TOWARDS OPTIMUM DESIGN OF MAGNETIC ADHESION WALL CLIMBING WHEELED ROBOTS

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ABSTRACT

Climbing and walking robots perform tasks that are too difficult, dangerous or time consuming for the human worker. The main design consideration in the climbing robot is its method of adhesion. The aim of this paper is to lay down the foundation for developing a design framework for magnetically adhering wheeled robots having magnets attached to the base of the robot. The different design parameters affecting the magnetic adhesion include the geometry of the flux concentration plate, effect of the variation of the air gap on adhesion and climbing performance, different materials for magnetic flux concentration and different magnetic arrangements. These different parameters affecting adhesion are simulated and optimized using Magnetostatic analysis in ANSYS simulation software.

Keywords: Wall climbing robot, magnetic adhesion optimization, robot design optimization

1 INTRODUCTION

Climbing and walking robots perform tasks that are too difficult, dangerous or time consuming for the human worker [1, 2] . The main design consideration in the climbing robot is its method of adhesion. Methods of adhesion include Magnetic, Pneumatic, Gecko and Vortex [3]. This paper focuses on magnetic adhesion for Wall climbing robots.

There are three different magnet deployment configurations to achieve adhesion in wheeled wall climbing robots. . They achieve adhesion by using magnetic wheels [4-10], magnetic tracks [11-13]and magnets attached to the base of the body [1].

A few researchers have tried to optimize adhesion based on magnetic wheel [4, 13]and magnetic track adhesion [11], but these have been limited to specific robots. Also, this work has focused on only one or two variables affecting the optimization. To our knowledge, no work has been done to address the entire possible optimization variables and especially the optimization of robot design with magnets attached to the body of the robot. This paper addresses all the possible optimization variables for magnetic adhesion when the magnets are attached to the body of the robot. The comparison of different optimization parameters gives a useful insight into stability of the robot and will help in deciding how to select different design parameters.

2 BACKGROUND

The aim of this paper is to lay down the foundation for developing a design framework for magnetically adhering wheeled robots.

The design cycle comprises of a two step process. The steps are to optimize design and to optimize adhesion. In design optimization, a static and dynamic force analysis is carried out. This analysis serves to optimize design parameters by considering the adhesion force requirement, dimensions of the robot, material properties to allow selection of materials,

the robot configuration and its center of gravity. The parameters obtained from this step provide a gateway to the second step of the design cycle, i.e. adhesion optimization.
The parameters for adhesion optimization depend on methods to strengthen the magnetic field using flux concentrator, the geometry of the flux concentrator, material of the flux concentrator, effect of the variation of the air gap on adhesion and climbing performance, different magnetic arrangements and the effect of wall thickness variations. Their effects are studied using simulations based on Finite Element methods using Magnetostatic analysis in ANSYS. Some of the results are validated by experimentation.

3 DESIGN OPTIMIZATION

Static and dynamic force analysis is necessary to analyze and design the optimum design parameters. In this section, Static and dynamic force analysis for the wall climbing robot is carried out.

3.1 Static Analysis

The stability of the wall climbing robot depends mainly on turn-over failure, sliding failure and roll-over failure as shown in Figure 1. Static analysis helps to find the design parameters to address these stability concerns.

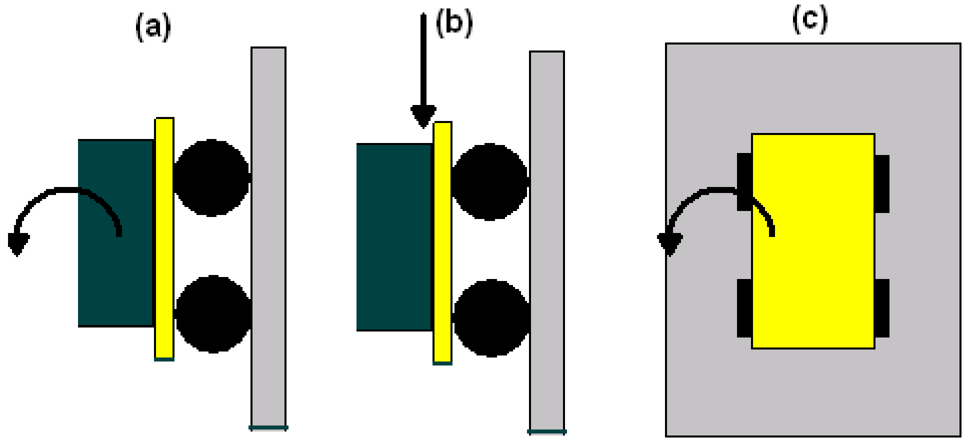


Figure 1: Stability factors a) turn-over failure; b) sliding failure, c) roll-over failure

3.1.1 Sliding avoidance

The ideal wall climbing robot should do climbing surface transitions and climb on surfaces with different slopes. To understand the forces acting on a robot, consider the forces acting on a robot resting on an inclined plane as shown in

Figure 2. The slope of the inclined plane is “θ”.
W= weight of the robot
θ = angle of inclination
F_m = magnetic adhesion force
μ = coefficient of friction of wheels
d = distance of centre of gravity from the climbing surface
L = distance between front and rear wheels

