DESIGN AND DEVELOPMENT OF POSITION CONTROL FOR ROBOT GRIPPER MECHANISM

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2019

DECLARATION

I declare that this thesis entitled " DESIGN AND DEVELOPMENT OF POSITION CONTROL FOR ROBOT GRIPPER MECHANISM " is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

Name : STEPHEN LING KIE KAI

Date :

APPROVAL

I hereby declare that I have checked this report entitled "Design and Development of Position Control for Robot Gripper Mechanism" and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Mechatronics Engineering with Honours

Signature : ....

Supervisor Name : ....

Date : ....

DEDICATIONS

To my beloved mother and father

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ABSTRACT

A robotic gripper is an end effector of robot arm that enables the automation system to manipulate and handling object. The objective of this project is to design and fabricate a robotic gripper mechanism with single degree-of-freedom (DOF) gripper coupled with DC geared brushed encoder motor using 3D printed parts. Besides, this project also aimed to design and compare the controller for position control of gripper mechanism using step inputs as well as to evaluate the performance of chosen controller under different testing environment and trajectory motion. The major challenge in this project is to obtain precise position of gripper validated through different input applied to the gripper as well as while it is undergoing a series of trajectory motion. In this project, a mechanical structure of robot gripper is fabricated with supported parts such as support frame and flange coupling are sketched in SOLIDWORKS and 3D printed for assembly. Controller tuning is done manually in Arduino IDE until minimal overshoot and shortest rise time and settling time are obtained and the control gains K_P, K_I, K_D are identified. The result showed that PID control appeared to be the best choice for development of position control for robot gripper mechanism as it provides moderate overshoot correction without sacrificing accuracy and reduction in rise time and settling time that ensures robot gripper's efficiency. The robot gripper is further tested on its performance under applied resistance and trajectory motion. PID position control is achieved as the gripper jaw is able to move to the desired position with minimal position error in shortest time. Error analysis supported the choice of PID controller to be applied in the development of position control for robot gripper mechanism with a RMSE value of 19.629 over a 12000 datum range. Experiments on object gripping revealed that the relationship between the rotation angle at actuating link and the displacement at target link is linear with a factor of 5/6. In a nutshell, this robot gripper can be applied and utilized in various application with the acceptable gripping position accuracy.

ABSTRAK

Penggenggam robot adalah pengeluar akhir lengan robot yang membolehkan sistem automasi memanipulasi dan mengendalikan objek. Objektif projek ini ialah mereka bentuk mekanisme penggenggam robot dengan satu *degree-of-freedom* (DOF) ditambah dengan motor penderia DC dilengkapkan dengan bahagian bercetak 3D. Selain itu, projek ini juga bertujuan untuk merekabentuk dan membandingkan pengawal untuk kawalan kedudukan mekanisme penggenggam menggunakan unit langkah serta untuk menilai prestasi pengawal terpilih di bawah persekitaran ujian yang berbeza dan gerakan trajektori. Cabaran utama dalam projek ini adalah untuk mendapatkan kedudukan yang tepat dari penggenggam yang disahkan melalui unit langkah yang berbeza yang digunakan untuk penggenggam serta satu siri gerakan trajektori yang mempunyai kedudukan berlainan. Dalam projek ini, struktur mekanikal penggenggam robot dibuat dengan bahagian yang disokong seperti bingkai sokongan dan penyambung aci motor yang dilukis dalam SOLIDWORKS dan dicetak secara 3D. Penalaan pengawal dilakukan secara manual di Arduino IDE hingga lajakan minimum dan waktu kenaikan terpendek dan masa penyelesaian diperoleh dan keuntungan kawalan K_P, K_I, K_D dikenalpasti. Hasilnya menunjukkan bahawa kawalan PID merupakan pilihan terbaik untuk pembangunan kawalan kedudukan untuk mekanisme penggenggam robot kerana ia menyediakan pembetulan lajakan yang sederhana tanpa mengorbankan ketepatan dan pengurangan masa meningkat dan masa penyelesaian bagi memastikan kecekapan robot penggenggam. Pengenggam robot akan diuji lagi pada prestasinya di bawah rintangan dan gerakan trajektori. Kawalan kedudukan PID dicapai apabila rahang penggenggam dapat bergerak ke posisi yang diinginkan dengan ralat kedudukan minima dalam waktu yang singkat. Analisis ralat menyokong pilihan pengawal PID untuk diaplikasi dalam pembinaan kawalan posisi bagi mekanisme penggenggam robot dengan nilai RMSE sebanyak 19.629 dalam lingkungan data sebanyak 12000 set. Eksperimen genggaman objek menunjukkan bahawa hubungan antara sudut putaran pada pautan penggerak dan anjakan pada pautan sasaran adalah linear dengan faktor sebanyak 5/6. Konklusinya, pengggenggam robot yang direkabentuk dalam tesis ini boleh diaplikasi dan digunakan dalam pelbagai aplikasi kegunaan with ketepatan penggenggaman yang boleh diterima.

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LIST OF SYMBOLS AND ABBREVIATIONS

P - Proportional term
I - Integral term
D - Derivative term
DC - Direct current
AC - Alternating current
K_P - Proportional gain
K_I - Integral gain
K_D - Derivative gain
PID - Proportional Integral Derivative
PWM - Pulse width modulation
MSE - Mean squared error
IDE - Integrated development environment
USB - Universal serial bus
DOF - Degree of Freedom
CAD - Computer aided design
SMA - Shape memory alloy
ppr - Pulse per revolution
emf - Electromotive force
ICSP - In circuit serial programming
RMSE - Root mean squared error

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CHAPTER 1

INTRODUCTION

1.1 Motivation

Robotics is the applied science of motion control for multi-axis manipulators and is a large subset of the field of “mechatronics” (Mechanical, Electronic and Software engineering for product or systems development, particularly for motion control applications). The tremendous challenge of 21st century is to develop robots and machines “intelligent” enough to learn how to perform tasks automatically and adapt to unforeseen operating conditions or errors in a robust and predictable manner, without the need for human guidance, instructions or programming [1]. At the current escalating rate of knowledge growth in the areas of robotics and automations, it is convincing to tell that “the best is yet to come” and the technology advancement in robotics will keep on improving to the point where almost all possible physical jobs will be completely automated at a very low production cost.

End effector is a generic term that includes all the devices that can be installed at a robot arm. In robotics, an end effector is a device or tool that is connected to the end of a robot arm [2]. Grippers are the most common type of end effector. Brands of robot grippers include Schunk, Robohand, PHD, SOMMER and Robotiq. There are numerous types of robotic gripper applications of where a robotic gripper can be used. Some common applications are grippers for known environment where parts are placed at predefined orientations; grippers for unknown environment such as pick and place task where flexibility of performing task is highly demanded; grippers for fragile object and medical applications. The most commonly used grippers are finger grippers, generally are two opposing fingers or three fingers like a lathe chuck. While choosing a gripper, several design considerations have to be taken in account, such as gripping force, weight, and supply of services.

International Federation of Robotics (IFR) has reported that global industrial robot sales have doubled over the past five years. Industrial robots play an increasingly important role in material handling and pick and place operations. The world’s first working robot named Unimate joined the assembly line at the General Motors plant in Ewing Township in 1961. Robots have revolutionized the industrial workplace ever since. Robots are changing the face of manufacturing. They are designed to move materials, as well as to perform a variety of programmed task in manufacturing and production settings. Massive effort has been emphasized on the development of an efficient robotic workforce with the introduction of Horizon 2020 and Industry 4.0 [3].

The industrial robotics market around the globe is expected to outstrip USD 40 billion by 2020, according to a new study by Grand View Research, Inc. [4]. Another suggestion by the same research agency suggests that the automotive robotics market will grow to USD 13.6 billion by 2025 and this represents annual growth of almost 14 per cent from 2016. The new World Robotics Report shows that a new record high of 381,000 units were shipped globally in 2017 – an increase of 30 percent compared to the previous year [5]. The tremendous growth of the robotic industries has a close relationship to the utilization of different of robotic actuators especially electrical motors. Therefore, it is utterly important for us to have brief of overview of electrical motor particularly in this project, a DC geared brushed motor with quadrature encoder is used as the actuator of the robotic gripper.

To understand what builds up the driving force of the motor, in its principle as stated in Faraday’s law, any change in the magnetic environment of a coil of wire will cause a voltage (emf) to be “induced” in the coil. The theory is explained when generators are able to produce voltage through mechanical energy to electrical energy conversion. Motors operate exactly in reverse of generators where electrical energy is converted to mechanical energy and used to manipulate mechanical part attached to the motor shaft. In motors, magnetic field created by permanent magnets in the stator interacts with current that is fed into the armature winding. The armature starts to rotate when the interaction between two magnetic fields occurs. In this project, a quadrature encoder is mounted at the rear shaft of the DC motor. The working principle and overview of motor is discussed as follow.

A motor encoder is an electrical mechanical device mounted to an electric motor that provides closed loop feedback signals by tracking the speed and/or position of a motor shaft.

A wide variety of motor encoder configurations such as incremental or absolute, optical or magnetic, shafted or hub/hollow shaft are available for different applications. Selection of motor encoder that will be utilized in desired application is dependent generally a few factors such as motor type, the application requiring closed-loop feedback, and the mounting configuration required.

Robotic gripper has been one of the most promising tools utilized by the emerging fast-paced competitive manufacturing industries in performing task that human bare hands can hardly carry out in terms of repeatability and precision handling [6]. A gripper coupled with microcontroller for position control will be developed, with carefully designed position control algorithm. Intelligent controller will be designed to control DC motor with encoder via Arduino microcontroller.

1.2 Problem Statements

This project primarily aimed to integrate a gripper mechanism that is able to manipulate object in production line for object shaping and pick-and-place function without causing damage to the object or to meet its performance requirement in terms of its functionality and flexibility. Type of gripper that will be deployed is to be highlighted as different functionality in terms of degree of freedom (DOF) and type of motor gives different level of performance. The mechanical design of the robotic gripper will decide its gripping capability and fundamental success of using an automated solution.

Mass production in assembly line of product requires not only the flexibility of the robotic manipulator but also its accuracy and efficiency of completing task. Therefore, design of controller will be the main challenge in accordance to the control target, such as position control, force control, stiffness control or compliance control. In this context, effect of noise and disturbance from environment or from mechanical part might affect the motor desired position and hence affects the performance of gripper in term of accuracy. Position control in this project focuses on DC motor and its position feedback encoder using a suitable controller.

In this project, the construction of the gripper mechanism consists of a metallic gripper module, a DC motor with encoder, mounted with a flange couple 3D printed with the help of computer aided design (CAD) software. The measured value from the DC motor encoder will be fed to the controller for position adjustment. Control parameters are to be determined in order to minimize the deviation of output value from its set point value.

1.3 Objectives

The objectives of this project are:

1. To design and fabricate a robotic gripper mechanism with single degree-of-freedom (DOF) gripper coupled with DC geared brushed encoder motor using 3D printed parts.
2. To design and compare the controller for position control of gripper mechanism using step inputs.
3. To evaluate the performance of chosen controller under different testing environment and trajectory motion.

1.4 Scope of the Project

This project will only deploy a single DOF robotic gripper with a total weight of the mechanism not exceeding 1kg. A higher weight of gripper would not be ideal for installation at the end of robot arm. On the other hand, this project will only focus on position control of robot gripper by manipulating the rotation of motor linked to the coupling attached to the gripper jaws. Position control of the gripper is achieved through commands from Arduino microcontroller tested through different types of controller and trajectory motion. Robot gripper deployed in this project is a simple gripper with two jaws linked to a flange couple that are driven by DC motor with incremental encoder mounted at rear shaft of the motor as feedback sensor. Maximum turning angle of robotic gripper does not exceed 65° from original closed position. This is corresponding to the maximum gripping length of not exceeding 55mm measured from original closed position.

CHAPTER 2

LITERATURE REVIEW

2.1 Organization of the Report

This chapter will present the theory and concept of the project in a more detailed structure which the discussion will be divided into several sub-chapters. The past studies that will be reviewed includes mechanism or mechanical design of robotic gripper which emphasizes on DOF, type and number of jaws/fingers, type of controller that will be utilized in controlling motor, design and optimization method used and field of applications of robotic gripper. Literature review is essential in this project as it provides a wide range of past reference from sources such as reference book, thesis, journal article, review paper, and also online materials that enlighten the path of searching best solution for this project.

