# Design and Analysis of Robotic Device for

# Cleaning Window Glass Panel in High Rise Building

By

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Dissertation submitted in partial fulfilment of
the requirements for the
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

Mechanical Engineering Programme

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Approved by,

____________________

(Prof. Dr. T. Nagarajan)

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TRONOH, PERAK

Dec 2010

# CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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DZULFIKRY ARIS

# ABSTRACT

This project is implemented to design the possible window cleaning robot for high-rise building. The study only focuses on designing a conceptual design where three main tasks being carried out. The first is to generate several design concepts based from engineering specification generated using QFD diagram which then elaborated using morphological chart. The best concept is then chosen by Pugh Evaluation Chart. The second step involves an engineering analysis on the selected design concept such as the static frictional force, suction cup force, and motor torque required. The final step is to come out with final design using AutoCAD.

Based from this, the final design of the robot is designed weighted approximately of 5kg and dimension of 500 x 500 x 200 $mm^3$. The window cleaning robot uses two motors and 4 suction cups where one of the motor acts to drive the robot vertically (upward/downward) and the other one horizontally while the suction cups are used to grip onto the windowpane. This thesis includes background and objectives of this research, design concepts, engineering analysis, the final design, discussion and a conclusion.

# ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my project supervisor, Prof. Dr. T. Nagarajan who had presently giving me guidance and support throughout the entire project. It would be difficult to complete this project without his guidance and support especially in the project resources, references and material.

My outmost thanks to my family who have given me support throughout this project. Not forgetting their eternally moral support and understanding of my academic responsibilities.

I would like to express my gratitude to my friends, especially to all my course mates who had given me help technically and mentally during the journey to accomplish this project. Thank you all for giving me technical advice, moral support and idea to enhance my project. Thank you.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background Study

Window cleaning in high rise building is currently having high demands in modern cities. As a result, window cleaners need to risk their life by climbing the wall using rope and gondola to do the cleaning. Currently most of them are still cleaned manually. Statistics shows that window cleaning is probably the most hazardous maintenance activity carried out on most work premises. At US only, average of 70 window washers die each year in the US, while another 130 are injured. [1]

By designing a mobile robot that can do the cleaning, this will help reducing the statistics. While there are already numbers of the same project outside, it is still not yet fully finished and commercialized; this project is done to bring in new ideas and innovation on the window cleaning robot to a new perspective.

## 1.2 Problem Statement

Currently, market demands many automatic windows cleaning system. From the survey, the requirements of window cleaning robot are listed below:

i. The size of the robot should be small and lightweight for mobility and portability
ii. The robot must be able to clean window's corner because fouling is left there often
iii. The robot must be able to sweep the windowpane continuously to prevent stripe pattern on a the window
iv. The robot can operate automatically during moving on the window

This project will basically cover up these requirements which are elaborated in details in this thesis to come out with a working conceptual design

## 1.3 Objectives

The objective of this project is to design a robotic device for used in cleaning window glass panel in high-rise building. The study only focuses on mechanical engineering design which is to start from scratch until coming to a working conceptual design.

## 1.4 Scope of Study

This project will be focusing on designing a window cleaning robots. The robots must include 4 mechanisms which are gripping mechanism, locomotion mechanism, cleaning mechanism and turning mechanism.

To come out to the final design, three main steps need to be carried out. The first part is the concepts generation where several concept designs are created based from the engineering specifications that are derived from customers' requirements. The engineering specifications are translated into QFD diagram for easier understanding before those specifications is derived into graphical concepts. The best concept is then decided based on Pugh's Chart.

The second part is the engineering analysis. Based on the best concept chose in the previous section, an analysis done to calculate the static frictional force involve in the robot system, the suction cup calculation and selection and the motor torque calculation and selection. And base from the first and second part, final conceptual design is drawn in CAD before the fabrication can be started which is not covered in this project.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Window Cleaning Robot Mechanism

In real life today, there are already exist numerous of climbing robots. There are several mechanisms that each of the climbing robots should have. There are climb mechanism, locomotion mechanism, and turning mechanism [2]. These mechanisms are essential to ensure the robot can grip onto the window glass, traverse around it vertically and do the cleaning.

To climb, those robots used various types of adhesion mechanism to grip the wall. Most of the adhesion systems used is suction cups, electrostatics chuck, effective adhesion and surface adaptability. The details of each of the mechanisms are as follows:

i. Suction cup

- Most commonly used in factory automation and is evacuated actively by a vacuum pump. Among the process is handling glass windows in car assembly line and handling of cartons of boxes in packaging line. It can be either a single large suction cup or multiple small suction cups on each of the robot's foot. The suction cup has excellent grip up to 1atm and ease of use. The gripping can be controlled simply by closing/opening the valve.

ii. Electrostatic chucks

- It is a device that achieves controlled adhesion by means of electrostatics. It is inspired by gecko foot that used electrostatic chuck (ESC) in place of Van der Waals interaction. A typical ESC has a shape of disc and has electrodes insulated by a dielectric material (ceramic, polymer). Characteristics of ESC are: a) it can be used in vacuum. b) Its rigidity combined with an uniformly distributed adhesion force do not deform thin delicate wafers, c) The high sensitivity to the surface roughness (due to the short range of the generated adhesion force) renders them ineffective in "normal" roughness surfaces (Ra>100um). Both, suction cups and ESC are active devices: adhesion can be switched on/off at will.

iii. Effective adhesion

- From a contact mechanics perspective, there is a relation between effective adhesion and compliance. This suggests that we can increase the effectiveness range for the ESC mechanism in more varies surfaces. It can be done by mimicking the same structure of gecko foot hair. It is costly since gecko foot hair is in micron. However to achieve o low cost but reasonable compliant device is by adopting 'striped down' version of the gecko foot hair.

Other than adhesion mechanism, we also need to consider the locomotion mechanism. It requires the following demands to apply the window cleaning robot for the practical use. The first is to clean the corner of the window because fouling is left there often, and we need to ensure to sweep the windowpane continuously to prevent making striped patterns on a windowpane. As shown in Figure 1 is the recommended working path that the robot should have.

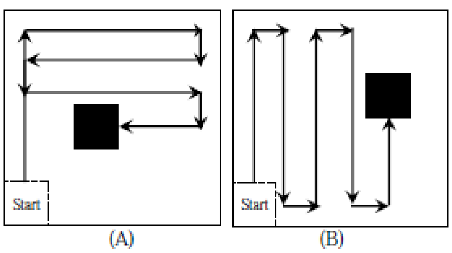



**Figure 1: Working path of window cleaning robot [2]**

Turning mechanism is a key to clean even at the corner of the window. Usual turning of a robot will have an arc (as shown in Fig. 2) while the good turning as shown in Figure 3

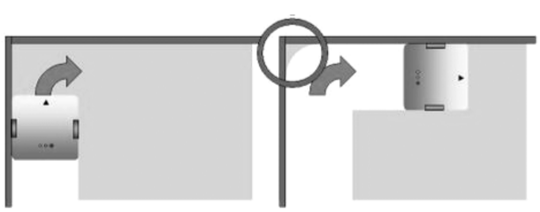


**Figure 2: Conventional turning strategy [2]**

**Figure 3: Good turning strategy [2]**

## 2.2 Existing Wall Climbing Robot and Apparatus

### 2.2.1 Small-size Window Cleaning Robot

There is already a window cleaning robot that is designed by two Japanese Tohru Miyake and Hidenori Ishihara [4]. The robot's weight is less than 5kg, including the weight of battery and washing water. The robot size 300mm x 300mm x 100mm. The robot mechanism as shown in Figure 4 was designed under focusing on the window cleaning robot for just a single windowpane. The robot moves on windowpane by two-wheel locomotion mechanism with holing the body on the surface using a suction cup vacuumed by a pump. The control system which includes traveling direction controller using accelerometer and traveling distance controller using rotary encoder and edge sensors were installed for autonomous operation.

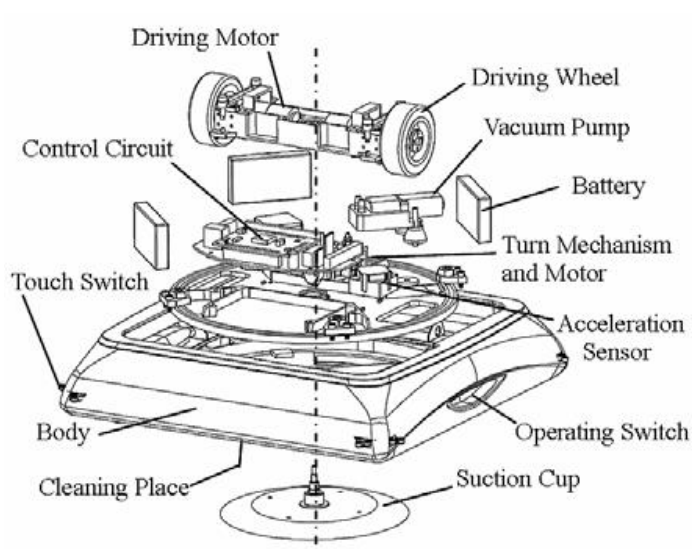



**Figure 4: The Tohru Miyake robot's structure [2]**

The most important point in the mechanism is the friction coefficient of suction cup and tire against the adhering surface, e.g. high friction between the tire and the surface of window can transmits the torque, and low friction between the suction cup and the surface of window can achieves to move the robot with holding the body on the window. PTFE (Polytetrafluoroethylene) was selected for the materials of surface of a suction cup, and silicon rubber for the material of tires. Vacuum pump Pressure is maximum -33.3 kPa with flow volume 2.5 l/min.

### 2.2.2 Biped Climbing Robot

This robot is design by Mark Minor, Hans Dulimarta, Girish Dang, Ranjan Mukherjee, R.Lal Tummala, and Dean Aslam from Mechanical and Electrical Engineering Department, Michigan State University. These robots must be sufficiently small to travel through confined spaces, such as ventilation ducts, and to avoid detection while traveling along the outside of a building. It is assumed that the robot will travel on smooth surfaces with varying inclinations, such as floors, walls, and ceilings, and walk between such surfaces. Thus, the robot must be capable of adapting and reconfiguring for various environmental conditions, be self-contained, and be capable of carrying wireless sensors, such as a camera or microphone and their transmitters. The purpose of deploying such a robot would be for inspection, isolating the source of a biological hazard, or for gathering information about a hostile situation within a building.

The Smart Robot Foot (SRF) grips the climbing surface and supports the weight of the robot. The SRF measures 40 X 40 X 25 $mm^3$ and weighs 35g with a 40mm diameter suction cup. The total power consumption is 0.5 watts. Its main components are a diaphragm-type motor-operated vacuum pump, a suction cup, a pressure sensor and a micro machined shape memory alloy valve. The pump is connected to the suction cup through a custom designed miniature aluminum connector. The connector integrates the SRF components and serves as a mounting platform for the robot body. The suction cup features cleats that increase the rigidity of the grip. The signal from the pressure sensor indicates whether the SRF is firmly attached to the surface. The SRF is released through actuation of the valve by a signal from the control unit.

The weight that is supported by the SRF is determined by testing it on different surfaces with loads applied parallel and perpendicular to the surface. In parallel configuration, the load is applied at a distance D from the clean glass surface. Results indicate that a 40mm diameter suction cup on a glass surface can support a parallel load of approximately 590gr 80mm from the surface and 365gr 120mm from the surface.

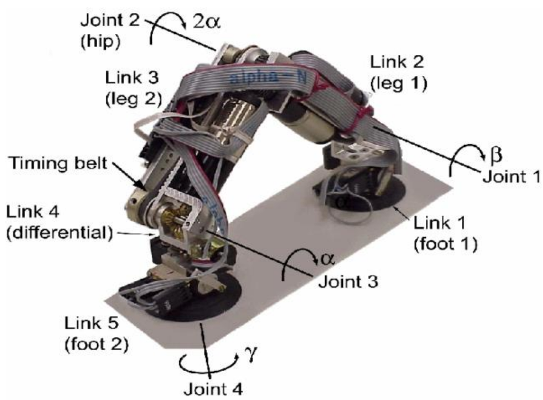



**Figure 5: Prototype of biped climbing robot [1]**

### 2.2.3 Window Climbing Robot without Vacuum Pump

The robot design by Stanford University, called Stickybot, draws its inspiration from geckos and other climbing lizards and employs similar compliance and force control strategies to climb smooth vertical surfaces including glass, tile and plastic panels. Stickybot use microspines to climb rough surfaces such a brick and concrete. To enable Stickybot to climb a variety of surfaces an analogous, albeit much less sophisticated, hierarchy of compliances has been employed. The body of Stickybot is a highly compliant under-actuated system comprised of 12 servos and 38 degrees of freedom. The torso and limbs are created via Shape Deposition Manufacturing, using two different grades of polyurethane.

The stiffest and strongest components of Stickybot are the upper and lower torso and the forelimbs, which are reinforced with carbon fiber. The central part of the body represents a compromise between sufficient compliance to conform to gently curved surfaces and sufficient stiffness so that maximum normal forces of approximately +/- 1N can be applied at the feet without producing excessive body torsion.

### 2.2.4 Patent 3,629,893 Window Cleaning Apparatus - Thomas Brown

This window cleaning apparatus was designed by Thomas Brown. [11] It is a portable cleaning device provided with a pad or sponge to contact a window for cleaning which is connected via a linkage to an electrically operated vibrator. As the device is moved over the surface of the window to be cleaned by an operator the vibrating motion causes the pad to clean the surface.

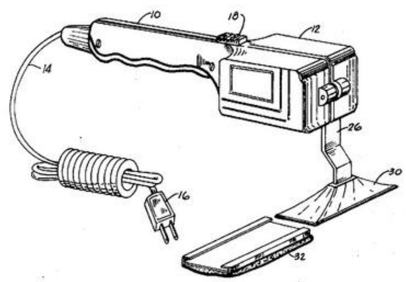


**Figure 6: Window Cleaning Apparatus - Thomas Brown [11]**

### 2.2.5 Patent 7,231,683 Window Cleaning Apparatus – Luis Carlos Cruz

The window cleaning apparatus was designed by Luis Carlos Cruz [12]. The window cleaning apparatus includes a guide track mounted on one side of a window frame and a second guide track mounted on a side of the window frame opposite the first guide wherein a cleaning assembly is retained and guided between and along a length of the first and second guide tracks. The apparatus further includes a means for selectively moving the cleaning assembly along the length of the guide track and over a surface of a window within the window frame thereby cleaning the surface of the window.

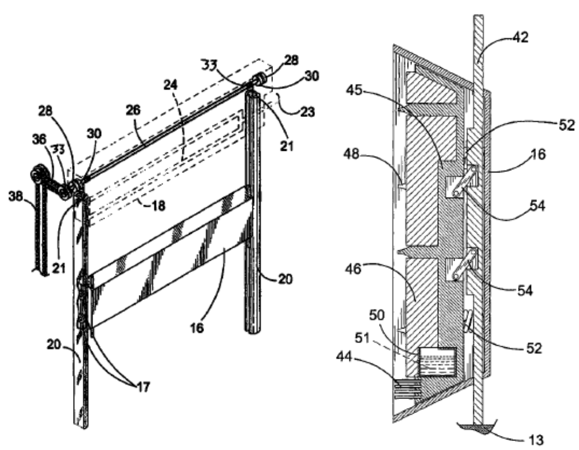


**Figure 7: Window Cleaning Apparatus – Luis Carlos Cruz [12]**

# CHAPTER 3

# METHODOLOGY

The methodology of the project is as shown in Figure 8. The methodology on how the project should be done is discussed further in chapter 4 to chapter 6.

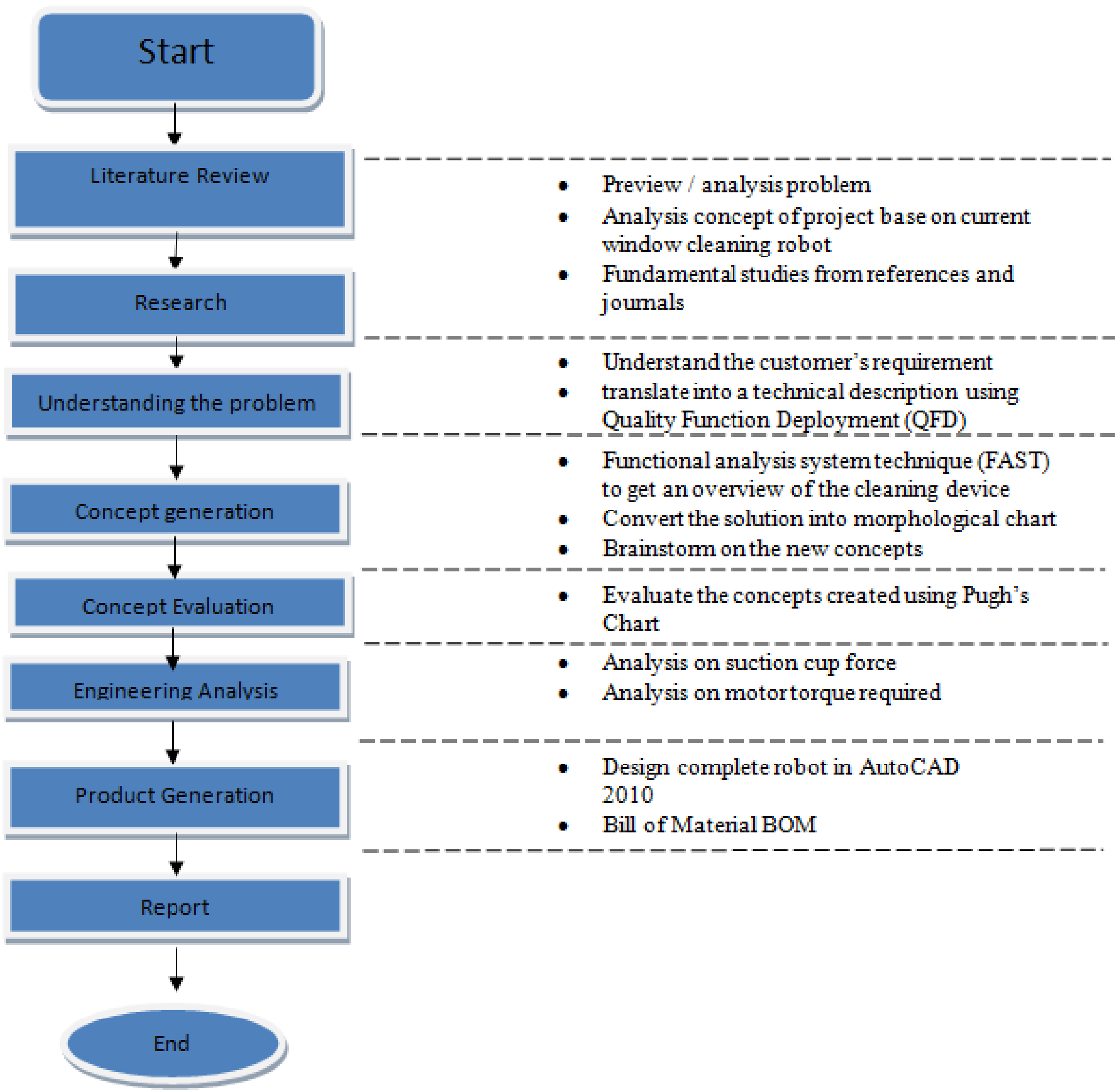



**Figure 8: The methodology of the project**

# CHAPTER 4

# CONCEPTS GENERATION

## 4.1 Understanding the Problem and the Development of Engineering Specification

Understanding the design is an essential for designing a quality product. This step is done to understand what are the customer's requirement for the window cleaning robot and translate it into a technical description of what needs to be designed.

