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SARJANA MUDA

MOTION STUDY OF BIONIC LEG USING HYDRAULIC MOTOR

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BACHELOR OF MECHATRONIC ENGINEERING

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“I hereby declare that I have read through this report entitle “Motion Study of bionic leg using hydraulic motor” and found that it has comply the partial fulfilment for awarding the degree of Bachelor of Mechatronic Engineering .”

Signature : ....

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MOTION STUDY OF BIONIC LEG USING

HYDRAULIC MOTOR

QUAK ZHI YUAN

A report submitted in partial fulfilment of the requirements for the degree of

Bachelor of Mechatronic Engineering

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2014

I declare that this report entitle “Motion study of bionic leg using hydraulic motor” is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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Date : ....

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ABSTRACT

Nowadays, several sicknesses such as stroke, injury on the lower limb and elder people cannot walk in a proper way due to joints' injury. These sicknesses may cause lots of inconvenient in their daily life especially when their lower limb cannot move well in a proper motion. From the research of journal, lots of designs regarding exoskeleton leg (bionic leg) were done to assist the human in term of gait. Different types of method proposed according to the research such as gravity balancing orthosis (GBO), MATLAB software as controller, sliding mode controller (SMC) and humanoid robot biped with heterogeneous legs (BRHL) and etc. Some methods relate to the hydraulic motion study and some relate to the motion of exoskeleton legs. Derivation of mathematical modelling on bionic leg in term of kinematic analysis is the first objective. Another objective of this project is to design the motion of bionic leg using hydraulic actuator for stand and sit position. Besides, analysis on the design of motion study of hydraulic actuator in overall performance to give accuracy and reliability for rehabilitation application was done. There are three phases to be undergone according to the objectives. The derivation of mathematical modelling on bionic leg in term of kinematic analysis was done for the phase 1.The design of motion of bionic leg using hydraulic actuator with stand and sit position was done in phase 2 whereas analysis of the overall performance is done for the phase 3 for bionic leg. FluidSIM used as simulation to test the forces relative to the time taken for the hydraulic actuator. The result to be expected achieve is that able to control the hydraulic actuator for stand and sit position and analysis on overall performance such as accuracy needed so that it suitable used for rehabilitation purpose.

ABSTRAK

Pada zaman ini, pelbagai penyakit seperti strok, kecederaan pada anggota badan yang lebih rendah dan orang tua yang tidak mampu berjalan dalam perjalanan yang betul atas sebab kecederaan pada sendi lutut. Semua penyakit ini akan memberi kesan dan menyusahkan aktiviti harian terutamanya sendi lutut yang tidak mampu bergerak dalam posisiyang betul. Dalam kajian jurnal, pelbagai reka bentuk mengenai exoskeleton kaki (kaki bionik) telah dikaji untuk membantu manusia dari segi gaya pengerakan. Terdapat pelbagai jenis kaedah yang dicadangkan menurut kajian jurnal seperti ' gravity balancing orthosis(GBO), 'MATLAB software' sebagai pengawal, ' sliding mode controller(SMC)' dan ' humanoid robot biped with heterogeneous legs(BRHL)', serta yang lain. Terdapat sebahagian kaedah yang mengenai dengan kajian pengerakan hidraulik da nada yang berkaitan dengan pengerakan kaki exoskeleton. Objektif utama ialah perolehan pemodelan matematik di kaki bionic dari segi analisis kinematik. Objektif kedua dengan projek ini adalah untuk reka bentuk kajian usul kaki bionik dengan menggunakan penggerak hidraulik pada gerakan yang digunakan bagi posisi berdiri dan duduk. Selain itu, analisis mengenai reka bentuk kajian gerakan penggerak hidraulik dalam prestasi keseluruhan untuk memberikan ketepatan dan kebolehpercayaan bagi pemulihan telah dikaji. Terdapat tiga tahap untuk dikaji berdasarkan objektif. Asal pemodelan matematik pada kaki bionik dari segi analisis kinematik telah dilaksanakan bagi fasa 1. Reka bentuk gerakan kaki bionik dengan menggunakan penggerak hidraulik bagi posisi berdiri dan duduk telah dilaksanakan dalam fasa 2 manakala analisis prestasi keseluruhan dilakukan bagi fasa 3 untuk kaki bionik. FluidSIM digunakan untuk menguji kuasa relatif kepada masa yang diperlukan untuk penggerak hidraulik daya .Hasil kajian yang dijangka mencapai ialah mampu mengawal penggerakan hidraulik untuk berdiri dan duduk serta analisis mengenai prestasi keseluruhannya seperti ketepatan yang diperlukan supaya ia boleh digunakan sesuai untuk tujuan pemulihan.

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LIST OF ABBREVIATIONS

Abbreviation	Description
VDHM	Variable displacement hydraulic motor
PID	Proportional, Integration, Derivative
SISO	Single Input Single Output
MIMO	Multiple Input Multiple Output
BRHL	Humanoid robot biped with heterogeneous legs
FCV	Flow Control Valve
PRR	Prismatic-revolute-revolute
GBO	Gravity balancing orthosis
COG	Centre of gravity
GA	Genetic Algorithm
HSS	Hydraulic servo system
VDHM	Variable (different) displacement hydraulic motor
DH	Denavit Hartenberg
LQR	Linear Quadratic Regulator
IEC	International Electrotechnical Commission

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Bionic legs had been developed few years recently. They are widely used for people whom had injury on their lower limb or loss of legs due to some accidents or sickness. This may cause inconvenient for them to walk in normal pattern and cause a lot of difficulty in their daily lifestyle. There are lots kind of application on the bionic leg either using pneumatic actuator or hydraulic actuator. Lots of studies had been done to improvise the development on bionic legs. The design on bionic leg itself are complex and require lots of engineering knowledge to enable the succeed in the project. In order to aid the elder people with difficulty to walk due to several illnesses or injury, the studies of bionic leg was introduced to aid them. Other than aid the patients, the previous research on the exoskeleton suit to let the soldier to carry heavy load for the running and climbing which include the armor or weapon. This may reduce the injuries on the lower limb and ease the soldier in term of their movement. The motion study of bionic leg using hydraulic motor was proposed to overcome and improve the situation for the real life application. This will improve their lifestyle and provide a comfortable condition for the elders whom faced difficulty on walking. This bionic leg which is used in rehabilitation should not be heavy weight and the material used for the design should be reliable so that it is not too heavy which may cause burden to them.

1.2 Motivation

Bionic which is also known as the bionical creativity engineering which is the method used to study and design of the engineering systems and modern. This bionic leg can be used in lots of field such as medical field which help patient in term of their walking gait during their physiotherapy. Patients are able to walk in a proper way with the aid of bionic legs using hydraulic actuator.

For instances, patient that had stroke may have difficulty to walk and statistic shown that there are nearly 1 in 6 people may have stroke in their lifetime. About 50, 000 Australians suffered these strokes and there are nearly 1000 strokes every week. For the global, there are over 420, 000 people living with stroke and this value may be predicted to be continue increase. This shown that the bionic leg is useful in medical field to aid these stroke patients and improve their daily lifestyle. [1]

For the injuries of sport, there are lot of sports activities can be categorized for different type of injuries. Sport such as football, soccer, basketball and baseball may have their own risk and injuries on different part of body. Statistics showed that sports such as basketball, football and soccer had the high risk of injuries on ankle and knee. Thus, this project of the bionic leg using hydraulic actuator able to aid these patients too. Figure 1.1 shows the bar chart of type of injury for different sports among age 25 to 40 years.[2]

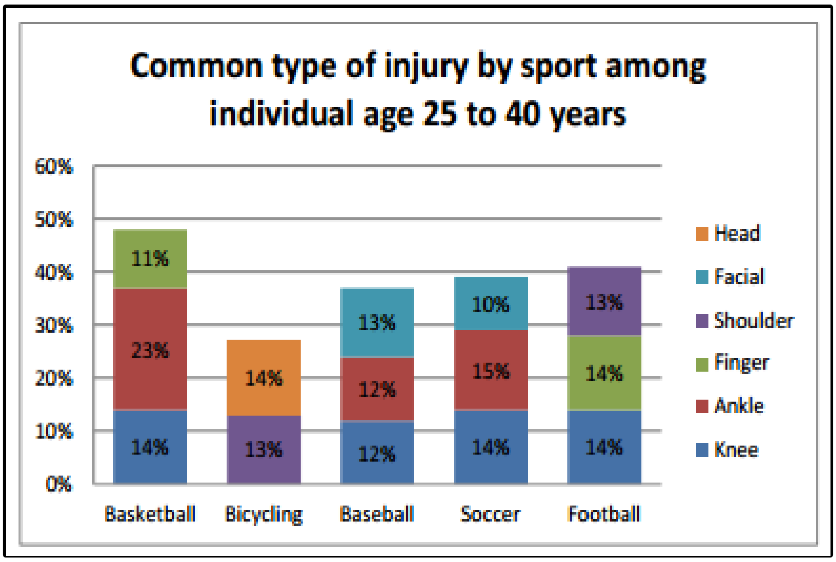


Figure 1.1 Type of injury by sport among age 25 to 40 years [2]

Figure 1.2 shows the number of injuries at the age of 25 to 40 years and by gender. We noticed that about nearly 80, 000 injured for the basketball sports and 93% of injuries were among men. For the soccer players, there were around 30,000 people injured and 83% of injuries are men whereas for the football, about 38,000 people injured and 88% were men. This statistic shows that how important on this research to aid those injuries especially on the lower limb and hydraulic actuator is used because hydraulic actuator able to withstand high load and accurate in position. [2]

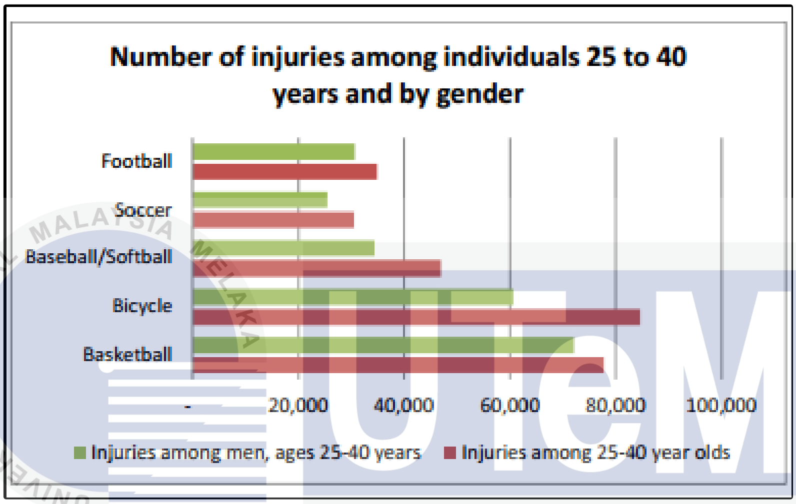


Figure 1.2: Number of injuries at the age of 25 to 40 years and by gender

1.3 Problem Statement

Most of the patient with several sicknesses such as stroke, injury on the lower limb and some elder people cannot walk in a proper way due to their joints' injury. These sicknesses may cause lots of inconvenient in their daily life especially when their lower limb cannot move well in a proper motion. Thus, this motion study with the used of bionic leg using hydraulic actuator is proposed to overcome the problem faced. These would benefit them and provide a more comfortable, reliable and convenient in their daily life. Besides, previous study on pneumatic actuator on the bionic legs had some limitation as well. In term of compression, the pneumatic cylinder is not always possible to get the uniform and constant piston speeds of compressed air. Besides, pneumatic cylinder only able to withstand 600 to 700KPa (6 to 7 bar) only compare with hydraulic cylinder which is able to withstand more load. Thus, in order to improve the efficiency of the pneumatic actuator, this project was proposed. Hydraulic cylinder can provide constant force and it is flexible whereby it can be stores under pressure for long periods. Hydraulic cylinder able to transfer huge amounts of power too. The hydraulic cylinder pressure can be controlled until the best pressure is selected depend on the load needed. For instance, pneumatic cylinder unable to withstand high load for the patient that had heavy weight and the pressure inside the pneumatic cylinder may not be constant flow which may cause the improper movement of the bionic leg. However, hydraulic cylinder may overcome this situation because the fluid flows in the hydraulic cylinder incompressible. Other than that, hydraulic cylinder is accurate for the control motion of extend and retract in term of its position.

1.4 Objective

1. To derive mathematical modelling of bionic leg in term of kinematic analysis.
2. To design the motion of bionic leg in application of hydraulic actuator for stand and sit position.
3. To analyze the overall performance in term of accuracy and reliability on the bionic leg using hydraulic actuator for rehabilitation application.

1.5 Scope

1. Derivation of mathematical modelling focus on the hydraulic actuator of one leg with two degree of freedom in term of kinematic analysis.
2. Stand and sit position with the use of two hydraulic actuator which include hip and knee parts on one leg is analyzed.
3. The analysis performance on hydraulic actuator done in experimental lab is discussed about time taken for hydraulic actuator to extend, retract and its velocity with different pressures, accuracy on hydraulic cylinder stroke position with the use

of limit switches and flex sensor as well as synchronization of two cylinder movement.

4. The analysis performance on accuracy done on hardware in term of the knee and hip rotation angle in stand and sit position with the used of limit switches.
5. This project focus on using the FluidSIM as computer simulation on hydraulic cylinder with forces provided and Arduino UNO R3 as microcontroller to actuate the hydraulic cylinders.

1.6 Significant of study

This proposed motion study of bionic leg using hydraulic motor will provide lot of opportunity and beneficial for the people who in difficulty of the walking especially for the elder people or people who had injury on the lower limbs. This study may improve the previous study which using pneumatic actuator by replacing it with hydraulic actuator in order to obtain high accuracy performance for rehabilitation purpose.

1.7 Report outlines

Chapter 1 discussed about the project background regarding the related project, problem statement, objectives, scope of research and significant of study. Chapter 2 was the literature review with its theory and the related on the previous work of research or study. Comparison on the review was done too. Chapter 3 discussed about the research methodology. Flow chart, K-chart, derivation of mathematical modelling in term of kinematic analysis, experimental design and implementation on hardware were done. Chapter 4 was the result obtained with the discussion for the experimental design, comparison on derivation of mathematical modelling in term of kinematic analysis in theory with result for the implementation on hardware. Chapter 5 was the conclusion for this project with the recommendation.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Bionic legs had been developed in several country and lots of research had been done. Bionic legs able to overcome lots of inconvenient for the people who had difficulty for the legs or lower limbs. They are able walk in the proper way with the aid of this latest development. Surachai Panich had proposed the design and simulation of leg-exoskeleton suit for rehabilitation. [3] Sunil K.Agrawal *et al.* described about the Gravity balancing exoskeleton which was used to unload our joint of the leg from gravity load over the motion within the range. [4] Hanz Richter *et al.* has proposed the Dynamic Modeling and Parameter Estimation of a Leg Prosthesis Test Robot. [5] Michael J. Plahuta has proposed study on the robust controller design for variable (different) displacement hydraulic motor (VDHM) whereby the feedback on control structure has two nested loops which is the outer and inner part of feedback looping. [6] Fei Li *et al.* has proposed a new gait of humanoid robot biped with heterogeneous legs (BRHL) to give a perfect test bed of smart bionic leg. [7] Jarissa Maselyne and Robin De Keyser described on how to control the relative movement of two linear moving parts in reality application for hydraulic application. [8**]** Yousheng Yang *et al.* mentioned about the leg mechanism of hydraulic actuated robot whereby it perform advantages whereby the minimum of the weight and volume, bigger forces and wide in term of the range of speeds are needed. Several studies had been discover to analyze the needed flow, pressure perform in the actuator chambers and efficiency of leg mechanisms which consist of two legs. [9] Michele Focchi *et al.* has described that the leg has two hydraulically actuated in term of degrees of freedom for the joints of hip and knee[10]. Dr Jafar M.Hassan *et al.* has proposed linear analysis to control electro-hydraulic system using proportional directional control valve. [11] Dechrit Maneetham and Nithin Afzulpurkarhas presented the model, simulation and high speed nonlinear hydraulic servo system (HSS) controlling. [12] Beshahwired Ayalew and Bohdan T.Kulakowski have proposed the cascade tuning for nonlinear control for the position of an electrohydraulic actuator. [13] Ayman A.Aly has proposed the PID parameters optimization with the used of Genetic Algorithm (GA) Technique for Electrohydraulic Servo Control System. [14] Dr. Christian Muller and Dr. H. F. Vanlandingham have described the nonlinear position feedback controller in an electrohydraulic robot arm. [15] Pornjit Pratumsuwan and Aphaiwong Junchangpood have proposed force and position control in the Electro-Hydraulic System by using a MIMO Fuzzy Controller. [16] Bengt Eriksson and Jan Wikander have proposed the force control for hydraulic cylinder towards a modular servo unit. [17] Yu Lin-ke *et al.* has proposed the fuzzy PID Control of direct Drive Electrohydraulic Position Servo System. [18] R. Firoozian B.Sc. and T.J.Lim have compared the Proportional, Integral, Derivative and active controlling technique for electrohydraulic servo motors. [19] From all the topic review above, this research can be categorized into several important data such as controller, microcontroller and type of actuator used.

2.2 Controller

The Dynamic Modeling and Parameter Estimation of leg prosthesis Test robot was proposed by Hanz Richter *et al.* Control system for the rotary actuator was controlled by single input single output (SISO) servo loop. For the sliding mode controller (SMC), it is used as development controller as it is good robustness properties. Real time control test was done to evaluate the ability of control system to operate in present of large force disturbances.[5] The design of the controller used classical type of loop shaping techniques and step response for mechanism of rocker arm was shown in graph. For motor model, in order to prevent saturation of the pump of supply, proportional controller was set to get the data step response for motor velocity control. Compared the PID controller and classical type of loop shaping techniques, the classical type of loop shaping techniques provide better design of flexibility.[6]

Iterative learning control (ILC) of open loop, closed loop and 1st order P-type of the open closed loop ILC is described because the artificial leg consist 4 bar closed chain mechanism. In term of control performance, controller module of 1st order P-type of the open closed loop ILC is designed in MATLAB Simulation. [7] Jarissa Maselyne and Robin De Keyser described on how to control the relative movement of two linear moving parts in reality application for hydraulic application. The speed of linear motion and time were taken in measured. Two PID controllers in inner loops used for speed control of each of the linear moving parts and one PI controller in outer loop control the phase difference between two parts so that synchronization is reached. Identification by using Prediction Error Method (PEM) is done with single input single output (SISO) model. Controller selected will be PID controller and FRTool used as graphical design tool. Transient analysis was done with an estimation of gain, time constant, dead time and bandwidth. 70% of data of PBRS experiments is performed using MATLAB. Cross validation was check whether it is able to reproduce data. For the controller, 'start speed' of each hydraulic motor need to be calculated so that it is able to synchronize for two linear motion. Several set points for phase difference was done and 30 degree lies in phase signal, sampling frequency and measurement errors. The signal suddenly jumps from a high positive value to high negative value and back again due to the noise on phase difference signal. [8]

Michele Focchi *et al.* has described that the leg has two hydraulically actuated in term of degrees of freedom for the joints of hip and knee. The actuation system consists of proportional valve with the asymmetric cylinders. Experimental result shows the advantages and disadvantages of Single Input and Single Output (SISO) versus Multiple Input and Multiple Output (MIMO) and linear versus non-linear algorithms controller in the application. PID controller, LQR controller and FL controller used as the controller design. PID controller design used in the specification of hip and knee where rise time, settling time and maximum overshooting were determined. LQR controller used to show a relationship between the state variables energy and controlling signals. FL controllers transform the non-linear system dynamic into linear system. Performances of controller were carried out to show the comparison among them. From the experiment, LQR controller had a larger phase delay compared with PID controller. FL controller scheme has the fastest in term of response because control scheme for model based that take in count on nonlinearities in its design. FL is the best controller whereby it has good tracking for the stretched leg configuration. Performance of LQR show a decreases at high frequencies because of linear controller operated at steady operation whereby investigation of the system cannot be estimated. [10] PID controller was used to overcome the overshoot and the system become stable which mean the natural frequency, damping coefficient and bulk modulus of elasticity of the liquid are the way to get good step response and stable system. [11] The new PD controller was introduced in this study. The main idea of HSS was the Simulink model for open loop system. The main idea of HSS was the Simulink model for open loop system. Modification of subsystem of hydraulic is to use for position of the valve, velocity of the valve and current of the input. Result on experiment for open loop system, velocity, step response for about 5 mega Pascal and 1 Hertz sine wave was compared with the open loop system, velocity, step response for 5 Mega Pascal and 1 Hertz sine wave for Simulink model. PD algorithm improves the performance and operation by the design of transfer function. [12]

There are two structure of controlling for nonlinear position control. First are the IO linearization system model with position of piston as output and the other one is a controller of cascade with a IO linearizing pressure force controller as an inner looping for feedback plus feed forward outer-loop position controller. Tuning procedure is demonstrated for IO position of linearizing tracking controller by showing the first on its equivalence with controller of cascade. Cascade controller has some advantages compared with IO linearizing controller. It provides a simple physical interpretation which aid for the linear gains. But cascade control structure involves in the online differentiation of force needed. Experimental result was done to know the tuning for nonlinear position controllers. It was shown that both controllers are almost equivalent with some possible differences due to signal processing. [13]

Ayman A.Aly has proposed the PID parameters optimization with the used of Genetic Algorithm (GA) Technique for Electrohydraulic Servo Control System. In this study, PID controller was designed for the attachment to system of electrohydraulic servo actuator in controlling the angular position. [14] From study, PID had improvised the hydraulic servo system performances in order to obtain minimum settling time with no overshoot and approximately zero steady state error. The closed loop control system used Runge-Kutta method of numerical integration technique with sampling time of 0.001s. Reciprocal of ITAE is modified for GA to evaluate the control performance of given feedback gains. Pornjit Pratumsuwan and Aphaiwong Junchangpood have proposed force and position control in the Electro-Hydraulic System by using a MIMO Fuzzy Controller. This controller has four inputs and three outputs whereby input variable consist of position error, velocity error, error of force and changes for the error of force. For the output variable, it consists of signal to drive proportional direction control valve to control position of an actuator. The total rules are 75 which represent in matric form. Crisp output is calculated by centre of gravity (COG) method. Result of MIMO fuzzy controller has better performance compared to multiple PID controllers. Besides, proposed EHS consumes less energy than conventional EHS. [16] A new controlling strategy of controlling force which can be controlled by optimal controller. Feed forward gain was calculated with feedback gain of regulator to produce a track on the reference force. [19]

Yu Lin-ke *et al.* have proposed the fuzzy PID Control of direct Drive Electrohydraulic Position Servo System. Fuzzy PID control algorithm has its own tuning of PID parameters and weaken the system saturation effectively, time delay, accuracy, dead zone and stability of hydraulic position. This study compared the traditional used of PIC control with the fuzzy PID controller which uses the s adaptive PID controlling parameters to reduce time delay and occurrence on dead zone impact serious nonlinear. Using MATLAB simulation, the results of closed loop step response of PID controlling and fuzzy PID controlling position able to be analysed. Parameters for the traditional PID controller tuning is difficult because of delay and high overshooting between the output of the system and targets controlling which is difficult to solve the fast response and stability of the system. Whereas for fuzzy PID control algorithm, it can reached automatically adjustment of PID parameters whereby the accuracy, performance and response speed are improvise. [18]

Proportional, Integral, Derivative and active controlling technique for electrohydraulic servo motors had been compared. In this study, the PID controller may cause instability in the systems. However suitable designed filter in active control, it is possible to construct the state variables in real time with active controlling law whereby the roots characteristic equation is shifted to arbitrary position s-plane from single feedback. [19] Table 2.1 shows the comparison between the studies in term of the controller used regarding on their own purpose with the advantages related with the studies themselves.

Table 2.1: Comparison of controller used with its advantages

No.	Author and Title	Controller	Advantages	Result
1	Hanz Richter et.al .,"Dynamic Modeling and Parameter Estimation of a Leg Prosthesis Test Robot"	Sliding Mode Controller(SMC)	SMC has good robustness properties.	The robot able to combine motion force of tracking.
2	Michael J. Plahuta and Matthew A. Franchek Hansjoerg , "Design of Robust controller for variable displacement of hydraulic motor (VDHM)"	PID controller	Classical loop shaping has greater design flexibility	Modelling system and design of controllers more efficient than common tuning PID controllers.
4	Jarissa Maselyne and Robin De Keyser, "Control of the relative movement of hydraulically driven linear moving parts"	PID controller	Able to synchronize two linear motion	Experimental result using prediction identification method.
5	Michele Focchi et. Al, "Control of a Hydraulically-Actuated Quadruped Robot Leg"	PID, LQR, FL controller as controller design	FL controller has the fastest response whereby it has good tracking.	-Larger phase delay of LQR compared with PID.
6	Dr. Jafar M. Hassan Oleiwi, "Linear Analysis to Control	PID controller	PID controller overcomes	Comparison between experimental

	an Electro-hydraulic System Using Proportional Directional Control Valve "		overshoot and system more stable.	and theory through analysis and verification.
7	Dechrit Maneetham and Nitin Afzulpurkar, "Modelling, simulation and high speed controlling for non-linear hydraulic servo System"	PD Controller	PD algorithm improve performance and operation	Comparison on the performance of controllers between nonlinear model of HSS with linearized approximation in term of velocity and displacement control.
8	Beshahwired Ayalew and Bohdan T. Kulakowski, "Cascade Tuning of Non-linear Position Controlling of an Electrohydraulic Actuator"	IO linearizing pressure force controller	Able to tune the nonlinear position control by using two control structure	Force is zero and friction was determined in real time.
9	Ayman A. Aly, Proportional, " Integral and Derivative parameters	PID controller	Improve performance of hydraulic	PID parameter optimized by Genetic

	optimization with Genetic Algorithm(GA) Technique for Electrohydraulic Servo Control System”		servo system	Algorithm(GA) which overcome the problems of system nonlinearities
10	Pornjit Pratumsuwan and Aphaiwong Junchangpood, “Force and position control in the Electro-Hydraulic System by using a MIMO Fuzzy Controller”	MIMO fuzzy controller	Better performance compared PID controllers	Fuzzy controller can be the alternative to control MIMO variable.
11	Bengt Eriksson and Jan Wikander, “Force control of hydraulic cylinder towards a modular servo unit”	Force Servo control	Able to overcome difficulty in tuning control parameter of hydraulic drive.	Versatile and simplification on site implementation
12	Yu Lin-ke et. Al., “Fuzzy Proportional, Integral and Derivative Control for position of direct Drive Electrohydraulic Servo System”	Fuzzy PID controller algorithm	-Able to obtain automatically adjustment of PID parameters -Response speed, accuracy and performances improved.	Comparison among traditional PID control and fuzzy PID controller through MATLAB simulation.
13	R. Firoozian B.Sc. and	PID and Active	Improvement	Active control

	T.J.Lim ,“ Comparing PID with active control technique for electrohydraulic servo motors”	control	in term of performance.	are better compare with PID control whereby PID controller can cause instability for system more than one modes of vibration as well as the existence of noise in the feedback signal.

2.3 Actuator

Gravity balancing exoskeleton which was used to unload our joint of the leg from gravity load over the motion within the range. This may give early quantitative assessment of the changes for kinematics and kinetic of walking style when human wear the exoskeleton leg. The test was done on the patient for range of motion for their knee and hip, weight of the bearing and speed of walking. Gravity balancing orthosis (GBO) was proposed which using springs that eliminate gravity torque at joints during the movement. From the analysis, the assistance of the gravity will increase the range of motion of joint of leg whereby nearly 50 % was located at hip and joint for stroke patient using single or two degree of freedom of the model of leg swing. Besides, training studies was done on patient whereby a style (pattern) template was displayed according to the stroke patient on screen of computer and as well as feedback on the pattern (gait) was given in real time. Gravity assistance drop from 100% to 0%. [4] Development, modeling and parameter estimation and preliminary feedback control of robot was analyzed. Firstly the machine design has two degree of freedom which name as hip vertical swing displacement and hip swing. DC motor, ball screw and linear slide is used for vertical motion stage. In term of robotic modeling, the system categorized as 3 link rigid robot with prismatic-revolute-revolute (PRR) configuration. Parameter estimation on ball screw torque and friction force was done. [5] Figure 2.1 shows the schematic of gravity balancing exoskeleton.

