Design and Analysis of Wall-Climbing Robot

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Abstract. A robot is a machine that can perform desired tasks with high accuracy and minimal human interference. Robots are employed to automate repetitive activities and work in unpredictable or hazardous environments. Depending upon the functionality, different types of robots, such as Automated Guided Vehicle, Articulated Robots, and Humanoids are developed. Wall-climbing robot is one which freely moves on surfaces like walls and ceilings. These are used in inspection and cleaning of walls. Design of wall-climbing robot deals in two aspects-locomotion mechanism, by using wheels and legs for mobility, and an adhesion mechanism to counter the force of gravity firmly with the help of vacuum suction or magnetic adhesion methods. The aim is to design a wall-climbing robot that travels on irregular surfaces. For achieving this, a Reverse Thrust and Wheel-driven type of robot was adopted. For climbing designer walls, the concept of hinges was used. Modelling and Simulation of the robot is done using SolidWorks software and performed the CFD analysis of the ducted fan using ANSYS Fluent.

Keywords: WCR - Wall Climbing Robot · Reverse Thrust · Wheel-driven Robot

1 Introduction

Robots are used to increase efficiency and ensure workers' safety. Recent years have seen the development of wall-climbing robots, which are mostly used for activities that are risky or expensive to conduct by a human operator in a difficult environment. These robots are popularly used for cleaning purposes and inspection of high-rise structures. The two main operational methods for classifying WCRs are adhesion and locomotion. The adhesion can be created using Suction cups, an elastic and flexible member which creates vacuum. It is capable of providing a large weight to force ratio. However, it is quite challenging to control attachment and detachment of the suction cups. Another method of adhesion is using Reverse thrust, which uses a vacuum impeller-based mechanism that is connected to a motor to establish adhesion to the surface. The pressure decreases due to the aerodynamic swirl effect created by the high-speed spinning of the impeller. As a result, the target surface is aerodynamically drawn to the generated negative pressure. The motion of the robot can be created using either Leg-based mechanism that uses step-wise operation, as required by the suction cups, as well as the ability of employing an obstacle avoidance system. Disadvantages of this strategy is the use of a highly complex control

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systems. Another method is using a Wheel-driven Robot. Wheel-driven locomotion is only used with reverse thrust-based WCRs because they can move continuously due to the continuous adhesion force they apply, even though they have trouble avoiding obstacles and can slip if not correctly managed.

2 Literature Review

Rohith M et al. [1] "Design and Development of Semi- Autonomous Wall Climbing Robot Mechanism": The purpose of this research paper is to present a wall climbing robot mechanism which can be easily scaled up and applied in various fields like, search and rescue, surveillance etc. The objective is to make a four wheeled robot which can climb and manoeuver surfaces at any inclination be it perpendicular, acute or obtuse.

Peng Liang et al. [2] "Force Analysis and Verification of Wall-climbing Robot with Rotor-propellers". This article introduces a wall-climbing robot that uses the reverse thrust of the propeller as the adsorption force.

Tohru Miyake et al. [3] "Basic studies on wet adhesion system for wall climbing robots" This paper reports a vacuum-based wet adhesion system for wall climbing robots. In this adhesion system, a suction cup adheres on a wet surface.

Hwang Kim et al. [4] "Development of a wall-climbing robot using a tracked wheel mechanism" In this paper, a new concept of a wall-climbing robot able to climb a vertical plane is presented. A continuous locomotive motion with a high climbing speed of 15m/min is realized by adopting a series chain on two tracked wheels on which 24 suction pads are installed.

3 Problem Statement

A wall climbing robot is the one that can climb vertical surfaces, against gravity, whilst adhering to the vertical surface. There are multiple adhesion techniques available, but the principle chosen for this project is "Reverse Thrust" produced by a brushless DC motor that powers a ducted fan. The primary problem statement driving the design is:

1) To create a WCR that can effectively adhere to the wall surface
2) The WCR should be capable to move on irregular surfaces with protrusions and depressions.

