STUDY ON VARIOUS ADHESION MECHANISM FOR A WALL CLIMBING ROBOT

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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LIST OF ABBREVIATIONS

Aberration

ESC	Electronic Speed Control
RPM	Revolution per Minute
PWM	Pulse Width Modulation
CAD	Computer Aided Design
FMEA	Failure Mode and Effects Analysis

Nomenclature

F	Thrust Force
P	Pressure
$\dot{m}$	Mass Flow rate
v	Velocity
V_e	Inflow velocity
V_{ac}	Aircraft velocity
V_{pitch}	Propeller pitch speed
ρ	Air density
a	Acceleration
A	Area through propeller
d	Diameter of propeller
r	Radius of propeller
g	Gravity
m	Mass
μ	Coefficient of Friction

ABSTRAK

Robot jenis memanjat dinding telah menimbulkan perhatian yang tinggi daripada dunia sejak ia dilahirkan pada tahun 1960-an. Fungsi utama robot jenis memanjat dinding adalah untuk memberi bantuan kepada manusia dalam persekitaran kerja yang berbahaya and berisiko. Tujuan kajian ini adalah untuk menciptakan mekanisma pelekatan untuk robot jenis memanjat dinding yang mampu berfungsi atas permukaan yang komplek. Kajian atas pelbagai pelekatan mekanisma dan rekabentuk dalam robot jenis memanjat dinding dijalankan untuk memahami konsep dan fungsi robot jenis memanjat dinding dalam market sekarang. Mekanisma pelekatan yang digunakan untuk robot jenis memanjat dinding dalam kajian ini adalah jenis mekanisma pendorong dengan kipas serta sistem lampiran bermagnet atas roda supaya robot dapat bergerak atas permukaan dinding yang menegak. Penggunaan motor tork yang tinggi akan dikawal oleh motor pemandu yang menyambung kepada “Arduino UNO” dan fungsinya untuk menentang geseran dan daya graviti semasa robot memanjat dinding. Selain itu, pengaturcara akan dicipta dengan menggunakan perisian “Arduino IDE”. Keputusan teori juga dihasilkan untuk mengesahkan keperluan daya yang berfungsi robot semasa mendaki atas permukaan dinding yang menegak. Akhir sekali, robot ini mampu melekat permukaan dinding sebaliknya tidak dapat bergerak atas permukaan almari yang berunsur ferromagnetik. Ini disebabkan ianya kehilangan tenaga semasa penghantaran dan daya yang dihasilkan tidak dapat meyokong robot bergerak atas dinding. Oleh itu, konsep pelekatan mekanisma telah dipastikan tetapi perlu penambahbaikan dari masa ke semasa untuk meningkatkan kestabilan and prestasi pendakian dinding robot.

ABSTRACT

A wall-climbing robot has provoked high attention worldwide ever since it was born in 1960's. The main function of a wall-climbing robot to survey human being in highly hazardous and dangerous working environment. The aim of this study is to design and develop adhesion mechanism for a wall climbing robot that is adaptable to the various wall surface. Study of various adhesion mechanism and the design structure on wall climbing robot is required in order to understand the concept and function of a wall climbing robot. The adhesion mechanism used in this wall climbing robot is pushing mechanism with propeller and magnetic attachment system on wheel design to allow the robot stick and move against the vertical wall surface. High torque motor that controlled by the motor-driven which attach with Arduino UNO is used to cover the friction and gravitational force when the robot is moving. With the aid of the Arduino IDE software, the algorithm is built up and the theoretical result is generated to verify the force needed to support the robot move on the vertical wall surface. However, the robot is able to attach on the vertical surface but unable to move against the vertical surface of the ferromagnetic cupboard. The failure analysis is described as power loss and the thrust force generated not strong enough to support the robot move against the vertical surface. Lastly, the concept of adhesion mechanism is work but there is some improvement that can be considered to improve the stability and performance of wall climbing robot.

CHAPTER ONE: INTRODUCTION

1.1 Introduction

With the new development of science and technology now, human being more prefers on the better working environment in order to achieve higher quality in their life. Therefore, most of the highly hazardous and dangerous jobs such as cleaning and inspection in high rise building have been automated by using the different type of robot. In order to survey human being in the dangerous working environment, wall climbing robot is designed and developed. The aim of the project is to design and develop adhesion mechanism for a wall climbing robot that is adaptable to the complex surface. There is some function can be implemented in wall climbing robot platform with a little bit of complexity such as reliable attachment to the surface, movement spreading over all the working area and the ability to cross obstacles. Besides that, wall climbing robot able has enough intelligence for the discrimination of obstacles situations and motion control function in a certain situation. *(Avvaru Subramanyam, 2014)*

One of the critical components of any wall climbing robot is its adhesive mechanism, which enables the robot to stick itself to the wall surface. There are different types of adhesion mechanism used in the design of wall climbing robot and mostly separated into few categories such as vacuum suction cup attachment system, magnetic attraction system, grasping mechanism, pushing adhesion with a propeller or negative pressure with an impeller and so on. Each of these mechanism system used in wall climbing robot has their own advantages and limitation in the real application. Most of these robots use passive suction cups where the robot can attach and remove its suction cups passively, or active suction chambers with seals to keep a pressure difference between the inside and the outside of these chambers. *(Mohamed Gouda Alkalla, 2017)* The advantages of air suction adhesion are the ability to climb any material type, not only ferromagnetic surfaces and it considers as mature technology among another mechanism system. The limitation of this mechanism system includes the noise produced, the air pump is required and it has the high demand for surface roughness.