2.2 Mechanical Design and Fabrication

2.2.1 Gripper Jaw Design

A. Krishnaraju et al. [6] designed a three fingered robot mechanism which aims to achieve various functionality in moving objects where it claims to be having higher gripper ratio. Gripper ratio is calculated by dividing maximum pay load in kilogram by the gripper weight. Therefore, we can observe the effect of the type of gripper mechanism, the driving power source and gripper opening and grip structure on the gripper ratio that a gripper module may have. The mechanism highlighted the design criteria which are kinematic structure selection, DOF calculation, skeleton material selection and dimensioning through torque requirements. In terms of performance, gripper force can be evaluated by multiplying applied force and the coefficient of friction. The gripper is designed to open about an angle of 28˚ when actuated using a servo motor of 12V which turns 90˚ in either direction, which gives a total of 180˚ movement. On the other hand, load carrying capacity may differs due to the robot application nature.

Zhang, Tao et al. [7] suggested a gripper jaws based on trapezoidal modules as in Figure 2.1 where the gripper jaws are capable of guiding the part into alignment and achieve the maximal linear contact with the part at its desired orientation. A numerical algorithm is developed based on enumeration on feasible design that exploits part geometry. The algorithm provided location of contacts, pushing, toppling, jamming and liftoff constraints. The form-closure grasp is optimal by measuring its total contacting length. The orientation of the trapezoidal gripper jaw is tested for assembly and found that it is at θ = 25˚ while the analysis yields the optimal jaw design of L= 16.2cm. Future objectives are set to validate the modular jaws design performance in terms of mass distribution, friction, shape variation and its reliability.

Figure 2.1 An example of optimal trapezoidal jaw design

Manz, Marc et al. [8] have worked extra miles in increasing dynamic payload capacity by implementing a gripper reflex mechanism. They developed a self-adaptive two-fingered robotic gripper that is capable of gripping parallel and non-parallel surface objects. A single motor is utilized in actuating the sampling system which consists of two fingers while the actuator is comprised of a BLDC external rotor motor and a strain wave gear. Tendon mechanism helped to distribute the operating power of this actuator to the fingers. This design of kinematics allows a stiff gripping characteristic for objects with parallel gripping surfaces and a self-adaptive gripping characteristic for non-parallel surfaced object. This design enables gripper to manipulate small objects and even objects that are bigger than the gripper itself and henceforth it is capable to grab objects at a position that is out of its center of mass.

W. Chen et al. [9] proposed a new flexure-based dual-axis compliant gripper that is driven by two piezoelectric actuator (PEAs). The gripper is developed with an asymmetric structure which can be divided into two parts each one of left and right parts and that made it into a 2 DOF micromanipulation for achieving grasping and rotating purposes. This is achieved when the left part generates lateral motion at the left jaw to grip a micro-object, while the right part produced vertical motion at the right jaw to rotate the micro-object. Pseudo-rigid-body model method is utilized in modelling the flexure-based compliant mechanisms. Both the gripping force and jaw's position are measured by three groups of calibrated strain gage sensors.

Early work on humanoid hand can be seen through the design and development of DIST-hand Dextrous gripper presented by Caffaz, Andrea et al. [10]. It is a 4-fingered 16 DOF tendon driven device. Each finger has 4 links connected by 4 joints that has rotation angle of greater 90 degrees which is very similar to human hands. The actuation of each finger involves 6 tendons made of polyester, routed through pulleys and driven by 5 DC motors. Ad Hoc rotation sensor is mounted on each joint to resolve the problem of controlling finger's motion using position and velocity feedback directly from the motor axes. The sensor is based on the use of solid-state Hall effect transducer which is contactless to the joint and significantly immune to noise.

It is extremely difficult and not cost-friendly for a robotic gripper especially when a multi-fingered humanoid hand is to be developed when it goes to general uses or educational purposes. Telegenov, Kuat et al. [11] developed an open source 3D printed 3-finger gripper platform that can fulfill the mentioned purposes. The underactuated fingers that are utilizing pulley and tendon driven mechanism which is light and inexpensive as well as high degree of adaptability but also on the contrary has low load capacity and wear resistance. Therefore, in this solution the researchers have proposed a mechanical linkage system and gear train transmission system as a substitute to the conventional pulley/tendon system as shown in Figure 2.2 below.

Figure 2.2 Worm wheel arrangement connecting to actuating worm in 3D view

2.2.2 Soft Robotic Gripper

Soft robotic grippers have been greatly deployed due to its ability to grasp and manipulate a wide range of objects. Elastomer is the most-widely utilized material in soft robotic grippers thanks to its large strains. Soft gripping can generally be categorized into three major categories which are actuation, controlled stiffness and controlled adhesion. However, there are some drawbacks in soft robotic gripper which are the challenges in miniaturization, lack of long term robustness, speed, and integration of sensing and control [12].

Modabberifar, Mehdi et al. [13] on the other hand introduced a gecko-inspired gripper using shape memory alloy for grasping flat surfaced objects. The gripper presented by the team claimed to be lighter in weight, cheaper, simpler and smaller without affecting the ability to maintain its adhesive pressure. This design uses a set of three opposing gecko-like adhesive pad actuated by SMA wire that are robust to the moments around the X and Y axes. The adhesive pad moves horizontally toward the gripper's center by a rapid contraction of the SMA wire. However, experiments on relationship between input voltage and shear and normal adhesion force revealed that the gripper has relatively low efficiency and demands a relatively large time interval for the subsequent SMA wire grasps to return to its original position.

Haibin, Yin et al. [14] also established a shape-memory-alloy made force grasping model for soft robotic gripper but focuses on variable stiffness. Embedded sets of SMA fibers in a variable stiffness mechanism was developed. Biology-inspired gripper where ideas are adapted from octopus's leg, elephant trunk usually exhibit a safer and more compliance control characteristics compared to rigid gripper that may exhibit precise positioning using different control strategies and algorithm. Series of conducted tests and experiments showed that grasping force is highly related to the stiffness and to the object's offset and coefficient of friction. The grasping force of the soft robotic gripper strengthen by a marked 48.7% when the Young's modulus of the SMA-2 wires elevated by 52%.

Reddy, P.V. Prasad et al. [15] commented on the ability of a universal gripper where the current industrial deployment of grippers are all highly specially designed by the industry for specific tasks. A robotic gripper is very much limited compared to human hand in terms of its mechanical complexity, practical utility and dynamic flexibility. Multi-fingered hand comprises of high complexity of high number of mechanical joints that might require force sensing or visual feedback in order to manipulate objects securely. On the other hand, universal gripper that consists of a single mass of granular material actuated pneumatically has great capability of grasping a wide variety of objects without any closed-loop feedback system.

2.2.3 Comparison between Gripper Design

Table 2.1 Gripper structural design comparison

No.	Type of Gripper	Actuators	Advantages	Disadvantages
1.	Three-fingered robotic mechanism	Servo motor	High gripping ratio,	Requires more actuator
2.	Two-fingered trapezoidal module	DC motors	Great alignment to most object surfaces, maximize linear contact with object at desired position	Less gripping load
3.	Self-adaptive two-fingered robotic gripper	BLDC external rotor motor and a strain wave gear	Stiff gripping for parallel surface object, self-adaptive gripping for non-parallel surfaced object	Tendon mechanism failure might occur if it is over-actuated
4.	Flexure-based dual-axis compliant gripper	Piezoelectric actuator (PEAs)	Can perform 2DOF micromanipulation	Complex structure, heavy and not portable
5.	Multi-fingered humanoid hand	DC servo motors	Can perform grasping task as human hands do	Extremely difficult to develop, not cost-friendly
6.	Soft robotic gripper	Hydraulic, SMA wires/fibres	Can grasp almost anything, lighter in weight	Relatively low efficiency in its gripping repeatability

2.3 Controller Design

Controller design is one of the main objectives to be achieved in this thesis where it serves as the manipulating factor of the position control of robot gripper mechanism. Literature review of controller design for robotic gripper application is discussed in the sections below.

2.3.1 PI Controller

PI controller is mainly utilized for eliminating the steady state error that is created from solely P controller. This controller is mainly used in the area of application where speed of the system is not the main goal. Since PI controller is not capable of predicting future errors of the system, it cannot help to reduce the rise time and eliminate the oscillations. This gives a negative impact to the overall stability of the system as well as the speed of the system response.

Past research on PI controller applied in robot gripper mechanism was presented in A. Eisinberg et. al. [16] work for assembling biomedical microdevices. After preliminary assessment of sensor linearity is completed, they applied system identification techniques to the instrumented microgriper system analysis, as a primary step to define an appropriate control strategy. PI force control of microgripper based on the feedback provided by the semiconductor strain gauges helped to improve the system accuracy by means of the integrative action. Since the motions in standard micromanipulation tasks are quite slow, bandwidth of few Hz was enough in their application. The results of the tracking experiments proves that PI control assured a good control of force during grasping.

A comprehensive work of PI tuning strategies was shown in the work by S. Chaitanya et. al. [17]. They proposed several control algorithms for position control of a shape memory alloy actuated gripper, which are model based proportional integral (PI), pulse width pulse amplitude modulated proportional integral (PI-PWPAM) and internal model sliding mode controller (IM-SMC). From the results simulated using three different PI based controller, model based PI controller has the longest rise time of 7.02s for a step position of 5mm compared to that of 0.47s for PI-PWPAM controller and 1.74s for IM-SMC controller.

2.3.2 PD Controller

On the other hand, PD controller is aimed to increase the stability of the system by improving control with the ability of predicting the future error of the system response. The derivative gain is applied to minimize or to the best extend eliminate the system overshoot and oscillations occurring in the output response of the system. The D mode is designed to be proportional to the variation of the output variable to prevent the sudden in the error signal bring about the sudden changes occurring in the control output. Since D directly amplifies the process noise therefore D-only controller does not exist.

In the mobile micromanipulation system developed by R. Jain et. al. [18], the piezoelectric actuator based micro gripper is controlled by PD controller for pick and place application as shown in Figure 2.3. The aim of the control strategy is to achieve system stability by satisfying critical damping condition or a response with zero overshoot. The PD control is best suited for piezoelectric actuator as it produces fast response time within short period, minimizing rise time and oscillation and compensates the transient error while handling the target object. Unlikely biomedical device assembly where response time is not the goal [16], PD control appears to be an adequate tool to help the piezoelectric actuator based fingers correct the misallignment of the peg within a short period.

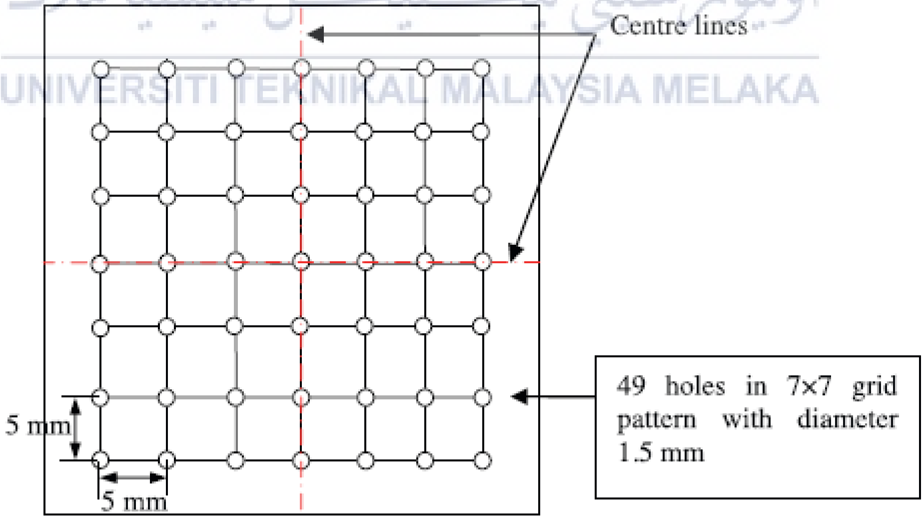

Figure 2.3 Grid map for micro robotic assembly

2.3.3 PID Controller

Proportional-Integral-Derivative (PID) controller has always been the choice of control strategies in industrial control systems when a controller is demanded to close the system loop. Their robust performance in a wide range of operating environments as well as their functional simplicity allow engineers to handle them in an elementary and straightforward manner. It can be utilized in regulating flow, temperature, pressure level and other industrial process variables. Without the presence of a controller, technicians may have to manually control water temperature in the industrial process in order to keep water temperature at fixed level. PID tuning on the other hand is the crucial part in this particular control strategy as it is the process of obtaining optimal proportional, integral and derivative gains to reach ideal response from a control system.

