Optimization of Distance Between Magnets for Magnetic Wall Climbing Robots

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***Abstract*— In this paper, an adhesion system used for magnetic wall climbing robots using permanent magnets is examined for its change in adhesion concerning the inter-magnet distance within the Yoke. Pocket milled ferrous material of high permeability named yoke is used to hold neodymium magnets in mobile wall-climbing robots. For a climbing robot, the self-weight is a significant parameter which needs to be at the minimum possible value. This simulation study is expected to help in bringing down the weight of the yoke holding magnets and help in finding the right inter magnet distance for the magnets used. Simulation studies were carried out for various inter magnet distances and the values are reported. An optimized distance was arrived using the simulation results thus obtained.**

Keywords: Wall climbing robot; Mobile robot; Permanent magnets; FEMM; Magnetic adhesion

I. INTRODUCTION

Steel is widely used in industrial structures in the industry. Often these structures need maintenance operations and regular inspection must be carried out for these structures to keep these in good health and functional. The inspectors and the operators must climb these structures to conduct the above-mentioned operations which are mostly located at a height above the ground which makes these operations of the high-risk category and thus involves high costs. In the industry Several operations are getting automated [1][2][3] and these high-altitude operations can also be automated using wall climbing systems.

Operators and inspectors perform these tasks on high raise buildings and structures using ropes and Specialized lifters. The operations is time consuming also the job is tiresome and repetitive in nature which makes this a perfect case of robotic operations.

To climb the vertical surfaces an adhesion mechanism is required by these systems [4]. Major adhesion mechanisms utilized by the climbing systems or robots are broadly classified based on the technology and is mainly subdivided into five categories [4-5], which include vacuum suction [6], biometric [7 – 10]], gripping [11 - 12], rail-guided [13-14] and magnetic [16] adhesion methods.

This paper focusses only the magnetic adhesion based on permanent magnets. The robot considered in this paper is a four-wheeled skid steer wall climbing robot having the adhesion based on permanent neodymium magnets.

The climbing systems based on permanent magnets a high permeability material to hold the magnets. This material uses is usually a carbon steel or a similar material which is engraved to accommodate the magnets. Previous studies have showed that yoke like material helps in concentrating the magnetic flux [17-20] also it provides physical strength to the magnets. The previous studies mainly focused on the various configurations and number of magnets and the inter magnet distance was not closely studied.

In this work, the placement of magnets in the yoke is investigated herein. The variation of adhesion is studied based on the distance between the magnets inside the yoke. The flux density is studied based on simulations using finite element method for magnetics. This study will help in reducing the overall weight of the robot which is a critical parameter in the wall climbing systems.

The remainder of the paper is organized as follows, Section 2 explains the materials used, Section 3 presents the steps involved in. section 4 discusses the results and Finally, the paper concludes with the summary and future scope of the paper.

II. MATERIALS USED

This simulation is carried out using the materials namely surface climbed made of ferromagnetic material, neodymium permanent magnets, and flux concentrator/yoke that holds the magnet/magnets.

2.1 Ferromagnetic surface

The magnetic climbing robots use the ferrous surface for adhering to the surface. This study uses a 1020 steel which is carbon steel and widely used in the industrial infrastructures.

2.2 Permanent magnets

The permanent magnets provide permanent adhesion and do not require the electric supply like electromagnets. The neodymium magnets (NdFeB) belong to this category and is counted among the most powerful permanent magnets. This is an alloy made out OF Neodymium, Iron, and Boron and having the chemical formulation as $Nd2Fe14B$. these magnets are named in a specific way the name starts with N starts with N and is followed by a 2-digit number. The N is for Neodymium and the number gives its maximum energy product in Mega-Gauss Oersteds (MGOe). This value goes up to N52 being the maximum available in the market to buy.

The better MGOe value means a better value of adhesion is offered by the magnets for similar sizes. The Market availability for these magnets is available for specifications beginning N30 and goes up to N52.

This study uses a commercially awaliabe magnets of dimensions 50*40*10 mm. for the simulations.