Working principle of magnetic adhesion mechanism is conducted by using magnetic force to attach the robot to the wall surface but it only applies to wall surface that consists magnetic permeability. This type of mechanism system is easy to control and obtain high load capacity as well as noise free. *(Wolfgang Fischer, 2007)* Another group of climbing robots, which are suitable only for the uneven and complex structures, such as, trees, poles and rough building surfaces, are using mechanical adhesion or grasping mechanism. These robots use grippers and claws for grasping the uneven surfaces. The advantage of this type of adhesion is the ability to climb irregular and rough surfaces, but not applicable to the flat and smooth surfaces. *(Fengyu Xu, Xingsong Wang and Guoping Jiang, 2012)*

It is noticed that there is no climbing robot that can handle different wall surface efficiently in the real application. Each climbing robot is suitable only for a narrow range of these varieties due to their limitation of the adhesion mechanism. Therefore, a propeller-type climbing robot is developed to climb any type of wall surface, such as ferromagnetic or non-ferromagnetic and regular or irregular surfaces with significant obstacles. This study focuses on design and development an adhesion mechanism for a wall climbing robot in order to enhance the stability and performance.

1.2 Problem Statement

The attachment mechanism is an important consideration in the design of the wall climbing robots because it allows the robot to stick itself to the wall surface against the gravitational force. There is few types of adhesion mechanism that has own advantages and disadvantages can be used for wall climbing robot on the different wall surface. Besides that, the locomotion part is one of the major issues in the design and develop a wall climbing robot. Therefore, adhesion mechanism and locomotion selection are important in the design of wall climbing robot in order to improve the stability and performance in the real application.

1.3 Objectives

There are few objectives obtained in this project:

1. To design and develop adhesion mechanism for a wall climbing robot that is adaptable to the various wall surface.
2. To improve the stability and performance of the wall climbing robot with suitable of design concept on adhesion mechanism and locomotion.

1.4 Scope of Project

The aim of this work is to design and develop adhesion mechanism for a wall climbing robot that is adaptable to the various surface. The scope of the project is listed as shown in Figure 1.1. A research study of various adhesion mechanism and design structure of wall climbing robot is required to be conducted in order to understand the design concept of adhesion mechanism used and wheels. Design software (SolidWorks) is used to create the CAD modeling for newly designed wall climbing robot. The structure of the mechanism system and a prototype of wall climbing robot will be fabricated. After that, the algorithm is built up and a theoretical result is stimulated by using Arduino software.

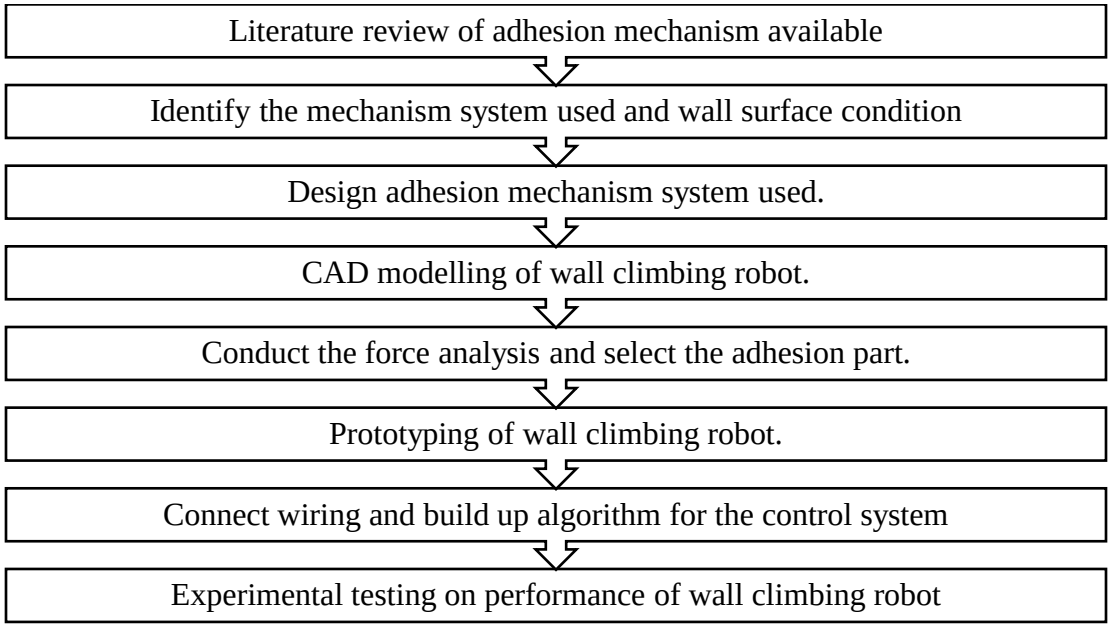


Figure 1.1: Scope of the project

1.5 Research Background

Robots have been advancing exponentially over the last three decades, moving beyond the traditional bounds of industrial applications into service missions sharing social spaces with humans Frey and Osborne have estimated that 47% of total U.S. employment will be replaced by robots and/ artificial intelligence (AI) in the near future. *(Osborne, 2013)* The initial main objective of the development of robots is to significantly improve the productivity and safety over a number of service task that is dull, dirty and/or dangerous. By using manual poses in the workforce, there is the high degree of the risk of failing, accidents and even in human fatalities. *(Organization, 2017)* Numerous incidents of accidents have been reported even with the use of gondolas in façade cleaning jobs or in construction jobs. Even there is no concrete data to prove that the presence of wall climbing robot able reduces the number of accident, but it is one of the appropriate options to substitute human being to carry out task under perilous circumstances.

The last few years have witnessed a strong, renewed interest in climbing and walking robotic technologies. Unique of its special characteristics, a wall-climbing robot has provoked high attention worldwide ever since it was born in 1960's. *(A.Nishi, 1996)* By now, a number of wall climbing robots have been exploited and some are in present use. In general, wall climbing robot is described as the robot developed to climb the wall by stick and move on the vertical surface of the wall against gravitational force by using suitable adhesion mechanism. High-rise tasks such as cleaning, painting, inspection, and maintenance of walls of large buildings or other structures require robots with climbing and manipulating skills. Motivated by these potential applications and inspired by the climbing motion of inchworms, variety type of wall-climbing robot with different adhesion mechanism is developed. However, there are several major challenge and limitation found in those research study and development of the wall climbing robot.