There are 8 steps involved in the process. These steps are then converted into Quality Function Deployment (QFD) chart [9]. The steps involved are shown in diagram below:

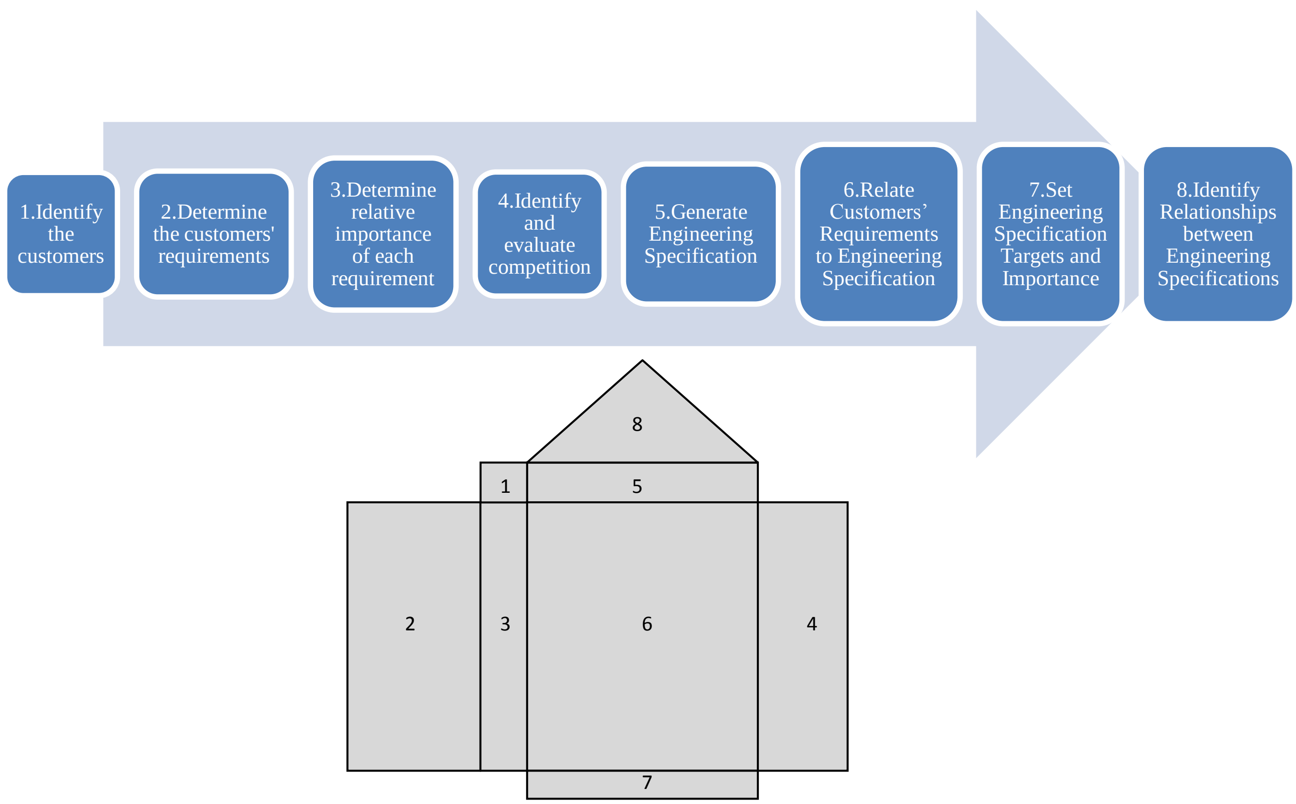



**Figure 9: Steps to create QFD Diagram**

### a) Step 1: Identify the Customers

The customer in this context is the window cleaning contractor which also the operator of the robot which is going to be designed.

**b) Step 2: Customer's Requirements**

In this step, the goal is to determine what is to be designed which means what the customer wants. From researches and observations, 12 main requirements are listed out. Table 1 indicates the requirements.

**c) Step 3: Relative Importance of the Requirements**

In this step, the importance of each of the customer's requirement is evaluated. This is accomplished by generating a weighting factor on a scale rate from 1 to 10 for each requirement where 10 being the most important while 1 unimportant. The weighting will give an idea on how much effort, time, and money to invest in achieving each requirement. The detail is listed directly in the QFD chart in Figure 11**.**

**Table 1: Customers' Requirement for Window Cleaning Device**

| **Requirement** | **Comments** |
|---|---|
| Lightweight | - Robot must be lightweight for easier operation/operational mass<br>- Max weight ≤ 5kg |
| Portable | - Robot should be easily moved to any side of the building<br>- Max dimension of 500mm X 500mm X 200mm |
| Power | Battery powered, 24 Vdc max, rechargeable |
| Safety Mechanisms | - Must have safety cord to prevent robot from falling in worst case scenario<br>- Must come with "safe mode" (low-power mode) which indicates the battery power is getting low |
| Stays within Window | - May only touch within 25mm of any part of clear window |
| Cleaning Fluid Allocation | - Must have container for water and cleaning fluid which able to carry at least 50mL H2O without leaking |
| Efficient/Clean Window | - Must clean every angle of window pane<br>- Operating time ≤ 5 min for each windowpane |
| Automated | - Must be fully autonomous or remote-controlled |
| Shutdown Process | - Must turn off all cleaning operations and signal when it is finished |
| Mobility | - Must not leave any unclean-able portions of window |
| No Risk of Damage | - May not damage window or frame |
| Attractive High Tech Look | - Considerate/ moderate look |
| Low Cost | - Must be low cost and reliable |

**d) Step 4: Identify and Evaluate Competition (Benchmark)**

The goal is to determine the competition's ability which is from the current window cleaning robot to meet each requirement. The purpose is to create awareness of what already exists and to reveal opportunities to improve on what already exists. From research, there are 3 window cleaning robot/apparatus that will be compared to which are:

i) Small-size Window Cleaning Robot

ii) Patent 3,629,893 – A window cleaning apparatus by Thomas Brown

iii) Patent 7,231,683 - A window cleaning apparatus by Luis Carlos Cruz

For each requirement, rating from 1 to 5 is given to the existing product which:

1. The product does not meet the requirement at all
2. The product meets the requirement slightly
3. The product meets the requirement somewhat
4. The product meets the requirement mostly
5. The product fulfills the requirement completely

**e) Step 5: Engineering specification**

The goal is to develop a set of engineering specification from each requirement. These are the restatement of the design problem in term of parameters of interest that can be measured and have target values. Without such information, engineers can't know whether if the system being developed will satisfy the customers.

**Table 2: Engineering Specification for the Window Cleaning Device**

| **Requirement** | **Engineering Specification** | |
|---|---|---|
| | **Description** | **Value/Attribute** |
| Lightweight | Operational mass | ≤ 5kg |
| Portable | Dimensions | ≤ 500mm X 500mm X 200mm |
| Power | Power Source | 24 Vdc max, rechargeable |
| Safety Mechanisms | i) Safety cord<br>ii) Low-power mode | |
| Stays within Window | Operating boundary | ≤ 30mm of glass |
| Cleaning Fluid Allocation | Water container | ≥ 50mL |
| Efficient/Clean Window | i) Operating time<br>ii) Clean all dust | ≤ 5min |
| Automated | Automated/remote-controlled | |
| Shutdown Process | i) Turn-off all process<br>ii) End signal | |
| Mobility | No blind/unclean spot | |
| No Risk of Damage | No damage | Window & frame receive no permanent damage |
| Attractive Look | Moderate look | |
| Low Cost | i) Low cost<br>ii) Reliability | |

**f) Step 6: Relate Customers' Requirements to Engineering Specification**

The goal is to relate the customers' requirements to engineering specification. The strength of this relationship can vary with some engineering specifications conveyed through specific symbols of numbers:

i) 9 = Strong Relationship
ii) 3 = Medium Relationship
iii) 1 = Weak Relationship
iv) Blank = 0 = No Relationship at all

The 0-1-3-9 values are used to reflect the dominance of strong relationship.

**g) Step 7: Set Engineering Specification Targets and Importance**

In this step, the basement of the QFD is filled. Here we set the targets and establish how important is it to meet each of them. There are three parts to this effort which are; calculate the specification importance, measure how well the competition meets the specification, and develop target for your effort.

From the QFD chart, we can determine the relative importance of each engineering specification through the use of the following algorithm, Eq. 4.1 [9]

$$\sum_j E_i C_j$$

Where:

$E_i$ = engineering specification number

$C_j$ = customer requirement weight

i = each engineering specification's column

j = each customer requirement row

The summations are written in the "Total" row of Figure 11. The following are the order of importance for the engineering specification that been observed:

1) Operational Mass
2) Dimensions
3) Low power mode
4) No blind/unclean spot
5) Automated/remote-controlled
6) Turn off all process
7) End signal
8) No risk of damage
9) Safety cord
10) Operating time

11) Power source
12) Low cost
13) Operating boundary
14) Water container
15) Clean all dust
16) Reliability

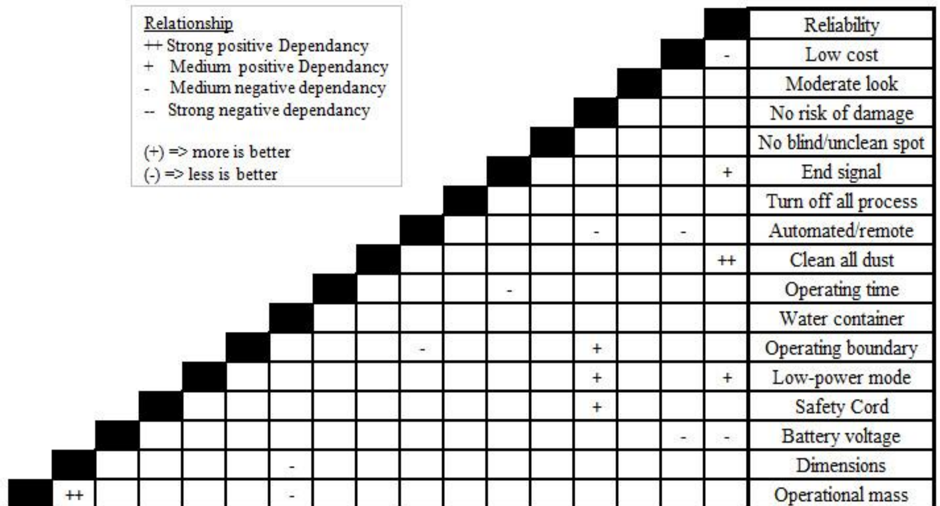
As expected, the weight and the size of the robot come out as the most important factors of our engineering specifications. Unexpectedly, the low power mode of the robot comes in third. This means that the customers asking for safety more than any other remaining criteria. The remaining factors follow closely after each other in value and more or less reflect competition scoring criteria accordingly.

**h) Step 8: Identify Relationships between Engineering Specifications**

Engineering specifications may be dependent on each other. Thus the roof is added to show that to meet one specification, there may be some positive or negative effect on others. The roof of the QFD shows diagonal lines connecting to the engineering specifications. The dependency between two specifications will be given a symbol which is as follows:

i) ++ Strong positive dependency
ii) + Medium positive dependency
iii) -- Strong negative dependency
iv) - Medium negative dependency

For example, at the QFD chart, we can see that between the dimensions and operational mass, there is a strong positive dependency where if the dimensions larger, the weight of the robot also increase.




| | | Operational mass (7kg) | Dimensions (0.7x0.7x0.35) | Battery voltage (24V dc) | Safety cord | Low-power mode | Operating boundary | Water container (50mL) | Operating time (5min) | Clean all dust | Automated/remote-controlled | Turn-off all process | End signal | No blind/unclean spot | No risk of damage | Moderate look | Low cost | Reliability | Small-size Window Cleaning Robot | Patent 3,629,893 | Patent 7,231,683 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lightweight | 10 | 9 | 3 | | | | | 1 | 1 | | 1 | | | | 1 | | 3 | | 5 | 4 | 1 |
| Portable | 10 | 3 | 9 | | | | | | | | | | | | | | 1 | | 5 | 4 | 1 |
| Power | 10 | 9 | 3 | 9 | | 9 | | | | | | | 9 | | | | 3 | | 4 | 1 | 1 |
| Safety Mechanisms | 10 | 1 | 3 | 3 | 9 | 9 | | | | | 1 | | | | 9 | | | 3 | 3 | 1 | 4 |
| Stays within Window | 9 | | 9 | | 1 | | 9 | | | | 3 | | | 3 | 3 | | | 1 | 5 | 4 | 5 |
| Cleaning Fluid Allocation | 9 | 9 | 3 | | | | | 9 | | 1 | | | | | | | | | 3 | 1 | 5 |
| Efficient/Clean Window | 8 | 3 | 1 | | | | | | 9 | 9 | 3 | 3 | | 9 | | | | | 3 | 2 | 3 |
| Automated | 7 | 3 | | | | 3 | | | 3 | | 9 | 9 | 3 | 9 | | | 3 | 3 | 5 | 2 | 5 |
| Shutdown Process | 7 | 1 | 1 | | | 3 | | | | | 3 | 9 | 9 | | | | | 1 | 1 | 2 | 4 |
| Mobility | 6 | 3 | 1 | | 3 | | 3 | | 9 | | | 3 | | 9 | | | | | 2 | 3 | 1 |
| No Risk of Damage | 5 | | | 2 | 9 | 9 | 3 | | | | 1 | | | | 9 | | | 1 | 2 | 4 | 5 |
| Attractive Look | 3 | 9 | 9 | 3 | | | | | | | 9 | 9 | | 9 | | 9 | | 3 | 3 | 2 | 5 |
| Low Cost | 3 | 3 | 1 | 1 | 1 | | | | 1 | | 3 | | | 1 | | 3 | 9 | | 1 | 3 | 1 |
| Measurement unit | | kg | $m^3$ | Vdc | - | | mm | mL | min | - | - | - | - | - | - | - | RM | - | | | |
| Target value | | < 7 | <0.17 | <24 | | | <25 | >50 | <5 | | | | | | | | <1000 | | | | |
| Importance rating | | **1** | **2** | **11** | **9** | **3** | **13** | **14** | **10** | **15** | **5** | **6** | **7** | **4** | **8** | **17** | **12** | **16** | | | |
| Total | | 407 | 339 | 142 | 165 | 267 | 114 | 91 | 160 | 81 | 196 | 195 | 174 | 246 | 172 | 36 | 118 | 81 | | | |

**Figure 10: QFD Diagram for Window Cleaning Device [10]**

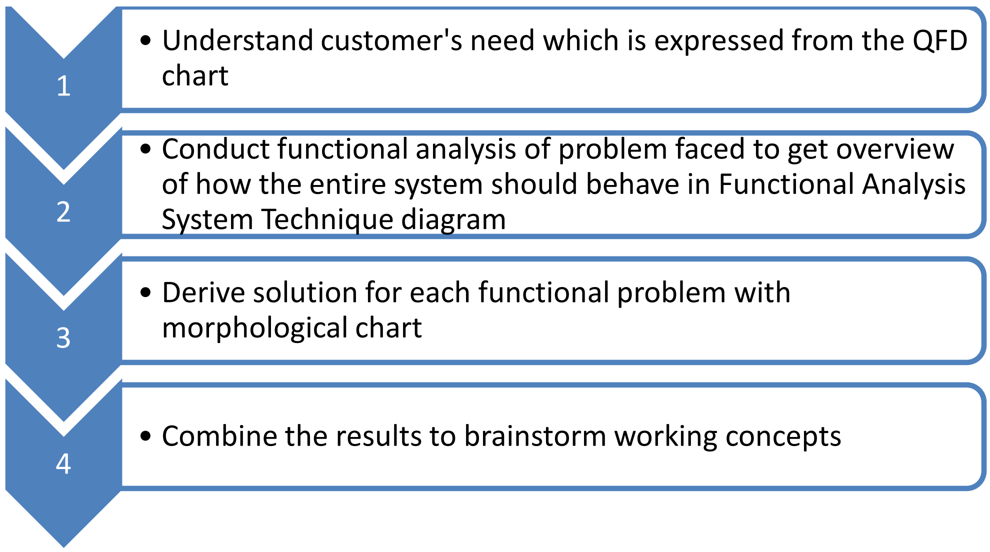
From this, we are then able to determine the relative importance of each engineering specification through the use of the following equation:

$$\text{Total Points} = \sum_j E_i C_j$$

Where: $\boldsymbol{E_i}$ = engineering specification number, $\boldsymbol{C_j}$ = customer requirement weight, i = each engineering specification's column, **j** = each customer requirement row

### 4.2 Concept Generation

After the importance ratings of engineering specifications have been determined, we can now move on to concept generation. The generation of our window cleaning robot concept can be explained in four-step process as follows:




Once we understand the relationship between the customer's requirements and engineering specification, a FAST diagram can be created where the solution of each problem faced will be drawn in an easy-to-understand diagram. To do this, we must first examine the functional issues of the overall problem which is cleaning a window. From this we can then propose elemental solutions to each issue which will later be synergized into a system of solution for the overall problem.

#### 4.2.1 Functional Analysis System Technique (FAST)

In this part, the function of the robot is determined and every option for each function is listed. The functional analysis begins with defining the functional objective which is to clean a window. We can then divide the robot system into two primary active functions which are the cleaning mechanism and locomotion mechanism. Apart from that there are three passive functions which are the dependability, assuring convenience and future enhancement. These elements will be inserted in a FAST diagram.

To clean the window glass, the cleaning surface of the robot must be engaged on the window. This means that the device requires a normal and tangential force to be applied to the window. The normal force provides cleaning friction and the tangential force to move the robot along the window.

For locomotion or traversing on window pane, there are two process needed. The first is to determine a route by maintaining a boundary and monitoring the position of the robot. Then for the second, the robot needs to apply motion along the already determined route.

Dependability means a degree to which an item is capable of performing its required function at any randomly chosen time during its specified operating period, disregarding non-operation related influences. In this context the device must exhibit active safety, passive safety, and indicate when the cleaning process completed. The active safety function should contain two sub-functions which are battery monitoring and low-battery alert. On the passive safety part, just one sub-function can be set which is to be harnessed to the window frame. And the last aspect of dependability is for the device to indicate when the process has completed by having another two sub-functions which is by flashing a finish light and determining a finish location.

In terms of assuring convenience, it relies on three functions which are intrinsic portability, ease of assembly, and ease of control. Intrinsic portability refers to the device's size where the device's size should be no greater than 500mm x 500mm x 200mm in assembled states. The device also should be easily assembled and disassembled minimizing the time and effort for the operator. It is also necessary to have the device to be easily controlled to allow the robot to cover all areas of the window.

For product enhancement, there will be 2 sub-functions which are the ability to carry fluid and allowing for upgrades. The device should be able to at least carry 50mL of cleaning fluid. At the same time, the device should be designed to allow for any upgrades in the future. This is important to reduce future cost addition to re-build the device if any upgrades are to be added.