Talib, M. A. A. et al. [19] have presented PID position control for 2-DOF robotic finger by evaluating the performance of motor when different load is applied. PID tuning is utilized to improve the position control performance by controlling the level of overshoot, rise time, peak time, settling time and the steady state error. The determination of the new gain parameters are then reimplemented to the system to evaluate robotic finger's performance at different angle and given different load. Experimental evaluation observed vibration of motor and produced overshoot before PID tuning is applied. Motor's position fluctuated for a while before settled to designated position. PID tuning served to reduce the error made and ensure the motor reached desired position within shortest time and least error. The controller values K_p, K_i, and K_d are obtained via trial and error method until the motor has reached its best performance.

One of control target that can be achieved using PID controller in robotic actuator is angular position control of DC geared motor. The stability of DC motor can be improved after compensating the friction effect as shown in M. Maung et. al. [20] work. The angular position error of the DC geared motor can be minimalized by the PID tuning method with very low error oscillations. This implied that the output motor rotation can achieve angular position that is very close to its desired position. The ability of noise reduction and suppressing oscillation of the actuator using PID tuning algorithm is also shown in K. Sailan et. al. [21] application for valve driving a hydraulic pump.

On the other hand, PID controller has significant performance in enhancing force control for robotic gripper. It is crucial that a robotic gripper is able to manipulate object without damaging it through active compliance control. Sadun, A.S. et al. [22] has established a 3-finger adaptive robotic gripper using PID control. The team utilized a modified FSR force sensor as feedback signal to be fed back to the controller for compliance control. The control strategy here aimed to achieve hybrid force position control with acceptable range of error evaluated by Pearson’s correlation method. For gripping compliance control, a range of 2N to 8N applied force is achievable for grasping a stiff spongy ball by directing finger’s angle to desired position. PID tuning hereby helped in removing the corrugated signal when the robotic fingers move to the desired position.

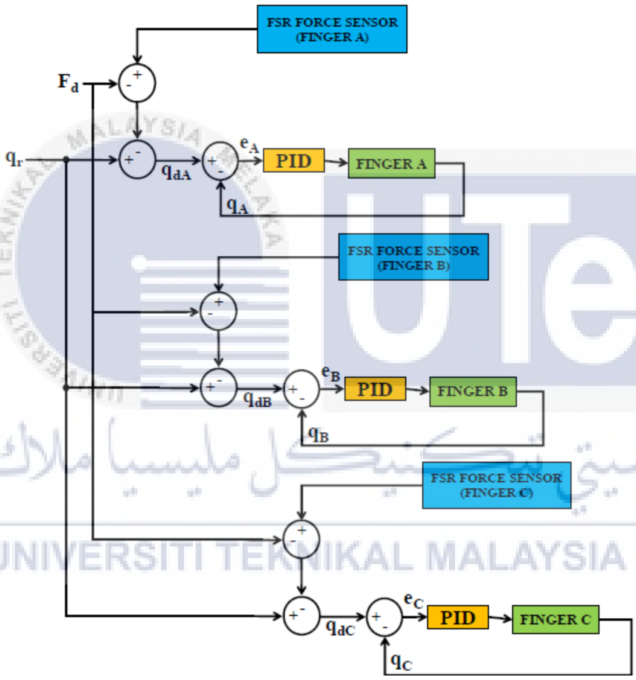

Figure 2.4 Block diagram for PID force control and position control

2.3.4 Fuzzy-PID Controller

Fuzzy PID controller is a type of PID controller that is tuned automatically by fuzzy logic algorithm. PID controller is a well-established method of providing closed-loop control in the attempt to obtain the actual output of a process as close to the targeted output as possible. However, the tuning process that is essential in obtaining such optimal output is always complicated. Fuzzy logic provides a way of dealing with imprecision and nonlinearity in complex control environments. PID auto-tuning using fuzzy logic control algorithm to produce varied PID gains depending on the disturbance occurred to the system. Fuzzy-PID is comparatively less expensive to establish than other intelligent system and is able to cover wider range of uncertainties in control.

Salleh, N.M. et al. [23] have implemented the fuzzy PID position control in determining three fingered robot hand for grasping varying loads. The settling time and rise time of the position transient response were taken to be the input for fuzzy logic control in order to identify optimal range of PID gain parameters that are set to be the output of the system. Fuzzy Inference System (FIS) is utilized to design the controller gains according to the input transient response parameters and will be used by the PID controller for controlling robotic fingertip and respond to the varying loads. Experimental results proved that Fuzzy-PID can improve the settling time and rise time of the system when no loads and varying loads are applied.

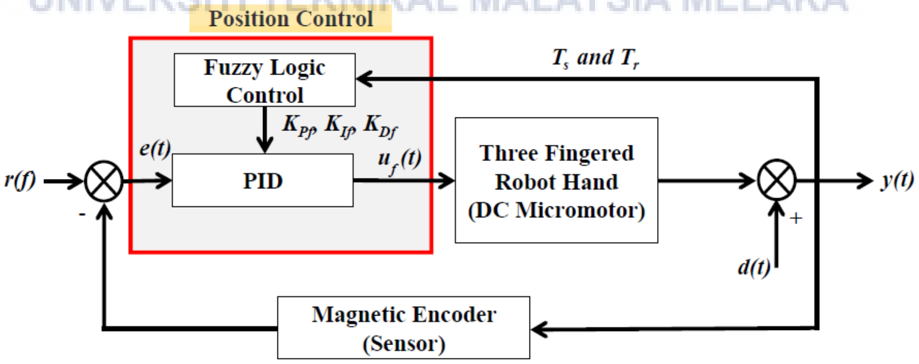

Figure 2.5 Overall block diagram for the control system

Du, Liang et al. [24] presented the significant control performance of fuzzy-PID control as well for dual-axis turntable servo system. The dual-axis turntable servo system served to reflect sunlight to the window of resident's house. The dual axis servo system is required to adjust mirror angle. A mathematical formulation of dual-axis turntable is first established followed by proposing fuzzy PID control algorithm. The control parameters are adjusted online via fuzzy logic the effectiveness is evaluated. Input of the fuzzy PID controller is fed from the end angle deviation value and its change rate in order to correct the three PID control parameters.

2.4 Application of Robotic Gripper

Robotic gripper has its significance in a variety field of applications such as industrial assembly, medical micromanipulation and manufacturing purposes. Ceccarelli, Marco et al. [25] proposed a robotic gripper for harvesting horticulture products. Handling horticulture products require a robotic gripper to grip object gently through precise position and compliance force control. The design issue in this application highlighted the difficulties in mechanical design such as number of grasp contacts and impact force on different sizes off product as the gripper is expected to imitate how picking horticulture products be done by human hand. Pneumatic actuator hereby can provide simple yet efficient force control for the gripper controlled by solenoid valves. In closed loop force control, the feedback analogue signal is given by a load-cell that is pre-installed at the fingertip.

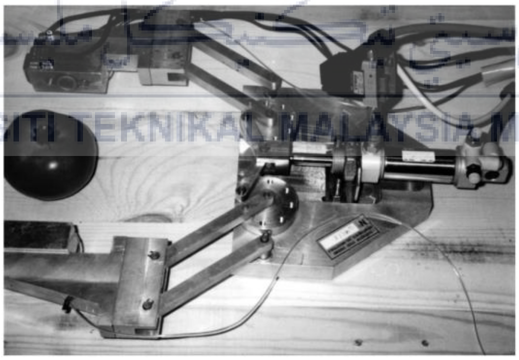

Figure 2.6 Pneumatically actuated gripper in picking horticulture product

A wide variety of gripers have been deployed for industrial applications where most of the design requirements focus on gripping without damage through force position control. Some grippers use friction forces to different surfaces of object which make the development of gripper to become very specific to designated task and not effective. Therefore, researchers searched through an alternative to introduce sensor-based friction gripper to ensure gripping task is able to be fulfilled at considerably low cost and efficient. Tolouei-

Rad, Majid et al. [26] have added range sensor and FSR force sensor to avoid object collision with gripper and execute proper gripper force for carrying different loads respectively.

Ali, Md. Hazrat et al. [27] on the other hand developed a vision-based gripper for industrial application as well. The challenges here include developing a relevant sequence of operations, proper communication between the camera/vision system and robot as well as the integration of system components. It includes image processing comprised of data acquisition, data processing and statistical output with web camera integrated with MATLAB tools. The centroid of the target object will be identified and objects will be sorted according to size, shape and color in a table file. Position control is the key challenge here the controller has to be able to pick and place the objects with different size and shape. With the help of Visual Basic as a connection between MATLAB and Robocell, the robot can finally perform pick and place task successfully.

Figure 2.7 Web camera mounted near to the gripper for image capturing

CHAPTER 3

METHODOLOGY

3.1 Introduction

The previous chapter had briefly discussed the design and development of robotic gripper through their mechanism, controller type as well as the control target and applications. This provides an overview on how this project should be implemented by identifying the design problem of the system to be designed, the design target that will drive us to propose the methodology to be applied in order to make the objectives practical. Therefore, this chapter will discuss on the method that will be utilized to develop position control system for robotic gripper mechanism through hardware integration with Arduino IDE software, experiments, and result validations under different environment. The overall project implementation flowchart is constructed as shown in Figure 3.1 below.

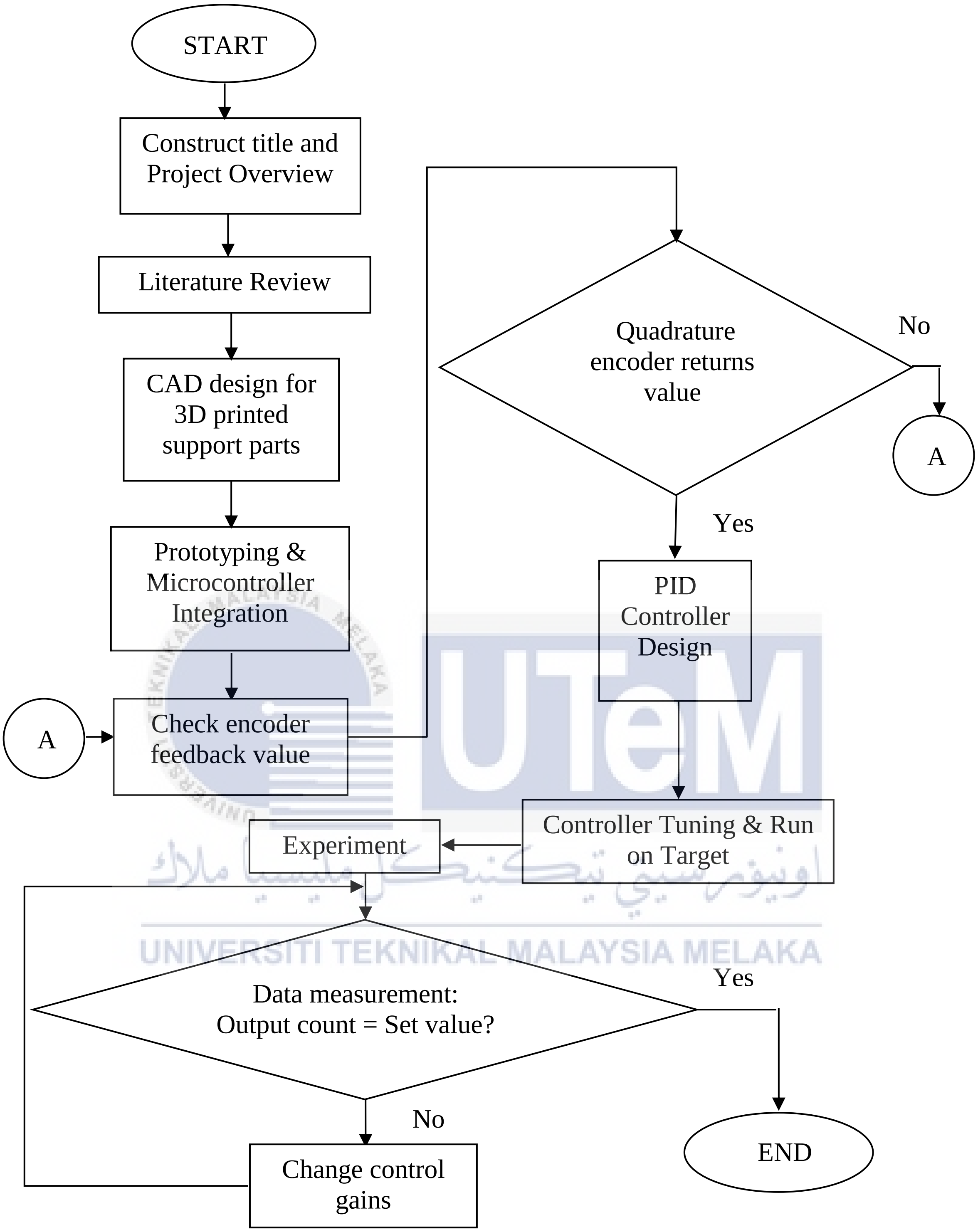

Figure 3.1 Overall flow chart of the project

3.2 Robotic Gripper Hardware Design

Mechanical structural design is one of the most significant part of this project as it has to be carefully designed according to the set objectives. After reviewing through past works and researches, this project will present a simple gripper jaw mechanism with single DOF, driven by interconnected gears that is coupled to the DC motor with encoder using a 3D printed flange coupling. As the motor actuated, the gripper interconnected links will move to open or to close according to the command given. Figure 3.2 below shows the structure of robotic gripper, the body part is made up of light weighted aluminium, a very light-weighted material and corrosion resistant.

