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A Comparative Study of Adhesion Mechanism for Wall Climbing Robots: Ring Magnet vs. Block Magnets

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Abstract. Magnetic adhesion is widely used in wall climbing robots on ferromagnetic surfaces. The Ring and block Neodymium magnets provide the necessary adhesion in permanent magnet-based climbing robots. In this article, the effectiveness of ring and block magnets are analysed using FEMM. for various magnet configurations. The adhesion force generated by ring and block magnets of a similar volume is compared and analysed. The results showed that the adhesion of ring magnets increases with the thickness of magnets. The maximum adhesion achieved in various ring magnets was compared with the adhesion generated by the arrangement of block magnets for two standoff distances and it was found that the adhesion generated by the block magnets were better in both cases. The ring magnets have constant standoff distance as per the rubber coating used and this enables them to operate seamlessly on irregular surfaces while the block magnet configurations provide excellent payload capabilities. In summary, numerical simulation results provided an understanding of the areas where the ring magnets can be used and the areas where the block magnets serve the purpose better.

1. Introduction

Magnetic adhesion is used in Wall climbing robots where the structure to be climbed is made up of ferrous material. Carbon steel and similar ferromagnetic materials are widely used materials in industrial structures. To keep these structures in good health regular maintenance and inspections needs to be performed at regular intervals. These operations are performed by human inspectors and these tasks involve hazardous environments. The risk involved as an inspector is numerous and one of the major hazards involved in the inspection that needs to be performed at heights. Also, Operations performed by operators are time-consuming, tiresome, and repetitive, making this an apt case for a robotic application more specifically a wall-climbing robot.

Wall climbing robots are robots that operate on vertical surfaces by adhering to the surface to perform various tasks as intended by the system. The climbing of the surface is accomplished by imparting a suitable adhesion mechanism. This mechanism if adherence may broadly belong to any of the five categories [1-2], which include vacuum suction [3] where the suction generated or the negative pressure serves the purpose of providing the necessary adhesion. In the biometric [4 – 7] kind of adhesion, the inspiration is from the living beings which climb the surface using micro hair structures like that of a lizard, the third type is kind of gripping [8 - 9] type where the proper controls are used to climb by holding the structures like that of a monkey climbing a tree. In rail-guided [10-12] kind of adhesion, rails are laid in advance which is used by robots to perform the target applications. The magnetic [13] adhesion methods use permanent magnets or electromagnets to provide the necessary adhesion required and this operates only on ferrous surfaces.

This work is focused on only the magnetic adhesion based on permanent magnets. Similar robots containing four wheels based on skid steer mechanism are compared in this paper. The wheel when made of magnets act as the adhesion unit which helps in adhering to the surface. The second type of robot uses block magnets in a specific configuration for providing the necessary adhesion for climbing on the ferrous surfaces. [14].

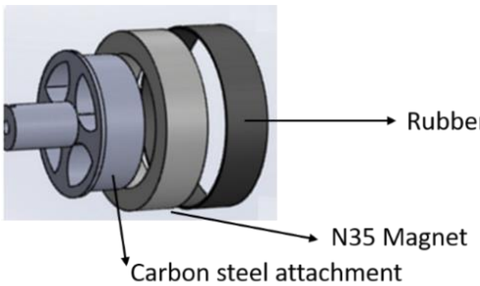
This work compares how the adhesion provided by the magnetic wheels [13] [17] and block magnets s [15] [16] perform based on weight to adhesion ratio. The flux density is studied based on simulations using the finite element method for magnetics.

Section 2 explains the materials assignment and simulation, section 3 discusses the results and Finally, the paper concludes with the summary and future scope of the paper.