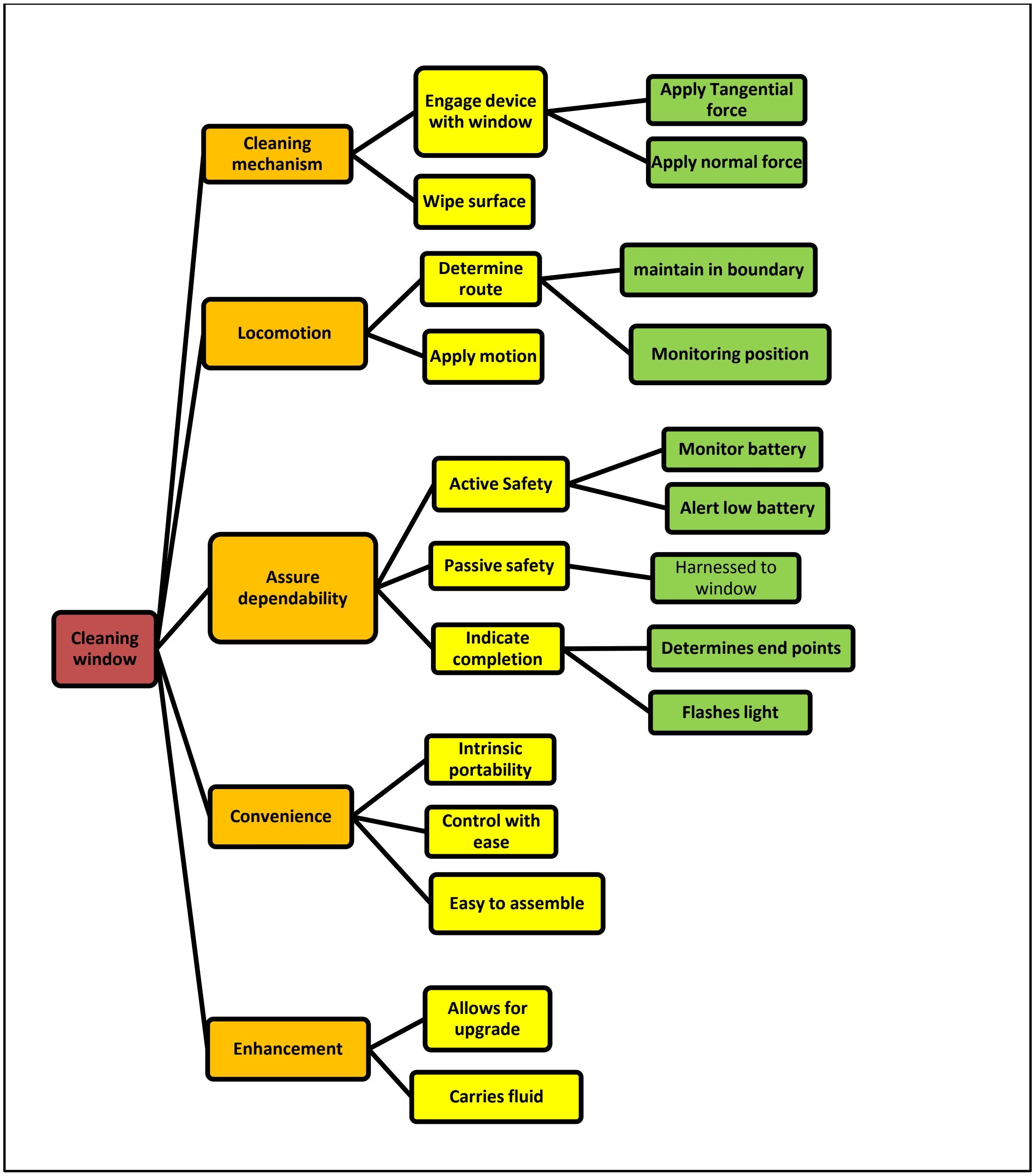



**Figure 11: FAST Diagram of the Window Cleaning Robot's**

### 4.2.2 Functional Solutions

By examining the FAST diagram, we are able to create possible solutions for each function stated. The solutions are listed out by constructing a Morphological chart together with the options. [9]

**Table 3: Morphological Chart –functional solutions**

| **FUNCTION** | **OPTIONS** | | | |
|---|---|---|---|---|
| **Wipe surface** | Porous media (sponge) | Scraping media (squeegee) | Brushed media (dry-eraser) | |
| **Apply Tangential Force (locomotion)** | Trans-wheel | Linear Slider | High friction wheels | Articulated motion |
| **Apply normal force (adhere)** | Magnets | Active suction cup (need pump) | Passive Suction cup | Suction fan (Based on Negative Pressure-Thrust |
| **Maintain boundary** | User control (using remote control) | Optical sensor (IR, ultrasonic, etc) | Physical sensor (pressure sensor, encoder) | Stepper motor position control |
| **Monitoring position** | User control (visual reference) | Software mapping (onboard PIC) | Implicit Mapping (record trajectory and speed) | |
| **Apply motion** | Linear actuator | Servo motor | DC gear motor | Stepper motor |
| **Harnessed to window** | Safety chord (rope, bungee cord) | Clamp to window | | |
| **Intrinsic portability** | Minimal parts | Low volume design | Low mass material | |
| **Control with ease** | User Control (remote) | User prescribed (articulated motion) | Automatic (computer/ sensor interface) | |
| **Determine end position** | Pressure sensor | Optical Sensor | User input | |
| **Monitor battery (flashes light when low)** | Incandescent light | LED | | |
| **Fluid carrier** | Plastic container | Soft pouch | Aluminum container | |
| **Drop water** | Spray | Sprinkler | | |
| **Allow for upgrades** | Free spaces | Flexible Dimension | | |

### 4.2.3 Concept brainstorming

In this part, several possible and potential window cleaning robot concepts are drawn. From the previous part where the functions and options are listed out, we can now assimilate our functional element solutions into a full system. There are four possible concepts that will be discussed in detail below:

a) Design 1 – Magnet-attached robot concept

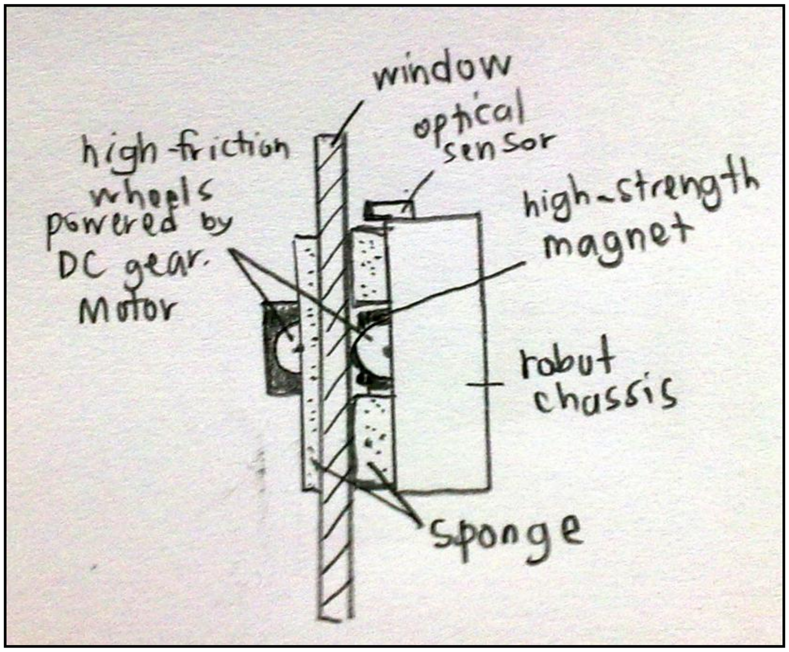



**Figure 12: Concept - Magnet-Attached Concept**

Based from the morphological chart, this design concept main cleaning media is two sponges fixed under the device and the other one on the other side of the window. It will as well act as upward frictional force on the window to counteract the downward force from the weight of the robot. To carry cleaning fluid, the device is installed with plastic container. For locomotion, this concept uses two trans-wheel located at the center of the device. Trans-wheel allows the device for turning in any direction. To let it remains in contact with the window, two high-strength magnets are used on each side of the window.

To apply motion, high torque and low speed DC geared motor is used. For moving forward, both motors could move in one direction while for turning, one motor could be moved forward and another one backwards. This provides the necessary normal force onto the device so that it can stay on the window. To maintain the device within the boundary (windowpane), physical sensor such as encoder is used. The encoder will detect the distance covered thus prevents the device from over-move.

In terms of intrinsic portability, the device use minimal number of parts where less than ten materials used. The device also low in volume which the maximum dimension is less that 500mm x 500mm x 250mm. As for the device control, it is semi-autonomous where the device needs to be setup on the window first then by pressing a switch it will move according to the path that has been set in the PIC.

After the device operation has finished, it needs to determine the end position before it stop. Thus, an optical sensor is installed at the head of the device to sense any trench which indicates the gap between two windows. In case of emergency, an LED is installed to indicate when the battery power is getting low.

b) Design 2 – 4-way Slider Robot with Active Suction Cup

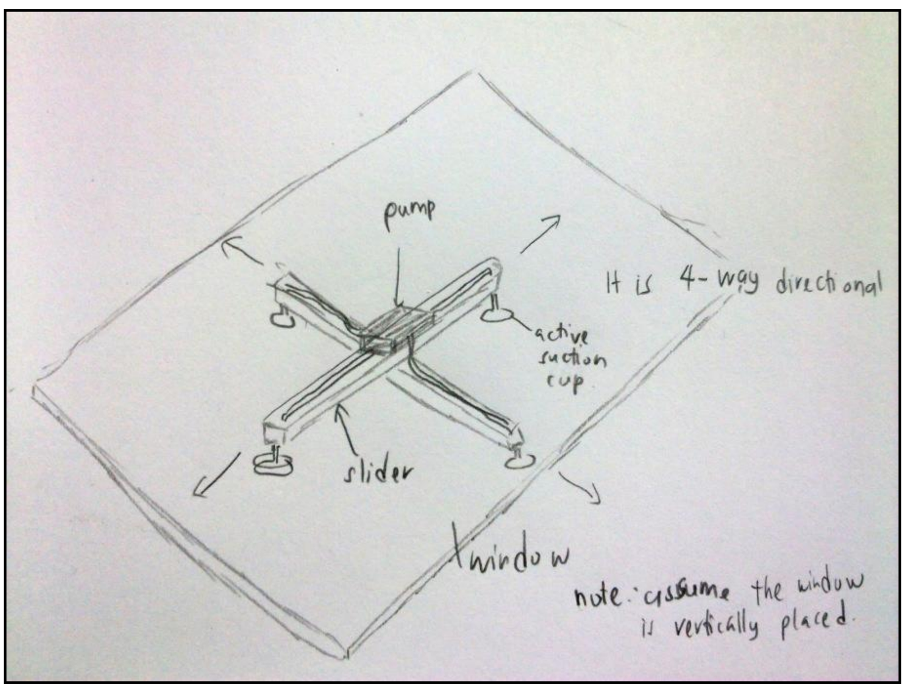



**Figure 13: Concept - 4-way Slider Robot with Active Suction Cup**

Same as design 1, this design concept uses sponge fixed under the device as the window cleaning media. To carry cleaning fluid, the device is installed with plastic container. For locomotion, this concept uses two linear sliders which are positioned in cross shape.

One linear slider is fixed on top of the other one so that it can provide with a four-way directional movement. To stay in contact with the window, the device use 4 suction cups powered by air pump where two of them located on each slider. When static, only two of the suction cups (the two must be on the same slider) will hold the window to allow the other linear slider to slide through. Once this slider reach its destination, the suction cups on each edge will grip and the other two at the other slide will release it’s gripping on the window.

To apply motion, two DC geared motor is used where one motor is placed on top of the upper slider while the other at the bottom of the lower slider. Pulley system is used to support the locomotion as can be seen in the picture. In terms of intrinsic portability, the device has at least ten materials, high volume design and also high mass material. The device is autonomous.

After the device operation has finished, it needs to determine the end position before it stop. Thus, four optical sensors are installed on each edge of the device’s linear slider to sense any trench which indicates the gap between two windows. In case of emergency, an LED is installed to indicate when the battery power is getting low.

c) Design 3 – 2 Wheels Robot with Passive Suction Fan

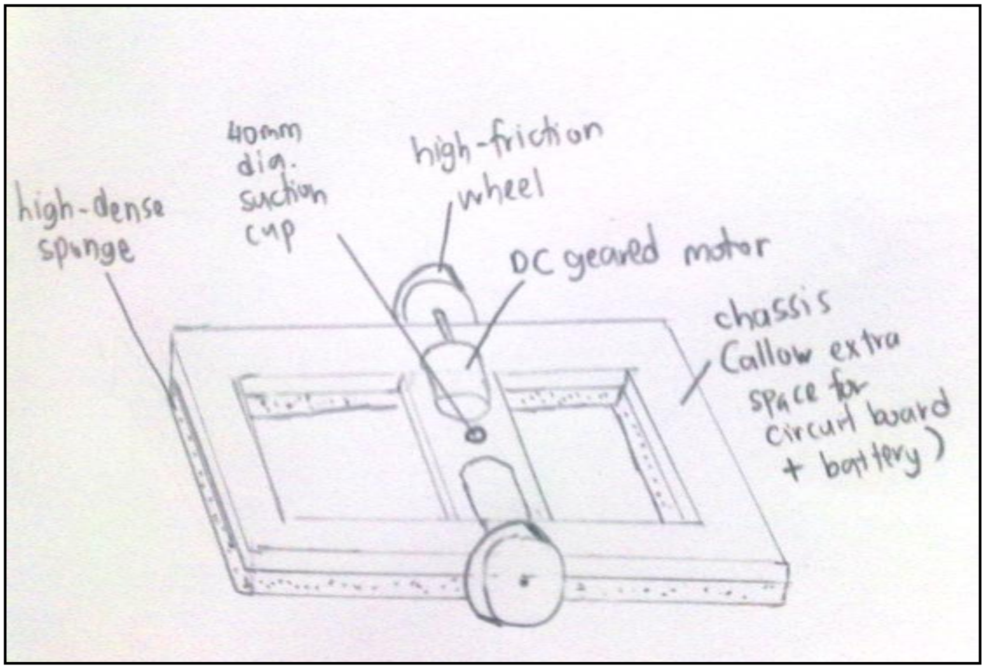



**Figure 14: Concept - 2 Wheels Robot with Passive Suction Fan**

For this design concept, sponge is used and fixed under the device's body as the window cleaning media. It will as well act as upward frictional force on the window to counteract the downward force from the weight of the robot. To carry cleaning fluid, the device is installed with plastic container. For locomotion, two high friction wheels are used. To apply motion, two DC geared motors are used where one is placed on each of the wheel. For the device to turn, one motor will move backward while the other one move forward. This turns the device in $90^o$ where the center point is the center of the device.

To provide normal force and let the device remains in contact with the window, one passive suction cup is used and placed at the center bottom of the device. The cup needs to be fixed manually onto the window at the starting point. **Alternatively, the suction cup used for this design concept can be replaced with a suction fan that used Negative Pressure Thrust (NPT) to adhere on the window.

In terms of intrinsic portability, the device use minimal number of parts of less than ten materials, low volume design and also low mass material. The device is autonomous. After the device operation has finished, it needs to determine the end position before it stop. An optical sensor is installed at the head of the device to sense any trench which indicates the gap between two windows. In case of emergency, an LED is installed to indicate when the battery power is getting low.

d) Design 4 – 3-Suction Cups with Linear Slider Robot

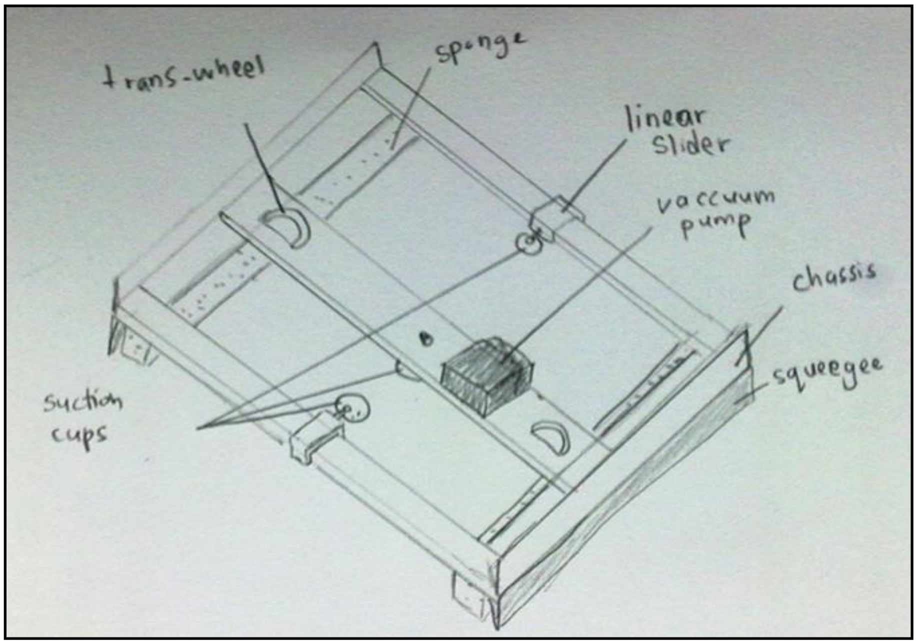



**Figure 15: Concept - 3-Suction Cups with Linear Slider Robot**

For this design concept, the same cleaning media as the first 3 is used which is sponge. Two sponges are placed at the bottom of the device with the addition of 2 squeegees at each end of the device to wipe excessive water. To carry cleaning fluid, the device is installed with plastic container. For locomotion, two trans-wheels are used allowing the device to move in any direction. At the same time, two linear sliders are used and placed on each side of the device.

To provide locomotion, two linear actuators are used. The cups suctioning process will be controlled by a vacuum generator. The 2 suction cups on each side of the robot are used for locomotion. These 2 suction cups will move simultaneously on the linear slider using the pushing force of linear actuator while the center suction cup gripping the window. Then at the end point, these 2 suction cups will grip the window while the center suction cup will release the gripping. The linear actuator will pull the 2 suction cups but since they are attached on the window, the whole robot body will move upward.

In terms of intrinsic portability, the device uses more than ten materials, high volume design and also high mass material. The device is autonomous. After the device operation has finished, it needs to determine the end position before it stop. An optical sensor is installed at the head of the device to sense any trench which indicates the gap between two windows. In case of emergency, an LED is installed to indicate when the battery power is getting low.

## 4.3 Concept Evaluation

This section focuses on evaluating our design concepts through analysis of the merits and limitations of every design, as well as through the use of a Pugh chart. The goal is to expend the least amount of resources on deciding which concepts have the highest potential for becoming quality product. In order to evaluate our concepts, the mechanisms of every design are listed out in Table 4.

**Table 4: Comparison of the design concepts**

| Design Concept | Mechanism | Components used |
|---|---|---|
| **Design 1** | a) Adhering mechanism | - two high-strength magnets are used on each side of the window |
| | b) Locomotion | - DC geared motor |
| | c) Turning mechanism | - DC geared motor |
| | d) Cleaning Mechanism | - Porous Media |
| | e) Base | - PVC |
| **Design 2** | a) Adhering mechanism | - 4 active suction cups with 2 vacuum generators |
| | b) Locomotion | - Linear sliding mechanism using linear slider powered using linear actuator |
| | c) Turning mechanism | - Linear sliding mechanism using linear slider powered using linear actuator |
| | d) Cleaning Mechanism | - Porous media |
| | e) Base | - Stainless steel |
| **Design 3** | a) Adhering mechanism | - One passive suction cup |
| | b) Locomotion | - DC geared motor |
| | c) Turning mechanism | - DC geared motor |
| | d) Cleaning Mechanism | - Porous media + squeegee |
| | e) Base | - Acrylic |
| **Design 4** | a) Adhering mechanism | - 4 active suction cups with 2 vacuum generators |
| | b) Locomotion | - Linear sliding mechanism using lead screw powered using DC geared motor |
| | c) Turning mechanism | - DC geared motor |
| | d) Cleaning Mechanism | - Porous media + squeegee |
| | e) Base | - Acrylics |

### 4.3.2 Concept selection

To aid in selecting the best concept, a Pugh Chart has been made for quantitative comparison of meeting the specifications stated earlier.

**Table 5: Pugh Chart [6]**

| Specification | Weight | Datum | Design 1 | Design 2 | Design 3 | Design 4 |
|---|---|---|---|---|---|---|
| Lightweight | 10 | 0 | - | - | + | - |
| Portable | 10 | 0 | - | + | + | + |
| Power consumption | 10 | 0 | + | - | + | + |
| Safety mechanism | 10 | 0 | + | + | + | + |
| Stays within window | 9 | 0 | + | + | + | + |
| Cleaning fluid allocation | 9 | 0 | + | - | - | + |
| Efficient/clean window | 8 | 0 | + | + | - | + |
| Automated | 7 | 0 | - | + | + | + |
| Shutdown Process | 7 | 0 | 0 | 0 | 0 | 0 |
| Mobility | 6 | 0 | - | - | + | + |
| No risk of Damage | 5 | 0 | - | 0 | - | + |
| Attractive Tech Look | 3 | 0 | 0 | 0 | 0 | 0 |
| Cost | 3 | 0 | - | - | - | - |
| Total (+) | | 0 | 46 | 44 | 62 | 65 |
| Total (-) | | 0 | 41 | 38 | 25 | 13 |
| Net Total | | 0 | 5 | 6 | 37 | 52 |
| Weighted Total (100 + Net Total) | | 100 | 105 | 106 | 137 | 152 |

The ratings are all based against the datum which is the Small-size Window Cleaning Robot designed by two Japanese Tohru Miyake and Hidenori Ishihara. From the Pugh chart, we can see that the best concept is design 4 (3-Suction Cups with Linear Slider Robot). In order to achieve our weighted total, subtract the “Total (-)” number from the “Total (+)” number and add 100 (as a means for measurement). The “Total (+)” number was found by adding the weight of every customer requirement that received a plus for that concept, and similarly the “Total (-)” number was found by adding the weight of every requirement that received a minus for that concept. From the chart, we can conclude that design 4 is the most suitable concept to be working on.

