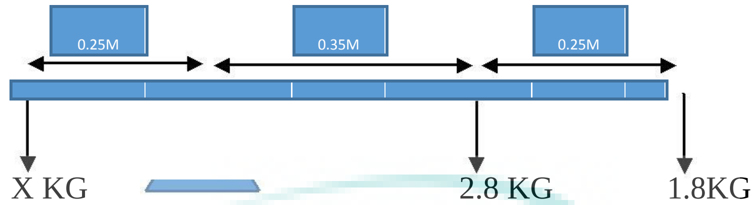

Figure 4.13: Counterweight diagram

*assume the counter weight distance from centre joint = 0.25 m

Length arm 1 = 0.35 m　　Mass arm 1 with motor = 2.8 KG

Length arm 2 = 0.25 m　　Mass arm 2 with motor = 1.8 KG

$\sum M = 0$ ↻

$$0.25\,w = (0.35 \times 2.8 \times 9.81) + (0.25 \times 1.8 \times 9.81)$$

$$w = 56.11\,N \qquad (4.33)$$

$$m = \frac{w}{g} = \frac{56.11}{9.81} = 5.7\,kg \qquad (4.34)$$

Figure below shows the parts for the counter weight mechanism. The parts are attached at the rear part of the arm 1 to make the structure balance.

Figure 4.14: Counter weight parts

4.6 THE TRAJECTORY MOTION FOR FLAT SURFACE

For the painting process, the surface for the process is flat surface. Therefore, the flat trajectory motion of the 3 DOF articulated robot need to be generated in order to perform the painting process as shown in the figure 4.5.

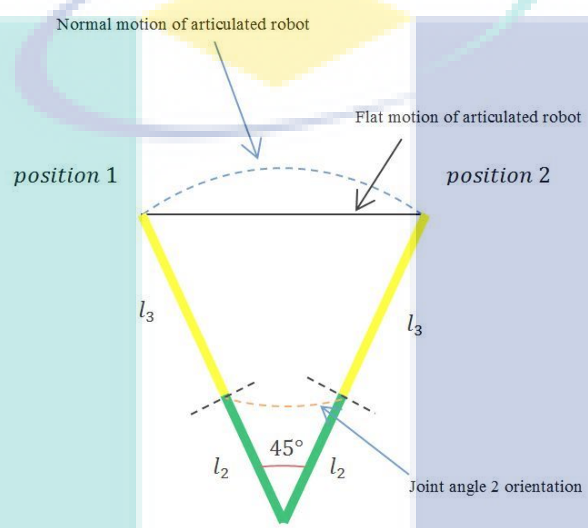

Figure 4.15: The desired flat trajectory motion for the articulated robot.

For the normal curve trajectory motion of the articulated robot, the joint angle of the links are constant except for the joint angle 1, which are change constantly until reach the desired second position. The radius of the arm is not change due to the curve line that obtains from the motion of the normal trajectory for the articulated. For the flat surface trajectory motion, the joint angle 1 and joint angle 2 are change due to reach the desired location of the in the flat line. Therefore, the coordinate of end effector need to be determined to obtain the desired joint angle for each links to produce the flat trajectory motion as tabulated in the table 4.2.

Table 4.2: The end effector coordinates in the flat surface of the painting process

Point	X Coordinate	Y Coordinate	Z Coordinate
1	49.84	0	41.24
2	48.52	3.18	41.24
3	47.21	6.36	41.24
4	45.89	9.54	41.24
5	44.57	12.72	41.24
6	43.26	15.89	41.24
7	41.94	19.07	41.24
8	40.62	22.25	41.24
9	39.31	25.43	41.24
10	37.99	28.61	41.24
11	26.67	31.79	41.24
12	35.36	34.97	41.24

By using the inverse kinematics equation that are obtain previously, the desired joint angle of each links according to the specific coordinate is able to determine.