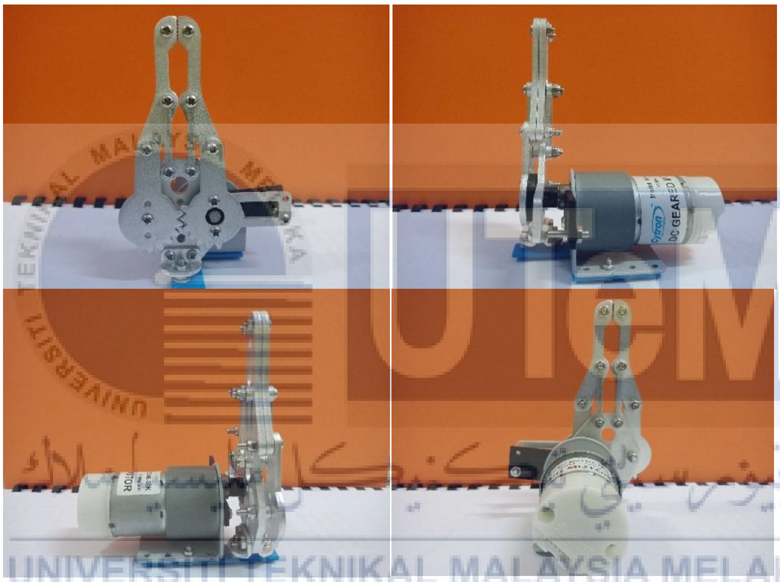

Figure 3.2 Front, rear and side view of the structure of robotic gripper

Table 3.1 Robotic gripper module specifications

Parameter	Value
Dimension (L × W × H/mm)	98 × 78 × 114
Degree of Freedom	1
Number of Links	6
Actuator	SPG30E-60K
Articulation Sensor	Quadrature encoder, 420ppr
Jaws Rotation Limitation	Rotational < 65°, Linear < 55mm

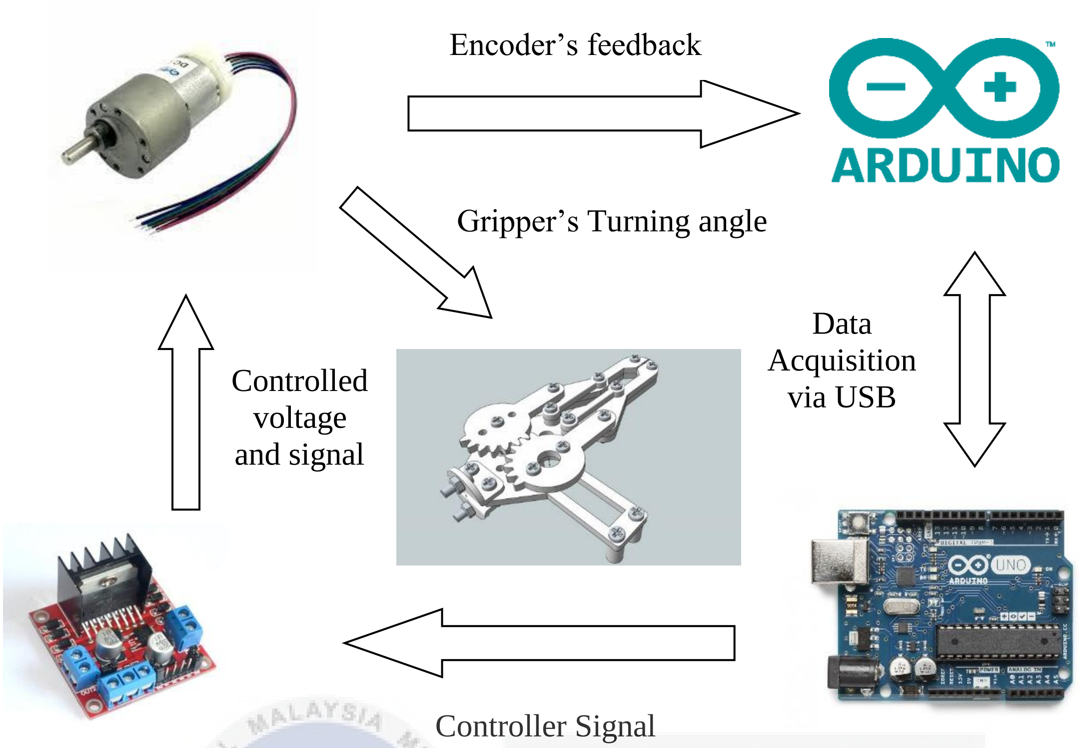

Figure 3.3 Hardware setup for robotic gripper mechanism

3.2.1 Hardware Specifications

The hardware specifications of this project are displayed in Table 3.1 and Figure 3.3 as well. It consists of a set of metallic robotic gripper, an Arduino UNO microcontroller, L298N motor driver module, DC geared motor with quadrature encoder, breadboard, 12V 7.2 Ah rechargeable battery and numerous jumper wires. The connection of encoder is bridged up a 1kOhm resistor for both channel A and B.

3.2.2 DC Brushed Geared Motor

The SPG30E-60K motor provides low speed high torque motor rotation with specifications as in Table 3.2. The quadrature hall-effect encoder value can be read through checking the pulse reading of the two hall effect sensors that are placed at 90 degrees apart to sense and produce two output A and B for clockwise and counterclockwise rotation. It provides 420 counts per main shaft revolution. Since the encoder is mounted on the rear shaft of the motor, the minimum resolution depends on the motor gear ratio.

Table 3.2 DC brushed geared motor specifications

Specifications	Descriptions
Model	SPG30E-60K
Operating Voltage	12V DC
Speed	51 – 100 rpm
Torque	2.01 – 3.00 kgf.cm
Current	< 600mA
Gear Ratio	60:1
Motor Diameter	37 mm
Shaft Length	15.5 mm

3.2.3 Quadrature Encoder

Figure 3.4 shows the encoder output waveform for counterclockwise rotation. We can see that channel B is leading channel A by 90 degree in phase whenever it changes state from LOW to HIGH or HIGH to LOW condition. This indicates that motor shaft is rotating in counterclockwise direction. Angular position of the gripper is manipulated by the motor rotation provided by the shaft. The encoder provides 7 counts per revolution of the rear shaft and 420 counts per main shaft revolution. This explains the gear ratio of SPG30E-60K motor of 1:60. The angular position of the gripper correspond to the motor angular position is determined by calculation as below:

$$\text{Angle of rotation (degree)} = \frac{Count\ Value}{XN} \times 360^{\circ} \qquad (3\text{-}1)$$

N = number of pulses generated by the encoder per shaft revolution

X is the encoding type; in this project encoding type ×2 is used

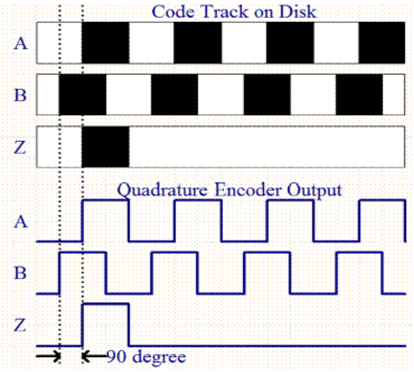

Figure 3.4 Output waveform of encoder reading for counterclockwise rotation

3.2.4 Arduino UNO

As mentioned in previous section, one of the major hardware implemented is none other than Arduino Uno microcontroller. It is a microcontroller board based on the ATmega328P with 6 analog inputs, 14 digital input/output (I/O) pins of which 6 can be used as PWM output, a 16MHz quartz crystal, an ICSP header, a power jack and a reset button. By simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery, any developer can get started very easily. This project implemented Arduino Uno microcontroller to drive the desired signal to the motor driver for motor shaft rotation and positioning purpose.

3.3 Controller Design and Tuning for Gripper Positioning

Upon completion of hardware setup for robot gripper mechanism, the controller design takes over the main role in position control of the robot gripper. Figure 3.6 shows the original position of the gripper or the origin where the robotic gripper position is defined with reference to the origin.

Arduino coding is designed in the IDE for encoder value decoding, set up input and output (I/O) pins for motor enable and direction control and PID controller. Output value of the encoder counts is read via digital input pin2 and pin3 of Arduino UNO board. The error value is calculated in real time and fed back to controller for calculation of position. The calculated signal will be fed into PWM signal via digital output pin9 to the enable pin of the motor driver. The overall block diagram of position control is presented as shown in Figure 3.5 below.

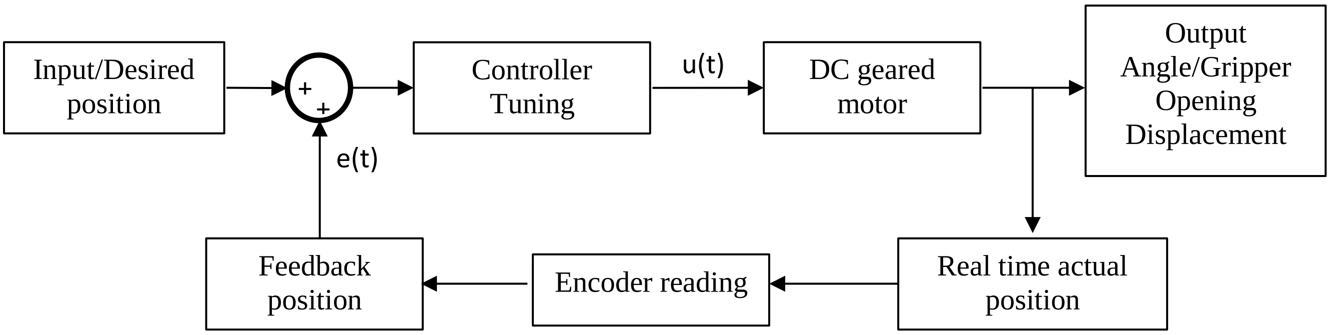

Figure 3.5 Overall block diagram of position control for robotic gripper mechanism

Figure 3.6 Original (closed) position of the robot gripper

3.4 Compare Controller Performances in Step input

This part presents the set up for experiments to compare the performance of different type of controllers in position control of robot gripper when a step input is applied. The controllers that are to be tested are PI, PD and PID controller. The calculation for typical gains in P term, I term and D term is shown in Figure 3.7. Each controller is about adding the term in particular controller type. K_P, K_I, and K_D are the tuning parameters that are to be manipulated during experiment to obtain an output response with shortest rise time, settling time and minimal overshoot. Transient response data is collected and recorded in the table presented in Chapter 4. The best controller will be further tested on its performance when external system disturbance is applied.

```
error = rotation - refValue; // reference value for desired position
deltaTime = stopTime - runTime; // change in time
P_ConOut = round(Kp * error); // P term
I_ConOut = round(I_ConOut + (error * Ki) * deltaTime); // I Term
D_ConOut = round(error * Kd/deltaTime); // D Term
PI_ConOut = P_ConOut + I_ConOut; // PI
PD_ConOut = P_ConOut + D_ConOut; // PD
PID_ConOut = P_ConOut + I_ConOut + D_ConOut; // PID
```