### 4.3.3 Window Cleaning Robot's Working Principles

From design 4, we work out on its possible working principle. Firstly in order to avoid passing over the same spot again and polluting the cleaned area, the cleaning path should lead from the building top to the ground. The robot generally moves along longitude, which is easy to realize. The robot cleaning's path are set in zigzag path. This is the easiest to program and the most effective cleaning path. The robot will start at lower-left of window pane and finish at lower-right of the window pane. In the next part, the algorithm of the robot motion during cleaning will be further discussed.

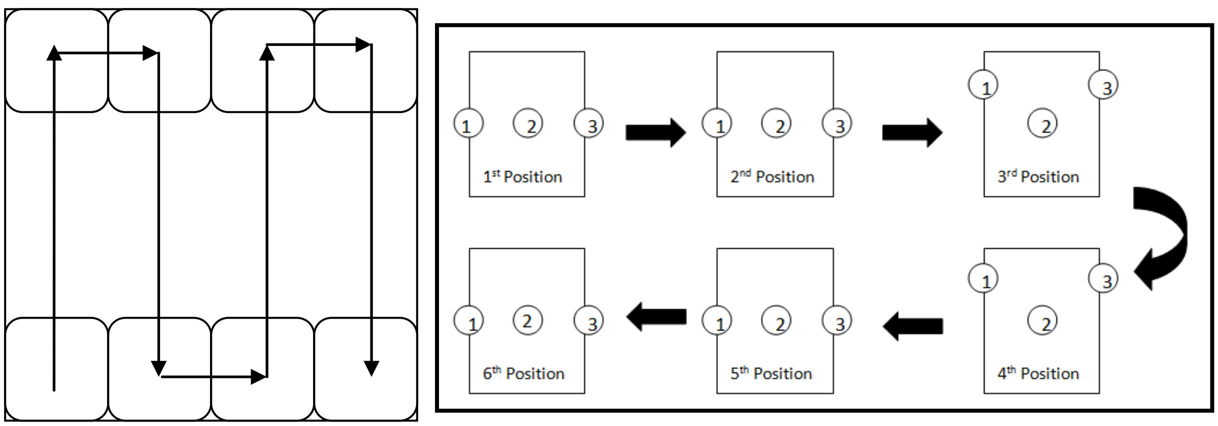



**Figure 16: The robot's cleaning path and suction cup system during operation**

**Table 6: The Conceptual Window Cleaning Robot Suction Cups working principles**

| Suction Cup Position | Suction cup 1 | Suction Cup 2 | Suction Cup 3 |
|---|---|---|---|
| 1) 1st position (all suction cup aligned at the center) | 1 | 1 | 1 |
| 2) 2nd Position (all suction cup aligned at the center) | 0 | 1 | 0 |
| 3) 3rd Position (carriage moving upward) | 0 | 1 | 0 |
| 4) 4th Position (suction cup 1 and 3 grip the window) | 1 | 0 | 1 |
| 5) 5th Position (whole robot moving upward) | 1 | 0 | 1 |
| 6th Position (Move horizontally) | 0 | 1 | 0 |

Explanation:

1. At this point, the robot is at starting position where all suction cups are gripping the window.
2. Suction cups 1 and 3 release the gripping to allow linear movement vertically. Suction cup 2 still gripping the window.
3. A motor rotates clockwise and rotating the lead screw that carries the carriage with suction cup 1 and 3 upward. Suction cup 1 and 3 not intact on the window while suction cup 2 intact on the window.
4. Suction cup 1 and 3 grip the window and suction cup 2 releases its gripping.
5. The motor rotates counter clockwise and rotating the lead screw that carries the carriage. Since suction cup 1 and 3 are gripping the window and suction cup 2 not, while pulling the carriage, the whole robot will eventually move upward.
6. Moving horizontally, suction cup 1 and 3 will release the gripping while suction cup 2 will grip the window. A DC geared motor that is mounted on top of suction cup 2 will turn the robot $90^o$ maximum to left or right.

For the robot motion on the windowpane, the robot will basically follow the sequence which is shown below. The values of A, B, C, D, and E are explained at the sub-function section

**Main functions**

1) A > B > Top IR sensor detect window boundary? No, repeat 1. Yes, go to 2)
2) E > Encoder finish calculates distance? No, continue E until complete, Yes, go to 3
3) C> D -> Bottom IR sensor detect window boundary? No, repeat 3. Yes, go to 4
4) E > Encoder finish calculates distance? No, continue E until complete, Yes, go to 5
5) Repeat step 1 to 4 > Right and Bottom IR Sensors detect window boundary? No, continue repeat, Yes, STOP process

| Sub-functions | Explanation |
| --- | --- |
| **Vertical Motion** | |
| A) Upward motion for carriage | i. Vacuum generator 1 for center suction cups ON<br>ii. Vacuum generator 2 for flank suction cups OFF<br>iii. Motor 1 ON rotate counter-clockwise<br>iv. Motor 2 OFF<br>**v.** Limit switch at top-end detect carriage, Motor 1 OFF |
| B) Upward motion for robot body | i. Vacuum generator 2 for flank suction cups ON<br>ii. Vacuum generator 1 for center suction cups OFF<br>iii. Motor 1 ON rotate clockwise<br>iv. Motor 2 OFF<br>v. Limit switch at bottom-end detect carriage, Motor 1 OFF |
| C) Downward motion for carriage | i. Vacuum generator 1 for center suction cups ON<br>ii. Vacuum generator 2 for flank suction cups OFF<br>iii. Motor 1 ON rotate clockwise<br>iv. Motor 2 OFF<br>v. Limit switch at bottom-end detect carriage, Motor 1 OFF |
| D) Downward motion for robot body | i. Vacuum generator 2 for flank suction cups ON<br>ii. Vacuum generator 1 for center suction cups OFF<br>iii. Motor 1 ON rotate counter-clockwise<br>iv. Motor 2 OFF<br>v. Limit switch at top-end detect carriage, Motor 1 OFF |
| **Horizontal Motion** | |
| E) Move to the right | i. Vacuum generator 1 for center suction cups ON<br>ii. Vacuum generator 2 for flank suction cups OFF<br>iii. Motor 2 ON rotate counter-clockwise<br>iv. Motor 1 OFF<br>v. Encoder detect wheels rotation 2.5 turn (wheel's circumference = 15.96cm, distance to travel = 40cm)<br>vi. Motor 2 OFF |

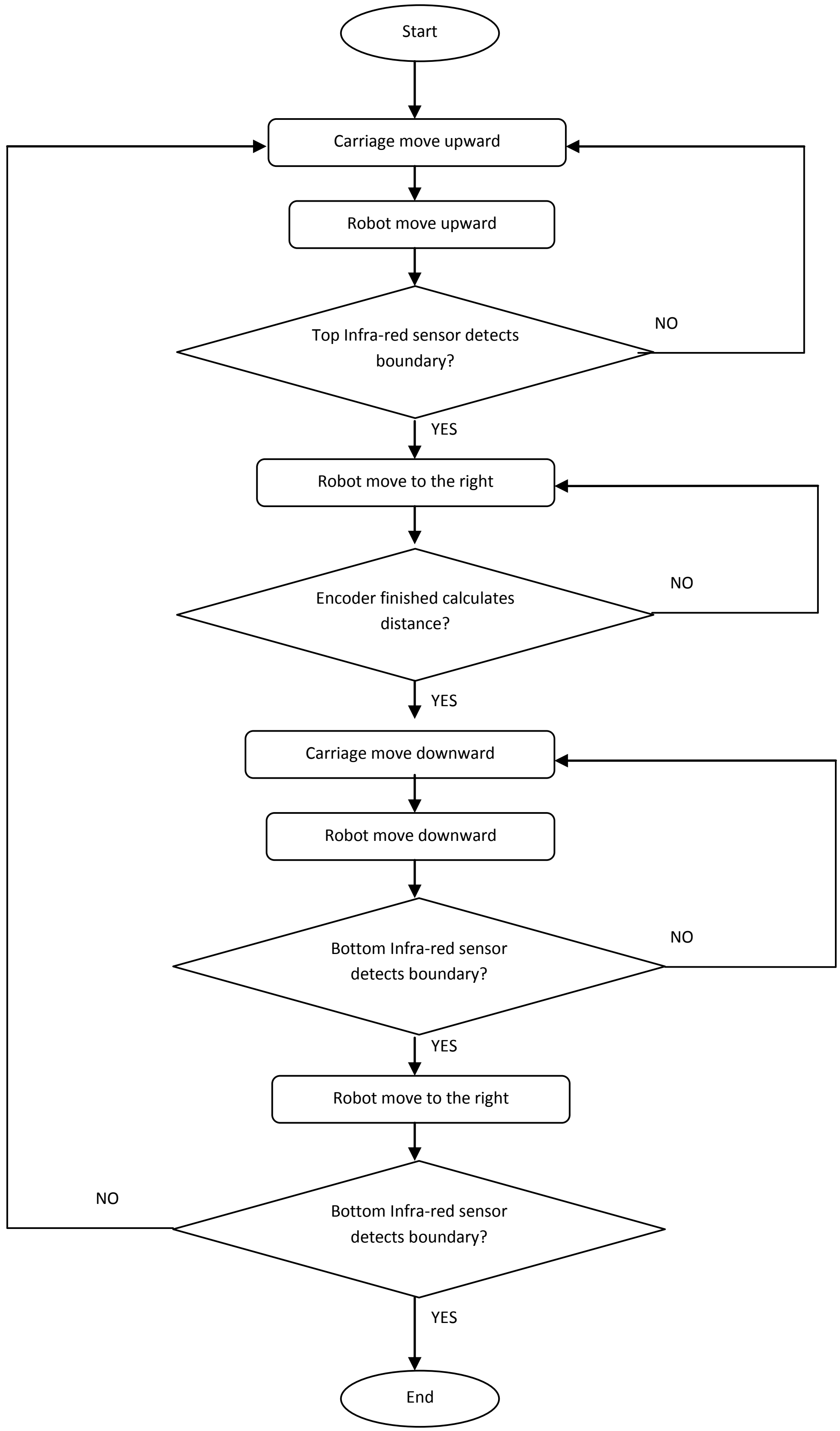
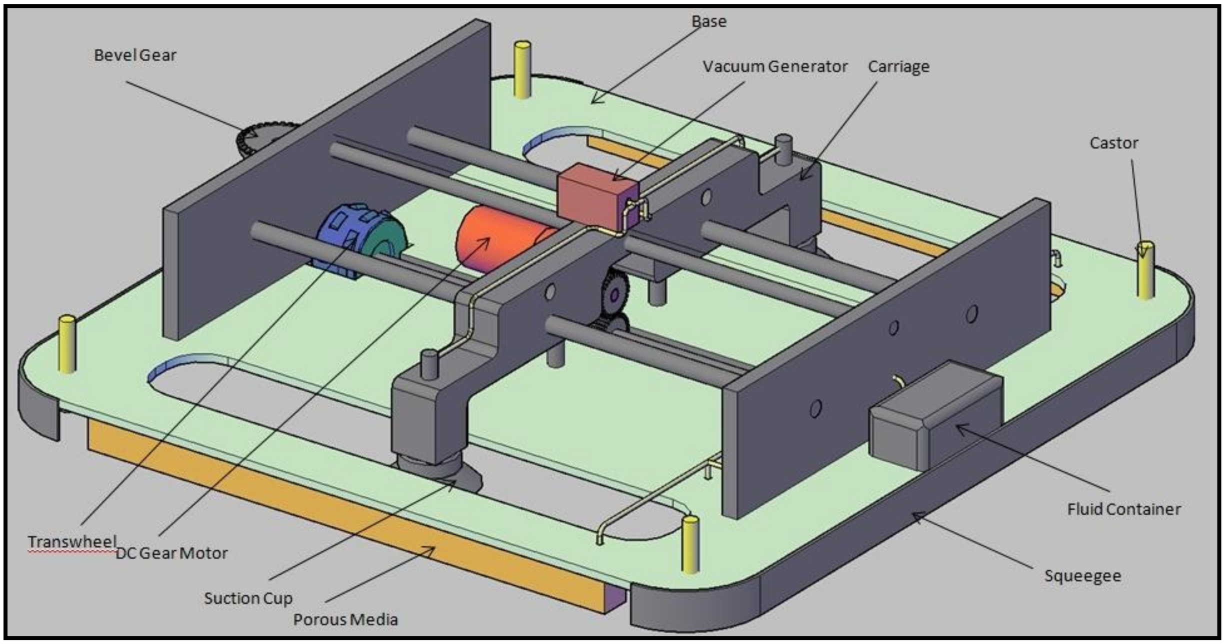



**Figure 17: Window Cleaning Robot's Motion Algorithm**

From the Pugh Chart and the working principles explained in the previous part, the first concept design can now be drafted into a CAD design as shown in the next page.



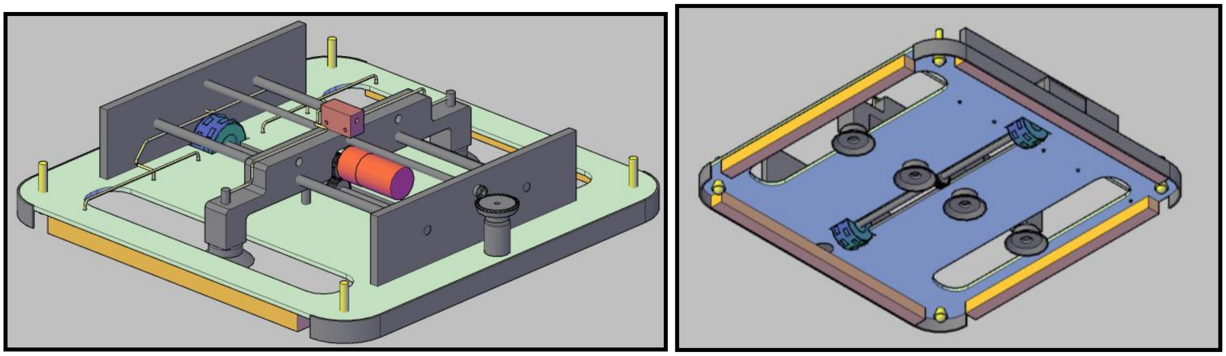



Figure 18: Initial Conceptual Design of the Window Cleaning Robot

# CHAPTER 5

# ENGINEERING ANALYSIS

We know from the previous chapter that the robot will uses two main components which is the suction cup powered by vacuum generator and two motors to provide motion to the robot. In order to ensure all mechanisms of the conceptual design is working perfectly, engineering analysis needed to be done. The first part in this section is to ensure the robot capability to adhere and hold firmly onto the window. The second part is to calculate forces involves during robot movement such as frictional force. The third part is to calculate the required motor torque for the motor to be able to lift the robot upward. And the last part is to analyze potential failure modes within the robot's system. The failures are classified by the severity and likelihood of the failures.

## 5.1 Suction Cup Gripping Force

To achieve a good adhesion, the suction cup need to have high gripping force and at the same time not too high so that we can reduce the torque and force of the motors that move the wheels. For forward movement, the robot will use linear actuator and the actuator needs to have a capacity to push or pull the robot weight. Thus, the calculation is done to ensure the right choice of suction cup and motors for the robot gripping and locomotion mechanism.

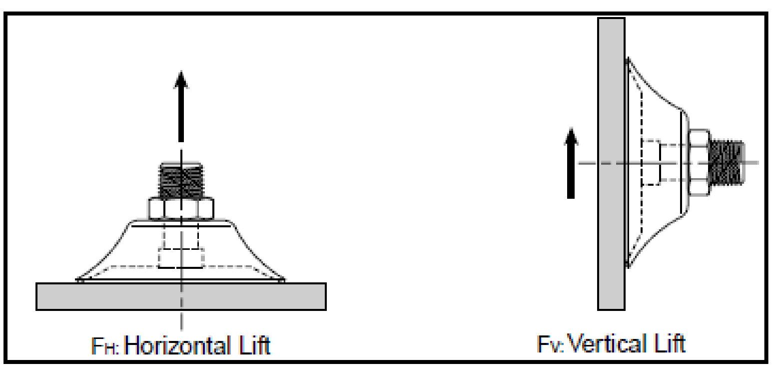



**Figure 19: Free Body Diagram of Suction Cup on the Window**

Horizontal lifting Force

Apply Newton Law to calculate the force on a 5 kg robot mass with a change in acceleration of $2m/s^2$ and a safety factor, $S_H$ of 2.[13]

$F_H(N) = mass(kg) \times (a_g + a) \times S_H$ (Eq. 5.1)

$F_H(N) = 5kg \times (9.81m/sec^2 + 2m/sec^2) \times 2$

$F_H = 118.1$ N

Vertical Lifting Force

Apply Newton Law to calculate the force on a 5 kg robot mass with a change in acceleration of $2m/s^2$ and a safety factor, $S_v$ of 4.

$F_v(N) = mass(kg) \times (a_g + a) \times S_v$ (Eq. 5.2)

$F_v(N) = 5kg \times (9.81m/sec^2 + 2m/sec^2) \times 4$

$F_v = 236.2$ N

Calculate the force on a 5kg mass with a dry surface, a change in acceleration of $2m/sec^2$, and a change in travel acceleration of $2m/sec^2$.

$F_M(N) = \sqrt{(F_V{}^2 + F_H{}^2)}$ (Eq. 5.3)

$F_M(N) = \sqrt{([(5kg\ x\ 2m/sec^2)\ x\ 4]^2 + [5kg\ x\ (9.81m/sec^2 + 2m/sec^2)\ x\ 2]^2)}$

$F_M(N) = \sqrt{(40kgm/sec^2)^2 + [118.1kgm/sec^2]^2}$

$F_M(N) = \sqrt{1600kgm/sec^2 + 13947.6kgm/sec^2}$

$F_M = 124.69$ N

At 90% of full vacuum and two suction cups working simultaneously, the area of the suction cup used can be calculated using equation 5.4 below. Since the robot uses two suction cups to hold onto the window pane, n = 2.