4 Methodology

The first step is choosing the type of adhesion and locomotion mechanism. A reverse thrust and wheel-driven robot is chosen because of the simplicity and the advantages associated with them such as low-weight. The next step is to choose the required electronic components. There are 2 main circuits present in the robot, namely circuit for adhesion and circuit for propulsion. Components involved in adhesion circuit are responsible to make WCR "stick" to wall. They include:

1) Brushless DC motor: A BLDC motor is an electronically commutated DC motor that does not have brushes. The kV rating of a brushless motor refers to how much RPM it turns per volt. So, a BLDC motor with a kV rating of 1000kV will spin at 1000 RPM when 1 V is applied.
2) Electronic Speed Controller (ESC): An ESC is an electronic circuit that controls and regulates the speed of an electric motor.
3) Ducted Fan: It is a multi-bladed fan in a tubular duct. It is simply a propeller with an additional nacelle covering the tips of the blade.

Components involved in propulsion circuit are responsible to impart motion to the robot and include:

1) HC-05 Wireless Bluetooth RF Transceiver: It is a bluetooth module that is designed for wireless communication.
2) Arduino UNO: A microcontroller board is called Arduino Uno. It acts as the brain of the robot.
3) L298N Motor Driver: A dual H-Bridge motor driver that enables simultaneous speed and direction control of two DC motors.
4) Motors, Wheels and Battery: Wheels and motor imparts motion to the robot. The metal gears motors have better wear and tear properties. The wheels chosen have a diameter of 0.065m (65 mm). A battery is a power source that provides the required voltage to each electronic component.

Once the components are chosen, the Circuit diagram can be constructed (Fig. 1).

The next step is to approximate the dimensions & weight of the robot for modelling purpose and to obtain the necessary specifications of the components. It is desired to create the robot as small as possible to reduce weight and to increase the efficiency. So, the modelling is started with size of 0.3m*0.3m*0.003m and with the components consuming least space. The weight of robot can be approximated using weight build-up schedule as follows (Table 1).

The weight of the robot can be approximated to1.5kg (1500gm). To account for "a safety factor" the weight is taken to be 1.7kg for calculations.

The specifications of the required Motor-battery combination can be obtained using mathematical equations.

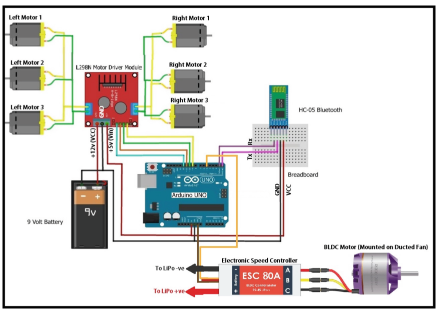


Fig. 1. Circuit Connections

Table 1. Weight Buildup Schedule

	Component	Weight (gm)	Quantity	Total Weight (gm)
1	Motors and Wheels	40	6	240
2	Motor Driver	26	1	26
3	Arduino UNO	25	1	25
4	HC – 05 Bluetooth Module	25	1	25
5	Battery	500	1	500
6	Ducted fan and BLDC motor	364	1	364
7	ESC	100	1	100
8	Wires	1	-	20
9	Chassis	200	1	200
	TOTAL			**1500**

Thrust is the "pushing" force that allows the WCR to stick to the target surface. The Free-body diagram of WCR at equilibrium is obtained as (Fig. 2):

Where, the total weight of the robot = $\boldsymbol{W}$

Friction force acting between the wheels and wall = $\boldsymbol{f}$

Coefficient of Friction = $\boldsymbol{\mu}$,

Reverse Thrust Force = $\boldsymbol{F_s}$

Driving Force of Wheel = $\boldsymbol{F_d}$

Torque produced by wheel motor = $\boldsymbol{T_m}$

Radius of wheel = $\boldsymbol{r_w}$

Normal reaction force = $\boldsymbol{N}$

Using Force balancing in all directions, the relation obtained is

$$F_s = \frac{W}{\mu} = \frac{Mg}{\mu}$$

Therefore, Minimum thrust force required is 28 N or ~ 2.8 kg-force. Using the data provided for thrust produced by an 1850 kV motor with different battery combinations,