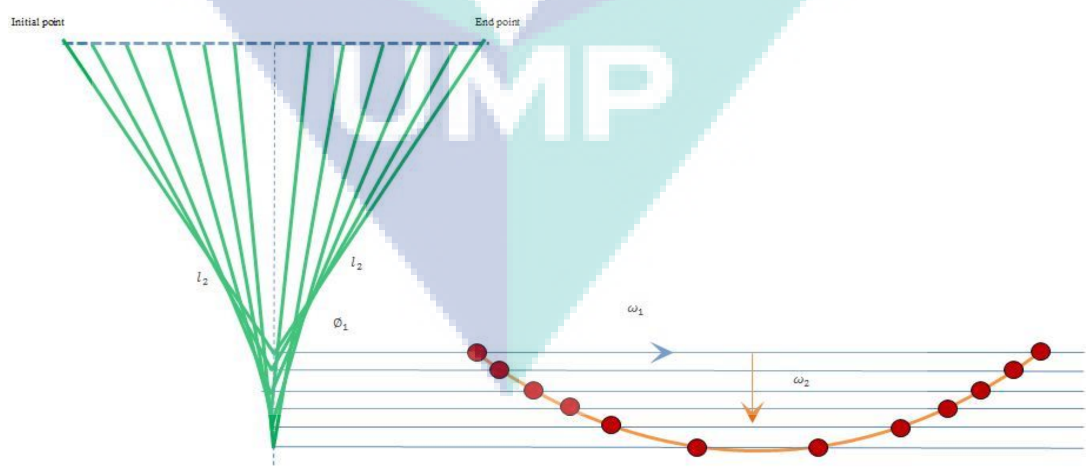

Figure 4.16: The flat trajectory motion.

Table 4.3: Each links joint angle value to reach the coordinate.

Point	Joint angle 1,	Joint angle 2,	Joint angle 3,
1	0	30	-50
2	3.75	33.25	-55.73
3	7.67	35.73	-60.05
4	11.74	37.52	-63.18
5	15.92	38.71	-65.23
6	20.18	39.31	-66.27
7	24.45	39.34	-66.31
8	28.71	38.79	-65.36
9	32.90	37.65	-63.40
10	36.98	35.90	-60.36
11	40.92	33.50	-56.16
12	44.68	30.32	-50.57

With this specific coordinate that obtain in the flat surface line, the value of the joint angle for each of link respectively to the coordinate can be determine as shown in the table 4.3. Due to the fact that, the flat trajectory motion can be generate to perform the painting process in the flat surface.

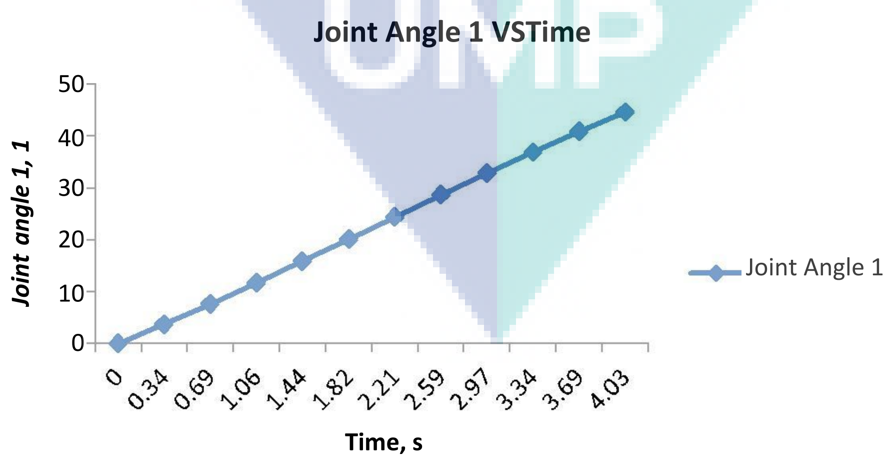

Figure 4.17: The graph of the joint angle 1, orientation in the flat trajectory motion.

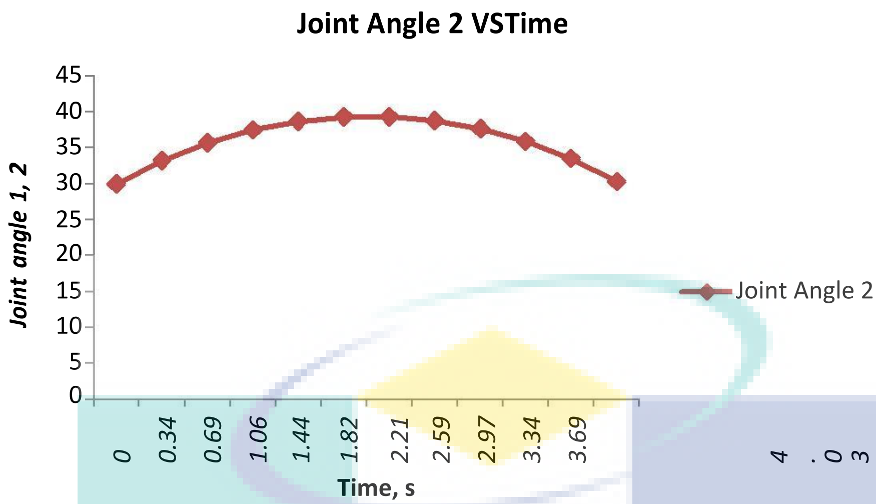

Figure 4.18: The graph of the joint 2, orientation in the flat trajectory motion.

