Design of a glass climbing robot

by

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Dissertation submitted in partial fulfillment of
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CERTIFICATION OF APPROVAL

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May 2007

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.

May 30th 2007

NGUYEN HUU PHUOC NGUYEN

ABSTRACT

Wall-climbing robot is very useful in substituting human labors in dangerous and repetitive tasks like cleaning glass window in high building, maintenance, and inspection in industrial storage tank. A success in developing a climbing robot presents a huge economic benefit. This project aims to design a remote-controlled climbing robot that is able to operate on a vertical glass window. An effective adhesion mechanism using suction cups and solenoid valves had been designed. The locomotion mechanisms design based on a crossed-bar mechanism, utilizing pinion and rack. Detail drawings of the design and the robot specification had been finalized. A prototype was fabricated to demonstrate the design concept and its functionality. Control system of the robot, which includes an electrical circuit integrated with a C program, had been developed. Finally the functionality of the fabricated prototype was tested.

ACKNOWLEDGEMENT

At the end of the project, in many aspects the author feels that the project has been a success. Particularly, what have been learnt and gained through the projects are invaluable. The project would have not been this success if the following people had not given their kind support.

First of all, I would like to express my deep gratitude to Mr. Shafriza, the project supervisor, for his guidance and encourage throughout the project. His relentless support has been a major contribution to the success.

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Last but not least, I would like to extend my gratitude to Dr. Naufal, the team manager, and the Robocon team members for their kindness in lending me components, material, lab tools and giving out their advices.

There are many other people who helped me to complete the project but I could not name here due to the space limitation. I seek for your understanding and please know that I appreciate your help.

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CHAPTER 1
INTRODUCTION

1.1 Background

Wall-climbing robot has been put in great attention and effort in recent decades. People are looking to exploit climbing-robot in numerous and much-needed applications such as cleaning glass window in sky crappers, carrying fire fighting in high building, inspection and maintenance in industrial storage tank, nuclear plant, petrochemical plant or oil platform. In those tasks, the environment is normally dangerous or hazardous to human workers. Therefore, robot which is capable of climbing up a vertical wall becomes more desirable and in high demand.

Climbing robot does not only help people to do dangerous works but also brings a huge economic benefit to them. Cleaning industry in Europe, for an instance, represents a market of more or less 100 billions of Euro per year, with a percentage of 80% of the figure due to labor cost [1]. This statistic shows a huge opportunity for commercializing climbing robot, and, possibly, for opening a new industry surrounding climbing robot.

A success in developing a climbing robot would help greatly in liberating human labor in dangerous works like cleaning window glass in sky scrappers, inspection nuclear storage tank, and also bring out a huge economic benefit.

1.2 Problem Statement

Looking at the tremendous potential of climbing robot, a number of climbing robots have been developed for various applications over the years. However, most of these robots are only engineering prototypes and have not been used extensively for any application [2]. This situation is mainly due to the technical challenges in developing a climbing robot, beside the economic constrains. The major challenges in developing a climbing robot are effective adhesion and detachment mechanism, and rough surface adaptation. Beside, the locomotion mechanism and controlling system are also great obstacles. In this project, the robot is designed for smooth surfaces such as glass or metal, therefore, the rough surface adaptation problem is minimized. The major problems are now narrowed down to effective adhesion and detachment mechanism, locomotion mechanism and controlling system.

1.3 Objectives and Scope of Study

The project aims to design a complete climbing robot with an effective adhesion and detachment mechanism, locomotion mechanism and control system that enable users, using remote controller, to control the robot climbing up and down a 90-degree glass wall and turning left and right when the robot is on the wall. The expectation is to come out with a detailed design of a climbing-robot which includes technical drawing, robot structure, list of the robot's components, and bill of materials. If time allows, a prototype will be fabricated to demonstrate the design. Although, economic factors exert heavy constrains in developing a climbing robot, they are not within the project's scope.

CHAPTER 2

LITERATURE REVIEW AND THEORY

This part aims to study the technical fundamental in designing a climbing robot, also to gain an understanding on the development of climbing robot and general designing criteria of climbing robot.

Recently various robots have been designed for wall cleaning and maintenance. There are three kinds of kinematics for the motion on smooth vertical surfaces: Multiple legs, a sliding frame and a wheeled and chain-track vehicle. Three different principles of adhesion which are magnetic equipment, thrust force, and vacuum pad are used by climbing robot. Actuator techniques can be classified into three categories: Electric, hydraulic and pneumatic. The literature review is summarized in the following diagram.

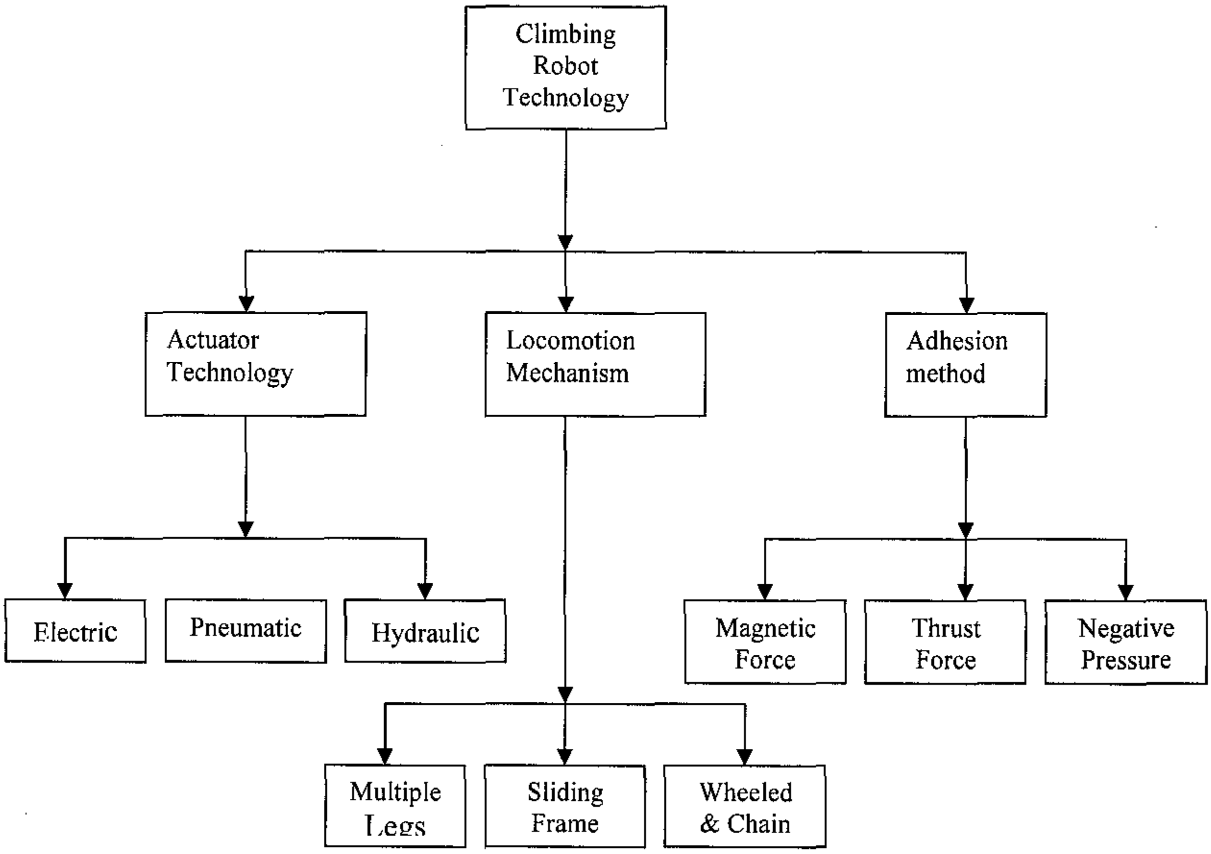


Figure 1: Overview of climbing robot technology

The following paragraphs will discuss in more detailed about the fundamental techniques used in climbing robot.

2.1 Actuator technique

There are three main actuator technologies - electric, hydraulic, and pneumatic. Hydraulic technology produces the highest force-to-weight ratio. However, it is difficult to build a system that can guarantee no linkages and in some industries, the risk of contamination by hydraulic fluid may not be acceptable. The pneumatic technology gives a higher force-to-weight ratio than the electric drive technology. In addition, the pneumatic technology is much cleaner than hydraulic and is inherently compliant which is essential far climbing walking machines. With new pneumatic components in the market which can support up to 20 bar pressures, pneumatic technology may be suitable for designing robots for many industrial applications. [3]

2.2 Kinematics for motion on smooth vertical surface

Currently there are some different kinds of kinematics for motion on smooth vertical surfaces: multiple legs, sliding frame, wheeled, and chain track vehicle.

The robots with multiple-legs kinematics are too complex due to a lot of degrees of freedom. The kinds of robots which always use vacuum suckers and grasping grippers for attachment to the buildings do not meet the requirements of miniaturization and low complexity. Some climbing robots have been developed to move on complex wall surfaces. The famous robot ROMA is a multifunctional self-supported climbing robot. It can travel into a complex metallic-based environment and self-support its locomotion system for 3D movements. Generally this kind of robots' construction and control is very complicated, and does not offer the high efficiency and simple operation required by a wall cleaning robot.

Sliding frame mechanisms normally consist of two frames, one can slide one each other while the other one is sucked to the wall. A kind of pneumatic cleaning robot was developed for cleaning the embassy of Canada by a company in Japan, but it cannot walk sideways. Since 1996 the group at the Robotics Institute of BeiHang University has been developing a family of sky cleaner autonomous climbing robots with sliding frames for glass-wall cleaning. [4]

The robots with the wheeled and chain-track vehicle are usually portable. The adhesion used by this kind of robot is always negative pressure or propellers, so the robots can move continuously. One kind of robot has a pair of wheels actuated by electrical motors in its negative pressure chamber, so that it can move on the wall flexibly. But it can only deal with plane walls without any obstacles. A new smart structure with two linked-track vehicles for a glass wall climbing robot was proposed in 2000. The robot's structure can be reconstructed so that it can move between the faces with a 0-90 degrees angle. Another climbing robot similar to the smart robot above in construction and actuation methods has also been developed in Japan; however with a weight over 100 kg it is too heavy. Akira Nishi and Hiromori Miyagi developed a kind of wall-climbing robot using the propulsive force of propellers. The robot is very light but the noise generated by propellers is too loud to use on glass walls. Even if the negative pressure chamber is not sensitive to a leakage of air, the negative pressure will not be enough for the safe and reliable attachment to the vertical surface when the robot crosses window frames.

2.3 Adhesion method

The adhesion methods used for climbing robots are divided into three categories: magnetic equipment, thrust force, and vacuum pad. The magnetic adhesion is heavy and only suitable for ferromagnetic surface. The thrust force, adopted with propeller can help robots avoid obstacles in movement, but its unsatisfied stability hinders this method from being used extensively. The vacuum pad, as the most commonly used adhesion method for the time being, can be used in even platforms such as glass, wall, and ceramics and so on. It is light and is easy to control, though it has the problem in supplying compressed air. [5]

2.4 Existing designs

Considerable effort has been dedicated to researching about locomotion mechanism and studying the existing designs. The main purpose is to have some view on how a climbing mechanism being designed, and the designing criteria of a climbing robot. Result of the study shows that there is quite a number of climbing robots existing. The mechanism varies from simple one like Zigzag mechanism to complicated one like Ninja-1, a quadruped climbing robot which able to climb and walk. The following paragraphs will discuss about some simple, but very effective, mechanisms and elaborate on the designing criteria.

2.4.1 *Robug II - An intelligent wall climbing robot*

This robot was developed by B.L Luk, A.A Collie, J.Billingsley from Portsmouth Polytechnic. The robot has the ability to climb over obstacles. It also has the intelligence to seek and verify food-hold allowing it to work in less well-defined environments. The robot has a high power-to-weight ratio so that it is capable of carrying tools and equipment for a variety of operations.

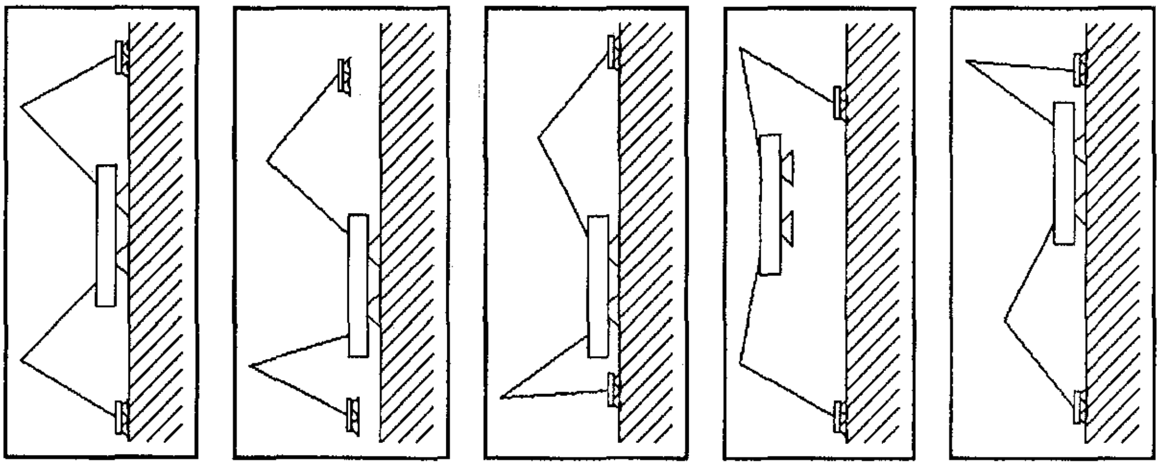


Figure 2a Figure 2b Figure 2c Figure 2d Figure 2e

Figure 2: Robug II movement

The normal resting position on the wall, the gripper feet, and the belly suckers of ROBUG II are firmly attached to the wall, as shown in figure 2. When the robot is moving forward, the following movements are implemented: [6]

- The robot releases all its gripper feet suckers, allowing all four legs to rise
- The front two legs then move forward and the back two legs move inward (Fig. 2b)

- The robot then pushed each foot down in tern with vacuum enabled. If any leg cannot get a secure grip on the surface, it carries on searching the area within reach until a secure grip is verified. the altitude after secure gripping on the surface is shown in the figure 2c
- The robot then releases its belly sucker and levers its body up and forward as shown in figure 2d.
- The body is then lowered and seeks a grip on the surface with its belly suckers. If the belly suckers cannot get a secure grip on the surface, the legs inch the body backward to seek a secure grip. The position after this has been achieved is shown in figure 2e

2.4.2 *Zigzag Robot*

This robot was developed by the same authors who developed **RobogII**, J.Billingsley, A.A Collie, B.L Luk from Portsmouth Politechnic. Zigzag has but one degree of freedom and strictly has no legs at all.

