Wall Climbing Robot Using Thrusters/Propellers

A Final Year Project Report

Presented to

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In Partial Fulfillment
of the Requirements for the Degree of
Bachelor of Mechanical Engineering

by

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ABSTRACT

This report reviews the designing and modeling of a hybrid-actuated robot which is able to climb vertically on a wall. It utilizes friction force produced by the wheels as well as the normal force generated by the propellers to climb on the wall. Thus, it is a hybrid-actuated system. The robot is mainly focused on the inspection of those areas where human reach is not possible or is costly or the environment is harsh for the humans. There is a window left for the modification of robot so that it could be deployed for a certain task after modifying it accordingly. This is possible only due to the thought process went into the flexible designing of this robot. The robot is controlled externally by a joystick controller, but path follower mechanism can be employed to make it autonomous. The formation of feedback control is possible by the use of sensors which continuously sense the environment and give feedback data to the controller. A novel method of steering is deployed here. The steering of this robot is mainly done by the propellers utilizing the Propeller Walk effect. A pair of right and left-handed propellers is used to achieve this task. In addition to the adhesion provided by the propellers, the steering is also made possible from these propellers hence the feedback system is developed with less of a hassle.

ACKNOWLEDGMENTS

First and foremost, we thank Allah for giving us strength to undertake and carry out this project.

We are extremely grateful to our supervisor, Dr. Yasir Ayaz, for his persistent guidance throughout the duration of this project. It would be an honor to extend our gratitude to Sara Babar for helping us with his experience and technical skills and for his continued support & encouragement.

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ABBREVIATIONS

BLDC	Brushless Direct Current
DC	Direct Current
FEA	Finite Element Analysis
MEMS	Micro Electromechanical Systems
IMU	Inertial Measurement Unit
IC	Integrated Circuit
AC	Alternating Current
LASER	Light Amplification by Stimulated Emission of Radiation
RPM	Revolution Per Minute
CAD	Computer Aided-Designing
GUI	Graphical User Interface
RC	Remote Control

NOMENCLATURE

V_O	Blade Tip Velocity
μ	Coefficient of Friction
F_R	Tire Traction Force

CHAPTER 1: INTRODUCTION

Motivation:

Since the end of the 80ties vertical wall climbing robots are being created for different types of application all over the world since these eliminate the risk of loss of human effort and human life. Towards the end of the 80ties and the beginning of the 90ties numerous projects concerning these robots for different circumstances were established in Japan. Some of them include cleaning robots for glass walls, ship exterior cleaning robots, rescue robots for fire brigades, inspection robots for steal tanks and wall. Most of the developments were unsuccessful because of the existence of adhesion problems and lack of advance technology. Also, the expenses for the programs to establish such robots were high. At the end of the 90ties mainly across the European sector, wide range of model machine were being produced for various sorts of applications like the assessment of channels and vessels in the petrochemical business, fixing and evaluation work in the construction and atomic industry or cleaning robots for enormous walls.

The structure having an ability to climb vertical buildings or inspect inside tanks and basins is gaining attention in recent times. The application of such robots is required in welding of ship hulls, the inspection of steel bridge or nuclear power plants etc. Many designed systems are available in market now one of them which is very common is called 'Rest'. It is a magnetic adhesion type robot which uses legs to climb the wall, but its movement and functioning is limited to the magnetic walls only. It is to be noted that mostly the climbing characteristic is required where we find it difficult, expensive and sometimes dangerous to reach as humans and may look out for easier replacements to help us overcome the issue.

Problem Statement:

"To Design a Wall Climbing Robot Using Propellers/Thrusters"

The suggested idea here is based on a hybrid actuation system in which a robot is made to climb up on a plain vertical wall. The adhesion between wall and robot is provided by the normal force generated by propellers which holds this robot onto the wall, and this is reinforced by the traction of tires and walls which is generated by the wheels' motor. The torque generated by tires make sure that it does not slip downwards and the thrust force from propellers allows it to remain attached to the wall and therefore enable the robot to stop anywhere on the wall.

Application:

Due to its high speed and design it can be used for inspection purposes even in nuclear power plants too. Sometimes due to the hazardous environment human reach is impossible for inspection where the wall climbing robot comes in handy. In addition to this it can also be used for the inspection of vessels and reactors. It can also be used for glass cleaning purposes on a high-rise building because of these characteristics.

- *Inspection of big concrete walls:* The design of this robot allows it to climb vertical concrete walls and thus can be used to inspect them.
- *Inspection of Bridges:* Instead of using heavy machinery and heavy-duty lift systems to enable a human to inspect high rise bridges we can deploy a team of these robots so that they can inspect the bridge with improved efficiency and at a reduced cost. Also, the time span is reduced drastically and the liberty to use different sensors for different surfaces makes it very useful for such inspections.
- *Cleaning and Paint Purposes:* the robot can be modified to make it clean and paint vertical walls. The catch, here, is that, the work is done in a considerably less amount of time, efficiency is greatly enhanced, and the painting is done uniformly over the wall. It can even make those patterns on the wall which are rather difficult for a human to construct.
- *Withstand Harsh Environment:* These robots can be deployed in those areas where human access is not possible which can be due to, radioactivity, high temperatures or any other severe environmental condition. With a suitable modification in the material selection, the robot can achieve this.
- *Externally Controlled:* The robot can be controlled by a joystick controller or the robot can be modified to follow a certain path-following mechanism.

CHAPTER 2: LITERATURE REVIEW

The design of this robot depends upon two major factors,

1. Locomotion Method
2. Adhesion Method

Locomotion tells us about how it will move on the surface of the wall and adhesion method tells us about how it will stick to the wall without falling. There are several options for both of these methods which include,

Options for Locomotion:

- Wheel driven
- Chain driven
- Crawler type
- Legged locomotion
- Locomotion based on arms and grippers

Options for Adhesion:

- Suction cup
- Suction cup crawler
- Vacuum type
- Magnetic type
- Rope/rail gripping
- Bioinspired adhesion

Selection Criterion:

For this wall climbing robot, wheel driven locomotion is chosen, and suction/adhesion is created by using thrusters/propellers. This choice is made after comparing different mechanisms and considering our requirement.

The crawler and legged robots are relative slower than wheel/chain driven type. Considering the time, it will take and the complex design of legged and crawler robots, wheel driven type was selected. Coming towards adhesion mechanism. The propellers are chosen because of their wide range of use. These are also quite light weight as compared to some other adhesion mechanisms like magnets which are heavier. The ease of control is also a major advantage. Also, this design can then be taken to next level by reversing the direction of propellers which will allow it to cruise through the air. That is however constrained by budget and complex control system. While each type has its own pros and cons and required conditions in which they work properly. Now having multiple design options, we need to look out our requirements and design a system which can fulfill our requirements and meet our demands within the constraints like money, feasibility and durability etc. Let’s look briefly into main characteristics of each type. Starting with the adhesion type, when we look into magnetic type robots, we see that they only work on ferromagnetic surfaces and possess heavy structure which is unfavorable. On the other hand, when we talk about vacuum-based robots are light and easy to control but it cannot work on cracked surfaces hence it is not suitable for inspection purposes. Now let’s discuss locomotion type robots at first, we have crawler type which moves at high speed, but it cannot work on rough surfaces. Then we have legged type robot which apparently copes up with rough surfaces well, but its speed is very low and has complex control system. Lastly have wheeled type wall climbing robot which moves with high speed and can overcome minor roughness on the wall. Now we see our requirements are high speed, high thrust against wall, easy to assemble design with budget. So, this is why we opted for thruster/propeller based design incorporated with wheels for better performance.

The main disadvantage of wheeled locomotion is that it can't be used for surfaces which have large obstacles on them. Since walls don't have such obstructions so this robot is well fitted for the required task.

Components:

A large portion of this robot is how well it can be controlled by implementing control systems. So, the electrical components which it will utilize are,

- Gear DC motors
- Brushless DC motors
- Connection wires
- Battery/External supply

The control system of this robot is depending upon microcontrollers which include,

- Arduino
- Inertial Measurement Unit (IMU) – MPU 6050
- IC- L293d for the interfacing of motors with Arduino

Pulse Width Modulation (PWM) plays a key role here. The mean power delivered by an electrical signal is reduced by slashing the signals into distinguishable parts. This process is known as Pulse Width Modulation (PWM).

The mechanical portion of this robot includes the study of

- Thrust Calculation
- Propeller selection and the motor which will suit its performance.
- Design optimization using Software (Fusion 360 etc.)
- Finite element analysis (FEA) using Software.

Gear DC motors:

The gear dc motor is simply a motor with a gearbox which ultimately increase the output torque on the expense of RPMs.

Figure 1: Gear DC motor

Brushless DC motor:

A brushless DC motor consists of a rotor in which the nodes of the coil are placed at a specified distance apart. By utilizing the hall effect sensor, those nodes are energized systematically to get uninterrupted rotation of the motor.

Figure 2: Brushless DC motor

Battery/External Supply:

Usually these types of robots accompany batteries with them to provide electricity. But that puts the limit on the time period for which it can be used without replacing the battery. The problem is solved by using external supply with battery as a backup system in case of the failure of external power supply.

But using external supply comes with its own toll. The overall weight is increased as the robot climbs the wall. So, the external supply is used for demonstration purpose mostly. This issue is somehow manageable. Converter is used to reduce the weight of the wire attached to the robot. This adds the weight of converter on the robot but the benefit of using it makes it ideal.

Arduino:

The microcontroller under use is Arduino. It is used to drive motors connected to the wheels and propellers. Arduino is at the heart of the entire control system of this robot.

Inertial Measurement Unit (IMU):

An inertial measurement unit (IMU) is an electronic device that is used to determine the position and orientation of a body. It does so by calculating the specific force and angular acceleration of the body and utilizes a

Figure 3: MPU-6050

combination of accelerometers, gyroscopes, and magnetometers.