$\frac{F_M}{n} = \frac{124.69\ N}{2} = 62.345N$ (Eq. 5.4)

From Eq. 5.4, the force value is compared in the Table A1 in Appendix A. The suction force determined which is greater than 62.435N and at 90% capacity of the vacuum is 64.8N and has the diameter of 30mm. By applying a safety factor of 2, it is recommended to select a suction cup with diameter of **60mm** with theoretical lifting force of **259N**. From table A1 in appendix A, we can then plot a graph of the suction force (N) vs. diameter of suction cup at 90% of operating vacuum pressure in Figure 21

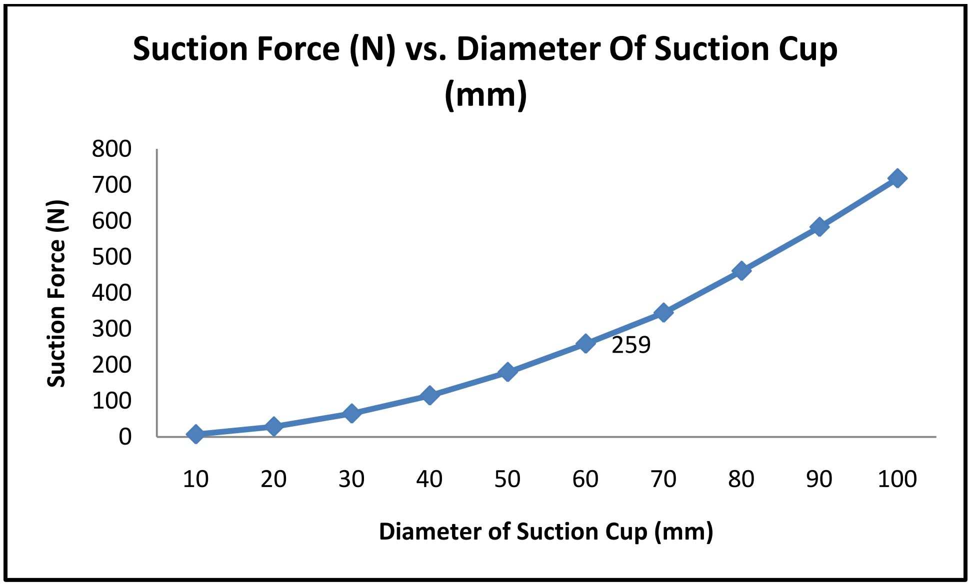



**Figure 20: Suction Force (N) vs. Diameter of Suction Cup (mm)**

## 5.2 Static Frictional Force

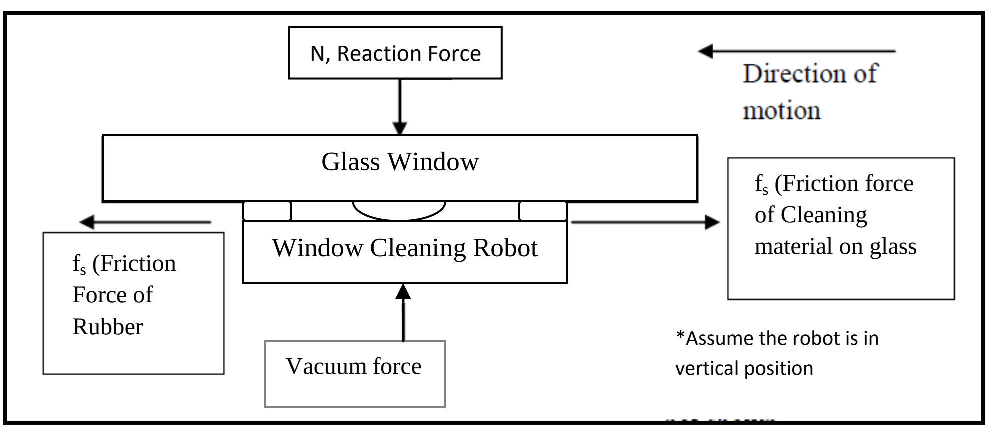



**Figure 21: Forces acting on the robot**

To find the force of static friction, we began by determining the normal force applied by the suction cups. Since we are using two suction cups during static (starting point), the suction cup force that is calculated in Eq. 5.6 is multiply by 2;

$$\mathrm{F_{total}} = \mathrm{F_M} \times 2 = 124.69\ \mathrm{N} \times 2 = 249.38\ \mathrm{N} \qquad \text{(Eq. 5.5)}$$

From [15], we determined that the coefficient of static friction between our cleaning surface (porous media) and glass can be approximated as $\mu_{f,c/g}$ = 0.4. From this, we then derive the value of cleaning static frictional force with the following relation:

$$F_{f,c/g} = \mu_f \times \mathrm{F_{total}} = 0.4 \times (249.38\ \mathrm{N}) = 99.75\mathrm{N} \qquad \text{(Eq. 5.6)}$$

According to Figure 22, as long as the force of static friction from the wheel rubber on the glass is greater than the static friction of the cleaning material on the glass, the robot will move. With a static coefficient of friction of rubber on glass of $\mu_{f,r/g}$ = 2.0,

$$F_{f,r/g} = \mu_{f,r/g} \times \mathrm{F_{total}} = (2.0)(249.38\mathrm{N}) = 498.76\mathrm{N} \qquad \text{(Eq. 5.7)}$$

$$\left(F_{f,r/g} = 498.76\mathrm{N}\right) > \left(F_{f,c/g} = (2.0)(99.75N) = 199.5N\right)$$

Since the condition is met, the robot can move sideways provided the motors supply the required torque. The next step is to explore what will happen when the robot tries to move vertically up the window. We assumed a total mass of the equipped master and follower units to be $M$ = 5.0 kg, as the engineering specification, even though our prototype would likely have a lower mass. This gives us a total weight force of:

$$F_g/g = 5.0\ \sin\theta \text{ (Where } \theta \text{ is the angle of incline of the robot)}$$

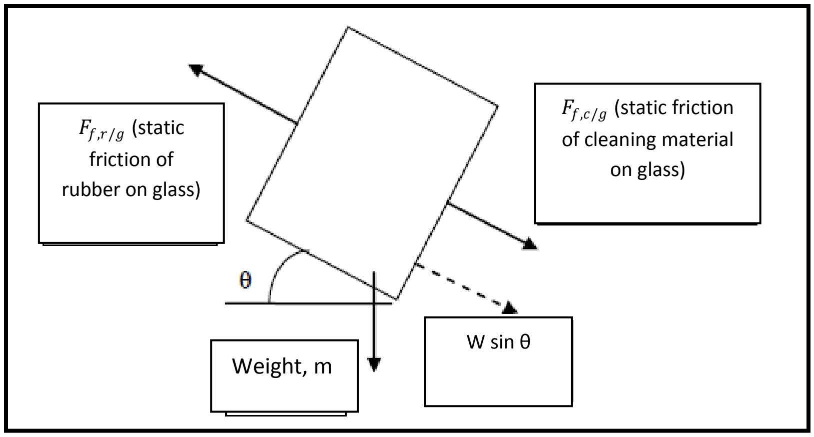



**Figure 22: Force of static friction of the Robot**

As shown in Figure 23 above, the force of static friction from the suction cup on the glass must overcome the static friction force of the cleaning surface on the glass (since that material is sliding on the glass, normally a kinetic friction force would be used, but the static friction force will be greater and may have to be overcome if the robot stops in this position), as well as the component of weight along that direction. With a static coefficient of friction of rubber on glass of $\mu f,r/g$ = 2.0,

$$F_{f,r/g} = \mu_{f,r/g} \times \mathrm{F_{total}} = (2.0)(249.38\mathrm{N}) = 498.76\mathrm{N} \qquad \text{(Eq. 5.8)}$$

$$F_{f,r/g} \geq \mu_{f,c/g} + F_g \sin\theta$$

$$498.76\mathrm{N} \geq \{99.57\mathrm{N} + (5.0 \sin\theta)(9.81)\} = \{99.57\mathrm{N} + 49.05 \sin\theta\}\mathrm{N}$$

Since this condition is met regardless of the angle to the horizontal, the robot will also move vertically up the window, provided the motors supply the required torque which is further investigated in the next part.

## 5.3 Torque Calculation

From the design concept created in chapter 4, we know that the robot uses leadscrew as a mean for vertical motion powered by a rotating motor. In this part, we calculate the torque required for the motor to initiate vertical motion of the robot.

Problem statement: A motor needed to be able to lift total weight of $m_{W+T}$ = 5kg. The power from the motor is transmitted to the stainless steel lead screw using two gears (crown gearing). The lead screw length, L = 0.4m, with the pitch, P = $10x10^{-3}$m, diameter, $D_L$ = 0.035m and its density, ρ = $7700kg/m^3$. The mitre gear connected directly to the motor has teeth, $N_2$ = 32, diameter, $D_{G2}$ = 0.033m and weight, $m_{G2}$ = 0.02 kg while the bevel gear connected directly to the lead screw; $N_1$ = 16, $D_{G1}$ = 0.0144m and $m_{G1}$ = 0.01 kg.

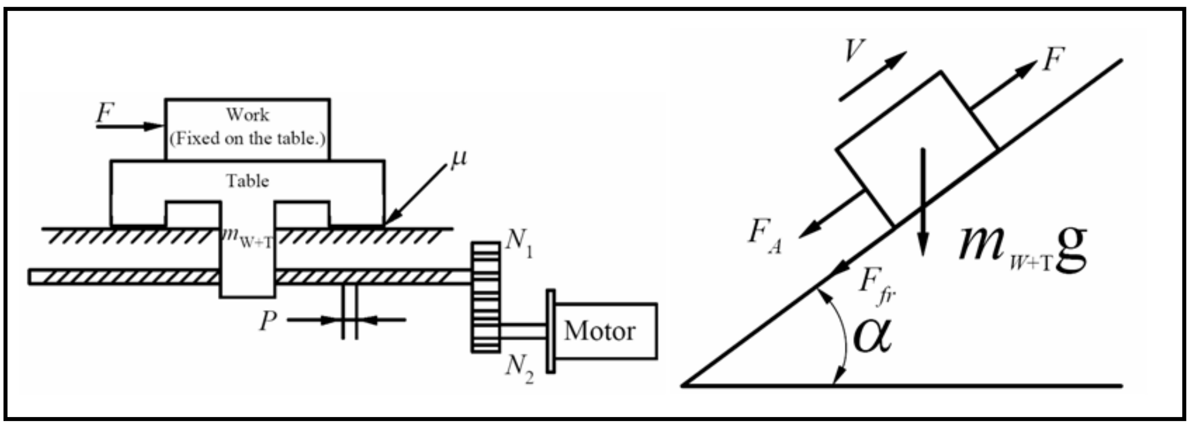



**Figure 23: Torque Calculation**

Where,

| | |
|---|---|
| $J_L$ – Inertia of the load [kg·m2] | $t$ – Time for velocity change = 2 [s] |
| $J_{G1}$ – Inertia of the Gear 1 [kg·m2] | $T_a$ – Acceleration torque [N·m] |
| $J_{G2}$ – Inertia of the Gear 2 [kg·m2] | $T_L$ – Load torque [N·m] |
| $J_S$ – Inertia of the lead screw [kg·m2] | $T_T$ – Total calculation torque [N·m], $T_T = T_L + T_a$ |
| $J_M$ – Inertia of the motor [kg·m2] | $T_M$ – Required motor torque [N·m], $T_M = K_S \cdot T_T$ |
| $J_T$ – Inertia of the system [kg·m2] | $K_S$ – Safety factor = 2 |
| $m_{W+T}$ – Weight of the work and the table =5 [kg] | α – Angle of inclination |
| $\omega_0$ – Initial velocity of the motor = 0 [rad/s] | μ – Frictional coefficient of sliding surfaces = 0.4 |
| $\omega_1$ – Final velocity of the motor = 4.2 [rad/s] | η – Efficiency (Reference Value is 0.85 to 0.95.) |
| | g – Gravity constant = 9.8 m/s2 |

**Solution:**

Inertia of the load,

$J_L = m_{W+T}\left(\frac{P}{2\pi}\cdot\frac{N_1}{N_2}\right)^2$ [kg. m$^2$] $=$ 5kg$\left(\frac{10\times10^{-3}m}{2\pi}\cdot\frac{32}{16}\right)^2 = 3.166\times10^{-6}$[kg. m$^2$] (Eq. 5.9)

Inertia of the Gear 1,

$J_{G1} = \frac{1}{8}m_{G1}{D_{G1}}^2\left(\frac{N_2}{N_1}\right)^2$ [kg. m$^2$] $= \frac{1}{8}(0.01kg)(0.0174m)^2\left(\frac{32}{16}\right)^2 = 1.5138\times10^{-6}$[kg. m$^2$] (Eq. 5.10)

Inertia of the Gear 2,

$J_{G2} = \frac{1}{8}m_{G2}{D_{G2}}^2$[kg. m$^2$] $= \frac{1}{8}(0.02kg)(0.033m)^2 = 2.7225\times10^{-6}$[kg. m$^2$] (Eq. 5.11)

Inertia of the leadscrew,

$J_S = \frac{\pi L \rho R^4}{2}$[kg. m$^2$] $= \frac{\pi(0.4m)(7700\,kg/m^{-3})(0.0175\,m)^4}{2}$[kg. m$^2$] $= 4.53756\times10^{-4}$[kg. m$^2$] (Eq. 5.12)

Total Inertia,

$J_{T=}J_L + J_{G1} + J_{G2} + J_S\left(\frac{N_2}{N_1}\right)^2$ (Eq. 5.13)

$J_{T=}3.166\times10^{-6} + 1.5138\times10^{-6} + 2.7225\times10^{-6} + 4.53756\times10^{-4}\left(\frac{32}{16}\right)^2$ [kg. m$^2$]

$J_{T=}1.2084\times10^{-4}$[kg. m$^2$]

Acceleration Torque,

$T_a = J_T\cdot a$ [N. m] $= 1.2084\times10^{-4}$[kg. m$^2$]$\left(\frac{4.2\text{rad}/s-0}{2}\right) = 2.538\times10^{-4}$[N. m](Eq. 5.14)

Load Torque,

$$T_L = \frac{P\left(F_m + \mu_{f,c/g} \cdot m_{W+T} \cdot g\right)}{2\pi\eta}(\sin\alpha)[\mathrm{N.m}] \quad \text{(Eq. 5.15)}$$

$$T_L = \frac{10\times10^{-3}m\,(249.38\ \mathrm{N} + (0.4)(5kg)(9.81m/s^2))}{2\pi(0.85)}(\sin\alpha)[\mathrm{N.m}]$$

$$T_L = 0.504(\sin\alpha)[\mathrm{N.m}]$$

Total torque,

$$T_T = T_a + T_L\ [\mathrm{N.m}] \quad \text{(Eq. 5.16)}$$

Required motor torque,

$$T_M = K_S \cdot T_T\ [\mathrm{N.m}] = 2 \cdot T_T\ [\mathrm{N.m}] \quad \text{(Eq. 5.17)}$$

The required motor torque, $T_M$ depended on the angle of inclination, $\alpha$ of the robot. Thus, a graph of angle of inclination, $\alpha$ vs. the required motor torque, $T_M$ is plotted. From the graph, we get to know that the required motor torque is the highest value in the graph which is **1.0085 N.m**. since the robot needs to move vertically at 90°.

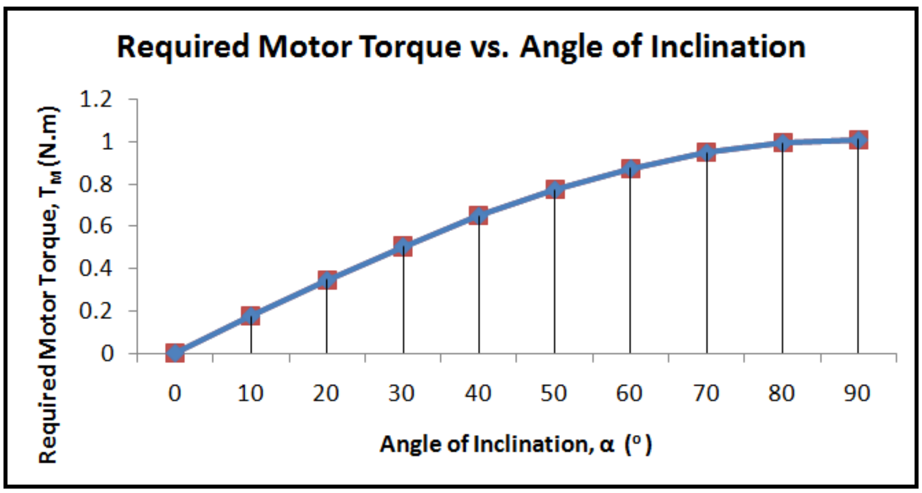



**Figure 24: Graph required motor torque vs. angle of inclination**

From this calculation, the motor selected is Cytron's DC geared motor MO-SPG-50-180K which has the rated torque of 1.9N.m and rated speed of 17RPM. [16]

## 5.4 Geometry and Required Pass Calculations

It is recognized that the number of passes the device needs to make across the window can be minimized by relating it to the height of the device. For the purposes of this calculation, a single pass is defined as one horizontal movement and one diagonal movement. The relation is shown in the graphical representation and can be seen below in Figure 26. Average window size of high building usually is 130cm x 200cm

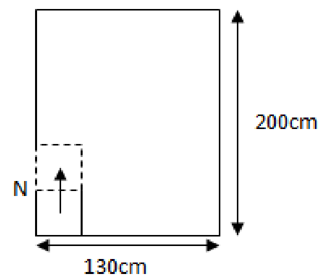



**Figure 25: Example of one pass**

Assuming the cleaning surface is the same height as the robot, the relationship between the device's height *(H)* and the number of passes required to cover the entire window *(N)* can be represented in the following relationship. Assume that the robot is in square shape, the height x width of the robot = $H^2$

$$N = \frac{200cm \ \times 130cm}{H^2} \times 1/E$$

In the above relationship, the value $E$ is the efficiency factor and represents the percentage of repeated area wiped. For example 100 percent efficiency would correspond to E=1, which in turn corresponds to zero overlap when cleaning in successive horizontal passes, while 50% efficiency would correspond to E=2, which indicates that half of the previously-cleaned area is overlapped in the next pass. Since we have determined the dimension of the robot should not exceed 500mm x 500mm in chapter 4, by choosing this dimension, the approximate number of passes, N in efficiency of 100%, 75% and 50% are 10.4, 13.8, and 20.8 respectively.

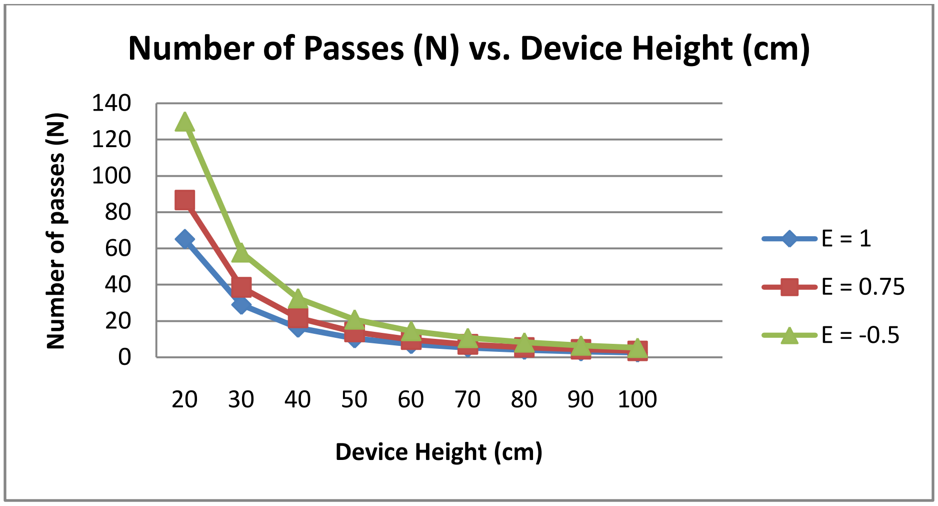



**Figure 26: Number of Passes (N) vs. Device Height (cm)**

### 5.5 Weight Calculation

From the analysis above, the hardware and components for the concept are listed out in the table below. The total weight of the components is estimated. Each of the component's weight are based from the web catalog of RS-Malaysia and Cytron Sdn. Bhd. From table below, estimated total weight is 3.375 kg, but the number might increase due to electronics components not included in the table. From the weight of the main components, we can estimate that the total weight of the robot will still be below 5kg which is within the specification.

**Table 7: Parts and Components Used in the Final Design of the Window Cleaning Robot**

| Hardware | | |
|---|---|---|
| **Parts and Components** | **Description** | Weight (g) = Unit(s) x weight per unit |
| Chassis - Acrylic Sheet 5mm | Hard, sturdy and lightweight suitable to be used as platform layers inside the robot. | 340 |
| 4 x Suction Cup | - To hold the robot on the window pane | 100 |
| 2 x Vacuum Generator | To generate vacuum suction force on suction cup | 315 |
| Lead screw | For vertical movement. Min of 20cm length | 50 |
| DC geared motor | - High torque, for sideways motion<br>- For actuating linear movement of the linear slider | 680 |

| | | |
|---|---|---|
| 2 x Trans-wheel | Multi-directional wheel, which allow forward and sideways movement | 60 |
| Plastic Container with cleaning fluid | - To carry water and cleaning fluid<br>- At least 50mL | 500 |
| Sponges | To brush dirt on window pane | 10 |
| Squeegee | To wipe excessive water on window pane | 20 |
| 4 x Infrared Sensor | Used to detect window pane boundary. Giving value 1 when it detects solid surface and 0 on transparent surface | 350 |
| Carriage | - To be the housing for two suction cups and a vacuum generator<br>- Act as hands of the robot | 500 |
| 2 x LiPo Rechargeable Battery 12V | - Supply power to the robot electronics system | 400 |
| Shaft | - Join the two trans-wheel together | 50 |
| 4 x Castor | - Provide extra support against the moment | 80 |
| | **Total Weight** | **3375** |

# CHAPTER 6

# PRODUCT GENERATION

## 6.1 Final Design

After finished the engineering analysis, we have come out with an improved design as can be seen in figure 28. The final dimension of the robot is 500 mm x 500mm x 200mm and an estimated of 5kg of weight. The detail drawings are included in Appendix C.