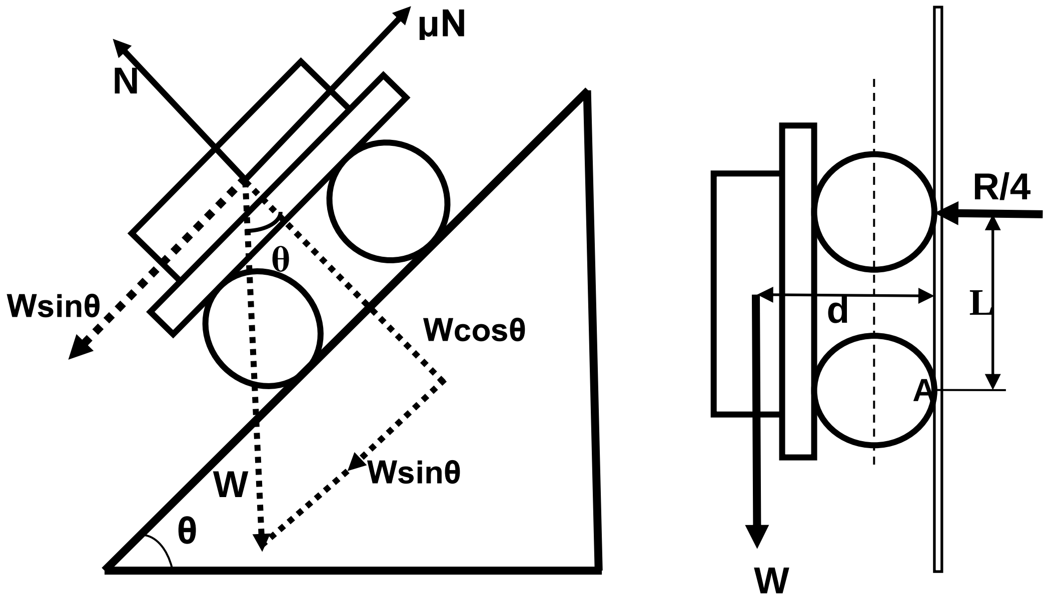


Figure 2: free body diagram of robot moving on an inclined plane

$$\sum F_y = W\cos\theta + F_m - N = 0$$
$$N = W\cos\theta + F_m$$
$$\sum F_x = W\sin\theta - \mu N$$
$$or$$
$$N = \frac{W\sin\theta}{\mu}$$
$$W\cos\theta + F_m = \frac{W\sin\theta}{\mu}$$
$$F_m = \frac{W\sin\theta}{\mu} - W\cos\theta$$

For the robot to avoid slipping

$$F_m > \frac{W\sin\theta}{\mu} - W\cos\theta$$

For the special case of wall climbing robot moving on a vertical surface

$$\theta = 90$$
$$F_m > \frac{W}{\mu} \qquad (1)$$

In order to avoid sliding/slipping of the robot, the magnetic adhesion force should be greater than W/μ. The stability of the robot can be increased by either increasing the coefficient of friction of wheel tyre or decreasing the robot weight.

3.1.2 Turn-over avoidance

From

Figure **2**, Taking moment about point A,

$$\Sigma M = W \times d + \frac{R}{2} \times L = 0$$
$$R = -\frac{2W \times d}{L}$$
$$F_m = R$$
$$F_m = -\frac{W \times d}{2L}$$

To avoid Turn over, the adhesion force should satisfy equation 2.

$$F_m > \frac{W \times d}{2L} \qquad (2)$$

For a given adhesion force, equation 2 can be satisfied by minimising the ratio $\frac{d}{L}$. This means that the centre of gravity should be as close to the surface as possible and the distance between the wheels should be large. Equation (2) shows that in order to avoid turnover, the robot centre of gravity should be kept as low as possible.

The stability criteria to avoid sliding and turn over:

$$F_m > \max\left\{\frac{W}{\mu}, \frac{W \times d}{2L}\right\} \qquad (3)$$

3.1.3 Roll-over avoidance

For simplicity, we assume that the shear force on the robot always acts perpendicular to the wheel. Consider Figure 3(a), the roll over moment M_r will then be

$$M_r = (W \times k) - 2(F_s \times L_1) = 0$$
$$(W \times k) = 2(F_s \times L_1)$$
$$2F_s = \frac{(W \times k)}{L_1}$$

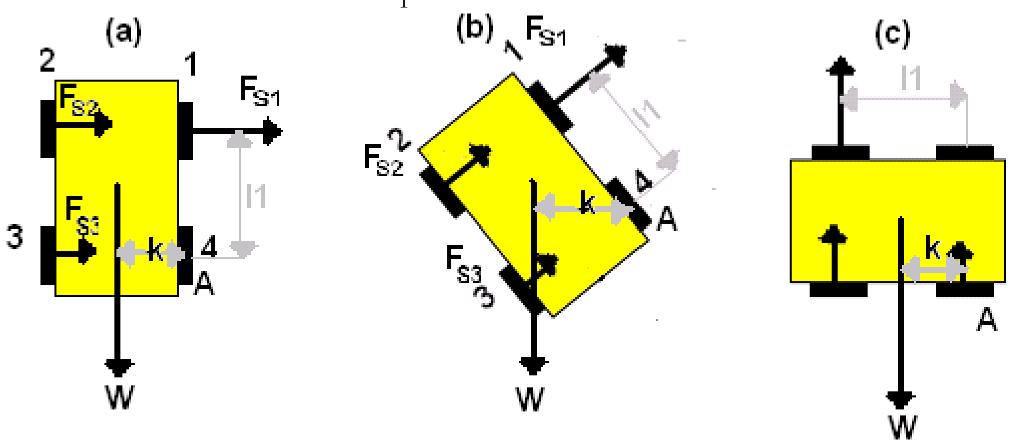


Figure 3: Roll-over forces when a robot is at different orientations on the wall

k=distance between centre of gravity and point A

F_s =shearing force on each wheel
L_1 =moment arm, distance between wheel 4 and 1