This robot is equipped with this unit. This unit senses the obstruction in the path of the robot. In our case that will be the wall. it will then send signal to Arduino to take necessary action so that wall climbing can be initiated.

IC- L293d:

This IC works on the dual H bridge configuration. This allows it to control two motors at the same time and it can even make these two motors to rotate on the opposite side at the same time. This IC is controlled by Arduino.

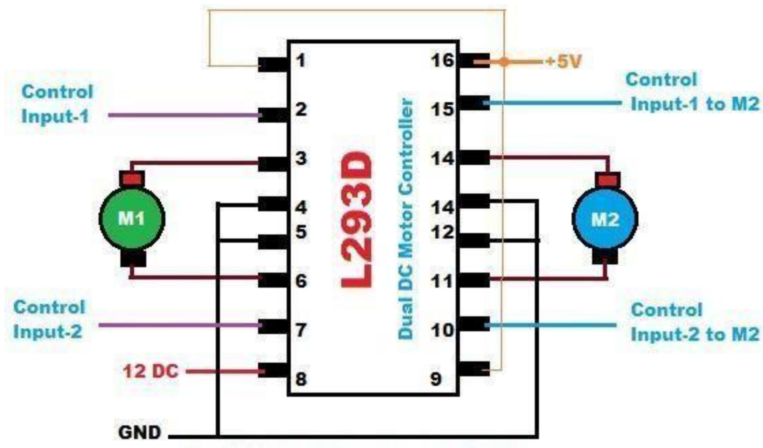


Figure 4: Dual H-Bridge configuration using L293d

Thrust Calculations:

The thrust of the propeller is used to create adhesion on the wall. it may be known as anti-drone in this regard. The thrust depends upon RPM, pitch, diameter and velocity of propeller. So, by using these values and putting it in the following formula, thrust is calculated.

$$F = 1.225\frac{\pi(0.0254 \cdot d)^2}{4}\left[\left(RPM_{prop} \cdot 0.0254 \cdot pitch \cdot \frac{1min}{60sec}\right)^2 - \left(RPM_{prop} \cdot 0.0254 \cdot pitch \cdot \frac{1min}{60sec}\right)V_0\right]\left(\frac{d}{3.29546 \cdot pitch}\right)^{1.5}$$

Propeller Selection:

diameter of the propeller is length of the the propeller. Whereas the pitch of the propeller is the angle between traverse direction and the straight line made from the angle of incidence. Both of these matter when selecting the propeller to get the required thrust.

Figure 5: Propellers

Design optimization:

The main optimization in this case is the weight optimization or you can say weight reduction using the software which in this case is Fusion 360. The weight reduction is done in order to decrease the weight of the whole package which ultimately reduce the requirement of thrust. Since decreasing thrust is the design optimization process.

Stress analysis:

The stress analysis is done in order to check whether the robot is able to withstand the loading conditions.

CHAPTER 3: METHODOLOGY

Design:

The first step to bring our idea to life was to make a design of our idea. For that purpose, we did not have much numerical values and qualitative data related to our projects as most of the research done on the propeller-based wall climbing robots is not open sourced. Hence, we had to design our system from the scratch. The most important factors in the design process were following:

1. Chassis Design
2. Propellers Selection
3. Motors Selection
4. Tires Design
5. Payload Calculation and Limit

Chassis:

First thing which we looked into was designing a chassis of our Wall Climbing Robot on which all the other components will be assembled. Chassis will bear maximum stresses as the force of the propellers will be directly acting on it. Initially we had to assume a size of the chassis ourselves as it was the first iteration of solving this designing problem and design is an iterative process. In future iterations, we changed values to decide the suitable motors attached to the propellers and the tires and hence finally we performed design optimizations Analysis on the chassis to find the most optimum design under our design conditions.

The initial design of the chassis included an assumption that it will have a size of 0.5 x 0.5 m^2. The material selection for the chassis was the key point to ensure its strength and factor of safety. Initially we tried to go with aluminum 6061 but it has a density of around 2700 Kgm^{-3} which makes the design quite bulky for climbing processes. Then we looked into acrylic sheets for the design of our chassis, it has a density of 1200 Kgm^{-3} which is less than that of aluminum and it is providing a good strength of 48.9 MPa as well. We could not find any suitable BLDC motor available in the market with the dimensions of 0.5 x 0.5 m^2 so we had to iterate our dimensions to determine a value on which we can find a standard BLDC motor from the market. We decided to go with the dimensions of 0.3 x 0.3 m^2 as there were several motors available in the market which can bear the load of this design dimensions. In simple words, we scaled down our design. The dimensions of the design are given below.

Length	0.3 m
Width	0.3 m
Thickness	0.002 m
Density	1200 Kgm^{-3}

Table 1: Design Dimensions

The chassis was machined using LASER Cutting and each individual part of the chassis was assembled with a Dice Tower scheme. This way, we were able to cut out base of the chassis of 0.3 x 0.3 m^2 dimensions alongside the top bridge to hold the motors and other connecting blocks out of an acrylic plate of 0.5 x 0.5 m^2. The LASER Cutting Scheme designed in Adobe Illustrator is attached below:

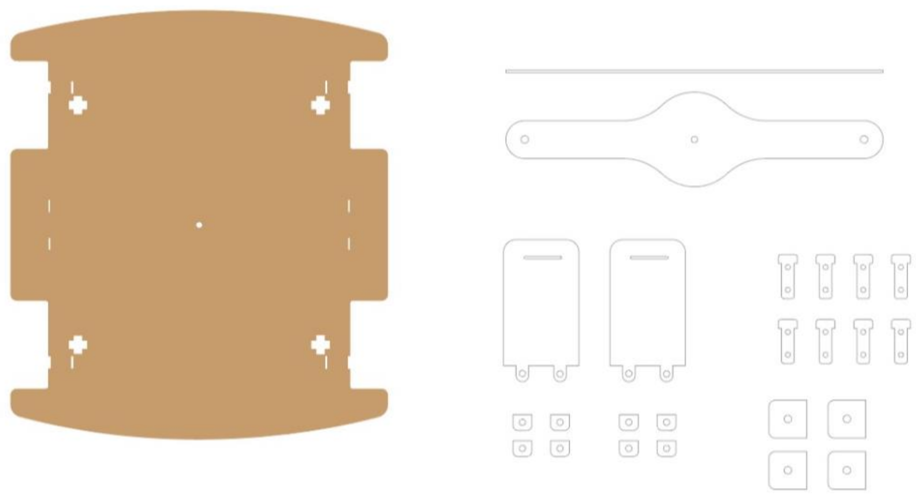


Figure 6: LASER Cutting Scheme

The above LASER Cutting Scheme was assembled to give us the following final Chassis assembly:

All the geared DC and BLDC motors are shown attached in this image to give an idea how they are connected to the chassis.

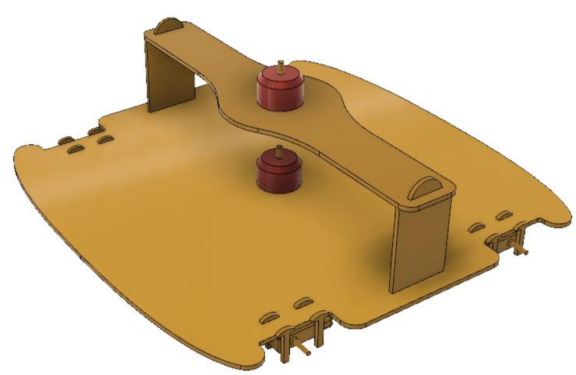


Figure 7: Chassis Assembly

Propellers:

Propellers are available in variety of standard forms in the market. We have to use brushless DC motors with them so that the torque and RPMs provided by the motor are directly applied to the propeller. To design propeller, the most important thing in our mind was the normal force. The normal force should be good enough to produce a friction force which is greater than the weight of the whole robot plus the payload.

The required thrust was calculated using the thrust to weight ratio which was initially set to 3 but it gave us a value of a propeller which was not available in the standard value. After several hit and trial attempts, we reached the value of 2.6. So:

$$\frac{Thrust}{Weight} = 2.6$$

Hence:

$$Thrust = 2.6 \times Weight$$

Hence, the thrust which we have designed for our design should have 2.6 times the value of weight. The total weight of the robot without any design optimization is 1.0924 kg including the wires and electronic circuitry. Using the design and geometry optimization technique, we reduced the mass of the robot by 21.69%. So, the mass of the robot after design optimization is 0.8739 kg. After combining the payload of 0.5 kg, we get a total mass of 1.3739 kg. So, the required thrust is 1.3739 x 2.6 which is 3.5721 kg. But we will be using two such thrusters whose combined thrust will be greater than the required thrust which is s3.5721 kg. We got to know this on the basis of 2 observations:

1. Due to propeller walk effect, if we use a right-handed propeller, the robot will tend to move towards right side. To cancel this propeller walk affect we will have to use two thrusters.
2. As we will be providing our robot a steering system through propeller walk mechanism (we will slow down the velocity of one propeller to turn to a specific side depending on the side towards which we want to turn. For example, if we want to move towards right, we will decrease the speed of left propeller.) so if we want a sharp turn, one propeller will instantly slow down and the other propeller will be working on its maximum thrust to provide enough friction force to overcome the weight. This is supported by the calculations as shown below.

Mass chassis + 200g components	0.8739 kg
Weight chassis + 200g components	8.5729 N
Payload	0.5 kg
Payload Weight	4.905 N

Total Mass	1.3739 kg
Total Weight	13.4779 N
Required Thrust	3.5721 kg
Total Thrust (For 2 thrusters)	7.1442 Kg
Normal Force	70. 0874 N
Friction Force	28.0349 N
Friction on one tire	7.0087 N

Table 2: Thrust and Normal Forces

The total friction at any time should be greater than the weight of whole robot and it can be achieved by the pair of propellers each having an identical thrust value in such a way that their sum is never less than the threshold value of 3.5721 kg during the course of whole motion. Ideally, we should go for the propellers with a thrust value of 3.5721 kg each and they should be used in pairs which means right-handed and left-hand propellers in a coaxial rotor configuration. But we can also use propellers of smaller values knowing the facts that the sum of thrusts should not be less than 3.5721 kg. Which means even if we use two propellers with 2 kg thrust each, we can get a 4 kg resultant thrust which will work perfectly fine for our robot.