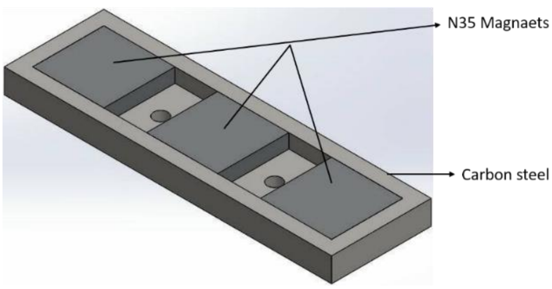
2. Material assignment and simulation studies

2.1. Materials Used

The study involves two types of Neodymium magnets namely ring magnets and block magnets which provide the necessary adhesion required for the wall-climbing robots. The magnetic wheels have ring magnets and they act as wheels as well as the adhesion module. Figure 1(a) shows how the ring magnets are placed in the magnetic wheel. The robots using block magnets use a carbon plate on which the magnets are kept in a specific arrangement at a distance from the surface climbed. Figure 1(b) shows how the magnets placed in the Yoke.



(a)



(b)

Figure 1. a) CAD model of a magnetic wheel with a ring magnet. b) block magnets arranged within YOKE

2.1.1. Permanent magnets

The ring and block magnets used in the simulations belong to a classification named Neodymium magnets and this is an alloy of Neodymium, Iron and Boron with a chemical composition of $Nd_2Fe_{14}B$. these magnets are counted among the most powerful permanent magnets. These magnets follow a naming scheme starting with ‘N’ for Neodymium and the following are the two numbers that give the maximum energy product in Mega-Gauss Oersteds (MGOe). The commercial availability begins at N30 and the value goes up to N52 but the limits of theoretical value go up to a maximum value is N64. The value of N35 is specified from the built-in materials library in FEMM.

The ring magnets provide the necessary adhesion required for wall climbing. The CAD representation is shown in figure 2 and figure 1 (a) show how that is used in a magnetic wheel. For the discussions and simulations, only one ring magnet is taken into consideration but the total is four such magnets that provide the necessary adhesion for the robot. The dimensions were selected as the standard size available in the market for the ring magnets.

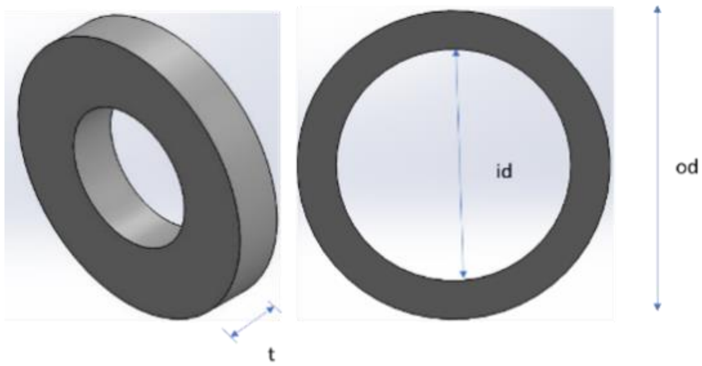


Figure 2. CAD model of ring magnets.

For the block magnets, two sets of neodymium magnets of grade N35 with dimensions of 50×40×10 mm and 50×40×10 is used for simulations. This is represented using a CAD model in figure 3. The simulation uses three magnets assembled inside of the yoke as shown in figure 1 (b).

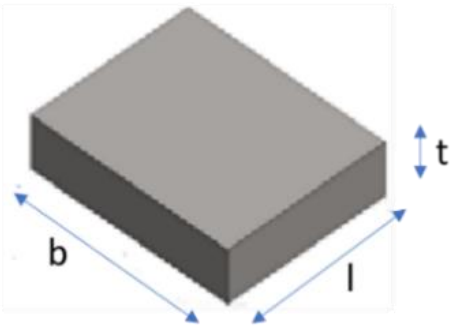


Figure 3. CAD model of block Magnets

2.1.2. Flux concentrator/ Yoke
The adhesion provided by the Neodymium magnets can be bettered by placing it inside of a material with high permeability [13] [14] [[15] [16] and this material is referred to as a yoke or flux concentrator. Also, this provides physical strength to the magnets which are otherwise brittle and could break easily. A yoke is made from Low carbon steel by milling a rectangular block according to the requirements of the magnets used. Once the milling is done the block magnets are placed in the groove that is milled and the polarity of the adjacent magnets are kept at the opposite polarity. This significantly improves the overall adhesion as per previous studies [15]. The material specified in the simulation for this block is 1018 steel. The representation is given in figure 1 (b).