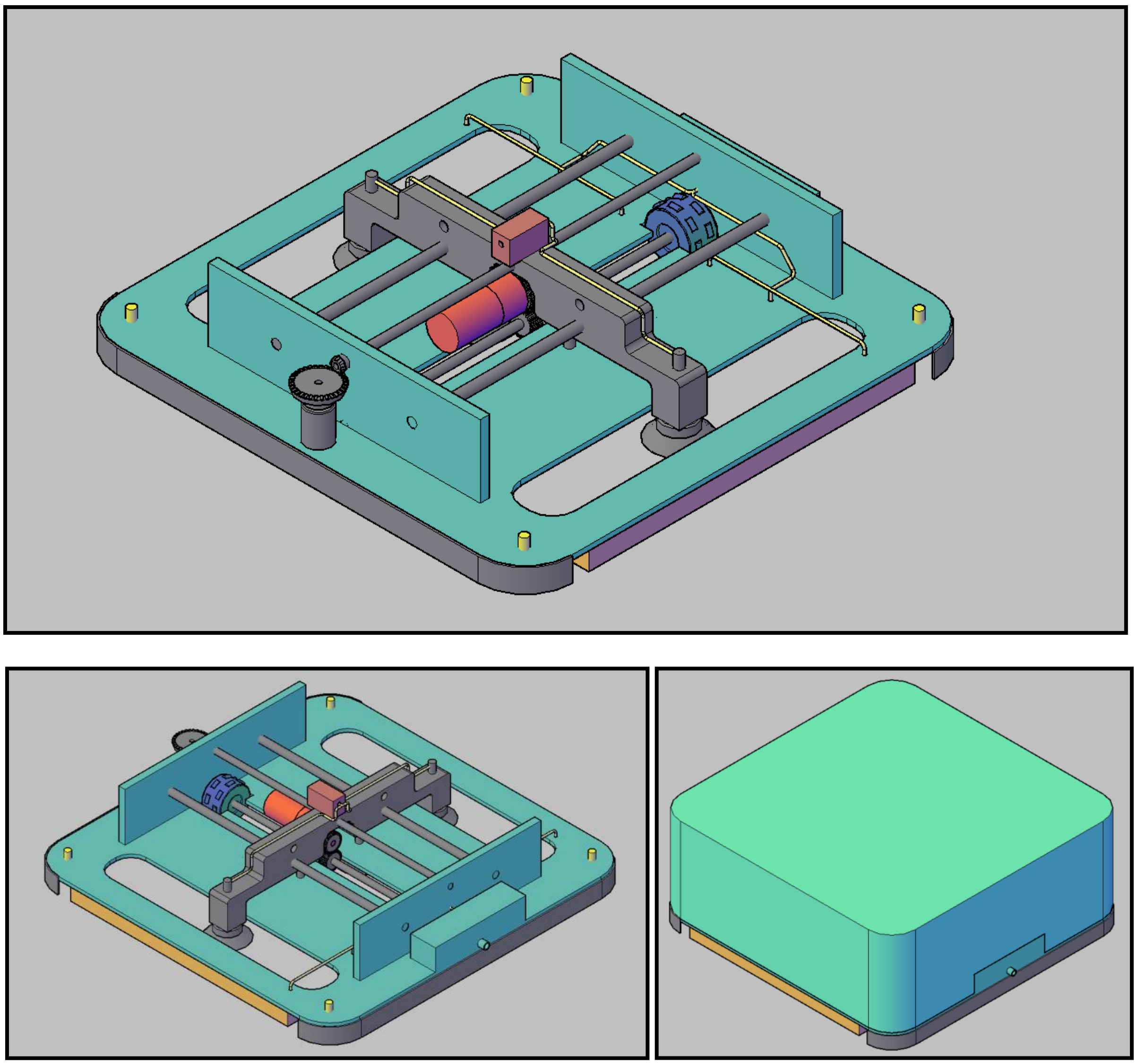


**Figure 27: Final design of the window cleaning robot**

## 6.2 Bill of Material

The overall cost of the project is approximately RM1188. The details of the total cost can be seen in Table 8 below. Most of the parts are supplied by RS Malaysia and Cytron Sdn. Bhd. The total cost is inclusive of the shipping cost.

**Table 8: Bill of Material**

| **Bill of Materials** | | | | | | |
|---|---|---|---|---|---|---|
| **Product:** Window Cleaning Device | | | | | **Date:** 15/09/10 | |
| | | | | | | |
| **Item #** | **Part #** | **Qty** | **Name** | **Material** | **Source** | **Price (RM)** |
| 1 | HD-AC-A4-5 | 1 | Acrylic Sheet 5mm | Acrylic | UTP Lab | 0 |
| 2 | PFG-60-NBR | 4 | Flat PFG Suction Cup 60mm dia. | Nitrile Rubber | RS Malaysia | 212.00 |
| 3 | ZH13BS-08-10 | 2 | Vacuum Generator | | RS Malaysia | 250.00 |
| 4 | N/A | 2 | Bearing ways | Polyethylene | Hardware Shop | 20.00 |
| 5 | N/A | 1 | Carriage | Acrylic | UTP Lab | 0 |
| 6 | MO-SPG-30-200K | 1 | DC gear motor | | Cytron Sdn Bhd. | 80.00 |
| 7 | MO-SPG-50-180K | 1 | DC gear motor | | Cytron Sdn Bhd. | 80.00 |
| 8 | CO-SPG | 2 | Motor Coupler | Aluminium | Cytron Sdn Bhd. | 30.00 |
| 9 | WL-TW-200 | 2 | Trans-wheel 2-inch dia. | Plastic | Cytron Sdn Bhd. | 140.00 |
| 10 | N/A | 1 | Water container | Plastic | Hardware Shop | 2.00 |
| 11 | N/A | 1 | Sponges | Artificial Fibre | Hardware Shop | 1.00 |
| 12 | N/A | 2 | Squeegee | Rubber | Hardware Shop | 5.00 |
| 13 | SRB20/30 | 1 | Bevel Gear | Steel | RS Malaysia | 10.00 |
| 14 | 521-6610 | 2 | Gear | Steel | RS Malaysia | 10.00 |
| 15 | N/A | 1 | Shaft | Stainless steel | Hardware Shop | 15.00 |
| 16 | N/A | 4 | Castor | Steel | Hardware Shop | 10.00 |
| 17 | N/A | 1 | Leadscrew 40cm | Steel | Hardware Shop | 25.00 |
| 19 | SK40C | 1 | PIC Development Board SK40C | | Cytron Sdn Bhd. | 63.00 |
| 20 | IC-PIC-18F4550 | 1 | PIC 18F4550 | | Cytron Sdn Bhd. | 35.00 |
| 21 | N/A | 1 | H-Bridge IC L293D | | Cytron Sdn Bhd. | |
| 22 | UP00B | 1 | USB Programmer UIC00A | | Cytron Sdn Bhd. | |
| 23 | LIP-11.1-2200 | 2 | LiPo Rechargeable Battery 12V 2200mAH | | Cytron Sdn Bhd. | 200.00 |
| | | | | | **TOTAL** | 938.00 |
| | | | | | | **Prepared by:** Dzulfikry Aris |
| | | | | | | **Checked by:** Prof. Dr. T. Nagarajan |

# CHAPTER 7

# CONCLUSION

## 7.1 Conclusion

The final design of the window cleaning robot in this project uses two motors to provide horizontal and vertical movement and two vacuum generators to power 4 suction cups. The suction cup diameter calculated is at least 60mm in diameter and the motor torque required is 1.0085 N.m. which are pretty much reasonable. This design incorporates traditional items and systems and transforms them into a final product that is reliable, innovative, and practical. From analysis done, the robot concept is proved applicable for the desired functionality. Since the design is only a proof of concept and therefore the actual cleanliness of the window is less of a concern than the ease of use, and controllability of the final product. The project is seen practically achieve its project scope and objectives to come out with a functional window cleaning robot for high rise building.

# CHAPTER 8

# REFERENCES

## 8.1 References


1. David Shamah, 2008, *Getting Robots in to Clean High-Rise Windows*, http://www.israel21c.org/technology/getting-robots-in-to-clean-high-rise-windows

2. Tohru Miyake and Hidenori Ishihara, 2006, *Mechanisms and Basic Properties of Window Cleaning Robot*, ieeexplore.ieee.org/iel5/8678/27509/01225543.pdf?arnumber=1225543

3. Gareth Branwyn, 2004, *Absolute Beginner's Guide To Building Robots*, Published by Que

4. Tohru Miyake and Hidenori Ishihara, 2006, *Development of small-size window cleaning robot by wall climbing mechanism*; http://www.iaarc.org/external/isarc2006-cd/www/ISARC2006/00159_200606062100.pdf

5. Adapted by Kenneth Grow DRM Associates, 2002, *Value Analysis and Function Analysis System Technique*, http://www.npd-solutions.com/va.html

6. Kevin Otto, 2007, *Pugh Concept Selection Process Summary Chart;* www.kevinotto.com/RSS/Software/Pugh%20Chart%20Template.xls

7. *Linear Thrust Calculation;* http://www.msitec.com/pdf/thrust_calculations.pdf

8. Joseph Edward Shigley, Charles Mischke, Richard G Budynas, Richard Budynas, 2003, *Mechanical Engineering Design 7th Edition*, Published by McGraw-Hill

9. David G. Ullman, 2009, *The Mechanical Design Process 4th Edition*, Published by McGraw-Hill

10. Hauser, J. R., and D. Clausing, 1988, *The House of Quality: Harvard Business Review*, pp. 63-73

11. Thomas Brown, 1971, *Window Cleaning Apparatus Patent 3629893*, http://www.wikipatents.com/US-Patent-3629893/window-cleaning-apparatus

12. Luis Carlos Cruz, 2003, *Window Cleaning Apparatus Patent 7231683*, http://www.patentstorm.us/patents/7231683/claims.html

13. Parker Pneumatic .Corp, 2004, Parker Vacuum Cup Product Selection, http://www.isiautomation.com/docs/ISIAutomation-ParkerVacuumCups.pdf

14. Leadshine Co. Ltd. , 2005, Motor Torque Calculation, http://www.leadshine.com/UploadFile/documents_software/Applications/Motor_Torque_Calculation.pdf

15. R. C. Hibbeler, Engineering Mechanics Statics 12th Edition in SI Units, 2009 , Published by Pearson Prentice-Hall

16. Cytron Tech. Sdn. Bhd., 2010, Cytron's DC Gear motor MO-SPG-50-180K, http://www.cytron.com.my/viewProduct.php?pid=Mw4cFxsaPRgUGCgMIgE8Dz8IrPd6ZYjxhV9oONed5pw=

## Appendix A – Suction Cup Force Equations [13]

# Selecting the Proper Vacuum Cup

### CAUTION

Selecting the type of vacuum cup, material, and size suitable for an application is important to the overall vacuum system. Calculating the forces involved for each application is recommended to determine the vacuum cup size. It should be noted that these calculations are basic theoretical guidelines and each application must be tested for actual results. With all vacuum applications, certain practical assumptions concerning cup materials, environmental conditions, and product characteristics to name a few, may not be consistent with the performance. Again, the user should determine the efficiency, performance, and safety factor of the cup selection.

## Calculating Pad Diameter and Forces

**Mass**

The term mass is a quantity of matter and its ability to resist motion when acted on by an external force. The magnitude of an object is represented as a certain number of kilograms (kg) and is symbolized as "m". The easiest way to determine the mass of an object is to measure the weight with a scale within the earth's gravitational field ($a_g$ = 9.81m/sec$^2$). Likewise, outside of any gravitational field, a mass could potentially be weightless.

**Forces**

For vacuum applications, force is a vector quantity in a defined direction either horizontal or vertical. The standard international unit of force is measured in Newtons (N) which is the equivalent of (kgm/sec$^2$). The force can be calculated by measuring the effect of a change in acceleration on a mass.

Newtons Law: F(N) = mass(kg) x $a_g$(m/sec$^2$)

Consider an object with a mass of 10kg. The gravitational force on this object would be:

F(N) = 10kg x 9.81m/sec$^2$ = 98.1 N

**Acceleration**

Acceleration is the change in velocity of a moving object. Acceleration is a vector, a directional quantity expressed in units of meters per second squared (m/sec$^2$) and symbolized as "*a*". To explain the magnitude of acceleration consider an object with a change in velocity of 2 meters per second (m/sec) over a 4 second time frame. The acceleration can be calculated with:

$$a = \frac{\triangle \text{ velocity}}{\text{time}} \qquad a = \frac{2\text{m/sec}}{4\text{ sec}} \qquad a = .5\text{m/sec}^2$$

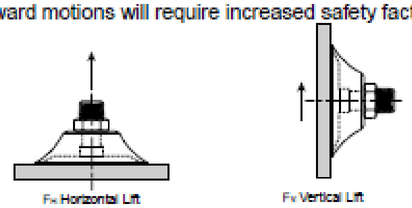
This is considered an average acceleration.

**Coefficient of Friction**

Certain values for coefficient of friction should be taken into consideration when calculating the combined forces in motion. Actual values between suction cups and surfaces are difficult to determine. Therefore, coefficient of friction values from published charts, should be used as a reference to adjust the safety factors accordingly.

**Lifting Forces**

When calculating lifting forces, safety factors of 2 for horizontal lifts and 4 for vertical lifts are minimum values. Applications with irregular shapes, difficult surfaces, and ackward motions will require increased safety factors.



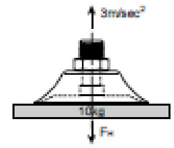

**Horizontal Lifting Force**

Apply Newtons Law to calculate the force on a 10kg mass with a change in acceleration of 3m/sec$^2$ and a safety factor of 2.

$F_H$(N) = mass(kg) x ($a_g$+ a) x $S_H$

$F_H$(N) = 10kg x (9.81m/sec$^2$ +3m/sec$^2$) x 2

$F_H$ = 256.2 N



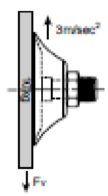

**Vertical Lifting Force**

Apply Newtons Law to calculate the force on a 10kg mass with a dry surface, a change in acceleration of 3m/sec$^2$ and a safety factor of 4.

$F_V$(N) = mass(kg) x ($a_g$+ a) x $S_V$

$F_V$(N) = 10kg x (9.81m/sec$^2$ +3m/sec$^2$) x 4

$F_V$ = 512.4 N




**Combined Vertical Lift and Horizontal Motion**

Calculate the force on a 10kg mass with a dry surface, a change in acceleration of 3m/sec$^2$, and a change in travel acceleration of 2m/sec$^2$.

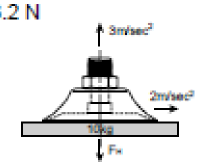
$F_M(N) = \sqrt{F_V^2 + F_H^2}$

$F_M(N) = \sqrt{[(10\text{kg x } 2\text{m/sec}^2) \text{ x } 4]^2 + [10\text{kg x } (9.81\text{m/sec}^2 + 3\text{m/sec}^2) \text{ x } 2]^2}$

$F_M(N) = \sqrt{(80\text{kgm/sec}^2)^2 + [256\text{kgm/sec}^2]^2}$

$F_M(N) = \sqrt{6400\text{kgm/sec}^2 + 65{,}536\text{kgm/sec}^2}$

$F_M$ = 268.2 N



## Analyze the Forces

Using the previous examples, consider an application where 4 cups have been selected to transfer the product.

Take the Horizontal Lifting Force ($F_H$) of 256.2 N and divide by the number of cups (4) to obtain the individual force for each cup.

$$\frac{256.2\ (N)}{4} = 64.05\ N/Cup$$

Refering to the chart below, at 60% vacuum, select a force greater than 64.05 N. The appropriate selection is a 40mm diameter cup which has a theoretical lifting force of 76.9 N.

The same calculation can be applied to the Vertical Lifting Force and the Forces in Motion examples to determine the cup diameter.

To convert Pounds ($Lb_f$) to Newton (N), multiply $Lb_f$ x 4.4.

## Calculate the Diameter of the Cup

For non-porus applications, calculate the cup diameter at 60% of full vacuum.

$$A = \left(\frac{m\ (a_g + a)}{n}\right) \times 10 \times S\ /\ P_v$$

$$A = \frac{10\ (9.81 + 3)}{4} \times 10 \times 2\ /\ 61 = 10.5\ cm^2$$

$$D = 20\sqrt{\frac{A}{3.14}}$$

$$D = 20\sqrt{\frac{10.5}{3.14}}$$

$$D = 37\ mm$$

A ($cm^2$) = Area
D (mm) = Diameter of Cup
S = Safety Factor
$P_v$ (kPa) = Operating Vacuum Pressure = 61kPa
n = Number of Cups

Refering to the chart below, at 60% vacuum, select a cup diameter equal to or greater than 37mm. The appropriate selection is a 40mm diameter cup which has a theoretical lifting force of 76.9 N.

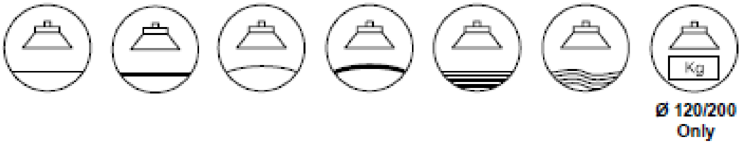
**Theoretical Lifting Force Per Cup** (Newton, N)

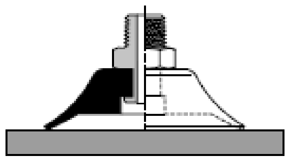
| Cup | | Vacuum Level | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 3 in hg | 6 in hg | 9 in hg | 12in hg | 15 in hg | 18 in hg | 21 in hg | 24 in hg | 27 in hg |
| Diameter | Area | 10.2 kPa | 20.3 kPa | 30.5 kPa | 40.6 Kpa | 50.8 kPa | 61 kPa | 71.1 kPa | 81.3 kPa | 91.4 kPa |
| mm | cm² | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% |
| 1 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.07 |
| 2 | 0.03 | 0.03 | 0.06 | 0.10 | 0.13 | 0.16 | 0.19 | 0.22 | 0.25 | 0.28 |
| 3.5 | 0.10 | 0.10 | 0.20 | 0.29 | 0.39 | 0.49 | 0.59 | 0.69 | 0.78 | 0.88 |
| 5 | 0.20 | 0.20 | 0.40 | 0.60 | 0.80 | 1.00 | 1.20 | 1.40 | 1.60 | 1.80 |
| 6 | 0.28 | 0.29 | 0.58 | 0.87 | 1.20 | 1.40 | 1.70 | 2.00 | 2.30 | 2.60 |
| 7 | 0.39 | 0.39 | 0.78 | 1.18 | 1.60 | 2.00 | 2.40 | 2.70 | 3.10 | 3.50 |
| 8 | 0.50 | 0.52 | 1.02 | 1.54 | 2.00 | 2.60 | 3.10 | 3.60 | 4.10 | 4.60 |
| 10 | 0.79 | 0.80 | 1.60 | 2.40 | 3.20 | 4.00 | 4.80 | 5.60 | 6.40 | 7.20 |
| 15 | 1.77 | 1.80 | 3.60 | 5.41 | 7.20 | 9.00 | 10.8 | 12.6 | 14.4 | 16.2 |
| 18 | 2.55 | 2.60 | 5.20 | 7.79 | 10.4 | 13.0 | 15.6 | 18.1 | 20.8 | 23.3 |
| 20 | 3.14 | 3.20 | 6.40 | 9.60 | 12.8 | 16.0 | 19.2 | 22.4 | 25.6 | 28.8 |
| 25 | 4.91 | 5.00 | 10.0 | 15.0 | 20.0 | 25.0 | 30.0 | 35.0 | 40.0 | 45.0 |
| 30 | 7.07 | 7.20 | 14.4 | 21.6 | 28.8 | 36.0 | 43.2 | 50.4 | 57.6 | 64.8 |
| 35 | 9.62 | 9.80 | 19.6 | 29.4 | 39.2 | 49.0 | 58.9 | 68.6 | 78.5 | 88.2 |
| 40 | 12.6 | 12.9 | 25.6 | 38.5 | 51.2 | 64.0 | 76.9 | 89.6 | 103 | 115 |
| 50 | 19.6 | 20.1 | 40.0 | 60.1 | 80.0 | 100 | 120 | 140 | 160 | 180 |
| 60 | 28.3 | 28.9 | 57.6 | 86.5 | 115 | 144 | 173 | 202 | 231 | 259 |
| 75 | 44.2 | 45.2 | 90.0 | 135 | 180 | 225 | 270 | 315 | 360 | 405 |
| 80 | 50.3 | 51.4 | 102 | 154 | 205 | 256 | 308 | 359 | 410 | 461 |
| 90 | 63.6 | 65.1 | 130 | 195 | 259 | 324 | 389 | 454 | 519 | 583 |
| 95 | 70.9 | 72.5 | 144 | 217 | 289 | 361 | 434 | 506 | 578 | 650 |
| 110 | 95.0 | 97.2 | 194 | 291 | 387 | 484 | 581 | 678 | 775 | 871 |
| 120 | 113.1 | 116 | 230 | 346 | 461 | 576 | 692 | 807 | 922 | 1037 |
| 150 | 176.7 | 181 | 360 | 541 | 720 | 900 | 1081 | 1260 | 1441 | 1620 |
| 200 | 314.2 | 321 | 640 | 961 | 1279 | 1601 | 1922 | 2241 | 2562 | 2880 |