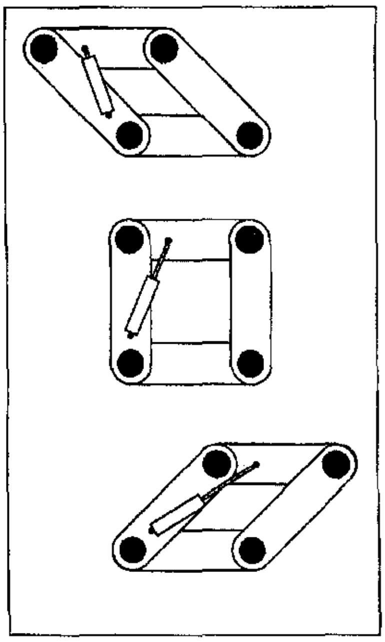


Figure 3: Zigzag Robot movement

Zigzag has the shape of a rhombus. Four links join together four vacuum grippers at the corners. A single diagonal pneumatic cylinder drives the machine so that it can form a square or have an acute or obtuse reference angle.

The angle of the device can be defined as the angle of the North_ West (i.e. top left) corner. The cylinder is connected across the corner, so that when it extends the corner angle becomes obtuse.

Suppose that at first this angle is square, so that the machine forms a square, and that all four grippers are holding. To move to the right (East) the South pair of gripper are switched off, leaving the machine supported only by the top pair. The cylinder now retracts, pulling the reference corner to an acute angle and moving the lower grippers to the right. When the cylinder reaches its stop, all four grippers are again engaged, after which the top suckers are switched off leaving only the South pair sucking. Now the cylinder extends, driving the North edge to the right as the angle becomes obtuse. At the end of the stroke, all four grippers are again turned on. This sequence of operations can be summarized as:

Grip North: Cylinder retract : Grip all
Grip South: Cylinder extend: Grip all

This sequence of operations can be repeated at will to take the machine to the right. Alternatively the sequence

Grip West: Cylinder extend: Grip all
Grip East: Cylinder retracts: Grip all

can be used to move up the wall. In order to change direction, however, it is necessary to bring Zigzag to a square position first, if the motions are to be truly at right angles. [7]

2.4.3 *Climbing microbot*

The session will discuss about one of the existing mechanisms designed by Jun Xiao and his colleagues. In principles, climbing robots must have a proper adhesive mechanism to ensure that they grip wall surfaces firmly and without sacrificing mobility. This robot adopts active suction feet, a bipedal articulated structure, and an under actuated mechanism to achieve a good balance between compactness and maneuverability, as shown in Figure 5. The robot is assumed to travel on smooth surfaces for reconnaissance purpose within a building. Thus, the restrictions such as small size, light weight, and low power consumption must be satisfied

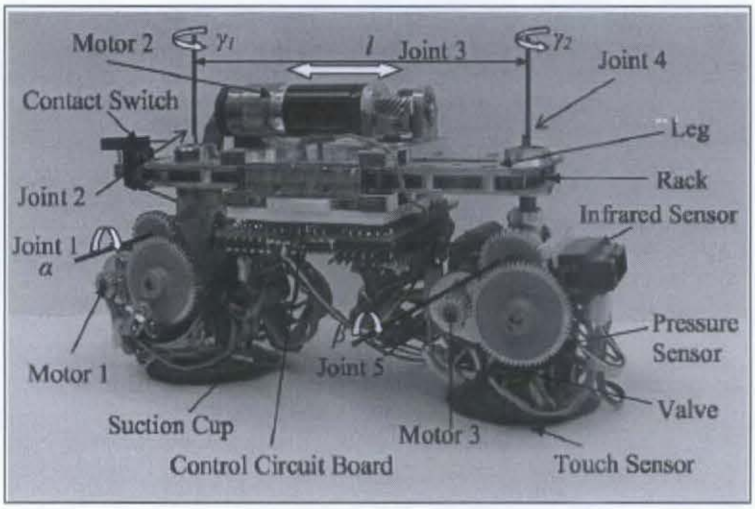


Figure 4: Picture of the wall-climbing microrobot.

The robot is supported by two suction feet which can stick on anticipated smooth and nonporous surfaces. The robot is able to climb walls, walk on ceilings, transit between two inclined surfaces, and crawl through pipes. The dimension of the prototype robot is approximately 80 mm in height and 50 mm in width. It weights 450 g. The under actuated mechanism enables the robot to drive five joints using only three motors, thus reducing both the weight and power consumption of the robot. Motors 1 and 3 independently joints 1 and 5; thereby adjusting the tilt angle of the suction foot 1 and foot 2 so that the robot can grip the surface firmly.

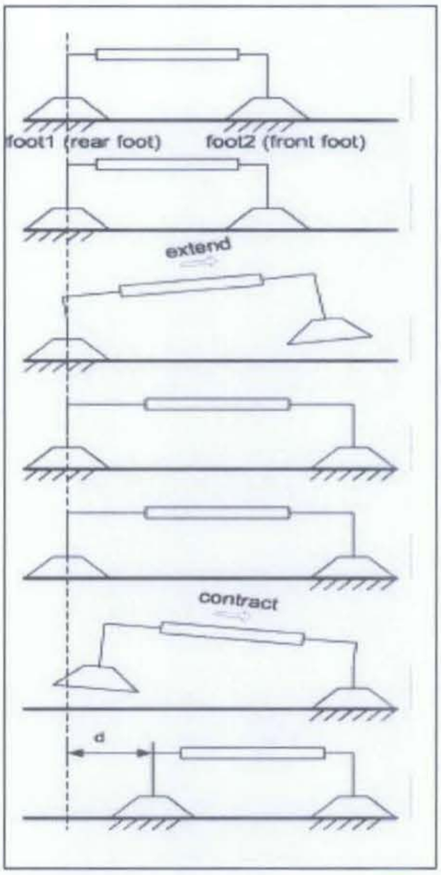


Figure 5: The Microbot's locomotion mechanism

Motor 2 is responsible for controlling joints 2, 3, and 4. Joint 2 and 4 are revolute joints providing steering capability of the feet relative to the legs. Joint 3 represents the prismatic motion of the legs that allows the robot expanding and contracting. The clockwise (CW) rotation of motor 2 causes contraction, i.e., both legs slide into the robot body; while the counterclockwise (CCW) rotation of motor 2 causes expansion, i.e., both legs translate out of the robot body.

The robot has three motion modes and the capability to switch between them. In each of the three modes, a particular subset of joints is driven and the remaining joints are locked to prevent rotation. Fig. 8 shows the top-down view of the robot and its motion modes. The switching between motion modes is achieved by the engaging/disengaging of the lock-pin. [8]

- **Translation Mode**: When both the lock-pin bearings are outside their cam slots, joint 2 and 4 are prevented from rotating; thereby the rotation of motor 2 causes translation motion of the legs

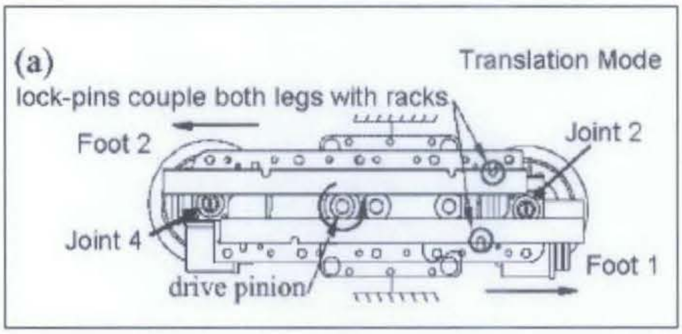


Figure 6: The microbot's translation mode

- A CCW rotation of motor 2 causes the legs to extend while a CW rotation causes them to contract. If the translation motion continues beyond a certain range, both in extension and contraction, one of the lock-pins will enter its cam slot on the body, causing the mode switch from the translation mode to spin-1 mode or spin-2 mode.

- **Spin-1 Mode**: When lock-pin on leg 1 enters its cam slot during contraction, it disengages the rack 1 from leg 1 and allows the CW rotation of foot 1 relative to leg 1 about joint 2. Meanwhile, since the lock-pin on leg 2 still couples the leg and rack motion, leg 2 will continue to contract and joint 4 is held fixed.

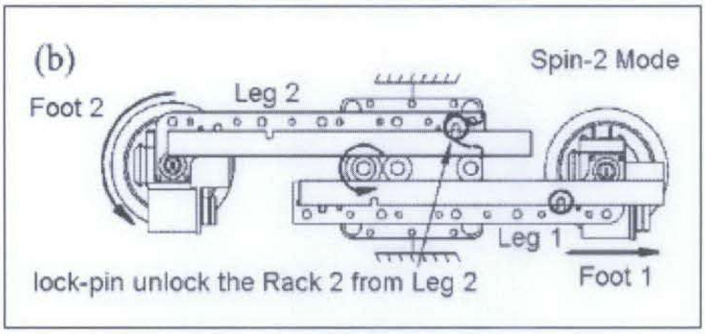


Figure 7: Spin-1mode.

- **Spin-2 Mode**: If the robot legs keep extending in translation mode, the lock-pin bearing on leg 2 will enter its cam slot and unlock the rack 2 from leg 2 causing the CCW rotation of foot 2 about joint 4. At mean time, leg1/rack1 pair continues to extend along joint 3 while joint 2 is held fixed.

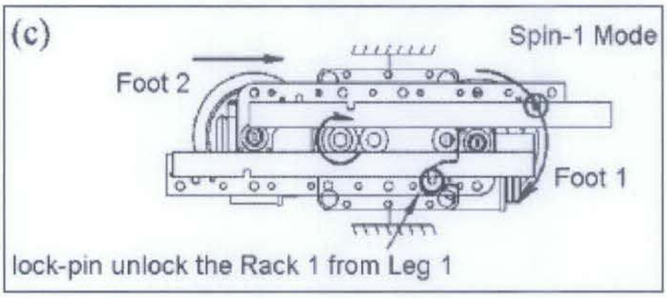


Figure 8: Spin-2 mode.

CHAPTER 3

METHODOLOGY AND PROJECT WORK

3.1 Procedure

To complete the project, the following major steps were taken:

- **Literature review**: This step is to study the current technology in climbing robot. The main activity here is searching and reading climbing-robot related information. There are two main sources of information: Internet and Library. With internet, it is recommended to visit credited online journals and database such as IEEE electronic library, Sprinkle Link. These sites are good to refer because the articles are written by professional and experts in the fields. The library provides more-general information about climbing robot.

- **Locomotion Mechanism design:** Design the locomotion mechanism of the robot and identify all the components involved in the design.

- **Adhesion and Detachment Mechanism design:** Design an effective adhesion and detachment mechanism for a glass wall.

- **Detail drawing:** Make detail drawings of the complete design.

- **Control system design:** Design the control system of the robot, including identify all the components needed for the system. This step will be started during the semester break, when the mechanism is finalized.

- **Make bill of materials:** List all the component/devices needed in this project, where to buy them, and how much are they.

- **Fabrication preparation**: This step involves purchasing or borrowing components and material needed to prepare for fabrication.

- **Fabricate a prototype :** Fabricate a prototype based on the design

3.2 Tools and equipments used

3.2.1 *Source of components and materials*

The majority of components and materials of this project are available in UTP. There are three major sources of components and materials: EE department's stores, the machining centre at building 16 and Robocon lab. All of the electronic components are borrowed from the EE's store at building 22, while the solenoid valves are borrowed from Instrumentation and Control lab at building 21. Aluminum solid cylinders are taken from the machining centre at building 16. Aluminum bars, motors and some electronic components are borrowed from Robocon lab. Items that need to purchase from outside (Ipoh and Tronoh) are suction hooks, bolts and nuts, and some aluminum rods.

3.2.2 *Machining centre*

The project requires a number of customized components, which cannot be purchased from the market. Therefore, it is mandatory to have a machining centre to fabricate those components. Fortunately, UTP offers an excellent machining centre at building 21, which houses machines for key machining processes such as lathe, milling, drilling, bending, and threading. Beside, the wire-cut lab at building 16 was also utilized to fabricate the racks and pinions.

3.2.3 *Circuit fabricating*

To fabricate a circuit it requires tools such as soldering-iron, multi-meter, pliers, and dis-soldering tool. The circuit fabrication of the project was done at Robocon lab. The EE department's lab also offer the facilities, however Robocon lab is more convenient since it operates at night time.

3.3 Generic designing process

The following flow chart will show the steps taken for both designing locomotion mechanism and adhesion mechanism.

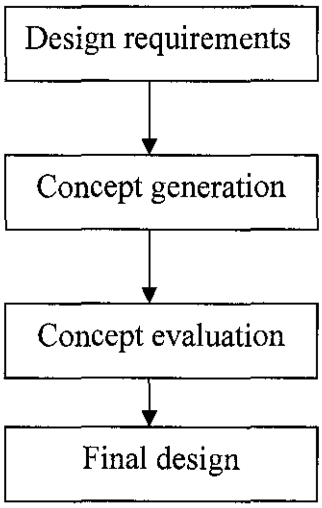


Figure 9: Designing process for adhesion and locomotion mechanism

3.4 Fabrication planning

3.4.1 *Fabricating location*

The locations for fabricating components and assembly work are the Robocon lab and the machining centre in building 21.

3.4.2 *Components and material planning*

A list of major components and material needed by the project is made as following.

Table 1: List of major components and material

Name	Specification	Qty	When required	Lead time	Where to get
Suction cup	Normal suction hook	8	Week 5	1 week	Tesco-Ipoh
Rack &Pinion	30 cm rack, pinion: m=2, dp = 40mm	4&8	Week 4	3 weeks	Fabricate
PIC	16F877A	1	Week 8	1 week	EE dept.'s store
Motor	3.54N.m,100rpm and 30rpm	2+4	Week 6	1 week	Robocon lab
Solenoid valves	24 V, 3-valve, automatic	4	Week 5	1 week	EE dept.'s store
Aluminum bar	8cmx2mm	2m	Week 4	2 week	Robocon lab
Aluminum solid cylinder	D= 25mm, L=12cm	16	Week 4	1 week	building 16 Lab
Electronic components	Refer to table 7	Table 7	Week 8	1 week	EE dept.'s store and Robocon lab
Spherical wheel	D=19mm	4	Week 7	4 week	RS component
RF remote control	>10 m range	1	Week 8	2 week	Ipoh RC car shop

3.4.3 *Fabrication scheduling*

The fabrication work started at week 4 and ended at week 12. For more detailed information, please refer to the **APPENDIX A3**

3.5 Time line

The first semester focus on literature review, designing locomotion and adhesion mechanisms of the robot. The second semester will be for designing the control system and circuit, detailed drawing, and fabrication. For more detailed schedule, please refer to the Gantt chart for semester 1 and 2 attached with the **APPENDIX A1 and A2**

CHAPTER 4

ANALYSIS AND DESIGN

4.1 Design criteria

Weight of the robot: The weight of a climbing robot varies with its application and technology, but a general principle is that the robot should be as light as possible. In this project, based on the material and components used the weight of the robot should be less than 5kg. The weight distribution is expected as following:

Table 2: Weight distribution

Item	Quantity	Weight (kg)
Battery	2	1.5
Motor	6	1.2
Solenoid valves	4	0.8
Other(frame, screw..)	N/A	1.5
Total		5.0

Payload: The robot is designed to carry a maximum additional load of 2kg.

Linear velocity: The robot is expected to achieve a linear velocity of 0.5m/min.

Types of climbing surface: The robot should be able to climb on a vertical glass wall.

Level of autonomy: The robot shall be controlled by a RF remote controller, and it should be able to complete one movement step automatically once the command is received from the user.