Figure 3.7 Arduino coding for PI, PD and PID controllers

3.5 Evaluate Controller Performance under Different Environment

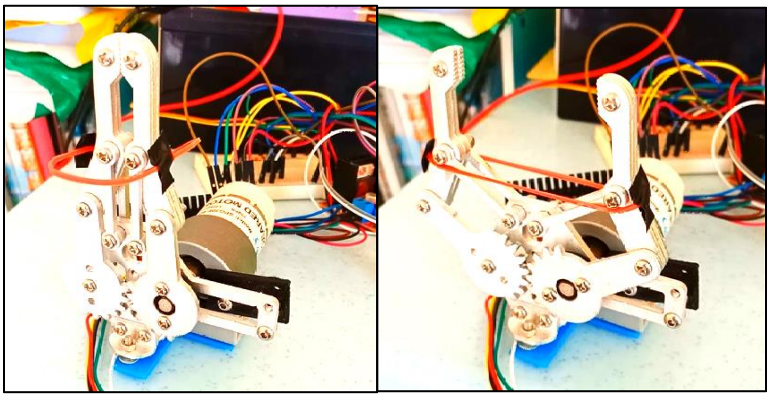

Figure 3.8 Resistant applied to the gripper jaw using a conventional rubber band

An external resistive force is applied to the gripper jaw using a normal rubber band as shown in Figure 3.8. This is to test the performance of the selected controller and verify the control gains tuned in previous section. The result recorded will be analyzed according to the output response data recorded as in Table 4.5 which are none other than rise time, T_R, settling time, T_S, peak time, T_P and percent overshoot.

3.6 Evaluate Controller Performance under Trajectory Motion

The performance of the PID controller on position control of robot gripper mechanism is further evaluated through experiments on its trajectory motion. The trajectory motion is designed to grasp object at its desired position. The trajectory plan started by opening gripper at 60˚ from origin to provide space for target object, followed by a counterclockwise 20˚ rotation for a rough grip of object. The motion is continued by a 10˚ counterclockwise rotation again for a close grip of object. Finally, the trajectory plan is ended by reopening the gripper jaw to its origin opening position which is at 60˚ from origin.

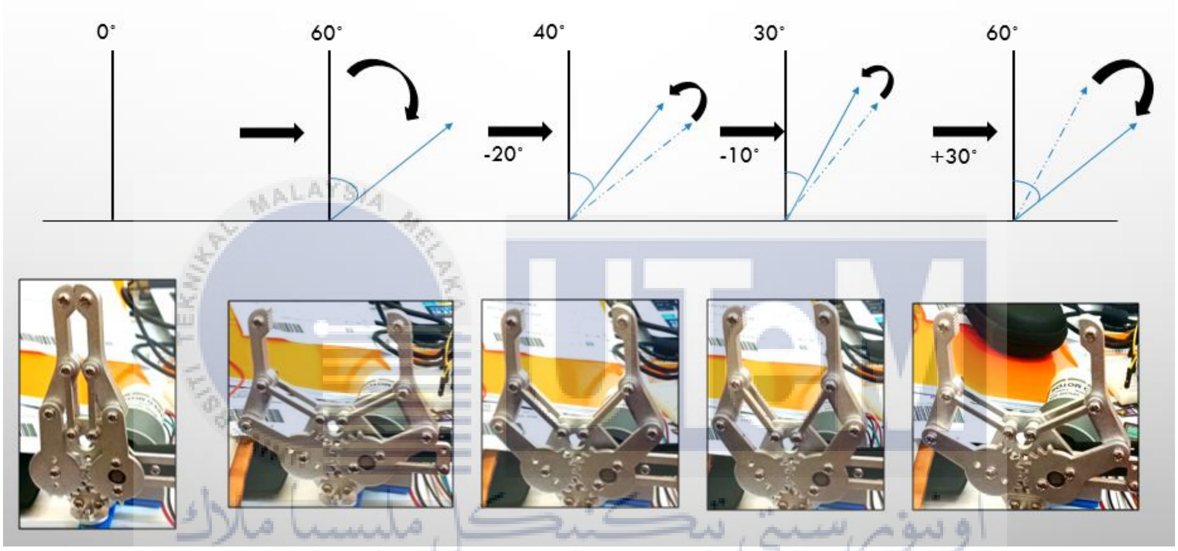

Figure 3.9 Robot gripper trajectory motion for grasping object

3.7 Determine Relationship between Actuating Link with Target Link Position

It is of utmost importance to determine the relationship between gripper's actuating link with its opening position. The position control of gripper mechanism aimed to provide gripper position in application with satisfactory consistency and accuracy in object manipulation. Therefore, the relationship between the rotation angle actuated by DC geared motor and the resulted displacement of the target link is highlighted. The angle of rotation of actuating gear link is calculated as shown in equation (3-1). To determine the relationship between both links, an experiment is conducted on measuring the displacement, d with an angle of rotation of 60˚. The experiment is conducted repeatedly for 5 times for opening motion and 5 times for closing motion to obtain an average ratio of rotation against displacement. After the relationship between both links is determined, another trajectory motion is designed in Arduino IDE to verify the result obtained from previous experiment. The result is plotted in MATLAB as shown in Figure 4.11 in next chapter.

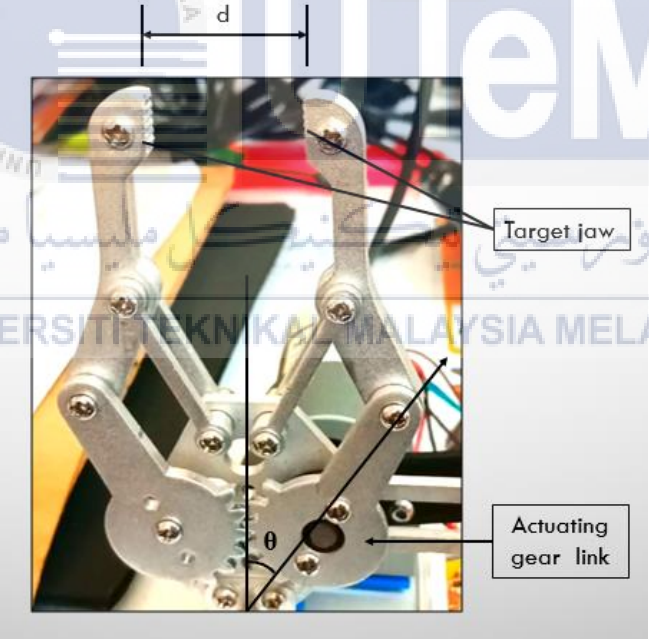

Figure 3.10 Correlation between angle of rotation, θ with displacement, d at target link

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter will present the expected results of the position control for robotic gripper mechanism. The experiment setups are aimed to achieve the set objectives in the very first chapter of this report. Methodology is the process of executing the objectives while this chapter will present the fruit of the labor and analyze the obtained results in detail.

4.2 PI, PD and PID Controller Performance at Step Input

4.2.1 PI, PD and PID Controller Performance at 51.5° from Origin

The step input applied is at 120 counts correspond to desired motor shaft rotation of 51.5° from its original position 0° calculated by applying formula in (3-1). Different type of controllers has been applied in Arduino coding by manipulating the control gains. Figure 4.1, 4.2 and 4.3 shows the output result of the gripper position plotted in MATLAB. Figure 4.4 is the graph that assemble transient response from three different controller.

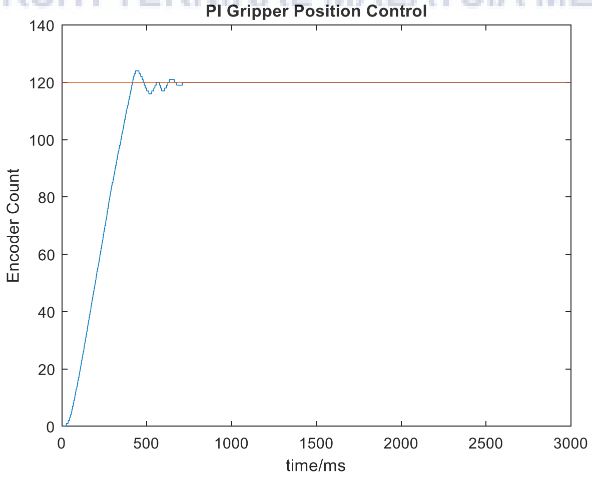

Figure 4.1 Output transient response of PI controller at 51.5°

Figure 4.2 Output transient response of PD controller at 51.5˚

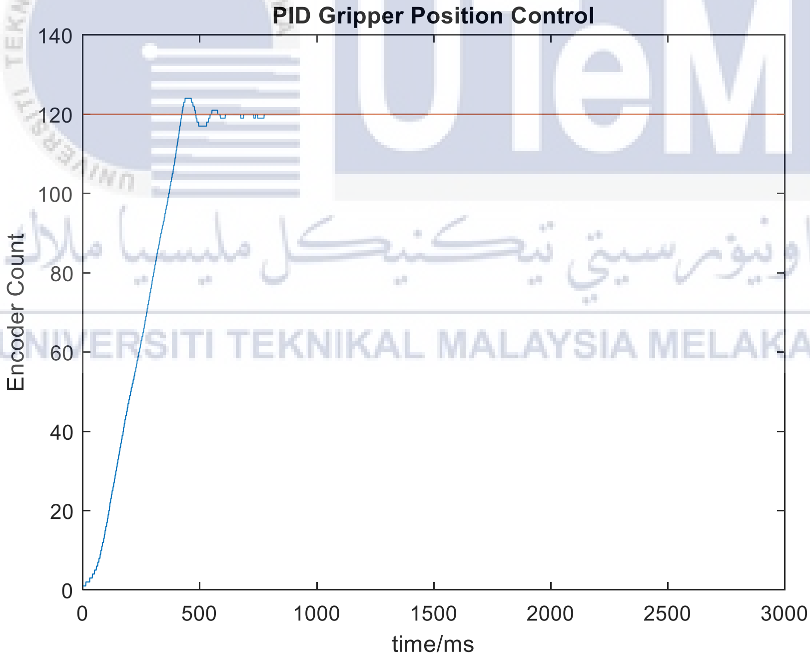

Figure 4.3 Output transient response of PID controller at 51.5˚

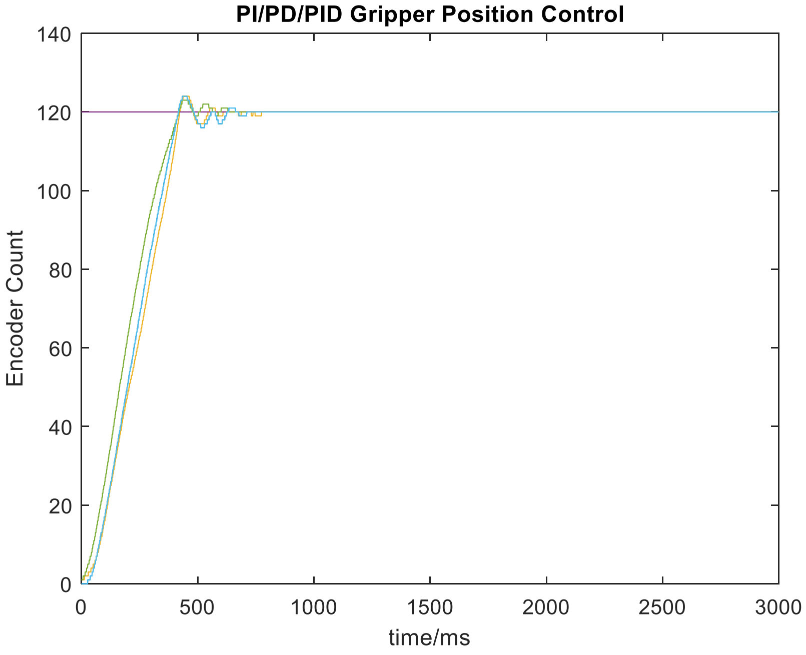

Figure 4.4 Output transient response of PI, PD and PID controller at 51.5˚

Table 4.1 Transient response data for PI, PD and PID controller

Type of controller	Encoder's Reading (degree/˚)		Rise Time, T_R (ms)	Settling time, T_S (ms)	Peak Time, T_P (ms)	Overshoot (%)
	Desired	Output				
PI	51.5	51.5	293	606	434	3.33
PD	51.5	51.5	297	458	433	2.50
PID	51.5	51.5	304	528	437	3.33

Table 4.2 Control gains of respective controller in experiment

Gain / Controller	Proportional, K_P	Integral, K_I	Derivative, K_D
PI	50.0	14.85	N/A
PD	50.0	N/A	60.0
PID	50.0	20.0	62.0

4.2.2 PI, PD and PID Controller Performance at 30˚ from Origin

Robot gripper changed its position from original position of 60˚ from origin set to 0 count to a new position of 30˚ from origin. This required a counterclockwise step input of -70 counts or an anticlockwise 30˚ rotation. Different type of controllers are applied as well in Arduino coding by manipulating the control gains. Figure 4.5, Figure 4.6 and Figure 4.7 shows the output result of the gripper position plotted in MATLAB.