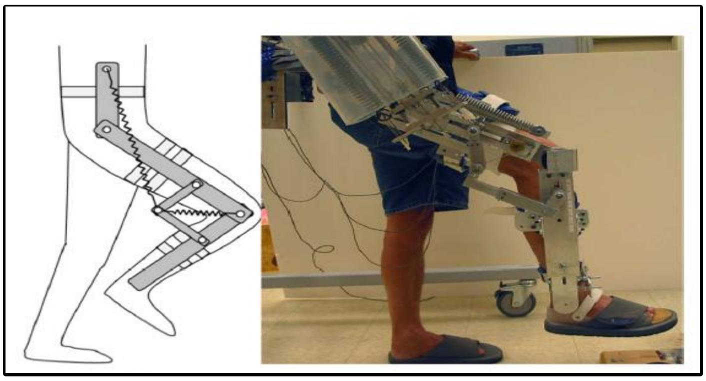


Figure 2.1: Schematic of gravity balancing exoskeleton [5]

Michael J. Plahuta has proposed study on the robust controller design for variable (different) displacement hydraulic motor (VDHM) whereby the feedback on control structure has two nested loops which is the outer and inner part of feedback looping. Inner loop controls rocker arm position and outer looping of the motor shaft velocity regulation. [6] Fei Li *et al.* has proposed a new gait of humanoid robot biped with heterogeneous legs (BRHL) to give a perfect test bed of smart bionic leg. The moment of inertia for joint (hip) of thigh, joint of knee, shank, joint of ankle and foot must small to decrease motor torque output. Knee joint has four rotation axes. Figure 2.2 shows the BRHL model. [7]

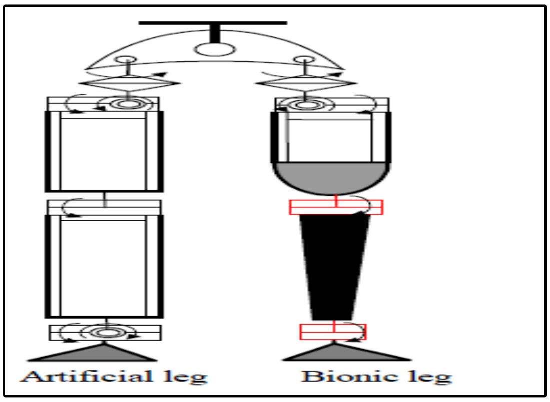


Figure 2.2: BRHL model [7]

The leg mechanism of hydraulic actuated robot whereby it perform advantages whereby the minimum of the weight and volume, bigger forces and wide in term of the range of speeds are needed. Several studies had been discover to analyze the needed flow, pressure perform in the actuator chambers and efficiency of leg mechanisms which consist of two legs. Comparison of two legs mechanism which use proportional 4 way valve(leg A)and proportional 3 way valve(leg B) with the linear actuator(leg A) and spring assisted rotary actuator(leg B). For the both mechanism, the numerical result shown are much larger than the theoretical one. The actual required flow depend on the actuator motion, leakage occur in the hydraulic components and the error to be controlled as well as load. The maximum needed flow for the mechanism of the leg which uses proportional 4 ways valve is twice larger than the one using proportional 3 way valve for theoretical and numerical result. This mean that flow of the supply of hydraulic actuation of leg A twice that of leg B. Thus, leg A in term power density is much smaller compared with leg B. The required flow pulse rate of every half second of leg A is larger compared with leg B. The leg A consists of high pressure in term of jumps in the chambers even without load. In term of efficiency, graph of efficiency against the time plot for the comparison of two leg mechanism had been plot. Efficiency of leg B was shown to be higher compare with leg A. This is lead to another four orifices used in four way valves (2 actuators) whereas for mechanism B, two orifices work at the same time. For hydraulically actuated with multi Degree of freedom of leg, the flow requirement can be minimize by using spring as a storage of power for reciprocal motion. An asymmetrical valve can be used to control the symmetrical valve as well as asymmetrical actuator and symmetrical of actuator to minimize the pressure in term of jumps in the actuator chambers. [9] Hydraulic cylinder was used for the actuated system as shown Figure 2.3 of the schematic drawing.

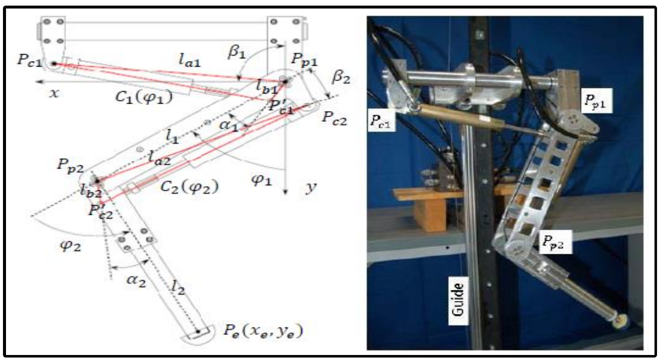


Figure 2.3: Schematic drawing of hydraulic cylinder with the system [9]

For another study, it has described that the leg has two hydraulically actuated in term of degrees of freedom for the joints of hip and knee. The actuation system consists of proportional valve with the asymmetric cylinders. [10] The cascade tuning for nonlinear control for the position of an electrohydraulic actuator had been proposed by Beshahwired Ayalew and Bohdan T.Kulakowski [13]. Figure 2.4 shows the photo and valve connection to the hydraulic cylinder whereas Figure 2.5 shows the schematic drawing of rectilinear actuator and servo valve.

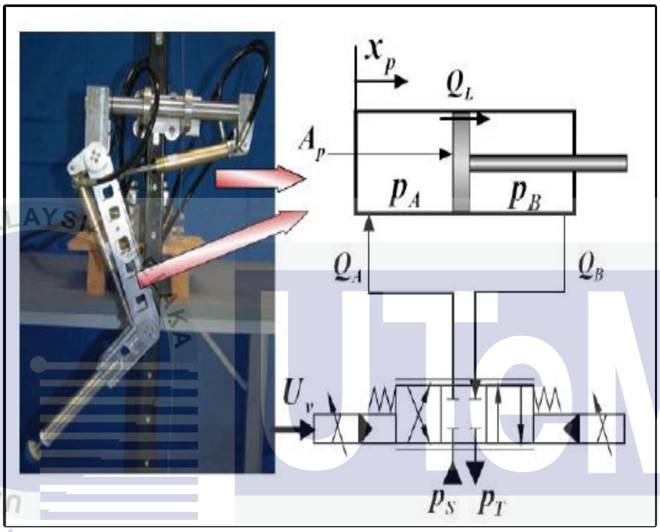


Figure 2.4: Photo and valve connection to hydraulic cylinder [13]

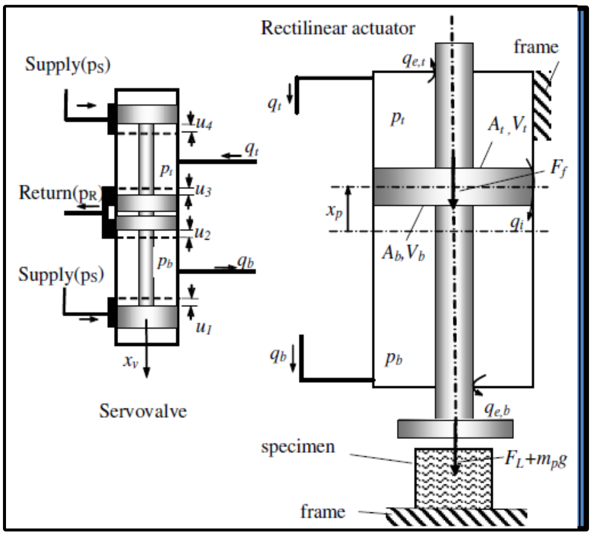


Figure 2.5: Schematic drawing of rectilinear actuator and servo valve [13]

Table 2.2 shows the type of actuator used with their respective criteria and advantages as well as disadvantages.

Table 2.2: Comparison on the type of actuator used with its criteria

Actuator Used	Hydraulic Motor	Hydraulic Cylinder	Spring Mechanism
Advantages	• Have high accuracy in term of motion • Able to adjust speed	• Able to control the stroke needed for the extension of legs • Reliable in term of design for bionic leg.	• Do not involve any other electrical components. • Only used springs.
Disadvantages	• Easily cause burn and irritation because of the pressurized fluid.	• Easily cause burn and irritation because of the pressurized fluid.	• Hard in term of controlling.
Power consumption	• High	• High	• None
Noise	• High due to aeration and cavitation.	• High due to aeration and cavitation.	• Slightly
Power to mass ratio	• Excellent power	• Excellent power	• None

There are different types of hydraulic motor such as hydraulic gear motor, vane motor piston motor and part turn actuators. Each of the hydraulic motor has its own features and their specific function to be used. Table 2.3 shows type of hydraulic motors with its' feature as well as parameter.

Table 2.3: Type of hydraulic motors [20]

Type of hydraulic motor	**Features**	**Parameters**
Hydraulic Gear Motor	• Low weight and size • high pressures • Low cost • Wide Range of speeds • Wide range of temperature	• Displacement volume from 3 to 100cc. • Maximum pressure around 250 bar • Speed range from 500 to 4000rpm • Maximum torque is 400Nm
Hydraulic Vane Motor	• Low noise level • Low flow pulsation • High torque at low speeds • Design is simple • Service will be easy	• Displacement volume from 9 to 214cc. • Maximum pressure around 230 bar • Speed range from 100 to 4000rpm • Maximum torque is 650Nm
Axial Piston Motor	• High speed with large displacement volume • High operating pressure	• Displacement volume from 10 to 1000cc. • Maximum pressure around 450 bar • Speed range from 500 to 11000rpm • Maximum torque is 10750Nm

From the Table 2.3, the possible selection of hydraulic motor is hydraulic vane motor because it has lower internal leakage compare with the gear motor. Besides, it consists of lower speed which is around 100 rpm which is suitable for the used on the bionic leg whereas the maximum operating pressure around 100 to 140 bar. Moreover, hydraulic vane motor has lower noise compared with gear motor. Normally for hydraulic piston motors, it is used in heavy duty hydraulic equipment such as for ship-crane, construction and others. Figure 2.6, Figure 2.7 and figure 2.8 shows the type of hydraulic motor which is hydraulic vane motor, axial piston motor and hydraulic gear motor.

Figure 2.6: Hydraulic vane motor [20]

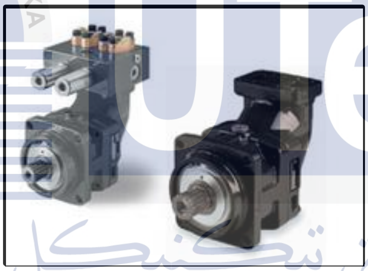


Figure 2.7: Axial piston motor [20]

Figure 2.8: Hydraulic gear motor [20]

There are lots of hydraulic cylinder can be used as an actuator for the bionic leg Normally there are two type of cylinders used such as single acting cylinder and double acting cylinder. The particular double acting cylinder has working pressure of 2000psi with smallest bore size of 1.125 in and 800 psi for the largest bore size of 8 in. [20] Figure 2.9 shows the double acting cylinder whereas Figure 2.10 shows the single acting cylinder.

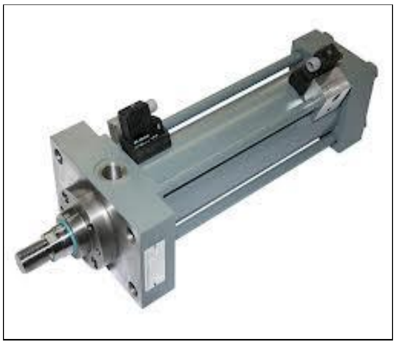


Figure 2.9: Double acting cylinder [20]

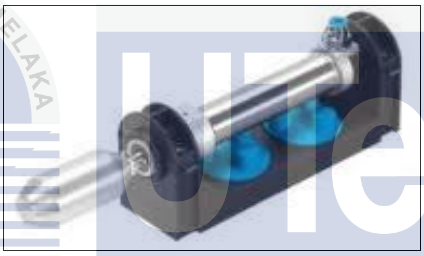


Figure 2.10: Single acting cylinder [20]

2.4 Microcontroller

There are two microcontroller were discussed here which is Arduino Uno R3 and Peripheral Interface Controller (PIC). PIC is known as Peripheral Interface Controller and it is different with PLC. It used an integrated chip(IC) as a controller. Whereas Arduino Uno is also a microcontroller board which used ATmega328 chip compared with PIC which normally used is PIC16F876A. Table 2.4 and Table 2.5 show the specification of both Atmega328 and PIC16F876A.

Table 2.4: Arduino Uno R3 specification [22]

Items	**Specification**
Microcontroller	ATmega328
Operating Voltage	5V
Input Voltage(recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	14(6 provide PWM output)
Analog Input Pins	6
DC current per I/O Pin	40mA
DC Current for 3.3V Pin	50mA
Flash Memory	32KB (ATmega328)-0.5KB used for boot loader
SRAM	2 KB (ATmega328)
EEPROM	1 KB (ATmega328)
Clock Speed	16 MHz

Table 2.5: PIC 16F876A Device features [23]

Key Features	PIC16F876A
Operating frequency	DC-20MHz
Resets(and Delays)	POR,BOR(PWRT,OST)
Flash Program Memory(14-bit words)	8K
Data Memory (bytes)	368
EEPROM Data Memory(bytes)	256
Interrupts	14
I/O ports	Ports A,B,C
Timers	3
PWM modules	2
Serial Communication	MSSP, USART
Parallel Communications	-
10-bit A/D modules	5 input channels
Analog Comparators	2

Instruction Set	35 instructions
Packages	28-pin PDIP 28-pin SOIC 28-pin SSOP 28-pin QFN

2.5 Summary of review

Table 2.6 shows the studies on with their purpose and the method proposed follow by the advantages. There are lots of studies according to the journals and the knowledge within it is different. Mostly MATLAB software is used with their respective controller for the close loop control system. Analysis on the simulation was done that is related to the controller used and the actuator used may be differing for different journals.

Table 2.6: Comparison of summarized solutions

No.	Studies	Purpose	Method proposed	Advantages
1	Design and Simulation of leg exoskeleton suit for rehabilitation	Rehabilitation purpose	Analysis and Simulated by MATLAB software	Position of hip, knee and ankle able to calculate by Denavit Hartenberg Equation.
2	Assessment Motion of a Swinging Leg and walking pattern Rehabilitation With a Gravity Balancing Exoskeleton	Unload joint of legs from gravity load over range of motion	Gravity balancing orthosis(GBO)	Test was done on stroke patient in term of range of motion and the spring used to eliminate gravity torque at joints.
3	Dynamic Modeling and Parameter Estimation of a Leg Prosthesis	Study prosthesis performance in	Rotary actuator controlled by Single Input	SMC has good robustness properties

	Test Robot	stand phase	Single Output(SISO) Sliding Mode Controller(SMC)	
4	Design of Robust controller for variable displacement of hydraulic motor (VDHM)	Study the feedback control structure	PID controller and classical loop shaping techniques	Classical loop shaping has greater design flexibility
5	The Bionic Design and Intelligent Control of Multiaxis Artificial Leg(BRHL)	Provide ideal test bed for development of intelligent bionic leg	MATLAB for control performance	Multiple axis artificial leg can be done on human normal walking pattern.
6	Control of the relative movement of hydraulically driven linear moving parts	To control two linear moving part in reality hydraulic application	-Identification using Prediction Error Method(PEM) -PID controller and FRTool as graphical design tool -MATLAB software for simulation	Able to synchronize two linear motion
7	Mechanisms of leg for Hydraulic Actuated Robots	To analyse the flow and pressure required in the actuator chambers and efficiency of two leg mechanisms	Experimental test(asymmetrical actuator and symmetrical actuator	-Efficiency of leg B higher than leg A. -Power density of leg B is bigger than A
8	Control of a Hydraulically-Actuated Quadruped Robot Leg	To shows the pros and cons of Single-Input and Single-Output(SISO) versus Multiple- input and Multiple -Output(MIMO),	PID, LQR, FL controller as controller design	- Larger phase delay of LQR compared with PID. -FL controller has the fastest response whereby it has good tracking.

		linear versus nonlinear controlling algorithms		
9	Linear Analysis to Control an Electro-hydraulic System Using Proportional Directional Control Valve	To study pressure drop, loading pressure and flow rate, extension velocity with and without external load	MATLAB software to determine natural frequency and damping ratio	PID controller overcomes overshoot and system more stable.
10	Modelling, simulation and high speed controlling for non-linear hydraulic servo system	To obtain system response by development on mathematical model	PD controller	PD algorithm improves performance and operation.
11	Cascade Tuning of Non-linear Position Controlling of an Electrohydraulic Actuator	To tune the nonlinear position control by using two control structure	The IO linearization of system model with position of piston , IO linearizing pressure force controller	-
12	Proportional, Integral and Derivative parameters optimization with Genetic Algorithm(GA) Technique for Electrohydraulic Servo Control System	To develop controller software that has ability to overcome the problems of system nonlinearities.	PID controller, PID parameter optimized by Genetic Algorithm(GA)	Improve performance of hydraulic servo system
13	Nonlinear position feedback controller for an electro- hydraulic robot arm	To improve the position feedback control by nonlinear filter	Nonlinear compensator	Improves system behaviour by reduce the nonlinear aspect of the system(overshoot and settling time)

14	Force and position control in the Electro-Hydraulic System by using a MIMO Fuzzy Controller	To control the input and output variables	MIMO fuzzy controller	Better performance compared PID controllers
15	Force control of hydraulic cylinder towards a modular servo unit	To proposed force control which overcome difficulty in tuning control parameter of hydraulic drive	Force Servo control	Versatile and simplification on site implementation
16	Fuzzy Proportional, Integral and Derivative Control for position of direct Drive Electrohydraulic Servo System	To compare the traditional PIC control and fuzzy PID controller	-Fuzzy PID controller algorithm -MATLAB software for simulation	-Able to obtain automatically adjustment of PID parameters, -Response speed, accuracy and performances improved.
17	Comparing PID with active control technique for electrohydraulic servo motors	To compare the performance of and active control	PID and Active control	Active control are better compare with PID control whereby PID controller can cause instability for system more than one modes of vibration as well as the existence of noise in the feedback signal.

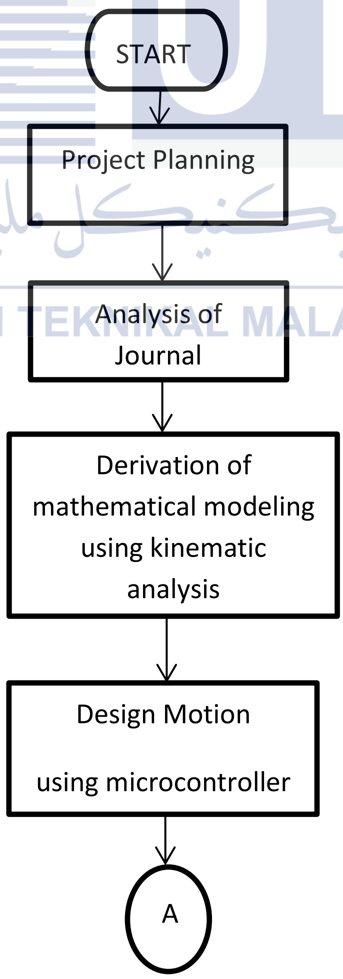
In conclusion, PID controller is mostly used as controller according to the research on journal and PID controller improves performance of hydraulic actuator system. However, this project was focus on using Arduino as microcontroller regardless of controller because it simplifies the hardware and software development used and it is easy to control. In term of actuator, hydraulic cylinder are the selection as it is more reliable for the bionic leg and the valve used is 4/3 way valve which is linear actuator. Double acting cylinder was selected as it can extend and retracted without spring but with hydraulically.

CHAPTER 3

METHODOLOGY

3.1 Flowchart

Flowchart is used to explain the procedure and steps that were done to accomplish this project. It showed the process step by step until the end of this project need to be done. Figure 3.1 shows the flowchart of the project which will be proceeding until the end.



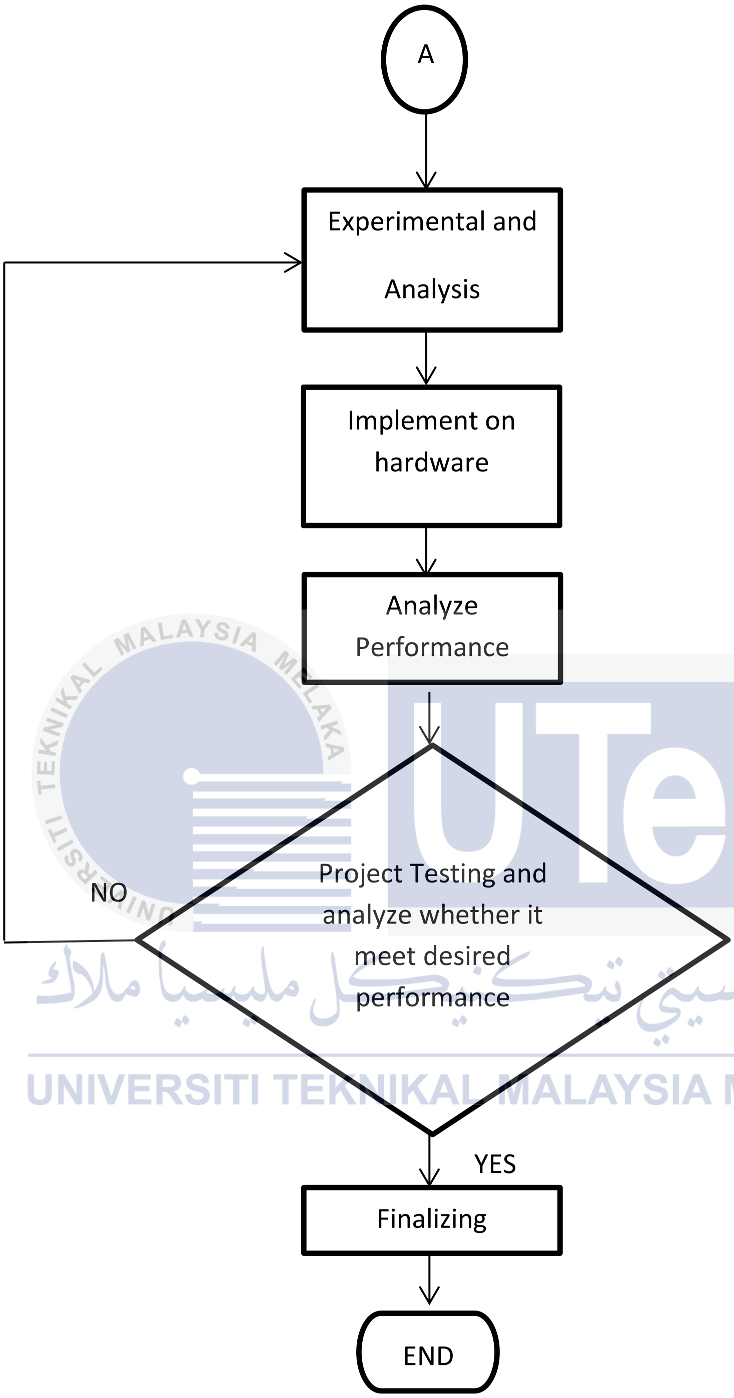


Figure 3.1: Flow chart of overall project

3.2 K-Chart

Figure 3.2 shows the K chart on the selection of title and which is included for the projects in term of actuator selection. For hydraulic actuator, hydraulic cylinders selected as an actuator and beneath it consist of hardware, software, theory and microcontroller. There were experiment and implement on hardware, electro-hydraulic circuit design and design of Arduino coding throughout this project. The test taken was the accuracy test, time and velocity with varies of pressure selected, fluidsim simulation and rotation angle on hip and knee. The derivation of mathematical modelling of bionic leg in term of kinematic analysis was done. Limit switches and flexibility sensor were used to control the motion of bionic leg. The frame with black color indicates the flow of system design in this project as shown in Figure 3.2.

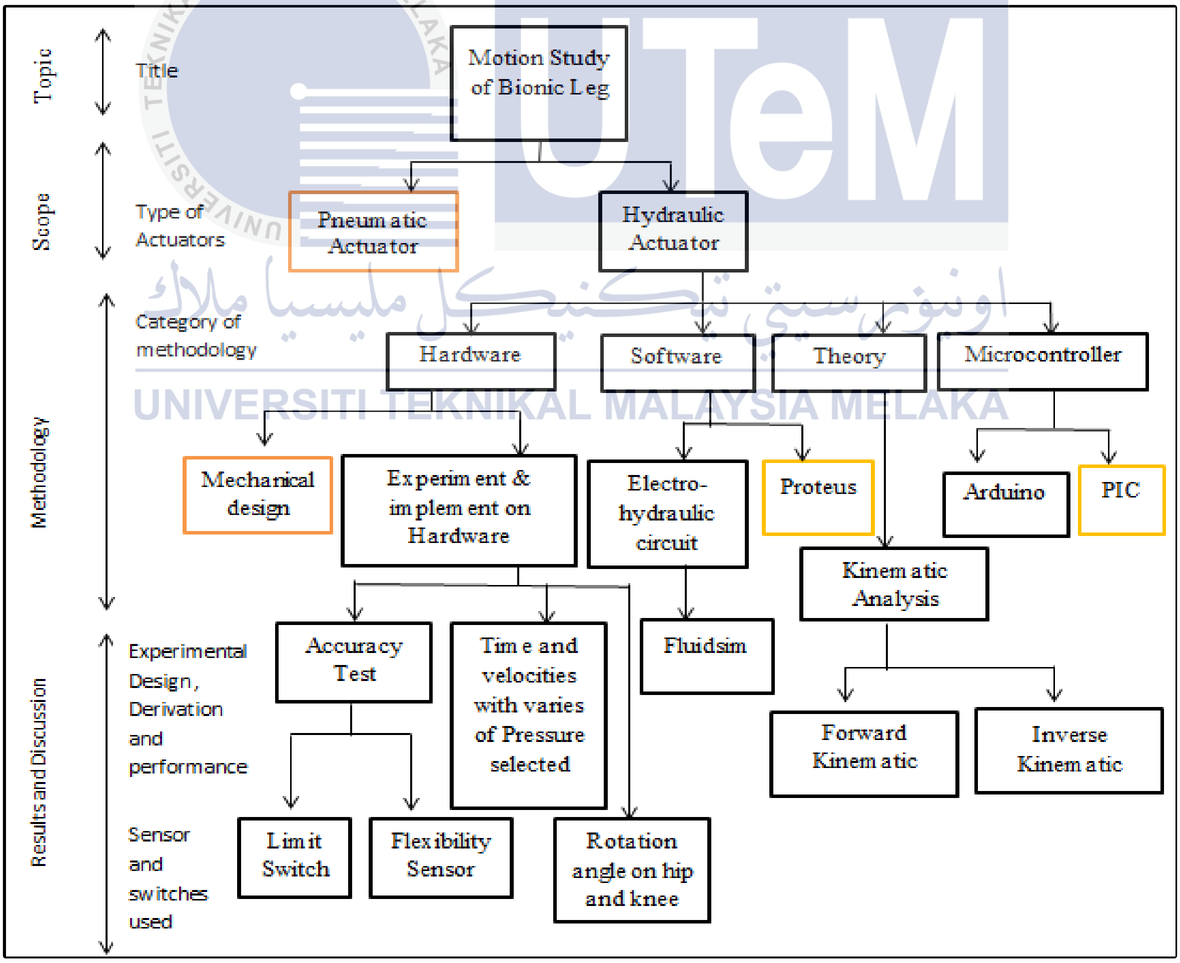


Figure 3.2: K-chart

3.3 Phases of Project

According to the objective, there are three phase to be conducted in the project. The detail of phases is explained as shown below.

1. To derive mathematical modelling of bionic leg in term of kinematic analysis.
2. To design the motion of bionic leg in application of hydraulic actuator for stand and sit position.
3. To analyze the overall performance in term of accuracy and reliability on the bionic leg using hydraulic actuator for rehabilitation application.

3.3.1 Phase 1: To derive mathematical modelling of bionic leg in term of kinematic analysis

For the phase 1, free body diagram of one bionic leg with hydraulic actuator is drawn. Derivation on the mathematical modelling of bionic leg based on the free body diagram in term of kinematic analysis. There are two type of kinematic which is forward and inverse kinematic. Type of hydraulic actuator and types of valves are selected.

3.3.2 Phase 2: To design the motion of bionic leg in application of hydraulic actuator

Firstly, the amount of hydraulic actuator used for one side of bionic leg is determined. Sizing of hydraulic actuator in term of rod diameter, piston bore and stroke length were determined. FluidSIM is used for the electro-hydraulic circuit design and simulation is done on the force acting on the double acting cylinder. Fritzing is used to draw and design the electric circuit with its schematic diagram before undergo the soldering part. Arduino Uno R3 is selected and the coding is designed to meet the desired condition whereas limit switches were used as the manipulated set of distances to control the extend and retract of hydraulic actuator. Besides, flexibility sensor was used to control the motion of double acting cylinder and the coding of Arduino Uno R3 was designed. Electrical circuit design for three limit switches, six limits switches and flexibility sensor were done too. Block Diagram of hydraulic actuator as shown in Figure 3.3 whereby input is the push button or flexibility sensor to control the hydraulic actuator to extend and retract whereas output is the position of hydraulic actuator extend and retract. Limit switches were used to set and fix the position of distances needed for the hydraulic cylinder extend and retract.

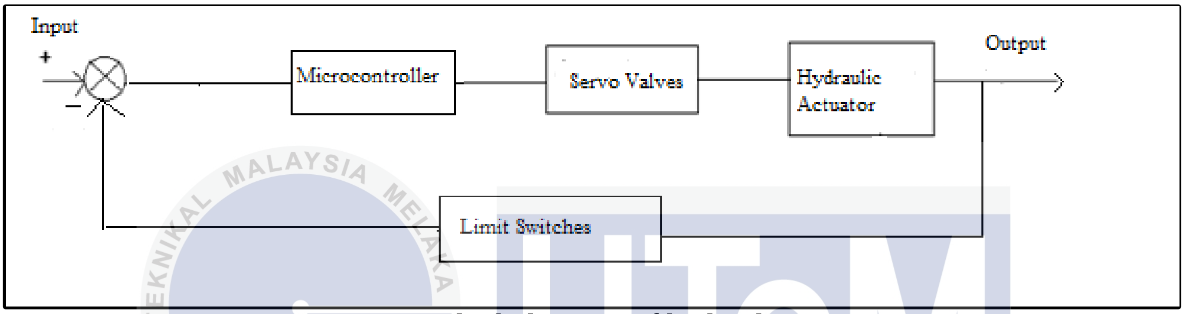


Figure 3.3: Block diagram of hydraulic actuator

3.3.3 Phase 3: To analyze the overall performance in term of accuracy and reliability on the bionic leg using hydraulic actuator for rehabilitation application

Few sets of experimental set up were done to analyse the extend and retract of hydraulic actuator with limit switches and different coding is designed to meet the condition. Analysis on time taken for hydraulic actuator to extend, retract and its velocity with different pressures, accuracy test on hydraulic cylinder stroke position with the use of limit switches as well as flexibility sensor and synchronization of two cylinder movement with different coding were done. Moreover, test on the six limit switches was done to obtain suitable pressure for the bionic leg .Data will be collected for analysis and improvement is made if any error occurs. Analysis done from experimental was applied on the hardware of bionic leg once the analysis and improvement obtained satisfying results. The finalize analysis on the bionic leg stand and sit position with rotation angle on hip and knee are done by using limit switches to set the distances for the hydraulic actuator need to be actuated. Accelerometer was used to obtain the rotation angle on hip and knee. Timing diagram was shown too for the experimental test.