4.2 Conceptual Design

4.2.1 *Locomotion mechanism design*

i *Design requirement*

The locomotion mechanism should facilitate achieving all design requirements of the robot. In more detailed, the design criteria are discussed in the following paragraph and given weighted factors to quantify their importance. The design criteria to be considered are:

Light weight: The maximum allowable weight of the robot is only 5kg, so light weight is the most important factor which is given a weight factor of 0.25.

Ease to fabricate: This criterion is about ease of fabricating the robot. It involves factors such as number of components, complexity of components, ect. It is given a weight of 0.2.

Ease to control: This criterion concerns about the complexity of the control system. How easy to control the robot accurately and smoothly. The weight for this criterion is 0.2.

Low power consumption: the more power the robot consume, the more energy supply is, therefore, the heavier the robot is. Battery is widely used in climbing robot because it is mobile and compact. However, if the robot is too heavy, battery is not sufficient to source, unless there are many of them. In this case, electricity must be supplied from ground, making the construction of the robot more complicated, and reducing its mobility. It is weighted at 0.15

Pay load: Pay load means the load that a robot can carry apart from its own weight. The robot is supposed to carry a maximum payload of 2kg only, therefore, this factor is considered less important with a weighted factor of 0.1.

Flexible movement: This factor reflects ability to move smoothly in omni-direction of the robot. Depending on applications, the importance of this factor varies. For applications like glass-wall cleaning, this factor is not really important, therefore, it is weighted at 0.1.

ii *Concept generation*

a *The crossed-bar mechanism*

The concept

The mechanism is two bars crossed at their centers, with a vacuum cup at each of the ends. The racks and pinion on each of the bars allow them to slide on each other, thus enable the robot move vertically and horizontally.

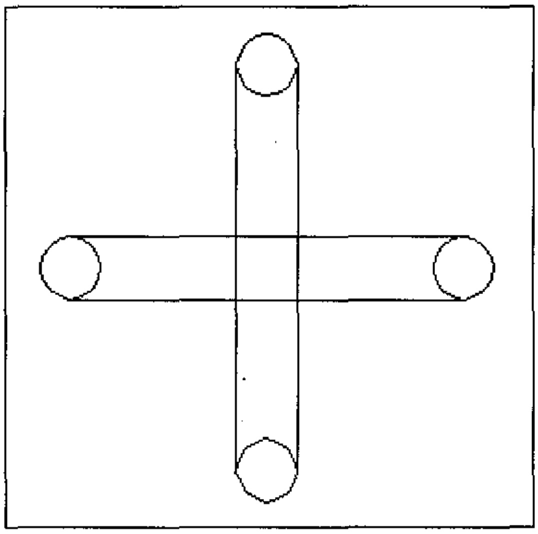


Figure 10: Conceptual crossed-bar mechanism-top view

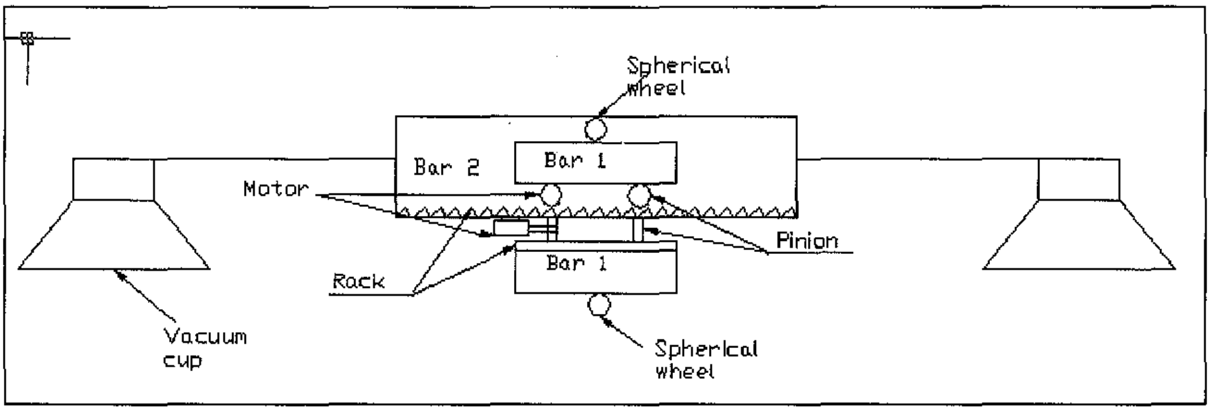


Figure 11: Conceptual crossed-bar mechanism-side view

Operation

Move Vertically

To move vertically, the vacuum cups of vertical bar (bar 2) activated, fixing the bar 2 to the wall. The motor attached to bar 1 runs, moving the bar 1 forward or backward.

Move Horizontally

The same operation applies here. The horizontal bar (bar 1) is now fixed to the wall. The motor attached to bar 2 runs, moving the bar 2 right or left.

Notes:

- If the movement needs to change from vertical to horizontal or vice versa, the bars need to be at their original positions, at their centers.
- The spherical wheels act as a support to the bars, minimizing the fictions between them while be able run at omni directions.

b *The 4-leg-pneumatic-actuated mechanism*

The concept

The mechanism consists of four (4) bars connecting to a centre joint by a mean of spherical joints. There are five suction cups at the ends of the bars and at the centre joint. The two bars on each side are connected to each other by a pneumatic cylinder.

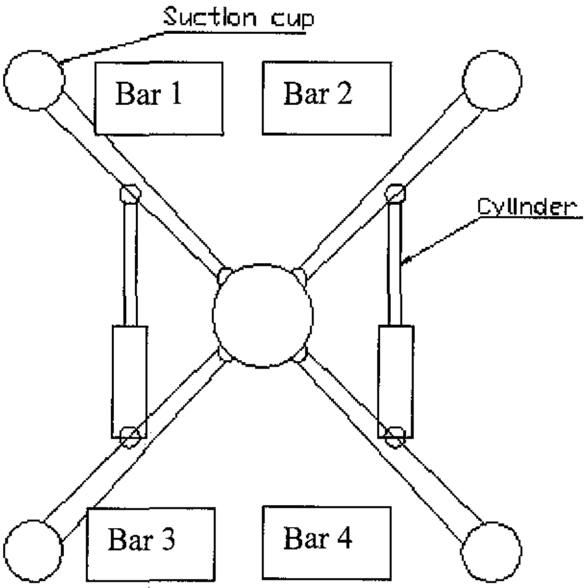


Figure 12: Conceptual 4-leg-pneumatic-actuated mechanism

Operation:

Moving vertically:

To move upward, the suction cups of bars 1 and 4 are activated, therefore fix the bars to the wall. The cylinder connected bars 1 and 3 retracts, puling the bar 3 upward; while the cylinder connected bars 2 and 4 extends, pushing the bar 2 upward. After moving upward, the bars 1 and 4 are now fixed to the wall by activating the corresponding suction cups. The cylinder connected bars 1 and 3 then extend, pushing bar 1 upward; while the cylinder connected bars 2 and 4 retracts, pulling bar 4 upward. After the above step, the robot has completed on vertical upward movement and it returns to its neutral position. The steps are the same for vertical downward movement.

Moving horizontally:

To move horizontally, the challenge is to change the direction of the robot from vertical to horizontal. This can be done by rotating the robot 90 degree, say, to the right. The rotation is done by rotating the legs three times, each time 30 degree, using extension, and retraction of the cylinders. The detail is discussed in the following:

1. Bars 1 and 3 are fixed, Both cylinder connected bars 1 and bar 3 and cylinder connected bars 2 and 4 then retract, rotating the legs 3 and 2 30 degree.

2. The bars 2 and 3 are then fixed, the cylinders extend, rotating the legs 1 and 4 30 degree.

3. The steps 1 and 2 repeat for three times.

4. After positioning the robot horizontally, the movement is the same as in vertical case.

iii *Concept evaluation and selection*

Actuator technique

The 4-leg-pneumatic-actuated mechanism uses two (2) pneumatic cylinders to drive the robot, while the crossed-bar mechanism uses two electric motors. In the concern of weight, pneumatic technology generally gives a higher force-to-weight than the electric drive technology; therefore, pneumatic technology is more favorable in designing a lightweight climbing robot. Beside higher force-to-weight ratio, a pneumatic actuator has the advantages of durability, high speed, less expensive and force capabilities. It can produce wide range of force by varying the pressure of the compressed air. However, pneumatic technology has its own disadvantages such as a need of a compressed air

source and a rather complicated controlling method. A pneumatic actuator requires a compressed air tank and a tubing system, which will add significant weight and complexity to the robot. Moreover, nonlinear dynamic properties such as air compressibility and friction effects prevent pneumatic actuator for accurate position control [10] Therefore, it will be a big challenge for the 4-leg-pneumatic-actuated mechanism to control the cylinder to rotate the legs to a specific angle accurately.
Although, an electric motor has a smaller force-to-weight ratio and a limited range of force, it is accurate, easy to control and is simple in construction. Pneumatic technology, on the other hand, has some disadvantages such as complexity in construction and complication in controlling.

Kinematics for motion

The 4-leg-pneumatic-actuated mechanism is capable of rotating around it; therefore, it is capable of traveling directly in any direction. However, changing the traveling direction takes time and the movement of the robot is not really continuous because only two legs are moving at a time. On the other hand, the crossed-bar mechanism is moving continuously in one direction and is able to change its direction in a short time. The movement of the robot is accurate due to the ease in controlling of electric motors. Even though the robot is capable of traveling in only two directions, to make a diagonal movement it must follow an L-route, it is acceptable for a robot used in wall climbing where most of movements are either vertical or horizontal.

Base on the analysis, it can be seen that the crossed-bar mechanism is slightly better than the 4-leg-pneumatic-actuated mechanism. However, it is difficult to decide which one is more suitable for this project. Therefore, we need to apply a more quantitative selection method to choose the best mechanism.

Weighted decision matrix

There are several selection methods such as Pugh's selection method, weighted decision matrix. The weighted decision matrix method is chosen because it is more intuitive and quantitative than the Pugh's selection method.

Table 3: Weighted decision matrix

Design Criterion	Weighted factor	Crossed bar mechanism		4-leg-pneumatic-actuated mechanism	
		score	Rating	score	Rating
Light weight	0.25	8	2	6	1.5
Ease to fabricate	0.2	8	1.6	6	1.2
Ease to control	0.2	7	1.4	6	1.2
Low power consumption	0.15	6	0.9	5	0.75
Pay load	0.1	6	0.6	8	0.8
Flexible movement	0.1	6	0.6	8	0.8
Total score			7.1		6.25

From the matrix, the crossed bar mechanism is clearly a better choice than the 4-leg-pneumatic-actuated mechanism. It has higher total score (7.1) than the other mechanism (6.25). Together with the analysis in the comparison section, we can conclude that the crossed bar mechanism is the most suitable one. Therefore, the crossed bar mechanism will be used in this project.

4.2.2 *Adhesion mechanism design*

i *Design requirement*

The adhesion mechanism design should satisfy all the requirements of the climbing robots. Ultimately, it should enable the robot to move safely on a vertical wall with a possible maximum load of 7kg. In addition, the design should promote ease of control and ease of fabrication criteria.

ii *Concept generation*

Concept 1: using a vacuum pump

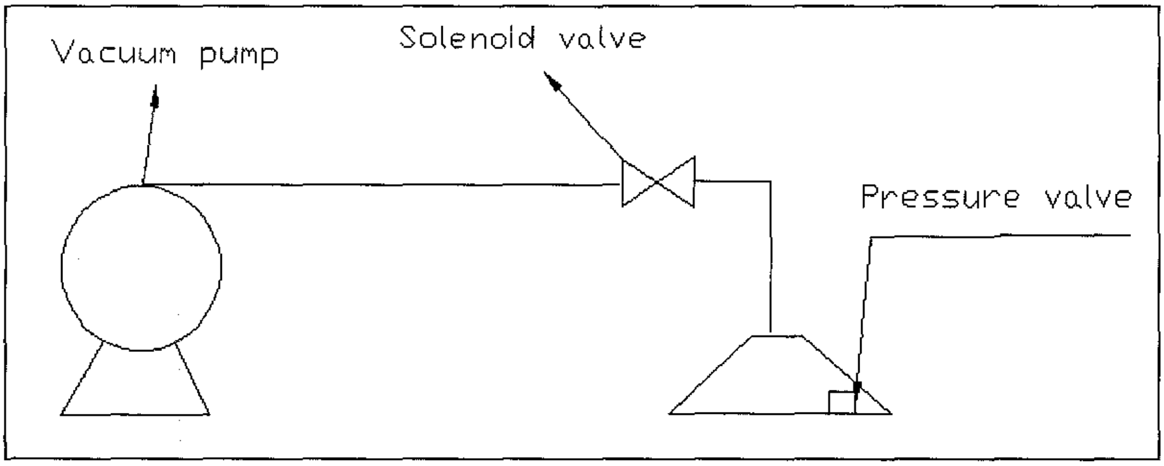


Figure 13: Adhesion mechanism concept- using vacuum pump

The negative pressure inside the vacuum cup is generated by the vacuum pump. The solenoid valve, which is controlled by the microprocessor, is used to activate or deactivate the vacuum cup. When the solenoid valve is open, the cup connects to the pump and air inside the cup is sucked by the pump, creating the desired negative pressure; when the solenoid valve is closed, the cup is connected to the atmosphere, therefore the cup is deactivated. The pressure valve is to indicate that the vacuum level has reached the desired value, and then to send a signal to the microprocessor to control the solenoid valve. In this mechanism, the vacuum level is easily and securely controlled.

Concept 2: using only solenoid valve

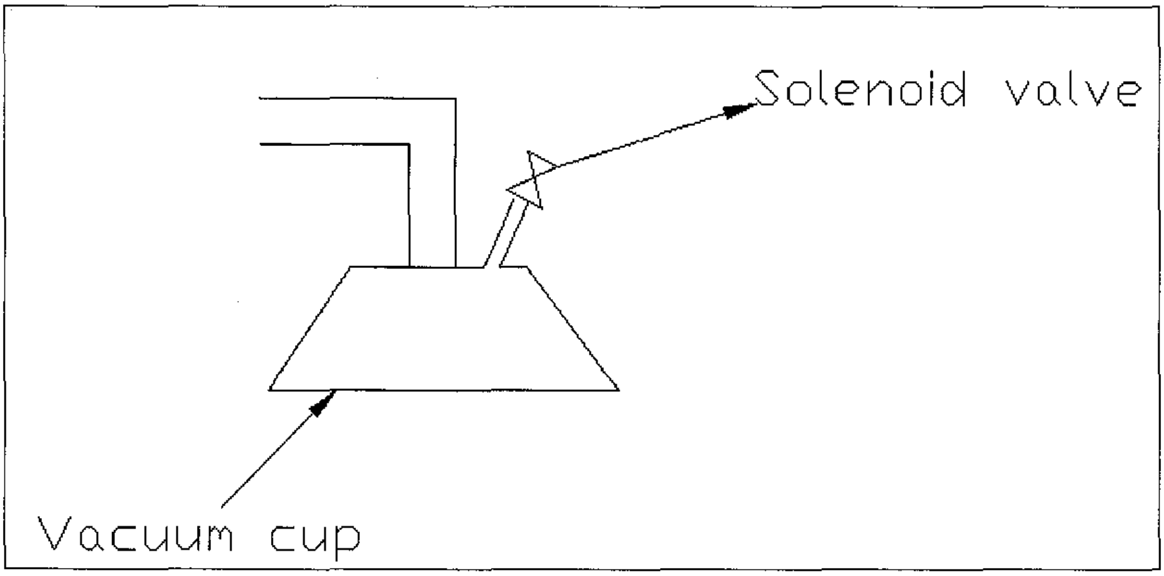


Figure 14: Adhesion mechanism concept- using solenoid valve

The negative pressure is generated by pressing the vacuum cup against the wall, while the solenoid valve is closed. The air inside the vacuum cup is squeezed out, creating a negative pressure. The cup is released when the solenoid valve is open, leveling the cup's pressure and the atmospheric one.

iii *Concept evaluation and selection*

The mechanism using vacuum pump is clearly more advanced, secured, and easily-controlled than the one using only solenoid valve. With the first mechanism, it can detect the level of vacuum through the pressure sensor, and therefore, the suction can be controlled precisely. In contrast, with the second mechanism, the level of vacuum when pressing the cup against the wall is not known, therefore the microprocessor does not know when the cup is firmly fixed to the wall to control the motion precisely and safely. However, the problem can be minimized or eliminated by delaying the pressing action long enough (about 2 seconds). Moreover, the second mechanism has clear advantages in ease of control and ease of fabrication over the first mechanism. The component availability conducted in Ipoh and some popular component website shows that the lightest vacuum pump available is 8 kg, which alone make the weight-designing criterion unachievable; not to mention its high cost and difficulties in ordering. Hence, the second mechanism will be used in this project

4.3 Embodiment Design

Up to this stage, the major design concepts have been identified and selected. However, the robot structure is not yet defined. This section will show how the design concepts assembled together to form the structure. Detailed analysis and calculation is also done in this section to determine the major specifications of the robot.