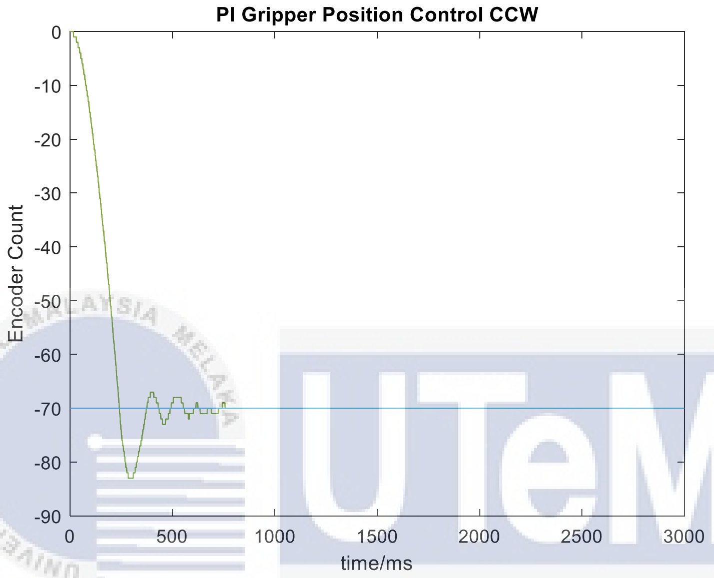

Figure 4.5 Output transient response of PI controller at 30.0˚

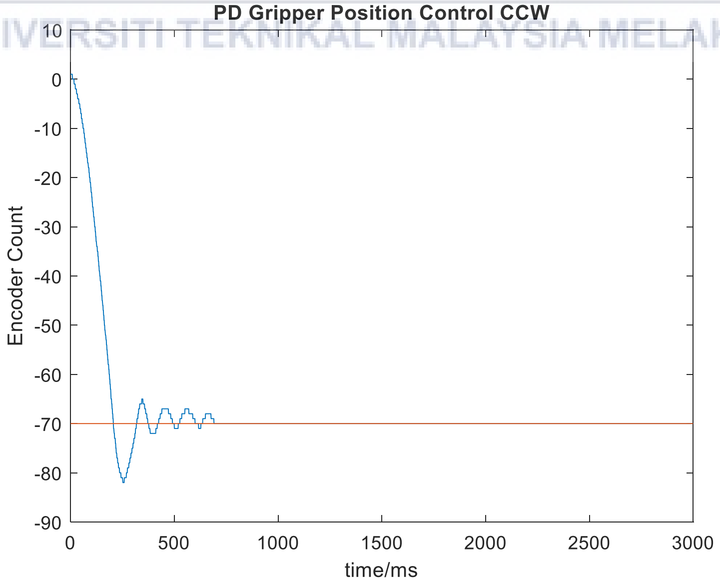

Figure 4.6 Output transient response of PD controller at 30˚

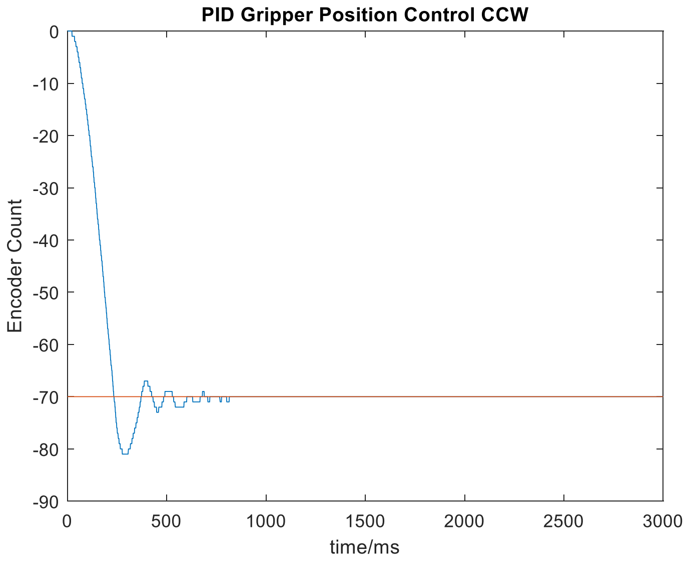

Figure 4.7 Output transient response of PID controller at 30°

Table 4.3 Transient response data for PI, PD and PID controller

Type of controller	Encoder's Reading (degree/°)		Rise Time, T_R (ms)	Settling time, T_S (ms)	Peak Time, T_P (ms)	Overshoot (%)
	Desired	Output				
PI	30	30	162	583	284	18.57
PD	30	30	144	677	258	17.14
PID	30	30	154	587	276	15.71

Table 4.4 Control gains of respective controller in experiment

Gain / Controller	Proportional, K_P	Integral, K_I	Derivative, K_D
PI	50.0	14.15	N/A
PD	50.0	N/A	60.55
PID	50.0	14.15	60.95

The results tabulated as in Table 4.1, Table 4.2, Table 4.3, Table 4.4 display the performance of different controller applied over position control of the gripper. All three controllers applied are able to achieve desired position. PI controller has a longer settling time among all three controllers, while PD controller possesses a little undershoot, likely a non-linear response at rising time. The D term has issues when a sudden variation such as a step respond is applied at input, instantaneously induces a sudden variation in the error e(t), which is multiplied by K_D and almost certainly saturates some components of the system.

For counterclockwise rotation, the position control observed a greater oscillation than that of clockwise position control. This could be caused by the unidentified system parameters which led to the tuning result that averagely contained quite an amount of oscillations.

PID controller on the other hand gives a moderate system overshoot, moderate overall stability, satisfactory error correction over response time and can be used for both fast and slow process variables. However, PID tuning brings about greater challenge in the process of obtaining optimal control gains. PID controller's performance is further tested under different environment and the results are presented in nest section.

4.3 PID Controller Performance Under Test Environment

4.3.1 PID Position Control Under Applied Resistance

An external resistive force is applied on the gripper jaws using a conventional rubber band. PID controller computes the feedback error and minimizes the oscillations of the motor. The output response of PID position control at given position of 140 encoder counts correspond to 60˚ clockwise rotation. The gripper opened and stopped accurately. The result is plotted in MATLAB as shown in Figure 4.4 below and Table 4.3 shows the output reponse data.

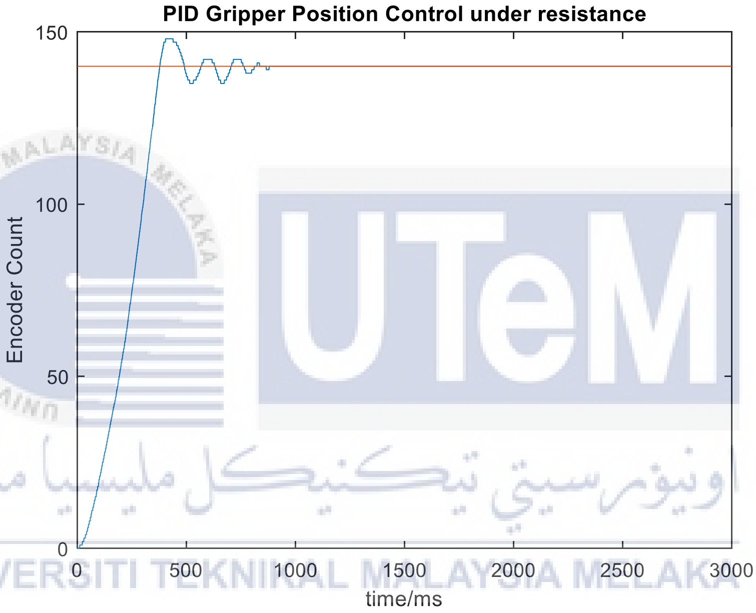

Figure 4.8 PID position control under resistant with K_P = 50.0, K_I = 20.0, K_D = 62.0

Table 4.5 Output response data of PID position control under applied resistant

Controller type	Rise Time, T_R (ms)	Peak Time, T_P (ms)	Settling time, T_S (ms)	Overshoot (%)
PID	272	404	690	5.71

It can be observed that gripper can still reach its desired position under applied resistant on the gripper jaws with the implementation of PID controller. The result obtained is satisfactory as the gripper does not oscillates much with a minor increase in percent overshoot of 5.71% compared to 3.33% under no resistant condition.

4.3.2 PID Position Control Under Trajectory Motion Set 1

The gripper is designed to manipulate object with accurate gripping position to avoid object damage. Therefore, a series of trajectory motion with varied positions is applied to the system to observe the performance of PID controller. Two different tuned gains and output response data are recorded in Table 4.4. Figure 4.5 and Figure 4.6 display the output response curve at desired position of 140, 93, 70, and 140 counts. Gripper opens at 60˚ clockwise (140 counts) before closes at 40˚ degree from origin or a 20˚ counterclockwise rotation. This is followed by a firmer grip at 30˚ from origin or a 10˚ counterclockwise rotation from previous position. The gripper finally opens at the position of 60˚ clockwise from origin.