The propeller which we will be using depends on the BLDC motor as well. That is why the propeller to be used in mentioned in the BLDC Motor Selection section of this report.

Motors:

The motor selection phase is one of the most difficult and important phases of a designing problem. We must select the motor which provide us exactly the same required torque and RPMs which we need. There are two types of motors being used in our design.

1. Gear DC Motors (for Tires)
2. Brushless DC Motor (For propellers)

Gear DC Motors (For Tires):

The motors used for the tires are simple TT DC motors which are generally used in robotic vehicles. For the purpose of inspection, we do not need as such very fast speed of forward motion and hence we can go with a small RPM motor as well. The RPM provided by a TT DC motor varies from 200 RPM to 290 RPM (these motors are available in several variety). We will be using the TT DC motor which has gears made of plastic so that we can have a small weight while climbing.

The specification sheet of this motor is given as below:

Rated Voltage	3~6V
Continuous No-Load Current	150mA +/- 10%

Min. Operating Speed (3V)	90+/- 10% RPM
Min. Operating Speed (6V)	200+/- 10% RPM
Torque: 0.15Nm	0.60Nm
Stall Torque (6V)	0.8kg.cm
Gear Ratio	1:48
Body Dimensions	70 x 22 x 18mm
Wires Length	200mm & 28 AWG
Weight	30.6

Table 3: Motor Specifications

Brushless DC Motors (For propellers):

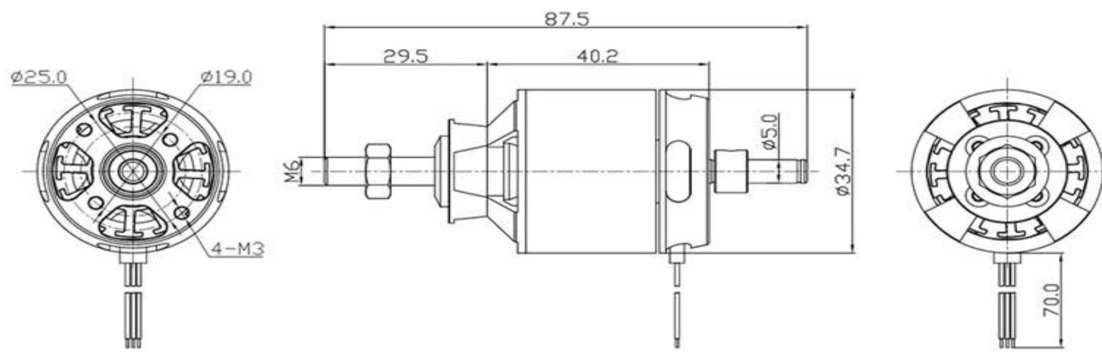
In a geared motor, we can get higher value of torque generated because of the gear ratios but at a higher gear and higher torque, the required RPM is very small. We know that the thrust of a propeller depends on the following factors:

1. Diameter of the propeller
2. Pitch (Blade Angle)
3. RPM of the Motor
4. Blade Tip velocity

We need a propeller which provides a thrust of 3.5721 kg. Such a propeller is not available with the exact same value. So, we went for a propeller available in the market with a blade diameter of 12 inches and thrust of 2.03 kg. So, when we will use a pair of these propellers, we will get a resulting thrust of 4.06 kg which is greater than our threshold value of 3.5721 kg. The whole model of the propeller is **“F450 F550 12*6 1045 Carbon Fiber Propeller Blade CW CCW Props”**.

The motor interfacing with this propeller is the next task. We need to have a motor which provides a thrust of 2.03 kg with each propeller. After searing a lot in the local market, we were able to find one such motor from a local vendor in G-11, Islamabad. The specifications of the selected BLDC motor **“C3542 920 KV”** are attached below:

MOTOR OUTLINE DRAWING



MOTOR PERFORMANCE DATA

MODEL	KV (rpm/V)	Voltage (V)	Prop	Load Current (A)	Pull (g)	Power (W)	Efficiency (g/W)	Lipo Cell	Weight (g) Approx
C3542	920	11.1	12×6	40	2030	444	4.6	2-4S	140

Table 4: Motor drawing and Performance Data

The motor can operate a 12 Inches diameter and a 6 Inches pitch propeller. The thrust we need is around 3.5721 kg so the highlighted region will work perfectly fine for us when we will use a pair of propellers.

Figure 8: Propeller Motor

Tires:

The Tires play an important role in the climbing process. They are combining with the surface, define the coefficient of friction. In our case, we are going with the tires of a simple four-wheel robotic kit tires. They provide a very good traction of around 0.4 coefficient of friction on a normal rough surface on a small speed. The tire and the motor set are given as follow:

Figure 9: Tires

Specification sheet of the TT motor is given above in the geared DC motor section.

Payload:

The payload is the weight of the application for which we will be using our robot. We are planning to use it for the inspection of the industrial plants such as nuclear power plants, boilers etc. For that, we need a good quality camera and a cable for power transmission. It will add around 0.5 kg of the weight on the robot. So, the total weight will be 1.3739 kg (sum of 0.8739 kg of the robot weight and 0.5 kg of payload).

Technical Engineering Drawing:

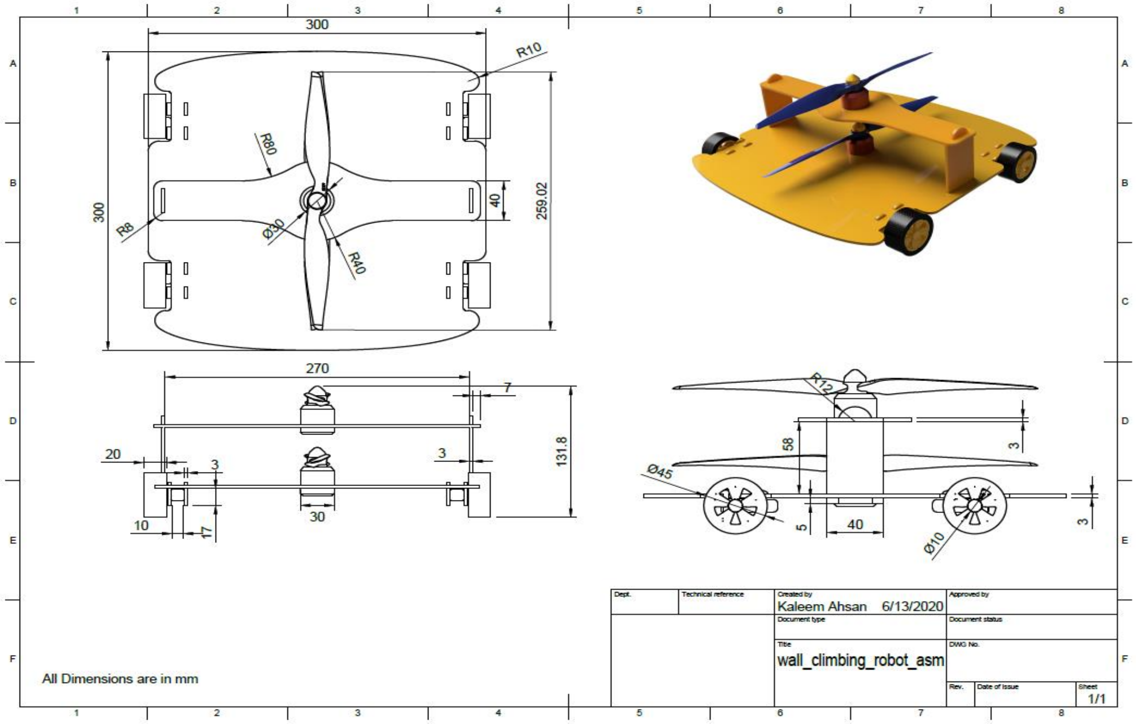


Figure 10: Engineering Drawing

CAD Model:

We made a detailed CAD model of our Wall Climbing Robot.

Rendered CAD Model:

A realistic rendered of the CAD model was created to add in the report to give readers an idea how the robot looks like in the real life. The realistic render is attached below:

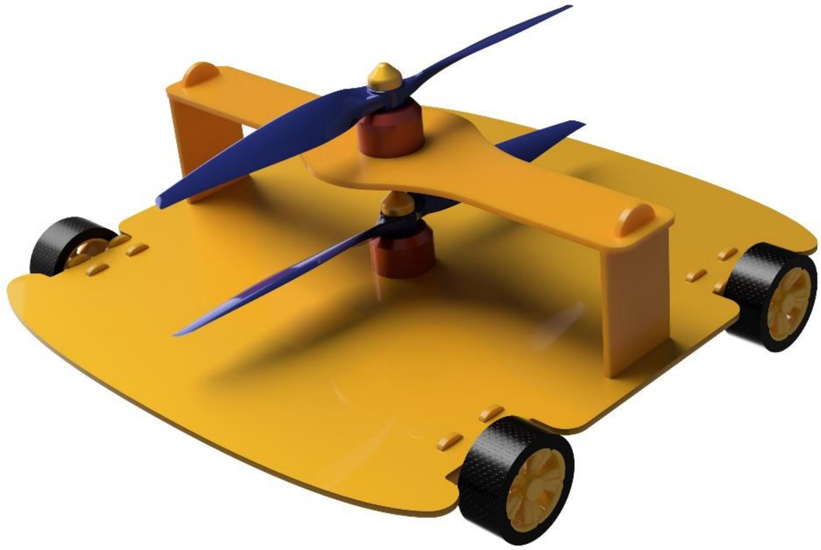


Figure 11: CAD Model (Rendered)