4.3.1 *Robot structure*

The figure bellow shows the structure of the robot.

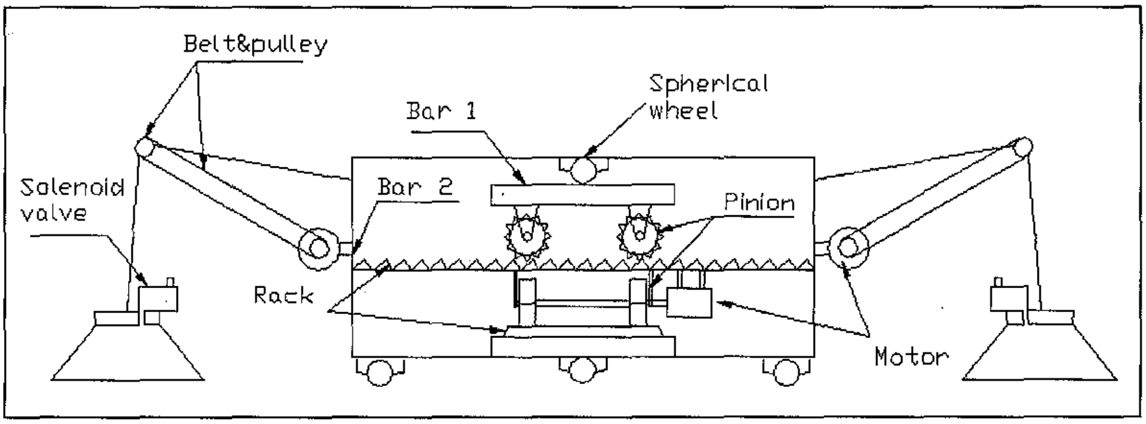


Figure 15: The robot structure

4.3.2 *Development of robot specifications*

This section will show the calculation applied to analyze the suction cup to determine the minimum safety pressure, which used to determine the specification of the rack motors, number of suction cups per one leg, the critical pressure, and the length of the rack.

i *Suction cup analysis*

The safety analysis is the most important consideration in designing the climbing robot, which should be secured firmly on the surface while climbing. There are two dangerous circumstances that could occur. One is slipping of the robot, and the other is falling of the robot. The following theory section will describe how the equations were derived and formulated. In this section the theoretical analysis is developed to find V_{min} for a single suction cup with moment and force applied on them.

Notation

R: Radius of the suction cup

Lo: Length from the small arc at 6, to the rotation axe (Z-axe)

N_a, N_b, N_ϕ: Force intensity at right side, left side and at the angle ϕ

Fx, Fy: Total force acting on the suction in X-direction (shear force), Y-direction (pull force)

Fp: Total force acting on the suction in y direction due to vacuum pressure

Fn, F_f: Total normal and friction forces acting on the suction cup

M, M_n: Total moment acting on the suction cup from outside and due to normal force, respectively.

P* Equivalent working pressure

V, V_f, V_s, V_{min} Vacuum pressure, critical vacuum pressure for suction cup's falling down, sliding and the minimum vacuum pressure for avoiding both falling down and sliding.

In this section, it is assumed that no elastic deformation takes place. The suction cup is a rigid body and the intensity N_{Φ}, of normal force F_n, between the suction cup and the contact surface distribute linearly along the X-direction as shown in the figure bellow. [11]

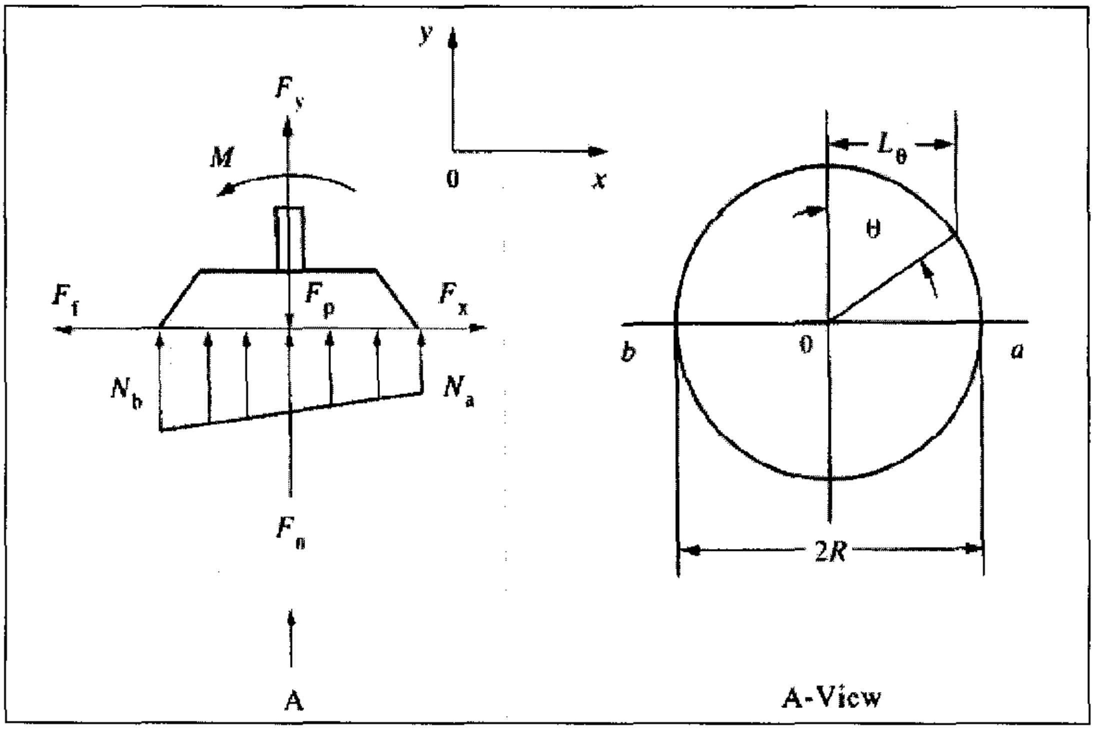


Figure 16: The schematic diagram of suction cup with force distribution

Based on the above assumptions for normal force as a function of the suction cup size and the extreme normal reaction forces intensity

$$\frac{N_\theta - N_a}{N_b - N_a} = \frac{R - R\sin\theta}{2R} \tag{1}$$

Equation (1) can be rewritten as:

$$N_\theta = \frac{N_a + N_b}{2} - \frac{N_b - N_a}{2}\sin\theta \tag{2}$$

The total normal force acting on the suction cup is

$$dF_v = 2N_\theta(Rd_\theta)$$

$$F_n = \int 2R(\frac{N_a + N_b}{2} - \frac{N_b - N_a}{2}\sin\theta)d_\theta = \pi R(N_b + N_a) \quad (3a)$$

The force acting on the suction cup due to vacuum pressure is

$$F_p = \pi R^2 V$$

And the force balance in the y-direction is

$$F_p + F_n - F_p = 0$$

Which can be expressed as:

$$F_p = \pi R^2 P^* \quad (3b)$$

Where

$$P^* = V - \frac{F_y}{\pi R^2} \quad (4)$$

Now, by setting (3a) equal to (3b), the following equation is obtained:

$$N_b + N_a = RP^* \quad (5)$$

The total moment about point "0" can be calculated as follows

$$dM_n = 2(R\sin\theta)(N_\theta Rd\theta)$$

$$M_n = \int_{-\pi/2}^{\pi/2}(2R\sin\theta)(\frac{N_b + N_a}{2} - \frac{N_b - N_a}{2}\sin\theta)(Rd\theta)$$

Or

$$M_n = -\pi R^2(N_b - N_a) \quad (6)$$

The moment balance for the suction cup is

$$M_n + M = 0$$

That is

$$M_n = \pi R^2(N_b - N_a) \quad (7)$$

From equations (5) and (7) the normal force at "a" and "b" can be written as

$$N_a = \frac{1}{2}(RP^* - \frac{M}{\pi R^2}) \quad (8)$$

$$N_b = \frac{1}{2}(RP^* + \frac{M}{\pi R^2}) \tag{9}$$

Therefore, to avoid the suction cup (robot) falling down, the normal force intensity at "a" should satisfy the following condition

$$N_a \geq 0 \tag{10}$$

By substituting equations (4) and (8) into (10), the equation relating vacuum pressure of the suction cup to the moment and the pulling force is obtained as

$$V \geq \frac{1}{\pi R^2}(\frac{M}{R} + F_y)$$

Thus, the critical vacuum pressure for falling down is

$$V_f = \frac{1}{\pi R^2}(\frac{M}{R} + F_y) \tag{11}$$

To avoid suction cup slippage from the surface, the following condition should be satisfied

$$|F_x| \leq F_f \tag{12}$$

Thus, F_f can be calculated as

$$F_f = F_n f \tag{13}$$

By substituting (3b) and (13) into (12). the following relationship is obtained

$$(\pi R^2 V - F_y) f \geq |F_x|$$

Thus, the critical vacuum pressure for sliding can be calculated by

$$V_s = \frac{1}{\pi R^2}(\frac{|F_x|}{f} + F_y) \tag{14}$$

Considering equations (3.11) and (3.14), the following minimum vacuum pressure is needed to avoid both falling and slippage of the suction cup from the surface:

$$V_{\min} = \max\lfloor V_s, V_f \rfloor.$$

The above analysis is done for ideal suction cup case, which assumes that there is no elastic deformation, the cup is a rigid body and the force intensity distributes linearly along the X axis. There might not be such a cup in reality, but it is necessary to ensure that the chosen cup (original cup) has a satisfactory conformation to the analysis.

Therefore, one experiment was conducted to test the performance of the chosen suction cup. The experiment aims to check if the suction cup is able to support the load determined from the analysis by hanging the load to the cup and measuring how long it takes the cup to slip. Firstly, the theoretical load is determined. Because the distance between the load and cup is very small, around 3mm, the total moment acting on the suction cup due to the load, M is negligible. By comparing the equation (11) and (14) it can be seen that:

$$V_{\min} = V_s = \frac{1}{\pi R^2}\left(\frac{|F_x|}{f} + F_y\right)$$

R = 0.025m, f = 1.1, $F_y = 0$ because there is no force in the direction perpendicular to the cup.

$$V_{\min} = \frac{1}{\pi(0.025)^2}\left(\frac{|F_x|}{1.1} + 0\right) = 463|F_x|$$

The minimum vacuum pressure is proportional to the load. The pressure inside a suction cup ranges from 0 Pa to $1.035\text{x}10^5$ Pa (1 atm). Assume the vacuum pressure of the suction cup is the midpoint of the range, which is $0.5175\text{x}10^5$ Pa.

$$F_x = \frac{V_{\min}}{463} = \frac{0.5175x10^5}{463} = 112N$$

Theoretically, the suction cup is able to support a weight of 112 N before starts slipping. The experiment was conducted at the Solid Mechanics Lab at building 18, on May 22nd with the supervision of Mr. Shairul Harun, the lab technician.

Figure 17: A picture of suction cup testing-37 N weight

Because due to the length of the hanger and the limitation of types of weight, the maximum weight can test was 37 N (35 N of the weight and 2 N of the hanger). The weight was hung for 30 minutes, and the suction cup shown no sign of slippage. The cup was then pulled manually hard, and it seemed that the cup could support comfortably (for at least 30 minutes) weight from 50 to 60 N. Although it is desired to conduct the experiment with higher weight, the current experiment result shows a satisfactory performance of the cup in consideration that at least four (4) cups will be used to support a maximum weight of 7 kg.

ii Number of suction cup per one leg and the critical pressure

From the suction cup analysis, the following minimum vacuum pressure is needed to avoid both falling and slippage of the suction cup from the surface:

$$V_{\min} = \max\lfloor V_s, V_f \rfloor$$

Where:

$$V_f = \frac{1}{\pi R^2}\left(\frac{M}{R} + F_y\right)$$

$$V_s = \frac{1}{\pi R^2}\left(\frac{|F_x|}{f} + F_y\right)$$

R: Radius of the suction cup

Fx, Fy: Total force acting on the suction in X-direction (shear force), Y-direction (pull force)

M **:** Total moment acting on the suction cup from outside

f: Friction coefficient between suction cup and glass wall

From the force analysis M = F_x*2 times radius of the pinion
Therefore:

$$V_f = \frac{1}{3.14 \times 0.025^2}\left(\frac{|F_x| \times 0.04}{0.025} + F_y\right)$$

$$V_f = 510(1.6|F_x| + F_y)$$

The friction coefficient between the suction cup and the glass wall is 1.1, therefore:

$$V_s = 510\left(\frac{|F_x|}{1.1} + F_y\right)$$

From the above two equations, it is obvious that V_f is always greater than V_s. Hence, the minimum vacuum pressure, V_{min} is equal to V_f

There is a little force, if any, pulling the suction cup in the direction vertical to the glass wall. Assume that this force is, F_y = 10N.

