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PROJECT REPORT

BEKU 4894

DESIGN AND DEVELOPMENT OF AN AUTOMATED WINDOW CLIMBING ROBOT

AHMAD FAHIM BIN MUSTAFA

Bachelor of Mechatronics Engineering

2014/2015

"I hereby declare read through this report entitle "Design and Development of An Automated Window Climbing Robot" and found that it has comply the partial fulfillment for awarding the degree of Bachelor of Mechatronic Engineering"

Signature : ……………………………………….

Supervisor's Name : DR. MUHAMMAD FAHMI BIN MISKON

Date : ……………………………………….

DESIGN AND DEVELOPMENT OF AN AUTOMATED WINDOW CLIMBING ROBOT

AHMAD FAHIM BIN MUSTAFA

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

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2014/2015

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Name : AHMAD FAHIM BIN MUSTAFA

Date : ....

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ABSTRACT

Window cleaning is the most dangerous jobs when it comes to clean the skyscraper. There are many types of window cleaning technique that apply in this job. These techniques are dangerous if highly safety precaution do not take seriously and can lead to serious accident and death. Many reports regarding accidents that involving falling from skyscraper which results in serious injury and death to window cleaning workers. Until today, we are still using the same methods that are dangerous to the workers. To overcome this problem, an automated window climbing robot was designed and developed by using double acting pneumatic cylinder with suction mechanism in order to help the robot climb the window glass. When develop a window climbing robot, the major problem is gravitational force exerted toward the earth. As the solution, a window climbing robot is develop using the vacuum suction mechanism as the main holding mechanism with the helping of suction cups. The desired path for the robot which can hold and move on window glass surface. Performance of the robot in term of velocity of robot, the theoretical holding force of robot and vacuum suction pressure required are analyzed in this research. In FluidSim Software, the double acting pneumatic cylinder is simulate to find its theoretical velocity. In the experiment, the prototype is travel upward vertically follow the path. The distance travel by the prototype is taken by time to complete the path. The velocity of the prototype can be calculated. The mass of the robot is $0.466\,kg$ and the theoretical holding force of the prototype is $55.654\,N$ where the friction value is 0.5. The diameter required for the suction cups is $35\,mm$ and the minimum pressure required to hold the robot is $9.5\,bar$ and the empirical acceleration is $30\,m/s^2$. For the experiment, the velocity of cylinder is increase significantly with the increasing of pressure. The average velocity of prototype is $0.48\,m/s$ to complete $50\,cm$ path.

ABSTRAK

Pembersihan tingkap adalah satu pekerjaan yang merbahaya apabila ia melibatkan pembersihan bangunan pencakar langit. Terdapat pelbagai jenis teknik pencuci tingkap yang diaplikasi di dalam perkerjaan ini. Teknik ini berbahaya jika langkah keselamatan tidak di ambil serius dan boleh membawa kepada kemalangan dan kematian. Banyak laporan mengenai kemalangan yang melibatkan pekerjaan ini dimana ia membawa kepada kecederaan serius dan kehilangan nyawa terhadap pekerja pembersih tingkap. Sehingga sekarang, mereka masih menggunakan kaedah yang berbahaya kepada pekerja. Untuk mengatasi masalah ini, robot memanjat tingkap direka bentuk dan dibangunkan dengan menggunakan satu silinder pneumatik bertindak berganda dan mekanisma penyedutan. Apabila membangunkan robot pemananjat tingkap ini, masalah utama dihadapi ialah tekanan graviti oleh dikenakan terhadap robot. Sebagai penyelesaian, satu robot memanjat tingkap dibangunkan dengan menggunakan mekanisma vakum penyedutan sebagai mekanisma pengangan utama dengan bantuan penyedut. Jalan yang digunakan oleh robot akan di reka dan dibangunkan. Prestasi robot dari segi halaju robot, daya pegangan teori robot dan sedutan vakum tekanan yang diperlukan dianalisis dalam kajian ini. Dalam Perisian FluidSim, silinder pneumatik bertindak berganda adalah simulasi untuk mencari halaju tujahan rodnya. Dalam eksperimen, prototaip berjalan menaik menegak mengikuti jalan yang disetkan. Jarak yang di lalui oleh prototaip diambil dengan masa yang diperlukan untuk melengkapkan jalan tersebut. Jisim robot adalah $0.466\ kg$ dan daya pegangan teori prototaip adalah $55.654\ N$ di mana nilai geseran ialah 0.5. Diameter cawan sedutan adalah $35\ mm$ dan tekanan minimum yang diperlukan untuk memegang robot adalah $9.5\ bar$ dan pecutan empirikal bagi pneumatik adalah $30\ m/s^2$. Untuk percubaan, halaju silinder adalah peningkatan ketara dengan peningkatan tekanan. Halaju purata prototaip adalah $0.48\ m/s$ untuk melengkapkan $50\ cm$ perjalanan.

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WCR	Window Climbing Robot
AC	Alternating Current
DC	Direct Current

CHAPTER 1

INTRODUCTION

1.0 Overview

In this chapter, there are sub-sections which will explain more details about the research background, motivation, problem statement, objectives, and scope of research. Those explanations will provide overall understanding for audience regarding the project that researcher design and develop. Furthermore, this research may be useful in the future after few modification and improvement.

1.1 Research Background

Nowadays, a major problem of the skyscrapers is cleaning at the outside of the building. There are some methods to clean the outside of the skyscrapers such as using Bosun's chair. The Bosun's chair are moving upward and downward in order to complete the cleaning task. In this method, the man power is used to complete the task. For example, Figure 1.1 and Figure 1.2 shows how the Bosun's chair is used to transport the worker to complete their task.

Figure 1.1: Workers complete their task using Bosun's chair

Figure 1.2: Worker cleaning the window using Bosun's chair

Besides Bosun's chair, there is another method that is very popular in this cleaning sector such as using platform. The platform is using cable that attach from the roof of the skyscrapers. The platforms are carrying the workers and their cleaning equipment to complete their cleaning task. This method is applied as shown as figure 1.3.

Figure 1.3: Cleaning workers are using platform to complete their task

Another popular method for cleaning window glass is using crane. The crane is using to transport the workers to the particular window glass at the ground. In this method, there is limitation on the height of the building because the crane is control on the ground as figure 1.4.

Figure 1.4: Workers using crane for their job

1.2 Motivation

By year 2014, there are many tall building have been built as the increscent of population. Most tall building can be seen in Hong Kong, Dubai, Taiwan and even Malaysia. Tall building usually comes up with some problem where a worker needs to risk their life for cleaning the building's window. Media reported many accidents happen to window cleaning workers and some of them faced death or disable for the rest their life. In January, 5 2008, Alcides Moreno, 37, fell almost $500\ ft.$ from the roof of a Manhattan skyscraper [1]. BBC News reported in April 22 1998, two window cleaners were killed when the cradle they were working in plunged $100\ ft.$ to the ground [2].

As conclusion, this project was undertaken to design a window cleaning robot that can replace the window cleaner's job. This robot is using simple pneumatic system and double acting cylinder as the main actuator of the robot with the helping suction cups to hold on window glass surface.

1.3 Problem Statement

There are several types of design of the robot that are need to analyze based on their performance in holding mechanism and locomotion mechanism. The design are mobile robot, walking robot and the rigging robot. Each of the design have their own performance in holding mechanism and locomotion mechanism based on mass of the robot, velocity of the robot moving on the window surface and the complexity of the holding mechanism.

Firstly, the most problem that occurred in developing a wall climbing robot is difficult for the robot to overcome the gravitational force exerted towards the earth. The key problem with this explanation is the mass of the robot. The mass of the robot will affect the gravitational force. When the mass of the robot increase, the gravitational force exerted on the robot also increase. So, a lightweight robot is suggest to overcome this problem. The window climbing robot design must have at least two separately part, first window cleaner and second is control system.

Secondly, the velocity of the robot is one of the major problem in designing the robot. Each of the design have their own performance on the velocity. For the mobile robot, the velocity is good but it have complex mechanism. For the walking robot, the velocity is fair, not as good as mobile robot and it have fair complex mechanism. For the rigging type robot, the velocity of the robot is fair but the robot is not handy and easy to operate because it have different mechanism to hanging the robot on the window surface.

Another problem happen is the robot tends to fall down when about to move if the suction and locomotion mechanism is not well synchronized. A suitable pneumatic system is design to hold the robot on the window surface. Number of suction cups also must take in account because it will increase the mass of robot.

Evidence suggests that holding and locomotion mechanism are among the most important factors for designing and develop a prototype of window climbing robot. For holding mechanism a vacuum suction with minimum number of suction cups needed and for the locomotion, it suggested a double acting pneumatic cylinder use as the main actuator of this robot.

1.4 Objectives

Based on the problem statement stated above, the objectives of this project are:

i) To design window climbing robot using double acting pneumatic cylinder with the vacuum suction mechanism.
ii) To design and develop the desired path for the prototype which can hold and move on window glass surface.
iii) To analyze performance of the robot in term of velocity of prototype, the theoretical holding force of robot and vacuum suction pressure required.

1.5 Scope of Research

The scope of this project is focused on design mechanical part of the robot. In the mechanical part, researcher concentrated on two elements such as suction mechanism and locomotion mechanism. Researcher also focus on analyze the different pressure in the suction cups and method to control the vacuum suction. This prototype is analyze by simulation and lab experiment are conducted to test this prototype. The simulation is using Festo FluidSim software, and the experiment is to find the velocity of the prototype by different pressure supply from the compressor by take a constant distance and time to complete the distance. The distance is $50\ cm$ and time taken the prototype will be recorded. This prototype will move in vertical straight line only on the window glass surface.

CHAPTER 2

PROJECT BACKGROUND AND LITERATURE REVIEW

2.0 Overview

This chapter consists of fundamental theories based on the characteristic of window climbing robot that are mention in chapter 1. Besides that, comparison between design, locomotion mechanism and holding mechanism of the robot based on the previous research are in the literature review.

2.1 Project Background

This subsection is the project background of this project. There are 3 part of fundamental theories that is major problem and must be take into account when develop the prototype of window climbing robot.

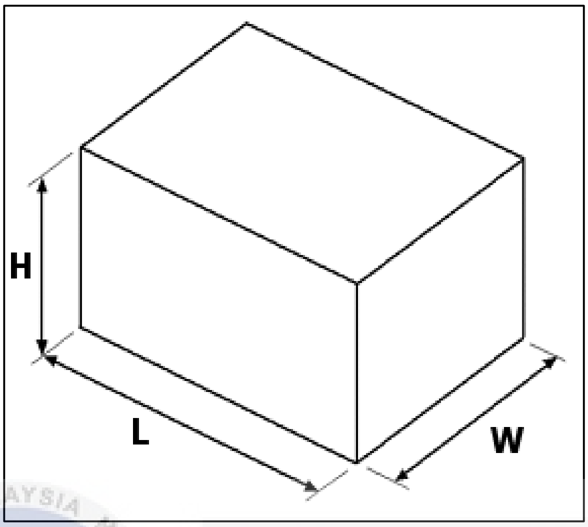
2.1.1 Mass of the prototype

The mass of the prototype can be calculated based on the equation (2.1). The mass of prototype must include all the component on the prototype.

$$m = L \times W \times H \times \rho \tag{2.1}$$

Where

m : $Mass\ of\ the\ prototype$



L : $Length\ (cm)$

W : $Width\ (cm)$

H : $Height\ (cm)$

ρ : $Density\ (g/cm^3)$

Figure 2.1: Dimension of the prototype

2.1.2 Theoretical Holding Forces

The holding force of the suction cups surges relatively with the difference between the environmental weight and the weight inside the cup. This implies the holding force is corresponding to the weight distinction and the suction space. Greater the contrast between climatic weight and weight in the suction cup, the more the possessions force. The force can contrast contingent upon a change of the weight distinction and region limits.

In this part, the suction cup will attach to the window glass and moving vertically. The holding force acting on the suction cup is calculated by using the equation (2.2). This lifting force is used to lift up the robot from bottom.

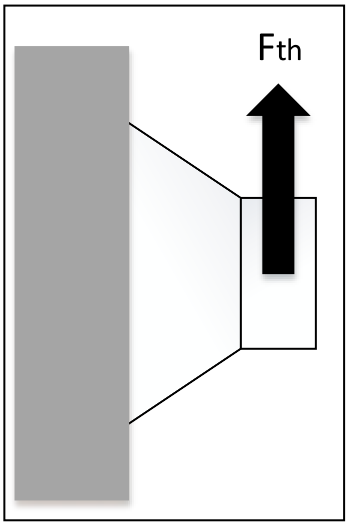


Figure 2.2: Lifting force on the suction cup

$$F_{th} = \frac{m}{\mu} \times (g + a) \times s \qquad (2.2)$$

Where

F_{th} : $Theoritical\ holding\ force$ (N)

m : $Mass(kg)$

g : $Acceleration\ due\ to\ gravity$ ($9.81\ m/s^2$)

a : $Acceleration\ of\ system\ (30m/s^2)\ consider\ the\ emergency\ of\ situation$

μ : $Coefficient\ of\ friction$

s : $Safety\ factor\ (vertical$: 1.5)

2.1.3 Suction Cup Diameter

Suction cups are utilized to hold and move robot on the window surface. The climatic weight presses the suction cup against the window surface when the air weight is greater than the weight between the suction cup and the window surface. This weight fluctuation is come to by connecting the suction cup to a compressor, which discharges the air from the space between the cups and the window surface. In the event that the suction cup is in association with the surface of the window, outside air can't enter it from the sides and a vacuum is created.

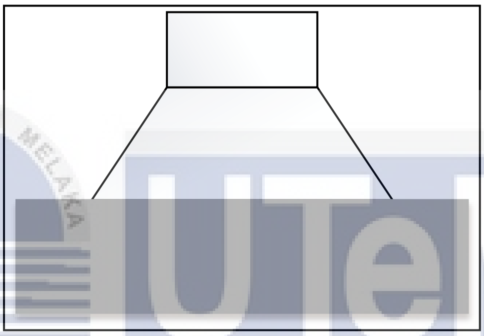


Figure 2.3: Suction cup

The diameter of suction cup is based on the theoretical holding force of the prototype. The theoretical holding force of the prototype is stated in equation (2.2). The shape of the suction cup is selected based on the surface of the window glass. As known the window glass surface is flat, smooth and undulating surface, so the type of suction cups selected is standard type. The diameter of suction cup is based on table 2.1.

Table 2.1: Diameter of suction cup [3]

Diameter (mm)	Suction Cup Round					Size (mm)	Suction Cup Oval
	Standard	Extra Deep	1.5 convolution bellows	3.5 convolution bellows	Bell shaped		Oval
2	0.10N	-	-	-	-	4×10	2.0N
4	0.46N	-	-	-	-	4×20	3.4N
6	1.10N	-	-	-	-	6×10	2.9N
8	2.30N	-	4.7N	3.9N	-	6×20	5.9N
10	3.90N	-	-	-	-	8×20	8.0N
15	8.50N	9.8N	12.9N	8.2N	-	8×30	10.9N
20	16.30N	17.0N	26.2N	20.8N	36N	10×30	15.2N
30	40.80N	37.2N	52.3N	42.4N	64N	15×45	32.0N
40	69.60N	67.7N	72.6N	63.4N	97N	20×60	62.8N
50	105.80N	103.6N	-	-	134N	25×75	92.5N
60	166.10N	162.5N	213.6N	-	245N	30×90	134.4N
80	309.70N	275.0N	-	-	375N	-	-
100	503.60N	440.8N	-	-	-	-	-
150	900.00N	-	-	-	-	-	-
200	1610.00N	-	-	-	-	-	-

2.1.4 Force act on Suction Cup

Based on the free body diagram in figure 2.4, the force acting on the suction cups is two, namely F_y and F_x. The F_y force is the force acting perpendicularly to the vertical surface and the F_x the force act to the gravitational force. The force F_x is equal to the W where it is weight of the robot. The force acting perpendicular toward the surface, F_y is the force acting on toward the ground, F_x multiply with coefficient of friction between suction cup and the vertical surface. From the equation (2.6), the required pressure can be determine.