Some capabilities and functionalities are desired for a wall climbing robot in the real application are identified, as for example attaching reliably to wall or surfaces, the most basic function for a wall climbing robot. Besides that, the design of wall climbing robot needs overcome obstacles on or gap between walls and adapting to various condition

on no seamless surface. A key feature of mobility lacking in many types of wall climbing robot available in the market is to make transitions between walls. Moreover, the current design of wall climbing robot also faced challenges in manipulating function, important skills for performing complex tasks on walls. *(Yisheng Guan, 2012)* Many adhesion technologies have been explored in the design of wall climbing mechanism, but there is improvement can be done in order to improve the stability and performance of current wall climbing robot available in the market.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

The main point of any wall climbing robot is its adhesive mechanism, which enables the robot to attach itself to the wall surface and it also is adaptive enough to allow the robot to be mobile so as to cover the required area. Therefore, the attachment mechanism is an important consideration in the design of the wall climbing robots. There are different types of adhesion mechanism used in the design of wall climbing robot and mostly separated into few categories such as vacuum suction cup attachment system, magnetic attraction system, grasping mechanism, pushing adhesion with a propeller or negative pressure with an impeller and so on. Both of these adhesion mechanisms have their own advantages and disadvantages in the current design. In this research study, the different type of adhesion mechanism used in current design of wall climbing robot is studied and described at next section.

2.2 Research Study on Different Type of Adhesion Mechanism

A. Vacuum Attachment Cup Mechanism

The common type of adhesion mechanism used in available wall climbing robot is the vacuum attachment cup mechanism which considers as mature technology among another mechanism available in the market. This research paper describes an electro-pneumatically vacuum cup attachment system used in an autonomous mobile robot which can move against vertical and horizontal wall surface as shown in Figure 2.1. This robot consist of six suction cup as the fixing system, there are three settings for two in triangular platform through which to ensure the robot able move along the vertical and horizontal surface.

Besides that, there are many motor reduction gear used to control the components such as linear motion platform, electro valves, the vacuum in suction cup and so on. A compact and fast actuation can be achieved by using a rack mechanism. The analysis of cup behavior under external force is carried out by the research team to investigate the robot fixing system with vacuum cup. In this paper, the system modeling and simulation are performed by using SolidWorks software (Cosmos Motion software package). After that, the control system of this robot is developed by a command system with LabView software in a data acquisition board 7344 National Instruments. *(T.C. Apostolescu, 2011)*

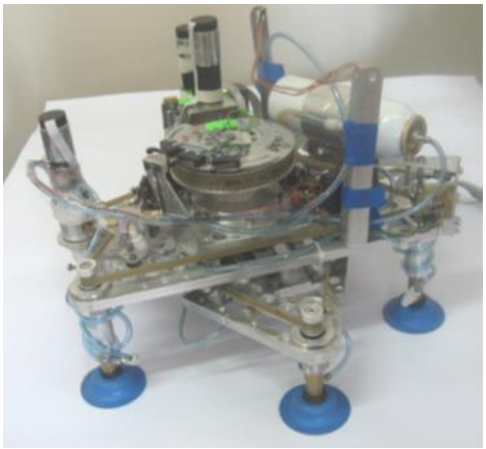


Figure 2.1: The Autonomous Mobile Robot

B. Permanent Magnetic Mechanism

The permanent magnetic mechanism used in the development of wall climbing robot is easy to control but it just applied to the ferromagnetic wall surface. The research paper describes that the design and analysis of the permanent magnetic system for a wall climbing robot with permanent magnetic tracks. The design of wall climbing robot is developed based on permanent adhesion mechanism and tracked locomotion. In this paper, there is a total of approximately 20 magnetic units used to provide enough strength to allow the robot stick on the wall. The magnetic units are attached on the top of the roller chains in the tracked locomotion of wall climbing robot.

This studies on permanent magnetic mechanism come from the concept of the physical structure of geckos' feet that allow them to stick to walls. Besides that, the research team also studied the concept of geckos' tail as its's tail able to keep the body in balance when moving on the wall against gravitational force. The wall climbing robot which assembled with robot frame, servo motor, transmission system and tracked locomotion with the permanent magnetic system as well as the anti-toppling system is shown in Figure 2.2. After that, the force analysis is carried out and the results of magnetic unit are verified by finite-element method. *(W. Shen, 2006)*

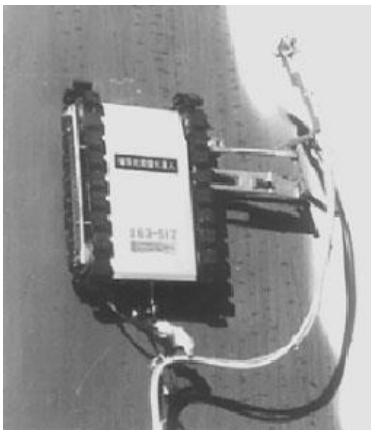


Figure 2.2: Wall-climbing robot for oil tank inspections.

C. Grasping Adhesion Mechanism

Besides that, new adhesion mechanism is developed for a climbing robot that able used for the inspection of a cliff surface and a dusty high altitude surface with small vibration. The research team analyzed the bionic structure of the cockroach legs and observed their morphological characteristics of the spiny claws on these legs. An initial mechanical structure of a wall-climbing robot was proposed based on a grasping claw and a climbing model with the dimension of 200 mm x 150 mm x40 mm. The mass of this robot is only 400 g but able to move with max speed 0.08 m/s and the maximum payload with 250 g.