3.4 Free body diagram of the bionic leg with hydraulic actuator for derivation of mathematical modelling in term of kinematic analysis

In term of the system modelling, the hydraulic actuator used was a double acting cylinder with the 4/3 way valve. The cylinder ports were connected to the valves and the piston extends to withstand the load. Y_{BF} and X_{BF} was the base frame whereas the θ_1 and θ_2 were the rotation angle of hip and knee. ϕ was the total length of θ_1 and θ_2. L_1 and L_2 were the actuators' length on hip and knee of one leg. Derivation of mathematical modelling on bionic leg in term of kinematic analysis was done. The bionic leg was a two link manipulator which had two degree of freedom (2 DOF). By using Denavit Hartenberg (D-H) convention, it can be used to describe the translation and rotation of these two links. Derivation on forward kinematic and reverse kinematic were done for the kinematic analysis. For forward kinematics, the input was rotation angle of hip and knee and output is the position of the actuator's length whereas for inverse kinematics, the input was the position of actuator length being set and the output is the rotation angle of hip and knee. This derivation was derived and the value of parameter was inserted for the unknown once the measurement was measured from the hardware. The test on the hardware for the rotation angle of hip and knee was compared with the derivation of mathematical modelling in term of kinematic analysis. Figure 3.4 shows the free body diagram of one bionic leg with two hydraulic actuator used.

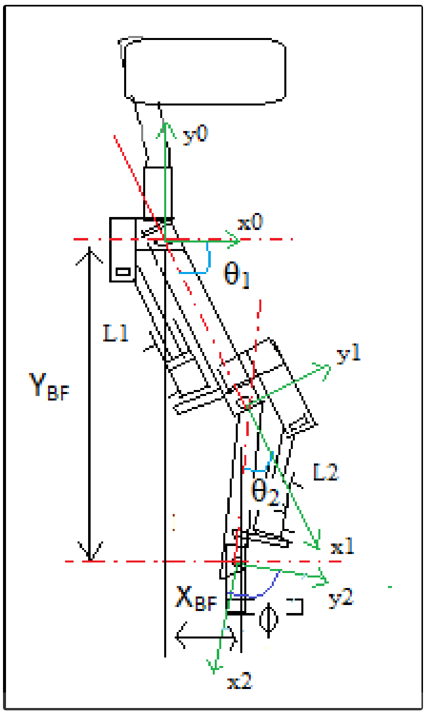


Figure 3.4: Free body diagram of one bionic leg with two hydraulic actuators

For the forward kinematic, the input is rotation angle of hip and knee and output is the position of the actuator's length. Two 4x4 matrices of homogeneous transformation T_i with the four basic transformation matrices are shown below.

$$^{i-1}T_i = (^{i-1}T_p)\,(^{P}T_Q)\,(^{Q}T_R)\,(^{R}T_i)$$

$$= R_z(\theta_i)\, D_z(d_i)\, D_x(a_{i-1})\, R_x(\alpha_{i-1}) \qquad (3.1)$$

Four basic transformations with their position and orientation as shown below:

$$R_z(\theta_i)=\begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & 0 \\ \sin\theta_i & \cos\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (3.2)$$

$$D_z(d_i)=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (3.3)$$

$$D_x(a_{i-1})=\begin{bmatrix}1 & 0 & 0 & a_{i-1}\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{3.4}$$

$$R_x\ (\alpha_{i-1})=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & \cos\alpha_{i-1} & -\sin\alpha & 0\\ 0 & \sin\alpha & \cos\alpha & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{3.5}$$

From equation 3.1,

$$^{i-1}T_i = \begin{bmatrix}\cos\theta_i & -\sin\theta_i & 0 & 0\\ \sin\theta_i & \cos\theta_i & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & d_i\\ 0 & 0 & 0 & 1\end{bmatrix} \text{x}$$

$$\begin{bmatrix}1 & 0 & 0 & a_{i-1}\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & \cos\alpha_{i-1} & -\sin\alpha & 0\\ 0 & \sin\alpha & \cos\alpha & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$= \begin{bmatrix}\cos\theta_i & -\sin\theta_i & 0 & 0\\ \sin\theta_i & \cos\theta_i & 0 & 0\\ 0 & 0 & 1 & d_i\\ 0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0 & 0 & a_{i-1}\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \text{x}$$

$$\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & \cos\alpha_{i-1} & -\sin\alpha & 0\\ 0 & \sin\alpha & \cos\alpha & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$= \begin{bmatrix}\cos\theta_i & -\sin\theta_i & 0 & \cos\theta_i a_{i-1}\\ \sin\theta_i & \cos\theta_i & 0 & \sin\theta_i a_{i-1}\\ 0 & 0 & 1 & d_i\\ 0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & \cos\alpha_{i-1} & -\sin\alpha & 0\\ 0 & \sin\alpha & \cos\alpha & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$
{}^{i-1}T_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i \cos\alpha_{i-1} & \sin\theta_i \sin\alpha_i & a_{i-1}\cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\theta_{i-1} & -\cos\theta_i \sin\alpha_{i-1} & a_{i-1}\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.6)
$$

The base frame is X_0, Y_0, Z_0 whereby the origin is at hip joint point. X_1, Y_1, Z_1 and X_2,Y_2, Z_2 frames can be fixed by D-H convention. Table 3.1 below shows the link parameters which consist of link 1 and link 2.

Table 3.1: Link parameter for bionic leg

Link #	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	L_1	0	θ_1
2	0	L_2	0	θ_2

$$
{}^{0}T_1 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & L_1\cos\theta_1 \\ \sin\theta_1 & \cos\theta_1 & 0 & L_1\sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.7)
$$

$$
{}^{1}T_2 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & L_2\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & L_2\sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.8)
$$

Let

$C_i = \cos\theta_i$, $S_{12} = \sin(\theta_1 + \theta_2)$

$= C_1S_2 - S_1C_2$

$C_{12} = \cos(\theta_1 + \theta_2)$, $\theta_{12} = \theta_1 + \theta_2$

$= C_1C_2 - S_1S_2$

Thus, for the T matrix,

$$^{0}T_{2} = {}^{0}T_{1}\,{}^{1}T_{2} \tag{3.9}$$

$$^{0}T_{2} = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & L_1\cos\theta_1 \\ \sin\theta_1 & \cos\theta_1 & 0 & L_1\sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & L_2\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & L_2\sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} \cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2 & -\cos\theta_1\sin\theta_2 - \sin\theta_1\cos\theta_2 & 0 & (L_2\cos\theta_2\cos\theta_1 - L_1\sin\theta_1\sin\theta_2) + L_1\cos\theta_1 \\ \sin\theta_1\cos\theta_2 + \sin\theta_1\sin\theta_2 & -\sin\theta_1\sin\theta_2 + \cos\theta_1\cos\theta_2 & 0 & (L_2\cos\theta_2\sin\theta_1 + L_2\sin\theta_2\cos\theta_1) + L_1\sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_{12} & -S_{12} & 0 & L_1C_1 + L_2C_{12} \\ S_{12} & C_{12} & 0 & L_1S_1 + L_2S_{12} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.10}$$

Thus, having the link dimension with the joint angles, the X and Y base frame (X_{BF} and Y_{BF}) of the origin can be obtained as shown below.

$$X_{BF} = L_1c_1 + L_2c_{12} \tag{3.11}$$

$$Y_{BF} = L_1s_1 + L_2s_{12} \tag{3.12}$$

For inverse kinematics, the input is the position of actuator length being set and the output is the rotation angle of hip and knee. For the homogeneous transformation, H of 4x4 matrixes as shown below:

$$H = \begin{bmatrix} R & 0 \\ 0 & 1 \end{bmatrix} \tag{3.13}$$

$$H = {}^{0}T_{2} \tag{3.14}$$

There are two parameter required only for the end effector of manipulator X_{BF} and $Y_{BF.}$ ϕ is introducing whereby it is the orientation of link 2 in the plane. Thus, assumption as shown below:

$$H=\begin{bmatrix} \cos\phi & \sin\phi & 0 & X_{BF} \\ -\sin\phi & \cos\phi & 0 & Y_{BF} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.15)$$

From equation 4.10 and 4.15, equate them to find θ_1 and θ_2 as shown below:

$$X_{BF}= L_2 \cos\theta_1 \cos \theta_2 – L_2 \sin\theta_1 \sin \theta_2+L_1\cos \theta_1 \quad (3.16)$$

$$Y_{BF}= L_2 \cos\theta_1 \sin \theta_2 – L_2 \sin\theta_1 \cos \theta_2+L_1\sin \theta_1 \quad (3.17)$$

$$\cos \phi = \cos\theta_1 \cos \theta_2 - \sin\theta_1 \sin \theta_2 \quad (3.18)$$

$$\sin \phi = \cos\theta_1 \sin \theta_2 - \sin\theta_1 \cos \theta_2 \quad (3.19)$$

By using trigonometric system, we can rewrite equation as shown below:

$$X_{BF} = L_1C_1 + L_2 C_{12} \quad (3.20)$$

$$Y_{BF} = L_1S_1 + L_2 S_{12} \quad (3.21)$$

$$\phi=\theta_1+ \theta_2 \quad (3.22)$$

Thus, we can use Algebraic solution as shown below to find θ_2:

$$X_{BF}^{\ 2} + Y_{BF}^{\ 2}= (L_1C_1 + L_2 C_{12})^2 + (L_1S_1 + L_2 S_{12})^2$$

$$= L_1^2 C_1^{\ 2} +2 L_1 L_2 C_1 C_2 + L_2^2 C_{12}^{\ 2} + L_1^2 S_1^{\ 2} +2 L_1 L_2 S_1S_{12}+ L_2^{\ 2}S_{\ 12}^{\ 2}$$

$$= L_1^2[C_1^{\ 2}+ S_1^{\ 2}] +L_2^2[C_{12}^{\ 2}+ S_{12}^{\ 2}]+2 L_1 L_2[C_1 C_{12} + S_1S_{12}]$$

$$= L_1^2 + L_2^2+2 L_1 L_2[C_1(C_1 S_2 -S_1 S_2) + S_1 (C_1 S_2 + S_1C_2)$$

$$= L_1^2 + L_2^2+2 L_1 L_2(C_1^2 C_2 + C_2S_1^2)$$

$$X_{BF}^{\ 2} + Y_{BF}^{\ 2} = L_1^{\ 2} + L_2^{\ 2} + 2\, L_1\, L_2 C_2$$

$$\cos\theta_2 \ = (X_{BF}^{\ 2} + Y_{BF}^{\ 2} - L_1^{\ 2} - L_2^{\ 2})/2L_1L_2$$

$$\sin\theta_1 = \sqrt{\frac{\begin{array}{l}[Y_{BF}^{\ 2}L_1^{\ 2} + Y_{BF}^{\ 2}L_2^{\ 2}\cos^2\theta_2 + X_{BF}^{\ 2}L_2^{\ 2}\sin^2\theta_2 + \\ 2L_1L_2Y_{BF}^{\ 2}\cos\theta_2 - 2L_1L_2Y_{BF}X_{BF}\sin\theta_2 - \\ 2L_2^{\ 2}Y_{BF}X_{BF}\cos\theta_2\sin\theta_2]\end{array}}{(X_{BF}^{\ 2} + Y_{BF}^{\ 2})(L_1^{\ 2} + L_2^{\ 2} + 2\,L_1\,L_2\cos\theta_2)}} \tag{3.23}$$

Thus, θ_1 and θ_2 can be found through these equations

3.5 Design of motion for bionic leg in application of hydraulic actuator for stand and sit position.

In phase 2, few considerations are taking into account such as actuator and valve selection, equipment used, electro-hydraulic circuit design, electrical circuit design and Arduino Uno R3 coding design to control sit and stand position with the use of limit switches as well as flexibility sensor.

3.5.1 Actuator Selection and Valve Selection

Double acting cylinder is selected as the actuator part and 4/3 way directional control valve with mid position closed is selected to control the direction of the flow of the fluid. Figure 3.5 shows the double acting cylinder and Figure 3.6 shows the symbol of double acting cylinder. Figure 3.7 shows the 4/3 way directional control valve.

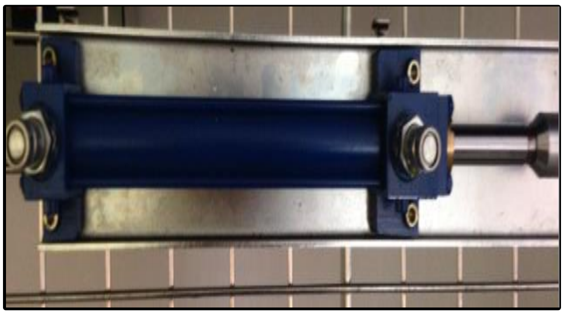


Figure 3.5: Double acting cylinder

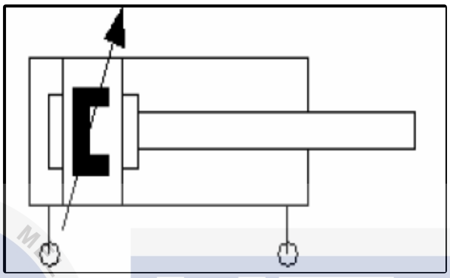


Figure 3.6: Symbol of double acting cylinder

Figure 3.7: 4/3 way directional control valve

The specification of double acting cylinder is shown in Table 3.2.

Table 3.2: Specification of double acting cylinder

Rod Diameter	1.5875 cm
Piston/bore diameter	3.81 cm
Stroke length	10.0 cm

3.5.2 Equipment Used

Figure 3.8 shows the pressure gauge that had being used during the experimental test to indicate the pressure that flows to the valve from the hydraulic tank.

Figure 3.8: Pressure Gauge

Figure 3.9 shows the flow control valve that had being used during the experiment test 2 and for the bionic leg to control the flow of fluid to the valve so that the double acting cylinder would not extend or retract too fast.

Figure 3.9: Flow Control Valve

Figure 3.10 shows the Compressed Air Regulator used and the pressure regulator which is also known as pressure relief valves were used to ensure that the tank do no exceed the predetermined values. Besides, it also maintain the operating pressure of the system.

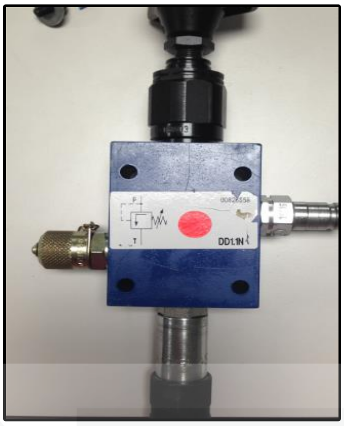


Figure 3.10: Compressed air regulator

Figure 3.11 shows the Connectors with hydraulic coupling to connect the valve to double acting cylinder as well as connection from tank to valve.

Figure 3.11: Connectors with hydraulic coupling

3.5.3 Electro-hydraulic circuit design

This electrohydraulic circuit design is mainly used for the fluidsim computer simulation. In the electro-hydraulic circuit design, there are 3 limit switches used to 3 set the distance of 0 cm, 5 cm and 10 cm for the double acting cylinder to extend and retract. Two hydraulic cylinder and two 4/3 way valve are used with flow control valve of 33%. Y1 and Y2 is the solenoid whereby Y1 will cause the double acting cylinder to extend and Y2 will cause the double acting cylinder to retract. When push button is pressed, the relay coil of R1 is passed through and the contact R1 is closed as well as pass through limit switch, K1. After that, the relay, G2 is passed through to activate solenoid Y1 for the extend of double acting cylinder. The double acting cylinder will pass through limit switch, K2 and then follow by limit switch K3. Thus, the relay, G1 is passed through and contact G1 is closed for the solenoid Y2 to activate for the retraction of cylinders. The double acting cylinders pass through again the limit switch K2 and K1. Whenever push button is released, the hydraulic cylinder will stop its motion. Figure 3.12 shows the International Electrotechnical Commission, IEC (electronic circuit) and Figure 3.13 shows hydraulic circuit of two double acting cylinders.

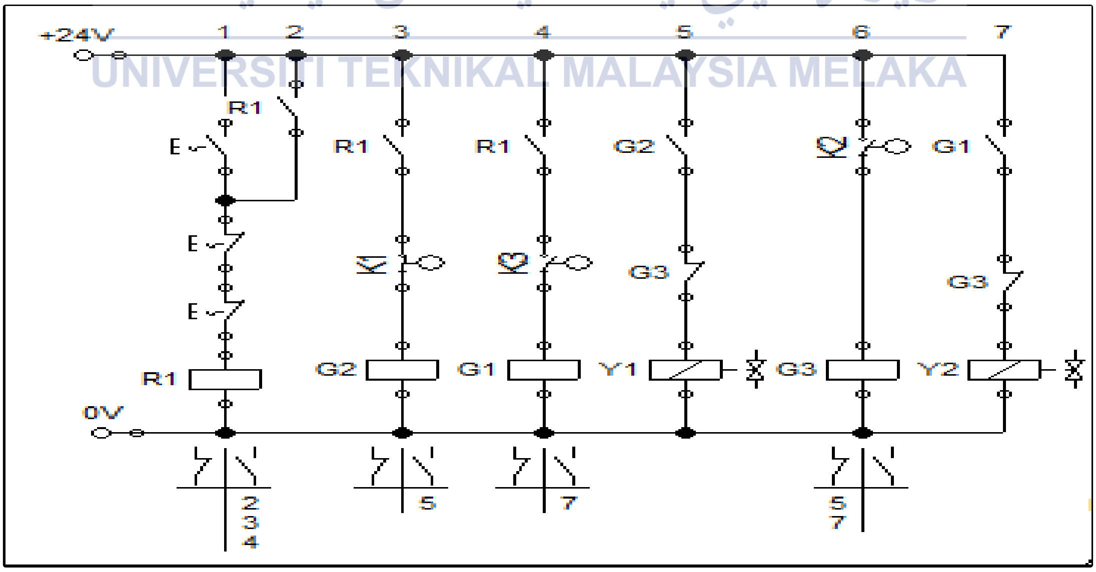


Figure 3.12: International electrotechnical commission, IEC

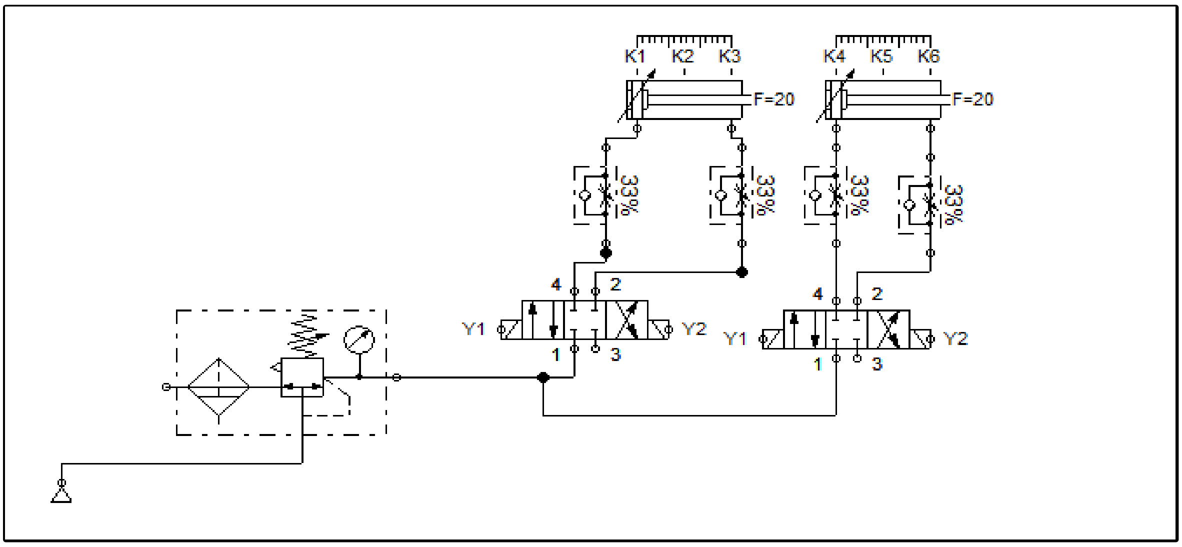


Figure 3.13: Hydraulic circuit of two double acting cylinders

3.5.4 Electrical circuit design

Firstly, 3 limit switches is used to set the position for the double acting cylinder to extend and retract. Four 5V relay modules were used to control 4 solenoid valves for the two double acting cylinders to retract and extend at hip and knee joint. 24V external power supply was needed to supply to these 5V relay modules to trigger them to normally closed state. Next, 6 limit switches were used to control the extend and retract of cylinders consequently and the experimental test were done in laboratory. Push button consist of green and red push button for the extend and retract of double acting cylinder. 10K ohm resistor was used for the limit switch and the push button and it is act as pull up resistor. Both digital pins and analogue pins were used. Moreover, flexibility sensor was used too and it is act as input switch to control the extend and retract of double acting cylinder. In addition, Fritzing was used to draw the schematic diagram and the connection of electrical circuit on virtual board. Figure 3.14 shows the schematic diagram of electrical circuit design. Figure 3.15 shows the actual connection on the virtual board for the electrical circuit flow.

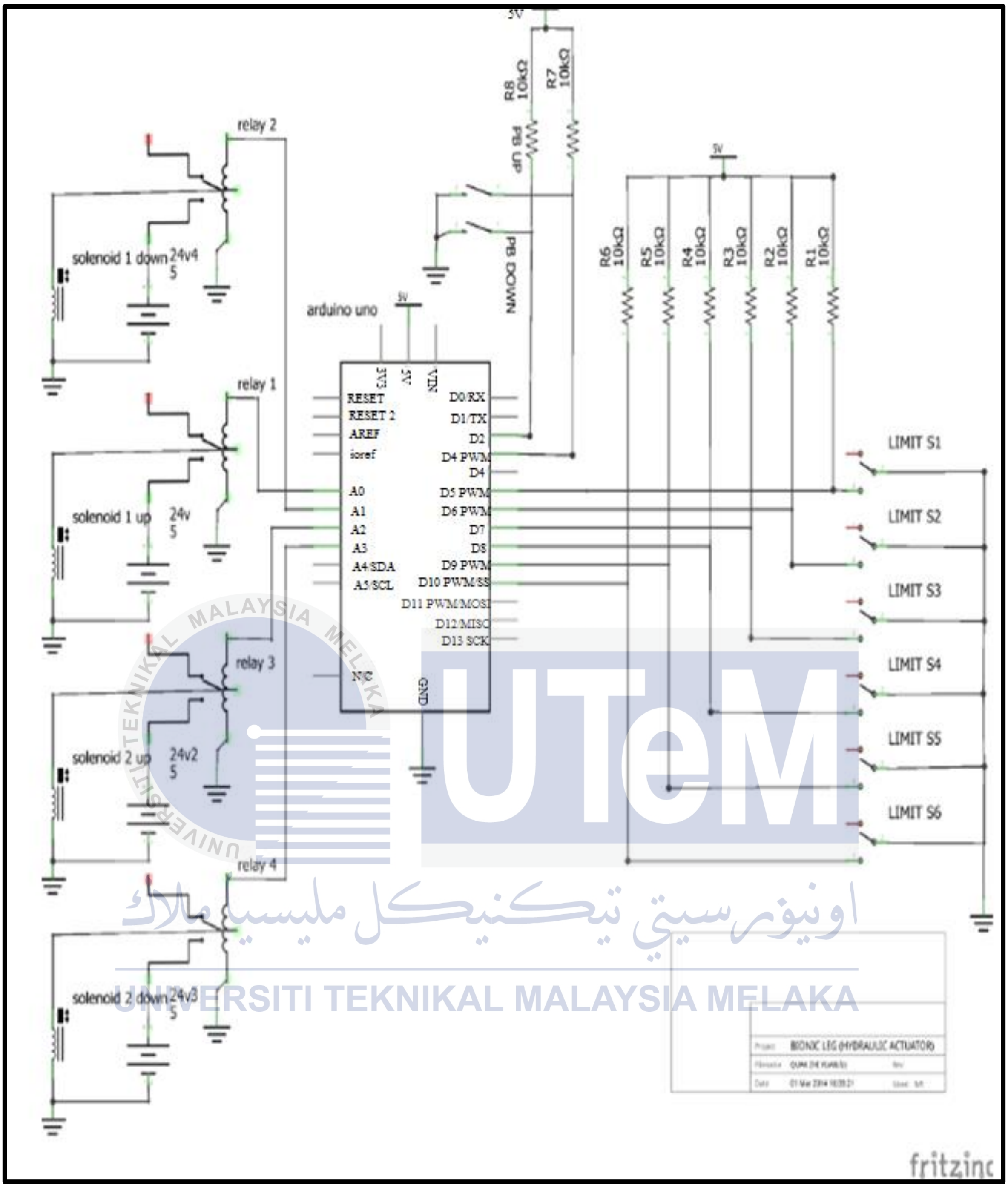


Figure 3.14: Schematic diagram of electrical circuit design

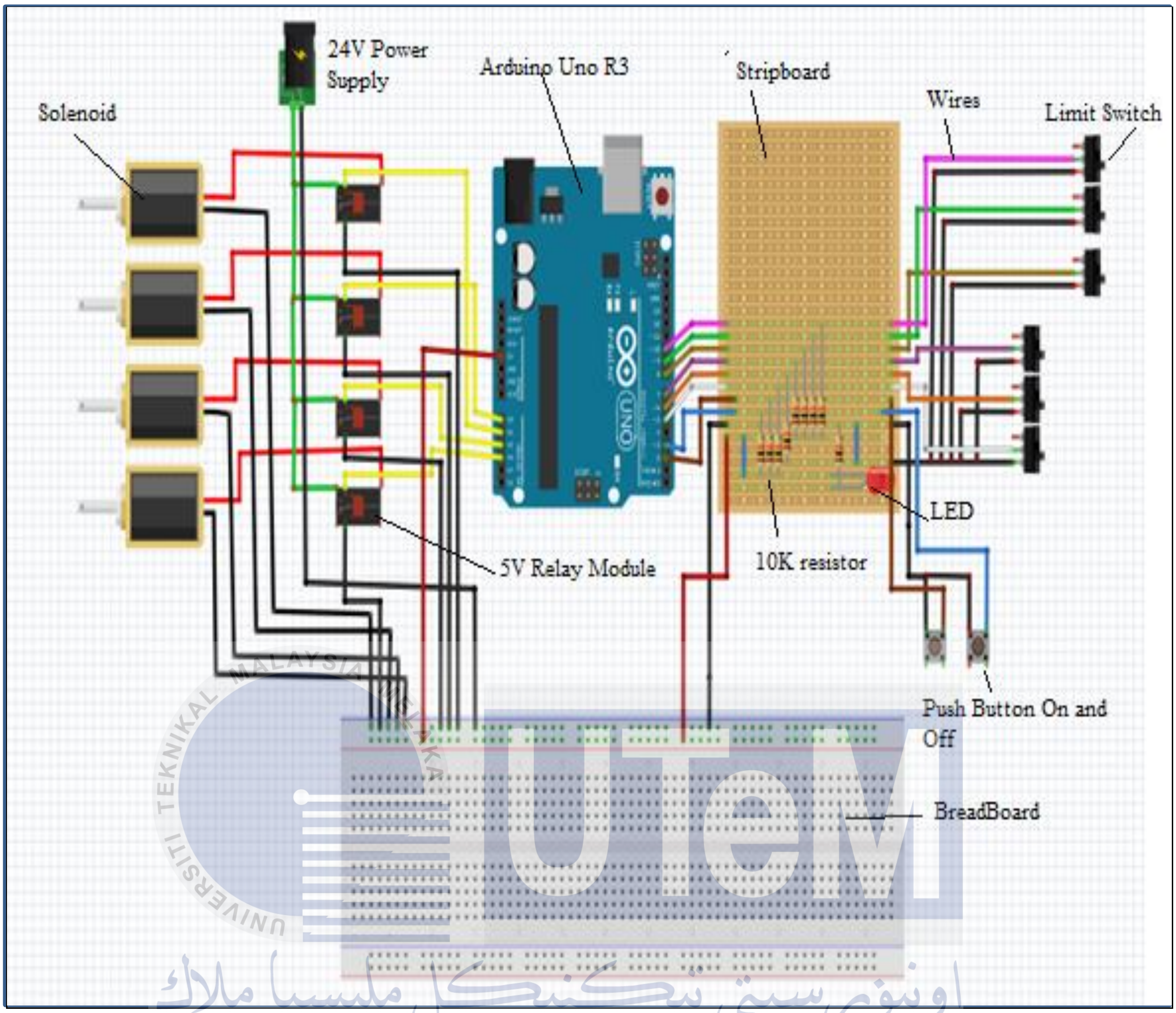


Figure 3.15: Actual connection on the virtual board for the electrical circuit flow

Both of Figure 3.14 and Figure 3.15 show the 6 limit switches used. However, another method of design is much easier with the use of 3 limit switches only and applied on the hardware. The number of relays used is still the same. Figure 3.16 shows the schematic diagram of 3 limit switches used. Both design had being done in experimental test and the analysis on 6 limit switches and 3 limit switches had done. The 2 cylinder need to be synchronized in term of their motion for extend and retract in stand and sit position. Thus, flow control valve is used in one of the cylinder so that both double acting cylinders can move at the same time. For the hardware implementation, only 3 limit switches with 4 relays are used to control the two hydraulic cylinder motions. Figure 3.17 shows the actual set up in term of electrical design circuit with the used of limit switches.