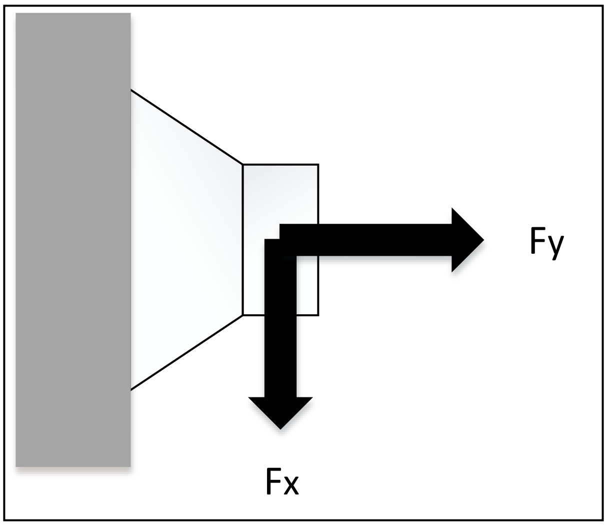


Figure 2.4: Forces acting on the suction cup

$$F_x = W$$

$$W = mg$$

$$F_x = mg \quad (2.3)$$

$$F_x = \mu . F_y$$

$$F_y = \frac{F_x}{\mu} \quad (2.4)$$

Substitute (2.3) into (2.4),then

$$F_y = \frac{mg}{\mu} \quad (2.5)$$

$$F = \mu PA$$

Rearrange the equation and finally:

$$P = \frac{F_y}{A} \quad (2.6)$$

Where

F_x : $Force\ acting\ toward\ gravity$

F_y : $Force\ acting\ perpendicular\ to\ surface$

W : $Weight\ of\ the\ prototype\ (N)$

m : $Mass\ of\ the\ prototype\ (kg)$

g : $Acceleration\ due\ gravity\ (9.81\, m/s^2)$

μ : $Friction\ value\ (0.5)$

P : $Pressure\ Required\ (kPa)$

A : $Area\ of\ Suction\ cup$

2.2 Literature Review

In this sub topic, there are 3 criteria that are needed to be considering while design and develop prototype window climbing robot. There are holding mechanism, locomotion mechanism and its path, and actuators. This subtopic will discuss in detail about all the criteria.

2.2.1 Holding Mechanism

Holding mechanism is a mechanism which is use to attach the robot on the window glass surface. The mechanism is main component of the development the window climbing robot. In this sub topic, there are several types of holding mechanism that are used by previous researcher. For example vacuum suction mechanism and magnetic attraction force mechanism. The mechanisms will describes and explains more detail in this subtopic.

2.2.1.1 Vacuum Suction Mechanism

Katsuki, Yamamoto and Ikeda state in Development of a High Efficiency and High Reliable Glass Cleaning Robot with a Dirt Detect Sensor that the holding mechanism of their robot is vacuum suction mechanism. This robot uses the vacuum suction cup in order to hold the robot vertically on the window surface. This robot is using 4 small suction cups in order to suck the window glass to prevent the robot from breaking away from vertical surface. Negative pressure is generated by the vacuum pump. The result of this research is the robot can move freely on the window surface by using the vacuum suction pump at $-70\ kPa$ for one suction cup. The table shows the specification of the window cleaning robot [4].

Table 2.2: Components of window cleaning robot [4]

Component	**Specification**
Motor	Futaba Co.: Model S3801, Stall torque: 11.2 $kg.cm$
Vacuum Solenoid valve	Takasago Co.: Model STV-2-M6, Normally Closed
Vacuum Pump	Matsushita Nitto Electric Co. Ltd: DP0140 Ultimate vacuum: $-53.3\ kPa$
Suction Cup	Lee Co.: Model Spare-204 Diameter: $40mm$

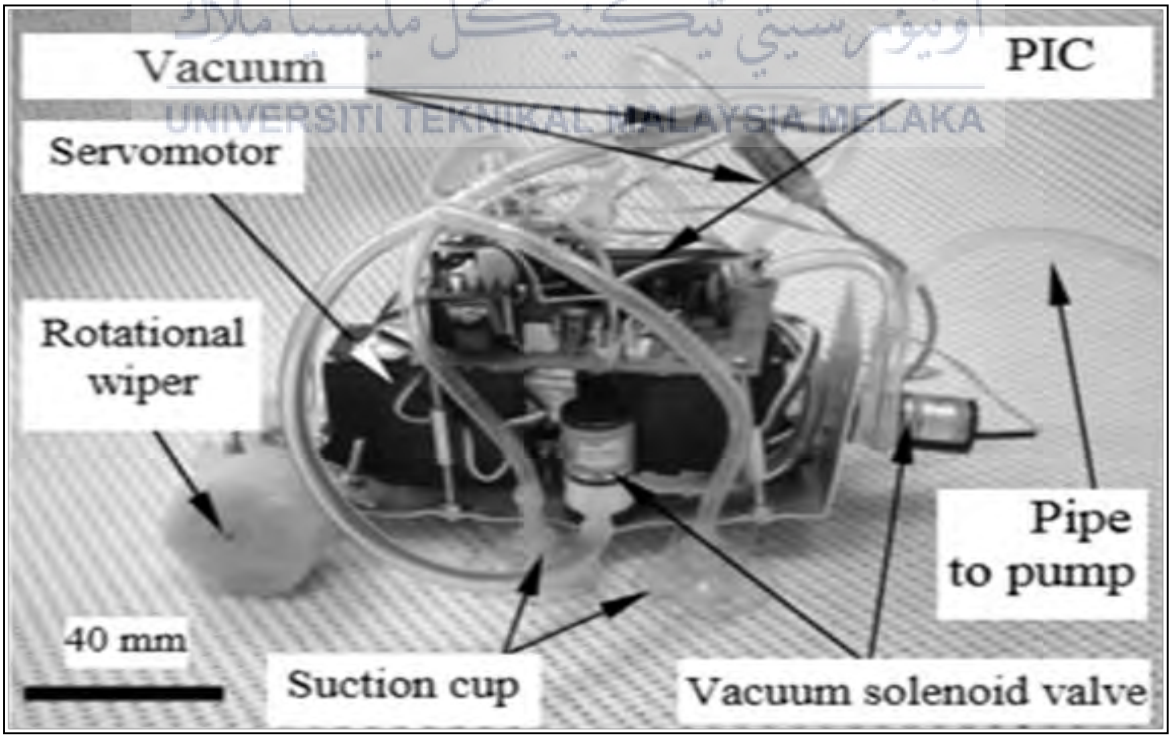


Figure 2.5: Window cleaning robot [4]

Another research is in A Small Window-Cleaning Robot for Domestic Use by Lui, Jiang and Hu also using the vacuum suction mechanism. In this research, there is only one big suction cup at the center of the robot. It mounted with revolving shaft that is needed to drive the robot. The suction cup selected from PTFE (Polytetrafluoroethylene) material. The suction force *S*, friction force at suction cup F_s, and Traction *T*, are calculated from the equation (2.7), (2.8), (2.9), and (2.10) [5].

$$S = PA \tag{2.7}$$

$$S = N_s + N_w \tag{2.8}$$

$$F_s = \mu_s N_s \tag{2.9}$$

$$F_w = \mu_w N_w \tag{2.10}$$

Where

P : *Negative pressure generated by the vacuum pump*

A : *Suction cup surface area*

N_s : *Normal component of reaction towards a suction cup*

N_w : *Normal component of reaction towards a drive wheels*

F_s : *Friction force at a suction cup*

F_w : *Friction force at a wheels*

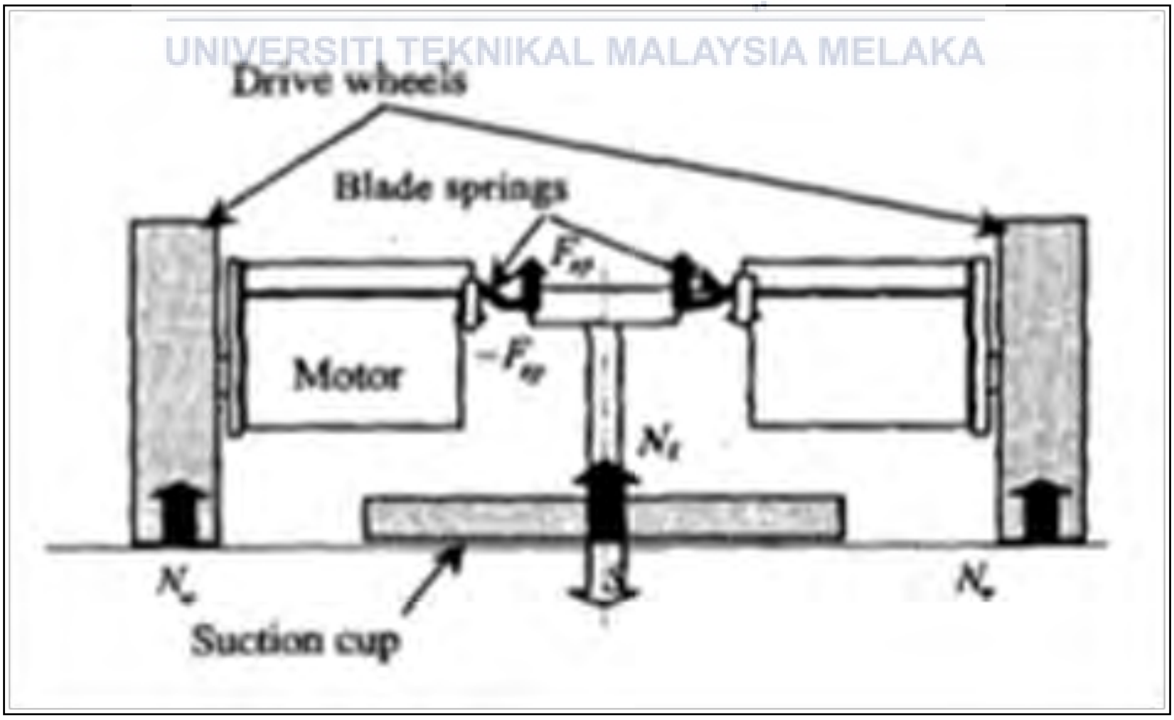


Figure 2.6: Basic structure of window cleaning robot [5]

2.2.1.2 Magnetic Attractive Force Mechanism

The magnetic attraction force mechanism are using in this research where the Windoro have four permanent magnet part at the inner and outer unit of Windoro. The magnetic force will act as holding mechanism for the Windoro and the Windoro inner and outer unit will sandwich the window glass. The inner unit of Windoro will control the attraction force of the robot. This mechanism will save the energy efficiency and it is safe to the robot from fall down [7].

Table 2.3: Specification for Windoro inner unit [7]

Component	Specification
Dimension	$200\ mm \times 200\ mm \times 50\ mm$
Weight	$1.6\ kg$
Continuous work time	$180\ min$
Power source	Li-ion battery, 11.1 v
Motors	DC servo motor ×2
Magnet	Ring shape neodymium ×4 [N50N52]

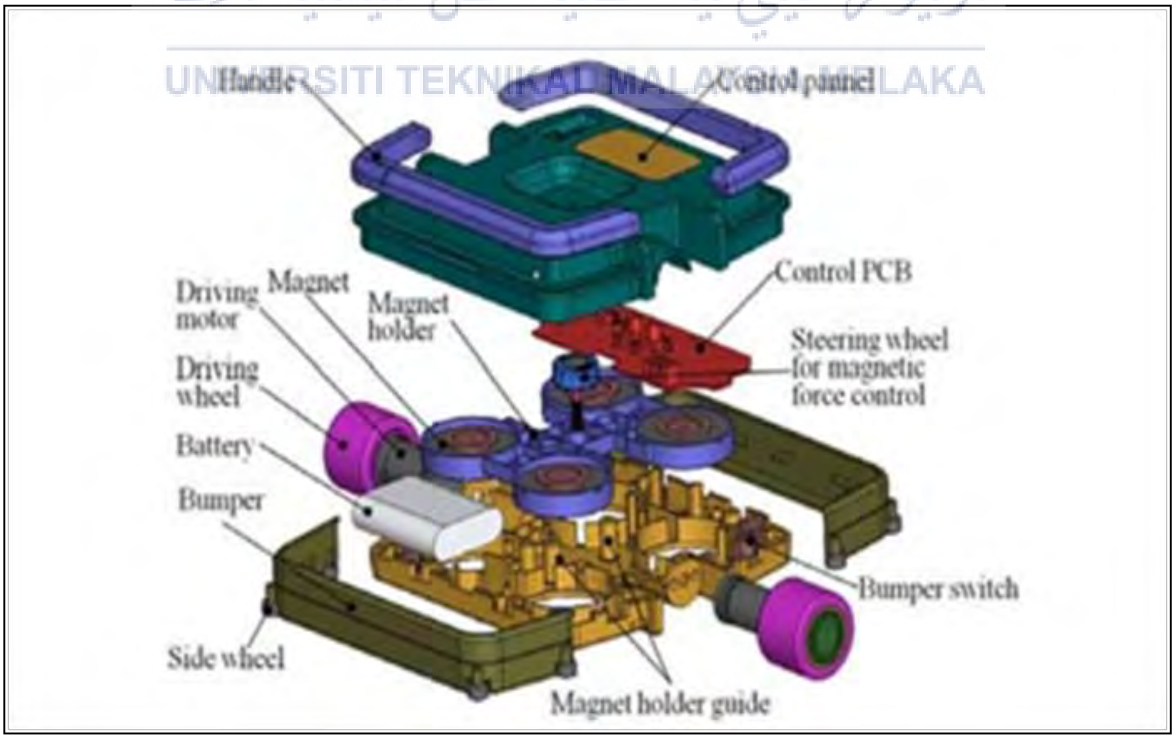


Figure 2.7: Windoro inner unit [7]

Table 2.3: Specification for Windoro outer unit [7]

Component	Specification
Dimension	$200\ mm \times 200\ mm \times 35\ mm$
Weight	$1.4\ kg$
Continuous work time	$180\ min$
Power source	Li-ion battery, $7.4\ v$
Motors	DC servo motor ×4 Pump motor×1
Magnet	Ring shape neodymium × 4 [N50≈N52]

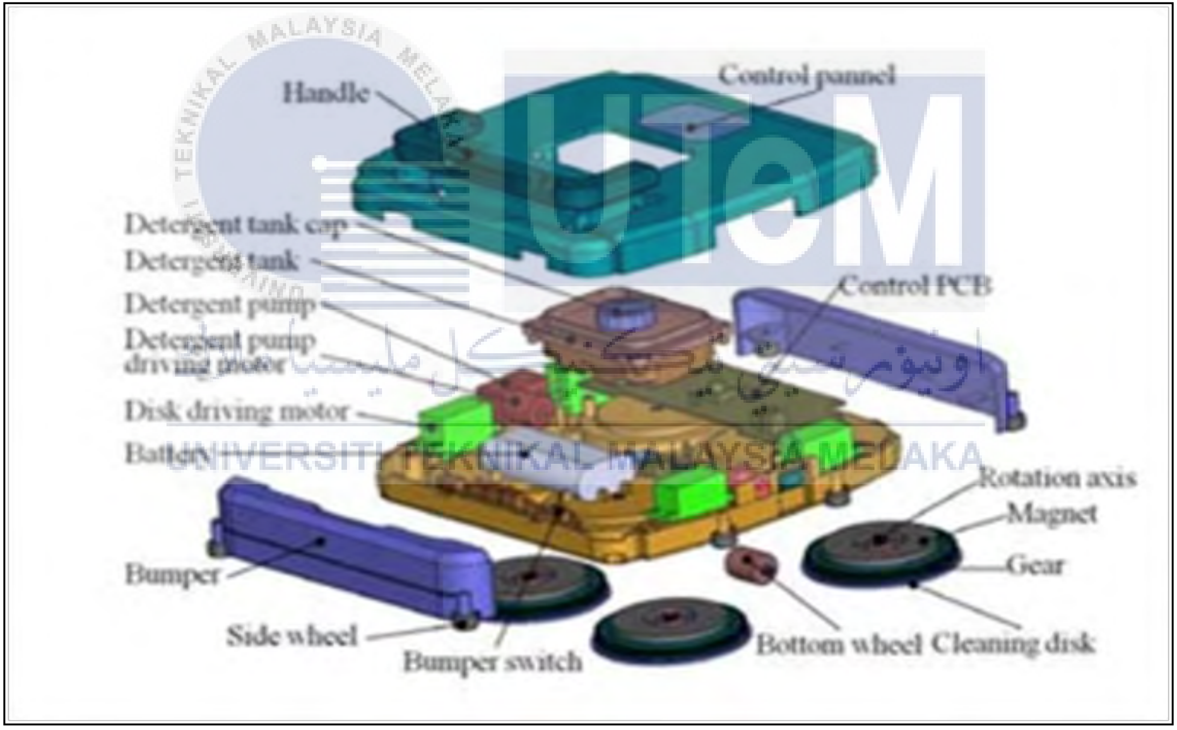


Figure 2.8: Windoro outer unit [7]

Finally, suction pumps are the best choice for holding mechanism of the window cleaning robot rather than magnetic force. It is essential equipment making the robot adhere to the surface of window glass [5]. It is because it easier to control the air pressure inside of suction cup and the weight of the air circuit component is lightweight, suitable for the window cleaning robot. Hence it makes enough hold force to hold the robot at the surface of the window.

2.2.2 Locomotion Mechanism and Desired Path

Locomotion mechanism is a mechanism which is use to drive the robot on the window glass surface. This mechanism is the main component of the development the window cleaning robot. In this sub topic, there are several types of locomotion mechanism that are used by previous researcher. For examples there are Two Drive Wheels, Walking and Rigging. The mechanisms will describes and explains more detail in this subtopic.

2.2.2.1 Two Drive Wheels Mechanism

In order to move freely on window glass surface, linearity and rotatability of the robot must be considered to achieve the smoothest desired path with minimum overlapping swipe for the robot. The Two Drive wheels have good linearity and rotatability and it only requires minimum one suction cup to adhere the surface of window glass. In this mechanism, the most important factors are the ratio of friction force of tire and suction cup. High friction between the tire and surface of the window glass transmits the torque while low friction between suction cup and surface of window glass are needed to achieve good linearity and rotatability of the robot on the window glass surface [6].

$$T = \frac{K\tau}{R_w} \tag{2.11}$$

$$F_s \ll T < F_w \tag{2.12}$$

Where

K : *Torque coefficient*

τ : *Torque generated by geared motor*

R_w : *Radius of wheel*

F_s : *Friction force at a suction cup*

F_w : *Friction force at a wheels*

Based on equation (2.12), material with low friction force is used as suction cup and the material with high friction force is used as tire.