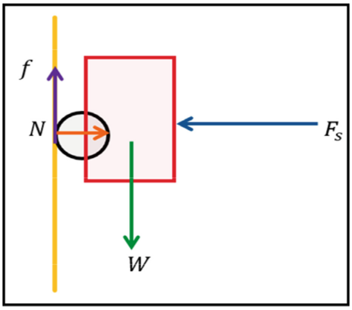


Fig. 2. FBD of robot for reverse thrust calculation [5]

Table 2. Ducted fan load testing data from manufacturer

Li-Po	6s (22.2V)	6s (24.0V)	6s (25.2V)
Thrust	3.57 kg	4.01 kg	4.32 kg
Current	103 A	117 A	126 A
Power	2286 W	2808 W	3175 W
ESC	120 A/ LV	150 A/ LV	150 A/ LV
Battery	3500 mAh – 40 °C	3500 mAh – 40 °C	3500 mAh – 40 °C

it is observed that thrust provided by 1850 kV BLDC motor with a 6s Li-Po battery of 25.2 V, at full throttle is 4.32 kg-force (Table 2).

For the robot to move, the wheel motor should produce a certain minimum torque, called driving-force of the wheels.

Consider the Free-body diagram of the robot when climbing upward (Fig. 3),

The Torque of the wheel-motor required is

$$T_m \geq (\mu F_s + W) r_w.$$

Forward Driving Force provided by all 6 wheels

$$f + W = \mu F_s + W = (0.6 * 28 + 15) = 32N$$

Forward Driving Force provided by 1 single wheel is 5.33 N

A wheel of Radius 32.5 mm is chosen. Therefore, minimum Torque required to move forward is

$$\begin{aligned} F_{d\,\text{single wheel}} * r_w &= 5.33 * 0.0325 = 1.87\text{N} - \text{m} \\ &= 0.187\text{kg} - \text{cm} \end{aligned}$$

A geared motor that produces a torque of 5 kg-cm is chosen for the wheels.

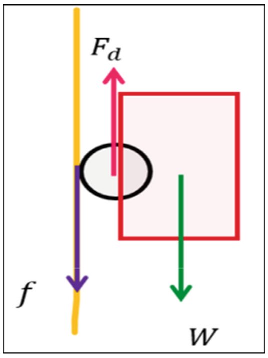


Fig. 3. FBD of robot for driving torque calculation [6]

The next step in the process was to create the CAD model of robot.

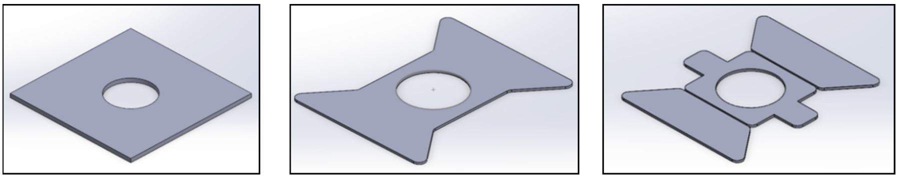
An initial chassis is designed in SolidWorks as per assumed dimensions. However, it was designed only as per the required dimensions and not optimized. Then the chassis is modified to reduce material in order to reduce weight. Then the chassis is the divided into 3 parts, connected with hinges, to tackle the problem of climbing irregular surfaces (Fig. 4).

The wheels, with suction cups attached to them are then added, so that the wheels can adhere to the wall without the help of reverse thrust. Then the electronic components including ducted fan, BLDC Motor, Arduino UNO board, L298N Motor Driver are assembled into the model.