Front View:

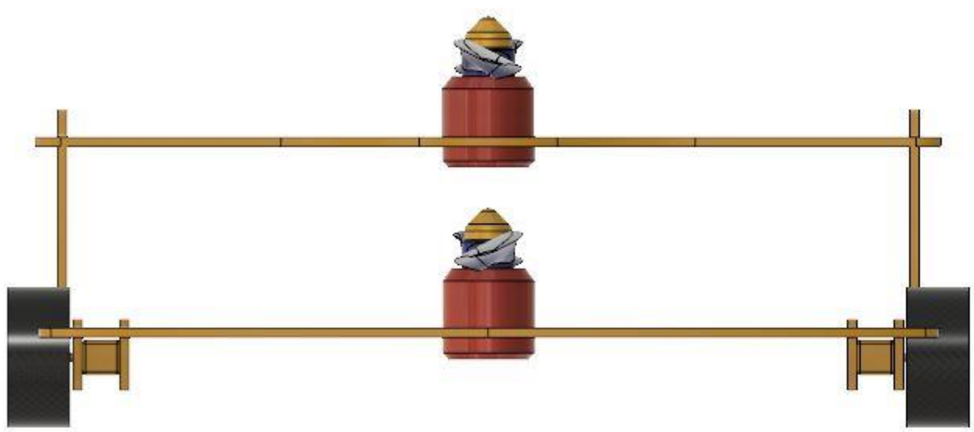


Figure 12: Front View of the Model

Right Side View:

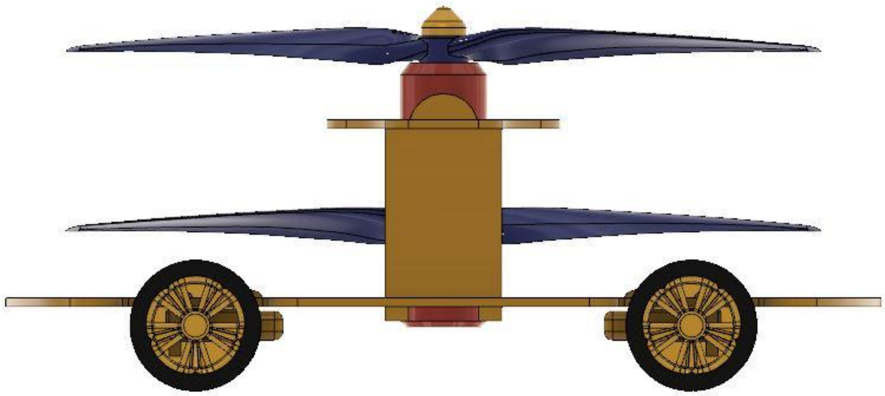


Figure 13: Right Side View of the model

Top View:

Figure 14: Top View of the model

Final Calculations Table:

All the calculations given above are summarized in the table given below:

Calculations		***Parameters***			
Weight chassis + 900g components (N)	8.573347476	Thrust /Weight Ratio	2.6	Length (m)	0.3
weight payload (N)	4.905	Payload (kg)	0.5	Width (m)	0.3
Total Mass (Kg)	1.3739396	Tire radius (m)	0.025	Thickness (m)	0.002
Thrust (Kg)	3.57224296	Reduction	0.2169	Density (kg/m^3)	1200
Total Thrust (For 2 thrusters) (Kg)	7.14448592			Friction Coefficient	0.4
Normal Force (N)	70.08740688				
Friction Force (N)	28.03496275				
Friction on one tire (N)	7.008740688	In case of one thruster			
Torque on each tire (N)	0.175218517	Friction Force (N)	14.01748138		
		Mass (Kg)	1.428897184		
Tire Gear DC Motor					
RPM	15				
Angular Velocity (rad/sec)	1.570796327				
Torque (Nm)	3.733643896				
Power (W)	5.864794118				
Force (N)	13.734				
Velocity (m/sec)	0.427027386				

Table 5: Final Calculations

CHAPTER 4: RESULTS AND DISCUSSION

Based on our calculations, project goals and assumptions we selected the material required for the manufacturing of the chassis of our robot, the type of tires required to achieved the targeted friction with the wall, the set of motors required to spin the tires against a surface and the BLDC motors required to spin the propellers at required torque and RPM values to get the desired thrust force.

WE performed following computational analysis of our design to verify and optimize our design.

1- Finite Element Analysis

2- Design Optimization

3- Motion Planning Using MATLAB Simulink

4- Thrust and Torque Calculation Using MATLAB Simulink

Finite Element Analysis:

To check the physical strength of our design, performing a Finite Element Analysis was very important. For that purpose, we purpose, we used Autodesk Fusion 360 to simulate our model for static load condition. As the model needs to bear continuous thrust and climb walls and curved surfaces, it will be under constant loads. These loads will generate stress concentrations in the corners and can deform the shape of the chassis as well resulting a permanent failure. All the components in the model are attached to the chassis and that is why the chassis will have to bear the reaction forces of all these components and in order to make a design which will not deform under these loading conditions, we had to perform a detailed Finite Element Analysis.

During the course of motion of the robot on a wall, the gravity will always be downwards, but the thrust force will be inside the wall and that is why the loading conditions of our robot are a little complex as compared to a car running on a road. During the path of its motion, the robot will be having a force in the range of 20 to 45 N. We considered the force applied by each thruster to be 30 N so total of 60 N force was applied on the model so that we can have a great value of the factor of safety.

Finite Element Analysis (Stress):

The stresses on the model can be seen from the below given image of the FEA Stress analysis performed using Fusion 360.

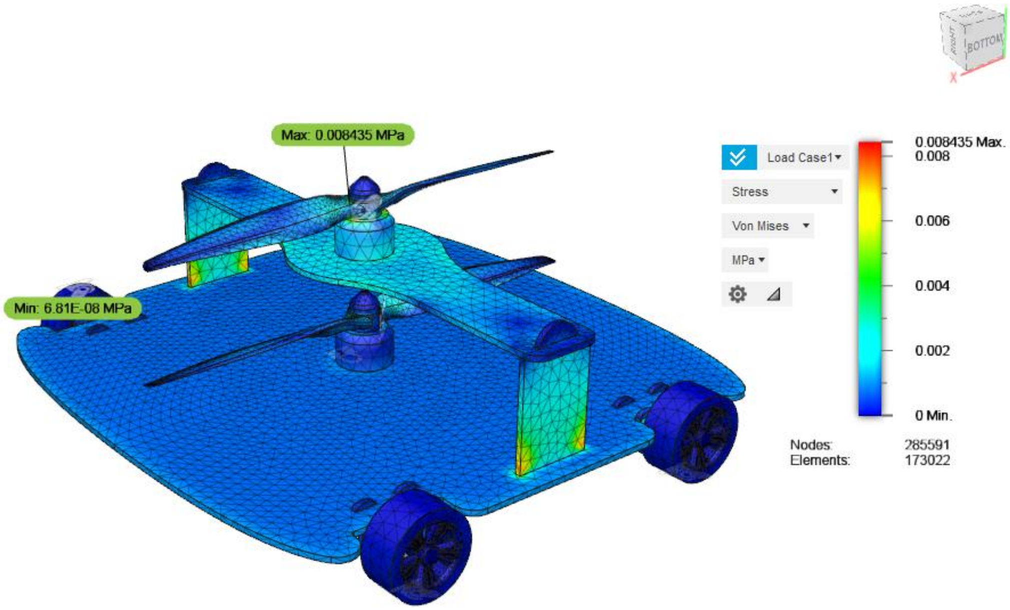


Figure 15: Stress Analysis

As it can be seen from the simulation results, the maximum value of stress on our robot is 0.008435 MPa and it is very small as compared to the Yield Strength or Ultimate Tensile Strength (UTS) of the materials to be used i.e., acrylic. Hence our design can bear all the loads acting on it during its working on a wall and can complete its journey without any permanent deformation.

Finite Element Analysis (Strain):

The strain produced in the model because of the applied stresses on the model can be seen from the FEA strain analysis performed on the robot:

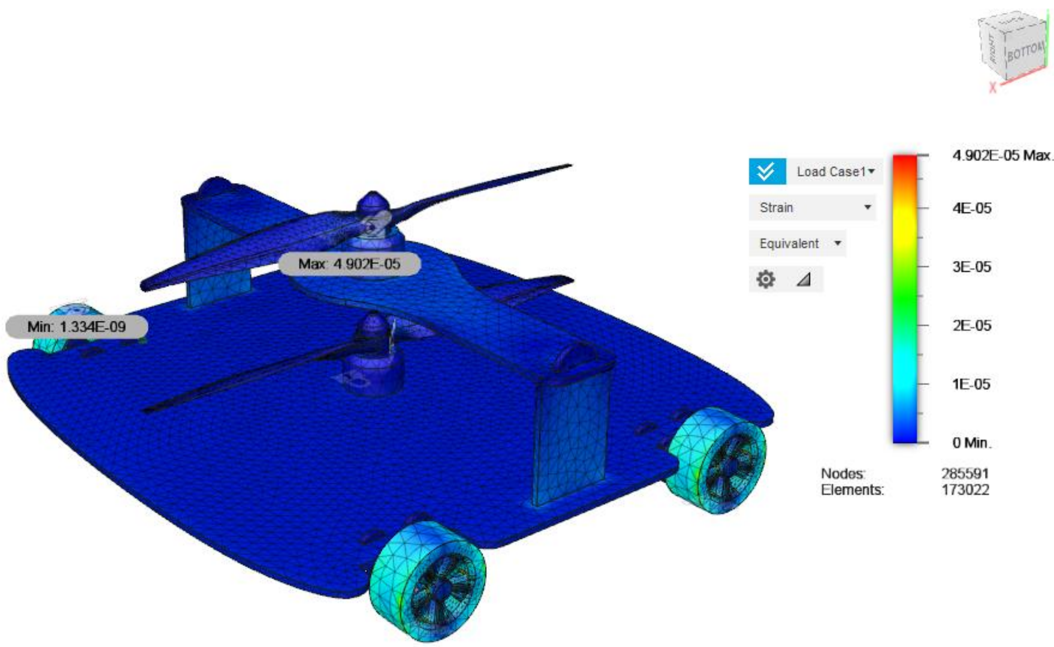


Figure 16: Strain Analysis

The results are very promising as the maximum value of the strain to be produced in our design is very less and cannot result into a permanent deformation. The strain on the tires are larger as compared to the chassis because of the material used to manufacture the tires is rubber and it is more elastic than acrylic with a smaller value of material stiffness which means to cause a one-meter deformation in the tires, we need smaller value of force as compared to the force we need to apply on the chassis to cause the similar amount of strain.