2.1.3. Ferromagnetic surface
The study uses 1018 steel as the ferromagnetic surface against which the magnets are tested. This steel falls under the category of low carbon steel which is widely used in industrial infrastructures. As per

previous studies [15] [16] [17], the adhesion for the surface climbed has a significant effect on adhesion. This factor was the reason for keeping the surface thickness at 10mm. so, this is the thickness selected for the simulation. This steel used in simul-ations is present in the material library of FEMM and this is utilized for the simulations.

2.2 Simulation using Finite Element Method

The software used for calculating the magnetic adhesion is FEMM version 4.2 [18] [19], and the methodology used is the finite element simulation for magnetics. This software is 2D software and is used for axis-symmetric problems. The magnetic wheel and the yoke holding magnets are simulated for the magnetic adhesion generated against the ferromagnetic surface that is climbed. the ring magnet is only considered in the simulation of magnetic adhesion. For the Yoke holding magnets, the two different standoff distance along with the magnets of two dimensions and the yoke of the appropriate dimensions are considered.

The problem involved belongs to the classification of magneto-statics as the magnetic fields do not vary concerning time. These kinds of problems in FEMM involves three stages namely: pre-processing, processing, and post-processing [18]. Initially, the problem needs to be specified as magnetostatics and the Frequency is set to 0. The depth of the problem needs to be specified as per the requirements along with the units.

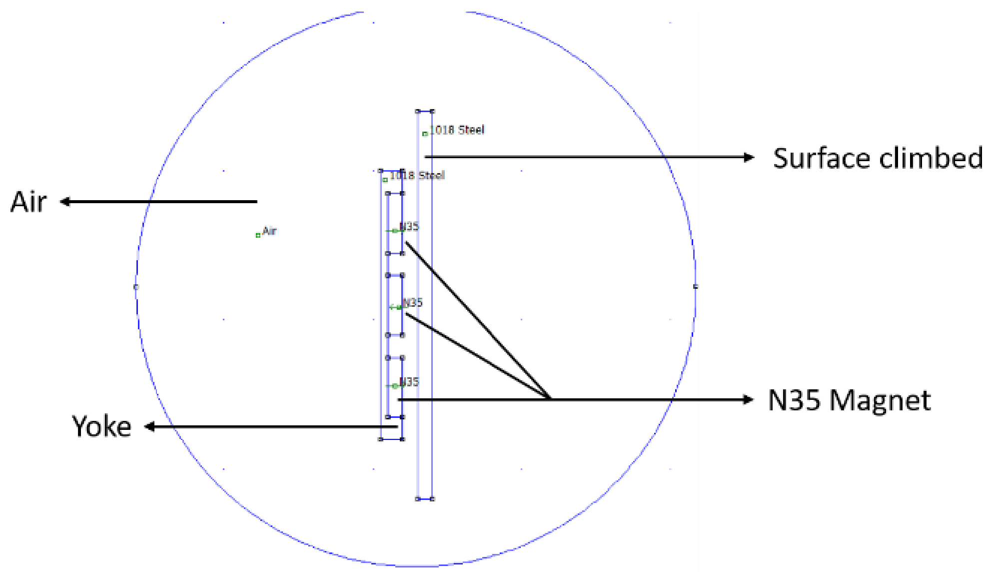


Figure 4. Assignment of materials in FEMM simulation for yoke holding Magnets

FEMM toolset is utilized in the drawing of the model and this is accomplished using the built-in pre-processor tools. The geometry is defined based on the problem that needs to be solved. Pre-processor tools include options to specify nodes in the defined problem domain, there is a tool that can be used to connect the nodes and there are arcs that can be used to build curves in the model. Once the model is built, we can start specifying the materials. The FEMM has a built-in library that can be utilized for specifying the materials used in the model. Once the model drawing is complete, we can set up the finite region of available space by enclosing it in a circle.