2.2.2.2 Walking Mechanism

In this mechanism, the researcher is using a quadruped robot that has four legs and connected by two chassis. The Forward pair of the leg is combination between the left and right foreleg construct forward beam and while the Rear pair of the leg is combination between left and right hind leg construct rear beam. The beams are installed with two shafts of servomotors respectively and the servomotors drive for rotational of two beams separately. The figure 2.8 shows the structure of the window cleaning robot at bottom view [5].

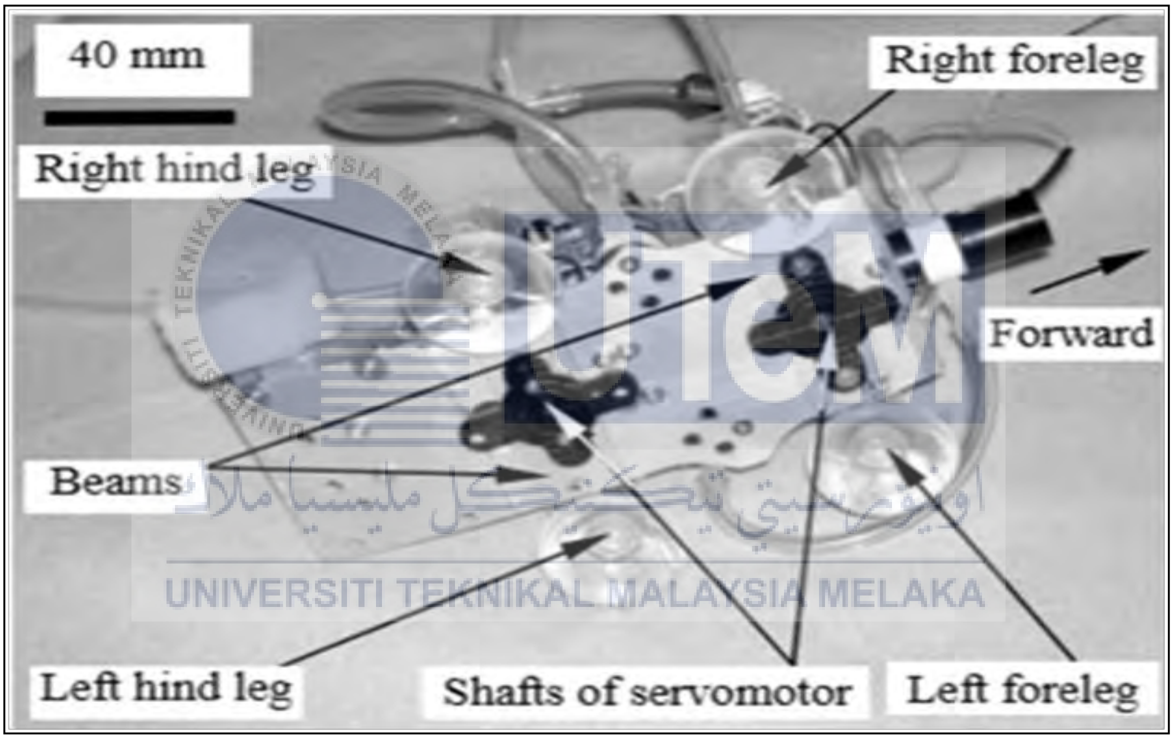


Figure 2.9: Bottom view of Window Cleaning Robot [5]

Figure 2.10 demonstrates six depiction for one movement cycle of the robot when it makes headway to the highest point of window. The starting stage (a) The LFRH leg as two position feet follow on the surface of the window glass and LHRF leg as two swing feet discharges from the surface. In stage (b) the robot moves 50% of "venture" by CCW revolution of the left foreleg being turn and CW pivot of the right rear leg being the turn. With this development, it will create stage (c) as indicated in Figure 2.10. Stage (d) shows LFRH leg discharges after LHRF leg follow at first glance window glass. In stage (e) the robot moves a large portion of "venture" by CW pivot of the right foreleg being turn and

CCW revolution of the left rear leg being the turn. With this development, it will produce stage (f). In conclusion, the development retreats to the starting stage and new step starts with the same strategy. The CW and CCW turn pillar with the same edge, will create straight development of the robot.

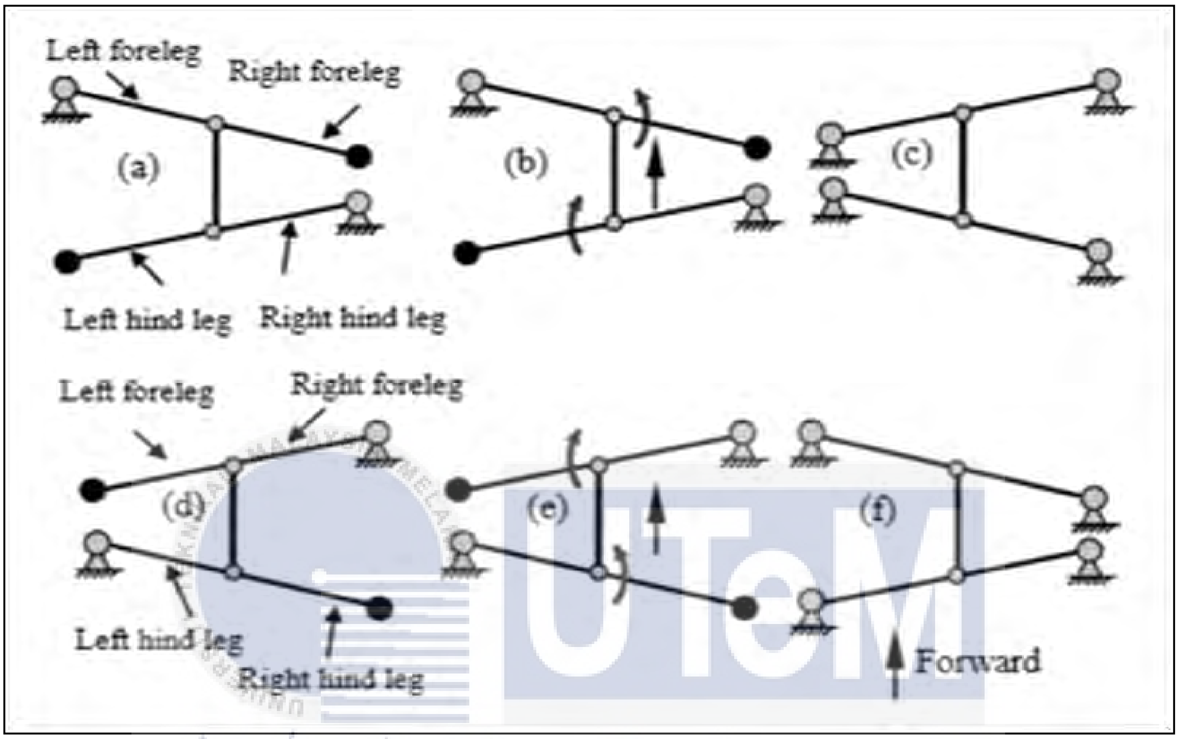


Figure 2.10: Forward movement of the Window Cleaning Robot [5]

2.2.2.3 Rigging Mechanism

In this mechanism, the robot will attach with the cable for the locomotion to rise or lowered by using pulley mechanism which is clearly shown in Figure 2.11. The roller is coupled to AC motor which rotates the roller at 60 revolutions per minute. The roller continuously rotate as the robot rose up. When the robot moves up, there are chances for the brushes to touch the surface of the glass due to wind or to the height of the building. To overcome this problem, a thrust fan is attached to make sure the brushes touch the window glass [4].

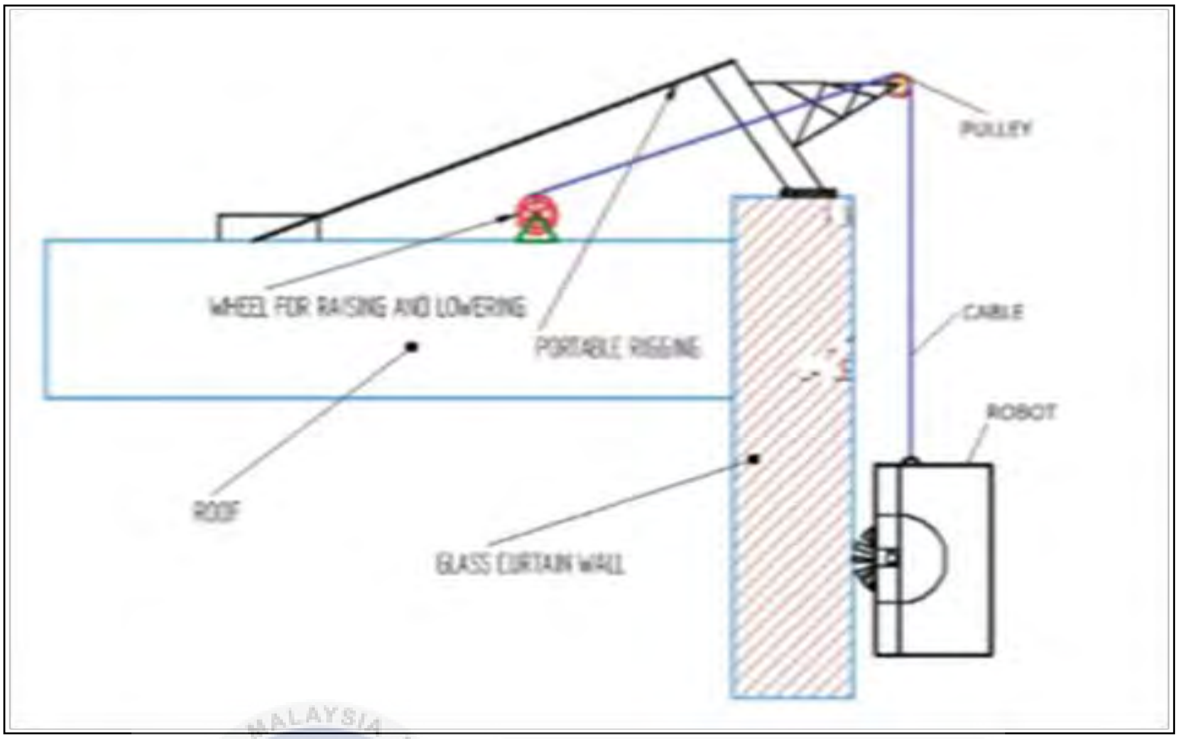


Figure 2.11: Schematic representation of rigging along with the robot [4]

2.2.2.4 Desired Path

Desired Path is the way that plan for the robot to clean the window glass surface with less covering of scope movement. In this examination, the researcher presents 3 sorts of movement to be specific vertical parallel movement, even parallel movement and form parallel movement. This way is emulating the most effective and solid cleaning employment scope. Taking into account the three way, even parallel movement is the fancied one in this study on the grounds that when water are use as fluid cleaning, the water will goes down towards the gravitational power. The window will messy again in the wake of cleaning. Thus, to maintain a strategic distance from this circumstance, even parallel movement was chosen as the coveted way for the window cleaning robot [7].

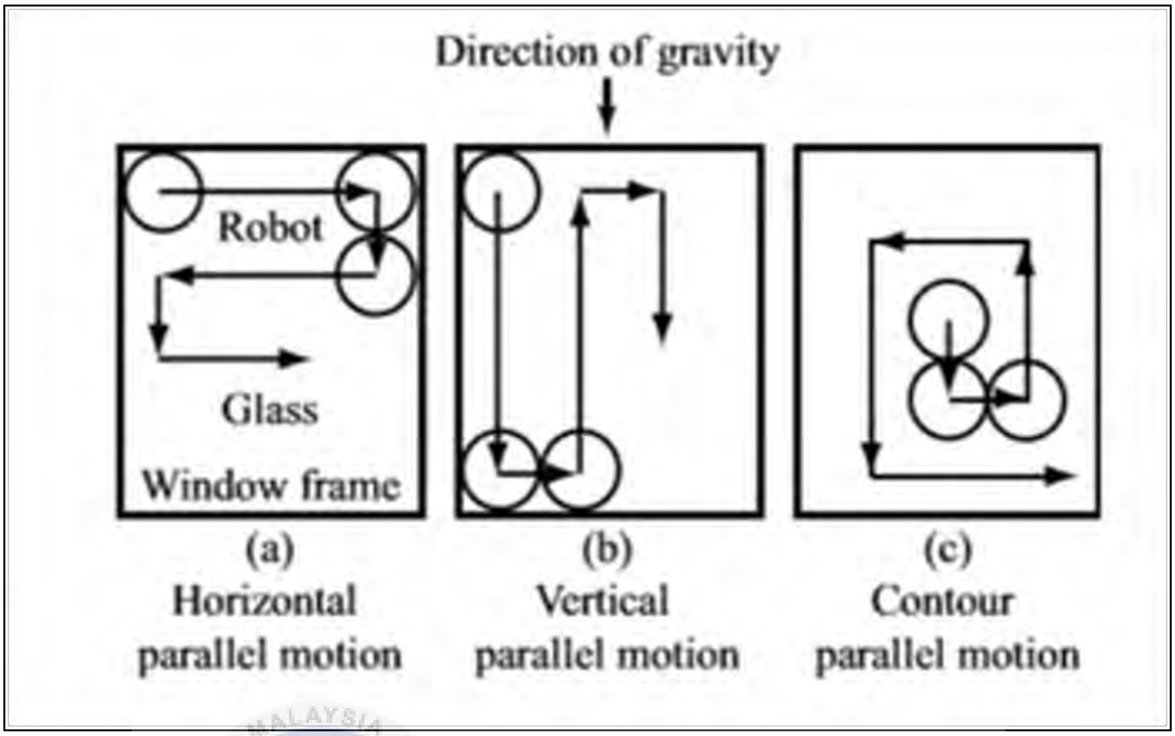


Figure 2.12: Desired path for robot [7]

These criteria are focusing on locomotion mechanism and trajectories of the window cleaning robot. Miyake and Ishihara compare characteristics of five types of locomotion mechanisms in term of mobility and complexity of mechanisms. There are crawlers, Two Drive Wheels, Walking, Parallel Link and Inch Warm [6].

Crawler mechanism has good linearity but the rotatability is not good. Velocity of this mechanism is fair. This mechanism need many suction cup that attached to the robot and that it makes the mechanism complexity and increase of mass of robot. The second mechanism is 2 drive wheels. It has good linearity and rotatability and it requires one suction cup only. Moreover, the velocity of this mechanism is also good because it have Two Drive Wheels and it easier to move on the surface of glass window. Locomotion mechanisms of the walking, parallel link and inch warm are suitable for the window cleaning robot but there are several problems such as velocity of these mechanism are not good and need so much suction cups. These mechanisms also have poor mechanisms complexity [6].

The main factors of the desired path come to default are gravitational force and dynamical effects. The gravitational force and dynamical forces effects increase decrease the driving torques of wheels equivalently based to the angles of the robot [7].

Therefore, horizontal parallel motion trajectory is selected for the trajectory of this robot to be employed with the crawling mechanism

2.2.3 Performance of the Actuator

In this subtopic, the performance of the actuator is discussed based on the selection previous researcher. The main actuator for this robot is pneumatic cylinder. All types of actuator that have been used in the previous researcher were described in this subtopic.

2.2.3.1 DC Geared Servo Motor

In this study, the main actuator is DC geared servo motor with rated torque is $930\ m/Nm$ and $29\ rpm$. This motor will drive the robot on the window glass surface and it mount with revolving shaft. The function of the shaft is to drive the robot to any direction without changing direction of suction cup and cleaning unit [6].

Table 2.5: Specification of the robot [6]

Component	**Specification**
Size	$300\ mm \times 300\ mm$
Weight	$2.0kg$
Motor	DC geared servo motors, $930\ m/Nm, 29\ rpm$
Rotary Encoders	$100\ pulse/rev$
Vacuum Pump	$-33.3\ kPa, 2.5\ l/min$
Power Source	$12\ V\ [external]$

. 2.2.32 Pneumatic cylinder

A great deal of previous research into Window Cleaning Robot has focused on the main actuator for the robot to move up vertically on the window glass. In this research, 3 pneumatic cylinder, x, y, and z are using to drive the robot. It also consists of brush cylinder and vacuum suckers. Zhang, H., Zhang, J., and Zong, G. uses the pneumatic technology because it offers low cost, high power to weight ratio and cleanliness instead of fluid drive. This research are compared 3 other prototype that their built [9]

For Sky Cleaner 1, they called it 'Washman'. The main body consists of two cross connected cylinder named X and Y. At the end of X and Y cylinder, there are short stroke cylinder Z. Cylinder Z function to lift and lower the suction cups in terms of Z direction. The cleaning efficiency is about $37.5\, m^2/hour$ [9].