Next, a mathematical model was conducted to identify the relationship between sharp hooks and bulges on the rough wall surface. Finally, several laboratory experiments are performed to verify the grasping stability of the wall climbing robot. The details of the climbing mechanism are discussed in the paper and some briefing mechanism can refer to Figure 2.3. In future work, the research team would like to focus more on designing a climbing robot in order to prove the performance of grasping claw model in this paper. *(J. S. Fengyu Xu, JinLong Hu, and GuoPing Jiang, 2016)*

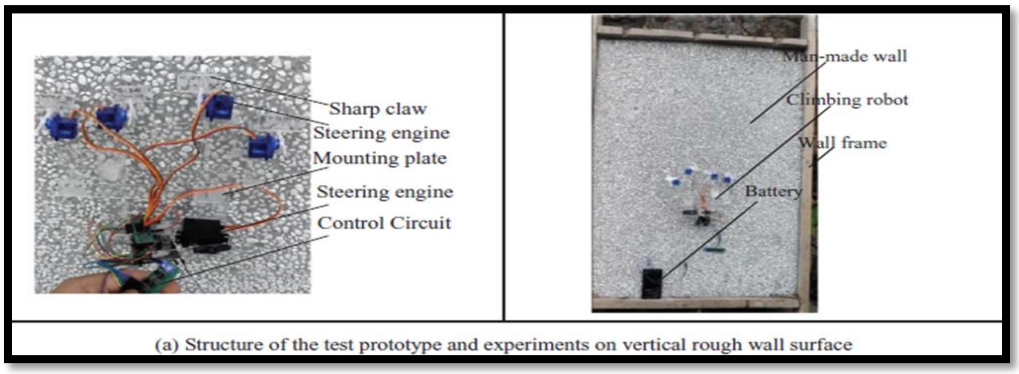


Figure 2.3: Climbing mechanism of the robot.

D. Negative Pressure with Impeller Type Mechanism

A wall climbing robot system is presented, called “LARVA”, developed for visual inspection of structures with flat surfaces as shown in Figure 2.4. The robot has two differential driving wheels with a suspension and an adhesion mechanism. An impeller and two-layered suction seals are used to develop the adhesion mechanism of wall climbing robots. It is designed to provide sufficient adhesion force and be controlled so that the robot can move freely on various wall surfaces. The research team conducted the static and aerodynamic modeling as well as the analysis of the adhesion mechanism, air leakage, and inner flow in design and control of the wall climbing robot.

Finally, the research team has conducted some experimental testing to identify the performances and feasibility of the robot on several kinds of walls. LAVRA uses an impeller in the adhesion mechanism and two wheels as a locomotive driving system which carries a huge payload as well as mobility in high speed. The locomotion mechanism of the proposed robot is different from in the sense that the two suspended driving wheels are placed outside of the vacuum chamber and front–side of the robot body. There is some limitation found in this robot, the wheels will slip and difficult to go straight when there is excessive suction pressure occurred. In future work, the suction pressure needs to be controlled at the optimal level to avoid the slip of wheels and the surface condition needs to consider properly for the wall climbing robots. *(Choi, 2012)*

Figure 2.4: Wall climbing robot, LAVRA

E. Propeller Type Adhesion Mechanism

There are few examples of wall climbing robot which using propeller type adhesion mechanism which thrust force is generated to support the robot on the vertical surface against the gravitational force. Through the historical data of propeller type wall climbing robot, the first climbing robot that using this adhesion mechanism was in the 1990s by Nishi and Miyagi (1991, 1993) where the only source of adhesion is propeller thrust force generated. There are two propellers used to support the robot structure with a number of passive wheels. Since this robot is too heavy weight and large size as well as low stability, it can't perform well in climbing high rise building. *(Nishi, 1991)*

Another example of propeller type of wall climbing robot which proposed by Disney Research Center, called "VertiGo" as shown in Figure 2.5. The adhesion mechanism in this robot also focuses on thrust force generated by two tillable propellers with passive steerable wheels. The limitation of VertiGo wall climbing robot is the stability problem which only thrust force generated as the source to generate the adhesion force. *(Beardsley, 2015)* Unfortunately, the adhesion mechanism which using the thrust force generated by the propeller in the design of wall climbing robot still has some problem on stability even it allows the robot move at any wall surface.

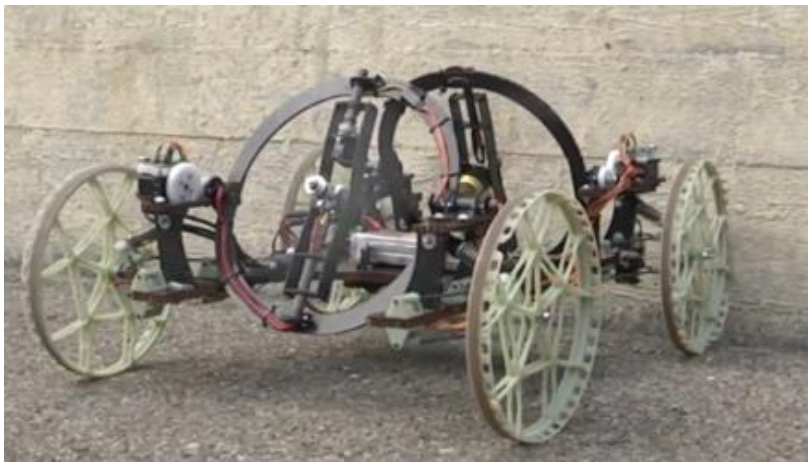


Figure 2.5: VertiGo wall climbing robot.

. Unlike the previous propeller type of wall climbing robot which only focuses on thrust force generated, this study focus on a hybrid actuation system which focuses on both propeller thrust force and wheel torque. In a theoretical way, this adhesion mechanism system able provides high stability and generate higher thrust force to support wall climbing robot on the vertical wall surface. Basically, the new designed of wall climbing robot will consist of three main units which are thruster units, driving units and control units as shown in Figure 2.6. There are two coaxial upturned propellers is used to generate the thrust force and cancel the drag moment while the two propellers are turning in opposite direction.