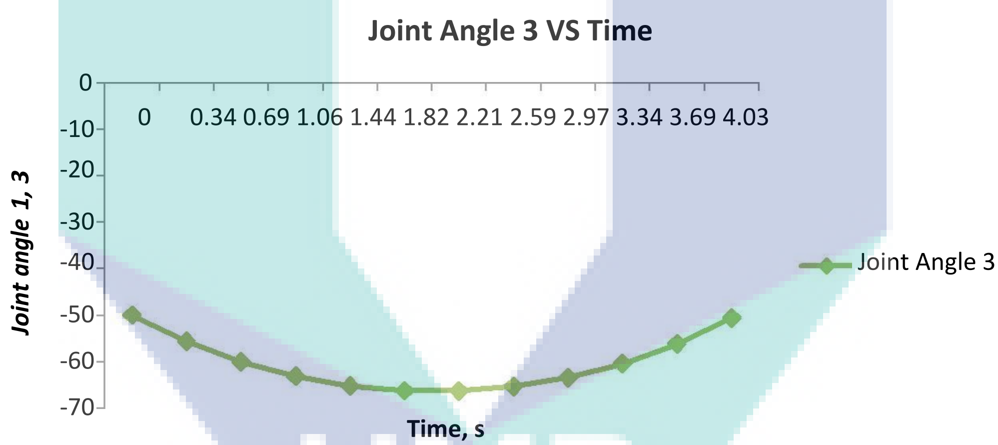

Figure 4.19: The graph of the joint 3, orientation in the flat trajectory motion.

The graphs show the relationship between the joint angle and the time travelled. In the figure 4.7, it shows that the relationship between joint angle 1 and the time is directly proportional. The joint angle 1 is increasing due to the increasing of the time. This is because the joint angle 1 are not effected on the changing of the coordinate. The joint angle 1 is continuously increasing until it reaches the desired angle. In the figure 4.8 shows that the relationship between the joint angle 2 and the time is positive projection. The initial joint angle 2 is 30 degrees and the final joint angle 2 is approximately 30 degrees. The maximum value of joint angle 2 is lies at 24.45 second which is 39.34 degrees. This is due to the coordinate of the end effector at that time is in the middle of the flat surface. The figure 4.9 shows that the relationship between the joint angle 3 and the time is negatively projection. The minimum value of joint angle 3 is lies on 24.45 second also where the value is -66.31 degrees.

Table 4.4: Angular velocity for each joint angle

Point	Time, s	Angular velocity 1,	Angular velocity 2,	Angular velocity,
1	0.00	0	0	0
2	0.34	11.03	97.79	-163.91
3	0.69	11.12	51.78	-87.03
4	1.06	11.08	35.40	-59.60
5	1.44	11.06	26.88	-45.30
6	1.82	11.09	21.60	-36.41
7	2.21	11.06	17.80	-30.00
8	2.59	11.08	14.98	-25.24
9	2.97	11.08	12.68	-21.35
10	3.34	11.07	10.75	-18.07
11	3.69	11.09	9.08	-15.22
12	4.03	11.09	7.52	-12.55

4.7 DISCUSSION

i. Derivation of Euler Lagrange

In finding the formulation of dynamic characteristics of the robot using Euler Lagrange, difficulties faced is on the derivation of the equation of motion. The variables are complex since we need to take into account about the mass, the dimensions and the moment of inertia of each parts. Every single derivation must be done carefully to avoid any mistakes and careless which eventually will affect the final result of the dynamic characteristics.

ii. Difference on result

For the experimental result, there is slight difference on the torque value of motor on arm 1 and arm 2. The possibilities that lead to the difference is the type of formula used in Euler Lagrange and experimental. It is undeniably that the formula used in experimental may not be as accurate as Euler Lagrange which has taken into account all the parameters needed such as mass, dimensions and moment of inertia. More research need to be conducted for future work to obtain the accurate technique on measuring the dynamic characteristics of the robot, experimentally.

iii. Designing problem

During designing stage, the problem faced were regarding the dimensions of the body. Since on market there will be parts that has specific dimensions. So the dimensions of the body must be tally with the part's confirmation from the company regarding the parts dimension is approved, by then the designing process can be proceed.