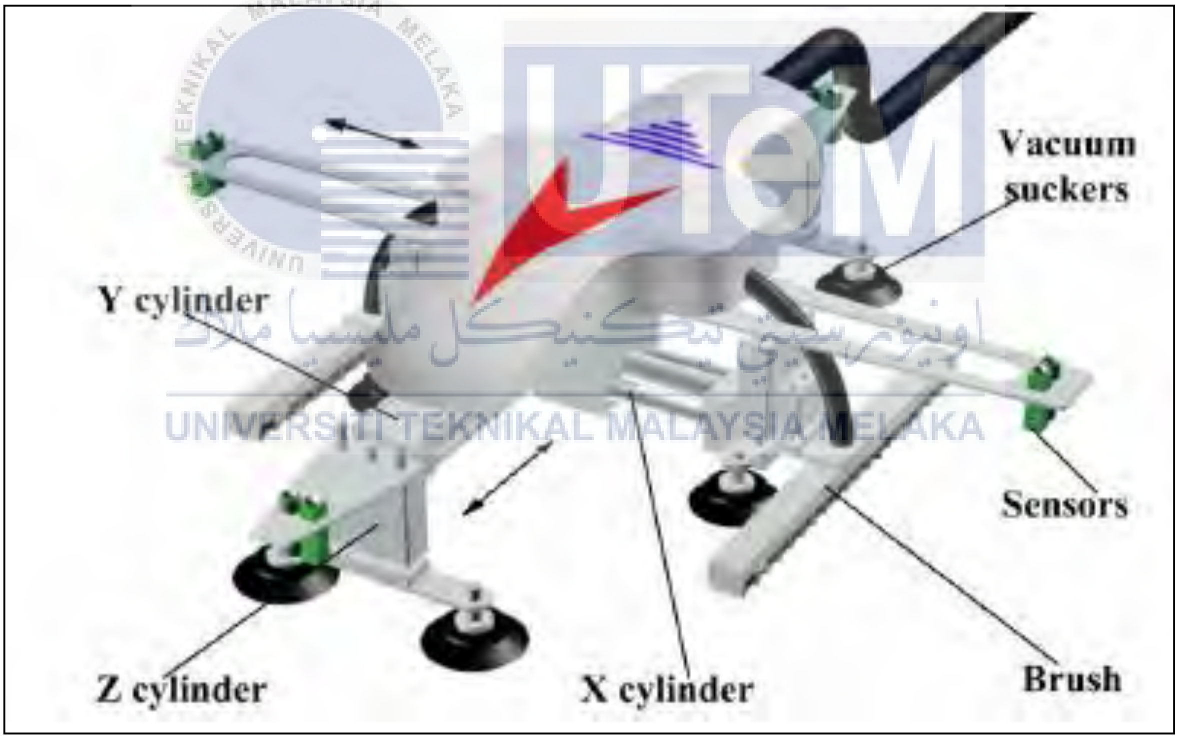


Figure 2.12: Sky Cleaner 1 [9]

Sky Cleaner 2 is upgrading from previous protoytype, it designed to be compact and easy to transport from place to place. It is consists with sixteen suction pads which can carry a load of approximately $45\ kg$ including its body weight. In this prototype, there are two pneumatic cylinders both in vertical and horizontal motion. At the center of the prototype, there is waist joint that can rotate the robot about 1.6° per step is turned in the present stage. This prototype have $75\ m^2/hour$ of cleaning efficiency [9].

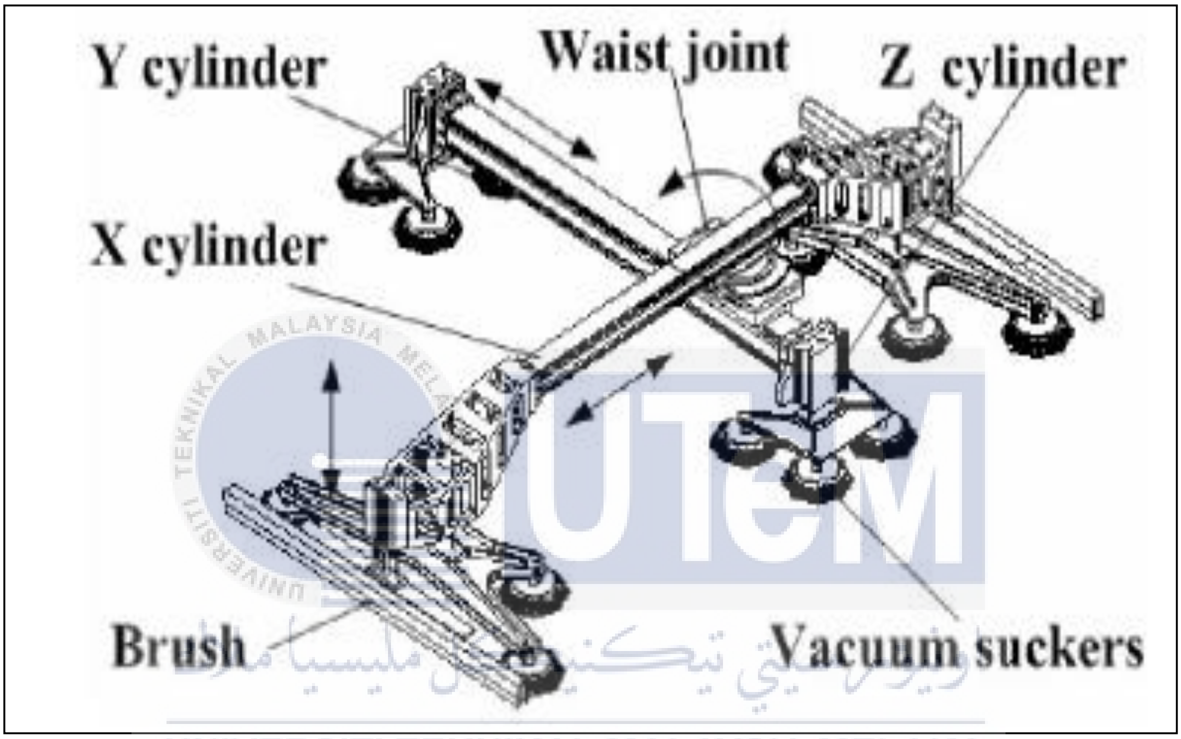


Figure 2.13: Sky Cleaner 2 [9]

2.3 Comparison of previous robot

Different theories exist in the literature regarding characteristics of window cleaning robot as presented in the table 2.6. The major characteristic for the window climbing robot is holding mechanism, locomotion mechanism, mass, dimension, and desired path and last but not lease, main actuator of robot.

Table 2.6: Comparison between previous robots

	WINDORO	**Window Cleaning Robot**	**Glass Wall Cleaning Robot**	**Small Window Cleaning Robot**	**Sky Cleaner**
Holding Mechanism	Magnetic Attractive Force 4 pair magnet between inner and outer	Vacuum Suction 1 Suction Cup $(\emptyset = 150mm)$	Thrust fan Rigging	Vacuum Suction 4 Suction Cup $(\emptyset = 40mm)$	Vacuum Suction 16 Suction Cup $(\emptyset = N/A)$
Locomotion Mechanism	Mobile	Mobile	Hanging	Walking	Crawling
Mass $(\boldsymbol{kg})$	Inner unit $(1.6kg)$ Outer unit $(1.4kg)$	$2.0kg$	N/A	$0.7kg$	$45kg$
Dimension $(\boldsymbol{mm^3})$	Inner unit $(200 \times 200 \times 50)$ Outer unit $(200 \times 200 \times 35)$	(300×300)	N/A	$(220 \times 130 \times 90)$	$(1136 \times 736 \times 377)$
Desired Path	Horizontal parallel	Horizontal parallel	Vertical	Vertical	N/A
Main Actuator	DC Servo Motor	DC Geared Servo Motor	AC Motor	Servo Motor	Pneumatic Cylinder

2.3.1 Holding Mechanism

This review will compare 5 different types of robot with their own characteristics. For the first characteristic is holding mechanism. Window Cleaning Robot, Small Window Cleaning Robot, and Sky Cleaner use vacuum suction system whereas WINDORO use magnetic attraction force and Glass Wall Cleaning Robot use thrust fan as their holding mechanism. For WINDORO, it have 4 magnet at the bottom of inner and outer robot. The inner and outer robot will sandwich the window glass. In term of complexity mechanism, the WINDORO have maximum complexity of mechanism compared with 4 other type of robot. The WINDORO must control the inner and outer unit at the same time whereas the other design just control unit only. Whereas, Glass Wall Cleaning Robot used a thrust fan in order to make sure the robot will hold on the window surface due to the environmental weather effect.

The differences between Window Cleaning Robot, Small Window Cleaning Robot, and Sky Cleaner is the number of suction cups use to hold the robot on the window glass surface. The number of suction cups is depends on the design of the robot. Referring table 2.6, the Sky Cleaner has the largest dimension with $1136mm \times 736mm \times 377mm$ follow by Window Cleaning Robot is $300\ mm \times 300\ mm$ and lastly Small Window Cleaning Robot is $220\ mm \times 130\ mm \times 90\ mm$. So, the bigger dimension of the robot, number of suction cup required also increase. The surface area covered by the suction cup is also important to determine the dimension of the robot. Calculation of determining the diameter of suction cup have been provided in subtopic 2.1.3.

Window Cleaning Robot use only one suction cup and the area of suction cup is $0.0176mm^2$ while Small Window Cleaning Robot use four similar suction cups and its total area are $0.0050mm^2$. Based on this area of suction cup, Window Cleaning Robot have bigger surface area covered than Small Window Cleaning Robot but it is difficult to control pressure inside the suction cup when just only one suction cup are using because when the system are malfunction, the robot will collapse and there is no contingency support for the holding mechanism of the Window Cleaning Robot. Unlike the Small Window Cleaning Robot, it have 4 small suction cups and will two suction cups will suck the glass surface at same time while other two suction cups will release in term of to move the robot with walking mechanism (refer figure 2.9).

2.3.2 Locomotion Mechanism

Comparison between the Small Window Cleaning Robot and the Sky Cleaner are based on the locomotion mechanism. By referring the table 2.6, Small Window Cleaning Robot is using walking mechanism whereas Sky Cleaner use crawling mechanism. Walking mechanism with multiple-leg kinematic are too complex to handle and there lots of degree of freedom compare the crawling mechanism by Sky Cleaner it have least number degree of freedom. To avoid more complexity in the robot, researcher suggested a prototype with least degree of freedom will used in developing design of the prototype.

The most striking result to emerge from the table is that Window Cleaning Robot, Small Window Cleaning Robot and Sky Cleaner use the same types of holding mechanism but different type of locomotion mechanism. Each of them have different locomotion mechanism. The different types of locomotion will affect the mobility of the robot. Window Cleaning Robot will continuously moving on the window surface without obstacle on the window glass surface compared to the Small Window Cleaning Robot and the Sky Cleaner that have limitation of moving on the window surface.

For WINDORO and Glass Wall Cleaning Robot, this two robot have different type of locomotion, WINDORO is mobile robot while Glass Wall Cleaning Robot is hanging robot to the wall. WINDORO will have good mobility of robot but Glass Wall Cleaning Robot is having limitation because it hanging with pulley mechanism. So, Glass Wall Cleaning Robot will have only vertically up and down on the window glass.

2.3.3 Mass and Dimension

Based on table 2.6, WINDORO, Window Cleaning Robot, Small Window Cleaning Robot are categorize in light mass robot whereas Sky Cleaner is heavy mass robot. Mass of the robot is depending of the holding mechanism of the robot whether it is suitable or not. For example, Sky Cleaner have mass 45 kg but it have vacuum suction mechanism that can hold the mass on the window surface vertically. Dimension of the robot plays importance rule in placement of the actuator and holding mechanism. Small Window Cleaning Robot and Sky Cleaner as mention in the table above choose to place their suction cups at the end of the leg while WINDORO and Window Cleaning Robot place wheels at the middle of the robot.

2.3.4 Desired Path and Main Actuator

WINDORO and Window Cleaning Robot have horizontal parallel path while Wall Glass Window Cleaning Robot and Small Window Cleaning Robot have vertical parallel path. When water is used for window cleaning, dirty water and dust will goes down and makes the cleaned glass dirty again. So, vertical parallel path are not suggested for cleaning window glass.

WINDORO, Window Cleaning Robot and Small Window Cleaning Robot have same main actuator that is DC Servo Motor while Sky Cleaner use Pneumatic Cylinder as their main actuator. The servo motor is suitable use for the mobile robot because have higher torque and can operate continuously without have complication on the system. Window climbing robot can be light weight and dexterous because pneumatic cylinder offers cleanliness, low cost and ready available in market.

2.4 Conclusion

Based on the fundamental theories and comparison of previous research, a simple window climbing robot can be develop using vacuum suction mechanism as it holding mechanism, crawling as it locomotion of the robot. The mass of must be reduce and a double acting pneumatic cylinder is selected as main actuator. All the development of robot and experiment will be discuss in detail in next chapter.

CHAPTER 3

METHODOLOGY

3.0 Overview

Project methodology consists of procedure and method that are used in project development. The theoretical analysis applies in this project development will be discuss in this chapter. This chapter will consists of project activity and planning, development project including mechanical, pneumatic and electrical system of the project, flow chart of the system and experiment conducted to prove the theoretical analysis.

3.1 Window Climbing Robot System

The window climbing robot system can play an important role in addressing the issue of its working mechanism, electro-pneumatic system, and calculation in designing the robot. In this chapter, working mechanism of the robot, air pneumatic system and calculation in designing the robot are described in detail.

3.1.1 Working Mechanism

Working mechanism plays a critical role in the maintenance of the window climbing robot to hold in the window glass surface. The working mechanism will describe more detail about how the window climbing robot will work. The hardware of this robot are design by two separate part, one is control system box consist of solenoid valve, Arduino UNO, relay and vacuum injector. The second part is the window climbing robot, consist of a Double acting cylinder as main actuator and suction cups as holding mechanism. The 4 mm

pneumatic tube is connected from the cylinder to the solenoid valve and 6 mm from suction cups to the vacuum injector.

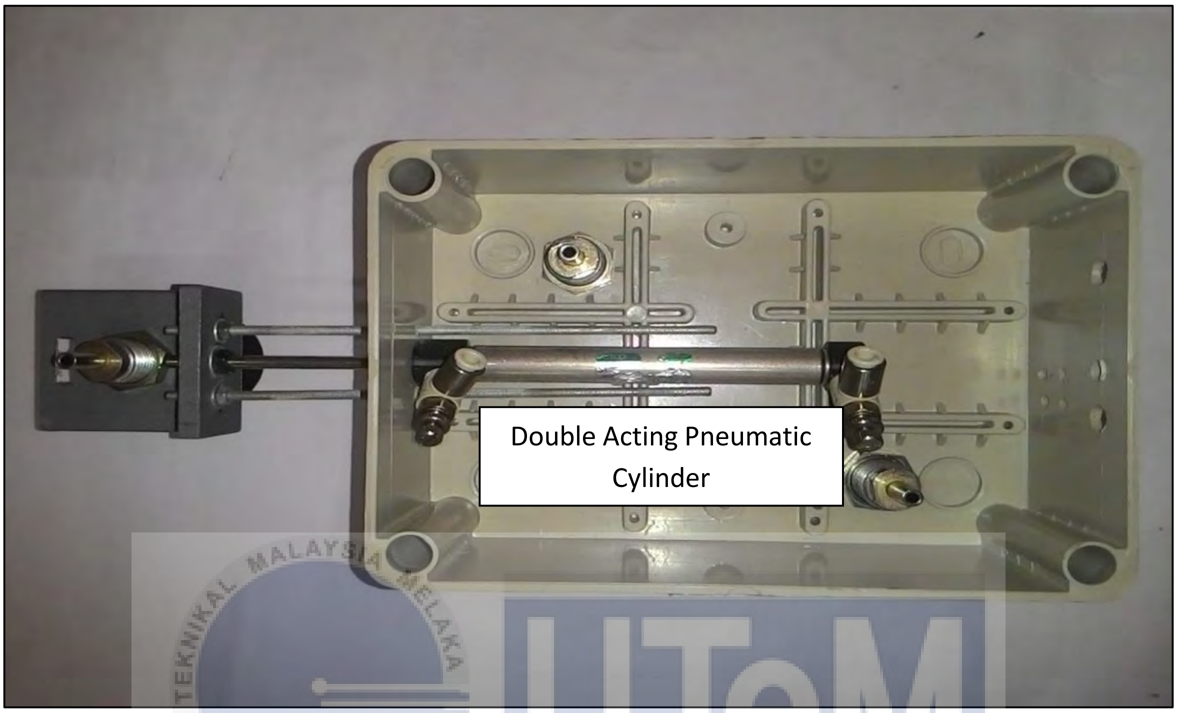


Figure 3.1: Prototype Window Climbing Robot (Top View)