The mathematical analysis is carried out to determine the required adhesion and wheel torque which important in the adhesion mechanism used. Besides that, dynamic simulation is performed by using ADAMS software to verify the result of the concept. The capabilities of the robot are tested with the way of climbing on the different type of wall surface. This result finding in this paper proved that the robot is achieved objectives that utilize propeller thrust and wheel torque in adhesion mechanism used. *(Mohamed Gouda Alkalla, 2017)*

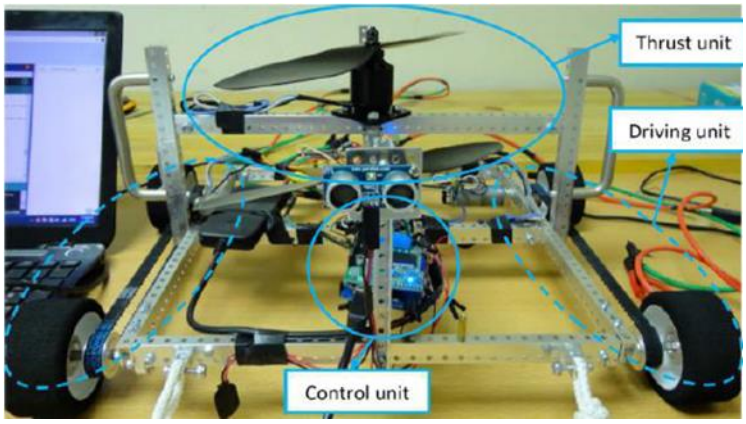


Figure 2.6: Hybrid Actuation system in wall climbing robot.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Research Study on Current Wall Climbing Robot

In recent few years, many manufacturing process and inspection jobs especially those with highly hazardous and dangerous to the human being have been automated by the different robotic application. A wall climbing robot was designed and developed to survey human being in high and dangerous working environment since 1960's. Based on the research study, there are many types of adhesion mechanism used with different locomotion in wall climbing robot which have their own advantages and limitation.

The common adhesion mechanism used in wall climbing robot is vacuum suction cup attachment system which the suction cup chamber used to allow the robot to attach on the wall by keeping a pressure difference between the inside and outside of these chambers. This adhesion mechanism is a mature technology and it allows the robot to attach with the different type of wall surface. However, it has the high demand for surface roughness and the noise is produced since air pump is required. Another simple adhesion mechanism used in wall climbing robot is magnetic adhesion mechanism by using magnetic force but it only can attach wall surface that consists the magnetic permeability. The magnetic attachment system is easy to control and obtain high capacity in the real application. Grasping mechanism which using the grippers and claws in a concept of cockroach legs is only suitable for the uneven and rough wall surface.

Lastly, the pushing adhesion mechanism in wall climbing robot is worked by using the thrust force generated by the propeller to support the robot run against the gravitational force. Therefore, this mechanism system allows the robot to attach to any type of wall surfaces. The adhesion mechanism and locomotion are critical components that need to be considered in design on working principle of a wall-climbing robot as it allows the robot to function and stick itself on the wall against the gravitational force. Therefore, adhesion mechanism and locomotion selection in the design of wall climbing robot is very important in order to improve the stability and performance in the real application.

3.2 Mechanism Design

After research study of adhesion mechanism of wall climbing robot was done, the problem statement and objectives in this project were identified. Brainstorming on the design concept of adhesion mechanism and locomotion in wall climbing robot was conducted to finalize the design of wall climbing robot. In this studyt, pushing mechanism that using thrust force generated by the propeller was used as adhesion mechanism to support the robot to attach on the wall against the gravitational force while the magnetic attachment mechanism was used in locomotion of robot wheels to allow robot attach on the magnetic wall surface as additional criteria in the design of wall climbing robot. The adhesion mechanism and locomotion used in this design will be further explained in next section.

Once the design is finalized, CAD model of wall climbing robot was drawn by using SolidWorks and will be explained on next section. The overall design of the wall climbing robot was shown in Figure 3.1. The wall climbing robot consists of four wheels which are two passive front wheels and two rear wheels that attached to DC geared motor. The servo motor was located on the right side and used to adjust the angle for the out-runner motor. The propeller was attached with the out-runner motor and the thrust force was generated to allow the robot to stick itself on the vertical wall surface.

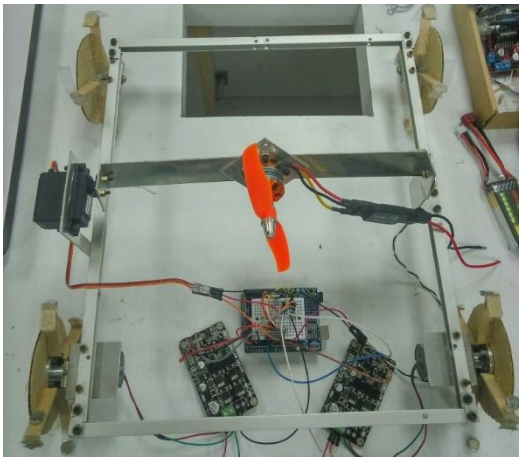


Figure 3.1: Overview of Wall climbing robot.