iv. Material selection problem

Availability of raw material and parts are limited because of some of those need to be bought from foundry shop such as large diameter of steel pipe for base cylinder, large size ball bearing, bevel gears and spur gears. The process can be very time consuming thus affecting the schedule of fabrication process. The struggle to find the company that provide the service of selling those specific parts also take time and affecting work schedule.

v. Fabrication process problem

Most of the machining process is the use of shearing machine to cut the sheet metal into designated dimensions, bending machine to bend the material into shape, hand grinder and floor grinder to cut the small parts, MIG welding machine to weld the parts and so on. The problem arose when those machines located in material laboratory and welding laboratory cannot be used due to maintenance services,

vi. Trajectory motion.

Besides determining the joint angles, the velocity of the each motor also need to be determine in order to make sure the flat trajectory motion have a smooth orientation a shown in the figure 4.6. Therefore, the angular velocity for each joint angle in the each point needs to be calculated and set respectively to the motors in the control system of the articulated robot as tabulated in the table 4.4. The speed of the base motor was set to 30% through the maximum PWM value which was 255. The time taken for the base motor to have 360 degree rotation is 32.5 seconds. With the speed of the lower arm motor was set to 37%, the time taken for the motor to complete 360 degree rotation also 32.5 second.

CHAPTER 5

CONCLUSIONS

The development of six degrees of freedom articulated painting robot is completed. In the perspective of development process, the robot is achieving the benchmark. The fabrication process involving the use of MIG welding machine, shear machine, bending machine and others has improved the technical skill on handling those machines which is important as an engineer. A few problems countered during the fabrication process but with a systematic planning all those problem were solved rightfully.

For the dynamic characteristics development, the formulation of Euler Lagrange really suits the nature of robotic system. The parameter of dynamic characteristics such as the velocity, acceleration and torque is successfully obtained using the Euler Lagrange concept as the theoretical result. There is a slight error on the experimental calculation of dynamic characteristics which make a few number is out of range thus an improvisation need to be done for future work regarding other robotic development.

The trajectory motion for the flat surface also successfully designed in order to perform the painting process in the flat surface. By using the inverse kinematics equation, the coordinates of the end effector in the flat line need to be determining in order to obtain the joint angles of each links to make sure the end effector orientation in the flat trajectory motion. Besides that, the angular velocities of the joint angle also have been obtained to make sure the orientation of the end effector lies on the straight line.

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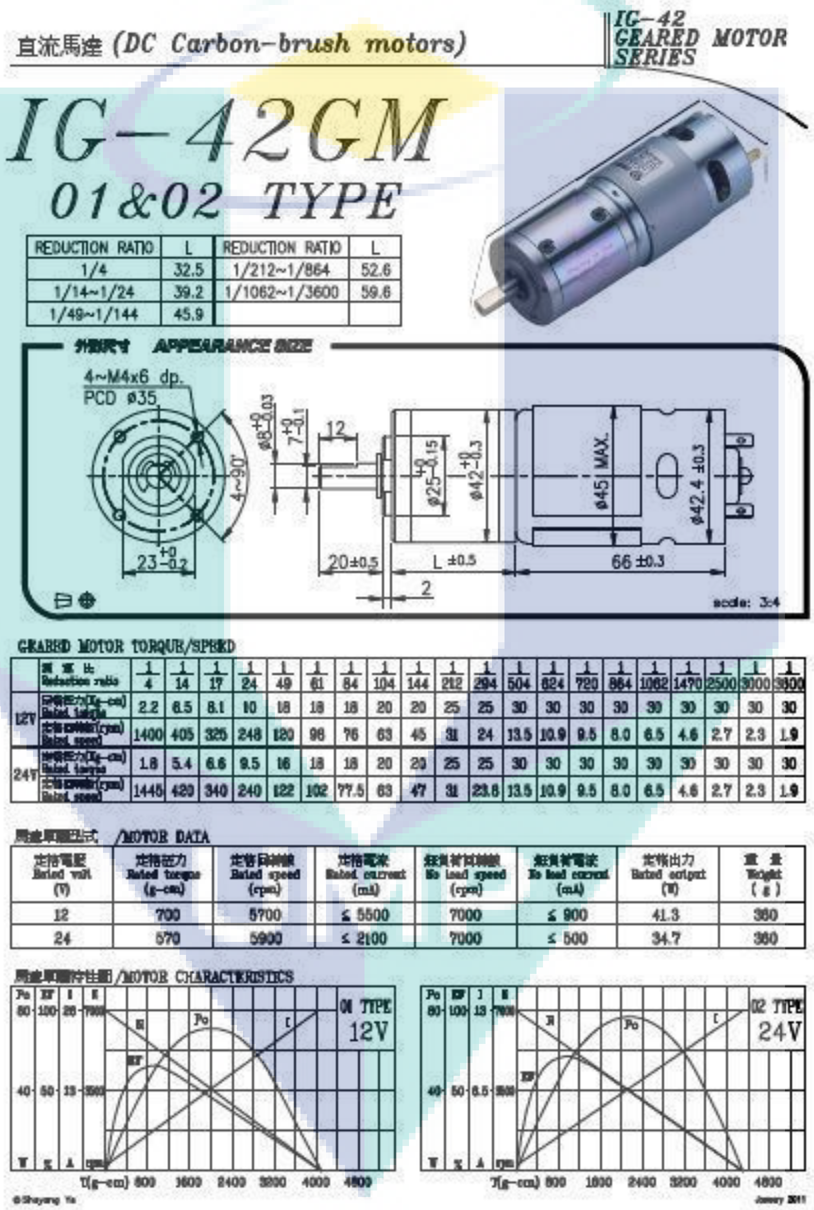
APPENDIX