The pressure inside a suction cup ranges from 0 Pa to 1.035×10^5 Pa (1 atm). Assume the operating pressure of a suction is the midpoint of the range, which is 0.5175×10^5 Pa. Substitute the values into V_f equation:

$$0.5175 \times 10^5 = 510(1.6|F_x| + 10)$$

$$F_x = 57.2N$$

Let S be the number of suction cup per one leg.

$$F_x = \frac{P}{2S}$$

P is the total maximum weight of the robot (including payload), which is 68.6N

$$S = \frac{P}{2F_x} = \frac{68.6}{2x57.2} = 0.6 \text{ cup/leg}$$

To ensure a safety factor greater than 3 (3.33), two cups are used for one leg in this design. The raising question is which 2 cups /leg being used, what is the critical operating pressure that keeps the robot from falling down. To find this value, substitute the new F_x, which equals to P/4 = 17.5 N, to the V_f equation:

$$V_f = 510(1.6x17.5+10) = 19380Pa \text{ or } 0.187 \text{ atm}$$

The vacuum pressure of a suction cup must not drop bellow this value to prevent the robot from falling down.

iii *Motor specification*

Design variables:

W = Weight of the robot and payload

V = linear velocity

N = Rotational speed (rpm)

t = time to reach full speed

J_0 = Moment of inertia of the motor

J = Moment of inertia of the pinions

τ_0 = Designed torque of the motors

$M_{1,2}$ = Moment exerted on pinion 1,2 by the weight of the robot

$F_{1,2}$ = Friction force exerted on pinion 1,2

$N, N_{1,2}$ = Normal force acting on the pinions by the spherical wheel and the rack.

P = Total weight of the robot

$P_{1,2}$ = Weight applied on the pinion 1, 2.

Assume that the angular velocity of the motor is 100rm or 10.5 rad/s.

Initial moment of inertia of the motor

Assume that the motor reaches its full speed, at zero load, after 0.5s. The acceleration is:

$$\alpha_0 = \frac{\omega_0 - 0}{0.5s} = \frac{10.5 - 0}{0.5} = 21rad/s^2$$

Assume that the motor can only run at 80% of its designed torque.

$$0.8\tau_0 = J_0\alpha_0$$

Initial moment of inertia of the motor:

$$J_0 = \frac{0.8\tau_0}{\alpha_0} = \frac{0.8\tau_0}{21} = 0.0381\tau_0 kg.m^2$$

Force analysis

This part is to calculate the maximum weight of the robot, given the designing criteria and the motor configuration.

Assumption:

1. The normal forces acting on the pinions, $N_{1,2}$, is always counter-balanced by the normal force acting by the containing bar, N, through the spherical wheel.
2. The centre of mass of the robot is at a distance of two times of the motor radius, 2R, from the motor shaft.
3. The worst situation occurs when the total weight of the robot is applied only on the motorized pinion.

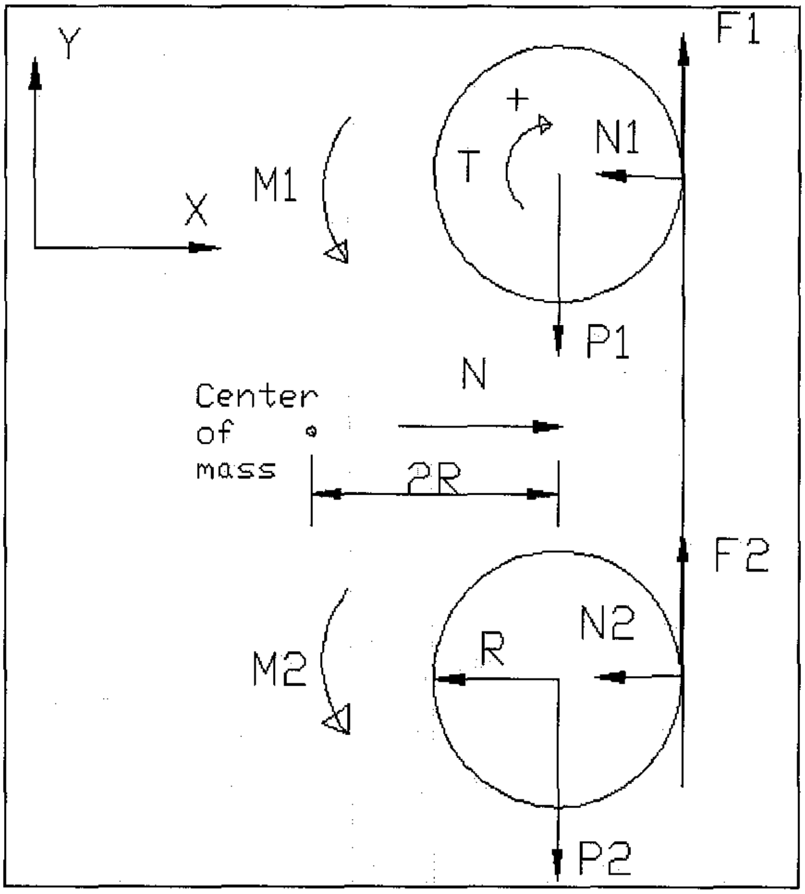


Figure 1: Free body diagram of the pinions-Side view

Moment balance around the motor shaft:

$$\tau - (M_1 + M_2) - (F_1 + F_2)R = (J + J_0)\alpha \tag{1}$$

Where

$$(M_1 + M_2) = (P_1 + P_2)2R \tag{2}$$

Calculate J:

Assume the pinions are thin disk

$$J = 2(\frac{1}{2}mr^2) = mr^2 \quad \text{(There 2 two pinions on one shaft)}$$

Mass of a pinion: m = 0.06kg

$$J = (0.06)0.02^2 = 2.4x10^{-5} kg.m^2 \tag{3}$$

Force balance in the Y-axis direction:

$$(F_1 + F_2) = (P_1 + P_2) = \frac{1}{2}P \tag{4}$$

Substitute (4) into (2), we have:

$$(M_1 + M_2) = PR = 0.02P \tag{5}$$

Assume that the motor can only run at 80% of its designed torque value:

$$\tau = 0.8\tau_0$$

The robot is expected to reach full speed after 2s, therefore:

$$\alpha = \frac{\omega_0 - 0}{2s} = \frac{10.5 - 0}{2} = 5.25rad/s^2 \tag{6}$$

Substitute (3), (4), (5) and (6) into (1), we have:

$$0.8\tau_0 - 1.5P(0.02) = (2.4x10^{-5} + 0.0381\tau_0)5.25$$

$$\tau_0 = \frac{0.03P + 1.26x10^{-4}}{0.6}$$

Where P = 70x9.8 = 68.6 N

$$\tau_0 = \frac{0.03 \times 68.6 + 1.26x10^{-4}}{0.6} = 3.43N.m$$

Therefore, the design requires a motor with torque at least equal to 3.43 N.m, and 100 rpm. The motor available in the Robocon lab has a satisfied specification: 3.54 N.m, 100rpm. Therefore, this motor is selected for the project.

i *Length of the rack*

Determining the length of the rack involves the following variables:

- Desired linear speed of the robot: 0.5 m/min
- Angular velocity of the motor: 100rpm or 10.5 rad/s
- Time taken to complete one moving step (Up, down, right or left)

The linear velocity of the motor is $V = \omega R = 10.5x0.02 = 0.21m/s$.

Let ℓ be the length of the rack, time taken by the motor to travel from center to an end of the rack is $\frac{\ell}{2x0.21} = 2.38\ell$ seconds.

The sequence of one moving step, for an instance, moving North step, is as following:

Table 4: Moving-North sequence

No	Sequence	Time taken (s)
1	Suction cups WE off	1
2	Legs WE up	2
3	Move North	2.38ℓ
4	Leg WE down	2
5	Suction cups NS off	1
6	Legs NS up	2
7	Pull North	2.38ℓ
8	Legs NS down	2

The total time for one step is: $10 + 4.76\ell$

In one step, the robot moves a distance 0.5ℓ. The linear speed of the robot is:

$$\upsilon = \frac{60}{10 + 4.76\ell} 0.5l = \frac{30\ell}{10 + 4.76l}$$

The relationship between linear speed and rack length is shown in the following chart.

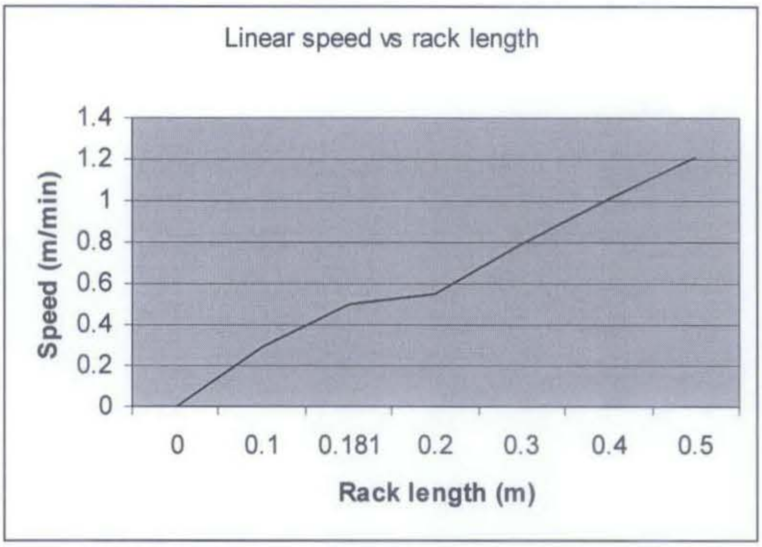


Figure 19: Linear speed and rack length relationship

From the above chart, it can be seen that the rack must have a minimum length of 0.181m to achieve the desired speed of 0.5m/min. However, the formulation is based on an assumption that the motor always operates at its full speed of 100rm, which is not always true. Therefore, to make room for possible decrease in the motor's speed and variation in the timing estimation, a rack length of 0.3 m is selected for this project.

With $\ell=0.3$ the time taken to complete one step is 10+4.76(0.3) = 11.428 seconds. To make the number of steps in one minute an integer, 4 in this case, the time taken is prolonged, by, for an example, increasing the moving North time. The corresponding linear speed is 4x0.15m/min = 0.6m/min.

Thus far, the number of suction cups per one leg, the specification of the rack motors, and the length of the rack have been determined. The following table summarizes the results.

Table 5: Summary of important motor's specifications

No	Item	Specification
1	Rack motor	3.54N.m, 100rpm
2	Suction cup/leg	2 cups/leg
3	Rack length	0.3m
4	Critical pressure	0.187atm
5	Weight	5kg
6	Payload	2kg
7	Linear speed	0.5m/min
8	Power	2x 12V batteries

4.4 Detail design

After the embodiment design, the robot structure is defined. Analysis also has been done to determine the specifications of the robot. In this section, the dimensions will be finalized. In addition, the list of components will be made and the operation of the robot will be determined.

4.4.1 *Detail drawing*

The detail drawings show finalized dimensions and shape of the robot. Some drawings will be shown in this part. For more drawings, please refer the **APPENDIX B**.

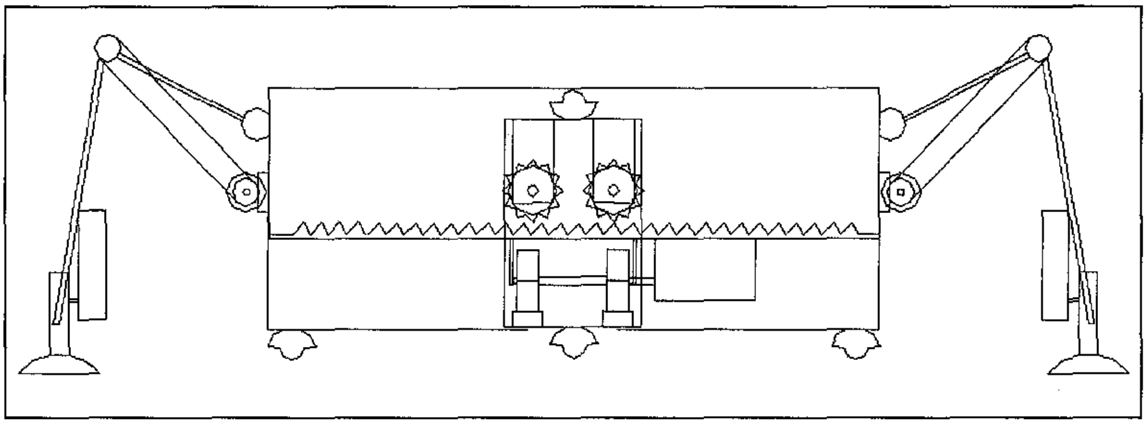


Figure 20: Finalized structure of the robot

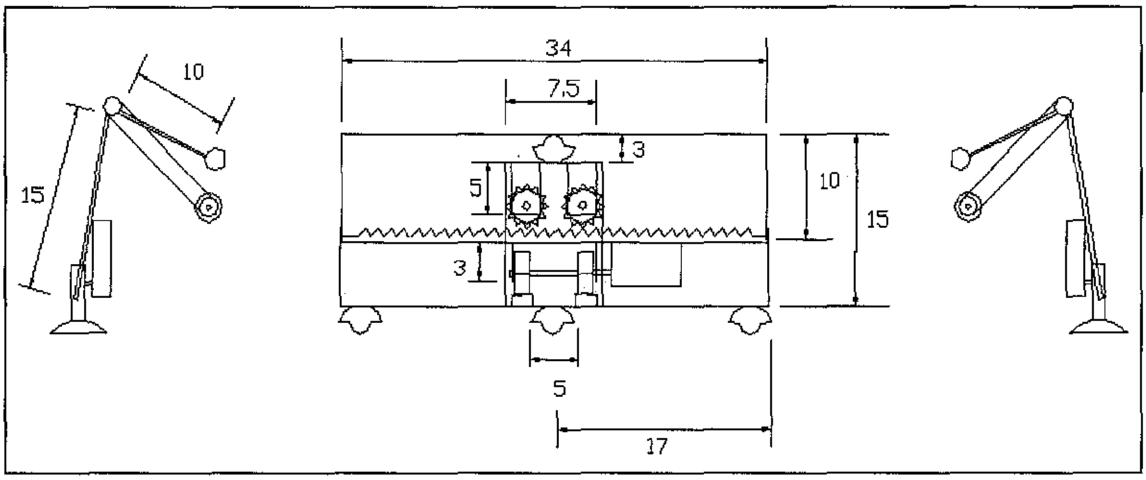


Figure 21: Detail drawing – side view

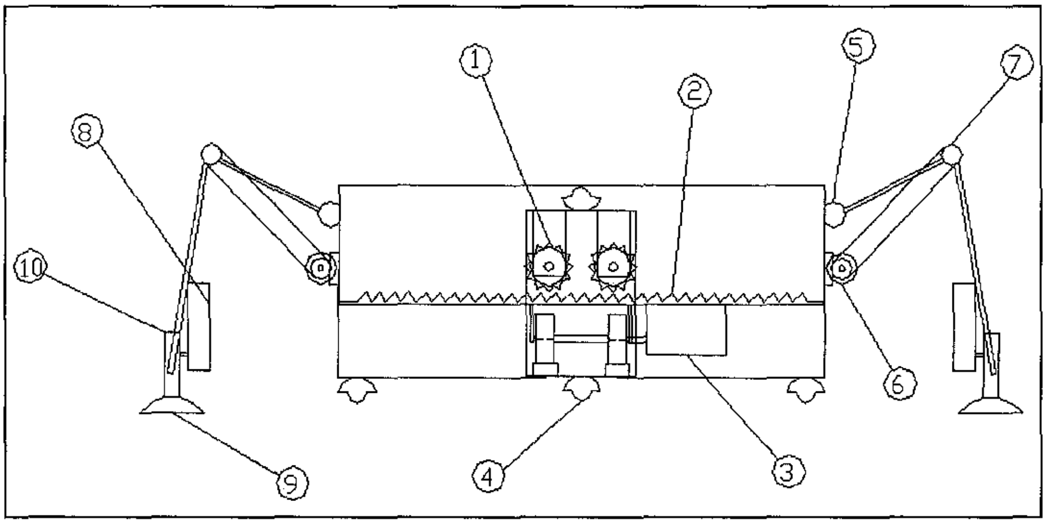


Figure 22: Component layout

4.4.2 *List of components*

Table 6: List of mechanical components

Description	Part #	Specification	Quantity	Source
Pinion	1	pinion: m=2, dp = 40mm	8	Fabricate
Rack	2	30 cm rack, p = 6mm	4	Fabricate
Rack motor	3	DC,3.54N.m,100rpm	2	Robocon Lab
Ball caster	4	D=19mm	4	RS component
Shoulder joint	5	Refer to drawing	8	Fabricate
Pulley	6	D=6mm, D=20mm	4	Fabricate
Elbow joint	7	Refer to drawing	4	Fabricate
Solenoid valve	8	DC 24V, 3/2 way single	4	EE dept.'s store
Suction cup	9	D=5mm	8	Tesco
Holding leg	10	Refer to drawing	8	Fabricate

4.4.3 *Movement sequence*

The robot is controlled by user through a remote controller. There are four controlling functions that enable an user to control the robot moving North, South, West or East.