If order to avoid roll over,

$$F_s \geq \frac{(W \times k)}{2L_1} \qquad (4)$$

The roll-over force varies with the angle of the robot on the wall (*Figure 3* (b) and (c)). This is due to the variation of the moment arm with different orientations of the robot.
The robot length (distance between the wheels) and the location of its centre of gravity are important design considerations. These parameters play an important role in determining the motion and stability of the wall climbing robot.

3.2 Dynamic Analysis

The design for the motor torque requirement will be based on torque analysis when the robot is moving upward. This is due to the fact that the torque required for a climbing robot to move will be maximum when the robot is moving upward. Consider a robot on a wall moving upward as shown in *Figure 4*.

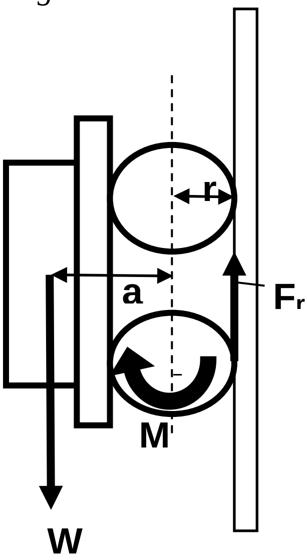


Figure 4: Moment force diagram for robot moving upward

a = distance between centre of gravity of robot and wheel centre
M = total torque required for the robot to move upward
M_w = torque required by each wheel
O = centre of the wheel
r = radius of the wheel
F_r = rolling force required
The moment about point O is

$$M - (W \times a) - F_r \times r = 0$$

$$M = (W \times a) + (F_r \times r)$$

$$F_r = \mu \times F_m$$

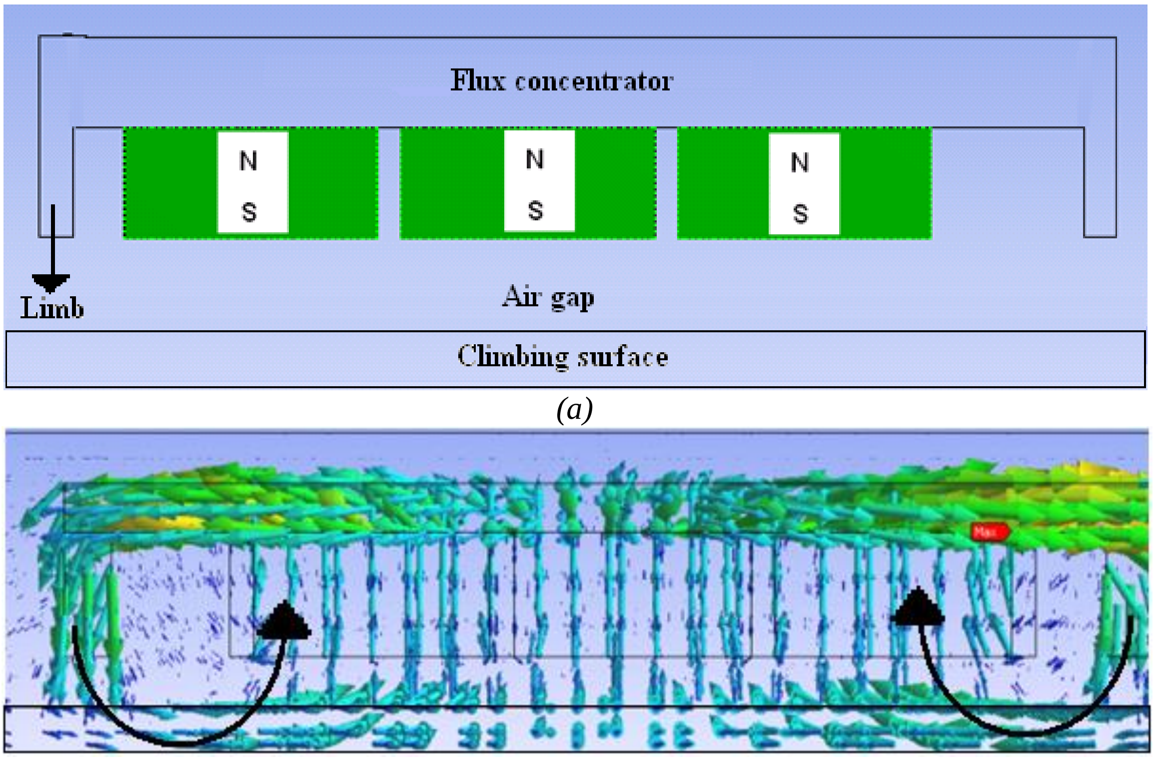
$$M = (W \times a) + (\mu \times F_m \times r) \qquad (5)$$