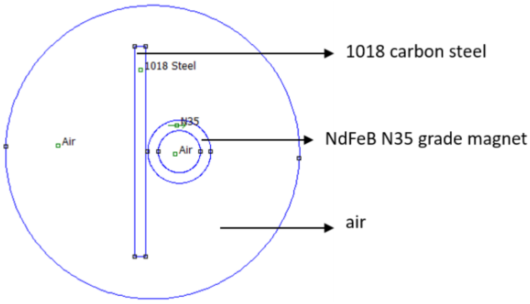


Figure 5. Assignment of materials in FEMM simulation for ring Magnet in the wheel assembly

These simulations involve three materials that are specified in the simulations namely N35 magnets, 1018 steel used for both the surface climbed and the yoke, and enclosure that is built around the model is assigned as air. Figure 4 shows the model and the material assignments made for the block magnets placed in the yoke. Figure 5 shows the assignments made for the ring magnets along with other material assignments made.

In the next step, the continuous problem is split up to simplify the computational load and it helps in solving the problem easily. This process of dividing the large problem space into smaller ones is often referred to as meshing. This task is and is performed by a built-in tool in FEMM which utilizes the triangular meshing algorithm. After splitting up the large problem, the finite element method is applied and the results can be viewed using the post-processing tools.

3. Results and discussions

The simulation studies for the calculation of adhesion force generated by ring magnets and block magnet configuration was carried out using FEMM. This study is conducted assuming that the robot operates using a skid steer mechanism. When magnetic wheels are used for providing adhesion it will be having four wheels. Similarly, robot utilising block magnets will also have a similar number of wheels and for adhesion three magnets are used as mentioned in section 2.1.3.

To find out how the adhesion varies for the ring magnets against the ferrous surface, the simulation studies were carried out for five different thicknesses. The adhesion obtained in the simulations is shown in table 1 for different thicknesses of ring magnets the outer diameter was fixed at 70mm for the simulations. The flux distribution for three different thickness is shown in figure 6.

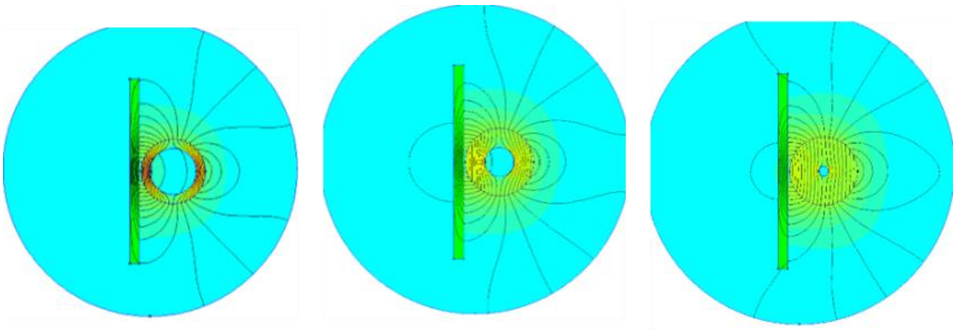
The weight of the given dimensions was obtained using solid works by specifying the material using the built-in library and the obtained weight is shown in table 2. It is evident from the results that the adhesion improves with the increasing thickness. A total of four wheels are used in the robot so the contribution from the overall weight can be obtained by multiplying the individual values by four.

Table 1. Adhesion generated by ring magnet using simulation

S.no	Inner diameter(mm)	Thickness (OD-ID)	Adhesion generated in Newtons
1	50	10	29.4
2	40	15	52.71
3	30	20	70.9
4	20	25	83.6
5	10	30	91.5

Table 2. Solid works model weight analysis based on dimensions for NdFeB ring magnets