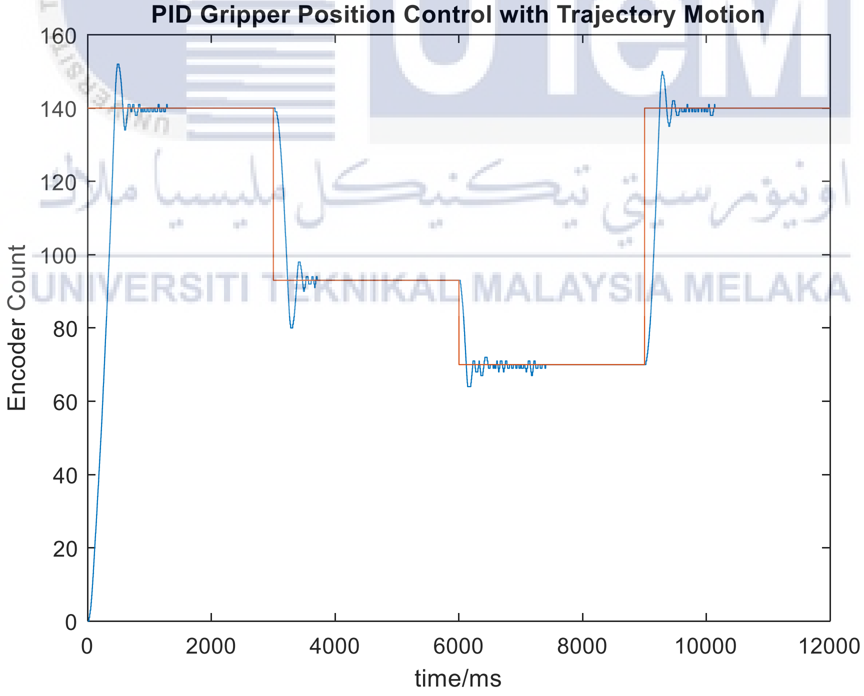

Figure 4.9 Trajectory output response Set 1

4.3.3 PID Position Control Under Trajectory Motion Set 2

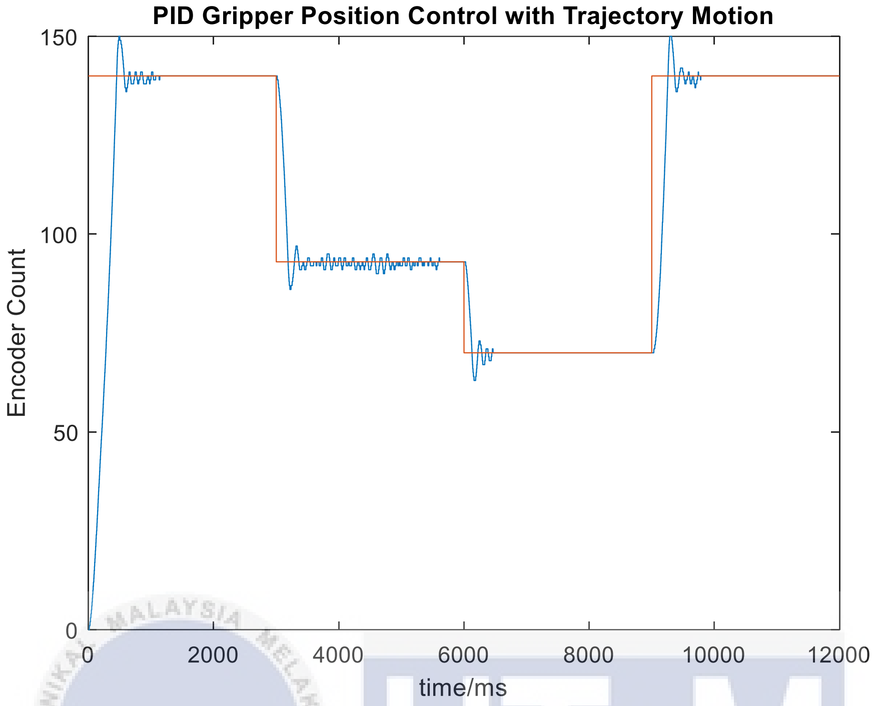

Figure 4.10 Trajectory output response Set 2

Table 4.6 Trajectory output response data

Test Set / Data	Set 1	Set 2
Proportional, K_P	54.05	53.95
Integral, K_I	16.15	16.15
Derivative, K_D	71.05	71.25
Rise Time, T_R (ms)	316	332
Settling time, T_S (ms)	943	970
Peak Time, T_P (ms)	478	487
Overshoot (%)	8.57	7.14

4.3.4 Error Analysis on PID Trajectory Position Control

It is necessary to evaluate and validate the system designed to ensure continuous improvement of system can be achieved. In this section, root mean square error (RMSE) is computed in Microsoft Excel and the results are tabulated in Table 4.5 as shown below. The data are taken over range of 12000 samples, representing the encoder position from every milisecond against the desired position.

Table 4.7 RMSE data for PID Trajectory Sets

No.	Trajectory plan	Sum of Squared-Errors (SE)	Mean Squared Error (MSE)	Root Mean Squared Error (RMSE)
1.	Set 1	5082690	423.5575	20.58051
2.	Set 2	4716980	393.087	19.82629

As we can observe from thetable above, the overall designed PID position control achieves a satisfactory performance with a RMSE value of 19.82629 over a datum ranges from 0 to 12000 miliseconds, each of 1ms per step which gives a total number of samples of 12000. By comparison, PID tuning parameter Set 2 has a better performance with an overall system overshoot of 7.14%.

4.4 Relationship between Angle of Rotation of Actuating Gear Link with Target Link Position

4.4.1 Determining Ratio of Rotation Against Displacement

An experiment was conducted to determine the relationship between the angle of rotation of actuating gear link with the position displaced by the target link. The displacement, d is measured for both opening and closing motion. The results were recorded as in Table 4.8 shown below.

Note: CW = Clockwise; CCW = Counterclockwise

Table 4.8 Correlation between angle of rotation and displacement

Experiment No.	Angle of Rotation, θ/°		Displacment, d/mm	Ratio, $\frac{d}{\theta}$
	Direction	Magnitude		
1	CW	60	50	0.8333
2	CW	60	50	0.8333
3	CW	60	49	0.8167
4	CW	60	50	0.8333
5	CW	60	51	0.8500
6	CCW	30	24	0.8000
7	CCW	30	25	0.8333
8	CCW	30	25	0.8333
9	CCW	30	26	0.8667
10	CCW	30	25	0.8333
Average				$0.83332 \approx \frac{5}{6}$

4.4.2 Verification of Correlation between Angle of Rotation with Target Link Displacement

A new trajectory motion is designed for grasping a cylinder of 45mm. The gripper is opened at d = 50mm correspond to 60˚ clockwise rotation, followed by a close grip at d = 40mm by applying a counterclockwise 12˚ rotation, and released the target object by reopened to d = 50mm position. The corresponding respond of the angle of rotation with the resulted displacement is plotted in MATLAB as shown in Figure 4.11. Table 4.9 recorded the output response data of the trajectory motion.

Table 4.9 Output response data of trajectory motion for rotation-displacement correlation verification

Proportional, K_P	53.95
Integral, K_I	14.25
Derivative, K_D	69.25
Rise Time, T_R (ms)	283
Settling time, T_S (ms)	660
Peak Time, T_P (ms)	443
Overshoot (%)	11.43

From the plot, we can observe that there were minor oscillations occurred at the rising and falling edges of gripper's trajectory motion where the maximum error of position in displacement was approximately 1mm at time = 3202ms. The object gripping was remained firm in the presence of minor oscillations. The gripper mechanism hereby has achieved satisfactory position control in the application of object grasping. Figure 4.12 showed the relationship between the rotation at actuating link and the displacement at the target link while object gripping is carried out. The linear graph displayed that the object gripping can be done by measuring the linear diameter of the object and the required rotation angle required can be computed easily.

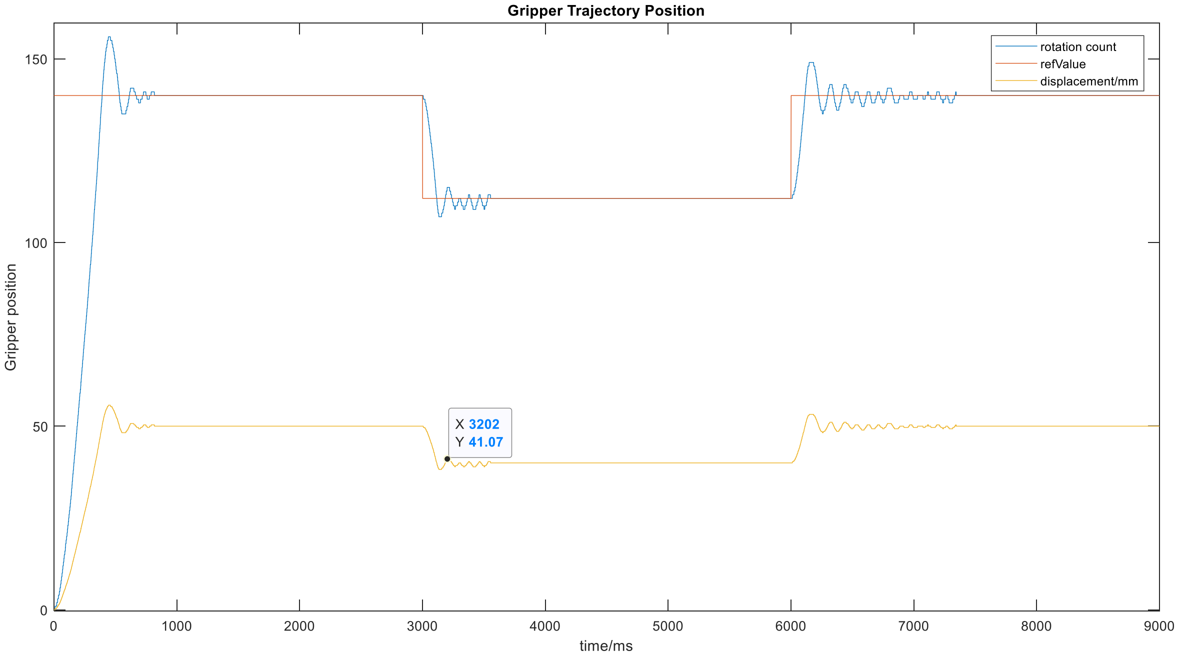

Figure 4.11 Trajectory plot for correlation of rotation-displacement

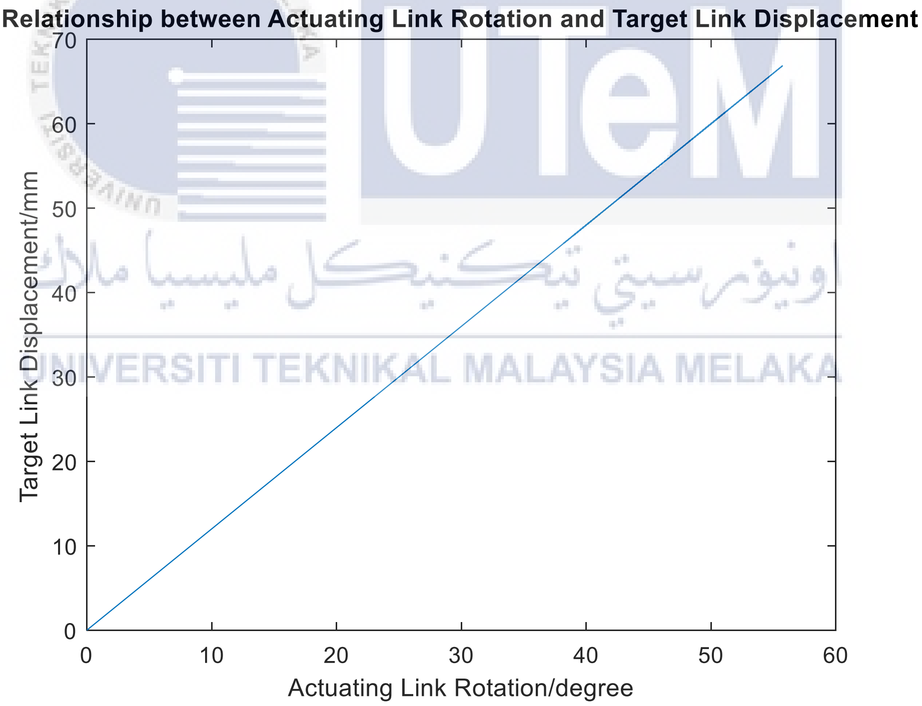

Figure 4.12 Relatonship between link rotation and link displacement

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This thesis presents comprehensive works on the design and development of position control for robot gripper mechanism using intelligent controller. A gripper mechanism has been built which consisted of a metallic robotic gripper, a DC geared brushed motor with quadrature encoder, a motor driver and Arduino UNO microcontroller that served as processing unit and data transfer agent from software to hardware implementation. The control parameters are computed using several types of controller coded in Arduino IDE and the control signal is converted into PWM signal and sent to the motor driver. The comparison on performances of different of controller has been carried out and from the result shown in previous chapter, it can be concluded that PID controller serves as the best controller of position control for robot gripper mechanism. PID controller's performance is further tested for trajectory motion and step motion with resistant applied. Error analysis shows that the system performed satisfactorily for gripper position control. PID controller has always served as to be more easy-to-implement controller real world system and is widely applied in industrial machines. All in all, this thesis concludes that the robot gripper mechanism developed with PID controller applied for position control is able to be utilized for various robotic application.

5.2 Future Works

In this project, PID controller is implemented in position control for robot gripper mechanism with system parameters not identified. This brings to the lack of stability of the system designed. Future work of identifying system parameters using MATLAB System Identification Toolbox and Design Optimization Toolbox is advisable. An algorithm that helps to improve PID tuning can be proposed to help elevate the efficiency of controller implementation and reduce the complexity of controller tuning process.

For further extension of work, this project can be tested on its performance reliability on gripper's gripping capabilities through force control of the gripper jaw. Load consideration and a more robust controller selection will help improving the system to a more stable system. The design of robot gripper can be improved by applying IR sensor to prevent damage of the structure brought about by the over rotation of the DC geared motor.