The next step is to verify the thrust produced by the propeller using Finite element analysis. This is performed on ANSYS for the ducted fan model being used. The purpose of this analysis was not only to prove that the concept of ducted could produce the required force but also to find out the values of force obtained at planes which are at certain fixed distances from the plane of the fan (Fig. 5).

Firstly, the propeller was imported into ANSYS Software and enclosures for static & rotary domain were created. Booleans is then used to create a rotary as well as a flow domain. Then, meshing is done and an input of 20,000 RPM for propeller and fluid flow from inlet to outlet, velocity streamlines, velocity contours, pressure contours and velocity vectors were obtained (Figs. 6, 7 and 8).

To verify the functioning of the hinge-concept, motion analysis is performed using simulation feature of SolidWorks software. A path with continuous increasing slope is created and 150 RPM is given to wheels. By this motion analysis it is observed that the hinge concept is successful in climbing the wall (Fig. 9, Table 3).



(a) Initial iteration of the chassis **(b)** Second iteration of the chassis **(c)** Final iteration of the chassis

Fig. 4. Iteration of the chassis

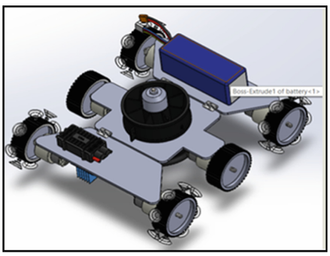
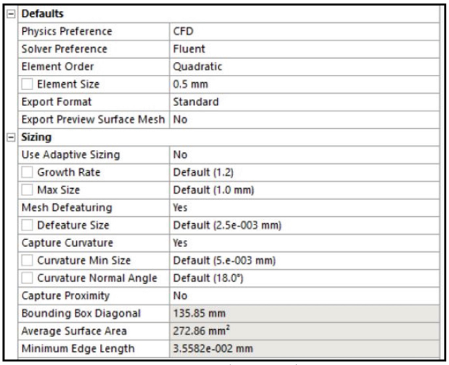
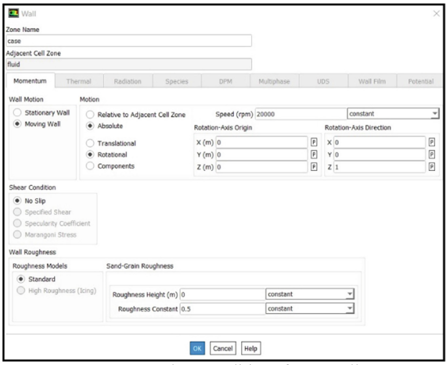


Fig. 5. Assembly of the components

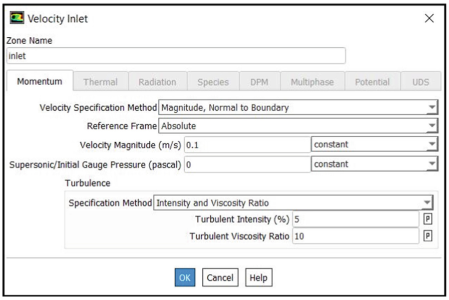


Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Element Order	Quadratic
Element Size	0.5 mm
Export Format	Standard
Export Preview Surface Mesh	No
Sizing	
Use Adaptive Sizing	No
Growth Rate	Default (1.2)
Max Size	Default (1.0 mm)
Mesh Defeaturing	Yes
Defeature Size	Default (2.5e-003 mm)
Capture Curvature	Yes
Curvature Min Size	Default (5.e-003 mm)
Curvature Normal Angle	Default (18.0°)
Capture Proximity	No
Bounding Box Diagonal	135.85 mm
Average Surface Area	272.86 mm²
Minimum Edge Length	3.5582e-002 mm