If there are "w" numbers of driver wheels, torque required by each wheel M_w will be

$$M_w = \frac{M}{w}$$

4 MAGNETIC ADHESION OPTIMIZATION

The magnetic adhesion properties can be studied by using finite element software. We use ANSYS Magnetostatic analysis. The magnets were first modelled in ANSYS design modeller. The magnet was then imported into ANSYS Magnetostatic analysis. Like all the Finite element methods procedure, the meshing of the magnets was carried out and the boundary conditions were defined and simulated. The results of the first set of simulations were verified by experimental results to validate the simulation setup and boundary conditions.



(a)

(b)

Figure 5: Magnetostatic analysis showing magnetic flux lines, (a): modelled block, (b): magnetic flux lines inside modelled figure

4.1 ANSYS Magnetostatic Analysis

The ANSYS Magnetostatic Analysis enables us to analyze different magnetic properties of the designed system. It includes flux density, field intensity, force summation, torque, energy and magnetic flux.

In *Figure 5*(a), schematic of magnetic circuit is shown. The magnetic circuit have flux concentrator, magnets and climbing surface (surface). Flux concentrator has limbs to direct he magnetic lines. It is desirable to design magnetic circuit with and air gap between climbing surface (usually steel) and magnets. In *Figure 5*(b), the north poles of all three magnets are facing the flux concentrator. The magnetic lines of force travel from

North pole into the flux concentrator. To complete the magnetic circuit, these flux lines enter into the South pole after passing through the wall as shown by black arrow.

4.2 Validation of ANSYS Magnetostatic Analysis

Two blocks of permanent magnets, one with an array of 3×3 magnets and other with array of 3×2 magnets were simulated as shown in Figure 6. The arrays were attached to a mild steel plate. This steel plate served to concentrate the magnetic flux lines and thus increases the magnetic adhesion force. N42magnets were used each having dimensions 50×50×25mm. The mild steel plate had a thickness of 10mm and dimension of 260×200mm and 260×160mm for 3×3 array and 3×2 array respectively.

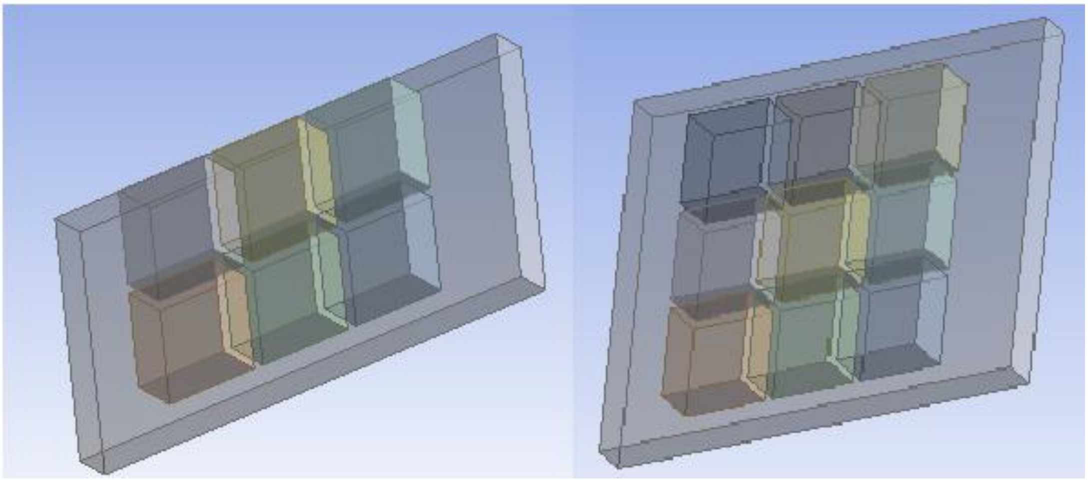


Figure 6: Blocks of magnetic array 3×2 and 3×3 with a steel plate serving as magnetic flux concentrator