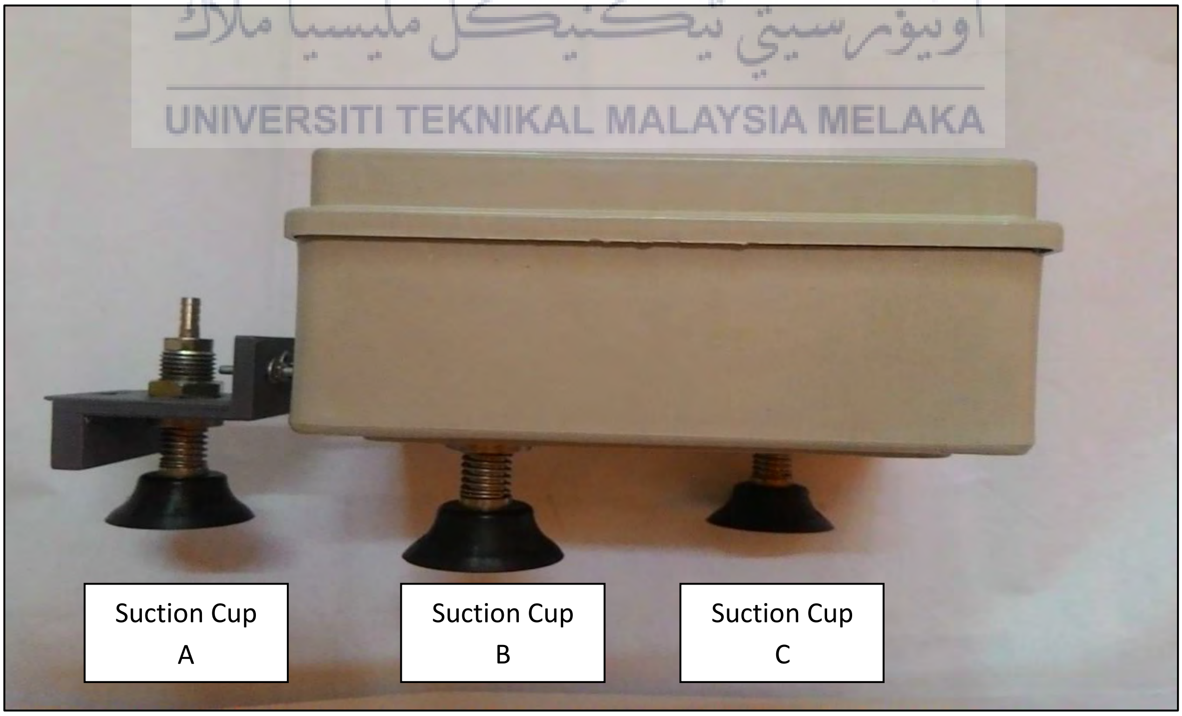


Figure 3.2: Prototype Window Climbing Robot (Side View)

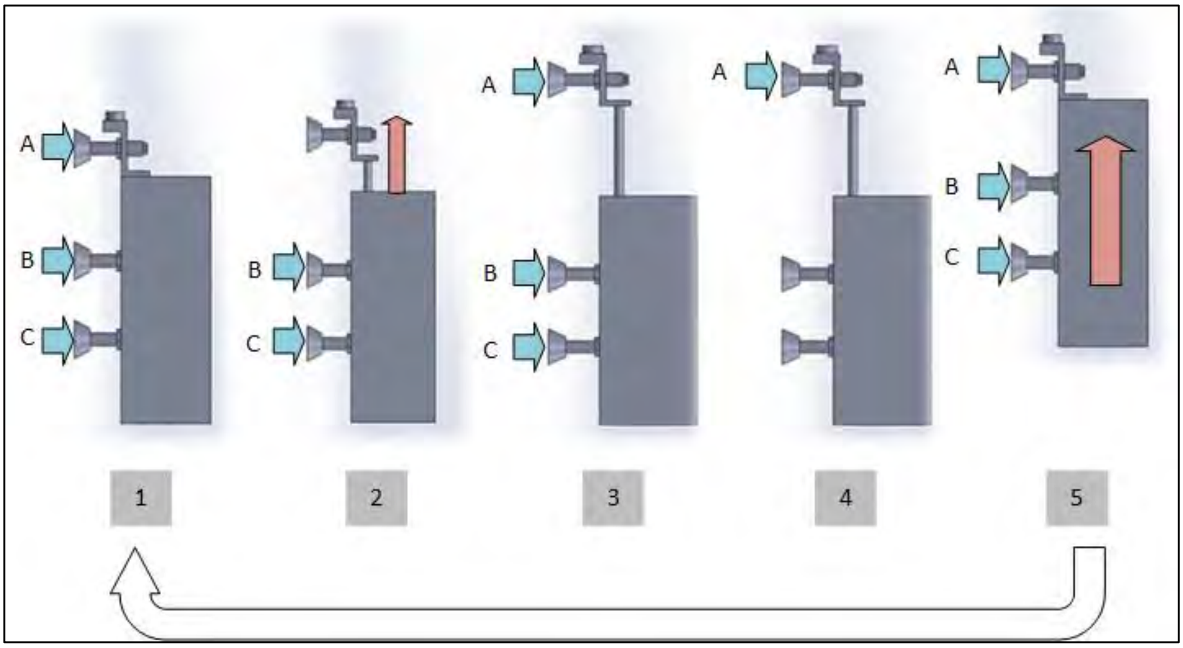


Figure 3.3: Working mechanism of the Window Climbing Robot

Based on the figure 3.3, the summary of working mechanism of window climbing robot in the table 3.1:

Table 3.1: Working mechanism and description

Condition	**Mode**	**Description**
1	Standby	All the suction cups are in vacuum condition Cylinder are in the initial position (retract)
2	Initial	Suction cups B and C are continue in vacuum condition Suction cup A are release condition Cylinder are begin to extend
3	Middle	All the suction cups are in vacuum condition Cylinder are fully extend
4		Suction cups B and C are release condition Suction cup A are in vacuum condition

		Cylinder are fully extend
5	Final	All the suction cups are in vacuum condition Cylinder are fully retract

Based on 5 condition of working mechanism robot, after the robot reached at condition 5, the robot will continue the cycle back from condition 1. The robot will continue moving upward

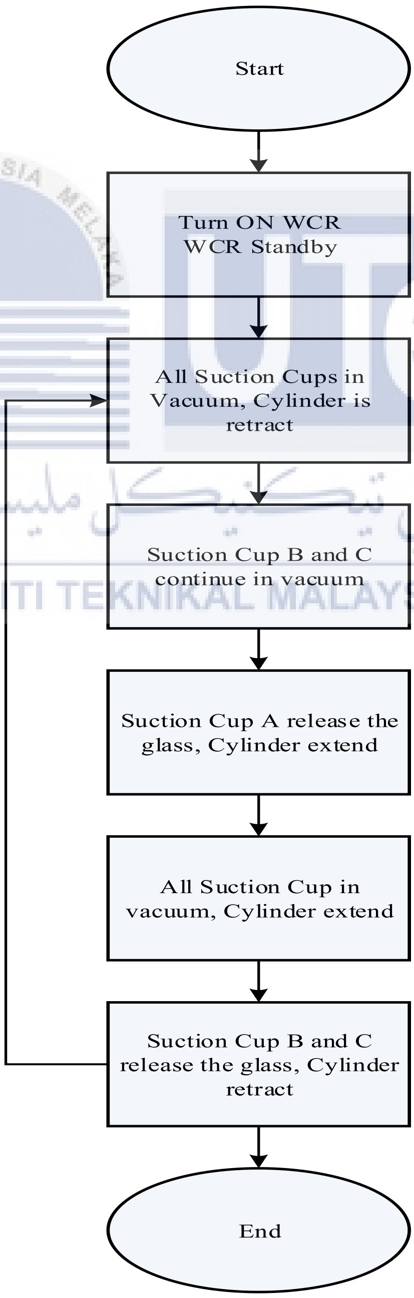


Figure 3.4: Flow chart operation of the automated Window Climbing Robot

3.1.2 Electro-Pneumatic System

Air pneumatic system has a pivotal role in the window climbing robot system. Suction cups play a critical role in the maintenance of the robot on vertical surface. This mechanism is chosen because it easier to handle rather than others mechanisms. Based on figure 3.5, firstly, the compressor connects directly to the solenoid valve to supply air via air service unit. The 3/2 way valve and 5/2 way valve can be set to "open" and "close" by relay and controlled by Arduino UNO. The vacuum injector is using to create vacuum pressure in each of suction cups. A great deal of previous research into pneumatic cylinder has focused on it mechanism to drive the robot on the vertical surface.

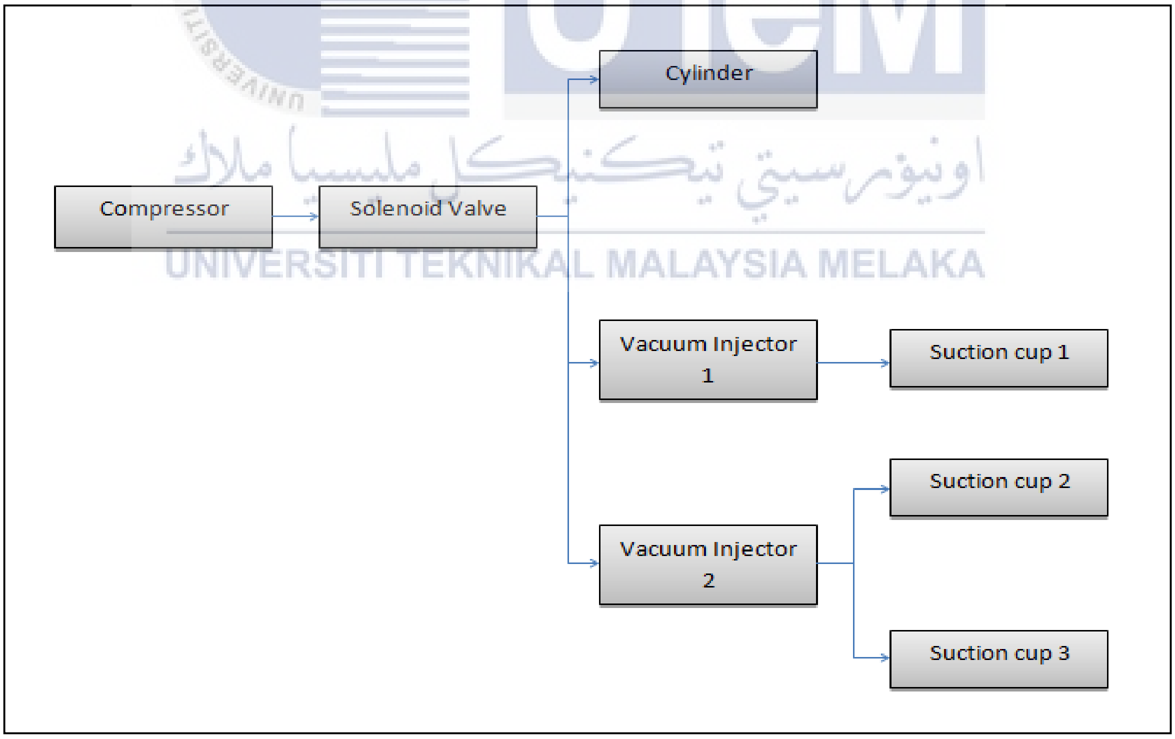


Figure 3.5: Vacuum suction flow diagram

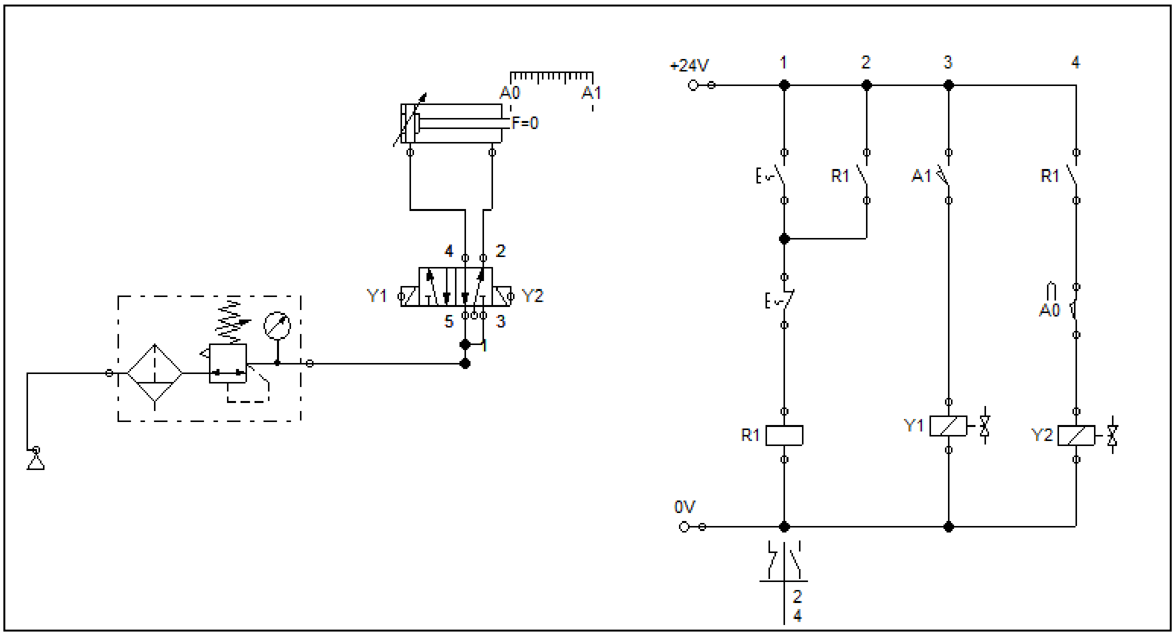


Figure 3.6: Electro-pneumatic circuit diagram in FluidSim [10]

The simulation of main actuator for this robot is simulated by using Festo FluidSim software. The circuit is design based on the working mechanism of the robot.

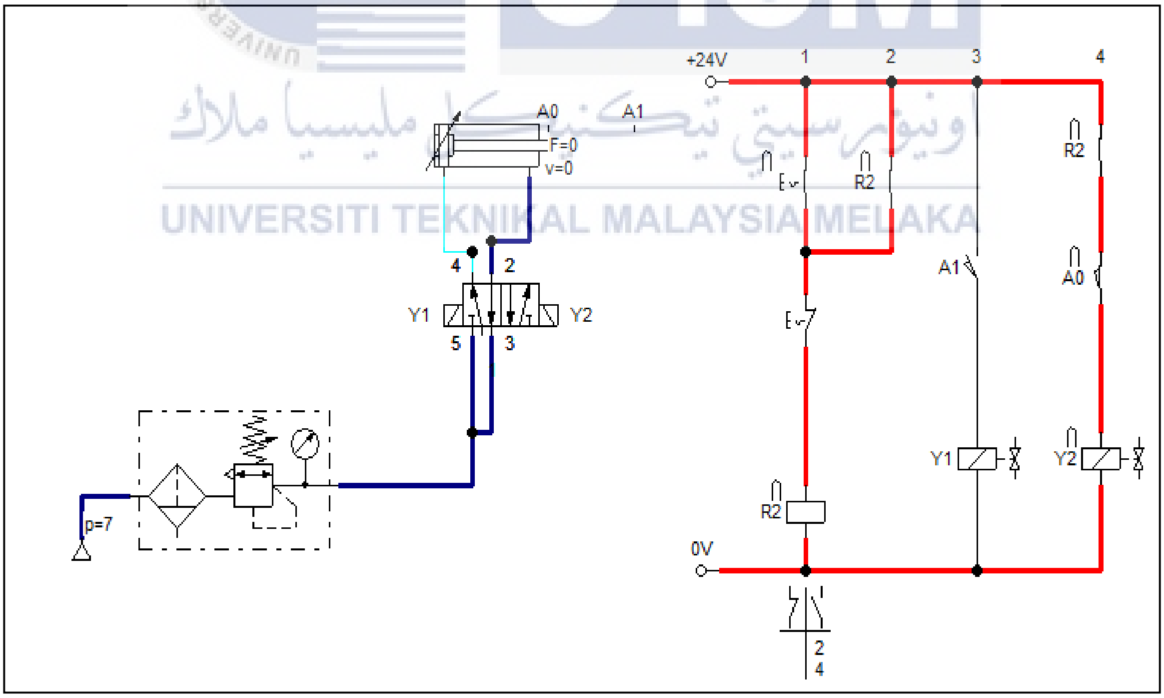


Figure 3.7: Double acting cylinder fully retracts

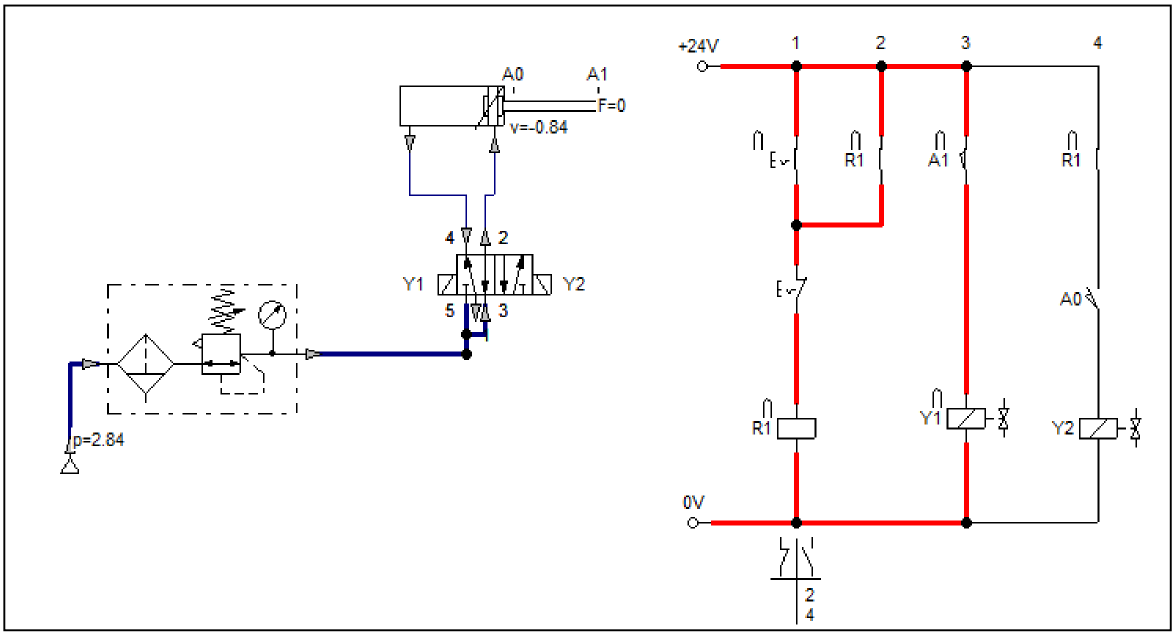


Figure 3.8: Double acting cylinder fully extend

From the figure 3.8, the solenoid valve Y1 will allow the air pneumatic to pass through the valve and fill in the cylinder, the air will push the cylinder to extend until it reach maximum extend.