Once the user select one function, the signal is sent to PIC, which is programmed to control the robot to complete the moving step. After each moving step, the robot is restored to its original position in which four suction cups are activated and the crossed bars are at the centre. The four moving steps are similar therefore the moving North step is presented here as a representative.

0. The robot is at original position
1. The suction cups WE are deactivated
2. The legs WE are lifted up
3. The rack motor 1 runs, moving the WE bar North
4. The WE bar touches the North limit switch, the rack motor stop, legs WE is moved down
5. The suction cups NS are deactivated
6. The legs NS are lifted up
7. The rack motor 1 runs (in reverse direction), moving the NS bar North
8. The centre limit switch is activated, the rack motor stop, legs NS is moved down

The robot now has completed the moving North step and ready to receive next command.

4.4.4 *Fabrication process*

This section defines the processes taken to fabricate the major components. The raw materials were taken from the CNC centre at building 16, therefore their dimensions are pre-determined.

Rack

To fabricate one rack, the following processes are taken:

1. Prepare an aluminum bar 2cmx1.5cmx30cm (Width x Thickness x Length)
2. Generate an Auto CAD 2002 drawing according to the specification
3. Transfer the program to the wire-cut machine
4. Fabricate the rack (by the technician)

Pinion

To fabricate 4 pinions, the following processes are taken:

1. Prepare an aluminum bar 10cmx10cmx2cm (Width x Length x Thickness)
2. Generate an Auto CAD 2002 drawing according to the specification
3. Transfer the program to the wire-cut machine
4. Fabricate the pinion (by the technician)

Shoulder joint

To fabricate 1 shoulder joint, the following processes are taken:

1. Prepare an aluminum solid cylinder in diameter of 25mm, and length of 7cm.
2. Turn the cylinder to diameter of 20 mm
3. Bore a hole of 10mm diameter through the cylinder
4. Mill of 1cm of the cylinder length
5. Drill two holes of 9 mm diameter along the length, on the centre line, and 5.5cm from each other.
6. Mill two slots of cm width, parallel with the centre lines of the 9 mm holes, and 2.5mm from the nearer end.

Holding leg

To fabricate 1 holding joint, the following processes are taken:

1. Prepare an aluminum solid cylinder in diameter of 25mm, and length of 7cm.
2. Turn the cylinder to diameter of 12 mm
3. Drill a hole of 10mm diameter, 67mm long from on end of the cylinder.
4. Drill a hole of 6mm diameter through the cylinder
5. Drill a hole of 4mm diameter, perpendicular to the cylinder and 30mm from the 6mm hole end.

4.5 Control system design

4.5.1 *Control system architecture*

The control system shows the relationship between the components in a block diagram. The result is shown as bellow.

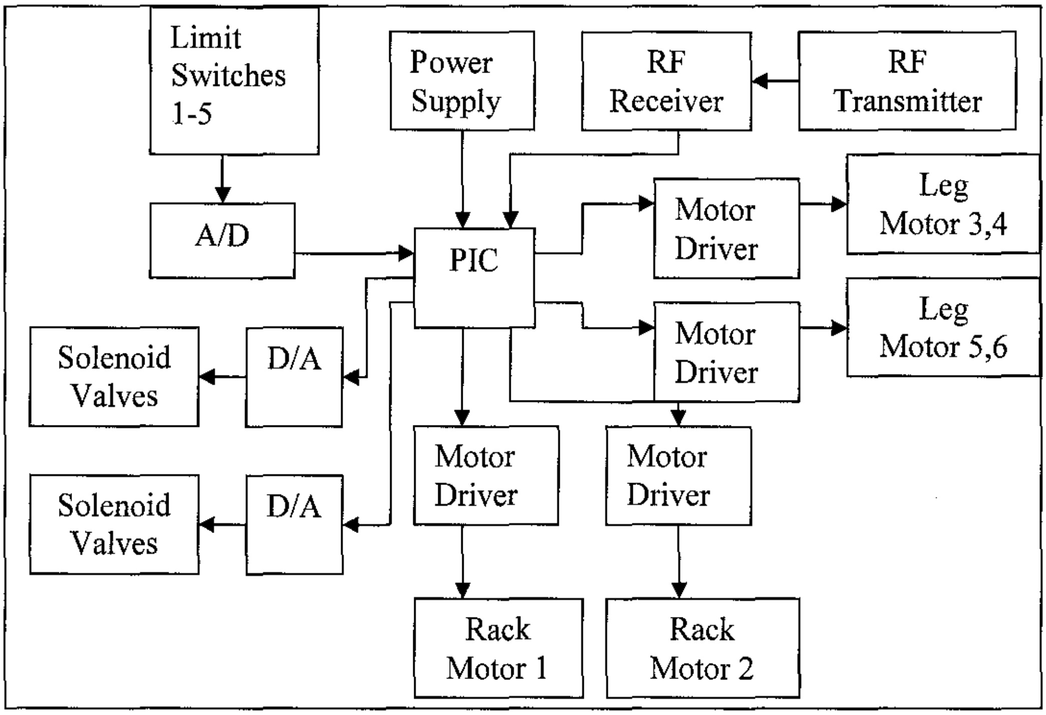


Figure 23: Control system architecture

The PIC is the "brain" of the robot, controlling all the operations of the robot. It receives inputs from users thru RF transmitter and receiver, and signal inputs from limit switches. Input from limit switches, in analog signals, is transferred to digital signals through an A/D circuit. The process is reversed for solenoid valves, whose digital signals received from PIC are converted to analog ones by an D/A circuit. To control the motors, PIC needs a circuit functioning as a motor driver to drive the motors.

4.5.2 *Circuit design*

The control system architecture shows the relationship between all the components. The electrical circuit will connect all the components together electrically that will help to control the robot.

A circuit has been designed using Eagle 4.13 software. The list of components is presented in the below table. For detailed information about the design, please refer to the circuit diagram at the **APPENDIX C1**

Table 7: List of electrical and electronic components

No	Component	Qty	Source
1	PIC 16F877A	1	EE Dept.'s store
2	Relay single input, 24 V	10	EE Dept's store + Robocon lab
3	Regulator 12V-5V	7805	EE Dept.'s Control lab
4	Crystal clock 4Mhz	1	EE Dept.'s store
5	RF remote controller set	1	Ipoh city toy
6	Opto 4N35	4	Robocon lab
7	Resistor (2.2k,1k,1.2k 4.7k)	10/each	EE Dept.'s store
8	Limit switch	5	Robocon lab
9	Transistor NPN QN2222	10	EE Dept.'s store

4.5.3 *Programming*

A program is downloaded to the PIC to process the inputs and send out outputs to control the robot. A C program has been written and tested successfully using PIC C Compiler software. The following figure shows the algorithm flowchart of the program.

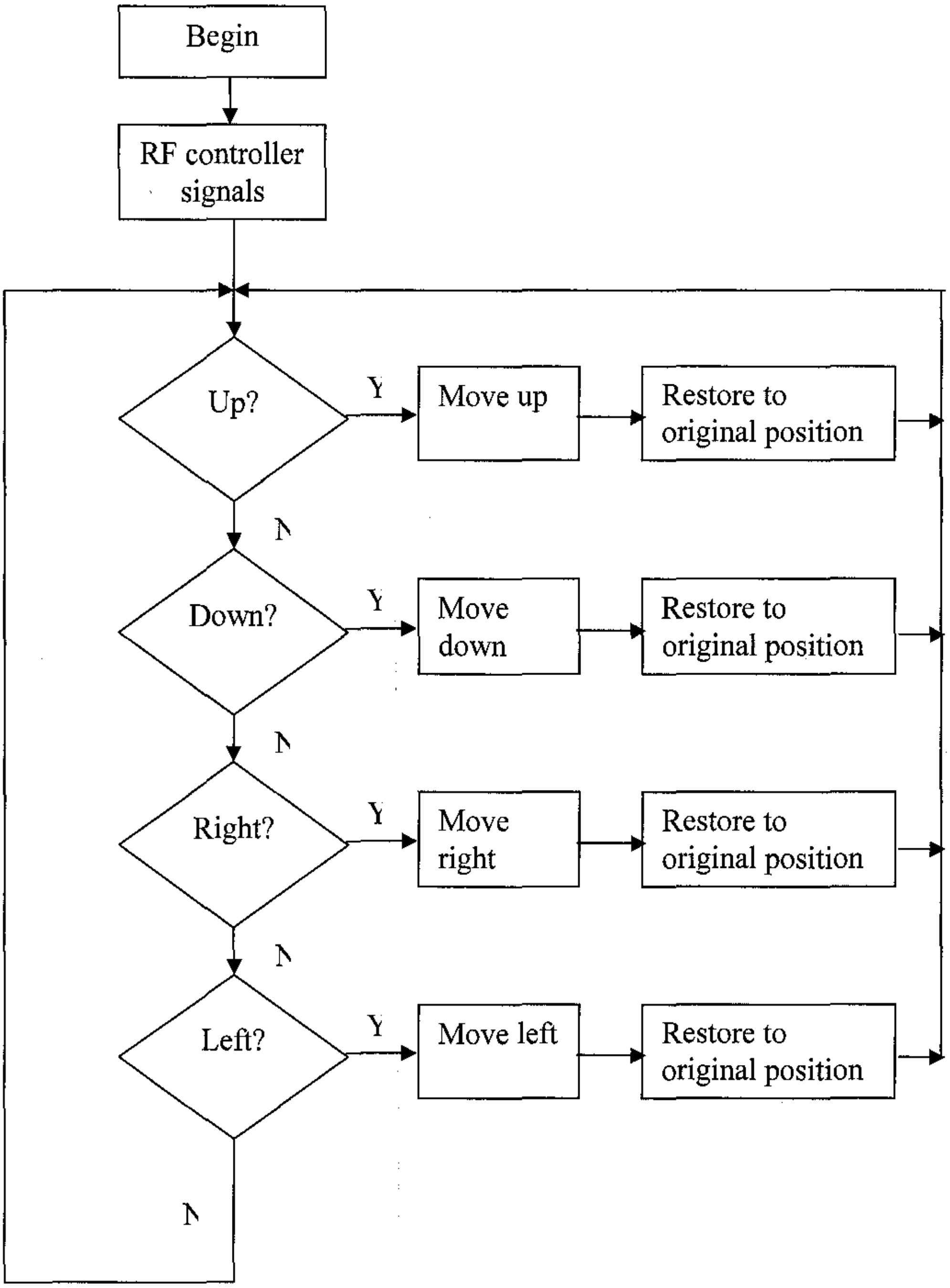


Figure 24: The program's algorithm flowchart

The program is attached with the **APPENDIX C2**

Chapter 5

Results and Discussion

5.1 Results

The results are divided into two main parts: Hardware prototype and control system, which consists of an electrical circuit and a C program.

5.2.1 *Hardware prototype*

An alpha prototype is completed in a period of 8 weeks to demonstrate the design concept. The picture bellow shows the final prototype.

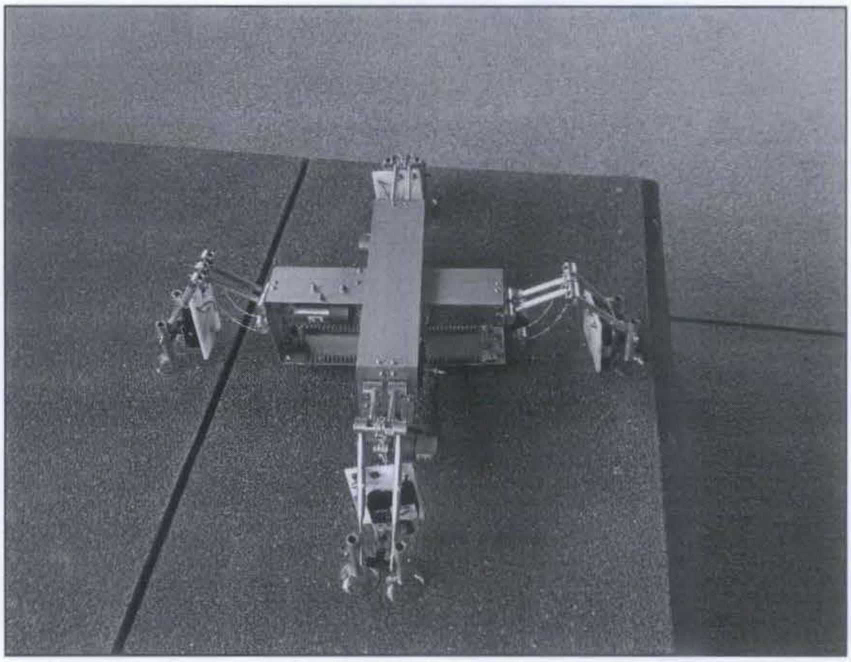


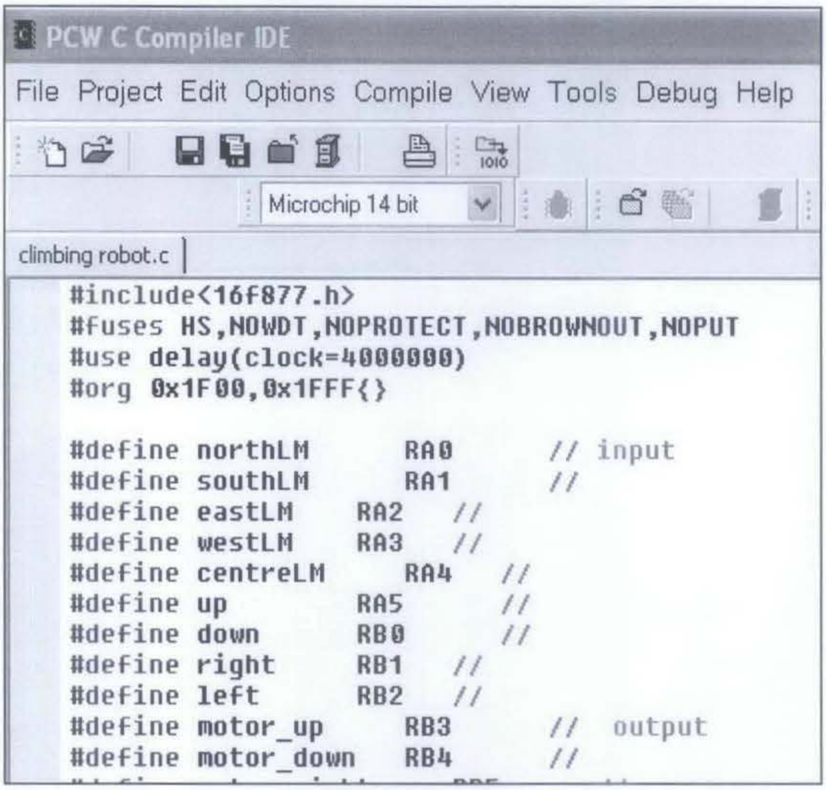
Figure 25: The prototype of the robot

5.2.2 *Control system*

An electrical circuit has been fabricated using the facilities at Robocon lab. The figure bellow shows a picture of it.