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APPENDICES

APPENDIX A ARDUINO CODING

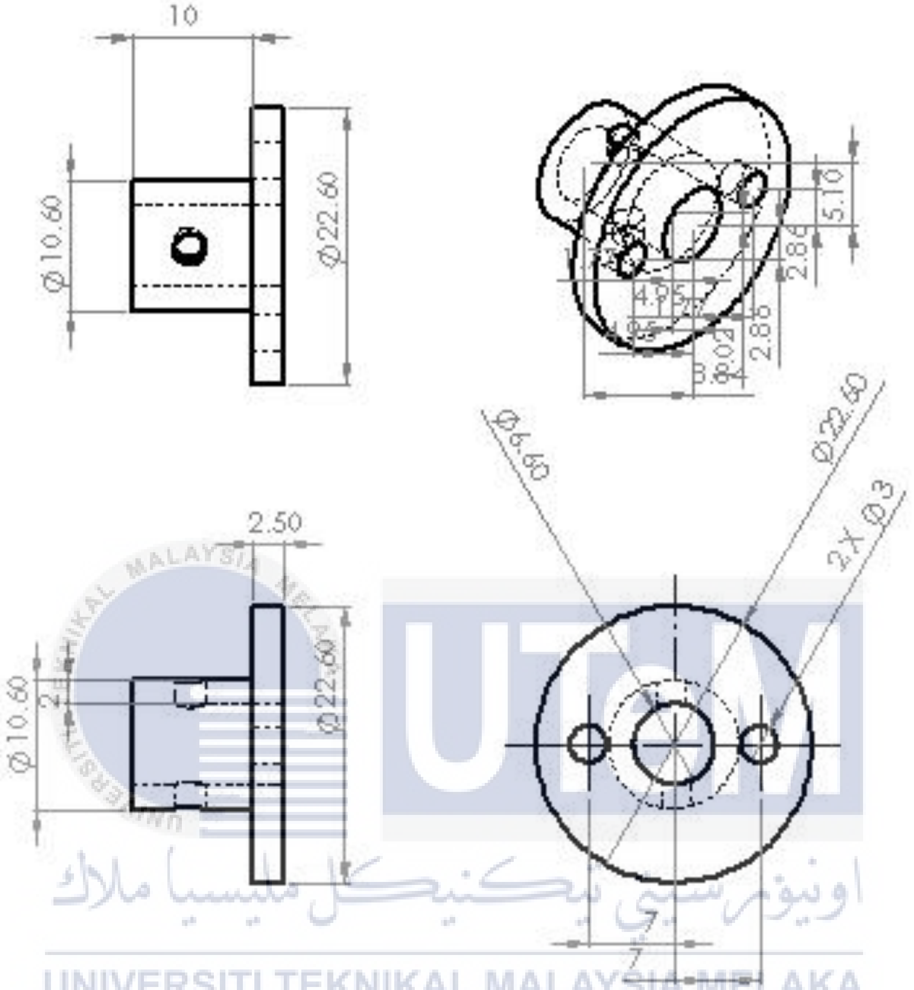
```
unsigned int EncoderA = 2;
unsigned int EncoderB = 3;
unsigned int postA, postB, preA, preB;
bool CW;
int rotation;
int refValue = 140;
unsigned int ENA = 9;
unsigned int IN1 = 5;
unsigned int IN2 = 6;
int error;
float Kp = 53.95;
float Ki = 16.25;
float Kd = 71.25;
int P_ConOut;
int I_ConOut;
int D_ConOut;
int PID_ConOut;
int deltaTime;

unsigned long runTime, stopTime;

void setup()
{
  Serial.begin(115200);
  pinMode(EncoderA, INPUT);
  pinMode(EncoderB, INPUT);
  pinMode(ENA, OUTPUT);
  pinMode(IN1, OUTPUT);
  pinMode(IN2, OUTPUT);

  digitalWrite(IN1, LOW);
  digitalWrite(IN2, HIGH);
  analogWrite(ENA, 0);

  runTime = millis();
}
```

```
void loop()
{
 while(millis() - runTime < 12000)
 {
  refValue = 140;
  if (millis() > 3000)
  {
   refValue = 93;
    }
  if (millis() > 6000)
  {
    refValue = 70;
  }
  if (millis() > 9000)
  {
    refValue = 140;
    }
  postA = digitalRead(EncoderA);
  postB = digitalRead(EncoderB);

  cal_angular_displacement(postA, postB);

  PID_controller();

  Serial.print(millis());
  Serial.print("\t");
  Serial.print(rotation);
  Serial.print("\t");
  Serial.println(refValue);

  stopTime = micros();
 }
 analogWrite(ENA, 0);
}

void cal_angular_displacement(unsigned int postA, unsigned int postB)
{
 if(preA != postA || preB != postB)
 {
  if(preA == 0 && preB == 0 && postA == 0 && postB == 1)
  {
    CW = true;
  }
  else if(preA == 0 && preB == 0 && postA == 1 && postB == 0)
  {
    CW = false;
  }
  else if(preA == 0 && preB == 1 && postA == 1 && postB == 1)
  {
    CW = true;
```

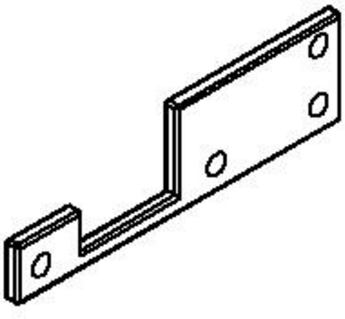
```
    }
    else if(preA == 0 && preB == 1 && postA == 0 && postB == 0)
    {
      CW = false;
    }
    else if(preA == 1 && preB == 1 && postA == 1 && postB == 0)
    {
      CW = true;
    }
    else if(preA == 1 && preB == 1 && postA == 0 && postB == 1)
    {
      CW = false;
    }
    else if(preA == 1 && preB == 0 && postA == 0 && postB == 0)
    {
      CW = true;
    }
    else if(preA == 1 && preB == 0 && postA == 1 && postB == 1)
    {
      CW = false;
    }
    if(preA != postA && CW == true)
    {
      rotation--;
    }
    else if(preA != postA && CW == false)
    {
      rotation++;
    }

    preA = postA;
    preB = postB;
  }
}

void PID_controller()
{
  error = rotation - refValue;
  deltaTime = stopTime - runTime;
  P_ConOut = round(Kp * error);
  I_ConOut = round(I_ConOut + (error * Ki) * deltaTime);
  D_ConOut = round(error * Kd/deltaTime);
  PID_ConOut = P_ConOut + I_ConOut + D_ConOut;
```

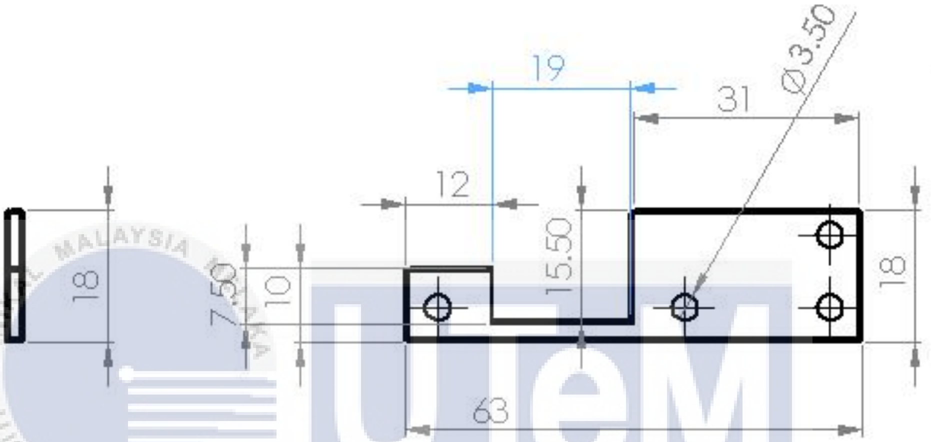
```
 if(error < 0)
  {
   //CW
   digitalWrite(IN1, LOW);
   digitalWrite(IN2, HIGH);
   analogWrite(ENA, PID_ConOut);
  }

  else if(error >= 0)
  {
   //CCW
   digitalWrite(IN1, HIGH);
   digitalWrite(IN2, LOW);
   analogWrite(ENA, PID_ConOut);
  }
}
```

APPENDIX B FLANGE COUPLE SOLIDWORKS SKETCH

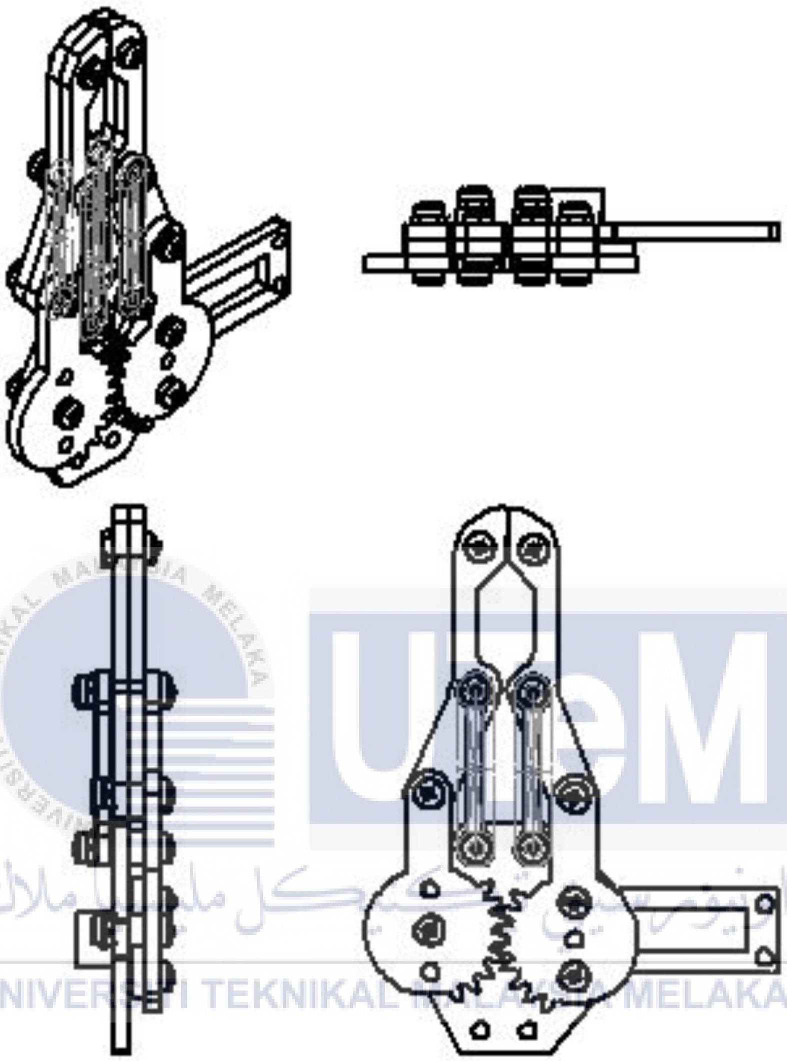


APPENDIX C SUPPORT FRAME SOLIDWORKS SKETCH



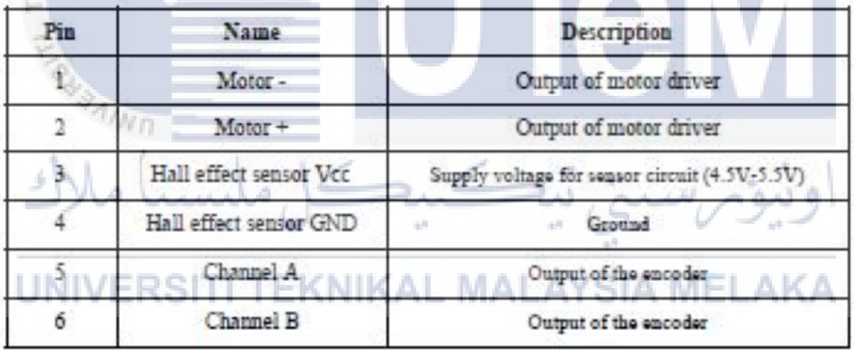


APPENDIX D ROBOT GRIPPER SOLIDWORKS SKETCH



APPENDIX E QUADRATURE ENCODER PIN DESCRIPTION

Figure 2.0 2020-06 connector pin descriptions



Pin	Name	Description
1	Motor -	Output of motor driver
2	Motor +	Output of motor driver
3	Hall effect sensor Vcc	Supply voltage for sensor circuit (4.5V-5.5V)
4	Hall effect sensor GND	Ground
5	Channel A	Output of the encoder
6	Channel B	Output of the encoder

APPENDIX F HARDWARE ELECTRICAL CONNECTION