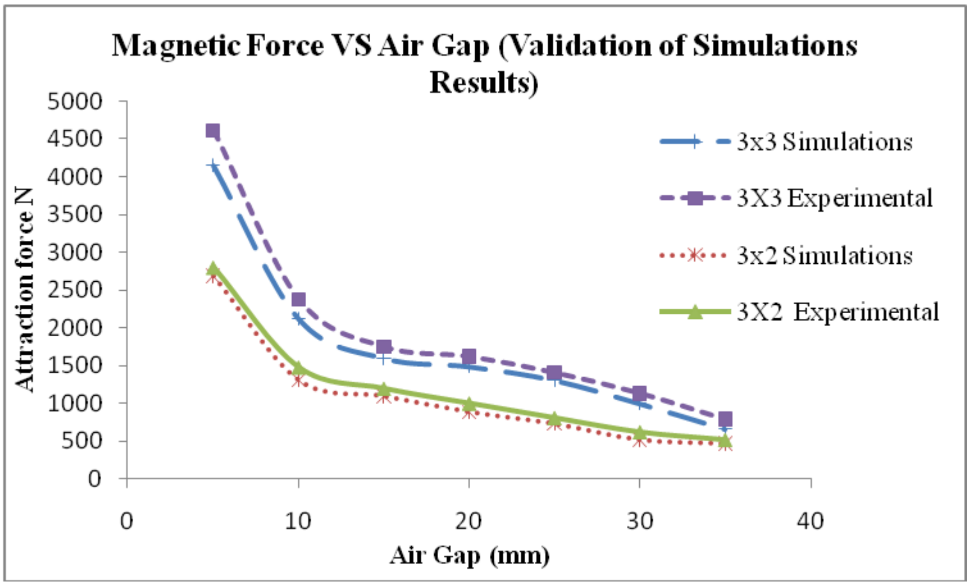


Figure 7: Magnetic force vs. air gap (Validation of simulation results), Experimental results taken from the development phase of CROCELLS robot [1].

In Figure 7, experimental results from our previous research work [1] were use to validate the simulations results. The maximum error was found to be 8% at very high adhesion forces. This is due to the experimental apparatus capacity at high loading conditions. The overall result shows a good agreement with the experimental results.

4.3 Magnetic Arrangements

Adhesion force due to different magnetic arrangements is shown in Figure 8. These magnetic arrangements include use of a flux concentrator, air gap variation from the wall surface and distance between the magnets.
The adhesion force is maximum when the magnets are 5mm apart. As the distance between magnets is increased, the adhesion force starts decreasing. Thus the closer the magnets on the robot base (flux concentrator), the higher will be the adhesion force.