3.1.3 Electrical System

This prototype Window Climbing Robot will use an Arduino UNO as main board of the robot. This microcontroller is choose because it easier to control, and help to conceptualize the program. The language of this microcontroller is also easier to understand and it will reduce the chances of error when the modification is done. Furthermore, this microcontroller is having enough pin connector to use for this robot.

The Songle SPDT Relay SRD $5V$ will use as electrically operated switch to send signal from microcontroller to trigger the solenoid valve $24V$. This relay SPDT is single Pole Double Throw. A common terminal connects to either of two others. Including two for the coil, such a relay has five terminals in total. Relays are used wherever it is necessary to control a high power or high voltage circuit with a low power circuit.

The main power supply for this prototype is $24VDC$ Power Supply Adapter. It function to switch on the $24V$ Solenoid Valve. It has output voltage $24VD$C and max output current 1A. The rated frequency is $50{\sim}60\ Hz$.

3.2 Experiment and Data Collection

In this part, several experiment and simulation have been done to investigate the performance of Window Climbing Robot based on its locomotion and vacuum suction performance.

3.2.1 Festo FluidSim Software

Objective: To identify the velocity of double acting pneumatic cylinder of prototype.

Based on Festo FluidSim Software, simulation for performance of double acting cylinder that is chosen as the main actuator of the Window Climbing Robot is investigated. In this simulation, the area piston is $78.53mm$ and the ring area is $12.57mm$. The different pressure is supply by compressor and velocity of cylinder extend and retract is recorded in the table. (Refer Appendix C table 4.5)

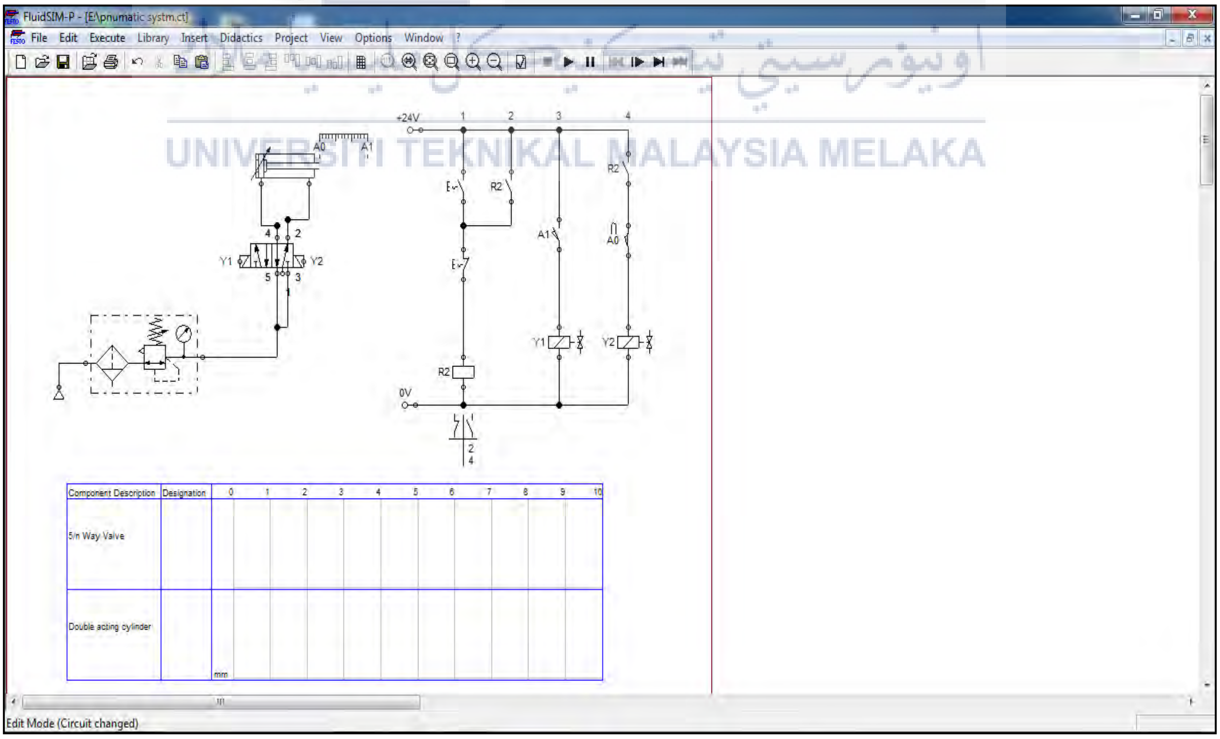


Figure 3.9: Simulation in Festo FluidSim software

3.2.2 Experiment on different pressure and time taken to complete path

Objective: To study the different pressure applied to the robot and time taken to complete path

In this experiment the different pressure was supply from the compressor to the prototype. The pressure applied from the compressor supply is stating from 4.0 bar until 7.0 bar and the increase about 0.5 bar. This experiment will repeated for 7 times. Record the initial pressure when the prototype is suck the white board at $0cm$ and the final pressure when the prototype reach the 50 cm distance or the prototype will collapse before reach the distance targeted.

The whiteboard are use as window glass in this experiment. The whiteboard is use in this experiment because it have smooth surface area like window glass and for safety precaution when doing this experiment.

The path for the prototype to complete is 50 cm distance as shown in figure 3.10. The prototype must place at the 0 cm . Start the stopwatch and record the initial value of pressure. When the prototype is not complete the path, mark the last point of the prototype achieve at the whiteboard. Measure the distance travel by the prototype from the 0 cm to the last point of prototype achieved. Time taken for the robot to reach the distance was taken using stopwatch. Record the data in the provide table (refer Appendix C table 4.6).

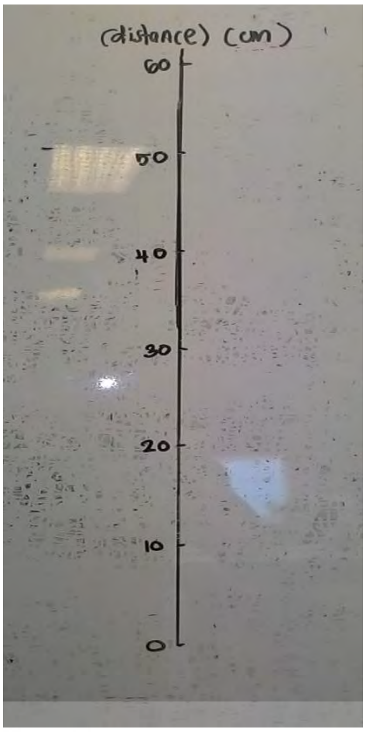


Figure 3.10: Path of the prototype

Figure 3.11: Side view of prototype in initial position

Figure 3.12: Top view of prototype in initial position

3.2.3 Safety precaution and Accuracy

When doing the experiment, there are some precaution step that need to take care and must be avoided to get an accurate data. First of all make sure the path of the prototype on the whiteboard is in accurate distance. The accuracy of the distance is $\pm 1\ cm$. The path is drawing using straight ruler.

The prototype must be monitored all time during the experiment because when doing the experiment the pressure supply from compressor will drop and it cannot hold the prototype to the whiteboard surface.

All the pneumatic tube and connector must in the good condition to prevent air leakage when the experiment in progress. Correct sizing tube and connector must be used to suction cups, solenoid valve and vacuum injector in order to get maximum air flow from the compressor.

3.3 Conclusion

In this chapter all the working step of the prototype is already shown including the designing of prototype, working mechanism, electro-pneumatic system and electrical system of the prototype. Simulation by Festo FluidSim software is already done and data have been recorded in the table. An experiment to investigate the different pressure to the prototype and time taken for prototype to complete the path is already done. The data of this experiment was recorded and shown in Appendix C. For the next chapter, detail analysis can be found based on the data collected in the experiment and simulation.

CHAPTER 4

RESULT AND ANALYSIS

4.0 Overview

This chapter will review about the experiments that have been conducted. There are result for the simulation by Festo FluidSim Software and the experiments that have been conducted. The formulas, results will be shown, analyzed and discussed in this chapter for the future support.

4.1 Result and Analysis of Data

In this subtopic, result from the simulation of Festo FluidSim and experiment will be discussed in detail. Detail calculation for selection diameter of suction cup and theoretical holding force, and pressure supply for the prototype have been calculated in this subtopic.

4.1.1 Calculation

In this subtopic, the detail calculation about the mass of the prototype, theoretical holding force, minimum pressure required and selection of diameter suction cups have been stated.

4.1.1.1 Mass of the Prototype

Mass of the prototype are already calculate based on equation (2.1) and the mass of prototype is

$$m = L \times W \times H \times \rho$$

$$m = 22.5cm \times 11.5cm \times 7.5cm \times 0.204\, g/cm^3$$

$$m = 466g$$

$$m = 0.466kg \tag{4.1}$$

So, based on the calculation in equation (4.1), the mass of the prototype is $0.466kg$.

4.1.1.2 Theoretical Holding Force

Based on equation (2.2), the theoretical holding force for the robot is

$$F_{th} = \frac{m}{\mu} \times (g + a) \times s$$

$$F_{th} = \frac{0.466kg}{0.5} \times (9.81\, m/s^2 + 30\, m/s^2) \times 1.5$$

$$F_{th} = 55.654\, N \tag{4.2}$$

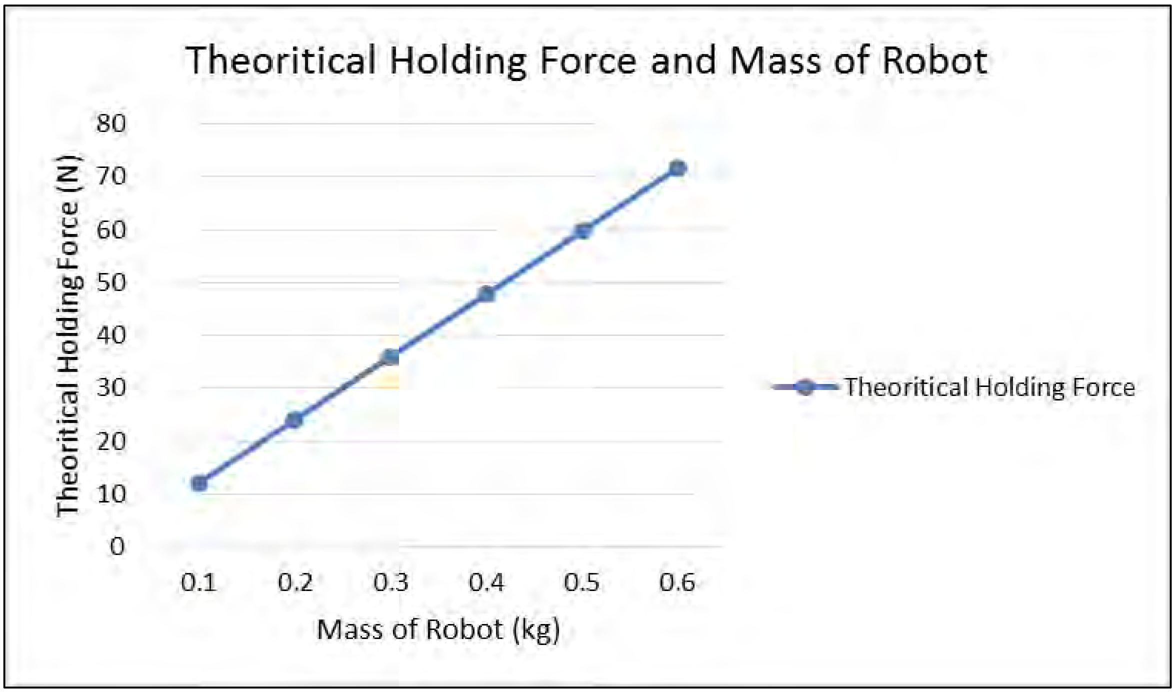


Figure 4.1: Theoretical holding force and mass of robot

The figure 4.1 illustrates the breakdown of masses with theoretical holding force. The graph shows that there has been a perfect liner growth in the number of theoretical holding force and mass of the robot. The gradient of the graph is 119.43. Theoretical holding force increase every 11.943 N as the number of mass of robot increases from 0.1 to 0.6.

The mass of prototype is $0.466kg$ and using equation (2.2), the theoretical holding force for the prototype to hold on the window glass surface is 55.654 N where $\mu = 0.5$, the empirical acceleration for pneumatic system is 30 m/s^2 and safety factor for vertical surface is 1.5.

Based on the equation (2.2), the theoretical holding force for different friction value is calculated. Friction value is based on the suction cup will tested on the different surface. There 3 types of surface will be tested namely oily, wet, and glass surface.

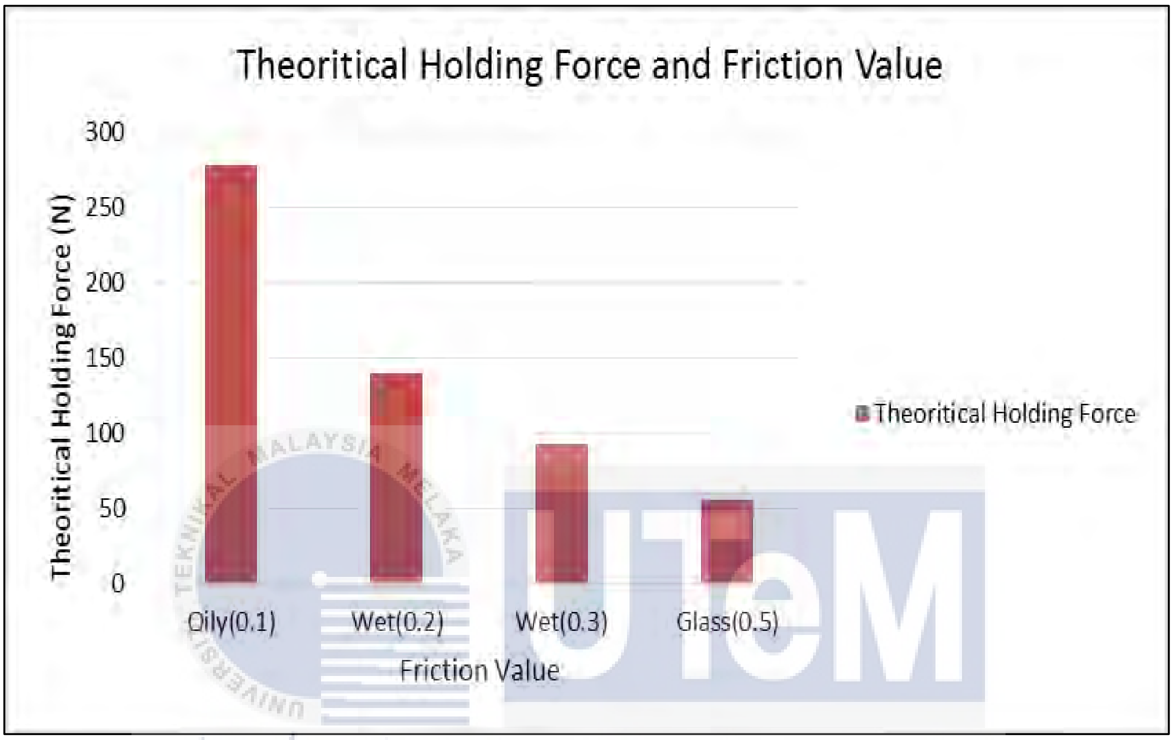


Figure 4.2: Friction values with theoretical holding force

The results obtained from the preliminary analysis of Friction values and theoretical holding force is presented in figure 4.2. The graph shows that there has been a gradually decrease of holding forces when the friction value is increase. The figure shows that the relationship is not perfectly linear. Theoretical holding force decreases $139.137\ N$ as the number of friction value increases from 0.1 to 0.2 , $46.378\ N$ as the number of friction value increases from 0.2 to 0.3, and only $37.103\ N$ as the number of friction value increases form 0.3 to 0.5 .