DC GEARED MOTOR TECHNICAL SPECIFICATION



直流馬達 (DC Carbon-brush motors)

IG-42 GEARED MOTOR SERIES

IG-42GM

01&02 TYPE

REDUCTION RATIO	L	REDUCTION RATIO	L
1/4	32.5	1/212~1/864	52.6
1/14~1/24	39.2	1/1062~1/3600	59.6
1/49~1/144	45.9		

APPEARANCE SIZE

GEARED MOTOR TORQUE/SPEED

	Reduction ratio	1/4	1/14	1/17	1/24	1/49	1/61	1/84	1/104	1/144	1/212	1/294	1/504	1/624	1/720	1/864	1/1062	1/1470	1/2500	1/3000	1/3600
12V	Rated torque (Kg-cm)	2.2	6.5	8.1	10	18	18	18	20	20	25	25	30	30	30	30	30	30	30	30	30
	Rated speed (rpm)	1400	405	325	248	120	96	76	63	45	31	24	13.5	10.9	9.5	8.0	6.5	4.6	2.7	2.3	1.9
24V	Rated torque (Kg-cm)	1.8	5.4	6.6	9.5	16	18	18	20	20	25	25	30	30	30	30	30	30	30	30	30
	Rated speed (rpm)	1445	420	340	240	122	102	77.5	63	47	31	23.8	13.5	10.9	9.5	8.0	6.5	4.6	2.7	2.3	1.9

MOTOR DATA

Rated volt (V)	Rated torque (g-cm)	Rated speed (rpm)	Rated current (mA)	No load speed (rpm)	No load current (mA)	Rated output (W)	Weight (g)
12	700	5700	≤ 5500	7000	≤ 900	41.3	360
24	570	5900	≤ 2100	7000	≤ 500	34.7	360

MOTOR CHARACTERISTICS

THE FORWARD KINEMATICS CALCULATOR

```
#include "math.h" #define
PI 3.141592
float Xvalue, Yvalue, Zvalue, a1, a2, a3, y3; int
junk;
float   anglemotor1;   float
anglemotor2;           float
anglemotor3;

void setup()
{Serial.begin(9600);
 Serial.flush();}

void loop()
{int a=0, b=0, c=0;
 Serial.println("Enter the Angle for Motor 1: ");
 while(Serial.available()==0);
 {anglemotor1 = Serial.parseFloat();
  Serial.print("Angle 1 = ");
  Serial.println(anglemotor1);
  a=1;
  while(Serial.available()>0)
  {junk=Serial.read();}}

 Serial.println("Enter the Angle for Motor 2: ");
 while(Serial.available()==0);
 {anglemotor2 = Serial.parseFloat();
  Serial.print("Angle 2 = ");
  Serial.println(anglemotor2);
  b=1;
  while(Serial.available()>0)
  {junk=Serial.read();}}

 Serial.println("Enter the Angle for Motor 3: ");
 while(Serial.available()==0);
 {anglemotor3 = Serial.parseFloat();
  Serial.print("Angle 3 = ");
  Serial.println(anglemotor3);
  c=1;
  while(Serial.available()>0)
  {junk=Serial.read();}}

  a1 = anglemotor1 * PI / 180;
  a2 = anglemotor2 * PI / 180;
  a3 = anglemotor3 * PI / 180;
```

```
 Xvalue = (25*cos(a1)*cos(a2))+(30*cos(a1)*cos(a2)*cos(a3))-
(30*cos(a1)*sin(a2)*sin(a3));
Yvalue = (25*sin(a1)*cos(a2))+(30*sin(a1)*cos(a2)*cos(a3))-
(30*sin(a1)*sin(a2)*sin(a3));
 Zvalue = (25*sin(a2))+(30*sin(a2)*cos(a3))+(30*cos(a2)*sin(a3))+39;

Serial.println();
Serial.print("X = ");
Serial.println(Xvalue,DEC);
Serial.println();

Serial.print("Y = ");
Serial.println(Yvalue,DEC);
Serial.println();

Serial.print("Z = ");
Serial.println(Zvalue,DEC);
Serial.println();}
```