Figure 26: A picture of the circuit

A C program has been written by using PIC C compiler. The following figure show a part of the program. The complete program is attached with the **APPENDIX C2**.



```
#include<16f877.h>
#fuses HS,NOWDT,NOPROTECT,NOBROWNOUT,NOPUT
#use delay(clock=4000000)
#org 0x1F00,0x1FFF{}

#define northLM      RA0      // input
#define southLM      RA1      //
#define eastLM    RA2   //
#define westLM    RA3   //
#define centreLM     RA4   //
#define up        RA5      //
#define down      RB0      //
#define right     RB1   //
#define left      RB2   //
#define motor_up     RB3      //  output
#define motor_down   RB4      //
```

Figure 27: A picture of the PIC C compiler

5.2 Testing

5.2.1 *Functionality testing of the prototype*

Objective

The objective of the experiment is to determine in how long the prototype is able to stick to a glass wall without showing any considerable slippage in the suction cups.

Methodology

The experiment was conducted at the ground floor of building 16, on May 23, 2007. The robot has been placed on the front glass wall of the building and it was recorded on video. The experiment stops when there is a noticeable slippage in the suction cups.

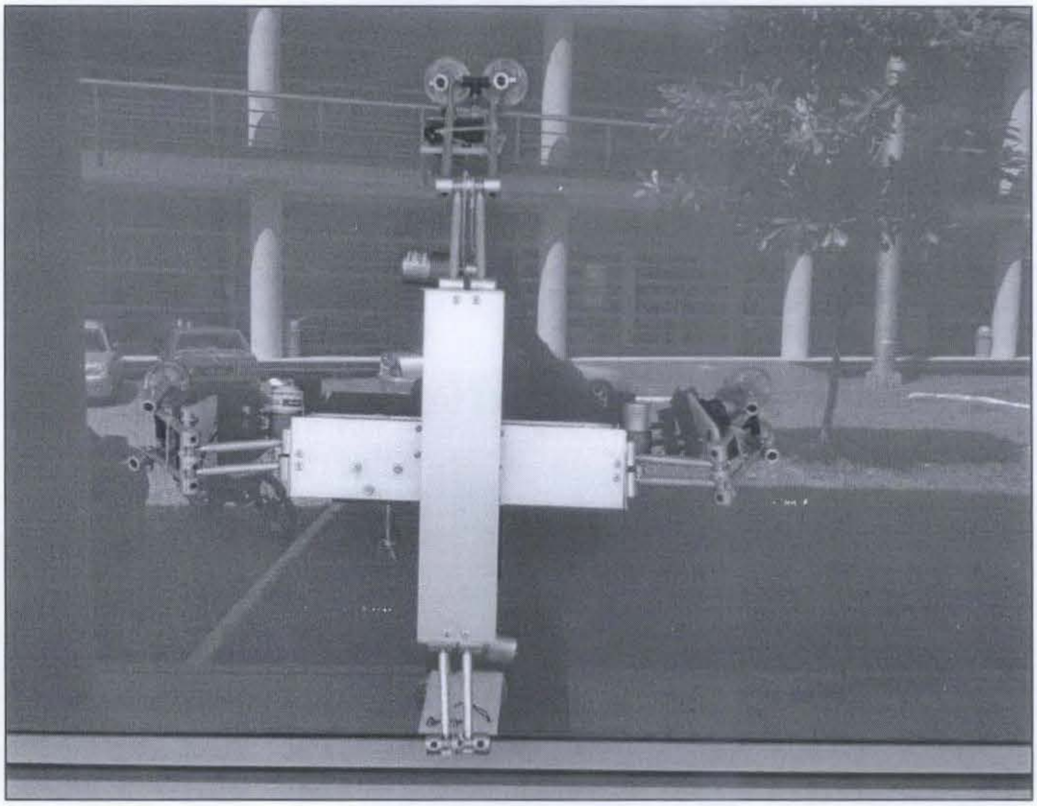


Figure 28: Functionality testing

Result

The video shows that the robot is able to stick on the wall for more than 6 minutes. Beyond 6 minutes, the cups started slipping.

Conclusion

The experiment shows that the prototype is able to stick to the wall for about 6 minutes. Six minutes is sufficient if notice that the time taken for one movement step is only 15 seconds. After each movement step, the suction cups are "refreshed" again and start a new 6-minute period. The result proves that the design is functioning as intended.

5.2.2 *Rack and pinion system testing*

Objective

The objective of the experiment is to determine if the rack and pinion system is working as designed.

Methodology

The prototype, without legs, was put on a horizontal surface. Voltage source of 12 V was then applied directly to the rack motors.

Result

The motors could drive the pinions running quite smoothly on the racks, even though the motion was not complete due to clashing between pinion's and rack's teeth.

Conclusion

There is some problems with the design that the teeth of the pinions and racks could not mesh. Analysis needs to be done to find the root causes, from which, solutions are proposed.

5.2.3 *Control system testing*

Objective

The objective of the testing to determine if the control system is working as designed.

Methodology

LEDs were used in lieu of the motors in the circuit. The C program was downloaded to the PIC and run to test the circuit. If the LEDs are lighting in a correct sequence in response to a signal from the RF controller, then the system is working properly. The test has been done at the Robocon lab firstly, and have been demonstrated to the examiners during the presentation.

Result

The LEDs were lighting in correct sequences in response to the signals from the RF controller.

Conclusion

The result proves that the control system is working as designed.

5.3 Discussion

This section discusses about the results in mechanical and electrical parts of the system.

The functionality experiment shows that after about 6 minutes, the suction cups started slipping. This is because pressures inside the cups drop. This is probably due to two reasons. Firstly, the leakage of air through the cup edge and the tube connection; secondly, the remaining air in the tube could reduce pressure in the cups. Because, the suction cups are not specialized ones the first problem happens. To encounter this, cups with better sealing (probably ones used in picking up metal sheet in automotive industry) is recommended. In the second problem, tubes are used to connect the cups with the solenoid valves and air might not have been totally pressed out of the tube, creating pressure inside the tube and reducing the pressure of the cups. To encounter this problem, larger cups are recommended so that the pressure drop can be accommodated.

The rack and pinion system testing result shows that the bars, driven by the rack motors, could travel on the rack quite smoothly. However, there is a problem with gear meshing. When the front not-running pinion set slides through the first rack, the back pinion set is sliding on the second rack and is supposed to slide through the first rack as well. However, the back pinion set often clash with the first rack, preventing the robot from moving. This is due to two possible reasons: the bar is bending, and the pinion might rotate while moving. After the front set goes off the first rack (so does the back set with the second rack), the bars bend down a bit (because there is no more reaction from the rack), making the pinion teeth a bit lower than the rack and therefore, mis-meshing happens. Beside, while moving between the first rack and the second rack, the back pinion set might rotate a bit, making the teeth not aligning with those of the rack, leading to mis-meshing. To encounter the bending problem, the bars need to be more bending-resistive by, for an example, attaching a steel or wood bar a long the bar. To encounter the rotating problem, the design could use a larger rack so that the pinion can travel continuously on the rack, eliminating rotation.

In the control system testing, there might be consideration that the circuit might not control the motors as it does with the LEDs due to difference in their operating currents. However, the consideration is not necessary in this case since the motors are controlled by relays, which connect them directly to the 12V source upon receiving HIGH signal from the PIC; while, the LED are connecting to the 12V source through a resistor, which helps to reduce its operating current.

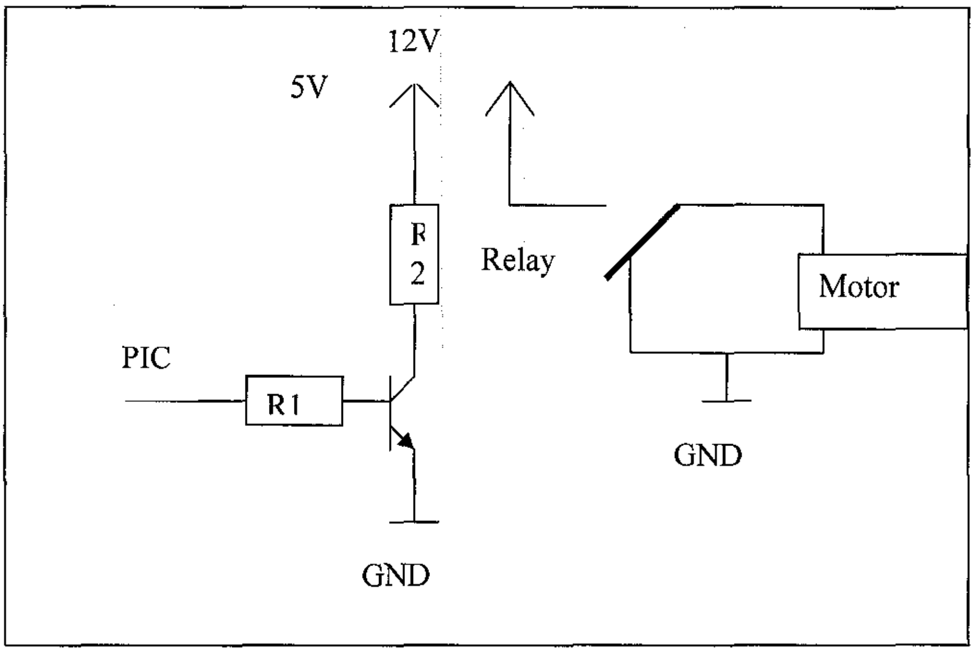


Figure 29: Controlling circuit for motor

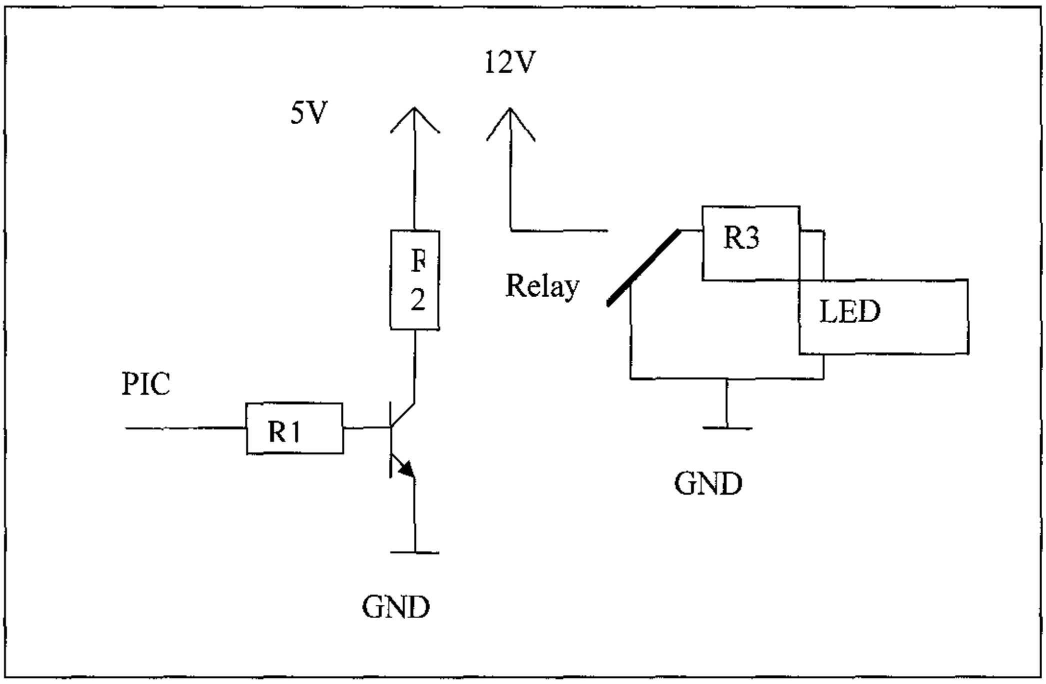


Figure 30: Circuit for controlling LEDs

Due to time limitation, the improvement has not been implemented yet. It is recommended for future development.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1 Realization of objectives

The objective of this project is to design a complete climbing robot with an effective adhesion and detachment mechanism, locomotion mechanism and control system that enable users, using remote controller, to control the robot climbing up and down a 90-degree glass wall and turning left and right when the robot is on the wall. As the results, a new adhesion and detachment mechanism, locomotion mechanism, and control system have been developed successfully. The detachment mechanism, in the author knowledge, is first time developed. It not only provides large adhesion force but also is very simple in controlling. The control system, which consists of an electrical circuit and a C program, allow users to control the robot wirelessly through a remote controller. The control system has been tested and proven working successfully. Although a prototype is optional for this project, one has been completed. It helps to communicate the design clearly, and is an indicator for the designing results and the effort that has been put in by the student. The functionality test of the prototype has been done and the result shows that the prototype functions as designed.

6.2 Knowledge and skill gained

This Final Year Project has given the student a great opportunity to apply and enhance further knowledge and skill learned. The project helps the student to recall and apply knowledge many areas such as designing, dynamic analysis, manufacturing process, industrial electronics, control system, and programming. It is the first time the student works on such a long and challenging project. The project helps to develop and nurture the student's independent study and working under pressure ability. Beside, the project also enhances further the student's designing and analytical skills through a synthesis problem. All those ability and skills are very important for the student to posses as an UTP graduate.

Furthermore, the project exposes the student to new and interesting knowledge and skill. While working on the control system design, the student has learnt how to design and fabricate an electrical circuit. It is very interesting and helpful, as the knowledge and skills are not emphasized in the Mechanical department. In addition, thanks to the fabrication works the student not only further enhances the skillfulness in using machines such as lathe, milling, and drilling but also learns to use various machines and tools such as bending, different types of saw, shearing. The experience helps to build up practical skills and the student's confidence in fabrication work.

6.3 Recommendation

At this stage, the prototype and control system have been completed. However, due to time limitation the integration of the prototype and the control system has not been done yet. It is recommended that continuing effort should be dedicated on the integration and later trouble shooting steps. From preliminary testing, it shows that there are problems with pinion and rack meshing. From the analysis in the discussion part, the problem could be overcome by making the rack continuously instead of two separate racks for one bar. Therefore, it is recommended the rack should be re-designed accordingly. In addition, it is also recommended that larger cups with better sealing should be used to accommodate for possible pressure drop in the connection tube over time. Beside, the current design is only meant for operation on glass wall without obstacles (window frame for an example). Further improvement can be made so that the robot is able to avoid certain type of obstacle.