4.1.1.3 Suction Cup Diameter

Based on calculation have been calculated in subtopic 4.1.1.1 and subtopic 4.1.1.2, the mass of the prototype is $0.466kg$ and the theoretical holding force is $55.654\ N$. The type of suction cup is round and standard based on the surface of the window glass is flat and slightly undulating surface. The diameter of suction cup is refer to the table 2.1. The diameter of suction cups is between $30\ mm - 40\ mm$. For the safety purpose $35\ mm$ diameter was chosen.

4.1.1.4 Force act on Suction Cup

Force of suction cup is determine to calculate the minimum pressure need by prototype to hold on vertical position on window glass surface. The mass of the prototype is $0.466kg$ and the gravitational force is $9.8\ ms^{-2}$, so based on the equation (4.3), the F_x is

$$F_x = mg$$

$$F_x = (0.466kg)(9.8ms^{-2})$$

$$F_x = 4.567kgms^{-2} \tag{4.3}$$

From equation (4.4), the F_y is

$$F_y = \frac{F_x}{\mu} \tag{4.4}$$

And the coefficient friction between rubbers (suction cups) on the glass is $\mu = 0.5$

$$F_y = \frac{4.567}{0.5}$$

$$F_y = 9.134N$$

Finally from the equation (4.5), the minimum pressure required is:

$$P = \frac{F_y}{A} \tag{4.5}$$

$$P = \frac{9.134\ N}{(\pi 0.0175^2)(1)m^2}$$

$$P = 9493.689kPa \approx 9.5bar$$

Based on the calculation given, we can conclude that the pressure need to hold the robot in vertical position is at least $9493.69\ kPa\ or\ 9.5\ bar$. The diameter of the suction cup is $35\ mm$.

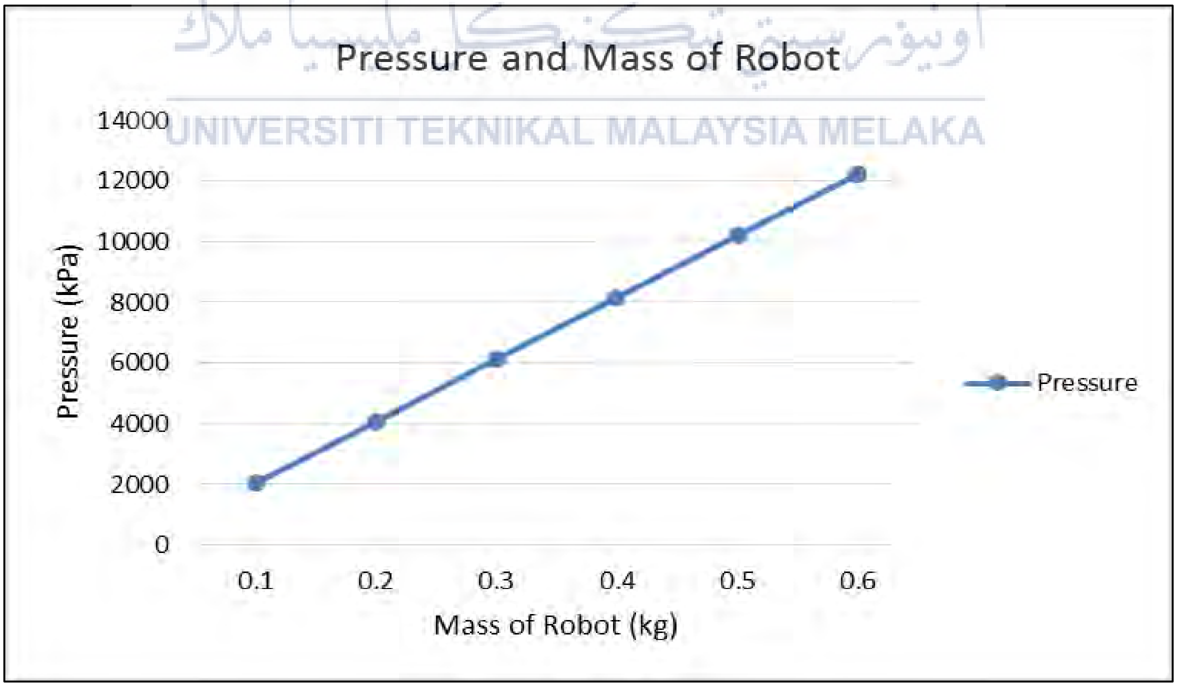


Figure 4.3: Pressure with mass of robot

Figure 4.3 shows the summary statistics for relationship between pressures with mass. A positive correlation was found between pressures and mass of the robot. The mass was increasing significantly with the pressures. The pressure is from the compressor supply. The gradient of the graph is 20371.8. The minimum pressure supply for $0.1kg$ mass of robot is 2037.2 kPa and the minimum pressure supply for 0.6 kg is 12223.1 kPa.

4.1.2 Festo FluidSim Software

Based on FluidSim software, the timing diagram for the double acting cylinder and 5/2 way solenoid valve are stated as diagram 4.1. The maximum extend of the cylinder is 78 mm and the piston area is78.54 mm^2 and the ring area is12.57 mm^2.

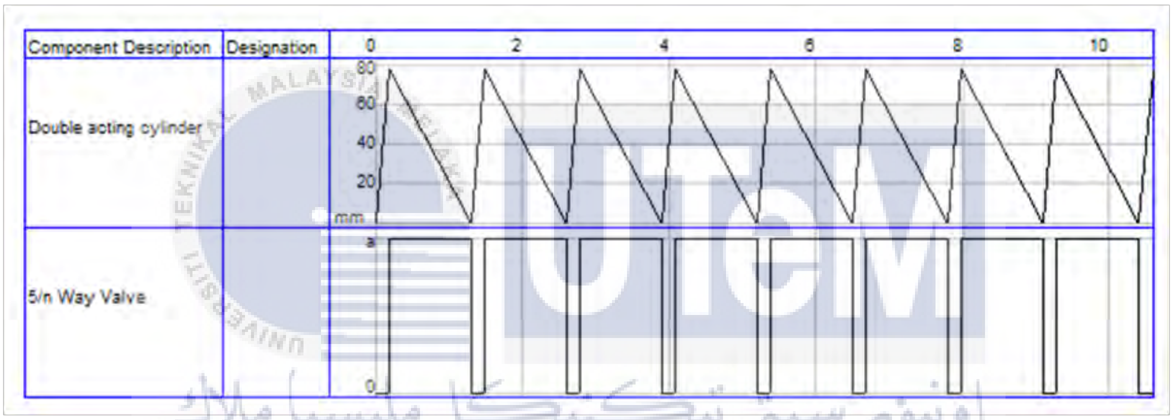


Figure 4.4: Timing diagram for 100 kPa

Figure 4.4 presents the timing diagram for the double acting cylinder with the 5/2 way valve when the compressor supply 100 kPa. The timing diagram shows the cylinder can completely extend and retract for 8 times in 10 seconds.

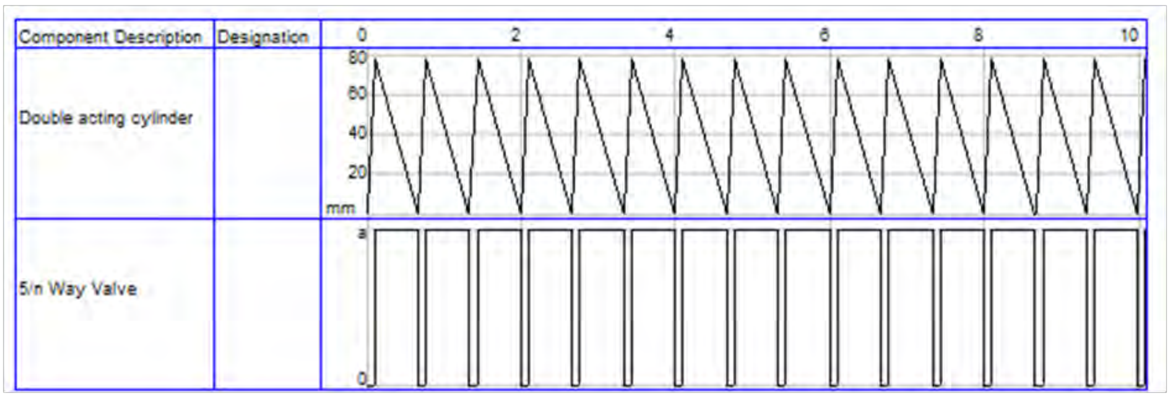


Figure 4.5: Timing diagram for 200 kPa

Figure 4.5 provides the timing diagram for the double acting cylinder with the 5/2 way valve when the compressor supply 200 kPa. The timing diagram shows the cylinder can completely extend and retract for 15 times in 10 seconds.

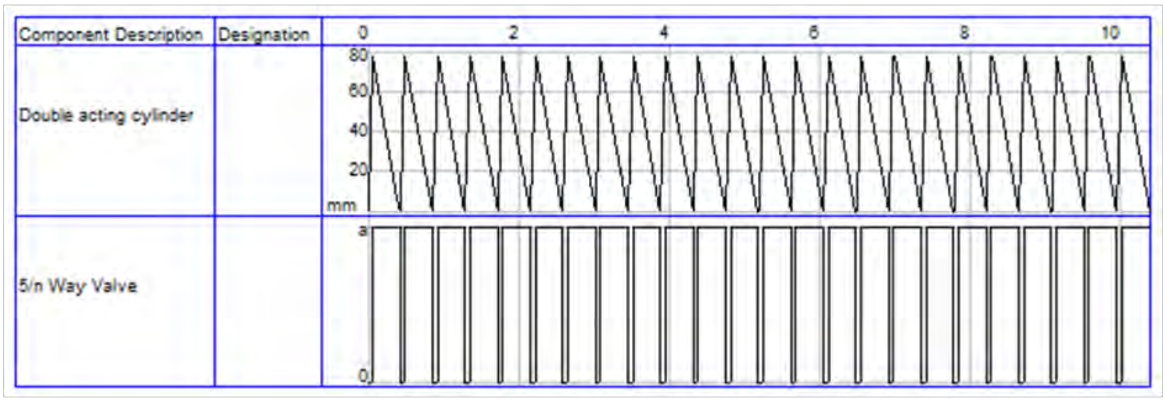


Figure 4.6: Timing diagram for 300 kPa

Figure 4.6 presents the timing diagram for the double acting cylinder with the 5/2 way valve when the compressor supply 300 kPa. The timing diagram shows the cylinder can completely extend and retract for 24 times in 10 seconds.

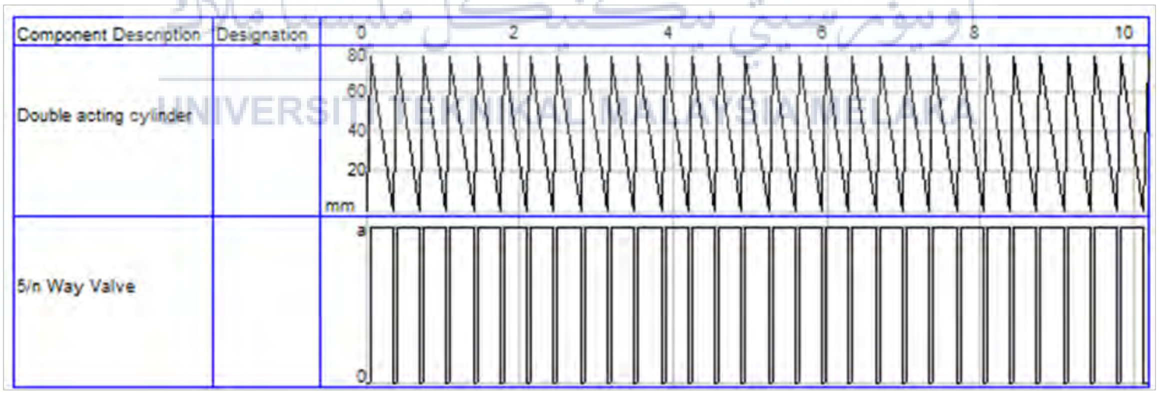


Figure 4.7: Timing diagram for 400 kPa

Figure 4.7 shows the timing diagram for the double acting cylinder with the 5/2 way valve when the compressor supply 400 kPa. The timing diagram shows the cylinder can completely extend and retract for 29 times in 10 seconds.

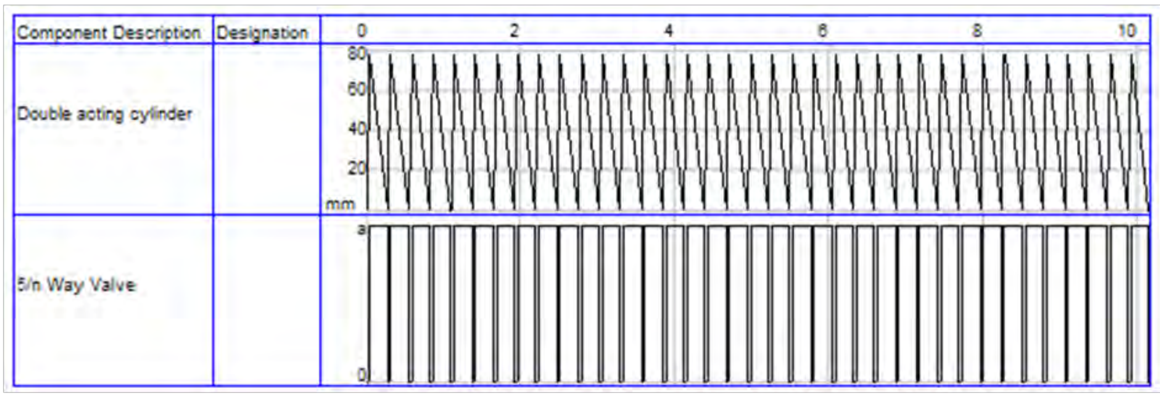


Figure 4.8: Timing diagram for 500 kPa

Figure 4.8 provides the timing diagram for the double acting cylinder with the 5/2 way valve when the compressor supply 500 kPa. The timing diagram shows the cylinder can completely extend and retract for 37 times in 10 seconds.

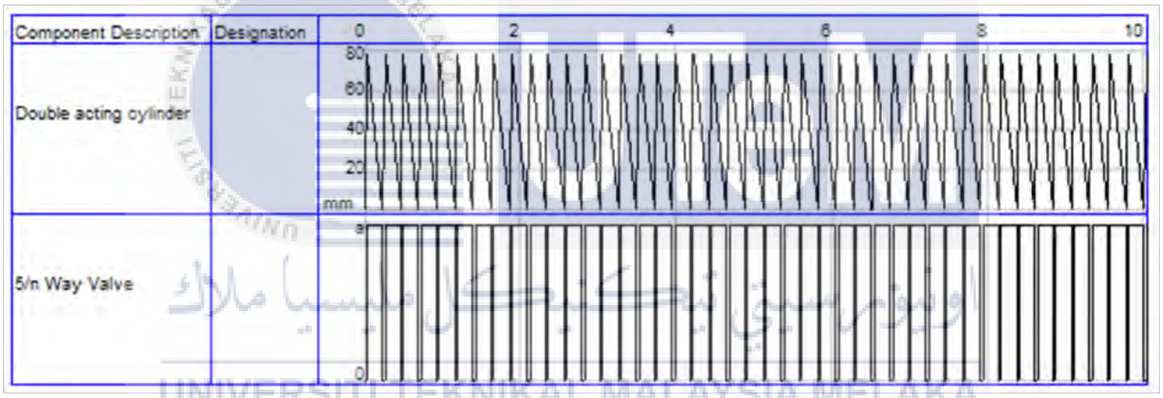


Figure 4.9: Timing diagram for 600 kPa

Figure 4.9 illustrates the timing diagram for the double acting cylinder with the 5/2 way valve when the compressor supply 600 kPa. The timing diagram shows the cylinder can completely extend and retract for 43 times in 10 seconds.

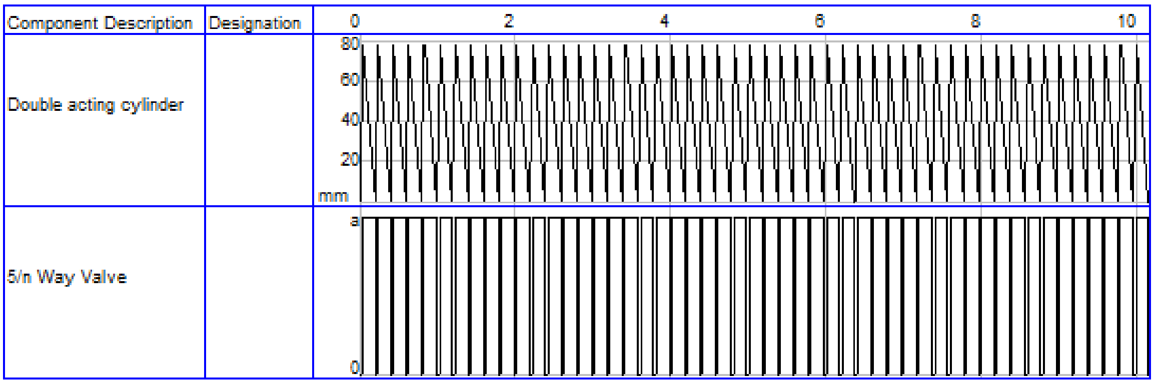


Figure 4.10: Timing diagram for 700 kPa

Figure 4.10 presents the timing diagram for the double acting cylinder with the 5/2 way valve when the compressor supply $700kPa$. The timing diagram shows the cylinder can completely extend and retract for 51 times in 10 seconds.