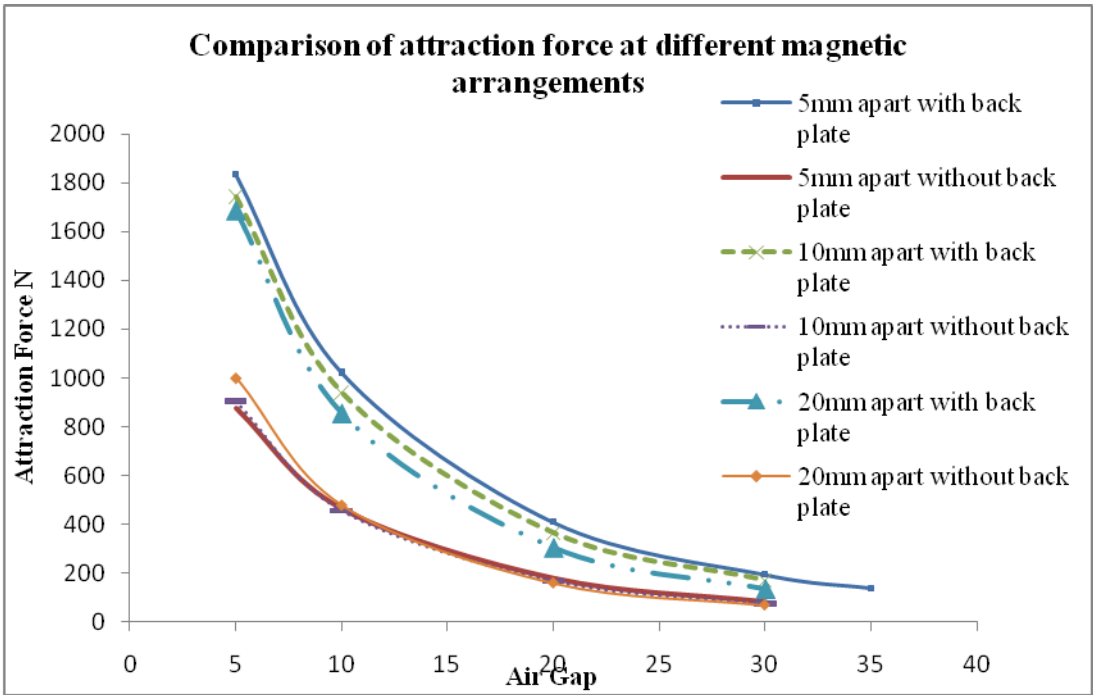


Figure 8: Different magnet arrangement to achieve optimum adhesion

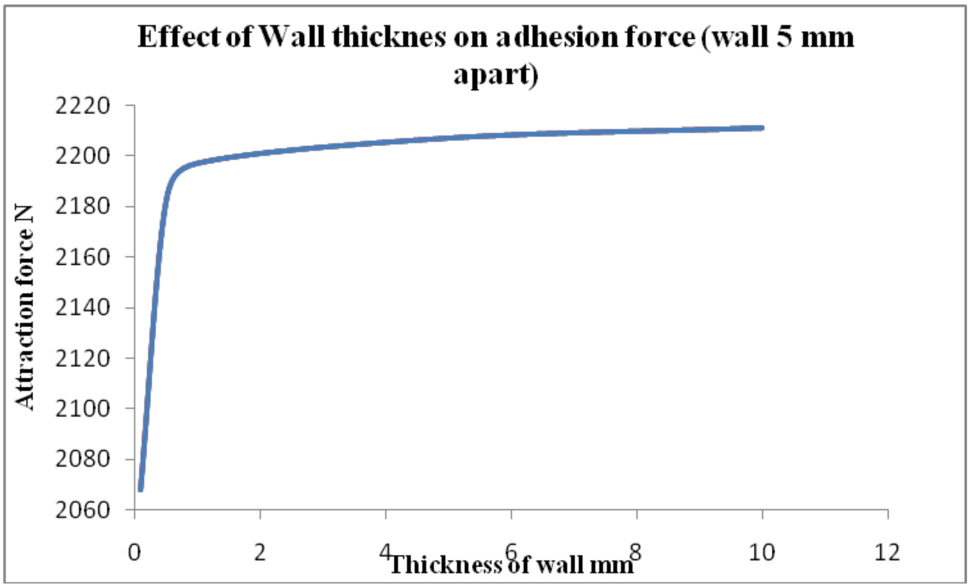


Figure 9: Effect of wall thickness on magnetic adhesion

Use of the concentrating back plate (flux concentrator) shows a significant increase in magnetic adhesion as the value jumps from 1000N to 1835N, thus almost doubling the magnetic adhesion.
The air gap refers to the distance between the face of the magnet and the wall. As this gap is increased, the magnetic adhesion decreases. This air gap is necessary to avoid obstacles in some cases and to avoid friction in all the cases. The friction at the wheel is desirable, but the friction at adhesion surfaces is not desirable.

4.4 Effect of wall thickness

For a specifc magnet, the wall thickness determines the ahdesion force. Simulations were carried out with a N52 magnet. The wall material used was structural steel. The adhesion force is minimum at a wall thickness of 0.1mm. When the thickenss of the wall is increased from 0.1mm to 1mm, the adhesion force increases gradually. At 1 mm, the magnetic flux is almost maximum. Any further increase in wall thickness does not have considerable effect on adhesion force as shown in Figure 9.

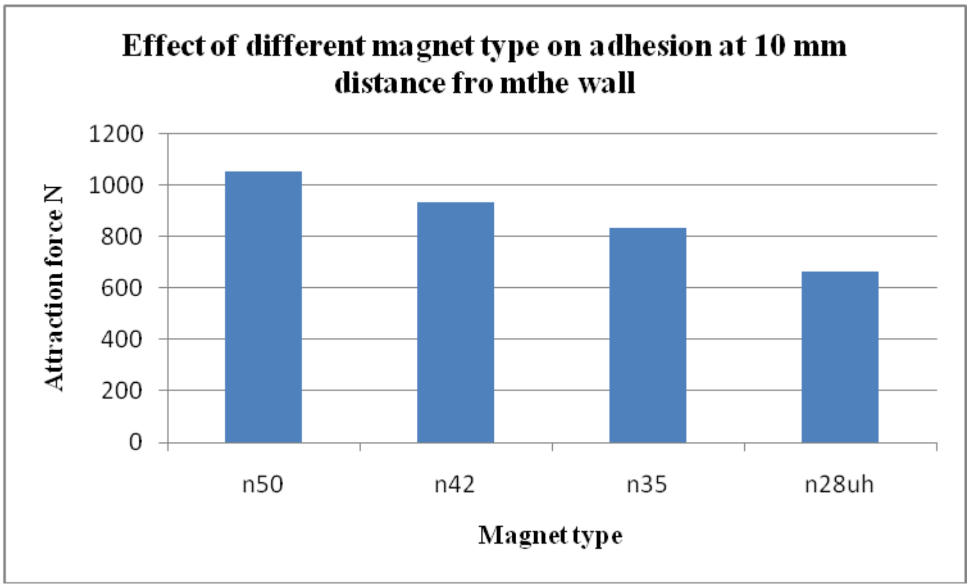


Figure 10: Effect of air gap on different magnets having different strength

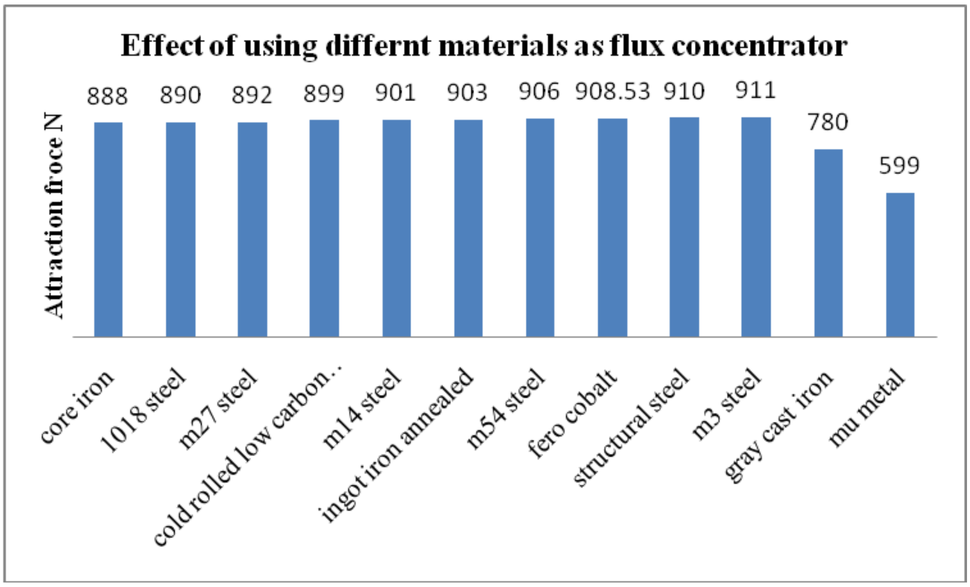


Figure 11: Effect of using different material for concentration plate (flux concentrator)

When using an air gap in the magnetic circuit, the stronger the magnet, the more adhesion force it will produce as shown Figure 10. N28UH is the weakest material in the analysis and thus producing the lowest adhesion force. N50, being the strongest magnetic force is more desirable when circuit have air gaps.