**Table A1: Theoretical Lifting Force per Cups (Newton, N)**

# Application Guide

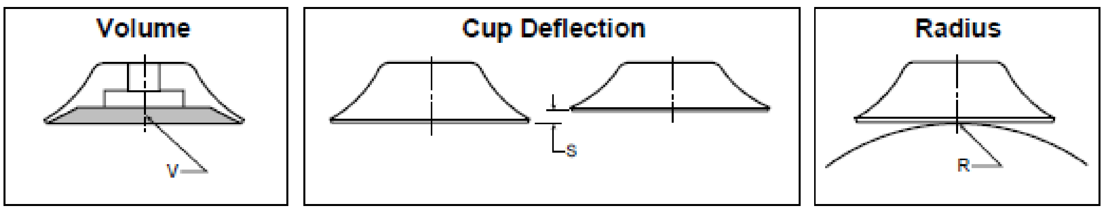
## Flat - Smooth Surface



- Products With Smooth Surfaces
- Products With Minimum Flex
- Products That Will Not Permanently Deform

## Main Data for Flat PFG Cups

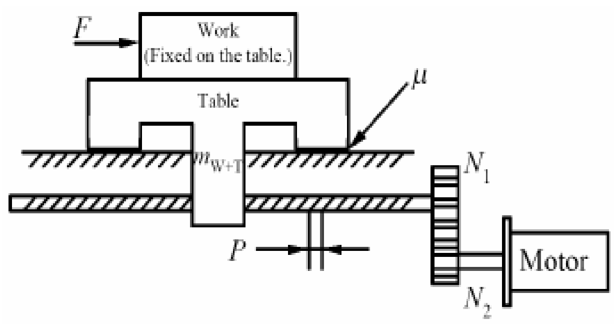


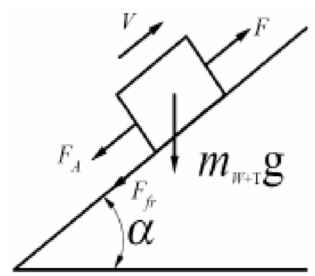

| Model Number | Cup Diameter Inches (mm) | Area cm² | Volume (V) Liters | Lifting Force @60% (N) | | Cup Deflection (S) mm | Radius (R) mm |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| PFG-1-* | .04 (1) | 0.008 | 0.00000015 | 0.05 | 0.025 | 0.1 | 1.6 |
| PFG-1.5-* | .06 (1.5) | 0.01 | 0.00000053 | 0.10 | 0.05 | 0.1 | 3.5 |
| PFG-2A-* | .08 (2) | 0.03 | 0.0000007 | 0.19 | 0.09 | 0.1 | 1.75 |
| PFG-3.5A-* | .12 (3) | 0.10 | 0.000002 | 0.59 | 0.29 | 0.2 | 2.0 |
| PFG-5A-* | .20 (5) | 0.20 | 0.000005 | 1.20 | 0.6 | 0.5 | 3.5 |
| PFG-6A-* | .24 (6) | 0.28 | 0.000008 | 1.70 | 0.85 | 1.0 | 4.0 |
| PFG-8A-* | .31 (8) | 0.50 | 0.00003 | 3.10 | 1.5 | 1.4 | 5.0 |
| PFG-10A-* | .39 (10) | 0.79 | 0.00007 | 4.80 | 2.4 | 1.5 | 6.0 |
| PFG-15-* | .59 (15) | 1.77 | 0.0004 | 10.8 | 5.4 | 1.9 | 6.0 |
| PFG-15A-* | .59 (15) | 1.77 | 0.0004 | 10.8 | 5.4 | 1.9 | 6.0 |
| PFG-20-* | .79 (20) | 3.14 | 0.0008 | 19.2 | 9.6 | 2.3 | 9.0 |
| PFG-20B-* | .79 (20) | 3.14 | 0.0008 | 19.2 | 9.6 | 2.3 | 13.0 |
| PFG-25-* | .98 (25) | 4.91 | 0.0013 | 30.0 | 15.0 | 3.0 | 17.5 |
| PFG-30-* | 1.18 (30) | 7.07 | 0.0018 | 43.2 | 21.6 | 2.0 | 26 |
| PFG-35-* | 1.38 (35) | 9.62 | 0.0026 | 58.9 | 29.5 | 3.0 | 31 |
| PFG-40-* | 1.57 (40) | 12.60 | 0.004 | 76.9 | 38.5 | 3.5 | 37 |
| PFG-50-* | 1.97 (50) | 19.60 | 0.007 | 120 | 60 | 4.0 | 41 |
| PFG-60-* | 2.36 (60) | 28.30 | 0.0090 | 173 | 87 | 5.0 | 70 |
| PFG-80-* | 3.15 (80) | 50.30 | 0.025 | 308 | 154 | 6.0 | 100 |
| PFG-95-* | 3.74 (95) | 70.90 | 0.035 | 434 | 267 | 6.0 | 150 |
| PFG-120-* | 4.72 (120) | 113.00 | 0.078 | 692 | 346 | 6.0 | 365 |
| PFG-150-* | 5.91 (150) | 176.70 | 0.177 | 1081 | 541 | 9.0 | 380 |
| PFG-200-* | 7.87 (200) | 314.20 | 0.425 | 1922 | 961 | 13.0 | 430 |

## Appendix B – Motor Torque Required Equations [14]

### ◆ Lead Screw Drive Loads

Lead screw drives are widely used in many applications, such as XY tables, slides, tool bit positioning, pick-and-place machines, engraving machines, microscope drives, and etc.




Inertia:

$$J_L = m_{W+T}\left(\frac{P}{2\pi}\cdot\frac{N_1}{N_2}\right)^2 \qquad [kg\cdot m^2]$$

$$J_{G1} = \frac{1}{8}m_{G1}D_{G1}^2\left(\frac{N_2}{N_1}\right)^2 \qquad [kg\cdot m^2]$$

$$J_{G2} = \frac{1}{8}m_{G2}D_{G2}^2 \qquad [kg\cdot m^2]$$

$$J_T = J_L + J_{G1} + J_{G2} + J_S\left(\frac{N_2}{N_1}\right)^2 + J_M \qquad [kg\cdot m^2]$$

Torque:

$$T_a = J_T a = \left(J_L + J_{G1} + J_{G2} + J_S\left(\frac{N_2}{N_1}\right)^2 + J_M\right)\frac{\omega_1-\omega_0}{t} \qquad [N\cdot m]^*$$

$$T_L = \frac{m_{W+T}gP(\sin\alpha + \mu\cos\alpha)}{2\pi\eta} \qquad [N\cdot m]$$

$$T_T = T_L + T_a \qquad [N\cdot m]$$

$$T_M = K_S T_T \qquad [N\cdot m]$$

$J_L$ – Inertia of the load [kg·m²]
$J_{G1}$ – Inertia of the Gear 1 [kg·m²]
$J_{G2}$ – Inertia of the Gear 2 [kg·m²]
$J_S$ – Inertia of the lead screw [kg·m²]
$J_M$ – Inertia of the motor [kg·m²]
$J_T$ – Inertia of the system [kg·m²]
$m_{W+T}$ – Weight of the work and the table [kg]
$\omega_0$ – Initial velocity of the motor [rad/s]
$\omega_1$ – Final velocity of the motor [rad/s]
$t$ – Time for velocity change [s]
$T_a$ – Acceleration torque [N·m]
$T_L$ – Load torque [N·m]
$T_T$ – Total calculation torque [N·m], $T_T = T_L + T_a$
$T_M$ – Required motor torque [N·m], $T_M = K_S \cdot T_T$
$K_S$ – Safety factor (Reference Value is 1.5 to 2.0.)
α – Angle of inclination [°]
μ – Frictional coefficient of sliding surfaces
η – Efficiency (Reference Value is 0.85 to 0.95.)
g – Gravity constant (9.8 m/s²)
*Please use the max acceleration of the specific application.

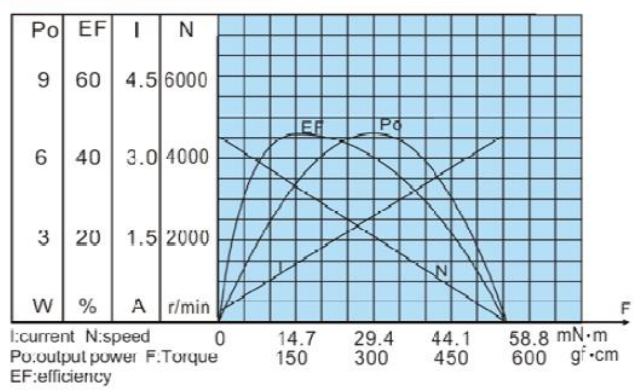

## SPG50 Series

Cytron Technologies

Output Power: 3.4W    Weight: ~300g

Typical applications: Labal printers、auto shutter、automatic stabilized voltage supply、grill、oven、cleaning machine、garbage disposers、household appliances、slot machines、money detector、automatic actuator、coffee machine、towel disposal、lighting、coin refund devices、peristaltic pump.

### MOTOR CHARACTERISTICS



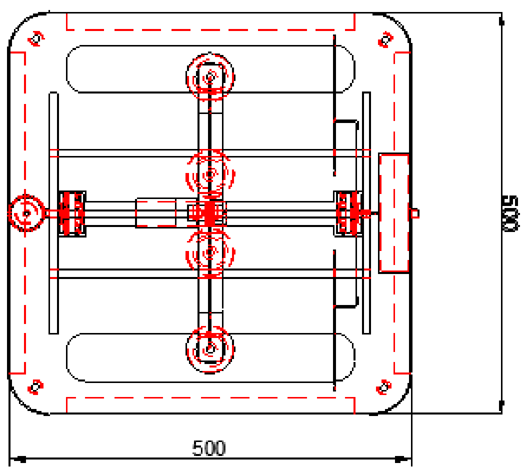

### MOTOR TORQUE/SPEED/CURRENT

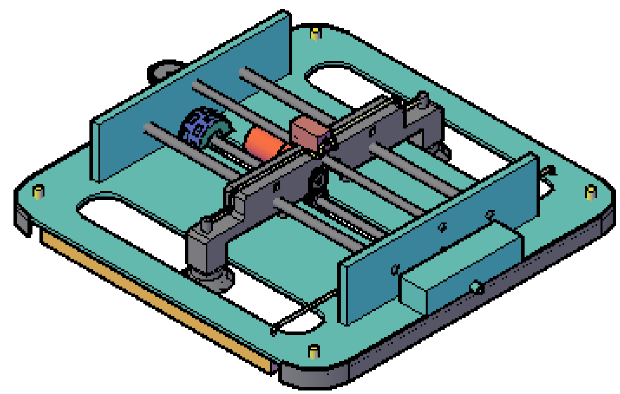
| | |
|---|---|
| Rated voltage | 12VDC |
| No load speed | 4500r/min |
| No load current | 220mA |
| Rated torque | 130gf • cm 12.74mN • m |
| Rated current | 0.9A |
| Rated speed | 3350r/min |
| Stall torque | 520gf • cm 50.96mN • m |
| Stall current | 3.4A |

**Motor selected for the robot system – Cytron DC gear motor**

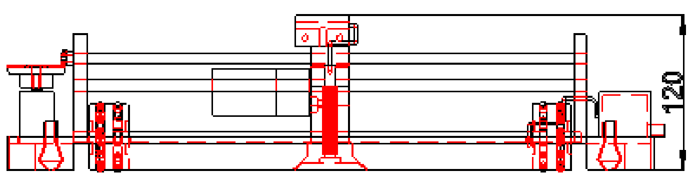
## Appendix C – Mechanical Parts Detail Drawings

Plan View

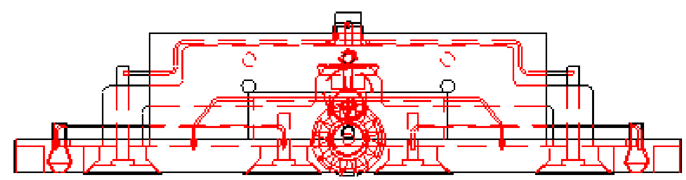


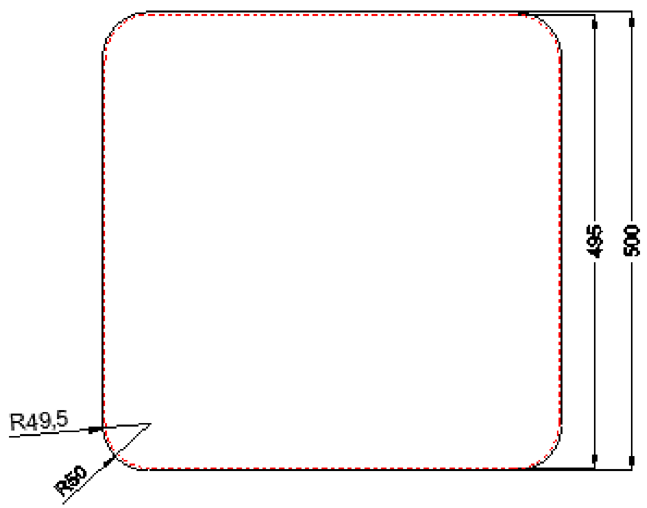
Front View

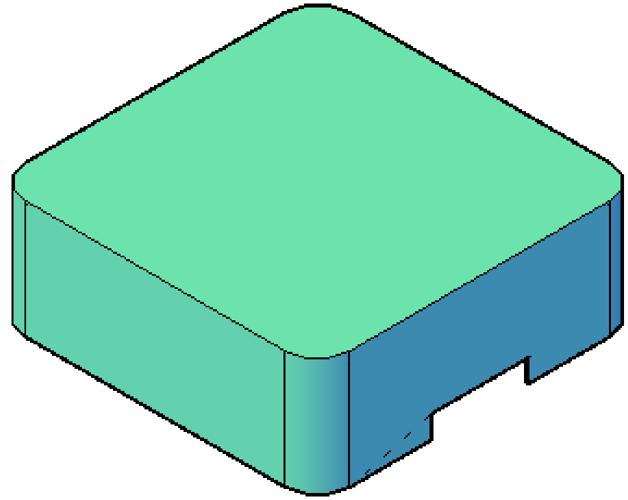


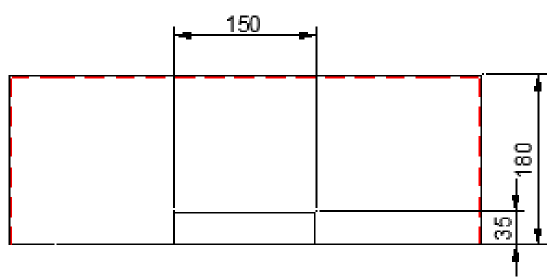

Side View

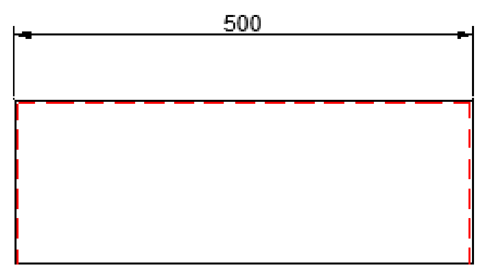


| | |
|---|---|
| Part Name: Window Cleaning Robot | Checked by: Prof. Dr T. Nagarajan |
| Prepared by: Dzulfikry Aris | Scale: 1:1 (mm) |

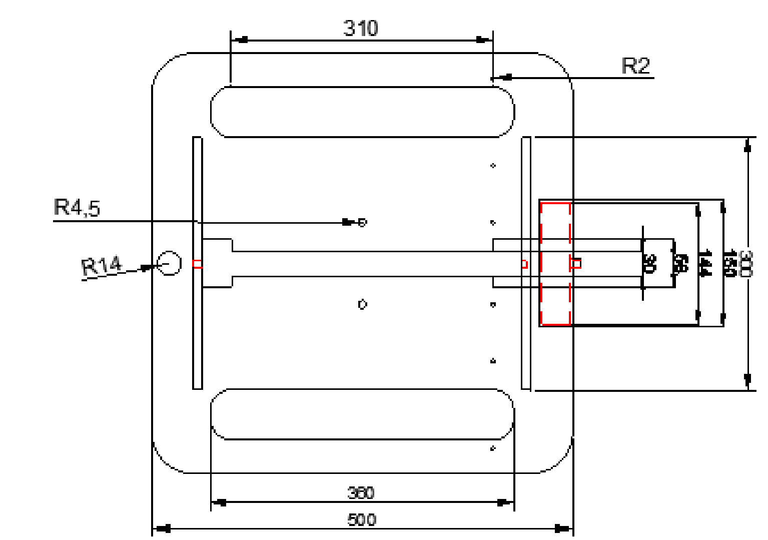


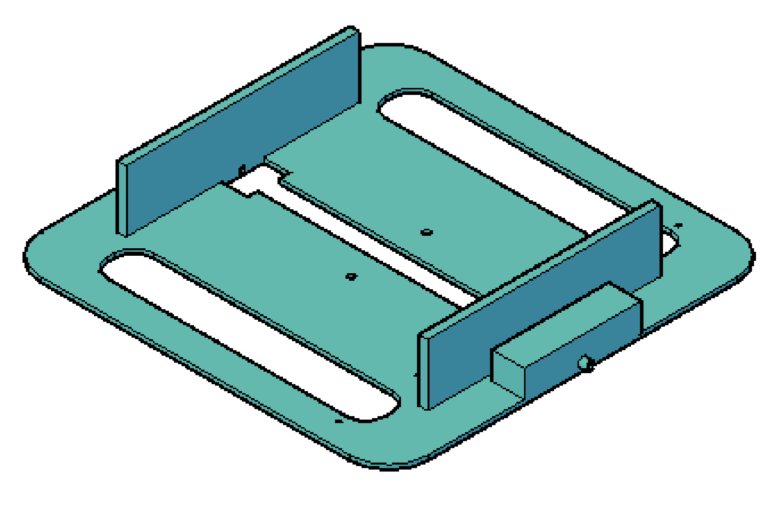



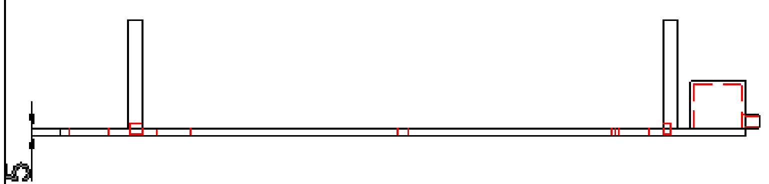


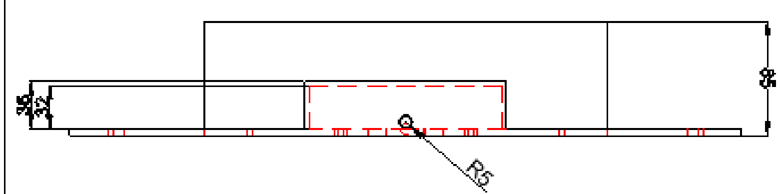




| | |
|---|---|
| Part Name: Top Cover | Checked by: Prof. Dr T. Nagarajan |
| Prepared by: Dzulfikry Aris | Scale: 1:1 (mm) |