3.2 Project Flow Chart

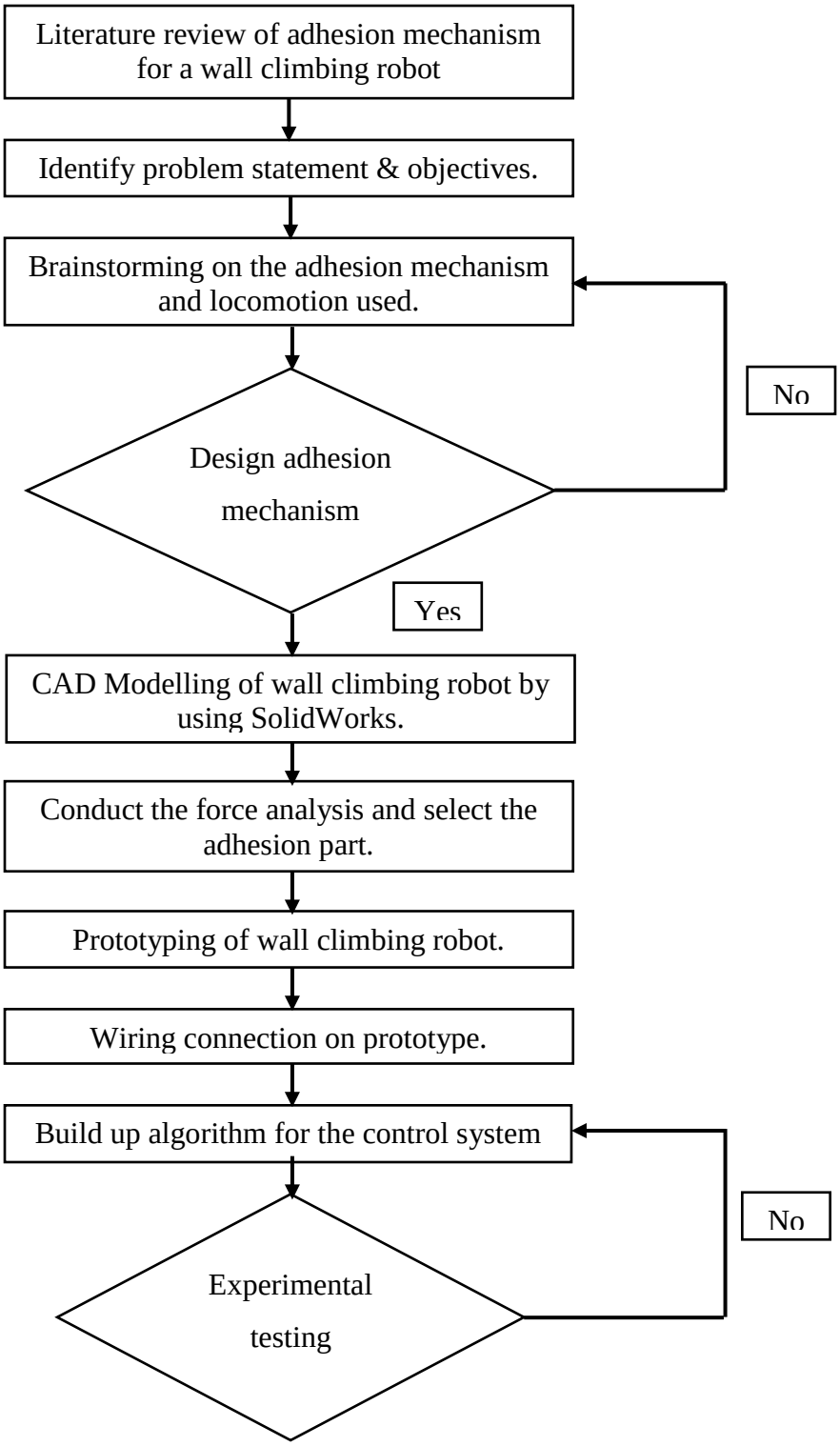


Figure 3.2: Project flow chart

3.3 CAD Modeling

After the design concept of adhesion mechanism and locomotion was confirmed, the CAD modeling of wall climbing robot was drawn by using SolidWorks as shown in Figure 3.3. In the CAD modeling shown, the wall climbing robot was separated into two main parts which are the robot body structure and robot wheels. The part components of wall climbing robot were described on Table 3.1 and the details can refer the appendix. Besides that, adhesion parts such as DC geared motor, servo motor, out-runner motor with propeller also be drawn in the CAD modeling. However, the control system device such as Arduino UNO, HC-05 Bluetooth module and MC10 C DC Motor driver will attach on the wall climbing robot frame.

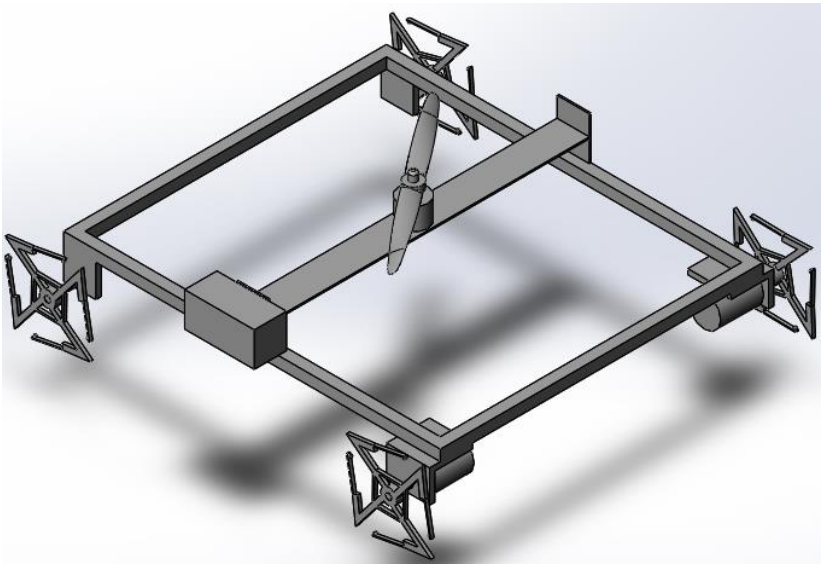
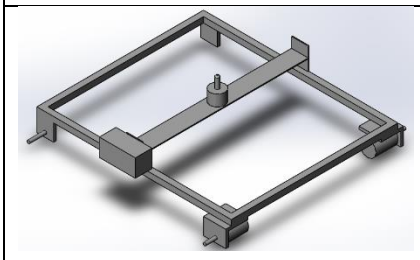
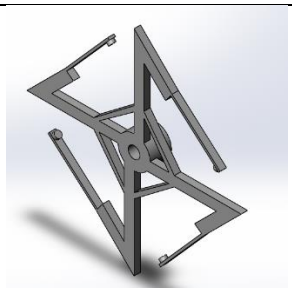


Figure 3.3: Overall CAD modelling of wall climbing robot.