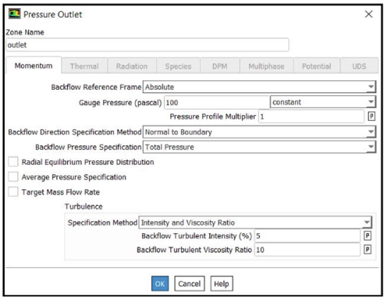
(a) Mesh properties



(b) Boundary conditions for propeller

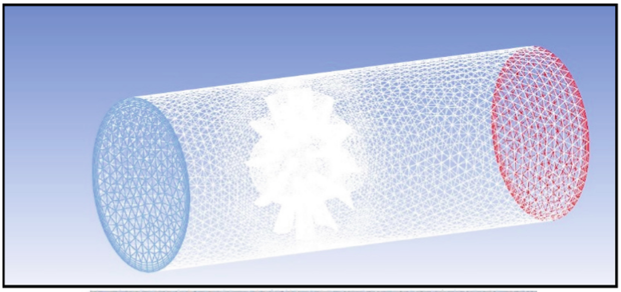


(c) Velocity inlet conditions



(d) Pressure outlet conditions

Fig. 6. ANSYS Fluent inputs



Domain	Nodes	Elements
fluid	861530	3000999

Fig. 7. Mesh and Mesh Information

5 Results and Discussions

The final CAD design is obtained as (Fig. 10):

Chassis members are connected through hinges, which allows independent motion of each member. This allows the robot to climb irregular surfaces easily, as verified

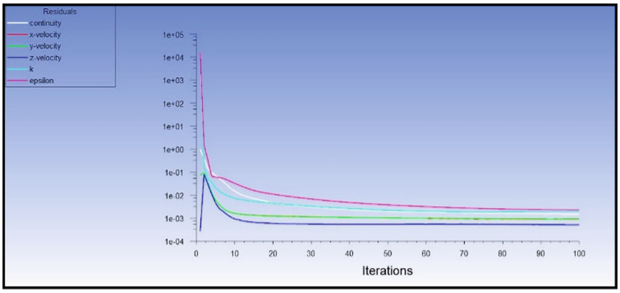


Fig. 8. Convergence plot

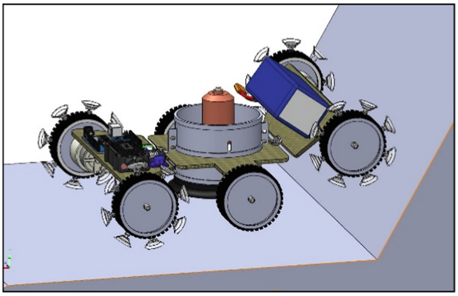


Fig. 9. Motion analysis of robot

Table 3. Specifications of the robot

	ITEMS	SPECIFICATIONS
1	Dimensions of chassis	0.3m*0.3m*0.003m
2	Weight	1.5 kg
3	Wheel diameter	0.065 m
4	Speed of robot	0.51 m/s
5	Suction motor	1850 kV BLDC
6	Driving motor	150 RPM, 5 kg-cm Torque
7	Power supply	6s Li-Po Battery 25.2 V

by motion analysis in SolidWorks. The simulation has produced satisfactory results (Fig. 11).

The CFD (Computational Fluid Dynamics) results are obtained as:

The **velocity contour**, can be observed below. The velocity contour shows the visual representation of the fluid velocity distribution within the given flow field (Fig. 12).

The above figure shows the **pressure contour** for the flow domain. It can be clearly observed that there is a suction effect produced by the propeller (Figs. 13 and 14).