Finite Element Analysis (Displacement):

To check how much the geometry will displace from its original constrained position because of the produced stresses and strain, a displacement Finite Element Analysis was also performed, and results are attached below:

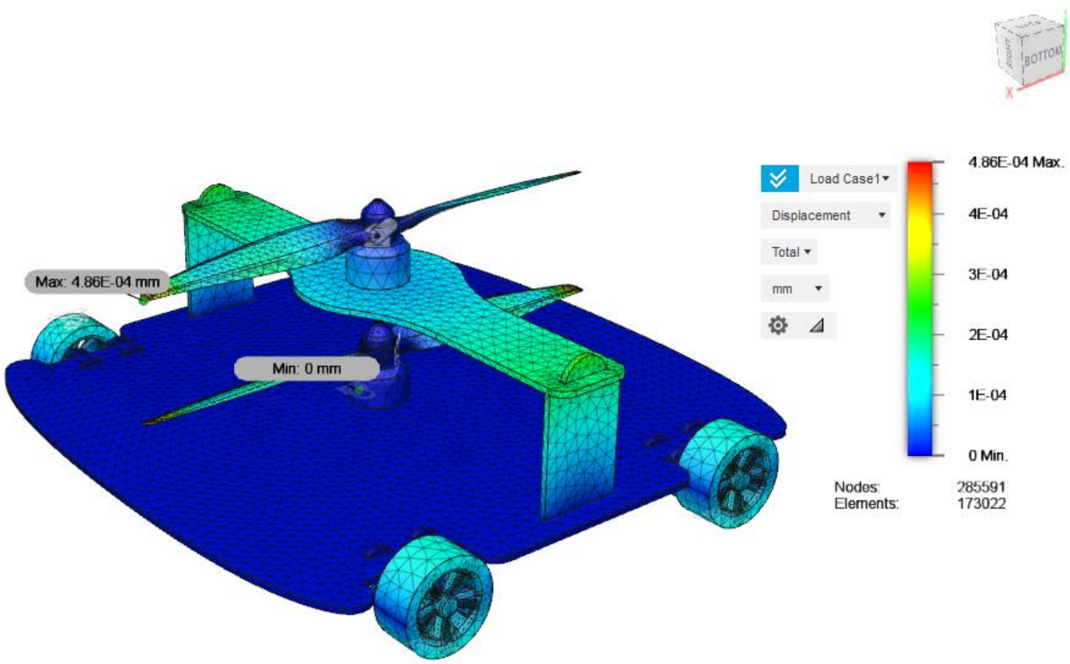


Figure 17: Displacement Analysis

The results of the strain analysis told us the deformation per unit length, but the displacement analysis is telling us the displacement in millimeters. The maximum value of displacement is 0.00048 mm which is almost zero and hence the model will now show any noticeable displacement during the course of its motion on a wall.

Finite Element Analysis (Reaction Forces):

The reaction forces generated inside the model under a fully constrained static stress Finite Element Analysis are shown below:

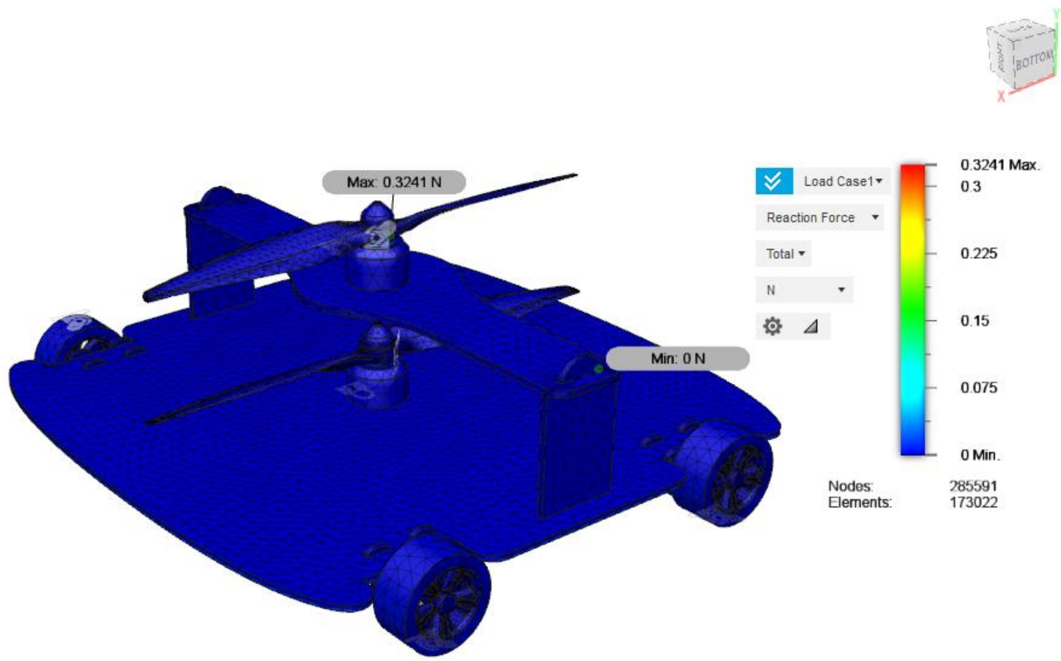


Figure 18: Reaction Force Analysis

The results are mostly evenly distributed and the reason behind it are the center of gravity and center mass of our robot which are exactly in the center of the chassis. As the robot will climb, due to the charging wire attached to it the downward weight on the robot will increase and hence the reaction forces on the bottom part of the robot will increase. But as the stress analysis previously discussed shows that there will be no significant deformation, we can conclude that the reaction forces will not exceed the yield point.

Finite Element Analysis (Contact Pressure):

The pressure generated inside the model because of the reaction forces was calculated using a Finite Element Analysis to ensure the self-induced stresses inside the model (apart from the external stresses) will not lead to a failure. The results are shown below:

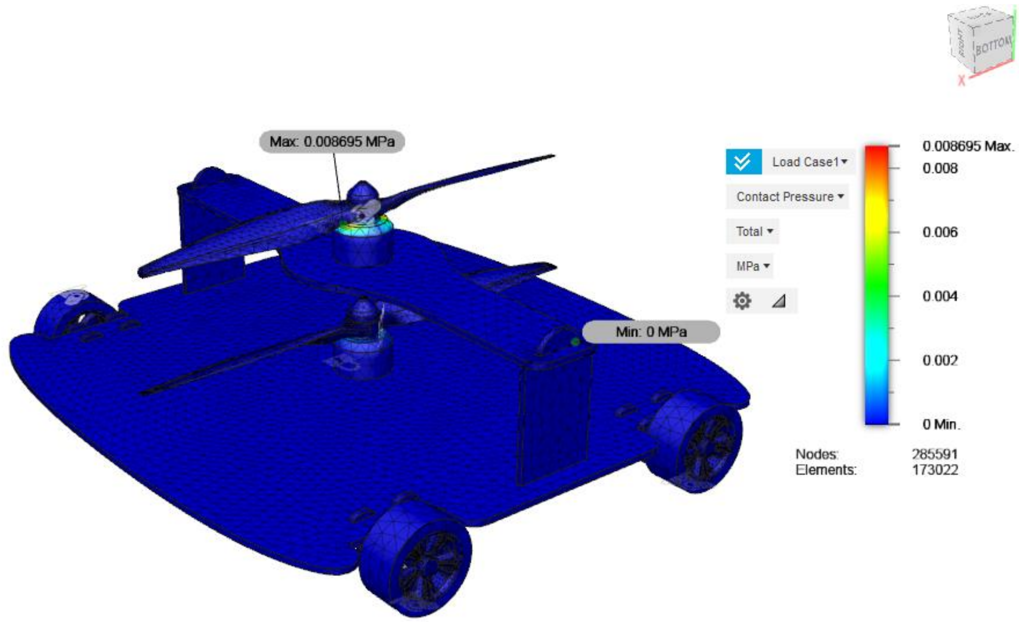


Figure 19: Constant Pressure Analysis

As the reaction forces are almost uniformly distributed on the model, the same goes for the pressures induced because of it. The values of the contact pressures are well below the yield strength point and hence it will not cause a permanent deformation or mechanical failure.

Summary of Finite Element Analysis:

In order to understand the Finite Element Analysis in a better way, we have attached a table below summarizing all the type of FEA analysis performed with the help of their maximum and minimum values so that anyone can get exact values of the all the quantities.