Table 3.1: Description on part components of wall climbing robot.

Part Component	Descriptions
	Part name = Body structure Dimension = 300 mm x 350 mm Material used = Aluminum
	Part name = wheel Dimension = ∅ 100 mm Material used = Wood stick, PVC (plastic pieces) and neodymium magnet

3.4 Adhesion Mechanism and Locomotion

In adhesion mechanism for wall climbing robot, pushing mechanism that using thrust force generated by the propeller was designed and developed as shown in Figure 3.4. As a theoretical concept, the combination of propeller and Turnigy D2826-6 2200 kV Out-runner Motor able to generate the high thrust force to allow the robot to attach to the wall surface when moving. The out-runner motor was able to rotate at 2200 rpm per voltage whiles 11.1 v LiPo rechargeable battery was connected with the Electronic Speed Control and Arduino UNO. Therefore, the propeller with Out-runner motor able to be rotated up to the maximum rotation speed of 24420 rpm. However, the speed of the out-runner motor will be controlled by using Electronic Speed Controller (ESC) which controls the amount of voltage flowing through the motor.

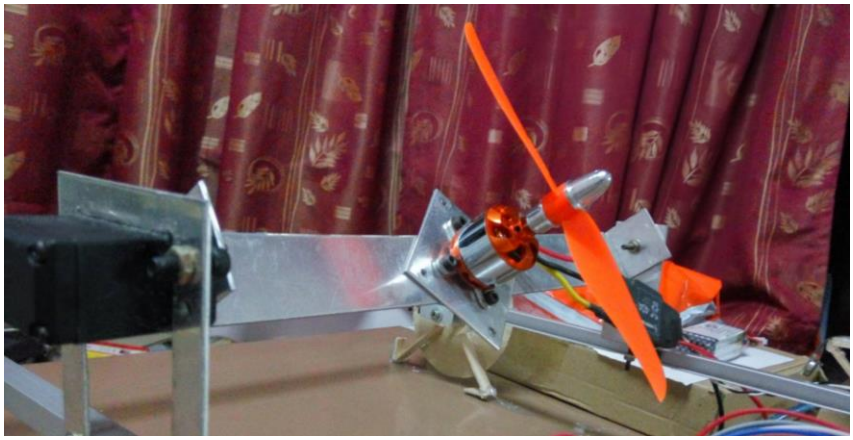


Figure 3.4: Pushing mechanism by using propeller in wall climbing robot.

For the design concept of adhesion mechanism for wall climbing robot, a propeller was used to create the thrust force within a fluid to move the robot on vertical wall surface against gravitational force. Thrust can be defined as the forward force produced by the propeller or rotor and it used to overcome the force of drag. The concept of this adhesion mechanism used in wall climbing robot is similar to the concept of vertical thrust generated in helicopters as shown in Figure 3.5. In helicopters, the net force produced by these blades is the Thrust, which acts perpendicular to the plane of rotation of blades as shown in Figure 3.6. *(Sharma, 2017)*

When the propeller is rotated at high RPMs, the relative airflow is generated to create the force that strong enough to support the object move forward against the gravitational force. The rotating propeller on wall climbing robot will create the high speed of moving air above them. The Bernoulli principle mentioned that the increase of the speed in moving air will decrease the pressure above the propeller. Thus, the higher air pressure below will move the propeller up and is able to move the rotor forward.

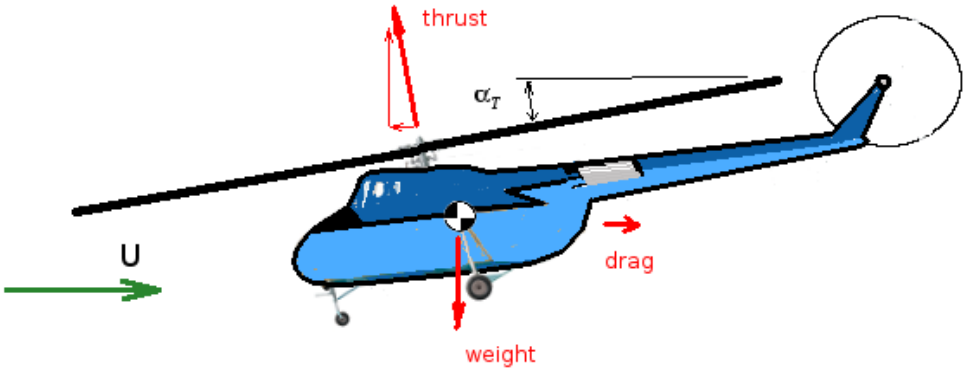


Figure 3.5: Principle of vertical thrust force used in helicopters.

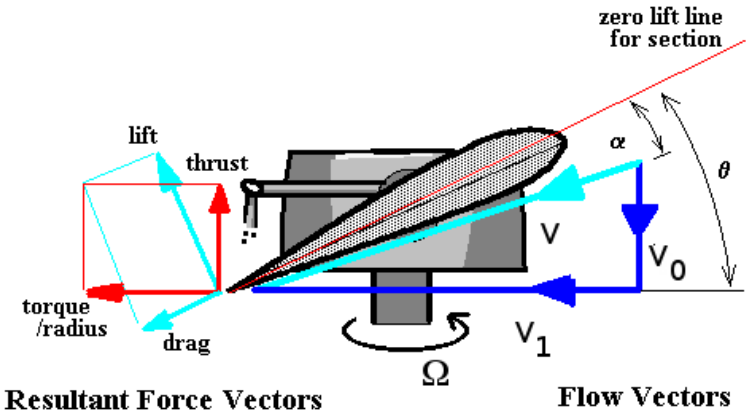


Figure 3.6: Cross section of the blade.