THE FLAT TRAJECTORY MOTION PROGRAM

```
#include "math.h" #define
PI 3.141592
double InverseX, InverseY, InverseZ, angleT, d,e,f,g,h,k,s,t,v,w, height; int
junk;

int pwmMotor1 = 9; int
dirMotor1 = 2; float
anglemotor1; float
calibrateangle1;

int pwmMotor2 = 10; int
dirMotor2 = 4; float
anglemotor2; float
calibrateangle2;

int pwmMotor3 = 11; int
dirMotor3 = 7; float
anglemotor3; float
calibrateangle3;

void setup()
{Serial.begin(9600);
 Serial.flush(); pinMode(pwmMotor1,
 OUTPUT); pinMode(dirMotor1,
 OUTPUT); pinMode(pwmMotor2,
 OUTPUT); pinMode(dirMotor2,
 OUTPUT); pinMode(pwmMotor3,
 OUTPUT); pinMode(dirMotor3,
 OUTPUT);}

void loop()
{Serial.println("Enter the Location X: ");
 while(Serial.available()==0); {InverseX =
 Serial.parseFloat();
  Serial.print("X = ");
  Serial.println(InverseX,DEC);
  while(Serial.available()>0)
  {junk=Serial.read();}}

 Serial.println("Enter the Location Y: ");
 while(Serial.available()==0); {InverseY =
 Serial.parseFloat();
  Serial.print("Y = ");
  Serial.println(InverseY,DEC);
```

```
  while(Serial.available()>0)
  {junk=Serial.read();}}

Serial.println("Enter the Location Z: ");
while(Serial.available()==0); {InverseZ =
Serial.parseFloat();
  Serial.print("Z = ");
  Serial.println(InverseZ,DEC);
  while(Serial.available()>0)
  {junk=Serial.read();}}

Serial.println("Enter the Angle of Trajectory Motion: ");
while(Serial.available()==0);
{angleT = Serial.parseFloat(); Serial.print("Angle of
  Trajectory Motion = "); Serial.println(angleT,DEC);
  while(Serial.available()>0) {junk=Serial.read();}}

float angleT_rad = angleT * PI /180; float
angleR = (180 - angleT) / 2; float angleR_rad
= angleR * PI / 180;
float length = (sin(angleT_rad))/(sin (angleR_rad) / InverseX); float
difference = length / 12;
float Xsecondpoint = InverseX - (cos(angleR_rad) * length); float
Ysecondpoint = sin(angleR_rad) * length;
float gradient = (Ysecondpoint - InverseY) / (Xsecondpoint - InverseX); float
Yintercept = Ysecondpoint - (gradient * Xsecondpoint);

float a1 = angle1 (InverseX, InverseY, InverseZ); float a2 =
angle2 (InverseX, InverseY, InverseZ); float a3 = angle3
(InverseX, InverseY, InverseZ);

float ya1 = difference;
float xa1 = ((ya1) - Yintercept)/gradient; float za1
= InverseZ;
float b1 = angle1 (xa1, ya1, za1); float b2
= angle2 (xa1, ya1, za1); float b3 = angle3
(xa1, ya1, za1);

float ya2 = ya1 + ya1;
float xa2 = ((ya2) - Yintercept)/gradient; float za2
= InverseZ;
float c1 = angle1 (xa2, ya2, za2); float c2
= angle2 (xa2, ya2, za2); float c3 =
angle3 (xa2, ya2, za2);
```

```
float ya3 = ya2 + ya1;
float xa3 = ((ya3) - Yintercept)/gradient;
float za3 = InverseZ;
float d1 = angle1 (xa3, ya3, za3); float d2
= angle2 (xa3, ya3, za3); float d3 = angle3
(xa3, ya3, za3);

float ya4 = ya3 + ya1;
float xa4 = ((ya4) - Yintercept)/gradient; float za4
= InverseZ;
float e1 = angle1 (xa4, ya4, za4); float e2
= angle2 (xa4, ya4, za4); float e3 =