4.5 Design of the flux concentrator

One of the major design considerations is the design of the flux concentrator. The geometry and construction material of the concentration plate plays an important role in optimizing the adhesion force. Figure 11 shows the variation of adhesion force, when different materials are used for the flux concentrator. The adhesion force is minimum when mu metal is used and maximum when structural steel is used. The use of a flux concentrator also serves to provide strength to the chassis of the robot. So the use of structural steel is desirable though the design will perform a trade-off to reduce the weight of the climbing robot.

4.6 Effect of different shape of the flux concentrator

The flux concentrator's shape affects the magnetic flux leakage as shown in Figure 12. When the limb of the flux concentrator is skewed inward, most of the magnetic flux leaks into the south pole without passing through the wall.

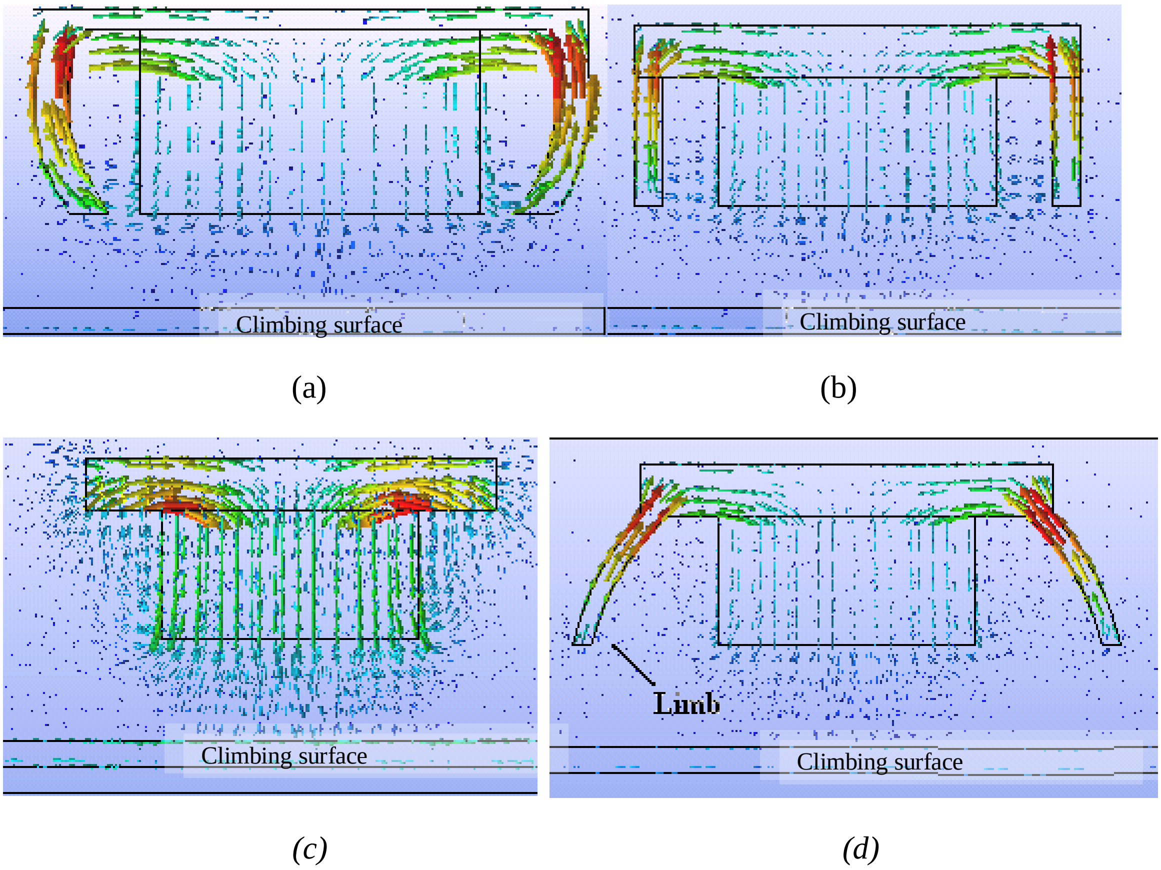


Figure 12: Magnetic flux leakage due to different flux concentrator shapes, (a): limbs inward, (b): straight limbs, (c): No limbs, (d): limbs outwards.

When the limbs are straightened the magnetic flux leakage is improved but is optimum when the limbs of the flux concentrator are skewed outward. When there is no limb the magnetic flux also leaks considerably more as compared to the straight or outward limb. Figure 13 shows that the adhesion force is maximum when the flux concentrator has limb skewed outwards. The adhesion force by this skewed outward shape is 50% more than the adhesion force produced by either without limb or inward limb.