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APPENDICES

APPENDIX A

Project schedules

APPENDIX A1

Gantt chart of FYP1

Gantt chart of FYP - 1st semester

Week/ Detail	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selection of topic	■	■												
Preliminary report			11-Aug											
Literature Review			■	■	■	■								
Progress report							8-Sep							
Locomotion Mechanism Design							■	■	■	■	■	■	■	■
Adhesion Mechanism design									■	■	■	■		
Interim report													3-Nov	

APPENDIX A2

Gantt chart of FYP 2

Grant chart of FYP - 2nd semester

Nguyen Huu Phuoc Nguy
M4679

Week/ Task	1	2	3	4	5	6	7	8	9	10	11	12
Calculation & Detail drawing	■	■	■									
Component&Material Preparation			■	■								
Control system & Electronic circuit design								■	■	■	■	■
Prototype Fabrication				■	■	■	■	■	■	■	■	■

APPENDIX A3

Fabrication scheduling

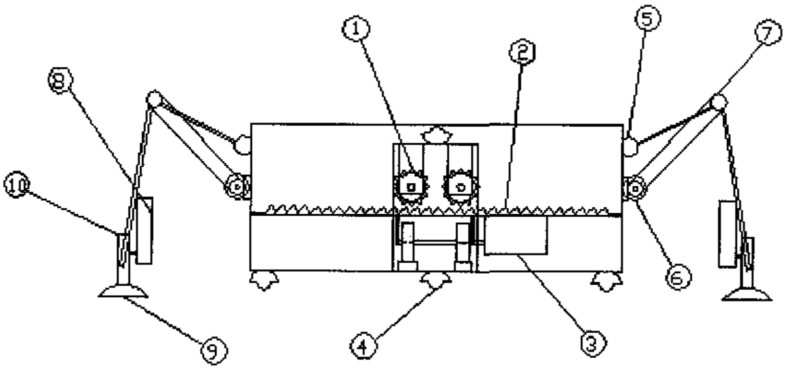
Act./Week	4	5	6	7	8	9	10	11	12	13
Purchasing and borrowing	■	■	■			■				
Fabricating component		■	■	■	■	■	■	■		
Designing& Fabricating circuit						■	■	■	■	
Assembling							■	■	■	
Programming								■	■	
Testing&Trouble shooting									■	■

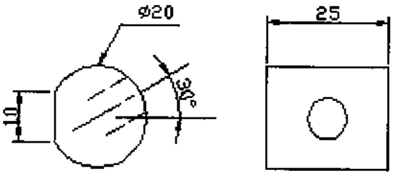
APPENDIX B

Detail drawings

APPENDIX B1

Parts drawing

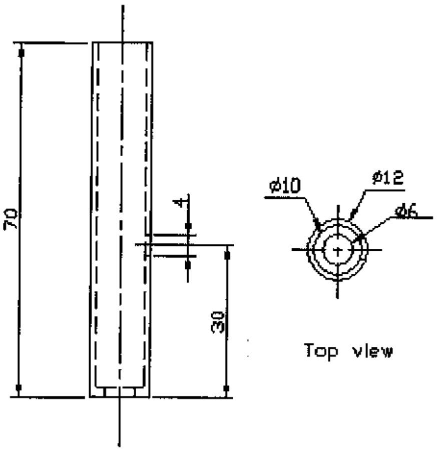




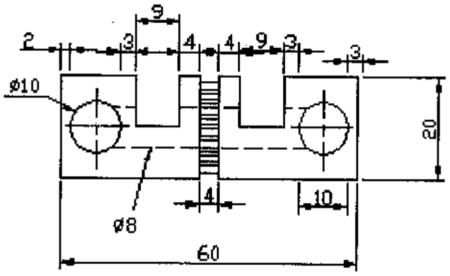
Side view

Top view

Part 5



Top view



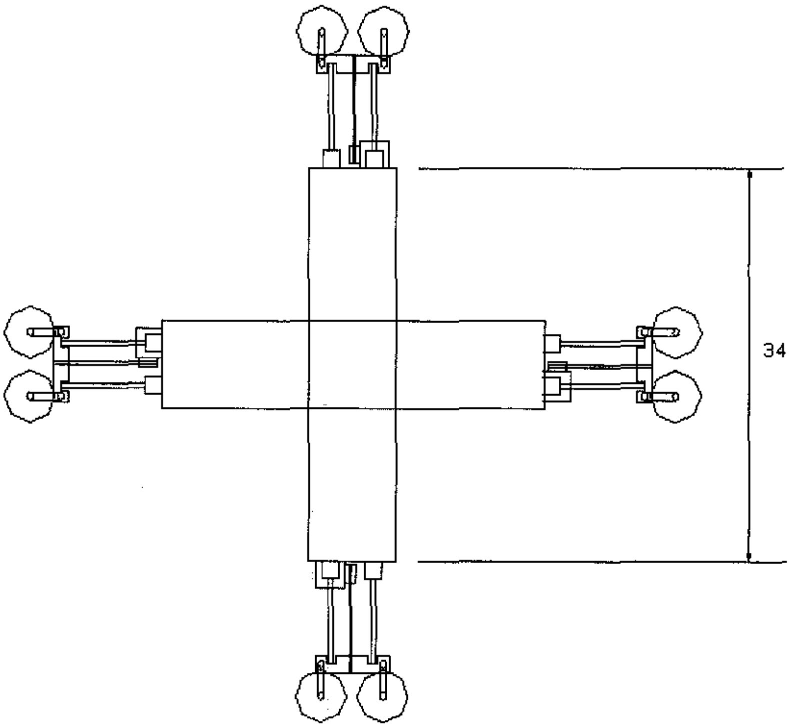
Front view

Top view

Part 7

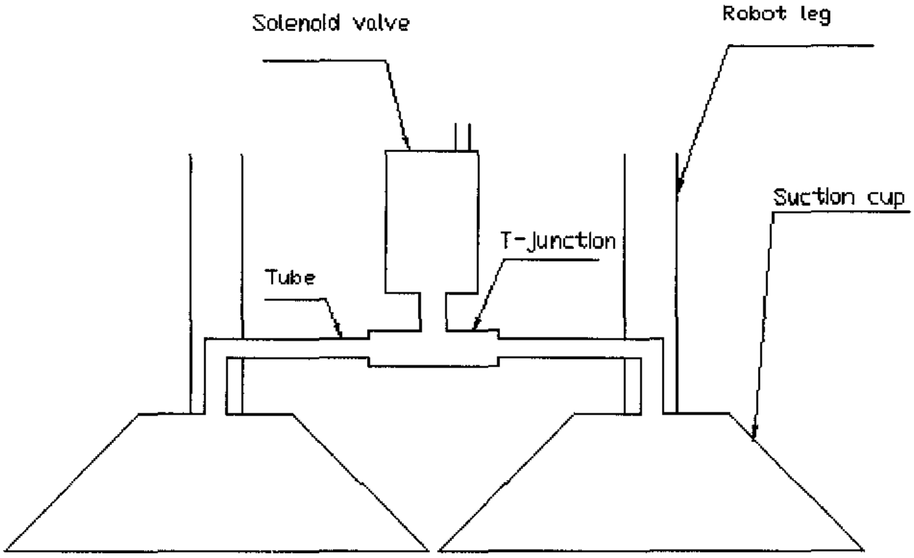
APPENDIX B2

Top view of the robot



APPENDIX B3

Suction cup assembly

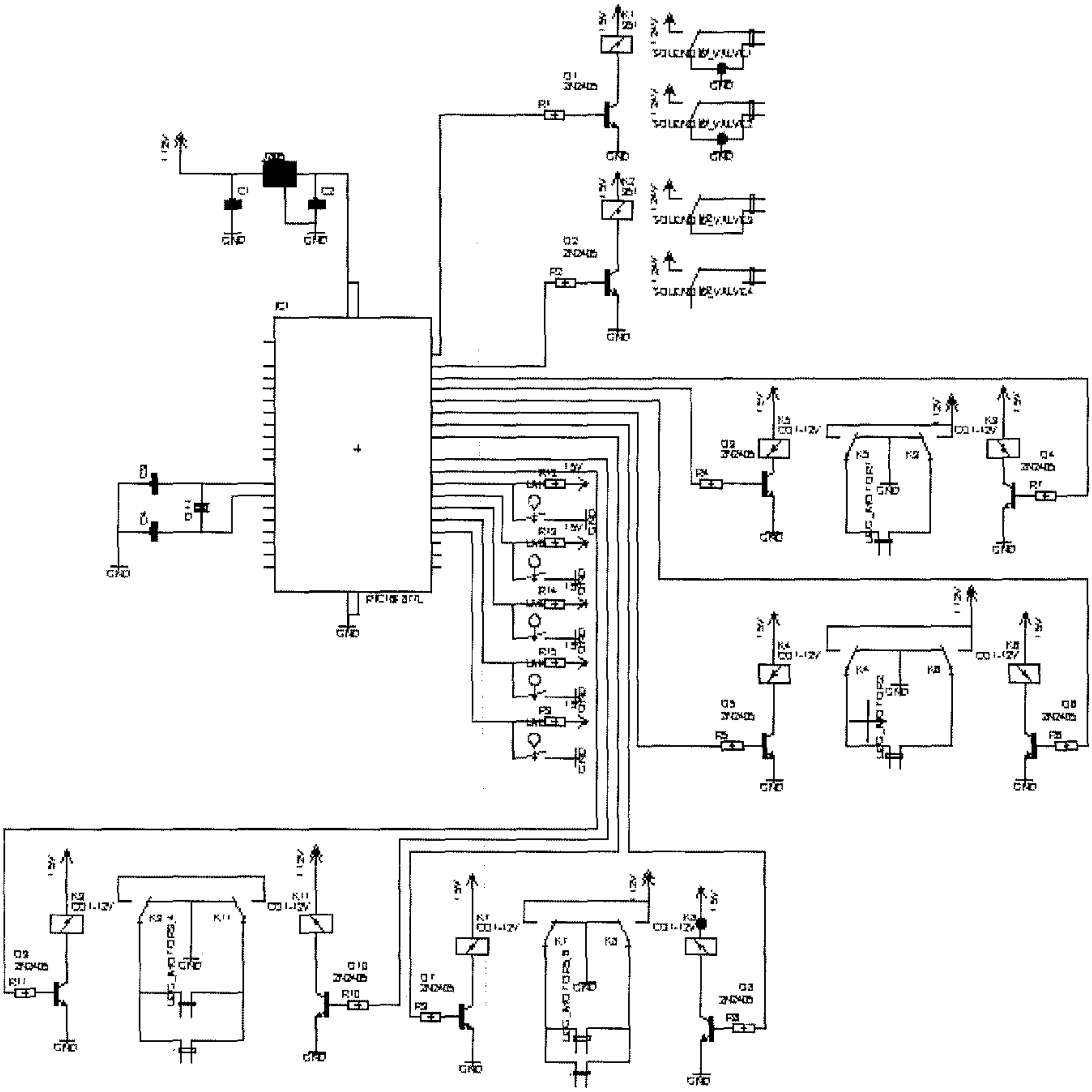


APPENDIX C

Control system

APPENDIX C1

Circuit drawing



APPENDIX C2

C program

```
#include<16f877.h>
#fuses HS,NOWDT,NOPROTECT,NOBROWNOUT,NOPUT
#use delay(clock=4000000)
#org 0x1F00,0x1FFF{}

#define northLM              RA0              // input
#define southLM              RA1              //
#define eastLM               RA2      //
#define westLM       RA3     //
#define centreLM     RA4     //
#define up             RA5            //
#define down                 RB0              //
#define right                RB1      //
#define left           RB2   //
#define motor_up             RB3              // output
#define motor_down RB4                //
#define motor_right          RB5              //
#define motor_left    RB6    //
#define legWE_up        RB7 //
#define legWE_down      RC0 //
#define legNS_up       RC1
#define legNS_up       RC2
#define solenoid12           RC3              //
#define solenoid34           RC4              //

int suctionWE, suctionNS;

void init ( void )
{
            TRISA = 0b11111111; // port A output
            TRISB = 0b11100000;
            TRISC = 0b00000000;
            TRISD = 0b00110010;
            TRISE = 0b00000001;
            PORTA = 0b00000000;
            PORTB = 0b00000000;
            PORTC = 0b00000000;
            PORTD = 0b00000000;
            PORTE = 0b00000000;
  suctionWE = 1;
  suctionNS =1;
}

//int horizontal_impossible (void)
//{
//if (centreLM=1 && ( motor_up=1 || motor_down =1)
//return 1;


void climb_up (void)
{
if (up ==1 && motor_left == 0 && motor_right== 0 && northLM==0)
motor_up=1;
if (northLM ==1)
motor_up =0;
}
}

void climb_down (void)
{
if (down==1 && motor_left == 0 && motor_right== 0 && southLM==0)
motor_down=1;
if (southLM ==1 || centreLM==1)
```

```
motor_down =0;
}

void turn_left (void)
{
if (left=1 && motor_up == 0 && motor_down== 0 && westLM==0)
motor_left=1;
if (westLM ==1)
motor_left =0;
}

void turn_right (void)
{
if (right==1 && motor_up == 0 && motor_down== 0 && eastLM==0)
motor_right=1;
if (eastLM ==1)
motor_right =0;
}

void pull_up (void)
{
if (northLM==1)
{
delay (30)
motor_down=1;
if (centreLM==1)
motor_down =0;
}

void pull_down (void)
{
if (southLM==1)
{
delay (30)
motor_up=1;
if (centreLM==1)
motor_up =0;
}

void pull_right (void)
{
if (eastLM==1)
{
delay (30)
motor_left=1;
if (centreLM==1)
motor_left =0;
}

void pull_left (void)
{
if (westLM==1)
{
delay (30)
motor_right=1;
if (centreLM==1)
motor_right =0;
}
void move_legWE_up (void)
{
delay (10);
legWE_up=1;
delay (10);
legWE_up =0;
suctionWE = 0;
}

void move_legWE_down (void)
{
delay (10);
```

```
legWE_down=1;
delay (10);
legWE_down =0;
suctionWE = 1;
}

void move_legNS_up (void)
{
delay (10);
legNS_up=1;
delay (10);
legNS_up =0;
suctionNS = 0;
}

void move_legNS_down (void)
{
delay (10);
legNS_down=1;
delay (10);
legNS_down =0;
suctionNS = 1;
}


void delay (int a)
{
int t,i;
for (t=1;t<=a;t++)
for (i=1;t<=16000;i++);
}

void main()
{

 init ();

While (1)
 if (up==1)
 {
 if suctionWE ==1
 move_legWE_up;
 climb_up ();
 }

 if (northLM == 1 && suctionWE == 0)
 {
 move_legWE_down ();
 pull_up ();
 }


if (down==1)
 {
 if suctionWE = 1
 move_legWE_up;
 climb_down ();
 }

 if (southLM == 1 && suctionWE == 0)
 {
 move_legWE_down ();
 pull_down ();
 }

 if (right==1)
 {
 if suctionNS == 1
 move_legNS_up;
 turn_right ();
```

```
}

if (eastLM == 1 && suctionNS == 0)
{
move_legNS_down ();
pull_right ();
}

if (left==1)
{
if suctionNS == 1
move_legNS_up;
turn_left ();
}

if (westLM == 1 && suctionNS == 0)
{
move_legNS_down ();
pull_left ();
}

}
```