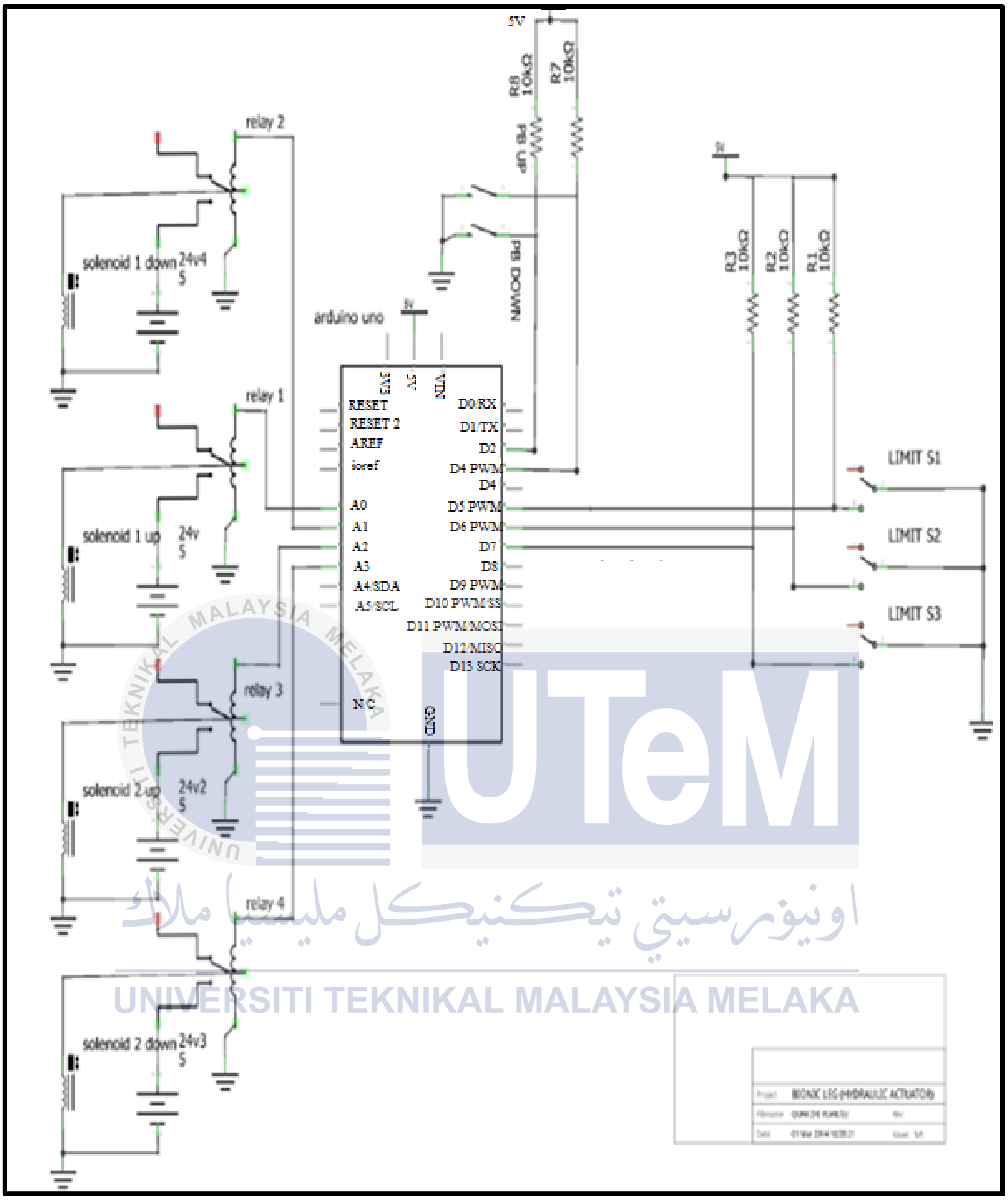


Figure 3.16: Schematic diagram of 3 limit switches used with 4 relays

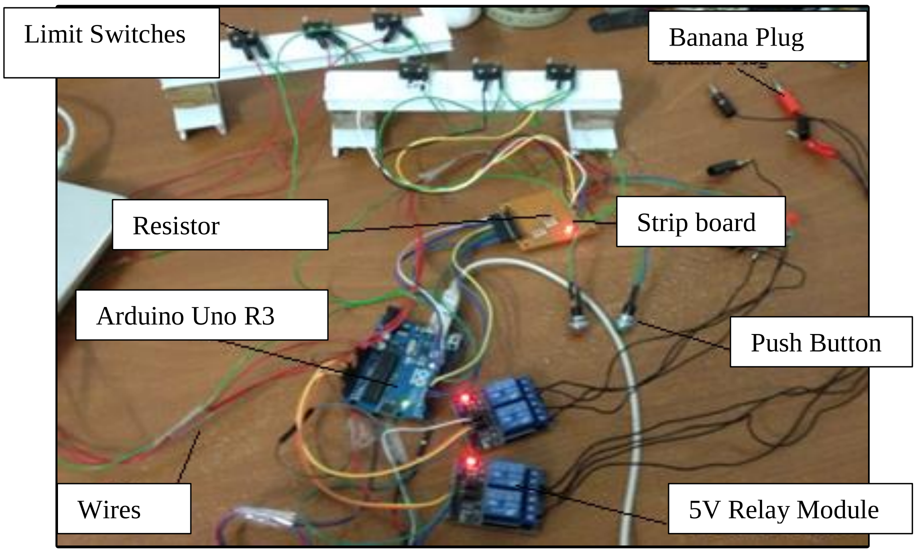


Figure 3.17: Actual electrical circuit design with the used of limit switches

Another electrical circuit design using flexibility sensor. Flex sensor act as input to control the motion of extend and retract of double acting cylinder. The red light on the 5V relay indicates that the relay was triggered and the red led indicate that there was circuit flow on the strip board as shown in Figure 3.17 of the actual electrical circuit design. Figure 3.18 shows the actual electrical circuit design with the flexibility sensor which used as an input to trigger the 5V relay module. Figure 3.19 shows the schematic diagram of flexibility sensor used with 4 relays.

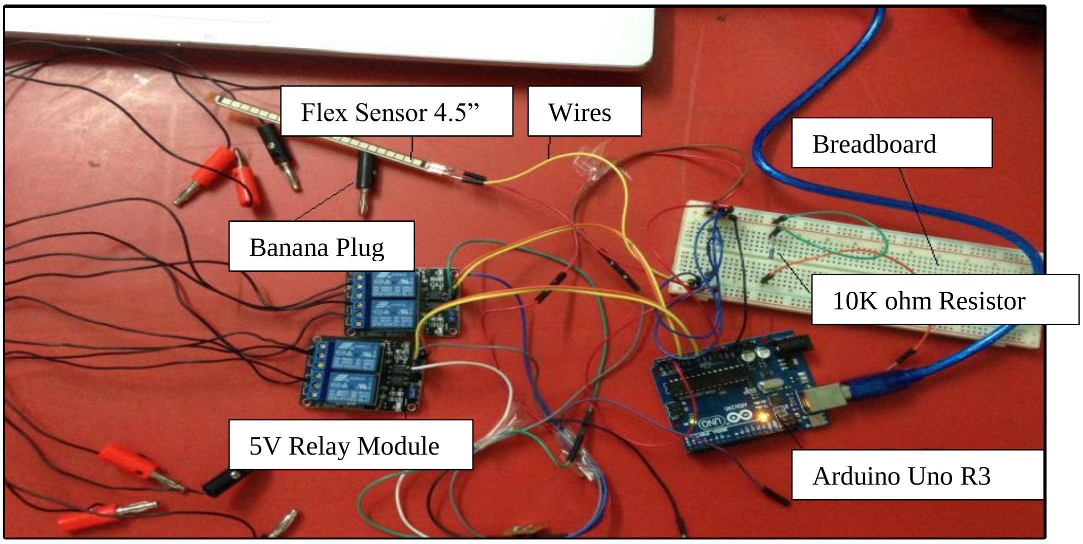
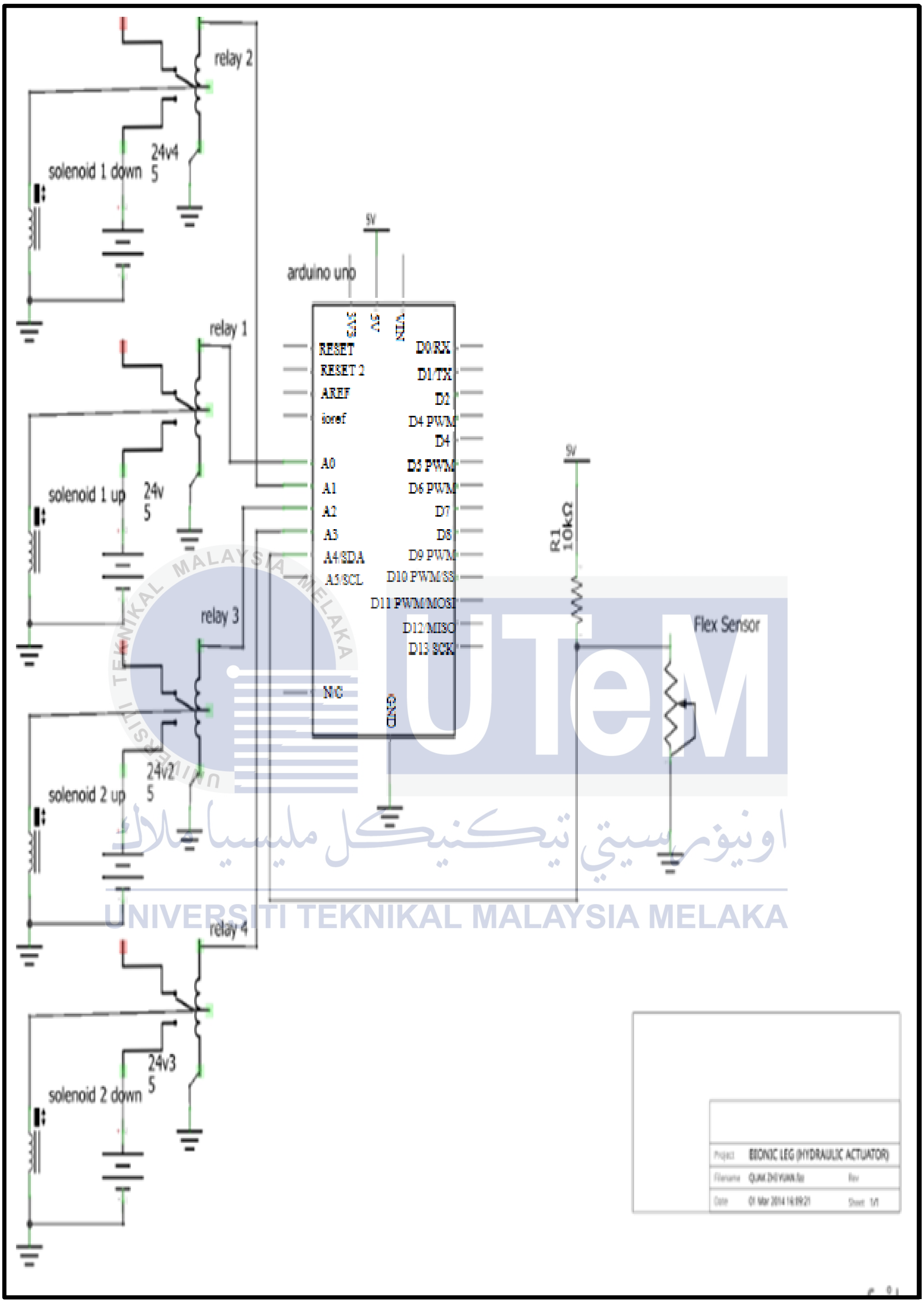


Figure 3.18: Actual electrical circuit design with the flexibility sensor



. Figure 3.19: Schematic diagram of flexibility sensor used with 4 relays

3.5.5 Arduino Coding Uno R3 design

There are two push buttons to be used with green and red buttons. Green push button indicates the extension of hydraulic cylinder and red push button indicates the retraction of hydraulic cylinder. Few pin selected as shown in Figure 3.20 and each pin selection as input and output had shown in Figure 3.21.

```
// Pin definitions
#define led      13
#define swDwn    2
#define swUp     3
#define swLim1   5
#define swLim2   6
#define swLim3   7
#define solUp    A0
#define solDwn   A1
#define solUp1   A2
#define solDwn1  A3
```

Figure 3.20: Pin definitions

```
Serial.begin(9600);          //
pinMode(led, OUTPUT);
pinMode(solUp, OUTPUT);
pinMode(solDwn, OUTPUT);
pinMode(solUp1, OUTPUT);
pinMode(solDwn1, OUTPUT);
pinMode(swDwn, INPUT);
pinMode(swUp, INPUT);
pinMode(swLim1, INPUT);
pinMode(swLim2, INPUT);
pinMode(swLim3, INPUT);


digitalWrite(led, LOW);    // I
digitalWrite(solUp, HIGH);
digitalWrite(solDwn, HIGH);
digitalWrite(solUp1, HIGH);
digitalWrite(solDwn1, HIGH);
```

Figure3.21: Pin selections for input and output

In the coding, case loop was used to command the double acting cylinder to extend to the desired position with the limit switch. Initially, all limit switches were in normally open state whereas the 5V Relay Module was in normally open state before being triggered. Limit switch will send the signal once the double acting cylinder contact with the limit switch. Then, the double acting cylinder will stop and wait for the next command. Green push button was pressed again to let the double acting cylinder to extend and contact with the third limit switch and then stop again. For the cylinder to retract, red button was pushed and the double acting cylinder will retract until the 3rd limit switch was not contact with the cylinder. Then, the red push button is pressed again until 2nd limit switch is not contact with cylinder. Lastly, the cylinder will return to its initial position. Similarly, these coding was applied on the hardware of one bionic leg. Two cylinders will move at the same time with the contact of limit switches. Serial monitor was used to indicate which push button was pressed and what the position of double acting cylinder is. Figure 3.22 shows the coding for the serial monitor and the upstate mean the motion of double acting cylinder in extend or retract motion. Upstate value -1 means no direction was selected and it means the double acting is stopped. Upstate value 1 mean in extend motion and upstate value 0 mean retract motion. Full coding of 3 limit switches and 6 limit switches used shown in Appendix B and Appendix C. Another coding was designed with six limit switches to control two double acting cylinders' motion whereby the first double acting cylinder will extend first and contact with limits switches accordingly until the another double acting cylinder fully extend and the six limit switches were normally closed. The full coding of this design was shown in Appendix D.


```
upState = -1;
Serial.println("Position: ");
Serial.println(limVal);
break;
```

Figure 3.22: Coding for the serial monitor

Figure 3.23 shows the example of serial monitor with the position of 0, 1, and 2 which indicate the position selected for the double acting cylinder to extend. Position 0 mean the first limit switch being contact with double acting cylinder whereas position 1 mean the 2nd limit switch being contact and lastly position 2 mean the 3rd limit switch being contact. Similarly Figure 3.24 shows the serial monitor of double acting cylinder retracts with position of 3, 2, and 1.

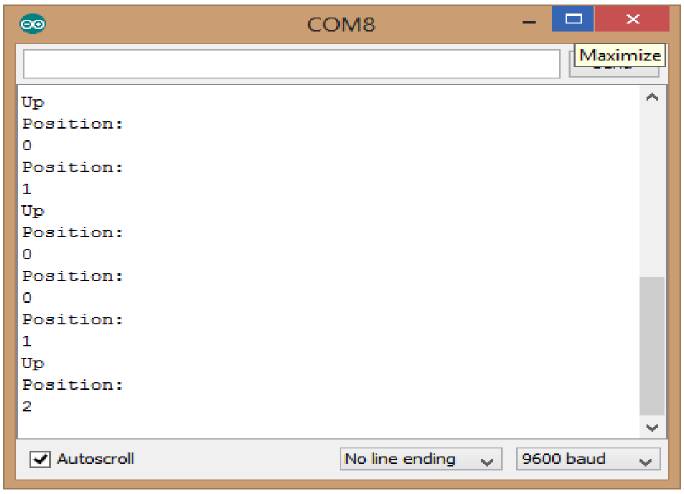


Figure 3.23 Serial monitor with the different position show hydraulic cylinder extend

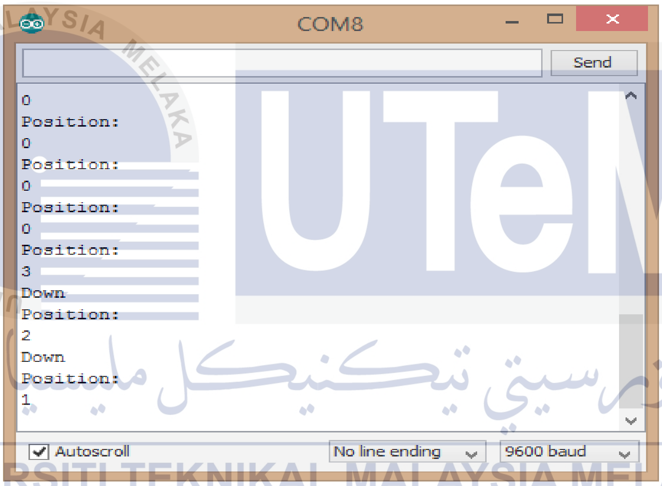


Figure 3.24: Serial monitor with the different position show hydraulic cylinder retract

For the Arduino coding used with flexibility sensor, there are slightly different with the previous coding with limit switches used. The analogue pin of A4 was selected as input pin for the flexibility sensor. Every flex sensor had their own value of initial resistance. The flexibility sensor used here was the flex sensor 4.5”. It was longer compared the flex sensor 2.2”. Flex sensor was used as voltage divider whereby the circuit itself must consist of one resistor 10K ohm. Initially, to test and get known the flex sensor value of unbent and bent through coding as shown in Figure 3.25.

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

void loop()
{
  int sensor, degrees;