Name	Minimum	Maximum
Safety Factor (Per Body)	1.5	2
Stress		
Von Mises	6.81E-08 MPa	0.008435 MPa
1st Principal	-0.005126 MPa	0.01236 MPa
3rd Principal	-0.01204 MPa	0.005177 MPa
Normal XX	-0.00676 MPa	0.009128 MPa
Normal YY	-0.01117 MPa	0.012 MPa
Normal ZZ	-0.007952 MPa	0.007572 MPa
Shear XY	-0.002823 MPa	0.004748 MPa
Shear YZ	-0.002021 MPa	0.001973 MPa
Shear ZX	-0.002204 MPa	0.002609 MPa

Displacement		
Total	0 mm	4.86E-04 mm
X	-2.481E-04 mm	2.987E-05 mm
Y	-4.81E-04 mm	4.802E-04 mm
Z	-1.172E-04 mm	1.287E-04 mm
Reaction Force		
Total	0 N	0.3241 N
X	-0.02286 N	0.07548 N
Y	-0.315 N	0.2622 N
Z	-0.02397 N	0.02426 N
Strain		
Equivalent	1.334E-09	4.902E-05
1st Principal	-1.41E-08	4.459E-05
3rd Principal	-4.624E-05	5.127E-10
Normal XX	-2.726E-05	2.456E-05
Normal YY	-1.979E-05	2.078E-05
Normal ZZ	-1.653E-05	1.55E-05
Shear XY	-4.169E-05	4.074E-05
Shear YZ	-1.632E-05	1.552E-05
Shear ZX	-2.854E-05	2.624E-05

Contact Pressure		
Total	0 MPa	0.008695 MPa
X	-0.002823 MPa	0.00464 MPa
Y	-0.006116 MPa	0.008223 MPa
Z	-0.00186 MPa	0.001952 MPa

Table 6: Summary of Finite Element Analysis

Design Optimization:

In design optimization, we optimize the geometry of our design based on the applied loads and constraints. We can also optimize the loads but in this section, we will only discuss the design optimization of the geometry of our robot.

In any system, there are certain components and geometry areas where the applied stresses have very less values and these areas do not play a very significant role in the overall strength and geometry of the model. But they do increase the weight of the model and if we remove these areas, we can remove this undesirable weight from our design. In designs such as ours where the machine has to work against the force of gravity cancelling the force of its weight, this design optimization technique can play a key role in reducing the weight of the design by keeping the efficiency and strength of the model constant. Design optimization can also help the actuators by allowing them working on lower values as the weight of the overall machine reduces and hence, we can save our energy input and use lower power values actuators as well.

To find such areas of undesirable weight in our wall climbing robot and reduce the weight of our design, we performed a design optimization analysis on our robot using Autodesk Fusion 360. The results of the design optimization analysis are attached below:

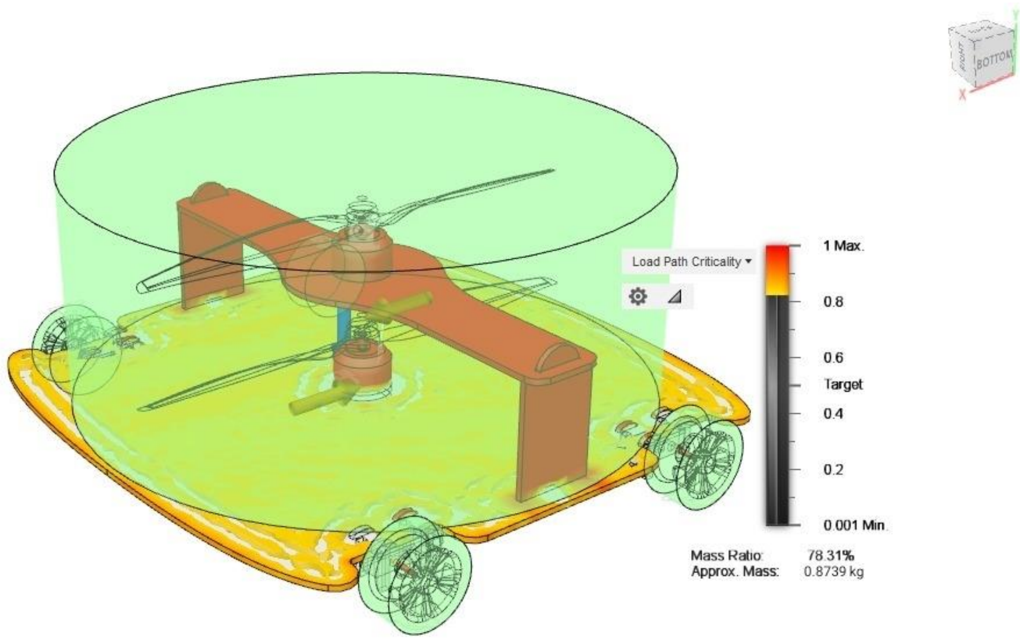


Figure 20: Design Optimization

The encircles areas are the ones which play a key role in the geometry and hence we instructed the software not to apply weight reduction design optimization on these areas. As we can see, there is almost 21.69% extra weight in our design which can be removed by cutting the patterns from the chassis as shown in the results. This weight will be removed during the process of LASER cutting and hence we will be able to reduce the weight of our design by 21.69%. This will help us use a BLDC motor of lower torque value which will consume less input power.

All the calculations provided in the previous section of the report, already includes the factor of design optimization. So, the weight provided in the previous sections were first theoretically calculated and then was optimized and updated.

Summary of Design Optimization:

The summary of the design optimization is given in the following table in the form of numerical values:

Name	Value
Mass Before	1.0924 kg
Mass After	0.8739 kg
Mass Ratio	78.31%
Mass Reduction	21.69%

Table 7: Design Optimization Summary

Motion Planning using MATLAB Simulink:

After Finite Element Analysis and Design Optimization, the next most important thing was to simulate the path of the motion of our robot and verify whether we can use the selected actuators in our robot or not. In order to simulate the motion of our robot against a wall and verify the values of actuator's torques we predicted theoretically, we needed to perform kinematic analysis of our Wall Climbing Robot and we performed these analyses using MATLAB Simulink.

The CAD model of the design was made in PTC Creo 3.0 and this design was imported in MATLAB Simulink using the CAD Import Library of MathWorks Organization for PTC Creo 3.0. After importing the CAD model, all the connections between different components of the bodies were defined as per their actual working and in order to define the contacts between the tires and the wall, Contact Force Library of MathWorks was used for the 2015a version of the MATLAB. In Simulink, the objects are defined in terms of a block diagram. We had to define several subsystems because of the complexity of our design. The main system of the design in the Simulink is shown below:

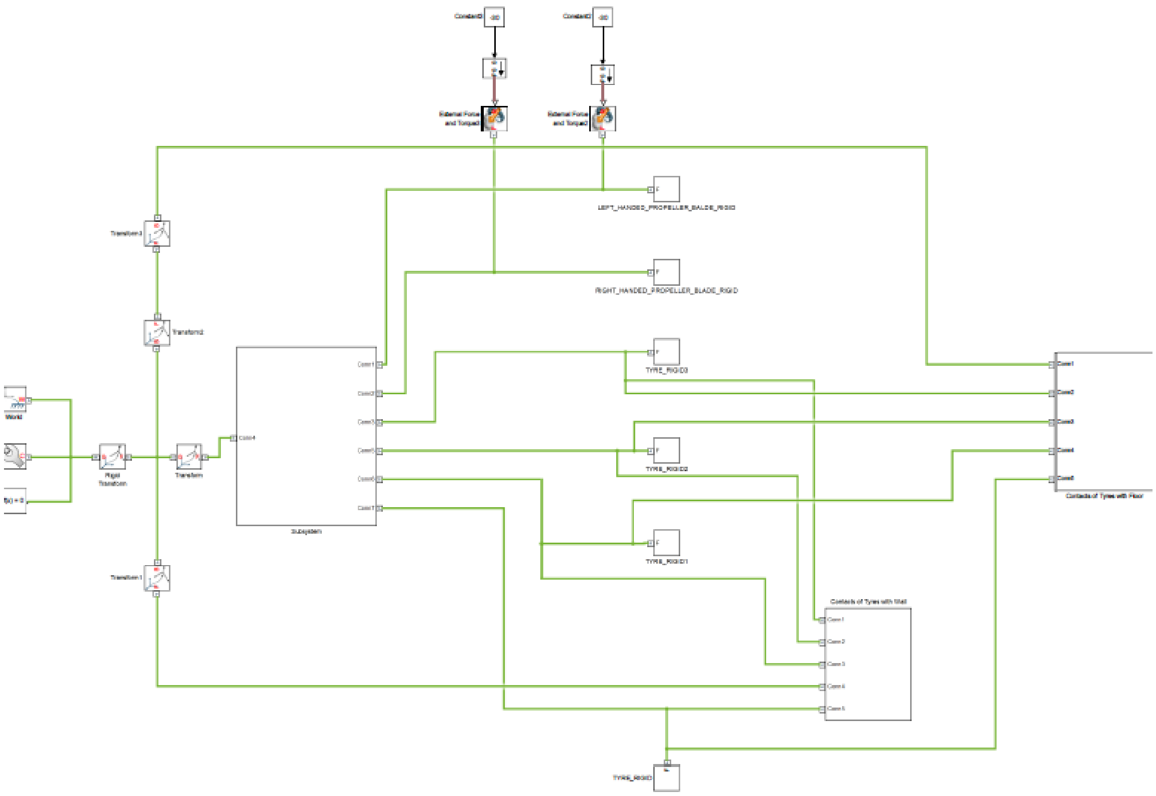


Figure 21: Main System (Simulink)

The first sub system which contains all the actuators and the input values going in them is shown below:

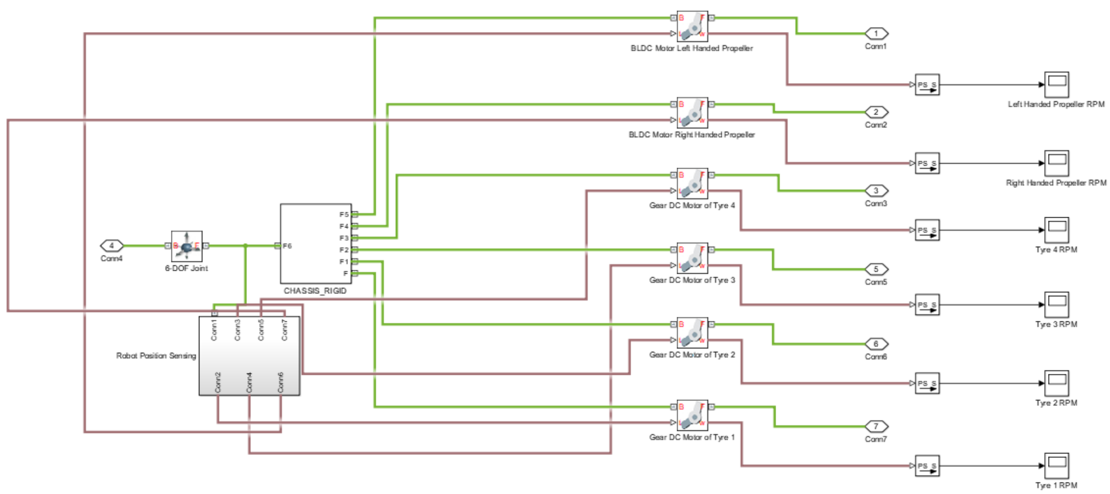


Figure 22: Subsystem (Simulink)

This subsystem can be defined as the plant of our system. All the torque values are provided to the robot using this system and they are monitored using the scope. As we plan to control our robot with a wireless remote control system, we are developing a closed loop feedback control for our robot in which the error is seen directly by the eyes of the person controlling the robot and hence he will be able to provide the feedback into the system depending on the error he sees with the help of the remote control. The control system of the robot is inside this plant subsystem. The control system is shown below:

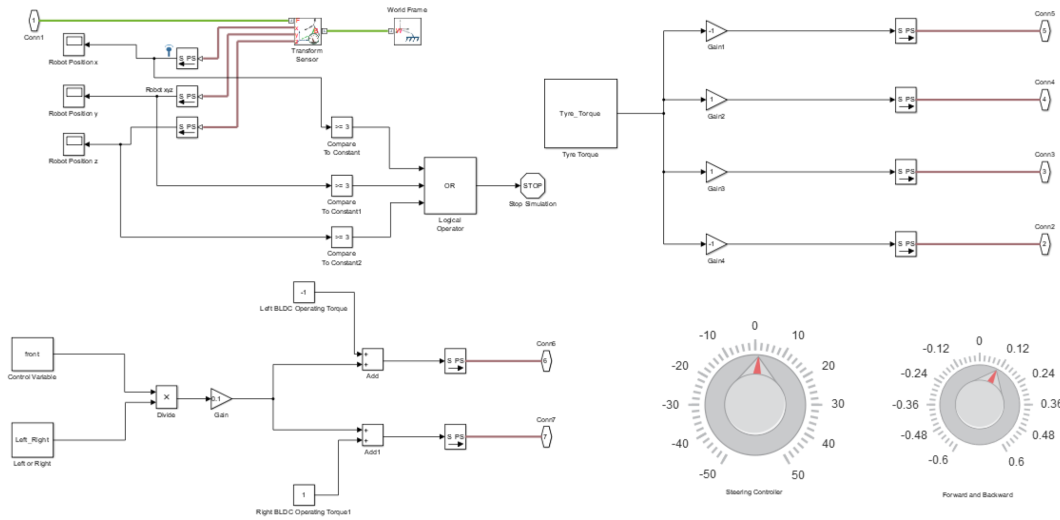


Figure 23: Control System (Simulink)

Here as we can that two knobs are present, the left knob is to steer the robot in a specific direction in the wall and the right knob is to move the robot forward and backward while climbing a wall or we can say that the right knob can increase or decrease the height of the robot. There is a scale calibration made for the purpose of steering in the lower left corner which will steer robot in any direction by 10 degrees by creating a 0.1 Nm torque difference between both the propellers. Let's say that we want to turn right by 10 degrees, so for that purpose we will give the command to increase the torque by 0.1 Nm in the right direction the help of the knob and the difference between the right and left handed propeller's torque will be 0.1 Nm to provide us the desired motion path. This way the steering of the robot can be done. The sensitivity of the scale can be increased or decreased by just simply changing the gain value of our calibration logic. Because the robot cannot climb more than 3 meters because of the power supply cable attached to it, there is a logic developed by sensing the position of robot in all three axes by applying the condition that if the distance covered in any direction will be greater than 3 meters, the robot will stop at this position. The communication using the remote-control system will be established using a remote controller and for that purpose wireless signal communicators will be used.

A screenshot of the model climbing the wall in Simulink Mechanics Explorer environment is shown below:

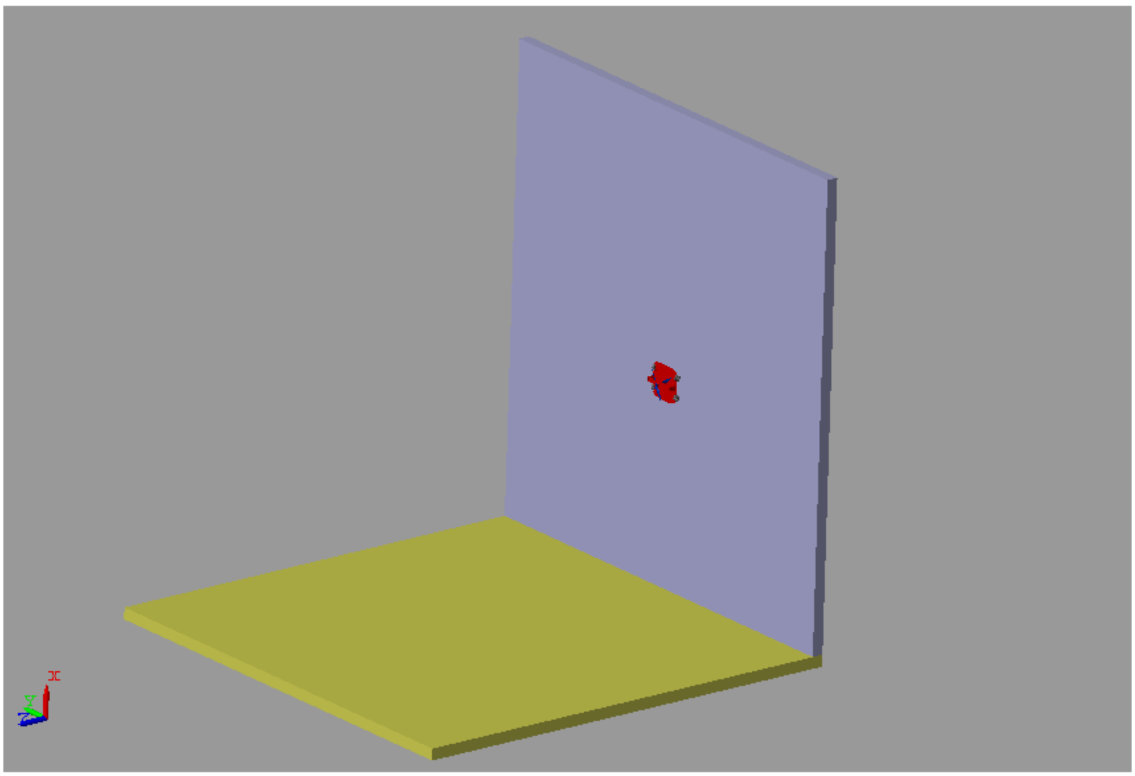


Figure 24: Simulink Mechanics Explorer

Thrust and Torque Calculation Using Simulink:

The purpose of this section is to verify the torque and thrust values we calculated theoretically using Simulink. Rather than calculating the torques, we are applying the values of the calculated torques and obtaining the values of RPMs generated to check if these RPM values are as per the values, we expected based on the standard values of the motors. We decided to perform the Thrust and Torque Analysis because of two main reasons:

1- Motors both BLDC and geared DC motors, are found in the market based on the values of their RPMs. So, we can get a range of motors to use for our project with the help of graphs generated by the Simulink analysis and then we can buy a standard motor from the market based on these results.

2- We are using a closed loop feedback control system and it is easier for us to feed torque as input signals and measure the RPMs of the tires and propellers using optical encoders to rectify the error in the closed loop feedback control system which will be operated by the user with the help of a remote control. We can integrate a GUI in the remote control and then the user will be able to check the difference of RPMs himself.

RPMs of the Left-Handed Propeller:

The RPMs of the Left-Handed Propeller are shown in the graph below. The units are radian per seconds as MATLAB version 2015a does not have radian per minute as a default unit of rotational velocity. They are negative as it is rotating in clockwise direction.

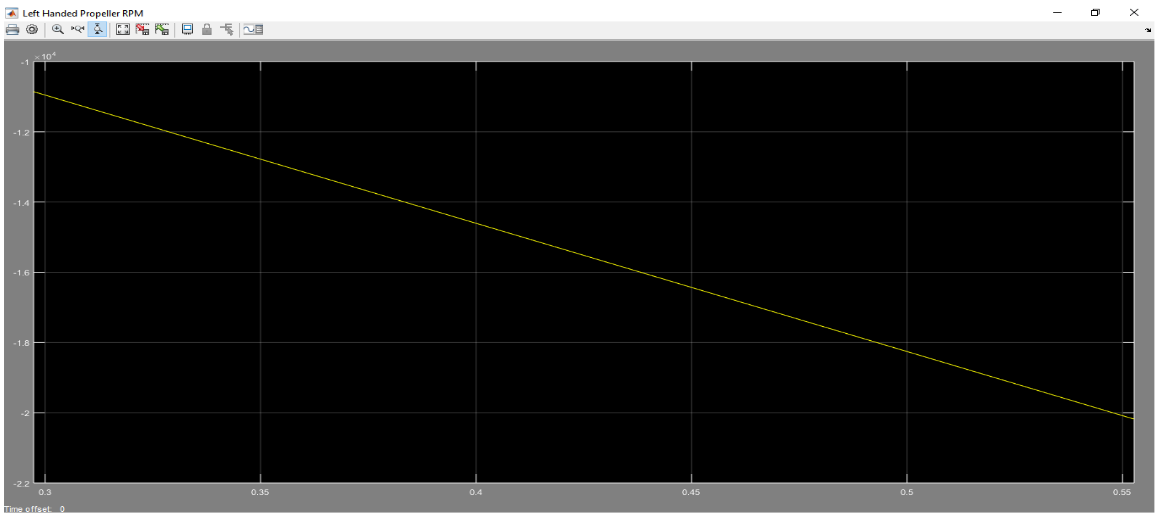


Figure 25: RPM Graph of Left-handed Propeller

The speed is increasing gradually because the motor is not given working voltage instantly, rather the voltages are established over the passage of time to maintain a smooth motion and keeping the other electrical components out of danger of burning because of sudden voltage spike. The values of radian per seconds verify our calculations as our selected motor have the exact same rotational velocity value when it reaches the desired torque and working voltage.