The most interesting finding from the figure 4.4 until figure 4.10 was that when the pressure increases the extending and retraction of the double acting cylinder are increase in time 10 seconds period. The results obtained from the preliminary analysis of timing diagram in figure 4.4 until figure 4.10 are summarized in table 4.4 (refer appendix C).

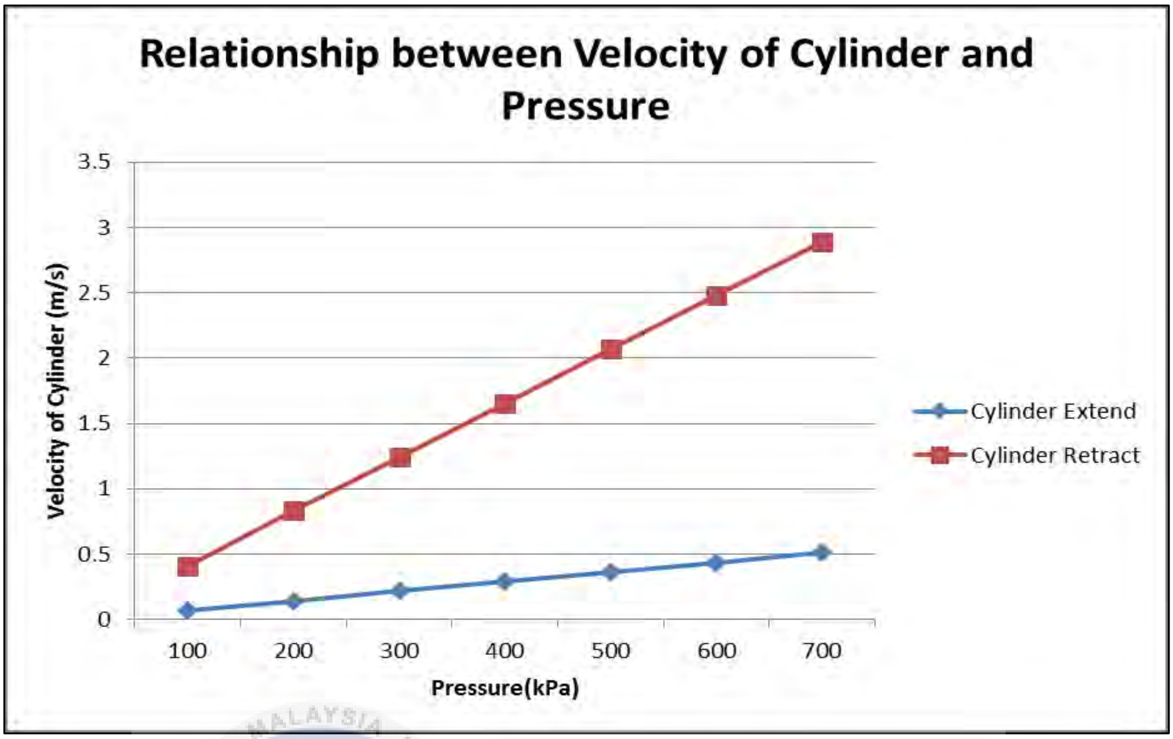


Figure 4.11: Pressure versus velocity of cylinder

Figure 4.11 shows the results obtained from the preliminary analysis for different pressure supply from compressor to the double acting cylinder and different velocity for extend and retract of the double acting cylinder in the simulation. The velocity of extend and retract for the same pressure are different because of the diameter of full bore diameter and piston rod diameter is different. So the velocity of extend and retract are not same.

For the cylinder retract, the differences of velocity for initial pressure and the final pressure is 2.48 m/s. the velocity are increase significant form 0.41 m/s to 2.89 m/s for the pressure from $100kPa$ to$700kPa$.

For the cylinder extend, the differences of velocity for initial pressure and the final pressure is 0.44 m/s. the velocity are increase gradually form 0.07 m/s to 0.51 m/s for the pressure from 100 kPa to 700 kPa.

The difference between velocities of extend and retract cylinder for pressure 100 kPa is 0.34 m/s. For another 200 kPa, 300 kPa, 400 kPa, 500 kPa, 600 kPa and $700kPa$ is 0.42 m/s, 1.02 m/s , 1.36 m/s , 1.71, 2.05 m/s, and 2.38 m/s respectively.

4.1.3 Experiment on different pressure and time taken to complete path

The table 4.5 (refer Appendix C) illustrates the breakdown of different pressure applied to the prototype of Window Climbing Robot, distance completed and time taken to complete the distance. One interesting finding is the pressure will drop half from initial pressure because the compressor used in this experiment is a small portable compressor only. It has small amount of tank capacity to store compressed air.

From the table 4.5, another important finding was that during experiment 1 and 2, the prototype cannot complete their path because the pressure to hold the prototype vertically on the whiteboard surface is behind the minimum pressure required steadily.

One unanticipated finding was that we can calculate the velocity of the prototype based on the data above. By using the formula (4.6), the actual velocity of robot can be determined:

$$Velocity(m/s) = \frac{distance(m)}{time(s)} \tag{4.6}$$

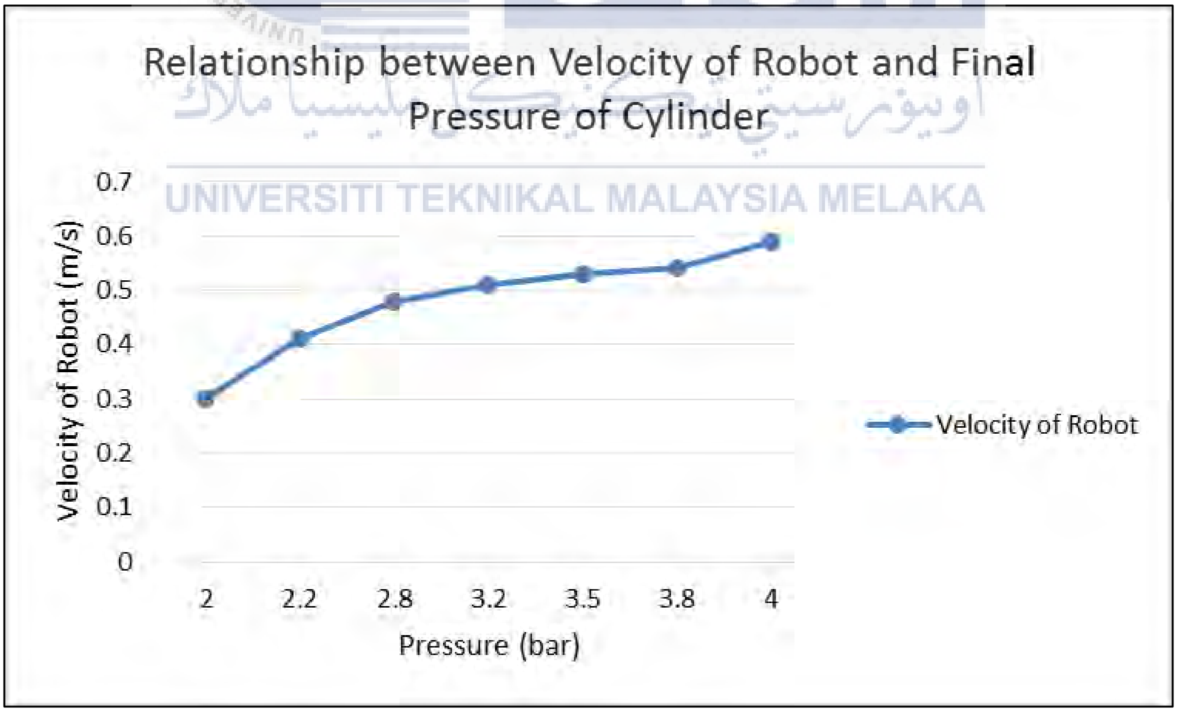


Figure 4.12: Relationship between velocity of robot and final pressure.

From the figure 4.12, the minimum final pressure 2 bar and the velocity of the prototype is 0.3 m/s. The distance achieve by the prototype is 42 cm. The maximum final pressure cylinder is 4 bar and velocity of prototype is 0.59 m/s and prototype are complete the path distance. The average velocity of the prototype based on the is 0.48 m/s.

Regression analysis between velocity and the pressure was used in the simulation to predict the actual performance velocity and pressure. The graph of relationship between velocity and pressure in the figure 4.11 is similar pattern to that obtained by the graph in figure 4.12. Both velocities in this graph are gradually increased, as the pressure increase.

Figure 4.13 shows that the sequence of prototype climbing the whiteboard surface. The maximum output stoke of the cylinder is $\pm 78\ mm$.The prototype will moving maximum 7.8 $cm\ per\ stroke$.

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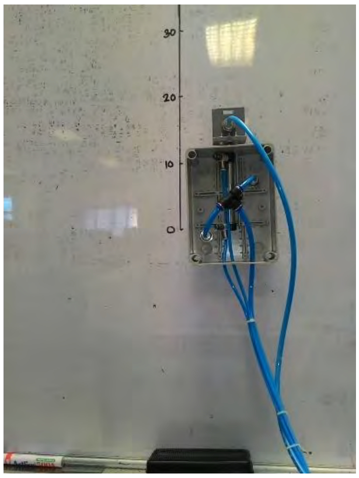

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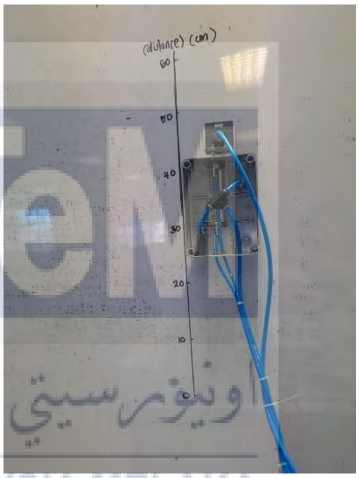

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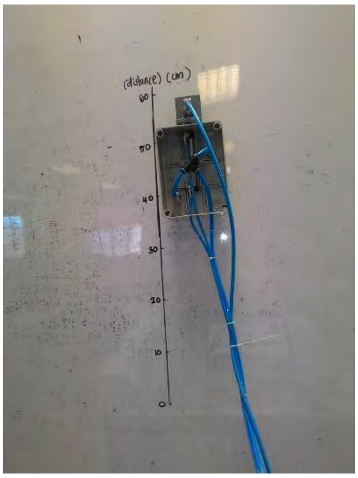

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Figure 4.13: Sequence of prototype climbing vertically on whiteboard.

CHAPTER 5

CONCLUSION

5.0 Conclusion

This project was undertaken to design and to develop an Automated Window Climbing Robot that can use to replace human when doing this job in higher places. This project is also to evaluate the performance of suction mechanism as holding mechanism of this robot.

Returning to the objectives posed at the beginning of this project, it is now possible to state that first objective of this project is achieve. The prototype have been develop and design by using a double acting pneumatic cylinder and vacuum suction mechanism as holding mechanism. The desired path of the robot is vertically upward and it can hold and move on the window glass. The performance of the prototype was analyze in term of velocity of prototype move, theoretical holding force of prototype and vacuum suction mechanism.

This research extends my knowledge about the suction mechanism that uses the suction cup as the main component. Detail calculation about the suction mechanism, fundamental and theories about the mechanism already stated in Chapter 2. Using Festo FluidSim software to calculate the velocity of the double acting pneumatic cylinder. For experiment, the objective is investigating the different pressure with the time taken for the prototype to complete the path. The distance of the prototype travel on whiteboard (as window glass) taken with time travel to get the velocity of the prototype. All the safety precaution and accuracy have been stated in Chapter 3.

In Chapter 4, result for the simulation by the Festo FluidSim software was conducted to measure the theoretical velocity of the main actuator of the prototype that is double acting cylinder. The result for the calculation part are for mass of prototype $0.466kg$. The theoretical holding force of the prototype is $55.654\ N$. Diameter of suction cup required is $35mm$ and pressure required to the vacuum suction system is $9493.69\ kPa\ or\ 9.5\ bar$. For the experiment part, the average velocity of the robot based on 7 experiment have done with different pressure supply to the vacuum suction system is $0.48\, m/s$.

So, the prototype are already design and finished. The prototype can be use as window climbing robot based on the calculation and experiment have been done to prove the prototype is safety and user friendly to the societies.

5.1 Recommendation

For the future recommendation, the prototype can be improve by adding another double acting pneumatic cylinder and the mass of the prototype can be increase. Prototype also can be improve by adding some rotation mechanism that will turn the robot horizontally. The robot also can be improve by adding short stroke pneumatic cylinder at z-axis to make sure the suction cups will suck the window glass perfectly.

An ultrasonic sensor can be added in this prototype in order to detect the obstacle. The sensor is to detect the obstacle on the window glass.

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APPENDICES

Appendix A

Window cleaner falls 47 storeys from skyscraper - and survives to tell the tale

Last updated at 00:58 05 January 2008

A window cleaner who plummeted 47 storeys from the roof of a Manhattan skyscraper is now awake, talking to his family and expected to walk again.

Alcides Moreno, 37, fell almost 500ft in the scaffolding collapse which killed his brother a month ago.

Somehow Moreno lived and spoke for the first time since the accident on Christmas Day.

Scroll down for more

Appendix B

You are in: UK

Wednesday, 22 April, 1998, 18:02 GMT 19:02 UK

Window cleaners fall to their death

Two window cleaners were killed when the cradle they were working in plunged 100ft to the ground.

The accident happened in the City of London, where the men were working on an annexe to Midland Bank's headquarters.

The cradle fell from the ninth floor onto a Ford Transit van. Both men, who worked for a contract cleaning firm, were pronounced dead at the scene by a doctor from the Helicopter Emergency Medical Service.

The London Ambulance Service said one of the dead men had suffered serious head injuries, and the other had severe chest, head and pelvic injuries.

A Swiss tourist who had been walking nearby at the time of the accident was treated for minor cuts from flying glass.

Staff at the Midland Bank offices were shaken by the tragedy.

One employee said: "They announced over the tannoy that there had been an accident, then we heard the sirens and the helicopter.

Appendix C

4.1.1 Calculation

Table 4.1: Result of different mass with pressure

$Mass(kg)$	$F_x\ (N)$	$F_y(N)$	$Pressure(-kPa)$
0.1	0.98	1.96	2037.2
0.2	1.96	3.92	4074.4
0.3	2.94	5.88	6111.5
0.4	3.92	7.84	8148.7
0.5	4.9	9.8	10185.9
0.6	5.88	11.76	12223.1

Table 4.2: Result on different mass and theoretical holding force

$Mass(kg)$	$Theoritical\ holding\ force, F_{th}(N)$
0.1	11.943
0.2	23.886
0.3	35.829
0.4	47.772
0.5	59.715
0.6	71.658

Table 4.3: Result between different Friction value and Theoretical holding force

$\boldsymbol{Friction\ value}$	$\boldsymbol{Theoritical\ holding\ force, F_{th}(N)}$
Oily(0.1)	278.272
Wet(0.2)	139.135
Wet(0.3)	92.757
Glass(0.5)	55.654

4.1.2 Simulation by Festo FluidSim Software

Table 4.4: Result of different pressure with velocity of double acting cylinder

$\boldsymbol{Pressure(kPa)}$	$\boldsymbol{Velocity\ extend(m/s)}$	$\boldsymbol{Velocity\ retract(m/s)}$
100	0.07	0.41
200	0.14	0.83
300	0.22	1.24
400	0.29	1.65
500	0.36	2.07
600	0.43	2.48
700	0.51	2.89

4.1.3 Experiment

Table 4.5: Result of different pressure, distance complete and time taken

No of experiment	***Initial Pressure*** (***bar***)	***Final Pressure*** (***bar***)	***Distance*** (***cm***)	***Distance complete*** (***cm***)	***Time taken*** (***second***)
1	4.0	2	50	42	126
2	4.5	2.2	50	48	118
3	5.0	2.8	50	50	104
4	5.5	3.2	50	50	98
5	6.0	3.5	50	50	94
6	6.5	3.8	50	50	92
7	7.0	4.0	50	50	88

Table 4.6: Result of final pressure, distance complete, time taken and velocity

No of experiment	***Final Pressure*** (***bar***)	***Distance complete*** (***cm***)	***Time taken*** (***second***)	***Velocity***(***m/s***)
1	2	42	126	0.3
2	2.2	48	118	0.41
3	2.8	50	104	0.48
4	3.2	50	98	0.51
5	3.5	50	94	0.53
6	3.8	50	92	0.54
7	4.0	50	88	0.59