  sensor = analogRead(4);
  degrees = map(sensor, 895 , 970, 0, 90);
  Serial.print("analog input: ");
  Serial.print(sensor,DEC);
  Serial.print("   degrees: ");
  Serial.println(degrees,DEC);
  delay(100);
}
```

Figure 3.25: Coding to test flex sensor values for unbent and bent

From the Figure 3.25, noticed that map() function was used here whereby it means that the number is re-maps from one range to another that is value of “from low” will map on “to low” whereas value of “from high” to “to high”. The flex sensor value get from the serial monitor was in bytes. Thus in order to get to know how much voltage supply to the Arduino, the flex sensor value need to divide by 1023 bytes and then multiply with 5V in order to get the voltage. Figure 3.26 shows the flex sensor 4.5” unbent value whereas Figure 3.27 shows the bent value of flex sensor. Full coding with flex sensor for one cylinder and two double acting cylinders were shown in Appendix E and Appendix F.

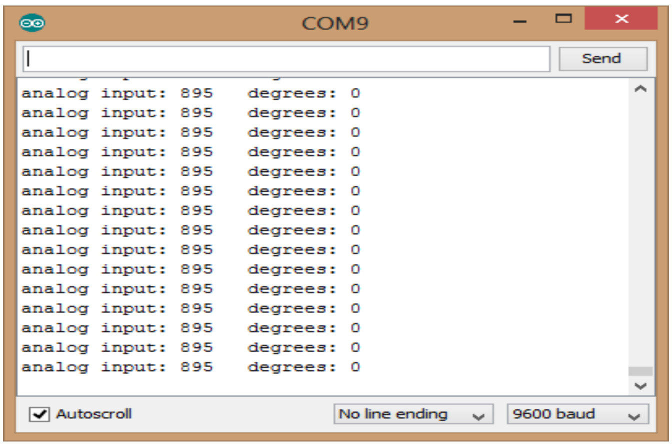


Figure 3.26: Flex sensor 4.5” unbent value

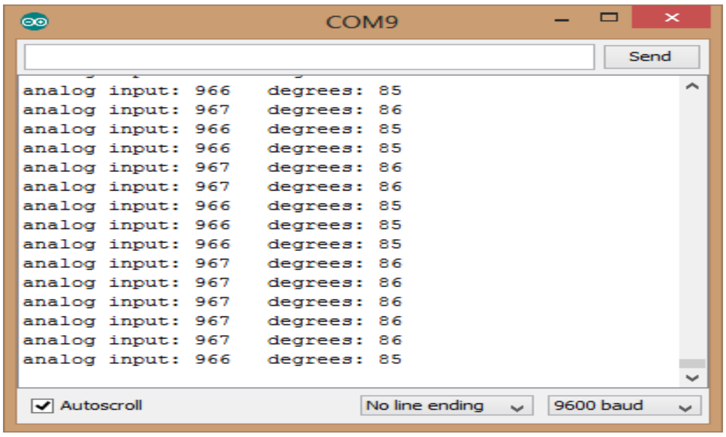


Figure 3.27: Bent value of flex sensor

3.6 Analyze the overall performance in term of accuracy and reliability on the bionic leg using hydraulic actuator for rehabilitation application

There are few tests being done to analyse the performance of the bionic leg. Experimental test in laboratory and implementation of the motion design on hardware had being done. Fluidsim simulation test was done too.

3.6.1 Fluidsim simulation test

Fluidsim is software that was used for simulation and creates a new design for the electro pneumatic as well as the electrohydraulic. The objective of this experimental test is to analyse the different forces applied on hydraulic cylinder whereby maximum force of the hydraulic cylinder able to withstand. Within the fluidsim, several components were needed as shown below:

1. Double acting cylinder
2. 4/3 Directional control valve
3. One way flow control valve
4. Quick exhaust valve

5. Distance rule
6. Air service

With all the components selected, a schematic diagram of hydraulic circuit can be drawn and analysis can be done. Few steps need to be followed as shown below. Firstly, the connection of all components must be correctly link to each others. Selection of pressure on the air service at 20 bar is chosen. The one way flow control valve was selected with the opening level of 33%. The force apply is 0 N initially and was repeated with 20N, 40N, 60N, 80N, 100N, 120N, 140N, 160N, 180N and 200N. The electrical power supply was switched on to activate it. The 4/3 DCV is activated to let the double acting cylinder extend with maximum stroke of 10cm Double acting cylinder passed through limit switch K1, K2 and K3. The state diagram was listed down and analyse the graph with respect to the applied force. The reading of each force was taken 3 times with average and standard deviation. As shown Figure 3.28, the initial parameter of a double acting cylinder was selected with different forces.

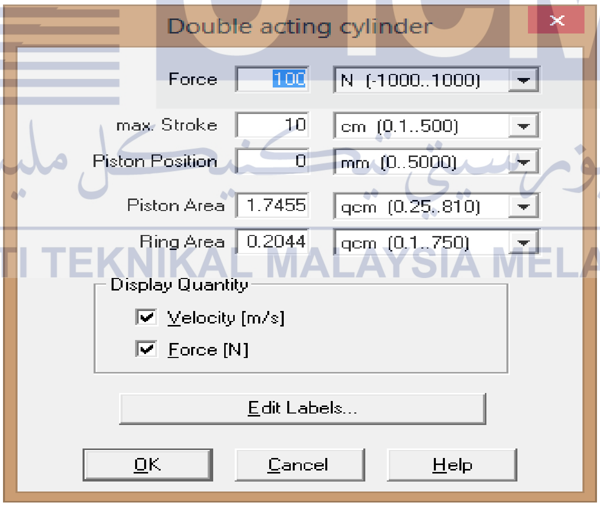


Figure 3.28: Initial parameter of double acting cylinder

Figure 3.29 shows the example of double acting cylinder extend at a distance of 5 cm with 20N force applied with its state diagram

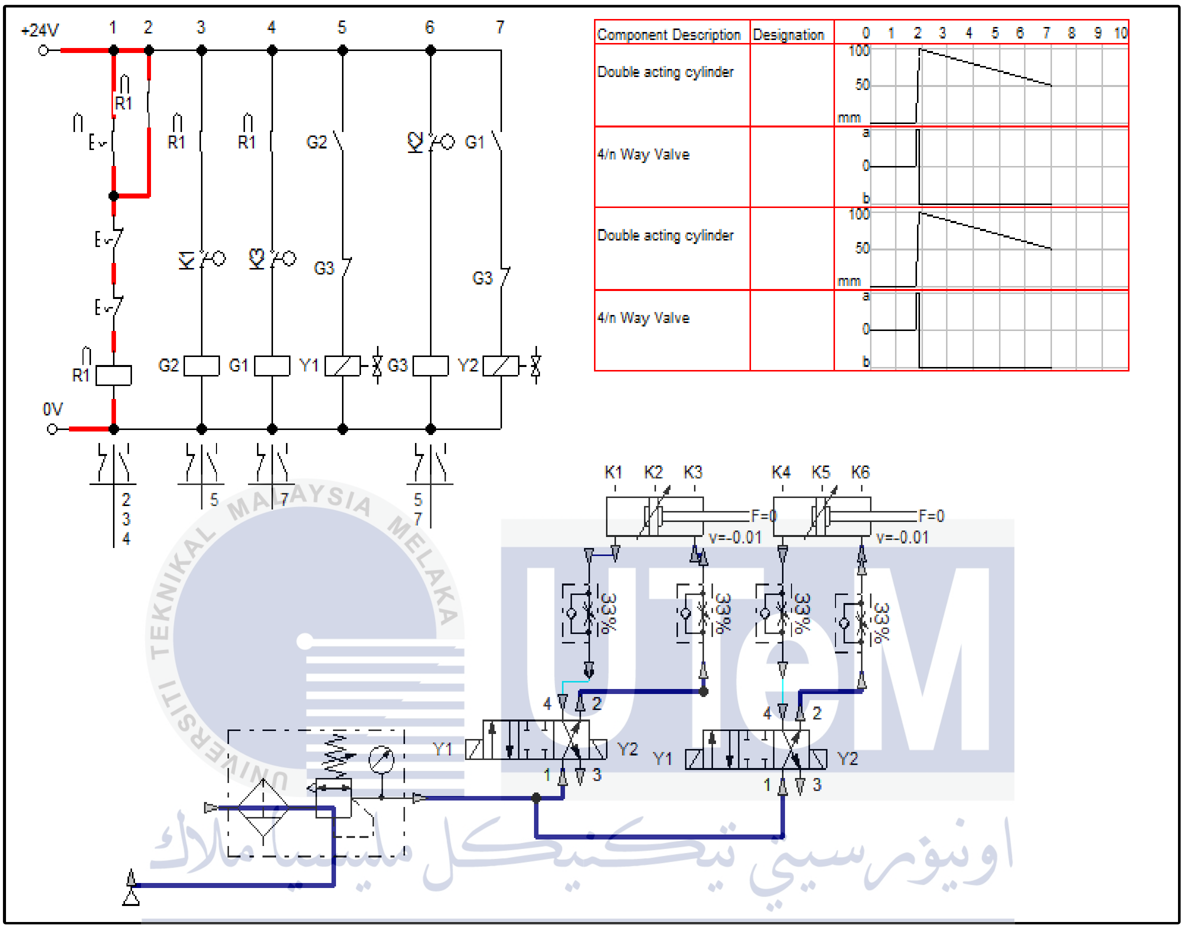


Figure 3.29: Double acting cylinder extend at a distance of 5 cm with 20N force applied with its state diagram

3.6.2 Experimental design

For experimental test, one double acting cylinder with 3 limit switches used to analyse the time taken for the hydraulic actuator to extend or retract with different pressures selected. Accuracy test on the one double acting cylinder to reach the desired position had being done too with the used of limit switches and flex sensor. Next, test on two hydraulic cylinder used with 3 limit switches had being done too with the FCV to synchronize the motion of two double acting cylinder on its position. Another test was done with the used of 6 limit switches on two double acting cylinder to analyse the time for the hydraulic cylinder to reach the desired position.

3.6.2.1 Experimental test 1

One hydraulic cylinder is used with 3 limit switches used to analyse the time taken for the hydraulic actuator to extend or retract with different pressures selected. The objective of this test is to analyse suitable pressure needed for the hydraulic cylinder which is able to implement on the hardware of bionic leg. Accuracy test had done to analyse the accuracy of double acting cylinder to extend and retract accurately. Several components needed to be used as shown below:

1. One double acting cylinder
2. Pressure Gauge
3. 3 limit switches
4. Oil Tank
5. Arduino Uno R3
6. Woods
7. PVC
8. 4/3 way directional control valve
9. Two 5V relay modules
10. Two Push buttons
11. Digital watch
12. Cable Tie
13. Compressed Air Regulator

Figure 3.30 shows the experimental test 1 set up whereas Figure 3.31 shows the one double acting cylinder extend and retract.

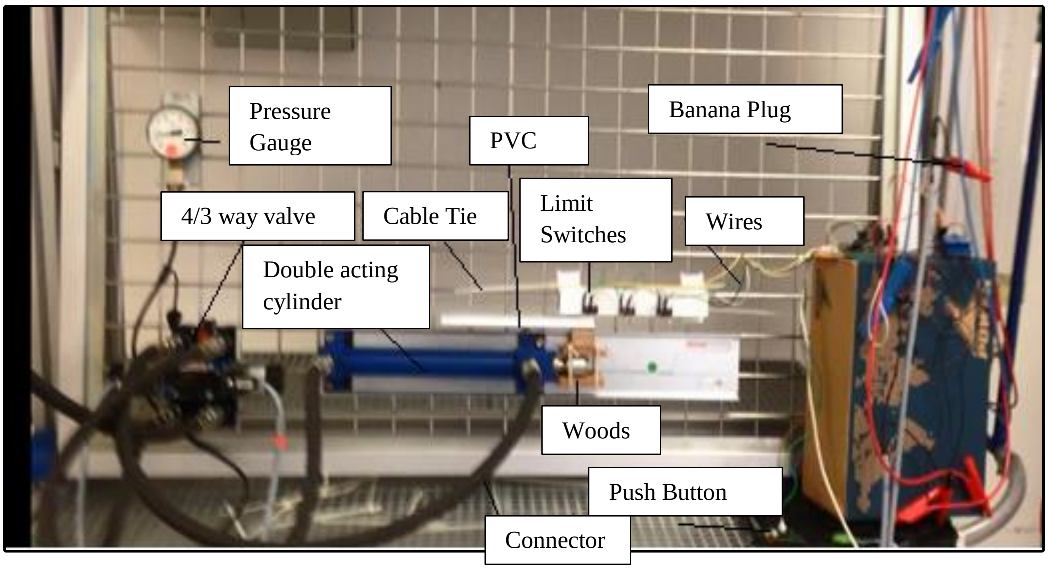


Figure 3.30: The experimental test 1 set up

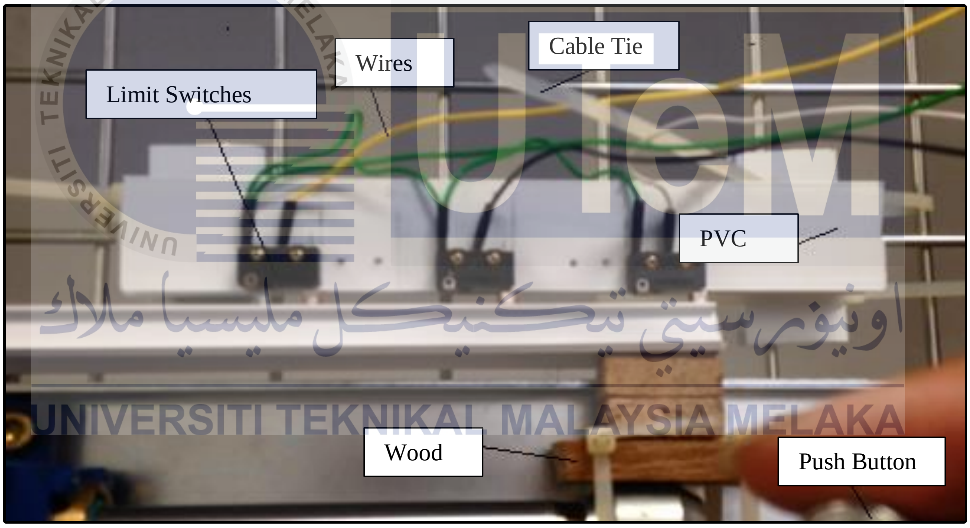


Figure 3.31: One double acting cylinder extend and retract

3.6.2.2 Experimental test 2

Two hydraulic cylinder used with 3 limit switches had being done with the flow control valve, FCV to synchronize the motion of two double acting cylinder on its position. This experimental test was used to implement on hardware as well. The objective of this experiment is to analyse the actual distance and the desired distance of the two double acting cylinder strokes. Initially test was done without FCV and another test was done to synchronize the two double acting cylinders to extend and retract. FCV can be 1 turn, 2 turn and 3 turn to control the flow of the fluids. Initially the pressure is set as 20 bar because below 20 bars, it is insufficient for the double acting cylinder to retract and extend. If too high pressure, it is not reliable for the implementation on bionic leg as high pressure will cause the double acting cylinder to extend and retract fast. Several components needed to be used as shown below:

1. Two double acting cylinder
2. Pressure Gauge
3. 3 limit switches
4. Oil Tank
5. Arduino Uno R3
6. Woods
7. PVC
8. Two 4/3 way directional control valve
9. Four 5v relay modules
10. Two Push buttons
11. Flow control valve, FCV
12. Digital Watch
13. Compressed Air Regulator
14. Cable Tie

Figure 3.32 shows the experimental test 2 set up of two double acting cylinders with 3 limit switches. Figure 3.33 shows the extent and retract of two double acting cylinders at the same time. Figure 3.34 shows the flow control valve used for one of the double acting cylinder.

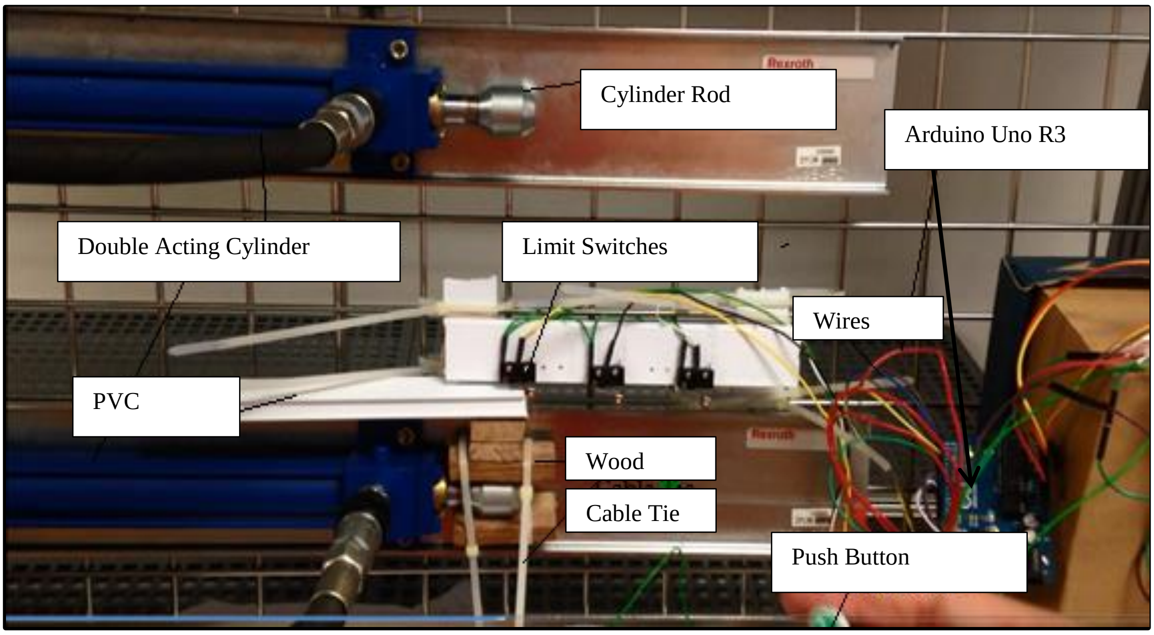


Figure 3.32: Experimental test 2 set up of two double acting cylinders with 3 limit switches

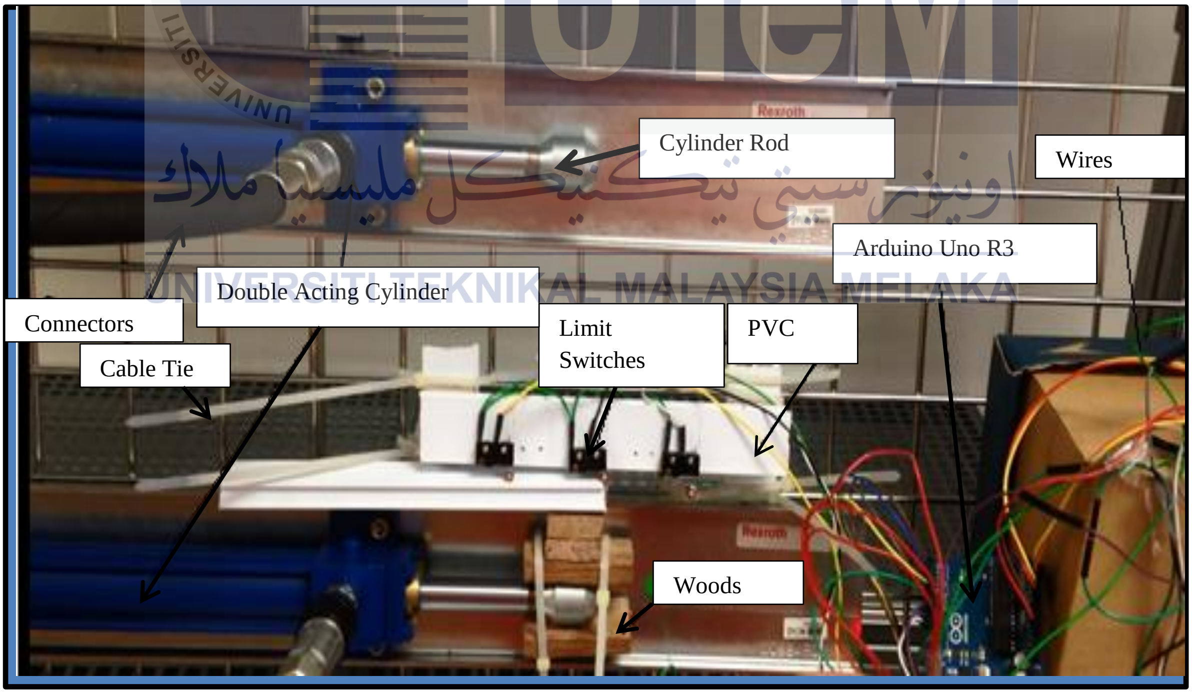


Figure 3.33: Extend and retract of two double acting cylinders at the same time

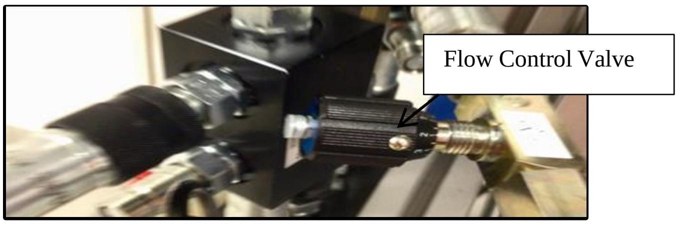


Figure 3.34: Flow control valve

3.6.2.3 Experimental test 3

Another test used 6 limit switches on two double acting cylinders to analyse the time for the hydraulic cylinder to reach the desired position. Analysis on the time taken for double acting cylinder to extend and retract with contact of 6 limit switch consequence with different pressures. The objective of this experimental test is to obtain the best pressure that is suitable for the implementation on bionic leg. However, this test may not implement on the hardware and it is just used to define the suitable pressure needed for the double acting cylinder to extend and retract. Several components needed to be used as shown below:

1. Two double acting cylinder
2. Pressure Gauge
3. 6 limit switches
4. Oil Tank
5. Arduino Uno R3
6. Woods
7. PVC
8. Two 4/3 way directional control valve
9. Four 5v relay modules
10. Two Push buttons
11. Digital Watch
12. Compressed Air Regulator
13. Cable Tie

Figure 3.35 shows the experimental test 2 set up of two double acting cylinders with 6limit switches. Figure 3.36 shows the extend and retract of double acting cylinder with sequences.

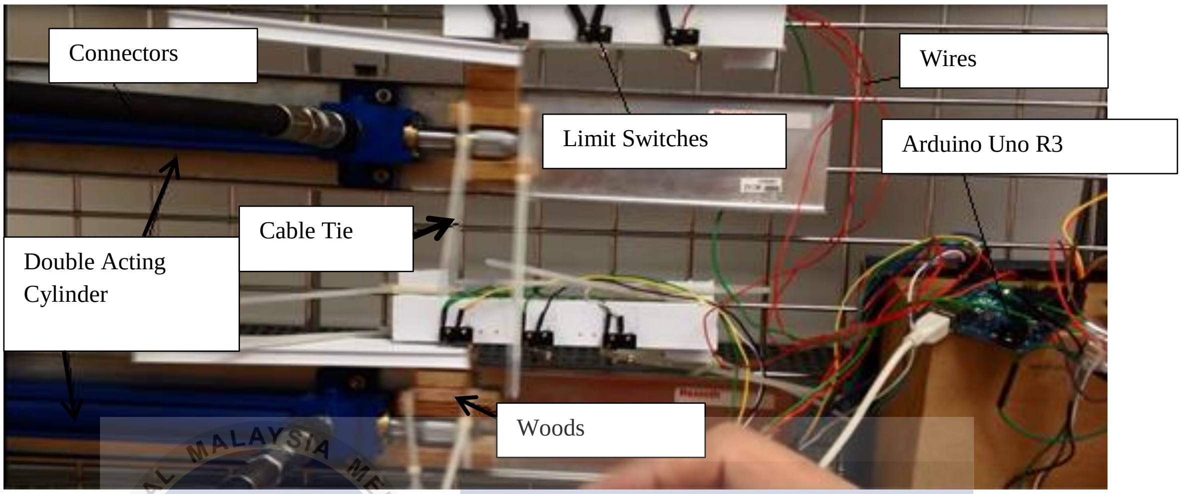


Figure 3.35: Experimental test 2 set up of two double acting cylinders with 6 limit switches

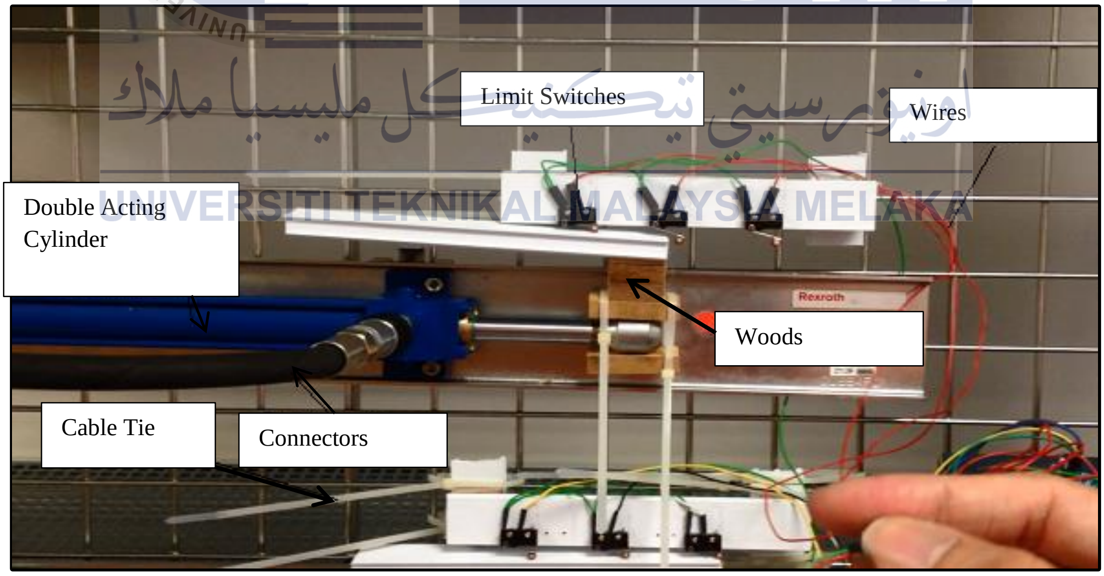


Figure 3.36: Extend and retract of double acting cylinder with sequences

3.6.2.4 Experimental Test 4

The extend and retract of hydraulic cylinder was controlled by flex sensor 4.5”. This experiment did not use limit switches for the position control. However, the bent of flex sensor itself was used to control the position of double acting cylinder to extend and retract. The main objective of this experimental test is to analyse the performance of flex sensor in term of its position control. One double acting cylinder was used for the accuracy test of the double acting cylinder. Moreover, two double acting cylinder was tested for the extend and retract using flex sensor. Several components needed to be used as shown below:

1. Two double acting cylinder
2. Pressure Gauge
3. Flexibility Sensor 4.5”
4. Oil Tank
5. Arduino Uno R3
6. Two 4/3 way directional control valve
7. Four 5v relay modules
8. Compressed Air Regulator
9. Measuring Tape

Figure 3.37 shows the overall set up of experimental test 4 of two double acting cylinders whereas Figure 3.38 shows the one double acting cylinder extend while flex sensor 4.5” was bent. Figure 3.39 shows the two double acting cylinders extend while flex sensor 4.5” was bent.

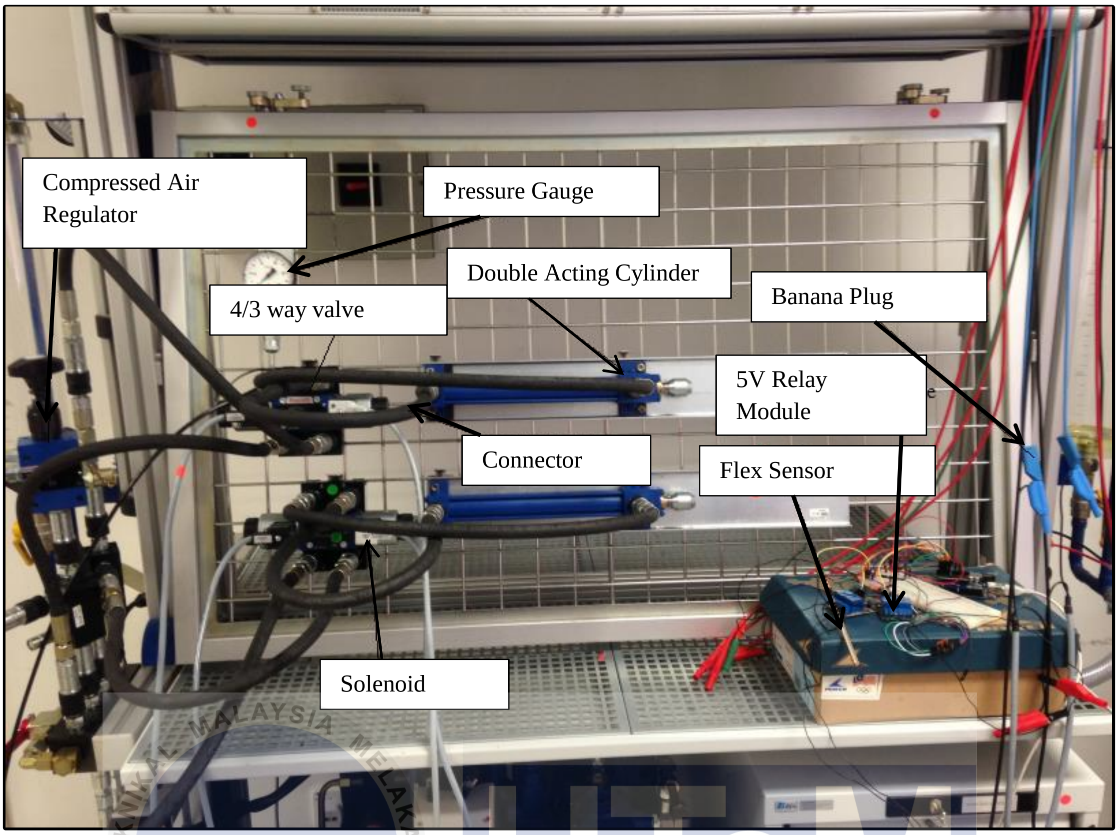


Figure 3.37: Overall set up of experimental test 4 of two double acting cylinders

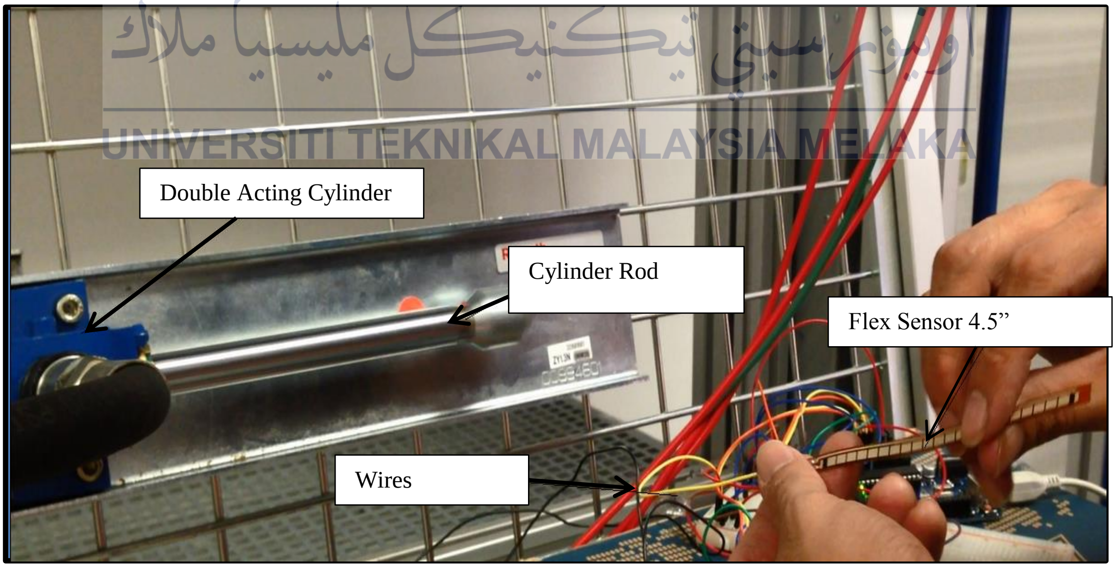


Figure 3.38: One double acting cylinder extend while flex sensor 4.5” was bent

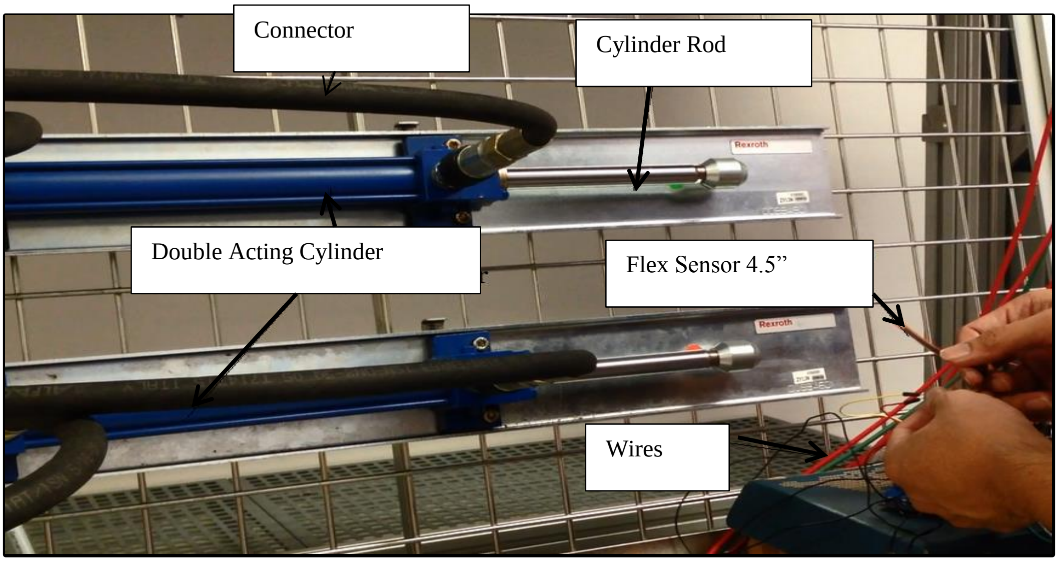


Figure 3.39: Two double acting cylinders extend while flex sensor 4.5" was bent

3.6.3 Implementation on hardware

Three limit switches is used for the implementation on hardware of one bionic leg. Rotation angle on hip and knee were found through the test on hardware and the actuator length L1, L2 and base frame of X_{BF} and Y_{BF} were found too to prove the mathematical modelling of hydraulic actuator for bionic leg in term of kinematic analysis for the rotation angle is approximately similar from the actual rotation angle on bionic leg of hip and knee. The objective is to validate the mathematical modelling for the rotation angle found on theory and hardware of the bionic leg through kinematic analysis is proximately similar. Inverse kinematic is used and the calculation was shown. Accuracy test with repeated number of times were done to analyse the rotation angle of hip and knee at sit and stand position. Figure 3.40 shows the bionic leg in standing position for hip and knee part. The double acting cylinder is fully retracted at this initial state. Figure 3.41 shows the bionic leg in sit position whereby the double acting cylinder is fully extend whereas Figure 3.42 shows the bionic leg in partial stand position. Note that θ_1 was measured from initial x-axis, X_0 whereas θ_2 was measured from x-axis, X_1.

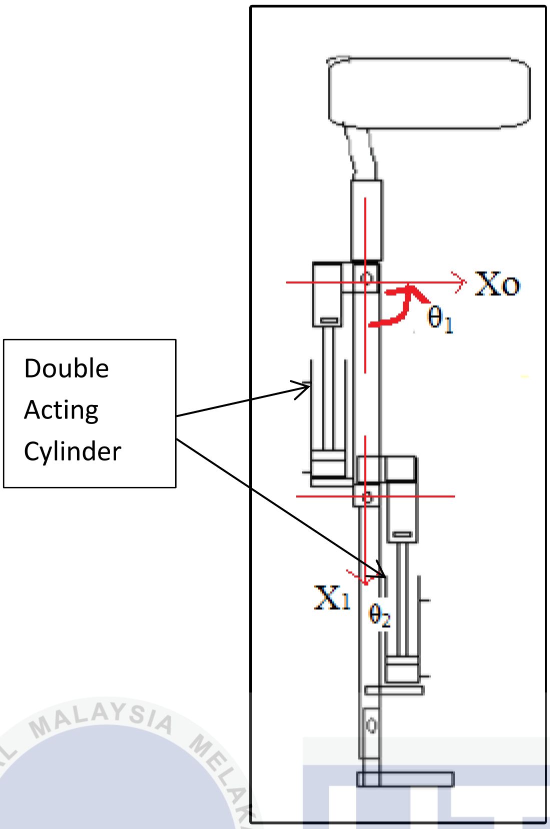


Figure 3.40: Bionic leg in standing position

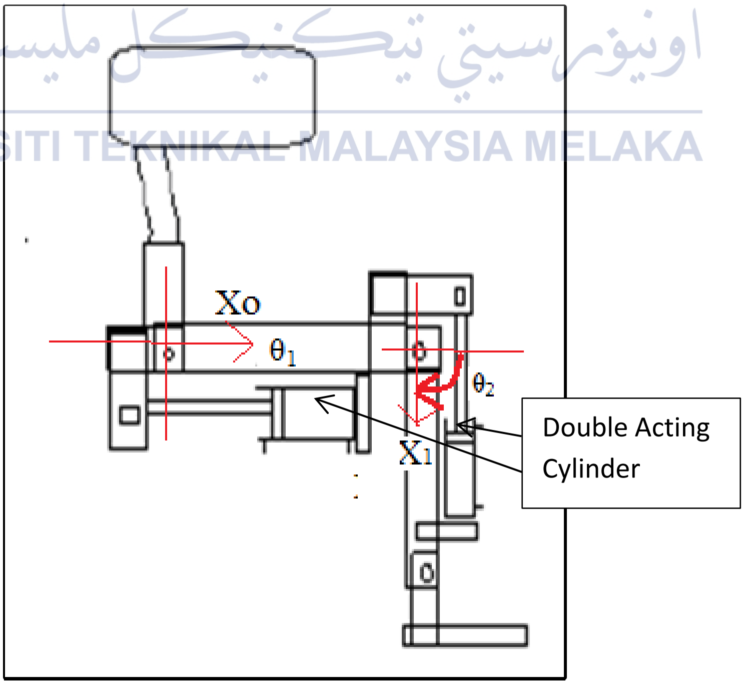


Figure 3.41: Bionic leg in sit position

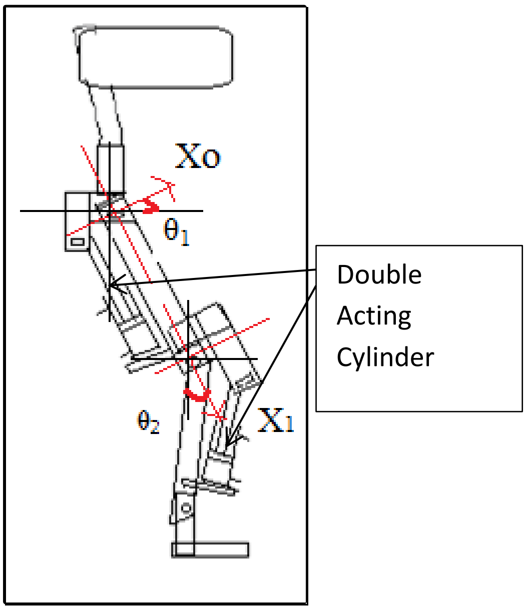


Figure 3.42: Bionic leg in partial stand position

The rotation angle of hip and knee can be obtained using protractor or accelerometer. This accelerometer is named as triple axis accelerometer whereby x-axis, y-axis and z-axis can be obtained. Only x-axis is used in here to obtain the rotation angle of the hip and knee. The accelerometer used must be ensure placed in right location in x-axis to get accurate result of rotation angle of hip and knee. The Arduino coding of accelerometer can referred to Appendix G. The main equipment used as shown below:

1. Two double acting cylinder
2. Pressure Gauge
3. 3 limit switches
4. Oil Tank
5. Arduino Uno R3
6. Two 4/3 way directional control valve
7. Four 5v relay modules
8. Two Push buttons
9. Flow control valve, FCV
10. Digital Watch
11. Compressed Air Regulator
12. Accelerometer / protractor
13. Cable Tie

Figure 3.43 shows the actual bionic leg in sit position whereas Figure 3.44 shows the actual bionic leg in stand position and Figure 3.45 shows the actual bionic leg in partial stand position. Figure 3.46 shows the accelerometer used on the bionic leg.

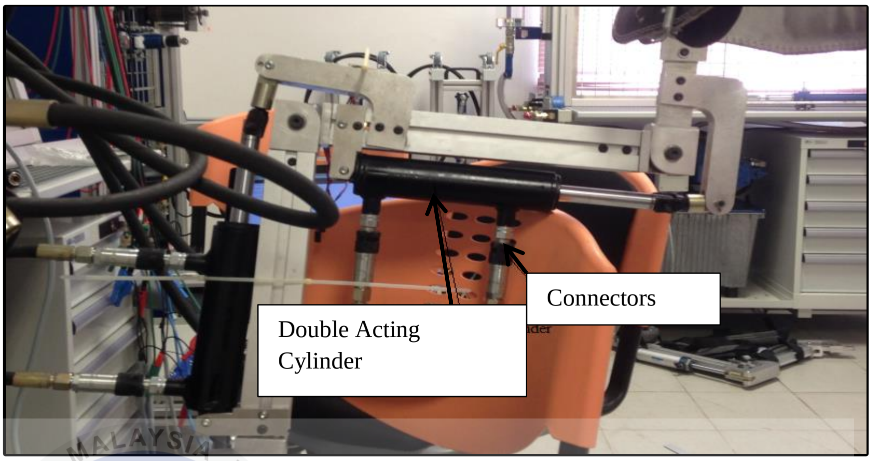


Figure 3.43: Actual bionic leg in sit position

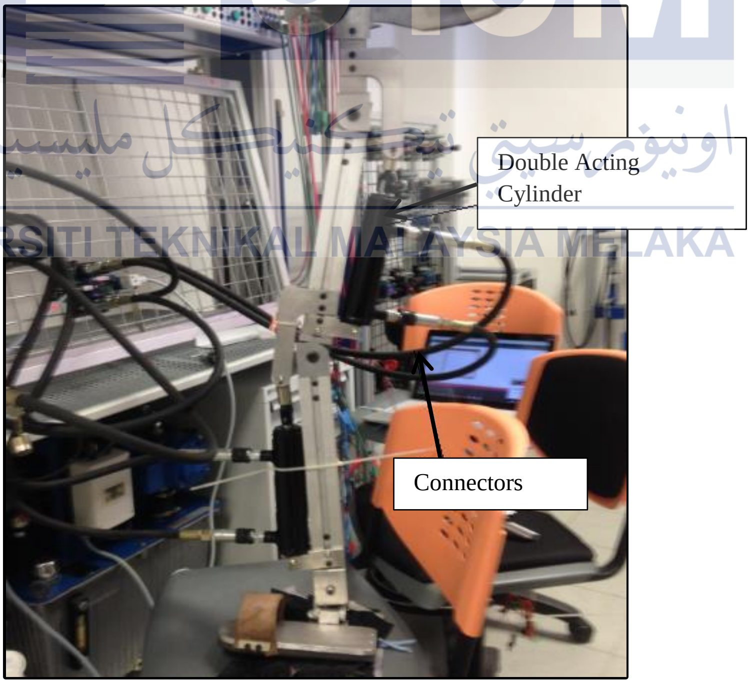


Figure 3.44: Actual bionic leg in stand position

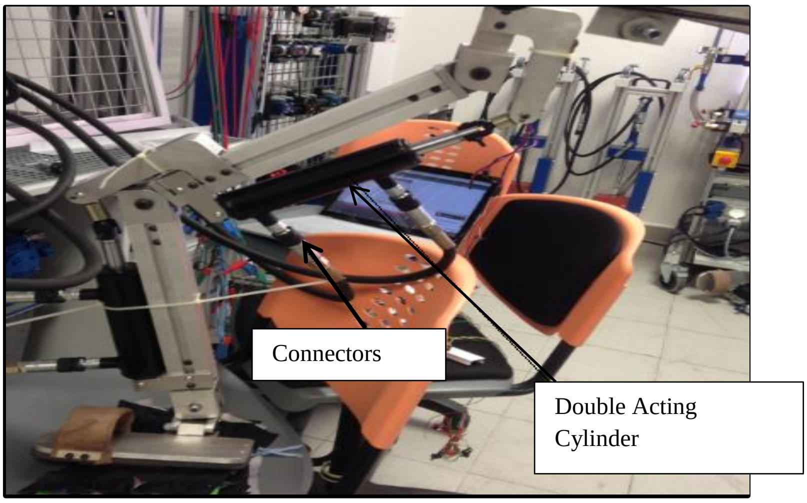


Figure 3.45: Actual bionic leg in partial stand position

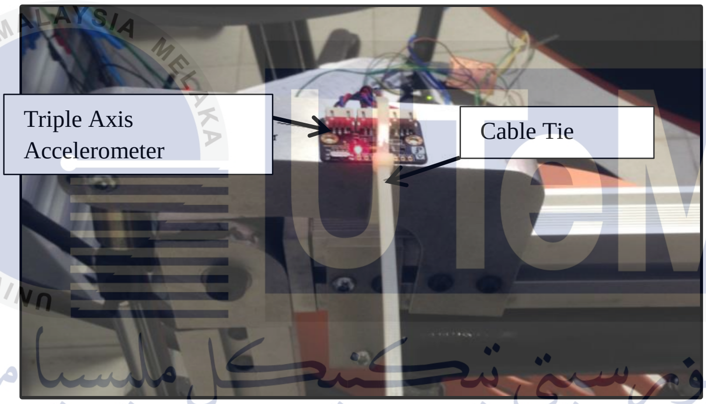


Figure 3.46: Accelerometer used on the bionic leg

3.7 Safety Precaution

Firstly, the experimental test must be done in careful way. The pressure supply by oil tank was high and ensured the connectors were successfully lock before turned on the flow from tank. Besides, the 24 V voltage supplied was high and danger. Thus ensure the wires connected to 5V relay module was safety and ensure no short circuit in the strip board. Moreover, troubleshoot the circuit design and ensure the flow of voltage from 5V relay module to solenoid. Whenever want to turn off the switched, ensure that the red long stick opening flow being pull up as shown in Figure 3.47. This is to ensure that the pump will not continue to supply fluid to the double acting cylinder. The red button was the emergency push button to turn on or off the flow from pump to 4/3 way valve. The black colour button was the push button to turn on the power supply to pump from oil tank to valve.

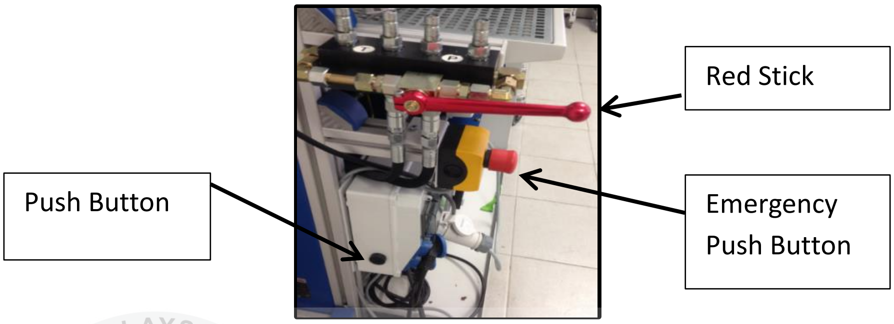


Figure 3.47: Push Button, emergency push button and the red stick

For the implement on bionic leg, oil seal was needed to prevent leakage occur between the connectors and hydraulic coupling. The design of coupling on bionic leg was slightly short for the thread. Thus, oil seal is used to avoid the leakage whenever fluid flow through the connectors. Figure 3.48 shows the oil seal used for the hydraulic coupling to attach to double acting cylinder.

Figure 3.48: Oil seal used for hydraulic coupling

CHAPTER 4

RESULT & DISCUSSION

4.1 Introduction

This chapter shows the fluidsim simulation, experimental test 1, 2, 3 and 4 as well as implementation on hardware. Comparison of limit switches and flex sensor 4.5" for the position control. The derivation on mathematical modelling on rotation angle of hip and knee at stand, sit and partial stand was compared with the actual value of rotation angle of hip and knee at stand, sit and partial stand.

4.2 Fluidsim simulation test

Table 4.1 shows the different forces acting on double acting cylinder with the different position of limit switches. Average time and average velocity were found as well as the standard deviation.

Table 4.1: Time taken for extend and retract of different forces acting on double acting cylinder

Forces, N	Position of limit switch, cm		Time taken, s			Average Time, s	Average Velocity, m/s	Standard Deviation
			R1	R2	R3			
0	Extend	0-5	0.6	0.6	0.6	0.6	0.0833	0
		5-10	0.6	0.6	0.6	0.6	0.0833	0
	Retract	10-5	5.1	5.1	5.1	5.1	0.0098	0
		5-0	5.1	5.1	5.1	5.1	0.0098	0
20	Extend	0-5	0.7	0.7	0.7	0.7	0.0714	0
		5-10	0.7	0.7	0.7	0.7	0.0714	0
	Retract	10-5	3.5	3.5	3.5	3.5	0.0143	0
		5-0	3.5	3.5	3.5	3.5	0.0143	0
40	Extend	0-5	0.7	0.7	0.7	0.7	0.0714	0
		5-10	0.7	0.7	0.7	0.7	0.0714	0
	Retract	10-5	2.6	2.6	2.6	2.6	0.0192	0
		5-0	2.6	2.6	2.6	2.6	0.0192	0
60	Extend	0-5	0.8	0.8	0.8	0.8	0.0625	0
		5-10	0.8	0.8	0.8	0.8	0.0625	0
	Retract	10-5	2.1	2.1	2.1	2.1	0.0238	0