RPMs of the Right-Handed Propeller:

The RPMs of the right-handed propeller are shown in the following graph obtained from MATLAB Simulink. The units are radian per seconds as MATLAB version 2015a does not have radian per minute as a default unit of rotational velocity. They are positive as it is rotating in anti-clockwise direction.

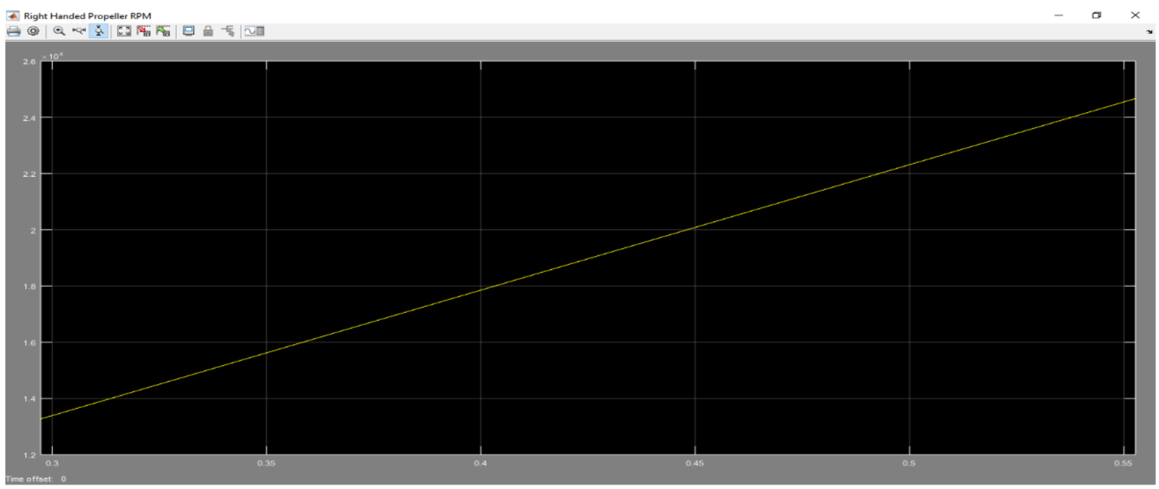


Figure 26: RPM Graph of Right-handed Propeller

The speed is increasing gradually because the motor is not given working voltage instantly, rather the voltages are established over the passage of time to maintain a smooth motion and keeping the other electrical components out of danger of burning because of sudden voltage spike. The values of radian per seconds verify our calculations as our selected motor have the exact same rotational velocity value when it reaches the desired torque and working voltage.

RPMs of the Tire:

The RPMs of the tires are shown in the following graph:

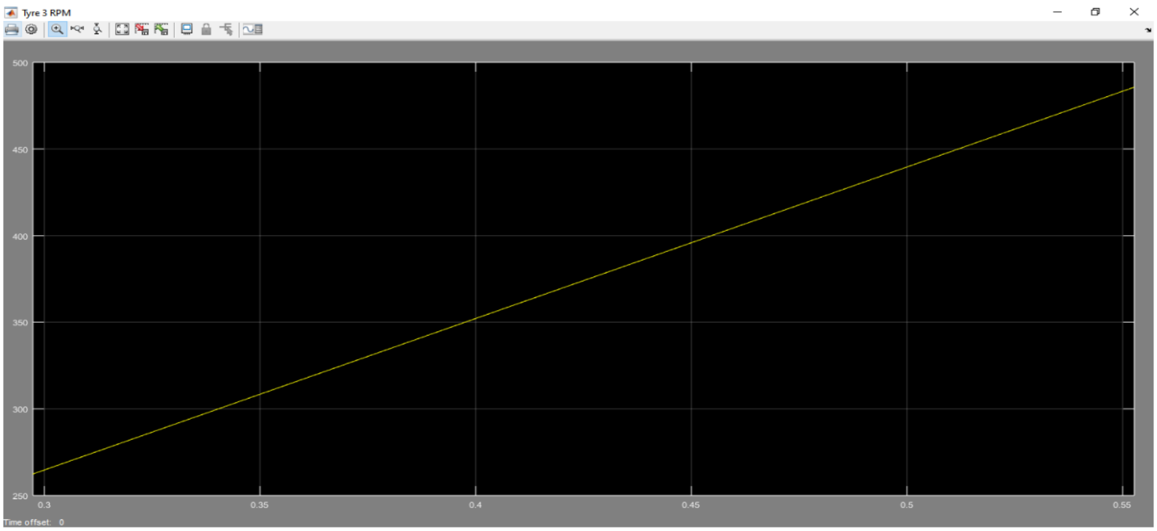


Figure 27: RPM graph of tires

This also verifies our calculations and justifies the TT geared DC motor we selected for our robot's tires. The speed is increasing gradually because the motor is not given working voltage instantly, rather the voltages are established over the passage of time to maintain a smooth motion and keeping the other electrical components out of danger of burning because of sudden voltage spike.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

So, this robot can move on the ground and it also has the ability to climb plain vertical walls. This robot consists of a feedback system, chassis and four wheels which are independently driven using gear DC motors. There are two propellers mounted on the chassis which are driven by Brushless DC (BLDC) motors. While on the vertical wall, the traction force between tires and wall is fortified by these propellers. The propellers continuously apply thrust on the walls and make sure that the robot doesn’t fall off from the wall. These propellers also help the robot to steer itself on the wall. This is done by utilizing the propeller walk effect generated by the two propellers in pair (Right and Left-handed Propellers). The motion of robot is externally controlled by a joystick controller. The closed loop feedback system is developed by the help of simulation software.

It is recommended that instead of going for the joystick controller, a line/path follower mechanism can also be employed. This would enable the robot to perform the task without controlling it manually. The human effort of controlling it will no longer be required. Also, by implementing this path follower system, the robot will be able to expand its applications to machine learning domain. By making the robot to study different paths, we will be able to get optimized results if the robot is allowed to go into an unknown path. Thus, this will give our robot the liberty to achieve Artificial Intelligence (AI) domain.

Another recommendation is that, the reach of this robot can further be expanded by using a propeller which has 2 D-O-F (Degrees of Freedom). This will enable us to inverse the direction of propellers. Hence the robot would be able to climb the ceiling by continuously applying thrust in the ceiling's direction (as it does with the wall).

Furthermore, such motor casings can be made which allows different tires to get attached to them. So, by using different mounts of tires for different surfaces of walls, this robot would be able to climb on many different surfaces. This would ultimately increase the applications of this robot.

This robot can already withstand severe conditions but changes in the building materials of this robot can also be done to make it usable in harsh environment, even in radioactive sites.

These are some of the recommendations from our side. This robot has a vast area of applications and a lot of modifications can be done depending on the specific need for the specific task required.

REFERENCES

Alkalla Mohamed, Mohamed Fanni, Abdelfatah Mohamed, Shuji Hashimoto. "Tele-operated propeller-type climbing robot for inspection of petrochemical vessels." *IEEE*, 2017: 18.

Fengyu Xu, Xingsong Wang, Guoping Jiang. "Design and Analysis of a Wall-Climbing Robot Based on a Mechanism Utilizing Hook-Like Claws." *International Journal of Advanced Robotic Systems*, 2012: 9.

Hafiz M. Abd-ur-Rehman, Fahad A. Al-Sulaiman, Aamir Mehmood, Sehar Shakir, Sehar Shakir. "The potential of energy savings and the prospects of cleaner energy production by solar energy integration in the residential buildings of Saudi Arabia." *Journal of Cleaner Production*,, 2018.

Hwang Kim, Dongmok Kim, Hojoon Yang, Kyouhee Lee, Kunchan Seo, Doyoung Chang and Jongwon Kim. "Development of a wall-climbing robot using a tracked wheel mechanism." *IEEE*, 2008: 9.

Mohamed G. Alkalla, Mohamed A. Fanni, Abdelfatah M. Mohamed. "A novel propeller-type climbing robot for vessels inspection." *2015 IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*, 2015.

Navaprakash Na, Uppu Ramachandraiahb, Muthukumaran Gc, Rakesh Vd, Ashutosh Pratap Singhe. "Modeling and Experimental Analysis of Suction Pressure Generated by Active Suction Chamber Based Wall Climbing Robot with a Novel

Bottom Restrictor." *International Conference on Robotics and Smart Manufacturing (RoSMa2018)*, 2018: 8.

Rajashekhar, C.R.M.V.V. Kumar, G.K.Dayananda. "Studies on cost effective glass wall." *National Conference on Challenges in Research & Technology in the Coming Decades (CRT 2013),*, 2013: 11.

Riad Hossain, Nafiz Ahmed. "Design and Implementation of a Wall Climbing Robot." *International Journal of Computer Applications*, 2018: 5.

Zhang, H. "Sky cleaner 3." *IEEE Robotics & Automation Magazine,*, 2006: 3.