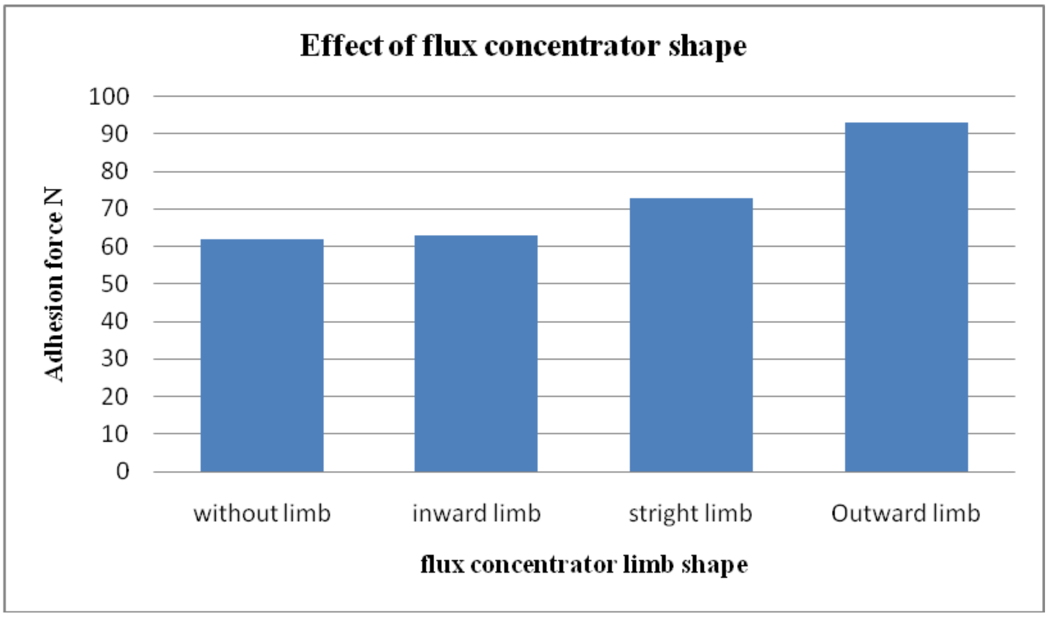


Figure 13: Effect of concentration plate shape

4.7 Effect of length of the flux concentrator

The magnetic adhesion force increases with flux concentrator size. This is due to reduction in flux leakage when length of flux concentrator is increased. Figure 14 shows that the magnetic adhesion is proportional to the flux concentrator length.

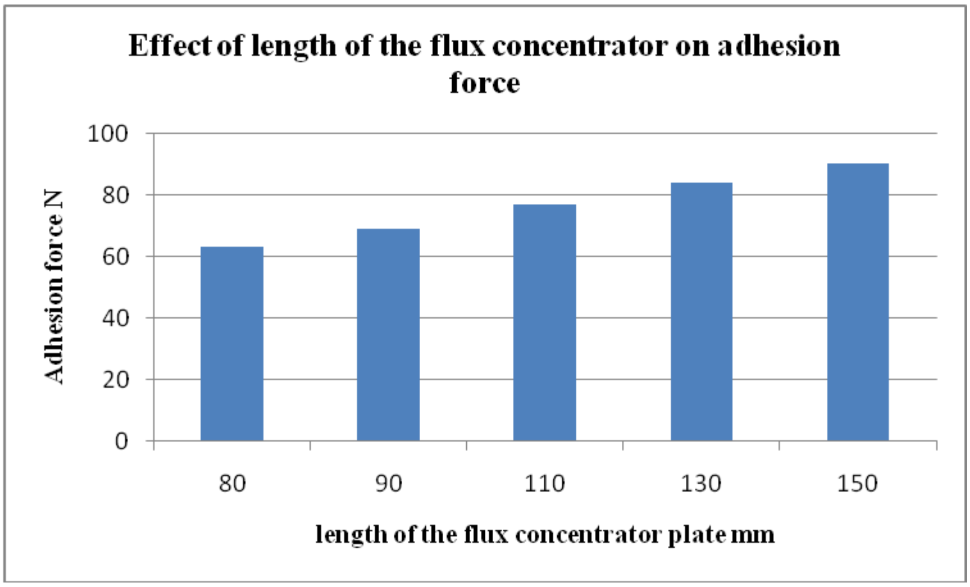


Figure 14: Effect of length of flux concentrator on magnetic adhesion

5 CONCLUSION

Different design parameters responsible for the stability of wall climbing robots were analyzed. These parameters help in laying down geometric properties, material properties and configuration of the robot. Finite Element methods were used to study the optimization of the magnetic adhesion. The study reveals the effectiveness of this approach in predicting the magnetic force for optimization purposes. The factors affecting magnetic adhesion are the type of magnet, air gap, configuration of magnetic array, flux concentrator material, shape and length, the effect of wall thickness, Optimization of these factors were carried out using FEM analysis. Some of the results of the simulations were applied and validated by comparing it with the results of our robot CORCELLS[1].
These results provide a foundation to construct design rules to develop a wheeled robot using magnetic adhesion with magnets attached to the base of the body.
Prototypes will be built based on these optimization results. Also optimization of robot with magnetic wheel will be carried out and will be compared.

6 REFERENCES

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