		5-0	2.1	2.1	2.1	2.1	0.0238	0
80	Extend	0-5	0.8	0.8	0.8	0.8	0.0625	0
		5-10	0.8	0.8	0.8	0.8	0.0625	0
	Retract	10-5	1.8	1.8	1.8	1.8	0.0278	0
		5-0	1.8	1.8	1.8	1.8	0.0278	0
100	Extend	0-5	0.8	0.8	0.8	0.8	0.0625	0
		5-10	0.8	0.8	0.8	0.8	0.0625	0
	Retract	10-5	1.5	1.5	1.5	1.5	0.0333	0
		5-0	1.5	1.5	1.5	1.5	0.0333	0
120	Extend	0-5	1.0	1.0	1.0	1.0	0.0500	0
		5-10	1.0	1.0	1.0	1.0	0.0500	0

	Retract	10-5	1.3	1.3	1.3	1.3	0.0385	0
		5-0	1.3	1.3	1.3	1.3	0.0385	0
140	Extend	0-5	1.0	1.0	1.0	1.0	0.0500	0
		5-10	1.0	1.0	1.0	1.0	0.0500	0
	Retract	10-5	1.2	1.2	1.2	1.2	0.0417	0
		5-0	1.2	1.2	1.2	1.2	0.0417	0
160	Extend	0-5	1.2	1.2	1.2	1.2	0.0417	0
		5-10	1.2	1.2	1.2	1.2	0.0417	0
	Retract	10-5	1.1	1.1	1.1	1.1	0.0455	0
		5-0	1.1	1.1	1.1	1.1	0.0455	0
180	Extend	0-5	1.3	1.3	1.3	1.3	0.0385	0
		5-10	1.3	1.3	1.3	1.3	0.0385	0
	Retract	10-5	1.0	1.0	1.0	1.0	0.0500	0
		5-0	1.0	1.0	1.0	1.0	0.0500	0
200	Extend	0-5	1.4	1.4	1.4	1.4	0.0357	0
		5-10	1.4	1.4	1.4	1.4	0.0357	0
	Retract	10-5	0.9	0.9	0.9	0.9	0.0556	0
		5-0	0.9	0.9	0.9	0.9	0.0556	0

The design of hydraulic circuit in fluidsim was done as shown above of the result. For the initial pressure, it is set as 20 bars for every forces applied on the double acting cylinder. The one way flow control valve is set as opening level of 33% so that the double acting cylinder do not extend and retract in fast motion. The extension and retraction of double acting cylinder must move in slow movement as it is applied to the bionic leg which is mainly for rehabilitation purpose. As the forces increase, time taken for the double acting cylinder to fully extend will be longer. Besides that, the velocity of piston to extend and retract was different depending on forces acting on the double acting cylinder. The larger the forces acting on the double acting cylinder, the slower the velocity for piston to extend. However, form the Table 4.1 shown, the time taken for the cylinder to retract getting faster as the forces increase. The velocity for the cylinder to extend getting slower as the force increase but the velocity for the cylinder retract getting faster as the forces increased. This velocity for the cylinder retracts getting faster due to the force acting opposed to the direction of cylinder extend. Standard deviation here shown that there are no value or reading that is spread and deviate.

4.3 Experimental Test 1

Table 4.2 shows the different pressure and different position of limit switch for the double acting cylinder to extend and retract with different time taken.

Table 4.2: Time taken for double acting cylinder to extend and retract at different position and different pressure

Pressure (Bar)	**Position of limit switch (cm)**		**Time taken (s)**					**Average Time(s)**	**Average Velocity (m/s)**	**Standard Deviation**
			R1	**R2**	**R3**	**R4**	**R5**			
10	Extend	0-5	0.54	0.63	0.53	0.63	0.63	0.592	0.0845	0.046648
		5-10	0.58	0.58	0.58	0.58	0.58	0.580	0.0862	0
	Retract	10-5	NA	NA	NA	NA	NA	NA	NA	NA
		5-0	NA	NA	NA	NA	NA	NA	NA	NA
15	Extend	0-5	0.43	0.46	0.41	0.46	0.46	0.444	0.1126	0.020591
		5-10	0.48	0.41	0.46	0.43	0.43	0.442	0.1131	0.024819
	Retract	10-5	1.01	1.05	1.13	1.08	1.08	1.070	0.0467	0.039497
		5-0	1.03	1.08	1.11	1.00	1.03	1.050	0.0476	0.039497
20	Extend	0-5	0.41	0.40	0.40	0.41	0.40	0.404	0.1238	0.004899
		5-10	0.41	0.41	0.40	0.41	0.41	0.408	0.1225	0.004
	Retract	10-5	0.58	0.58	0.55	0.56	0.56	0.566	0.0883	0.012
		5-0	0.55	0.56	0.55	0.58	0.56	0.560	0.0893	0.010954

25	Extend	0-5	0.31	0.35	0.35	0.33	0.33	0.334	0.1497	0.014967
		5-10	0.31	0.36	0.31	0.30	0.36	0.328	0.1524	0.026382
	Retract	10-5	0.45	0.46	0.45	0.45	0.48	0.458	0.1092	0.011662
		5-0	0.43	0.41	0.46	0.42	0.45	0.434	0.1152	0.018547

Table 4.3 shows the accuracy test of double acting cylinder to extend and retract at pressure of 20 bars. The test was done for 20 times to analyse the accuracy of hydraulic cylinder to extend to desire position that had being set.

Table 4.3: Accuracy Test of double acting cylinder to extend and retract at pressure of 20 Bars using limit switches

Number of tests	**Extend**		**Retract**	
	Position:5cm	**Position:10cm**	**Position:5cm**	**Position:0 cm**
1	5cm	10cm	5cm	0cm
2	5cm	10cm	5cm	0cm
3	5cm	10cm	5cm	0cm
4	5cm	10cm	5cm	0cm
5	5cm	10cm	5cm	0cm
6	5cm	10cm	5cm	0cm
7	5cm	10cm	5cm	0cm
8	5cm	10cm	5cm	0cm
9	5cm	10cm	5cm	0cm
10	5cm	10cm	5cm	0cm
11	5cm	10cm	5cm	0cm
12	5cm	10cm	5cm	0cm
13	5cm	10cm	5cm	0cm
14	5cm	10cm	5cm	0cm
15	5cm	10cm	5cm	0cm
16	5cm	10cm	5cm	0cm
17	5cm	10cm	5cm	0cm
18	5cm	10cm	5cm	0cm

19	5cm	10cm	5cm	0cm
20	5cm	10cm	5cm	0cm

Figure 4.1 shows the timing diagram of the on double acting cylinder. Push Button, limit switches and cylinder are analysed on when they extend and retract with the time. T represents the time taken for the double acting cylinder extend and retract and the times can be 5T, 6T and onwards until the double acting cylinder fully retract.

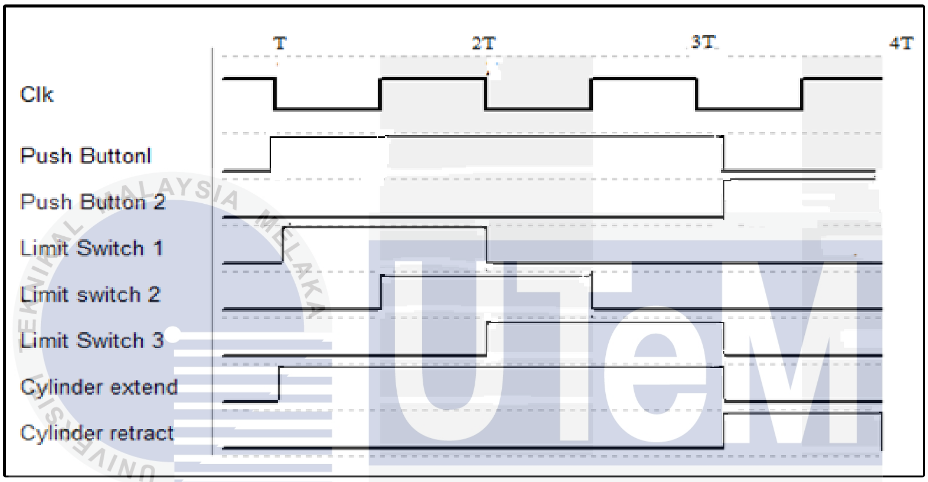


Figure 4.1: Timing diagram of hydraulic cylinder

Different pressures were done with the limit switches at different position. The NA mean non applicable for the percentage error. Notice that the pressure of 10 bar unable to let the cylinder to retract because the pressure is too small and insufficient to retract. The higher the pressures, the faster the double acting cylinder extend to desired position and this is similar too for the retract of double acting cylinder. Few times for the double acting cylinder to extend and retract were tested to get the average time. As pressure increase, the time for the cylinder to extend and retract becomes faster whereas it was slower for the double acting cylinder to retract compared the cylinder extend because of different fluid flow and friction within cylinder whereby the fluid was flow back to tank.

Accuracy test was done too and surprisingly the double acting cylinder able to reach the desired position for the entire 3 limit switches. During the experimental test, troubleshooting on the electrical circuit was important as the connection might be wrong and the relay used is 5v relay module. This is because arduino Uno R3 is 5v relay which used to activate the solenoid valve. The relay can be directly connected to the arduino uno R3. Pull up resistor in the electrical circuit design was used too. The standard deviation here was small and we can indicate that the data we get is mostly similar and very small. Graph 4.2 shows the pressure against velocity that obtained from the results.

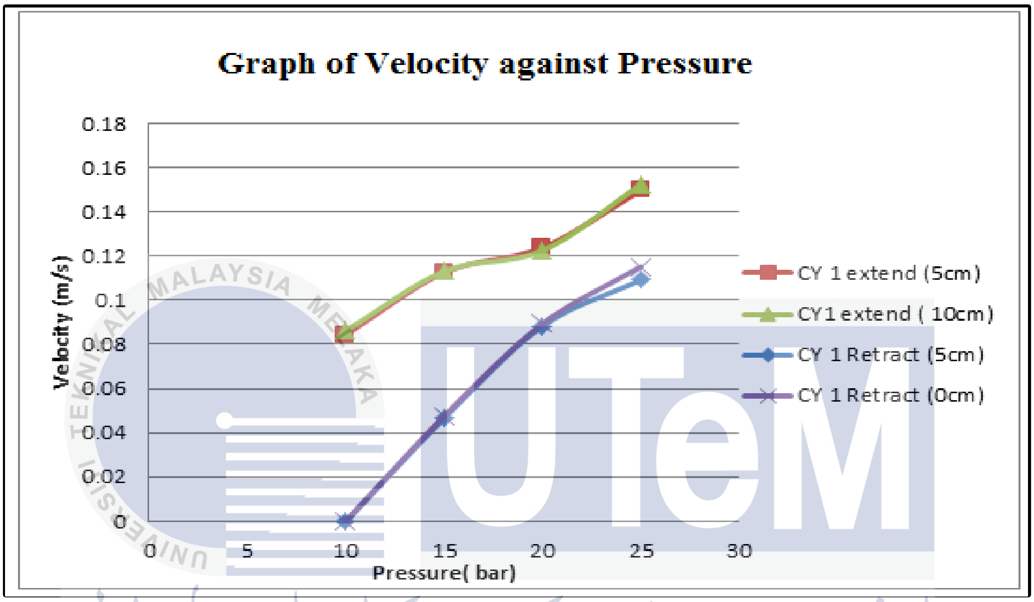


Figure 4.2: Graph of Velocity against Pressure

From the graph shown in Figure 4.2, as pressure increase the velocity for the double acting cylinder increase slightly. For instance, at pressure of 10 bars the velocity for the cylinder extend is 0.0845 m/s whereas for pressure of 15 bars the velocity is 0.1126 m/s with an increment of 0.0281 m/s. For the retraction, as the pressure increase the velocities also increase slightly. The velocity of cylinder retract is slower than the velocity of cylinder extend. This case occur although the pressure for each extend and retract is same due the fluid flow in the cylinder and this two cylinder can be connected in series with only one 4/3 way valve used. However, the method used here is two 4/3 way valve for two cylinder because it is easier to design the coding for the varies type of motion for bionic as shown in experimental test 3. If use the cylinder connection in series, both cylinder can move at the same time but there are limitation to design the motion of bionic leg. Thus, flow control valve is used as shown in experimental 2 to synchronize the both hydraulic cylinder.

4.4 Experimental Test 2

Table 4.4 shows the actual distance and desire distance of two double acting cylinders to extend and retract with the use of flow control valve. All the tests is at pressure of 20 Bar. Cylinder 1 is the one with limit switch whereas cylinder 2 is without limit switch and used with FCV.

Table 4.4: Actual distance and desire distance of two double acting cylinders to extend and retract with the use of flow control valve

Pressure (Bar)	FCV at cylinder 2 (No. of Turns)	Desired distance (cm)		Actual Distance (cm)					Average distance (cm)	% error (%)
				R1	R2	R3	R4	R5		
20	0	Cylinder 1 extend	5	5	5	5	5	5	5.00	0
			10	10	10	10	10	10	10.0	0
		Cylinder 2 extend	5	4.6	4.5	4.7	4.7	4.7	4.64	7.2
			10	8.7	8.5	8.6	8.6	8.7	8.62	13.8
		Cylinder 1 Retract	5	5	5	5	5	5	5.00	0
			0	0	0	0	0	0	0	0
		Cylinder 2 Retract	5	6.7	6.5	6.6	6.6	6.6	6.60	32.0
			0	4.9	4.8	4.8	5	5	4.90	NA
	1	Cylinder 1 extend	5	5	5	5	5	5	5.00	0
			10	10	10	10	10	10	10.0	0
		Cylinder 2 extend	5	5.3	5.1	5.2	5.2	5.2	5.20	4
			10	9.3	9.4	9.4	9.4	9.4	9.38	6.2
		Cylinder 1 Retract	5	5	5	5	5	5	5.00	0
			0	0	0	0	0	0	0	0
		Cylinder 2 Retract	5	5.2	5.1	5.1	5.1	5.1	5.12	2.4
			0	1.3	1.3	1.2	1.2	1.2	1.24	NA

	2	Cylinder 1 extend	5	5	5	5	5	5	5.00	0
			10	10	10	10	10	10	10	0
		Cylinder 2 extend	5	5.2	5.1	5.1	5.1	5.1	5.12	2.4
			10	9.7	9.7	9.8	9.8	9.8	9.76	2.4
		Cylinder 1 Retract	5	5	5	5	5	5	5.00	0
			0	0	0	0	0	0	0	0
		Cylinder 2 Retract	5	4.9	5	5	5	5	4.98	0.4
			0	1.1	1.0	1.1	1.1	1.0	1.06	NA
	3	Cylinder 1 extend	5	5	5	5	5	5	5.00	0
			10	10	10	10	10	10	10.0	0
		Cylinder 2 extend	5	5	5	5	5	5	5.00	0
			10	10	10	10	10	10	10.0	0
		Cylinder 1 Retract	5	5	5	5	5	5	5.00	0
			0	0	0	0	0	0	0	0
		Cylinder 2 Retract	5	5	5	5	5	5	5.00	0
			0	0	0	0	0	0	0	0

Figure 4.3 shows the timing diagram of two double acting cylinders with 3 limit switches. Push button 1 is for the cylinder to extend and push button 2 is the retraction for the cylinder. T represented the time taken for double acting cylinder to extend and retract at different time.

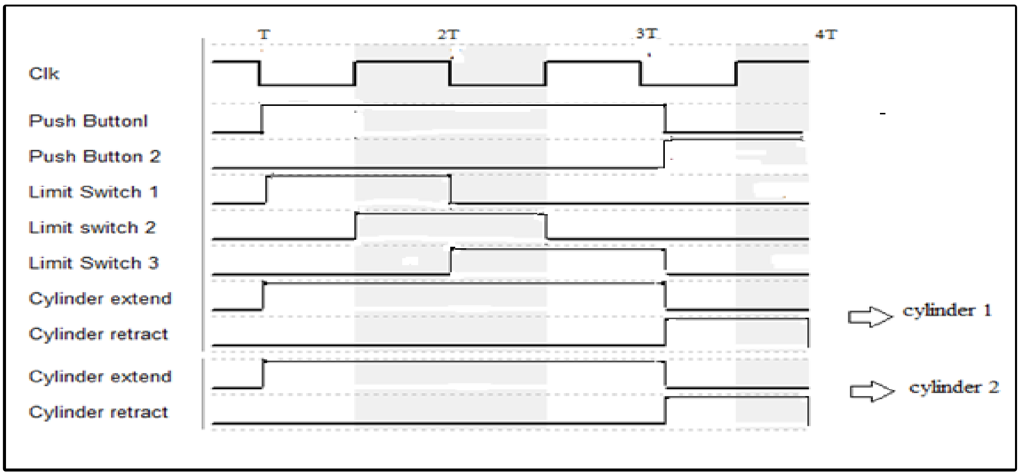


Figure 4.3: Timing diagram of two double acting cylinders

Pressure of 20 bars was set with different number of turn for FCV at cylin der 2. Two double acting cylinders were used and only 3 limit switches used to control the desired position for the double acting cylinder to extend and retract. Initially FCV was not used. However, problems occur during the extend of double acting cylinder 2 whereby it cannot meet the desired position as double acting cylinder 1. Thus, FCV was used to control the fluid flow with same pressure so that both double acting cylinders can move at the same time. This design was used for the hardware as to prove the mathematical modelling in term of kinematic analysis. Notice that double acting cylinder 1 which is with limit switches had the good accuracy whereas for the cylinder 2, the number of turn of FCV was control so that both double acting cylinders can move at the same time. For the FCV 3 turns, the distance for the both double acting cylinder extend and retract is the same which meet the desired positions.

In term of percentage error, the double acting cylinder 1 had zero percentage error as it meet the actual distance whereas for the double acting cylinder 2, there were percentage errors. As the number of flow control valve (FCV) turn increase, the percentage errors were reduced until the 3^{rd} turn of FCV, the percentage error was zero. NA here means there were percentage error for the double acting cylinder 2 but the percentage error value cannot count. Thus with the used of flow control valve, the two double acting cylinder able to extend and retract at the same time with same distance which had being fixed.

4.5 Experimental Test 3

Table 4.5 shows the 6 limit switches used and experimental test on the time taken for cylinders to contact each of the limit switches. Different pressure of 15 bars, 20 bars, 25 bars and 30 bars were done in this test. The test of each pressure on time taken was repeated 3 times and the average time and average velocity as well as standard deviation were found. L1 represented limit switch 1 and L2, L3, L4, L5 and L6 represent the different limit switches.

Table 4.5: Time taken for the double acting cylinder to extend and retract at different limit switches with different pressures

Pressure (Bar)	Position of limit switch (cm)		Time taken (s)					Average Time(s)	Average Velocity (m/s)	Standard Deviation
			R1	R2	R3	R4	R5			
15	Extend	L2	0.41	0.43	0.53	0.63	0.63	0.526	0.0951	0.094149
		L3	0.50	0.48	0.58	0.58	0.58	0.544	0.0919	0.044542
		L4	0.48	0.48	0.43	0.46	0.45	0.460	0.1087	0.018974
		L5	0.48	0.48	0.48	0.43	0.43	0.460	0.1087	0.024495
	Retract	L4	2.01	2.30	2.43	2.00	2.01	2.150	0.0233	0.180333
		L3	2.01	2.01	2.30	2.20	2.30	2.164	0.0231	0.130935
		L2	1.02	1.01	1.03	1.01	1.01	1.016	0.0492	0.008000
		L1	1.03	1.01	1.02	1.05	1.02	1.026	0.0487	0.013565
20	Extend	L2	0.41	0.42	0.40	0.41	0.41	0.410	0.1220	0.006325
		L3	0.41	0.43	0.42	0.42	0.41	0.418	0.1196	0.007483
		L4	0.36	0.36	0.36	0.36	0.35	0.358	0.1397	0.004000
		L5	0.35	0.36	0.36	0.36	0.36	0.358	0.1387	0.004000
	Retract	L4	0.56	0.56	0.56	0.56	0.57	0.562	0.0890	0.004000
		L3	0.55	0.56	0.56	0.56	0.56	0.558	0.0896	0.004000
		L2	0.58	0.57	0.58	0.58	0.58	0.578	0.0865	0.004000
		L1	0.55	0.55	0.55	0.55	0.55	0.550	0.0909	0
25	Extend	L2	0.31	0.35	0.31	0.36	0.38	0.342	0.1462	0.027857
		L3	0.31	0.26	0.27	0.31	0.27	0.284	0.1761	0.021541
		L4	0.26	0.25	0.24	0.25	0.26	0.252	0.1984	0.007483
		L5	0.26	0.25	0.24	0.24	0.26	0.250	0.2000	0.008944
	Retract	L4	0.38	0.37	0.37	0.39	0.38	0.378	0.2103	0.007483
		L3	0.45	0.40	0.48	0.47	0.46	0.452	0.1106	0.027957
		L2	0.45	0.45	0.47	0.46	0.45	0.456	0.1096	0.008000
		L1	0.43	0.41	0.42	0.40	0.43	0.418	0.1196	0.011662
	Extend	L2	0.31	0.32	0.26	0.26	0.26	0.282	0.1773	0.027129
		L3	0.31	0.26	0.27	0.29	0.31	0.288	0.1736	0.020396

		L4	0.23	0.25	0.24	0.25	0.25	0.244	0.2049	0.008000
		L5	0.23	0.24	0.24	0.24	0.25	0.240	0.2083	0.006325
30	Retract	L4	0.45	0.38	0.41	0.39	0.39	0.404	0.1238	0.024980
		L3	0.40	0.39	0.40	0.39	0.38	0.392	0.1276	0.007483
		L2	0.31	0.35	0.35	0.32	0.31	0.328	0.1524	0.018330
		L1	0.39	0.35	0.31	0.35	0.35	0.350	0.1429	0.025298

This experiment was done with different pressures as well as 6 limit switches used. Each 5v relay module was used to activate the solenoid. Two 4/3 way hydraulic valve was needed to control the direction of flow of valve. Notice that at pressure 20 bars, the repeated reading on the time taken is almost the same for the extend and retract of the double acting cylinder. For every cylinder extend and retract at different limit switches as well as position, the time taken also varied. Standard deviation is determined too and the coding was changed to meet the desired condition. Pressure of 20 bars is selected as it is very stable which mean the double acting cylinder able to move at the same time evenly for 6 limits switches consecutively. At 20 bars, the standard deviation shows the lowest value compared other pressures which was unstable in term of fluid flow in the double acting cylinder. The retraction time is longer than extension because of the different fluid flow for extend and retract as well as the FCV being used. Figure 4.4 shows the time extend and retract against limit switch position which had being fixed.

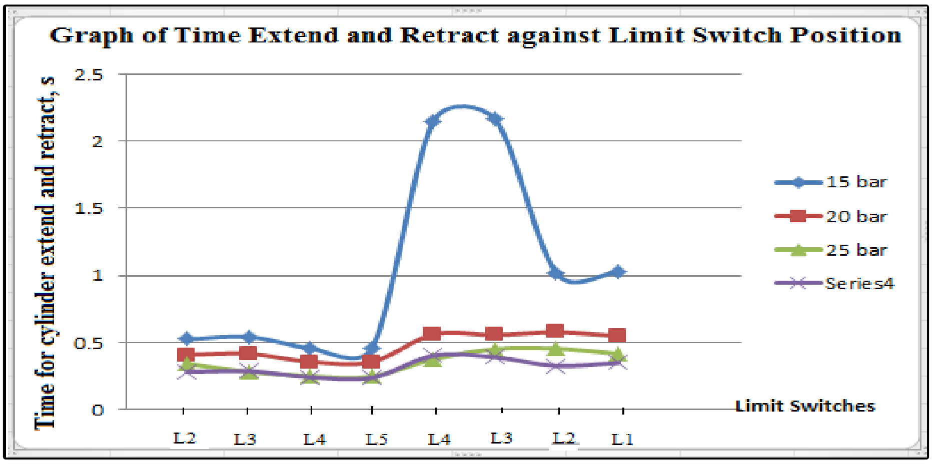


Figure 4.4: Graph of Time Extend and Retract against Limit Switch Position

Figure 4.4 shows the graph of time taken for the cylinder to extend and retract with different position set for the limit switches. Initially for the low pressure of 15 bar, the cylinder retract very slow for L4, L3, L2 and L1. This is due to low pressure supply and the fluid flow unable to push the cylinder for it to retract. Besides, there are fluid that already exist in cylinder for the extend previously when double acting cylinder retract, thus the friction on it will cause the cylinder move slower. For the pressure of 20 bar, the time taken for the cylinder to extend almost same and for the retraction, cylinder also move at almost same time for each limit switch.

4.6 Experimental Test 4