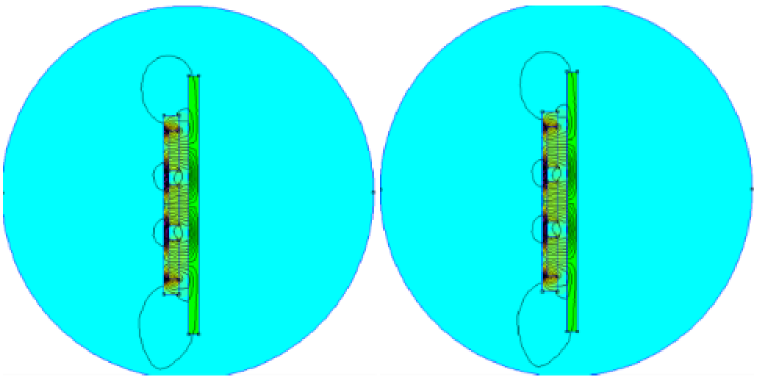
Dimensions of the ring magnet (od x id x t)	Mass of the magnet (grams)
60 x 10x10	284
60 x 20x 10	265.07
60 x 30 x10	235.62
60 x 40 x 10	194.39
60 x 50 x 10	159.04



(a) (b) (c)

Figure 6. simulation results for inner diameter a)50 b)30 c)10

Similarly, the studies were carried out for the Block magnets and the flux distribution is shown in figure 7. Based on the weight obtained from the ring magnets the nearest commercially available block magnets were selected for simulations. The dimensions of magnets are 50 x40 x 10 and the second magnet was 50 x50 x 10. The simulations were carried out by keeping the magnets in the order as mentioned in section 2.1.3 and the simulation was carried out for two standoff distances.



(a) (b)

Figure 7. Simulation of Yoke holding magnets a) 50x40x10mm magnets b) 50x50x10 magnets

The weight of a single magnet with dimensions of 50 x 50 x10 stands at around 234.38 grams and 187.5 50 for the dimension 50 x 40 x 10. As three magnets are used as specified, the weight of magnets must be multiplied by three. The yoke holding magnets provided an adhesion of 405N for a gap of 10mm and reducing the gap to 5mm increases the adhesion force to 793N. Similarly, the second configuration provided 650N for the 10mm gap and the adhesion improved to 1259N on the reduction of the gap to 5mm.

From the simulation results, the adhesion provided by block magnets in the given configuration provides a better weight to adhesion ratio. Nevertheless, certain factors need to be considered to evaluate these in real-world scenarios. When ring magnets are used in the wheels for providing adhesion, additional wheels are not required for locomotion. Whereas the block magnets additional wheels are required which will add to the weight of the robot. The rubber coating on the ring magnets helps in having a constant standoff distance from the surface climbed which in turn helps in providing adaptability to a wide variety of surfaces. Also, the load acting is distributed and the weight acting is not acting on the structure of the robot. whereas in the case of block magnets the load acting is very strong and it acts where the yoke is attached to the body. Thus, special care has to take care of the design for robots involving the block magnets. The surface unevenness will also be a major limiting factor for the block magnets as the adhesive force changes with every small change in the standoff distance whereas this will not be an issue in the ring magnets.

4. Conclusion

In this article, the effectiveness of ring and block magnets are analysed using simulations. These magnets are tested against a ferrous surface of 10 mm. The adhesion force generated by ring and block magnets of a similar volume is compared and analysed for magnetic wall-climbing robots. The simulation studies were carried out using FEMM version 4.2.

The study compared the adhesion force generated by both ring and block magnets. The adhesion offered by the ring magnets were simulated for five different thicknesses and it was found that there was an appreciable improvement in adhesion with the increasing thickness. The maximum of tested ring magnets was compared with the adhesion generated by the block magnet configuration of similar volume. It was found that the block magnets placed in the yoke offered superior load carrying capabilities and it was further improved when the standoff distance was reduced. Further, the discussions concluded that the adaptability to the surface is better offered by the magnetic wheels and the better load capabilities are offered by the block magnet configurations.

This study was limited to simulation results and could be further extended by experimental validations. Also, the possibilities of using the wheels and block magnets together in the designs need to be further investigated.