As mentioned in mechanism design, the wall climbing robot consists of four wheels as the design in term of locomotion as shown in Figure 3.7. Each of the two rear wheels were attached with DC geared motor while the front passive wheels were free to rotate. The wall climbing robot can run in multidirectional motions and the direction was controlled by using Arduino Motor Driver. Therefore, the turning direction of the motor can change from clockwise direction to anticlockwise direction by the motor driver used. By referring the algorithm code in the appendix, the robot was defined to move forward when the motor is rotated in a clockwise direction while it was moving backward when the motor is rotated in an anticlockwise direction.

Figure 3.7: Front view on design of wheels in wall climbing robot.

Besides that, the magnetic attachment mechanism was used in locomotion of robot wheels to allow robot attach on the magnetic wall surface as additional criteria in the design of wall climbing robot. In general, magnetic wheels are one of the key components to produce adhesive force for the current wheeled robot. The use of neodymium magnets to produce a constant magnetic field which allows the robot attach to the ferromagnetic wall surface with the use of wheels to move. The magnetic attachment mechanism used in the design of wheels no need to spend energy in the adhesion process and is able to support the pushing mechanism by the propeller in wall climbing robot. In this project, the design of wheels is different with the available magnetic wheels in the market and there are only four magnets used in one wheel which able to reduce the cost.

3.5 Mathematical Analysis

Every aspects has to be considered carefully and mathematical analysis is required in order to build a stable and efficiency wall climbing robot in pushing mechanism with propeller. Components used in adhesion mechanism such as propeller and outrunner motor must selected based on the power and required as incompatibility will affect the performance of wall climbing robot. Moreover, the driven source in motor selection is one of the consideration before prototyping of robot. Therefore, mathematical analysis such as calculation on thrust force required was described.

A. Calculation on Thrust Force Required

In pushing mechanism with propeller in wall climbing robot, the critical factor is the thrust force generated by propeller which support the robot to run against the wall during the operation. Therefore, the thrust force required of the robot must be determined in order to select suitable propeller and motor used in this project.

Static thrust is defined as the amount of thrust force generated by a propeller that used to adhere the robot on the wall in static mode. Firstly, the amount of power absorbed by the propeller from motor is determined to use for static thrust force calculation. The equation can be written as: *(Dickey, 2013)*

$$Power = Prop\ Constant\ x\ rpm^{\ Power\ factor} \quad (1)$$

Where the power is in watt and rpm in thousands. In Equation (1), the value of propeller constant and power factor used can refer to Table 1 in Appendix.

The next step is to determine the thrust force produced by a propeller. The thrust force produced by propeller is calculated from the theory of Newton 2nd Law which state that "Force is equal to mass times acceleration: F = ma". In this case, Newton 2nd Law is mentioned that "Force is equal to time rate of change of momentum: F $=\frac{d(mv)}{dt}$ where the momentum is defined as mass time velocity. The equation can be written as:

$$F = \frac{d(mv)}{dt} = \frac{m(dv)}{dt} = ma \tag{2}$$

Thrust force generated by propeller is work by accelerating the air molecules, which mean that the total thrust of propeller is the sum of the all the individual thrust generated by accelerated air molecules. Assume that the mass of each of the molecule is constant, the Equation (2) can be rewritten as:

$$F = \frac{d(mv)}{dt} = \left(\frac{dm}{dt}\right) v = \dot{m}v \tag{3}$$

Next, the air molecule is consider to have a mass flow rate through the propeller at a constant velocity. In general, the velocity of the air molecules pass through the propeller will form thrust force as the air molecules started out at static mode and then were start accelerated in dynamic mode.

Therefore, the equation of static thrust force generated by propeller is written as:

$$F = \dot{m}V_e \tag{4}$$

Where the $V_{e\ is}$ the inflow velocity through propeller. In the dynamic mode, propeller will only generated thrust by the air velocity. Then, the dynamic thrust force is written as:

$$F = m\,\Delta\dot{V} = \dot{m}(V_e - V_{ac}) \tag{5}$$

Where the V_{ac} is the aircraft velocity in m/s. Since the $\dot{m}$ is equal to density of air times the cross sectional area through which the air is flowing times the air velocity, the equation is written as:

$$\dot{m} = \rho A V_e \tag{6}$$

Substituting equation in $\dot{m}$, the Equation (5) is rewritten as:

$$F = \rho A V_e (V_e - V_{ac}) = \rho A {V_e}^2 - \rho A V_e V_{ac} \quad (7)$$

Where A is the cross sectional area and the equation of A is written as:

$$A = \pi r^2 = \frac{\pi d^2}{4} \quad (8)$$

Substituting equation in A, the Equation (7) is rewritten as:

$$F = \rho \frac{\pi d^2}{4} {V_e}^2 - \rho \frac{\pi d^2}{4} V_e V_{ac} \quad (9)$$

By factoring the area term out, the Equation (9) can be simplified as:

$$F = \rho \frac{\pi d^2}{4} ({V_e}^2 - V_e V_{ac}) \quad (10)$$

As reminder that: F is the thrust force generated, ρ is the air density, d is the propeller diameter and then V_e is the inflow velocity through propeller while V_{ac} is aircraft velocity. Assume that the V_e is approximately equal to pitch speed of the propeller. The pitch of propeller in unit of inches is consider as the theoretical distance forward when propeller is moving based on the pitch angle. Based on the RPMs and pitch of propeller, the equation of pitch speed is written as:

$$V_{pitch}(mph) = RPM_{prop} \cdot Pitch_{prop}(in) \cdot \frac{1\ ft}{12\ in} \cdot \frac{1\ mile}{5280\ ft} \cdot \frac{60\ min}{hr} \quad (11)$$

In order to identify the air density, the ideal gas law $P = \rho RT$ is used. The air density is assumed as $\rho = 1.225\ kg/m^3$. The, the V_{ac} is set as zero and Thrust force is in unit of newton (N). Since the prop diameter, *d* and prop pitch, *pitch* are measured in unit of inches, therefore the conversion factor of 0.0254 is used to convert inches to meters.