Table 4.6 shows the accuracy test on one double acting cylinder using flexibility sensor. The two double acting cylinders were not tested here for the accuracy test because the flex sensor was hard for the position control for these two double acting cylinders.

Table 4.6: Accuracy Test of double acting cylinder to extend and retract at pressure of 20 Bar using Flex Sensor 4.5”

Number of tests(n)	Extend		Retract	
	Position:5cm	Position:10cm	Position:5cm	Position:0 cm
1	4.5cm	10.0cm	5.6cm	0cm
2	5.0cm	9.0cm	5.5cm	0cm
3	5.5cm	9.8cm	5.4cm	0cm
4	4.6cm	9.7cm	5.1cm	0cm
5	5.8cm	10.0cm	5.2cm	0cm
6	5.6cm	9.6cm	5.3cm	0cm
7	4.5cm	9.7cm	5.6cm	0cm
8	4.4cm	9.5cm	5.8cm	0cm
9	4.8cm	9.9cm	5.9cm	0cm

10	5.7cm	9.8cm	5.5cm	0cm
11	5.4cm	9.6cm	5.0cm	0cm
12	5.5cm	9.6cm	5.0cm	0cm
13	4.5cm	9.7cm	5.1cm	0cm
14	5.1cm	9.4cm	5.2cm	0cm
15	5.2cm	9.9cm	5.3cm	0cm
16	5.0cm	10.0cm	5.5cm	0cm
17	5.3cm	10.0cm	5.6cm	0cm
18	5.1cm	9.8cm	5.4cm	0cm
19	5.0cm	9.0cm	5.3cm	0cm
20	5.1cm	9.0cm	5.0cm	0cm

Noticed that the position control using flex sensor was hard and difficult to obtain the desired distances compare with the used of limit switch to fix the distance needed. For the flex sensor 4.5", the resistance of unbent and bent for every single flex sensor was totally different. The degree for the flex sensor bent may be vary for each time we need to extend or retract the cylinder and within the Arduino coding , there were condition need to be set on how much flex sensor 4.5" should bent to extend and retract the cylinder. When bent the flex sensor 4.5" at certain degree, the analogue input A4 will trigger the 5V relay module for the double acting cylinder to extend. When the flex sensor 4.5" unbent, the 5V relay module inactive and cause the double acting cylinder stop. This situation same for the retraction of double acting cylinder. Thus, it was hard for the position control to be exact compare with the use of limit switches to fix the distances. Figure 4.5 shows the graph of position of cylinders against the number of tests taken using flex sensor 4.5" to control.

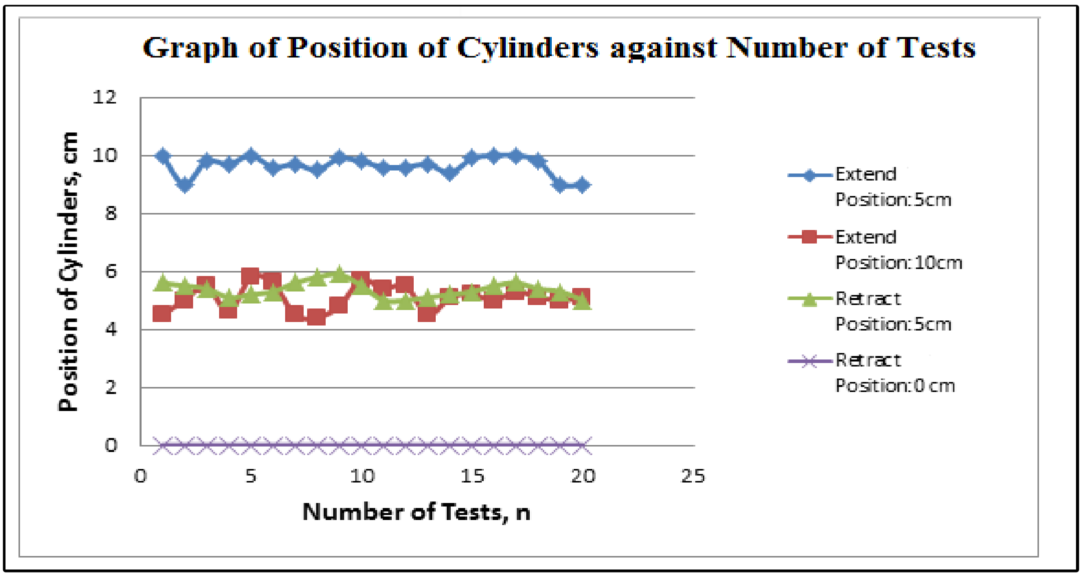


Figure 4.5: Graph of position of cylinders against the number of tests taken

4.7 Comparison of Limit Switches and Flex Sensor performance for position control

From the experimental test 1 and experimental test 4, we noticed that the limit switches used for the position control was better than using flex sensor as input to control double acting cylinder. Position control for double acting cylinder was needed because the pressure supply for the double acting cylinder was 20 Bars which is high. Without position control, the double acting cylinder only can fully extend and retract in term of motion. Flex sensor 4.5" can also control the position needed for the double acting cylinder to extend. However, the position control was not accurate compare with the used of push button with limit switches. The resistance for the flex sensor unbent was 30K ohms whereas for the 90^o bent of flex sensor, the resistance reached 50K ohms. Besides, each of the flex sensor value was varied and this value need to obtain to set the condition needed. Flex sensor 4.5" can be used for the control of continuous motion but in term of position control, it was not accurate compared with the used of limit switches as well as push button to control the double acing cylinder to extend or retract.

From experimental test 2, two double acting cylinders were used with 3 limit switches. The position control was accurate for both double acting cylinder moves at the same time with the used of flow control valve (FCV). When forward push button (green) was pressed, the double acting cylinder will extend to the desired distance until the limit switches being contact and then stop and wait for the next command. When forward push button was pressed again, the double acting cylinder will extend again to contact with next limit switches and then stop. The sequence was same for the double acting cylinders to retract when reverse push button was pressed (red). The position control for the double acting cylinder to extend and retract was much more accurate for this method compared with the used of flex sensor 4.5". Thus, limit switches with push button was selected and implement on the bionic leg.

4.8 Implementation on hardware

Accuracy test on the hip and knee in term of rotation angle was done for sit and stand position at different distance whereby the limit switch locate at different position. The test was repeated for 5 times. Table 4.7 shows the accuracy test on the rotation angle of hip and knee at sit and stand position. X_{BF} and Y_{BF} were measured and recorded down for the kinematic analysis and find the rotation angle through theoretical. FCV valve is used to synchronize the two cylinders as tested in experimental 2. Pressure selected is 20 bars.

Table 4.7: Accuracy test on the rotation angle of hip and knee at sit and stand position

No. of test taken(n)	**Position of Limit Switches (cm)**		**Rotation Angle, θ**		**X_{BF}**	**Y_{BF}**
			Hip (θ_1)	**Knee `(θ_2)**		
1	Stand	0	88^o	2^o	3.8	82.30
	Partial Stand	5	45^o	45^o	35.50	67.50
	Sit	10	0^o	90^o	41.20	41.20

2	Stand	0	90^{o}	2^{o}	3.8	82.30
	Partial Stand	5	45^{o}	45^{o}	35.50	67.50
	Sit	10	0^{o}	90^{o}	41.20	41.20
3	Stand	0	88^{o}	1^{o}	5.7	82.20
	Partial Stand	5	45^{o}	45^{o}	35.50	67.50
	Sit	10	0^{o}	90^{o}	41.20	41.20
4	Stand	0	90^{o}	0^{o}	0	82.40
	Partial Stand	5	45^{o}	45^{o}	35.50	67.50
	Sit	10	0^{o}	90^{o}	41.20	41.20
5	Stand	0	90^{o}	0^{o}	0	82.40
	Partial Stand	5	45^{o}	45^{o}	35.50	67.50
	Sit	10	0^{o}	90^{o}	41.20	41.20
6	Stand	0	88^{o}	1^{o}	5.7	82.20
	Partial Stand	5	45^{o}	45^{o}	35.50	67.50
	Sit	10	0^{o}	90^{o}	41.20	41.20
7	Stand	0	88^{o}	1^{o}	5.7	82.20
	Partial Stand	5	45^{o}	45^{o}	35.50	67.50
	Sit	10	0^{o}	90^{o}	41.20	41.20
8	Stand	0	90^{o}	2^{o}	3.8	82.30
	Partial Stand	5	45^{o}	45^{o}	35.50	67.50
	Sit	10	0^{o}	90^{o}	41.20	41.20
9	Stand	0	90^{o}	0^{o}	0	82.40
	Partial Stand	5	45^{o}	45^{o}	35.50	67.50
	Sit	10	0^{o}	90^{o}	41.20	41.20
10	Stand	0	90^{o}	0^{o}	0	82.40
	Partial Stand	5	45^{o}	45^{o}	35.50	67.50
	Sit	10	0^{o}	90^{o}	41.20	41.20
11	Stand	0	90^{o}	0^{o}	0	82.40
	Partial Stand	5	45^{o}	45^{o}	35.50	67.50
	Sit	10	0^{o}	90^{o}	41.20	41.20
12	Stand	0	90^{o}	0^{o}	0	82.40
	Partial Stand	5	45^{o}	45^{o}	35.50	67.50
	Sit	10	0^{o}	90^{o}	41.20	41.20

13	Stand	0	90°	0°	0	82.40
	Partial Stand	5	45°	45°	35.50	67.50
	Sit	10	0°	90°	41.20	41.20
14	Stand	0	90°	2°	3.8	82.30
	Partial Stand	5	45°	45°	35.50	67.50
	Sit	10	0°	90°	41.20	41.20
15	Stand	0	90°	2°	3.8	82.30
	Partial Stand	5	45°	45°	35.50	67.50
	Sit	10	0°	90°	41.20	41.20
16	Stand	0	90°	0°	0	82.40
	Partial Stand	5	45°	45°	35.50	67.50
	Sit	10	0°	90°	41.20	41.20
17	Stand	0	90°	0°	0	82.40
	Partial Stand	5	45°	45°	35.50	67.50
	Sit	10	0°	90°	41.20	41.20
18	Stand	0	90°	0°	0	82.40
	Partial Stand	5	45°	45°	35.50	67.50
	Sit	10	0°	90°	41.20	41.20
19	Stand	0	90°	0°	0	82.40
	Partial Stand	5	45°	45°	35.50	67.50
	Sit	10	0°	90°	41.20	41.20
20	Stand	0	90°	0°	0	82.40
	Partial Stand	5	45°	45°	35.50	67.50
	Sit	10	0°	90°	41.20	41.20

For this test, the rotation angle was determined for the hip and knee in term of θ. Sit position and stand position was taking into account too. X_{BF} and Y_{BF} was the base frame which was determined to prove that the theoretical value of rotation angle is same as the measured value of rotation angle. Accuracy test was done with several numbers of tests taken to get the rotation angle on hip and knee. In theoretical of the inverse kinematic, we need to find the rotation angle. Thus, actuator length of knee, L_2 and hip, L_1 as well as base frame of X and Y needs to be known from the hardware. Figure 4.6 shows the standing position of bionic leg.

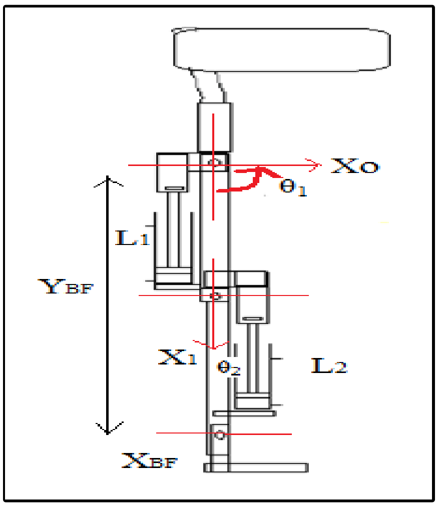


Figure 4.6: Standing position of bionic leg with label

Theoretically,

Initially for standing position of the double acting cylinder fully retract,

$$X_{BF} = 0 \tag{4.1}$$

$$Y_{BF} = \text{Total length of actuator length for hip and knee}$$
$$= L_1 + L_2 \tag{4.2}$$

From equation (4.23),

$$\cos\ \theta_2 = (X_{BF}^2 + Y_{BF}^2 - L_1^2 - L_2^2)/2L_1L_2$$

$$\theta_2 = \cos^{-1}(X_{BF}^2 + Y_{BF}^2 - L_1^2 - L_2^2)/2L_1L_2$$

$$= \cos^{-1}(L_1^2 + L_2^2 + 2L_1L_2 - L_1^2 - L_2^2)/\ 2L_1L_2$$

$$= \cos^{-1} 1$$

$$\text{Thus, } \theta_2 = 0 \tag{4.3}$$

$$\sin\ \theta_1 = \sqrt{\frac{[Y_{BF}^{\ 2}L_1^{\ 2} + Y_{BF}^{\ 2}L_2^{\ 2}\cos^2\theta_2 + X_{BF}^{\ 2}L_2^{\ 2}\sin^2\theta_2 + 2L_1L_2Y_{BF}^{\ 2}\cos\theta_2 - 2L_1L_2Y_{BF}X_{BF}\sin\theta_2 - 2L_2^{\ 2}Y_{BF}X_{BF}\cos\theta_2\sin\theta_2]}{(X_{BF}^{\ 2} + Y_{BF}^{\ 2})(L_1^{\ 2} + L_2^{\ 2} + 2L_1L_2\cos\theta_2)}}$$

$$= \sqrt{\frac{[(L_1+L_2)^2 L_1^{\ 2} + (L_1+L_2)^2 L_2^{\ 2} + 0 + 2L_1L_2(L_1+L_2)^2 - 0]}{(L_1+L_2)^2(L_1^{\ 2}+L_2^{\ 2}+2\,L_1\,L_2\cos\theta_2)}}$$

$$= \sqrt{\frac{[(L_1+L_2)^2(L_1^{\ 2}+L_2^{\ 2}+2L_1L_2)]}{(L_1+L_2)^2(L_1^{\ 2}+L_2^{\ 2}+2\,L_1\,L_2)}}$$

$\theta_1 \quad = \sin^{-1} 1$

Thus,

$$\theta_1 = 90^0 \tag{4.4}$$

Figure 4.7 shows the bionic leg at sit position whereby the double acting cylinder was fully extend.

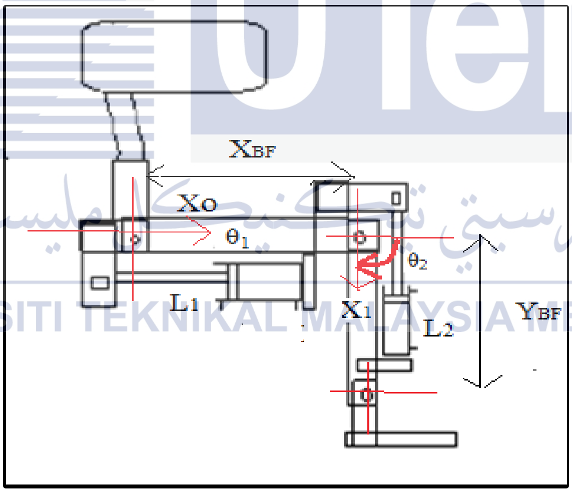


Figure 4.7: Sit position of bionic leg with label

For sit position of double acting cylinder fully extend,

$$Y_{BF} = L_2 \tag{4.5}$$

$$X_{BF} = L_1 \tag{4.6}$$

$$\cos\theta_2 = (X_{BF}^{\ 2} + Y_{BF}^{\ 2} - L_1^{\ 2} - L_2^{\ 2})/2L_1L_2$$

$\theta_2 = \cos^{-1}(X_{BF}^2 + Y_{BF}^2 - L_1^2 - L_2^2)/2L_1L_2$

$= \cos^{-1}(L_1^2 + L_2^2 - L_1^2 - L_2^2)/2L_1L_2$

$\theta_2 = 90^0$ (4.7)

$$\sin\theta_1 = \sqrt{\frac{[Y_{BF}^2L_1^2 + Y_{BF}^2L_2^2\cos^2\theta_2 + X_{BF}^2L_2^2\sin^2\theta_2 + 2L_1L_2Y_{BF}^2\cos\theta_2 - 2L_1L_2Y_{BF}X_{BF}\sin\theta_2 - 2L_2^2Y_{BF}X_{BF}\cos\theta_2\sin\theta_2]}{(X_{BF}^2 + Y_{BF}^2)(L_1^2 + L_2^2 + 2L_1L_2\cos\theta_2)}}$$

$$\theta_1 = \sin\theta^{-1}\sqrt{\frac{[L_2^2L_1^2 + 0 + L_1^2L_2^2 - 2L_1L_2L_1L_2}{(L_1^2 + L_2^2)(L_1^2 + L_2^2)}}$$

$= \sin\theta^{-1}\ 0$

Thus,

$\theta_1 = 0^0$ (4.8)

Similarly, when both double acting cylinder extend at a distance of 5 cm as shown in Figure 4.8 with the label axis.

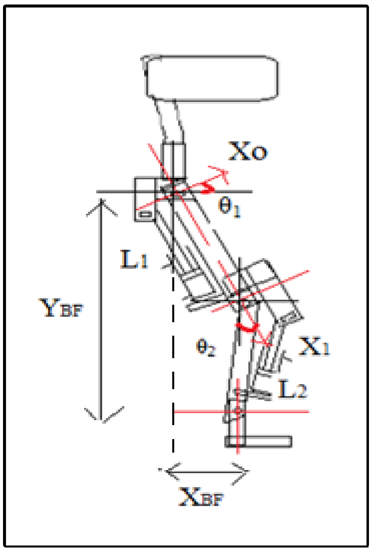


Figure 4.8: Partial Stand position of bionic leg with label

Total L_1 = Cylinder 1 length + 5 cm+ extension on other parts

=24.5cm + 5 cm + 11.7cm (4.9)

=41.20 cm

Total L_2 = Cylinder 2 length + 5 cm+ extension on other parts

= 24.5cm + 5 cm + 11.7cm (4.10)

= 41.20 cm

X_{BF} = 35.5 cm (4.11)

Y_{BF} = 67.5 cm (4.12)

$\cos\theta_2 = (X_{BF}^2 + Y_{BF}^2 - L_1^2 - L_2^2)/2L_1L_2$

$= (35.5^2+67.5^2- 41.2^2- 41.2^2)/2(41.2)(41.2)$

$\theta_2 = \cos^{-1} 0.7133$

$=44.5^o$

$\approx 45^o$ (4.13)

$$\sin\theta_1 = \sqrt{\frac{[Y_{BF}^2 L_1^2 + Y_{BF}^2 L_2^2 \cos^2\theta_2 + X_{BF}^2 L_2^2 \sin^2\theta_2 + 2L_1L_2Y_{BF}^2\cos\theta_2 - 2L_1L_2Y_{BF}X_{BF}\sin\theta_2 - 2L_2^2Y_{BF}X_{BF}\cos\theta_2\sin\theta_2]}{(X_{BF}^2+Y_{BF}^2)(L_1^2+L_2^2+2L_1L_2\cos\theta_2)}}$$

$$= \sqrt{\frac{(67.5^2)(41.2^2)+(67.5^2)(41.2^2)cos^2 45+(35.5^2)(41.2^2)sin^2 45+ 2(41.2)(41.2)(67.5^2)cos45-2(41.2)(41.2)(67.5)(35.5)sin45- 2(41.2^2)(67.5)(35.5)cos45sin45}{(35.5^2+67.5^2)(41.2^2+41.2^2+2(41.2)(41.2)cos45}}$$

$$= \sqrt{\frac{16854537.98}{33709075.96}}$$

$= \sin^{-1} 0.7071068$

$\theta_1 = 45^o$ (4.14)

Practically, the rotation angle of hip and knee was found as shown previous Table 4.7. Total numbers of 20 tests were taken and the rotation angle of hip and knee during sit position was slightly different for the several initial tests. This is due to the hardware design whereby the double acting cylinder for knee and hip part was not tightly attached to the extension although cable tie was used to tighten the double acting cylinders. The extension used to connect with double acting cylinders were not design properly whereby the extension was slightly longer which cause the double acting cylinder slightly face outwards and thus affect reading obtained for the rotation angle of hip and knee. However, for the last few result from the tests proved that the measured value for the rotation angle of hip and knee was approximately same as the theoretical value for rotation angle of hip and knee from derivation of mathematical modelling of bionic leg in term of kinematic analysis. The accelerometer used must located in x-axis and must tighten too to avoid inaccurate reading obtained from serial monitor. Figure 4.9 shows the design of bionic leg whereby the double acting cylinder need to be tightening with cable to reduce the error occurs.

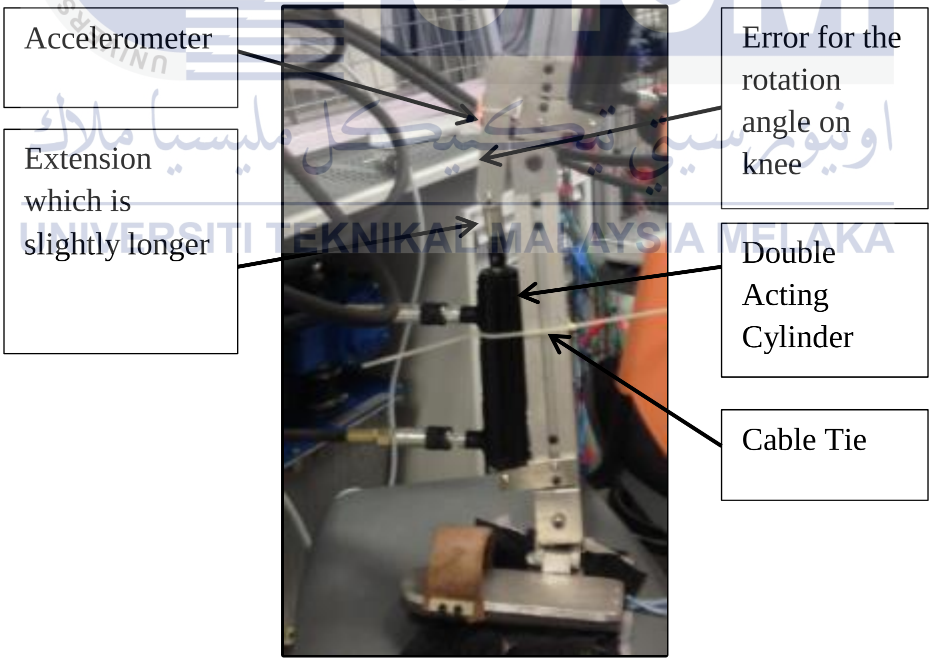


Figure 4.9: Design of bionic leg whereby cable tie is used to tighten double acting cylinder

4.9 Potential application

This project is able to benefit most of the people who have difficulty to walk for their lower limb. The motion study on bionic leg using hydraulic actuator able to overcome the limitations from the previously used of pneumatic cylinder. The difficulty to walk for elder people may reduce and improve their daily lifestyle. They will able to walk freely to any location independently without the aid of family because this project was done to aid them. One of the advantages of using this bionic leg with hydraulic actuator was that the double acting cylinder able to withstand higher load compare with the used of pneumatic cylinder. This bionic leg can be widely used for the rehabilitation purpose and field that can be involved was the physiotherapy. This bionic leg trained and aid patient whom legs injured to walk and gained back patient's confident as well as hope that they will recover as soon as possible.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In conclusion, the derivation of mathematical modelling on bionic leg in term of kinematic analysis was achieved. FluidSIM was used to do the experimental simulation test for the forces and time taken for the double acting cylinder to fully extend. The design of the motion of bionic leg in application of hydraulic actuator for stand and sit position was achieved. Besides, analyze on overall performance for the design of motion of hydraulic actuator to give accuracy and reliability for rehabilitation application was achieved. The comparison on the limit switches with flex sensor performance was done and the selected choice used to implement for the bionic leg. The motion study of bionic leg using hydraulic actuator was able to overcome the limitation done previously for pneumatic actuator. Implementation on hardware was done and rotation angle of hip and knee was measure using accelerometer or protractor to validate and compared with the theoretical rotation angle values of hip and knee in term of kinematic analysis. The oil seal was used to prevent leakage of fluid occur on the double acting cylinder and the cable tie was used to minimize the error reading occur on the accelerometer because of the extension design to attach the double acting cylinder.

5.2 Recommendation

From this study, it is recommended that the further study on the stability of bionic leg itself whenever standing phase and walking phase were done for the further research. Besides, the other method to control the motion of bionic leg can be done by using force sensor for the further research. Moreover, wireless controller can be done for the next research by using Xbee shield with Arduino Uno R3. The movement of bionic leg itself was complex and the study of movement in continuous motion can be done for further research with different method of controller. The design of bionic leg can be improvised to be more portable in term of bionic leg’s weight. This may reduce the extra weights that burden the patient or users to use it.

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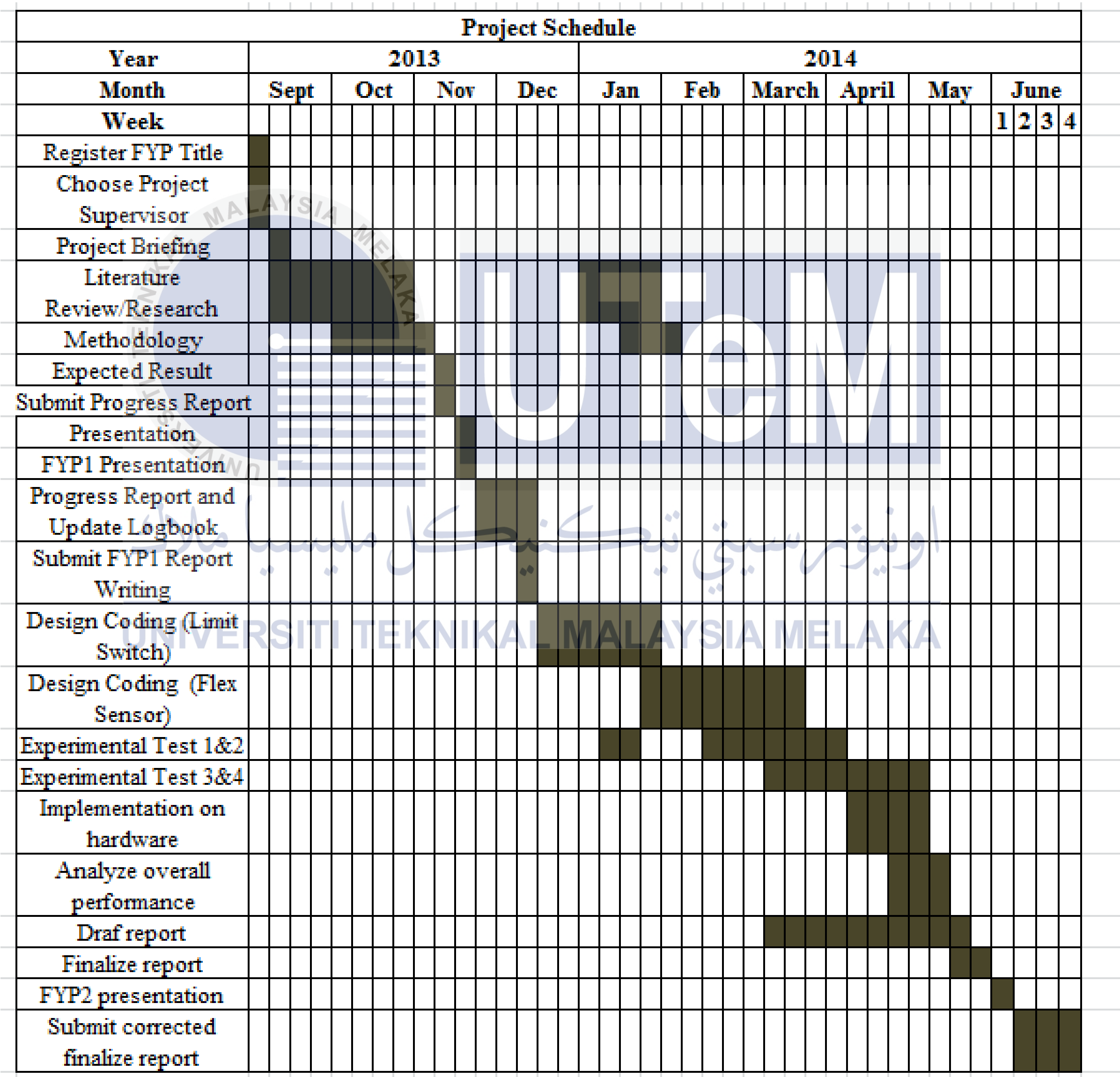
APPENDIX A

Gantt Chart



APPENDIX B

Arduino Coding with the use of 3 limit switches