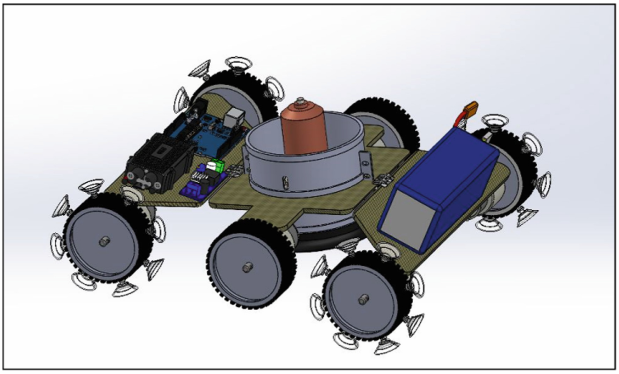
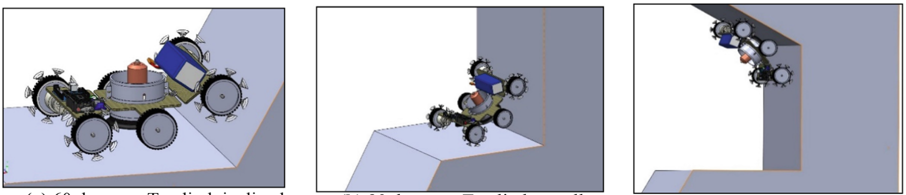


Fig. 10. Final assembly of the robot

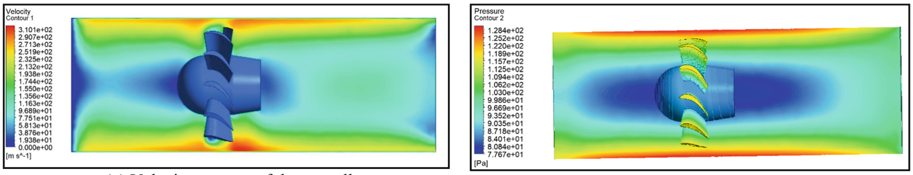


(a) 60 degree – To climb inclined slope

(b) 90 degree – To climb a wall at right angle

(c) 120 degree – To climb a wall protruding wall

Fig. 11. Different cases of wall climbing



(a) Velocity contour of the propeller

(b) Pressure contour of the propeller

Fig. 12. Velocity and Pressure contour of the propeller

The analysis results also showed a suction force of **32.8N**, which correlates with the calculation from the FBD in Fig. 8.

The graph was plotted between variations of Thrust force obtained against distance of ducted fan from the obstructing surface.

6 Conclusions

1. By following the constraints, Design and Analysis of Wall Climbing Robot using SolidWorks, ANSYS, Arduino IDE software's are performed. The force required for robot to adhere to the wall is 28N or 2.8 kg force and the thrust provided by the motor is 4.32 kg force or 43.2 N. Hence the WCR WILL ADHERE TO THE WALL. The

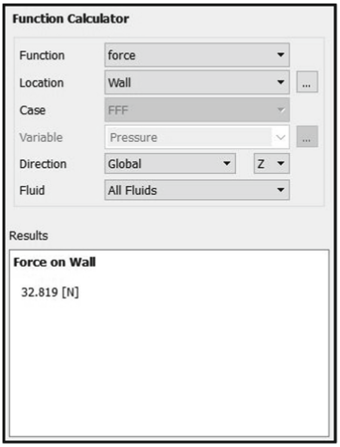


Fig. 13. ANSYS result showing force acting on wall due to the propeller

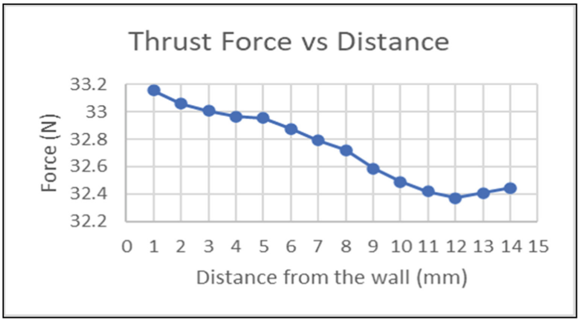


Fig. 14. Suction force vs distance from surface

minimum torque required from each wheel motor to drive the WCR is 0.187 kg-cm. The motors chosen for wheels provide 5 kg-cm of torque. Hence the WCR WILL CLIMB THE WALL.

2. Found optimal mechanical solution to climb irregular surfaces using flexible chassis members connected by hinges. Hinges are constrained to rotate 270 degrees, along with the chassis member, which makes it flexible and allows the WCR to climb irregular walls.

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