angle3 (xa4, ya4, za4);

float ya5 = ya4 + ya1;
float xa5 = ((ya5) - Yintercept)/gradient; float za5
= InverseZ;
float f1 = angle1 (xa5, ya5, za5); float f2
= angle2 (xa5, ya5, za5); float f3 =
angle3 (xa5, ya5, za5);

float ya6 = ya5 + ya1;
float xa6 = ((ya6)- Yintercept)/gradient; float za6
= InverseZ;
float g1 = angle1 (xa6, ya6, za6); float g2
= angle2 (xa6, ya6, za6); float g3 = angle3
(xa6, ya6, za6);

float ya7 = ya6 + ya1;
float xa7 = ((ya7) - Yintercept)/gradient; float za7
= InverseZ;
float h1 = angle1 (xa7, ya7, za7); float h2
= angle2 (xa7, ya7, za7); float h3 = angle3
(xa7, ya7, za7);

float ya8 = ya7 + ya1;
float xa8 = ((ya8) - Yintercept)/gradient; float za8
= InverseZ;
float i1 = angle1 (xa8, ya8, za8); float i2
= angle2 (xa8, ya8, za8); float i3 =
angle3 (xa8, ya8, za8);

float ya9 = ya8 + ya1;
float xa9 = ((ya9) - Yintercept)/gradient; float za9
= InverseZ;
float j1 = angle1 (xa9, ya9, za9); float j2
= angle2 (xa9, ya9, za9); float j3 =
```

```
angle3 (xa9, ya9, za9);

float ya10 = ya9 + ya1;
float xa10 = ((ya10) - Yintercept)/gradient;
float za10 = InverseZ;
float k1 = angle1 (xa10, ya10, za10); float k2
= angle2 (xa10, ya10, za10); float k3 =
angle3 (xa10, ya10, za10);

float ya11 = ya10 + ya1;
float xa11 = ((ya11) - Yintercept)/gradient; float za11
= InverseZ;
float l1 = angle1 (xa11, ya11, za11); float l2
= angle2 (xa11, ya11, za11); float l3 =
angle3 (xa11, ya11, za11);

float n1 = b1 - a1; float o1 =
b2 - a2; float p1 = -(b3 - a3);
float n2 = c1 - b1; float o2 =
c2 - b2; float p2 = -(c3 - b3);
float n3 = d1 - c1; float o3 =
d2 - c2; float p3 = -(d3 - c3);
float n4 = e1 - d1; float o4 =
e2 - d2; float p4 = -(e3 - d3);
float n5 = f1 - e1; float o5 =
f2 - e2; float p5 = -(f3 - e3);
float n6 = g1 - f1; float o6 =
g2 - f2; float p6 = -(g3 - f3);
float n7 = h1 - g1; float o7 =
h2 - g2; float p7 = -(h3 - g3);
float n8 = i1 - h1; float o8 =
i2 - h2; float p8 = -(i3 - h3);
float n9 = j1 - i1; float o9 = j2
- i2; float p9 = -(j3 - i3); float
n10 = k1 - j1; float o10 = k2 -
j2; float p10 = -(k3 - j3); float
n11 = l1 - k1; float o11 = l2 -
k2; float p11 = -(l3 - k3);
prints(xa1, ya1, za1);
prints(xa2, ya2, za2);
prints(xa3, ya3, za3);
prints(xa4, ya4, za4); prints(xa5,
ya5, za5); prints(xa6, ya6, za6);
prints(xa7, ya7, za7); prints(xa8,
ya8, za8); prints(xa9, ya9, za9);
prints(xa10, ya10, za10);
prints(xa11, ya11, za11);
```

```
prints(a1, a2, a3);
prints(b1, b2, b3);
prints(c1, c2, c3);
prints(d1, d2, d3);
prints(e1, e2, e3);
prints(f1, f2, f3);
prints(g1, g2, g3);
prints(h1, h2, h3);
prints(i1, i2, i3); prints(j1,
j2, j3); prints(k1, k2, k3);
prints(l1, l2, l3);

 motor1(a1);
 motor2(a2);
 motor3(a3);
 delay(10000);
 motor3(p1);
 motor2(o1);
 motor1(n1);
 delay(500);
 motor3(p2);
 motor2(o2);
 motor1(n2);
 delay(500);
 motor3(p3);
 motor2(o3);
 motor1(n3);
 delay(500);
 motor3(p4);
 motor2(o4);
 motor1(n4);
 delay(500);
 motor3(p5);