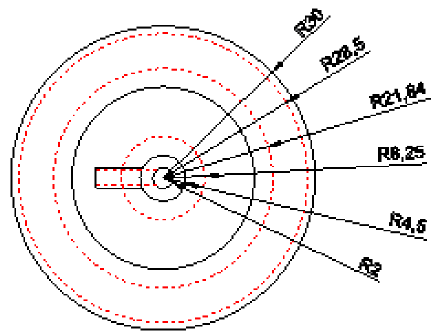



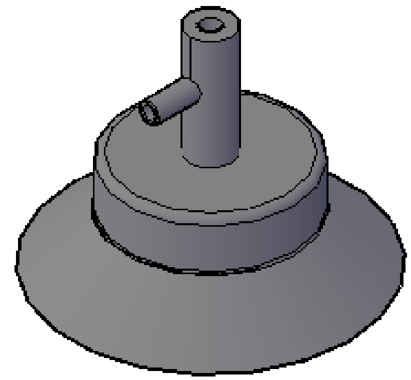


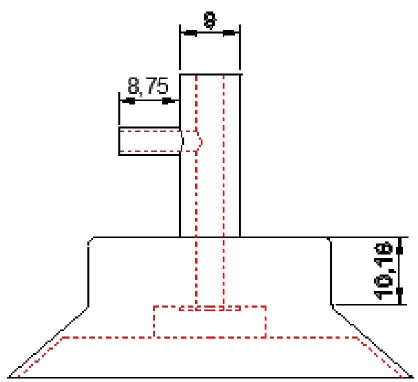

| | |
|---|---|
| Part Name: Base | Checked by: Prof. Dr T. Nagarajan |
| Prepared by: Dzulfikry Aris | Scale: 1:1 (mm) |

Plan View

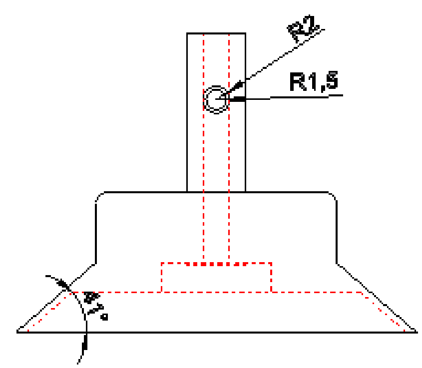


Front View

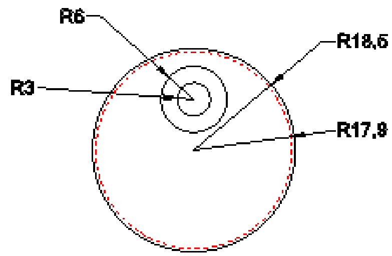


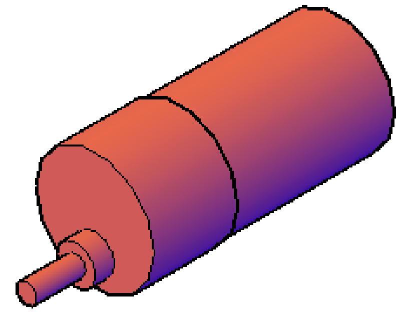

Side View



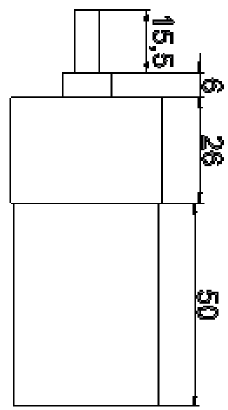

| | |
|---|---|
| Part Name : Suction Cup 60mm dia. | Checked by: Prof. Dr T. Nagarajan |
| Prepared by: Dzulfikry Aris | Scale: 1:1 (mm) |

Plan View

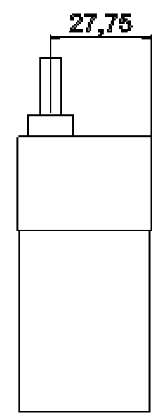


Front View

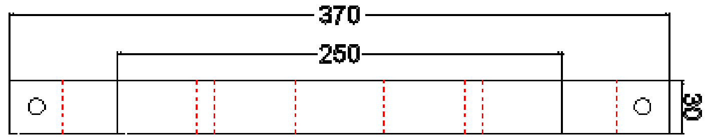


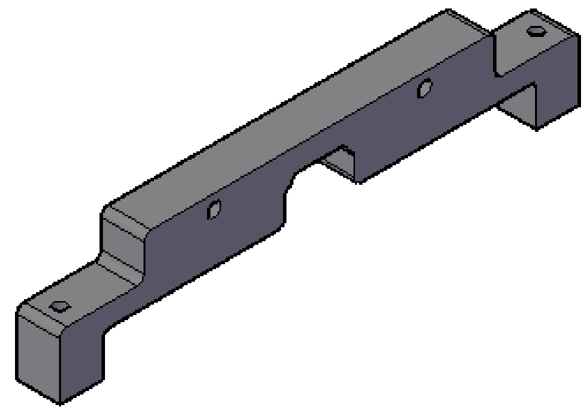

Side View



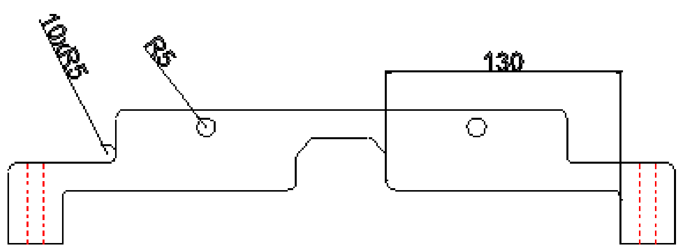

| | |
|---|---|
| Part Name: DC Geared Motor | Checked by: Prof. Dr T. Nagarajan |
| Prepared by: Dzulfikry Aris | Scale: 1:1 (mm) |

Plan View

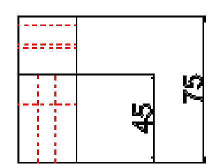


Front View

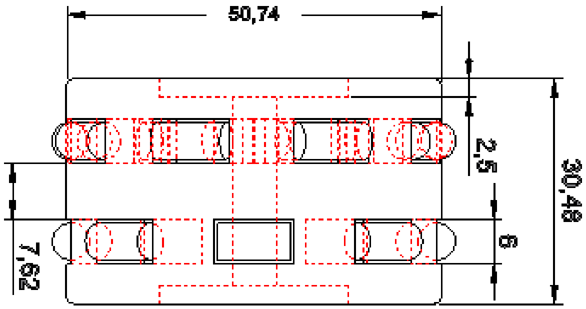


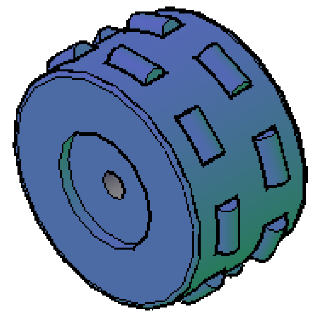

Side View



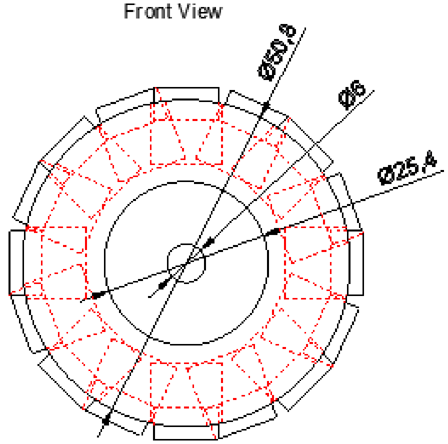

| | |
|---|---|
| Part Name : Carriage | Checked by: Prof. Dr T. Nagarajan |
| Prepared by: Dzulfikry Aris | Scale: 1:1 (mm) |

Plan View

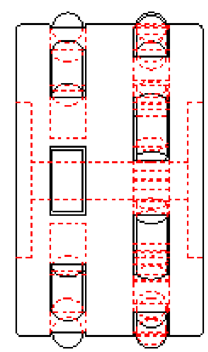


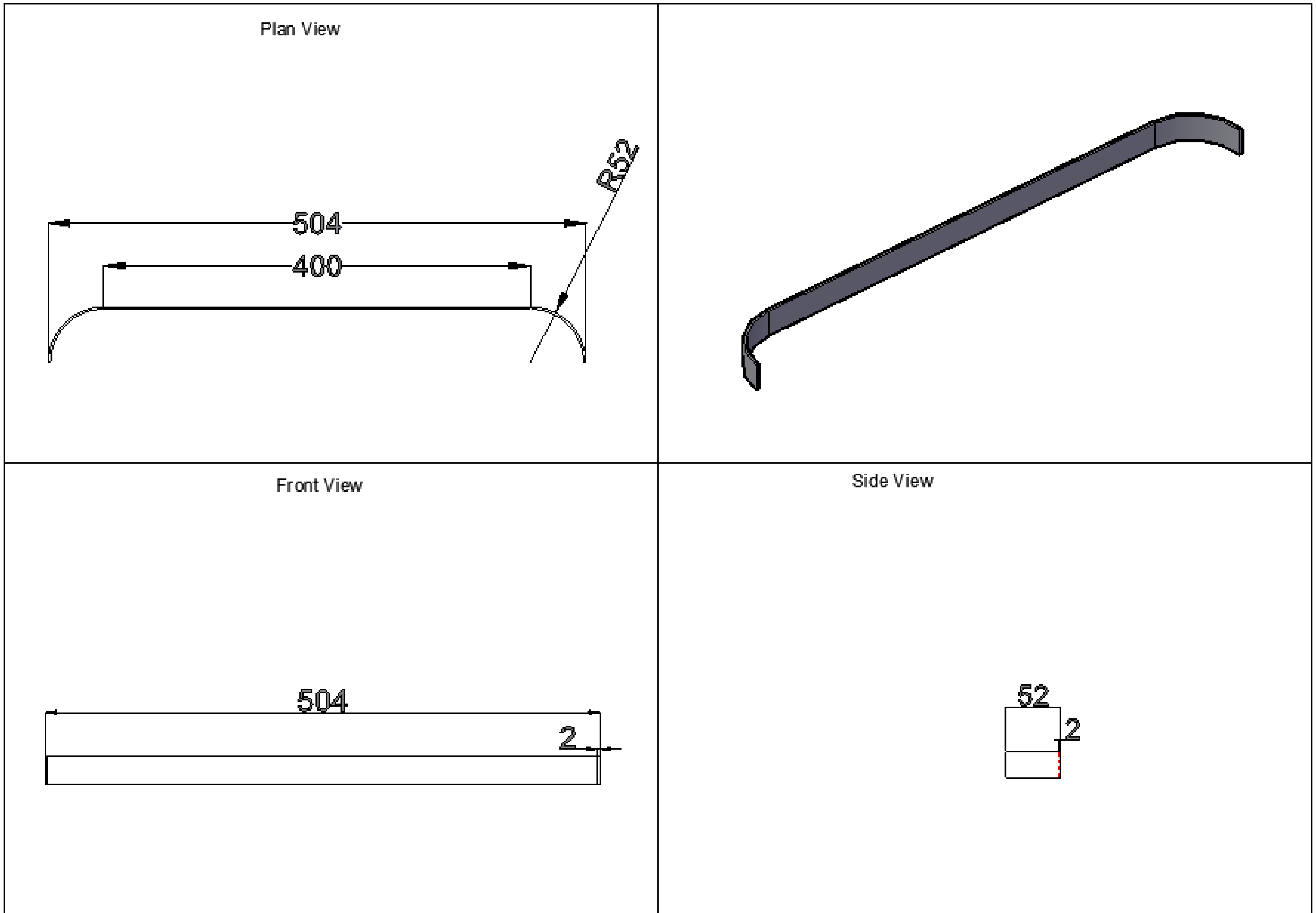
Front View




Side View

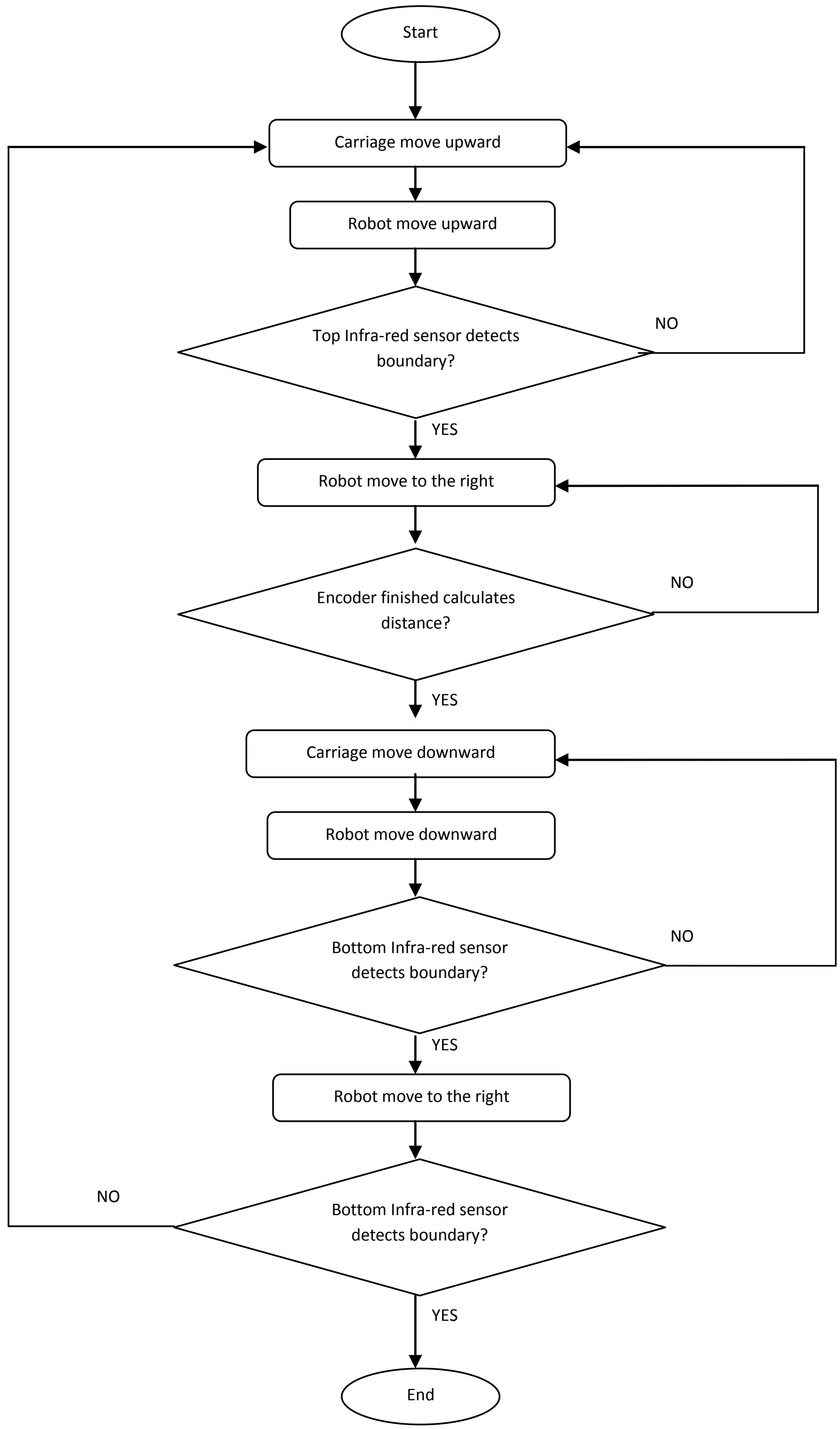


| | |
|---|---|
| Part Name : Transwheel | Checked by: Prof. Dr T. Nagarajan |
| Prepared by: Dzulfikry Aris | Scale: 1:1 mm |




| | |
|---|---|
| Part Name: Squeegee | Checked by: Prof. Dr T. Nagarajan |
| Prepared by: Dzulfikry Aris | Scale: 1:1 (mm) |

## Appendix D – Robot’s Working Principle Algorithm & Programming Code



## Programming Code

```
void main(void)
{
	LED=0;
	VAC=0;

	if(!switch1)
	{
		while(1)
		{
			UP();
			if(!IRtop)
			RIGHT();

			DOWN();
			if(!IRbottom)
			RIGHT();

			if(!IRbottom&&!IRright)
			stop();
		}
	}
	if(switch2)
	{
		while(1)
		{
			LED=1;
			encodefor(2);
			VAC=1;   // on vacuum motor
```

```
                    roam_normal();
                    VAC=0;   // off vacuum motor
                    homebase();
          }
     }
}
//---------------------------------------------------------------------------------------------------------------------------
UP(void)
{
     while(1)
     {
     vaccenter=1;
     vacflank=0;
     motorcarriage=1;
     motorshaft=0;
     DelayMs(1000);

     vaccenter=0;
     vacflank=1;
     motorcarriage=0;
     motorshaft=0;
     DelayMs(1000);

     while(!LMtop)
     }
}
//---------------------------------------------------------------------------------------------------------------------------
DOWN
{
```

```
	while(1)
	{
	vaccenter=0;
	vacflank=1;
	motorcarriage=0;
	motorshaft=0;
	DelayMs(1000);

	vaccenter=1;
	vacflank=0;
	motorcarriage=1;
	motorshaft=0;
	DelayMs(1000);

	while(!LMbottom)
	}
}
//----------------------------------------------------------------------------------------------------------------------------------
RIGHT
{
	while(1)
	{
	vaccenter=1;
	vacflank=0;
	motorcarriage=0;
	motorshaft=1;
	encodfor(2); // 2.5 wheel's rotation

	vaccenter=0;
```

```
            vacflank=1;
            motorcarriage=0;
            motorshaft=0;
//          DelayMs(1000);
}
}
//-------------------------------------------------------------------------------------------------------------------------------
LEFT
{
            while(1)
            {
            vaccenter=1;
            vacflank=0;
            motorcarriage=0;
            motorshaft=1;
            encodfor(2); // 2.5 wheel's rotation

            vaccenter=0;
            vacflank=1;
            motorcarriage=0;
            motorshaft=0;
//          DelayMs(1000);
```

## Appendix E – Project Schedule

| No | Activity | Subject | 1 | 2 | 3 | 4 | 5 | 6 | Mid- semester break | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Review | Continuation on Project Work<br>Planning for design | ■ | | | | | | | | | | | | | | |
| 2 | Develop methodology | Re-work on:<br>i) Problem Statement<br>ii) Concept Generation<br>iii) Concept Evaluation | | ■ | ■ | | | | | | | | | | | | |
| 3 | Develop methodology | iv)Product Generation<br>v) Product Evaluation | | | | ■ | | | | | | | | | | | |
| 3 | Documentation | Submission of Progress Report 1 | | | | ● | | | | | | | | | | | |
| 4 | Develop methodology | Product Evaluation: i) Engineering Analysis<br>ii) Design for Cost, Manufacture, Assembly, Etc.<br>iii)) Detail Drawing | | | | ■ | ■ | ■ | | ■ | ■ | ■ | | | | | |
| 5 | Documentation | Seminar | | | | | | | | | ● | | | | | | |
| 6 | Documentation | Submission of Progress Report 2 | | | | | | | | | ● | | | | | | |
| 7 | Analytical analysis | Wrap up of project data | | | | | | | | | | | ■ | ■ | | | |
| 8 | Documentation | Poster Exhibition | | | | | | | | | | | | ● | | | |
| 9 | Documentation | Overall project review | | | | | | | | | | | | | ■ | ■ | |
| 10 | Documentation | Submission of dissertation final draft | | | | | | | | | | | | | | | ● |
| 11 | Documentation | Oral presentation | | | | | | | | | | | | | | | ● |
| 12 | Documentation | Submission of Dissertation (hard bound) | | | | | | | | | | | | | | | |