References

[1] Chu, B., Jung, K., Han, C.S. and Hong, D., 2010. *A survey of climbing robots: Locomotion and adhesion. International journal of precision engineering and manufacturing*, **11**(4), pp 633-647.
[2] Nansai, S. and Mohan, R., 2016. *A survey of wall climbing robots: recent advances and challenges*. Robotics, **5**(3), p.14
[3] Brusell, A., Andrikopoulos, G. and Nikolakopoulos, G., 2016, June. *A survey on pneumatic wall-climbing robots for inspection*. In 2016 24th Mediterranean Conference on Control and Automation (MED) (pp. 220-225). IEEE.
[4] Hou, X., Su, Y., Jiang, S., Cao, P., Xue, P., Tang, T., Li, L. and Chen, T., 2019. *Space climbing robot feet with microarray structure based on discrete element method*. International Journal of Robotics and Automation, **34**(1).
[5] Chattopadhyay, P. and Ghoshal, S.K., 2018. *Adhesion technologies of bio-inspired climbing robots: A survey*. International Journal of Robotics and Automation, **33**(6)

[6] Menon, C. and Sitti, M., 2005, April. *Biologically inspired adhesion based surface climbing robots*. In Proceedings of the 2005 IEEE International Conference on Robotics and Automation (pp. 2715-2720). IEEE.
[7] H. Anandakumar and K. Umamaheswari, A bio-inspired swarm intelligence technique for social aware cognitive radio handovers, Computers & Electrical Engineering, vol. **71**, pp. 925–937, Oct. 2018. doi:10.1016/j.compeleceng.2017.09.016
[8] R. Arulmurugan and H. Anandakumar, Early Detection of Lung Cancer Using Wavelet Feature Descriptor and Feed Forward Back Propagation Neural Networks Classifier, Lecture Notes in Computational Vision and Biomechanics, pp. 103–110, 2018. doi:10.1007/978-3-319-71767-8_9
[9] Krosuri, S.P. and Minor, M.A., 2003, September. *A multifunctional hybrid hip joint for improved adaptability in miniature climbing robots*. In 2003 IEEE International Conference on Robotics and Automation (Cat. No. 03CH37422) (**1**, pp. 312-317). IEEE.
[10] Warszawski, A., 2003. *Industrialized and automated building systems: A managerial approach*. Routledge.
[11] Bach, F.W., Rachkov, M., Seevers, J. and Hahn, M., 1995. *High tractive power wall-climbing robot*. Automation in construction, **4**(3), pp.213-224.
[12] Elkmann, N., Felsch, T., Sack, M., Saenz, J. and Hortig, J., 2002, October. *Innovative service robot systems for facade cleaning of difficult-to-access areas*. In IEEE/RSJ International Conference on Intelligent Robots and Systems (**1**, pp. 756-762). IEEE.
[13] Jose,J.;Dinakaran,D.;Ramya,M.M.;Harris,D.G.A *Survey on Magnetic Wall-Climbing Robots for Inspection*. International Journal of Mechanical and Production Engineering Research and Development. **8**(6), Dec 2018, 59-68
[14] Sahbel, A., Abbas, A. and Sattar, T., 2019. *Experimental and Numerical Optimization of Magnetic Adhesion Force for Wall Climbing Robot Applications*. International Journal of Mechanical Engineering and Robotics Research, **8**(1), pp.18-24.
[15] Jose, J., Dinakaran, D., Ramya, M.M., Kuppan Chetty, R.M., Tokhi, M.O. and Sattar, T.P., 2020. *Investigations on the effect of wall thickness on magnetic adhesion for wall climbing robots*. International Journal of Robotics and Automation. DOI: 10.2316/J.2021.206-0441
[16] Jose, J., Elankavi, R.S., Dinakaran, D., Chetty, R.K. and Ramya, M.M., 2020, December. *Optimization of Distance Between Magnets for Magnetic Wall Climbing Robots*. In 2020 3rd International Conference on Intelligent Sustainable Systems (ICISS) (pp. 1574-1578). IEEE.
[17] Wang, R. and Kawamura, Y., 2016. *An automated sensing system for steel bridge inspection using GMR sensor array and magnetic wheels of climbing robot*. Journal of Sensors, 2016.
[18] Meeker, D., 2010. Finite element method magnetics. FEMM, **4**, p.32.
[19] Baltzis, K.B., 2008. The FEMM Package: *A Simple, Fast, and Accurate Open Source Electromagnetic Tool in Science and Engineering*. Journal of Engineering Science & Technology Review, **1**(1)