 motor2(o5);
 motor1(n5);
 delay(500);
 motor3(p6);
 motor2(o6);
 motor1(n6);
  delay(500);
  motor2(o7);
  motor3(p7);
  motor1(n7);
  delay(500);
  motor2(o8);
  motor3(p8);
```

```
motor1(n8);
delay(500);
motor2(o9);
motor3(p9);
motor1(n9);
delay(500);
motor2(o10);
motor3(p10);
motor1(n10);
delay(500);
motor2(o11);
motor3(p11);
motor1(n11);
delay(500); }

float angle1(float InverseX, float InverseY, float InverseZ) {float
d=InverseY/InverseX;
 anglemotor1 = (atan (d))*180/PI; return
 anglemotor1;}

float angle3(float InverseX, float InverseY, float InverseZ) {float
u1 = pow (InverseX,2) + pow(InverseY,2);
 e = (u1 + pow (InverseZ-39,2) - 625 - 900)/ 1500; float
 e1 = acos (e);
 anglemotor3 = e1*180/PI; return
 anglemotor3;}

float angle2(float InverseX, float InverseY, float InverseZ) {float
u1 = pow (InverseX,2) + pow(InverseY,2);
 d=InverseY/InverseX; anglemotor1 =
 (atan (d))*180/PI;
 e = (u1 + pow (InverseZ-39,2) - 625 - 900)/ 1500; float
 e1 = acos (e);
 anglemotor3 = e1*180/PI;
   = (InverseZ-39)/ sqrt(u1);
   = (atan (f))*180/PI;
   = (30 * sin(e1))/(25 + (30*cos(e1)));
 k =      (atan      (h))*180/PI;
 anglemotor2 = g + k; return
 anglemotor2;}

void motor1(float anglemotor1)
{if (anglemotor1>0)
 {calibrateangle1 = anglemotor1 * 34 / 17;
  analogWrite(pwmMotor1,50);
  digitalWrite(dirMotor1,HIGH);
  delay(calibrateangle1/360 * 28600);
```

```
    analogWrite(pwmMotor1,0); }
  else if (anglemotor1<0)
  {calibrateangle1 = (-anglemotor1) * 34 / 17;
    analogWrite(pwmMotor1,50);
    digitalWrite(dirMotor1,LOW);
    delay(calibrateangle1/360 * 28600);
    analogWrite(pwmMotor1,0);}
  else{analogWrite(pwmMotor1,0);}}

void motor2(float anglemotor2) {if
(anglemotor2>0)
  {calibrateangle2 = (anglemotor2*2) * 23 / 21;
    analogWrite(pwmMotor2,77);
    digitalWrite(dirMotor2,LOW);
    delay(calibrateangle2/360 * 55350);
    analogWrite(pwmMotor2,0);}
  else if (anglemotor2<0)
  {calibrateangle2 = (-anglemotor2 * 2) * 23 / 21;
    analogWrite(pwmMotor2,77);
    digitalWrite(dirMotor2,HIGH);
    delay(calibrateangle2/360 * 55350);
    analogWrite(pwmMotor2,0);}
  else{analogWrite(pwmMotor2,0);}}

void motor3(float anglemotor3) {if
(anglemotor3>0)
  {calibrateangle3 = anglemotor3 * 25 / 21;
    analogWrite(pwmMotor3,77);
    digitalWrite(dirMotor3,LOW);
    delay(calibrateangle3/360 * 11030 * 12);
    analogWrite(pwmMotor3,0);}
  else if (anglemotor3<0)
  {calibrateangle3 = (-anglemotor3) * 25 / 21;
    analogWrite(pwmMotor3,77);
    digitalWrite(dirMotor3,HIGH);
    delay(calibrateangle3/360 * 11030 * 7.5);
    analogWrite(pwmMotor3,0);}
  else{ analogWrite(pwmMotor3,0);}}
void prints(float anglemotor1, float anglemotor2, float anglemotor3) {
Serial.println();
  Serial.print("Angle 1 = ");
  Serial.println(anglemotor1);
  Serial.print("Angle 2 = ");
Serial.println(anglemotor2);
Serial.print("Angle 3 = -");
Serial.println(anglemotor3);
Serial.println()
```