```
/*
  Sketch: Cylinder_driverR2.ino


  On pressing a forward switch, the routine turns on a relay to trigger a hydraulic valve that
  moves a cylinder forwards until a limit switch is reached. Three limit switches are used'
  ;[
  to move step by step on each switch press.
  Similarly a reverse switch turns on reverse solenoid to return the shaft to previous position
  Components used:
  ---------------
  1x Arduino UNO
  2x 2 channel relay module
  3x Limit switches
  2x push button switches
  4x Relays 5V
*/
// Pin definitions
#define led      13
#define swDwn   2
#define swUp    3
#define swLim1  5
#define swLim2  6
#define swLim3  7
#define solUp   A0
```

```
#define solDwn  A1
#define solUp1  A2
#define solDwn1 A3

// Variables
int moveDwn, moveUp;        // Up/Down switch values
int upState;                // Up/down Status
int sw1Pos, sw2Pos, sw3Pos;  // Limit Switch position variable
int limVal;                 // Limit Value

void setup()
{
  Serial.begin(9600);     // Serial comm for debugging
  pinMode(led, OUTPUT);
  pinMode(solUp, OUTPUT);
  pinMode(solDwn, OUTPUT);
  pinMode(solUp1, OUTPUT);
  pinMode(solDwn1, OUTPUT);
  pinMode(swDwn, INPUT);
  pinMode(swUp, INPUT);
  pinMode(swLim1, INPUT);
  pinMode(swLim2, INPUT);
  pinMode(swLim3, INPUT);

  digitalWrite(led, LOW);   // Initialise, turn off everything
  digitalWrite(solUp, HIGH);
  digitalWrite(solDwn, HIGH);
  digitalWrite(solUp1, HIGH);
  digitalWrite(solDwn1, HIGH);
}
```

```
void loop()
{
  // Routine to select up/down status of system
  // upState = 0 -> move down, upState = 1 -> move up, upstate = -1 -> stop
  moveDwn = digitalRead(swDwn);              // Read switch status
  moveUp = digitalRead(swUp);
  if (moveDwn == LOW && moveUp == HIGH)      // If move down pressed
  {
   digitalWrite(led, LOW);
   upState = 0;                              // Status = move down
   Serial.println("Down");
  }
  else if (moveDwn == HIGH && moveUp == LOW) // If move up pressed
  {
   digitalWrite(led, HIGH);
   upState = 1;                              // Status = move up
   Serial.println("Up");
  }
  delay(100);

  // Detect position of cylinder shaft
  sw1Pos = digitalRead(swLim1);              // Read limit switches
  sw2Pos = digitalRead(swLim2);
  sw3Pos = digitalRead(swLim3);

  if (sw1Pos == LOW) limVal = 1;             // Limit switch 1 active
  if (sw2Pos == LOW) limVal = 2;             // Limit switch 2 active
  if (sw3Pos == LOW) limVal = 3;             // Limit switch 3 active
  if (sw1Pos == HIGH && sw2Pos == HIGH && sw3Pos == HIGH) limVal = 0;
  // All limit switches not active
```

```
if (upState == 1)       // If Up motion selected
{
 switch (limVal)
 {
  case 0:            // If no limit switch active

   while ( digitalRead(swLim1) == HIGH) // until limit switch 1 & 4 active
   {
   digitalWrite(solUp, LOW);            // Turn on up solenoid
   digitalWrite(solUp1, LOW);
   }
   //upState = -1;               // upState is -1 means no direction is selected
   Serial.println("Position: ");        // Send values to PC
   Serial.println(limVal);
   break;                       // Exit
  case 1:            // If limit switch 1 active
   do
   {
    digitalWrite(solUp, LOW);         // Turn ON up solenoid
    digitalWrite(solUp1, LOW);
   }
   while ( digitalRead(swLim2) == HIGH); // until limit switch 2 &5 active
   digitalWrite(solUp, HIGH);            // Turn OFF up solenoid, so stop motion
   digitalWrite(solUp1, HIGH);
   upState = -1;                    // upState is -1 means no direction is selected
   Serial.println("Position: ");        // Send values to PC
   Serial.println(limVal);
   break;                       // Exit

  case 2:            // If limit switch 2 active
   do
```

```
      {
        digitalWrite(solUp, LOW);        // Turn ON up solenoid
        digitalWrite(solUp1, LOW);
      }
      while ( digitalRead(swLim3) == HIGH); // until limit switch 3 & 6 active
      digitalWrite(solUp, HIGH);          // Turn OFF up solenoid, so stop motion
      digitalWrite(solUp1, HIGH);
      upState = -1;                       // upState is -1 means no direction is selected
      Serial.println("Position: ");       // Send values to PC
      Serial.println(limVal);
      break;                              // Exit
  }
}
if (upState == 0)     // If Down motion selected
{
  switch (limVal)
  {
    case 0:           // If no limit switch active
      delay(200);                         // Wait, do nothing
      Serial.println("Position: ");       // Send values to PC
      Serial.println(limVal);
      break;                              // Exit
    case 1:           // If limit switch 1 active
      do
      {
        digitalWrite(solDwn, LOW);        // Turn ON Down solenoid
        digitalWrite(solDwn1, LOW);
      }
      while ( digitalRead(swLim1) == LOW);  // until limit switch 1& 3 inactive
      digitalWrite(solDwn, HIGH);         // Turn OFF down solenoid, so stop motion
      digitalWrite(solDwn1, HIGH);
      upState = -1;                       // upState is -1 means no direction is selected
```

```
      Serial.println("Position: ");        // Send values to PC
      Serial.println(limVal);
      break;                              // Exit
    case 2:            // If limit switch 2 active
      do
      {
        digitalWrite(solDwn, LOW);        // Turn ON Down solenoid
        digitalWrite(solDwn1, LOW);
      }
      while ( digitalRead(swLim2) == LOW);  // until limit switch 2& 4 inactive
      digitalWrite(solDwn, HIGH);           // Turn OFF down solenoid, so stop motion
      digitalWrite(solDwn1, HIGH);
      upState = -1;                         // upState is -1 means no direction is selected
      Serial.println("Position: ");        // Send values to PC
      Serial.println(limVal);
      break;                              // Exit
    case 3:            // If limit switch 3 active
      do
      {
        digitalWrite(solDwn, LOW);        // Turn ON Down solenoid
        digitalWrite(solDwn1, LOW);
      }
      while ( digitalRead(swLim3) == LOW);  // until limit switch 3 & 6inactive
      digitalWrite(solDwn, HIGH);           // Turn OFF down solenoid, so stop motion
      digitalWrite(solDwn1, HIGH);
      upState = -1;                         // upState is -1 means no direction is selected
      Serial.println("Position: ");        // Send values to PC
      Serial.println(limVal);
      break;                              // Exit
    }
  }
}
```

APPENDIX C

Arduino Coding with the use of 6 limit switches

```
Sketch: Cylinder_driverR2.ino

  On pressing a forward switch, the routine turns on a relay to trigger a hydraulic valve that
  moves a cylinder forwards until a limit switch is reached. Six limit switches are used'
  ;[
  to move step by step on each switch press.

  Similarly a reverse switch turns on reverse solenoid to return the shaft to previous position

  Components used:
  ---------------
  1x Arduino UNO
  2x 2 channel relay module
  6x Limit switches
  2x push button switches
  4x Relays 5V
*/

// Pin definitions
#define led     13
#define swDwn   2
#define swUp    3
#define swLim1  5
#define swLim2  6
#define swLim3  7
```

```
#define swLim4  8
#define swLim5  9
#define swLim6  10
#define solUp   A0
#define solDwn  A1
#define solUp1  A2
#define solDwn1 A3

// Variables
int moveDwn, moveUp;          // Up/Down switch values
int upState;                  // Up/down Status
int sw1Pos, sw2Pos, sw3Pos,sw4Pos,sw5Pos,sw6Pos;   // Limit Switch position variable
int limVal;                   // Limit Value

void setup()
{
  Serial.begin(9600);        // Serial comm for debugging
  pinMode(led, OUTPUT);
  pinMode(solUp, OUTPUT);
  pinMode(solDwn, OUTPUT);
  pinMode(solUp1, OUTPUT);
  pinMode(solDwn1, OUTPUT);
  pinMode(swDwn, INPUT);
  pinMode(swUp, INPUT);
  pinMode(swLim1, INPUT);
  pinMode(swLim2, INPUT);
  pinMode(swLim3, INPUT);
  pinMode(swLim4, INPUT);
  pinMode(swLim5, INPUT);
  pinMode(swLim6, INPUT);

  digitalWrite(led, LOW);   // Initialise, turn off everything
```

```
 digitalWrite(solUp, HIGH);
 digitalWrite(solDwn, HIGH);
 digitalWrite(solUp1, HIGH);
 digitalWrite(solDwn1, HIGH);
}

void loop()
{
 // Routine to select up/down status of system
 // upState = 0 -> move down, upState = 1 -> move up, upstate = -1 -> stop
 moveDwn = digitalRead(swDwn);          // Read switch status
 moveUp = digitalRead(swUp);
 if (moveDwn == LOW && moveUp == HIGH)     // If move down pressed
 {
  digitalWrite(led, LOW);
  upState = 0;                    // Status = move down
  Serial.println("Down");
 }
 else if (moveDwn == HIGH && moveUp == LOW) // If move up pressed
 {
  digitalWrite(led, HIGH);
  upState = 1;                    // Status = move up
  Serial.println("Up");
 }
 delay(100);

 // Detect position of cylinder shaft
 sw1Pos = digitalRead(swLim1);          // Read limit switches
 sw2Pos = digitalRead(swLim2);
 sw3Pos = digitalRead(swLim3);
 sw4Pos = digitalRead(swLim4);
 sw5Pos = digitalRead(swLim5);
```

```
sw6Pos = digitalRead(swLim6);

if (sw1Pos == LOW) limVal = 1;          // Limit switch 1 active

if (sw2Pos == LOW) limVal = 2;          // Limit switch 2 active

if (sw3Pos == LOW) limVal = 3;          // Limit switch 3 active

if (sw4Pos == LOW) limVal = 4;          // Limit switch 4 active

if (sw5Pos == LOW) limVal = 5;          // Limit switch 5 active

if (sw6Pos == LOW) limVal = 6;          // Limit switch 6 active

if (sw1Pos == HIGH && sw2Pos == HIGH && sw3Pos == HIGH&& sw4Pos == HIGH&& sw5Pos ==
HIGH&& sw6Pos == HIGH) limVal = 0;

// All limit switches not active

if (upState == 1)      // If Up motion selected

{

 switch (limVal)

 {

  case 0:           // If no limit switch active


   while ( digitalRead(swLim1) == HIGH) // until limit switch 1 & 4 active

   {

   digitalWrite(solUp, LOW);           // Turn on up solenoid

   }

   //upState = -1;                  // upState is -1 means no direction is selected

   Serial.println("Position: ");        // Send values to PC

   Serial.println(limVal);

   break;                           // Exit

  case 1:           // If limit switch 1 active

   do

   {

     digitalWrite(solUp, LOW);         // Turn ON up solenoid

   }

   while ( digitalRead(swLim2) == HIGH); // until limit switch 2 &5 active

   digitalWrite(solUp, HIGH);            // Turn OFF up solenoid, so stop motion

   upState = -1;                      // upState is -1 means no direction is selected

   Serial.println("Position: ");        // Send values to PC
```

```
  Serial.println(limVal);
  break;                    // Exit

 case 2:           // If limit switch 2 active
  do
  {
   digitalWrite(solUp, LOW);       // Turn ON up solenoid

  }
  while ( digitalRead(swLim3) == HIGH); // until limit switch 3 & 6 active
  digitalWrite(solUp, HIGH);        // Turn OFF up solenoid, so stop motion
  upState = -1;                  // upState is -1 means no direction is selected
  Serial.println("Position: ");      // Send values to PC
  Serial.println(limVal);
  break;                    // Exit

  case 3:          // If no limit switch active

  while ( digitalRead(swLim4) == HIGH) // until limit switch 1 & 4 active
  {
  digitalWrite(solUp1, LOW);     // Turn on up solenoid

  }
  //upState = -1;                  // upState is -1 means no direction is selected
  Serial.println("Position: ");      // Send values to PC
  Serial.println(limVal);
  break;                    // Exit

 case 4:           // If limit switch 1 active
  do
  {
   digitalWrite(solUp1, LOW);       // Turn ON up solenoid
```

```
      }
      while ( digitalRead(swLim5) == HIGH); // until limit switch 2 &5 active
      digitalWrite(solUp1, HIGH);            // Turn OFF up solenoid, so stop motion
      upState = -1;                       // upState is -1 means no direction is selected
      Serial.println("Position: ");        // Send values to PC
      Serial.println(limVal);
      break;                              // Exit

     case 5:            // If limit switch 2 active
      do
      {
       digitalWrite(solUp1, LOW);         // Turn ON up solenoid

      }
      while ( digitalRead(swLim6) == HIGH); // until limit switch 3 & 6 active
      digitalWrite(solUp1, HIGH);            // Turn OFF up solenoid, so stop motion
      upState = -1;                       // upState is -1 means no direction is selected
      Serial.println("Position: ");        // Send values to PC
      Serial.println(limVal);
      break;                              // Exit
   }
 }
 if (upState == 0)      // If Down motion selected
 {
  switch (limVal)
  {
     case 0:            // If no limit switch active

      delay(200);                         // Wait, do nothing
      Serial.println("Position: ");        // Send values to PC
      Serial.println(limVal);
      break;                              // Exit
```

```
case 1:          // If limit switch 1 active
 do
 {
  digitalWrite(solDwn, LOW);        // Turn ON Down solenoid
 }
 while ( digitalRead(swLim1) == LOW);  // until limit switch 1& 3 inactive
 digitalWrite(solDwn, HIGH);          // Turn OFF down solenoid, so stop motion
 upState = -1;                       // upState is -1 means no direction is selected
 Serial.println("Position: ");        // Send values to PC
 Serial.println(limVal);
 break;                              // Exit

case 2:          // If limit switch 2 active
 do
 {
  digitalWrite(solDwn, LOW);        // Turn ON Down solenoid

 }
 while ( digitalRead(swLim2) == LOW);  // until limit switch 2& 4 inactive
 digitalWrite(solDwn, HIGH);          // Turn OFF down solenoid, so stop motion
 upState = -1;                       // upState is -1 means no direction is selected
 Serial.println("Position: ");        // Send values to PC
 Serial.println(limVal);
 break;                              // Exit

case 3:          // If limit switch 3 active
 do
 {
  digitalWrite(solDwn, LOW);        // Turn ON Down solenoid

 }
```

```
while ( digitalRead(swLim3) == LOW);  // until limit switch 3 & 6inactive
digitalWrite(solDwn, HIGH);           // Turn OFF down solenoid, so stop motion
upState = -1;                      // upState is -1 means no direction is selected
Serial.println("Position: ");        // Send values to PC
Serial.println(limVal);
break;                             // Exit


case 4:             // If limit switch 1 active
do
{
  digitalWrite(solDwn1, LOW);        // Turn ON Down solenoid
}
while ( digitalRead(swLim4) == LOW);  // until limit switch 1& 3 inactive
digitalWrite(solDwn1, HIGH);          // Turn OFF down solenoid, so stop motion
upState = -1;                      // upState is -1 means no direction is selected
Serial.println("Position: ");        // Send values to PC
Serial.println(limVal);
break;                             // Exit


case 5:             // If limit switch 2 active
do
{
  digitalWrite(solDwn1, LOW);        // Turn ON Down solenoid


}
while ( digitalRead(swLim5) == LOW);  // until limit switch 2& 4 inactive
digitalWrite(solDwn1, HIGH);          // Turn OFF down solenoid, so stop motion
upState = -1;                      // upState is -1 means no direction is selected
Serial.println("Position: ");        // Send values to PC
Serial.println(limVal);
break;                             // Exit
case 6:             // If limit switch 3 active
```

```
      do
      {
        digitalWrite(solDwn1, LOW);        // Turn ON Down solenoid


      }
      while ( digitalRead(swLim6) == LOW);  // until limit switch 3 & 6inactive
      digitalWrite(solDwn1, HIGH);          // Turn OFF down solenoid, so stop motion
      upState = -1;                         // upState is -1 means no direction is selected
      Serial.println("Position: ");        // Send values to PC
      Serial.println(limVal);
      break;                               // Exit
    }
  }
}
```

APPENDIX D

Arduino Coding with the use of 6 limit switches whereby double acting cylinder extend accordingly

```
  Components used:
  ---------------
  1x Arduino UNO
  2x 2 channel relay module
  6x Limit switches
  2x push button switches
  4x Relays 5V
*/

// Pin definitions
#define led     13
#define swDwn   2
#define swUp    3
#define swLim1  5
#define swLim2  6
#define swLim3  7
#define swLim4  8
#define swLim5  9
#define swLim6  10
#define solUp   A0
#define solDwn  A1
#define solUp1  A2
#define solDwn1 A3
// Variables
```

```
int moveDwn, moveUp;         // Up/Down switch values
int upState;                 // Up/down Status
int sw1Pos, sw2Pos, sw3Pos,sw4Pos,sw5Pos,sw6Pos;   // Limit Switch position variable
int limVal;                  // Limit Value


void setup()
{
  Serial.begin(9600);        // Serial comm for debugging
  pinMode(led, OUTPUT);
  pinMode(solUp, OUTPUT);
  pinMode(solDwn, OUTPUT);
  pinMode(solUp1, OUTPUT);
  pinMode(solDwn1, OUTPUT);
  pinMode(swDwn, INPUT);
  pinMode(swUp, INPUT);
  pinMode(swLim1, INPUT);
  pinMode(swLim2, INPUT);
  pinMode(swLim3, INPUT);
  pinMode(swLim4, INPUT);
  pinMode(swLim5, INPUT);
  pinMode(swLim6, INPUT);


  digitalWrite(led, LOW);   // Initialise, turn off everything
  digitalWrite(solUp, HIGH);
  digitalWrite(solDwn, HIGH);
  digitalWrite(solUp1, HIGH);
  digitalWrite(solDwn1, HIGH);
```

```
}
void loop()
{
  // Routine to select up/down status of system
  // upState = 0 -> move down, upState = 1 -> move up, upstate = -1 -> stop
  moveDwn = digitalRead(swDwn);             // Read switch status
  moveUp = digitalRead(swUp);
  if (moveDwn == LOW && moveUp == HIGH)      // If move down pressed
  {
   digitalWrite(led, LOW);
   upState = 0;                             // Status = move down
   Serial.println("Down");
  }
  else if (moveDwn == HIGH && moveUp == LOW) // If move up pressed
  {
   digitalWrite(led, HIGH);
   upState = 1;                             // Status = move up
   Serial.println("Up");
  }
  delay(100);

  // Detect position of cylinder shaft
  sw1Pos = digitalRead(swLim1);           // Read limit switches
  sw2Pos = digitalRead(swLim2);
  sw3Pos = digitalRead(swLim3);
  sw4Pos = digitalRead(swLim4);
  sw5Pos = digitalRead(swLim5);
  sw6Pos = digitalRead(swLim6);
  if (sw1Pos == LOW) limVal = 1;          // Limit switch 1 active
  if (sw2Pos == LOW) limVal = 2;          // Limit switch 2 active
  if (sw3Pos == LOW) limVal = 3;          // Limit switch 3 active
  if (sw4Pos == LOW) limVal = 4;          // Limit switch 4 active
```

```
if (sw5Pos == LOW) limVal = 5;          // Limit switch 5 active

if (sw6Pos == LOW) limVal = 6;          // Limit switch 6 active

if (sw1Pos == HIGH && sw2Pos == HIGH && sw3Pos == HIGH&& sw4Pos == HIGH&& sw5Pos ==
HIGH&& sw6Pos == HIGH) limVal = 0;

// All limit switches not active




if (upState == 1)      // If Up motion selected

{

 switch (limVal)

 {

  case 0:           // If no limit switch active


   while ( digitalRead(swLim1) == HIGH) // until limit switch 1 & 4 active

   {

   digitalWrite(solUp, LOW);          // Turn on up solenoid


   }

   //upState = -1;                // upState is -1 means no direction is selected

   Serial.println("Position: ");       // Send values to PC

   Serial.println(limVal);

   break;                       // Exit


  case 1:           // If limit switch 1 active

   do

   {

    digitalWrite(solUp, LOW);         // Turn ON up solenoid

   }

   while ( digitalRead(swLim2) == HIGH); // until limit switch 2 &5 active

   digitalWrite(solUp, HIGH);          // Turn OFF up solenoid, so stop motion

   upState = -1;                   // upState is -1 means no direction is selected

   Serial.println("Position: ");       // Send values to PC

   Serial.println(limVal);
```

```
    break;                          // Exit

  case 2:           // If limit switch 2 active
    do
    {
      digitalWrite(solUp, LOW);          // Turn ON up solenoid

    }
    while ( digitalRead(swLim3) == HIGH); // until limit switch 3 & 6 active
    digitalWrite(solUp, HIGH);           // Turn OFF up solenoid, so stop motion
    upState = -1;                        // upState is -1 means no direction is selected
    Serial.println("Position: ");        // Send values to PC
    Serial.println(limVal);
    break;                          // Exit

    case 3:           // If no limit switch active

    while ( digitalRead(swLim4) == HIGH) // until limit switch 1 & 4 active
    {
    digitalWrite(solUp1, LOW);           // Turn on up solenoid

    }
    //upState = -1;                      // upState is -1 means no direction is selected
    Serial.println("Position: ");        // Send values to PC
    Serial.println(limVal);
    break;                          // Exit

  case 4:           // If limit switch 1 active
    do
    {
      digitalWrite(solUp1, LOW);         // Turn ON up solenoid
    }
```

```
      while ( digitalRead(swLim5) == HIGH); // until limit switch 2 &5 active
      digitalWrite(solUp1, HIGH);            // Turn OFF up solenoid, so stop motion
      upState = -1;                    // upState is -1 means no direction is selected
      Serial.println("Position: ");        // Send values to PC
      Serial.println(limVal);
      break;                           // Exit

    case 5:            // If limit switch 2 active
      do
      {
        digitalWrite(solUp1, LOW);          // Turn ON up solenoid

      }
      while ( digitalRead(swLim6) == HIGH); // until limit switch 3 & 6 active
      digitalWrite(solUp1, HIGH);            // Turn OFF up solenoid, so stop motion
      upState = -1;                    // upState is -1 means no direction is selected
      Serial.println("Position: ");        // Send values to PC
      Serial.println(limVal);
      break;                           // Exit
  }
}

if (upState == 0)       // If Down motion selected
{
  switch (limVal)
  {
    case 0:            // If no limit switch active

      delay(200);                      // Wait, do nothing
      Serial.println("Position: ");        // Send values to PC
      Serial.println(limVal);
      break;                           // Exit
```

```
case 1:            // If limit switch 1 active
 do
 {
  digitalWrite(solDwn, LOW);        // Turn ON Down solenoid
 }
 while ( digitalRead(swLim1) == LOW);  // until limit switch 1& 3 inactive
 digitalWrite(solDwn, HIGH);           // Turn OFF down solenoid, so stop motion
 upState = -1;                         // upState is -1 means no direction is selected
 Serial.println("Position: ");        // Send values to PC
 Serial.println(limVal);
 break;                               // Exit

case 2:            // If limit switch 2 active
 do
 {
  digitalWrite(solDwn, LOW);        // Turn ON Down solenoid

 }
 while ( digitalRead(swLim2) == LOW);  // until limit switch 2& 4 inactive
 digitalWrite(solDwn, HIGH);           // Turn OFF down solenoid, so stop motion
 upState = -1;                         // upState is -1 means no direction is selected
 Serial.println("Position: ");        // Send values to PC
 Serial.println(limVal);
 break;                               // Exit

case 3:            // If limit switch 3 active
 do
 {
  digitalWrite(solDwn, LOW);        // Turn ON Down solenoid
 }
 while ( digitalRead(swLim3) == LOW);  // until limit switch 3 & 6inactive
```

```
digitalWrite(solDwn, HIGH);          // Turn OFF down solenoid, so stop motion
upState = -1;                        // upState is -1 means no direction is selected
Serial.println("Position: ");        // Send values to PC
Serial.println(limVal);
break;                               // Exit

case 4:          // If limit switch 1 active
do
{
  digitalWrite(solDwn1, LOW);        // Turn ON Down solenoid
}
while ( digitalRead(swLim4) == LOW);  // until limit switch 1& 3 inactive
digitalWrite(solDwn1, HIGH);         // Turn OFF down solenoid, so stop motion
upState = -1;                        // upState is -1 means no direction is selected
Serial.println("Position: ");        // Send values to PC
Serial.println(limVal);
break;                               // Exit

case 5:          // If limit switch 2 active
do
{
  digitalWrite(solDwn1, LOW);        // Turn ON Down solenoid

}
while ( digitalRead(swLim5) == LOW);  // until limit switch 2& 4 inactive
digitalWrite(solDwn1, HIGH);         // Turn OFF down solenoid, so stop motion
upState = -1;                        // upState is -1 means no direction is selected
Serial.println("Position: ");        // Send values to PC
Serial.println(limVal);
break;                               // Exit

case 6:          // If limit switch 3 active
```

```
      do
      {
        digitalWrite(solDwn1, LOW);         // Turn ON Down solenoid


      }
      while ( digitalRead(swLim6) == LOW);  // until limit switch 3 & 6inactive
      digitalWrite(solDwn1, HIGH);           // Turn OFF down solenoid, so stop motion
      upState = -1;                       // upState is -1 means no direction is selected
      Serial.println("Position: ");        // Send values to PC
      Serial.println(limVal);
      break;                              // Exit
    }
  }
}
```

APPENDIX E

Arduino coding of Flex Sensor with one double acting cylinder

```
#define solUp   A0
#define solDwn  A1
int flexpin=A4; // select flex sensor at pin A4
int pos=90;     //initially at position 90
int flex[0];    // flex value at 0
int x=0;
void setup()    // select output and input pin
{
 Serial.begin(9600);
  pinMode(solUp, OUTPUT);
  pinMode(solDwn, OUTPUT);
  pinMode( A4, INPUT);
  digitalWrite(solUp, HIGH);  // initial state for solenoids which is inactivate
  digitalWrite(solDwn, HIGH);
}
void loop()
{
flex[x]=analogRead(flexpin); // read flexsensor value
if(Serial.available())      // print flex sensor value on serial monitor
{
Serial.println(flex[x]);
delay(100);
}
```

```
if (flex[x]>800)       //the value show the resistance of flex sensor in bytes
{
digitalWrite(solDwn, HIGH);  //initially solenoid down is inactive
delay(50);
}
else
{
digitalWrite(solDwn,LOW);  // solenoid down activate
delay(50);
}
if (flex[x]>855)
{
digitalWrite(solUp, HIGH); //initially solenoids up is inactive
delay(50);
}
else
{
digitalWrite(solUp,LOW); // solenoids up activate
delay(50);
}
}
```

APPENDIX F

Arduino coding of Flex Sensor with two double acting cylinder

```
#define solUp   A0
#define solDwn  A1
#define solUp1  A2
#define solDwn1 A3
int flexpin=A4;   // select flex sensor at pin A4
int pos=90;       //initially at position 90
int flex[0];      // flex value at 0
int x=0;
void setup()   // select output and input pin
{
Serial.begin(9600);
pinMode(solUp, OUTPUT);
pinMode(solDwn, OUTPUT);
pinMode(solUp1, OUTPUT);
pinMode(solDwn1, OUTPUT);
pinMode( A4, INPUT);
digitalWrite(solUp, HIGH);  // initial state for solenoids which is inactivate
digitalWrite(solDwn, HIGH);
digitalWrite(solUp1, HIGH);
digitalWrite(solDwn1, HIGH);
}
void loop()
{
flex[x]=analogRead(flexpin);    //read flexsensor value
```

```
if(Serial.available())
{
Serial.println(flex[x]);  // print flex sensor value on serial monitor
delay(100);
}
if (flex[x]>800)     //the value show the resistance of flex sensor in bytes
{
digitalWrite(solDwn, HIGH);     //initially solenoids down is inactive
digitalWrite(solDwn1, HIGH);
delay(50);
}
else
{
digitalWrite(solDwn,LOW);      // solenoids down activate
digitalWrite(solDwn1,LOW);
delay(50);
}
if (flex[x]>855)
{
digitalWrite(solUp, HIGH);    //initially solenoids up is inactive
digitalWrite(solUp1, HIGH);
delay(50);
}
else
{
digitalWrite(solUp,LOW);   // solenoids up activate
digitalWrite(solUp1,LOW);
delay(50);
}
}
```

APPENDIX G

Arduino coding of Accelerometer

```
void setup()
{
  Serial.begin(9600);
}
int analog_x,analog_y,analog_z;
float vol_x,vol_y,vol_z;
float add_x,add_y,add_z;
float g_x,g_y,g_z;
float degree_x,degree_y,degree_z;
void loop()
{
 analog_x=analogRead(0);
 analog_y=analogRead(1);
  analog_z=analogRead(2);
  vol_x=analog_x*5.0/1024;//convert analog_x-->voltage value(v)
  vol_y=analog_y*5.0/1024;
  vol_z=analog_z*5.0/1024;
 //range x: 0.85 - 2.61    1.8
 //      y: 0.96 - 2.53    1.74
 //      z: 0.72 - 2.23    1.48
  add_x=vol_x-1.72;//calculate the added x axis voltage value
  add_y=vol_y-1.74;
  add_z=vol_z-1.48;
  g_x=add_x/0.78;//calculate the gram value
  g_y=add_y/0.8;
  g_z=add_z/0.8;
```

```
 if(g_x<=1&&g_x>=-1) //We use this condition to prevent the overflow of asin(x).( If x>1 or x<-1, asin(x)=0)
 {
 degree_x=asin(g_x)*180.0/PI;//calculate the degree value
 degree_y=asin(g_y)*180.0/PI;
 degree_z=asin(g_z)*180.0/PI;
 }
 //fix the overflow condition
 if(g_x>1)
 degree_x=90;
  if(g_x<-1)
 degree_x=-90;
  if(g_y>1)
 degree_y=90;
  if(g_y<-1)
 degree_y=-90;
  if(g_z>1)
 degree_z=90;
  if(g_z<-1)
 degree_z=-90;
//  Serial.print("x:");
 Serial.println(degree_x);
//  Serial.print(" y:");
//  Serial.print(degree_y);
//  Serial.print(" z:");
//  Serial.println(degree_z);
 delay(200);
```