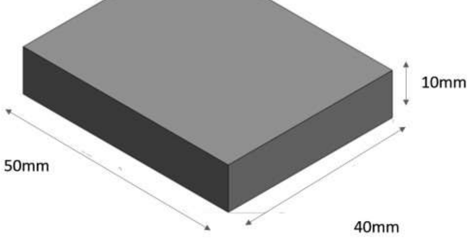

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Figure 1: dimensions of magnets in the simulations

In the simulations, a Neodymium magnet with the dimensions shown in figure 1 is used. In the simulations the grade specified is N35 as this grade of magnets are is widely available in the market. Three of these magnets are used in the simulations.

Table 1

Properties N35 and N52 magnets[19]

Grade of Magnets	Energy product of the magnet BH $_{max}$, MGOe	Remanent magnetization B_r, T	Coercive force H_{cB}, KA/m	Electric Conductivity γ, MS/m
N35	34	1.2	905	0

2.3 Flux concentrator/ Yoke

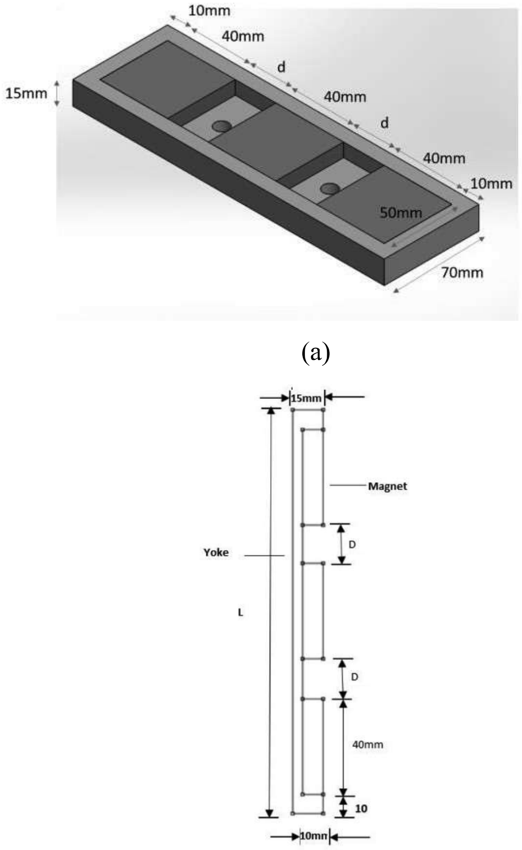
Earlier studies have indicated that the adhesion of rare earth magnets can be significantly improved by placing it inside a high permeable material [14]. This material is generally referred to as toke and also it can be called a flux concentrator.

Table 2:

Properties1020 steel

Saturation flux density B_{sat}	NaN
Coercivity H_c, A/m	0
Relative permeability μ	760
Electric conductivity γ, [MS/m]	5.8

This work primarily investigates the distance between the magnets that is optimal in such a way that the weight of the yoke remains minimal. Here the 1020 steel is used as the material for yoke in simulations. The distance ‘d’ in figure 2 is varied to find the optimal distance between the magnets.



(a)

(b)

Figure 2 (a) Representative image of magnets arranged inside of a yoke (developed using Solidworks software). (b)Dimensions as per the FEMM model (L depends on the D, Inter-magnet distance).

III. SIMULATION USING FINITE ELEMENT METHOD

To find out the adhesion generated by the magnets, FEMM v4.2 software is used.[21][22] This software tool is used to perform the finite element simulation and thus approximating the adhesion under the different scenarios modelled.The workflow involved is shown in figure 3.

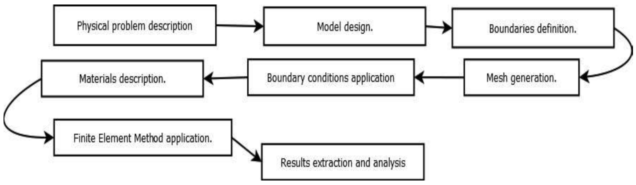


Figure 3: Workflow in FEMM

The problem of this kind comes under the magnetostatics problem. In this software, three steps are to be performed for solving the problem, namely: pre-processing, processing, and post-processing.

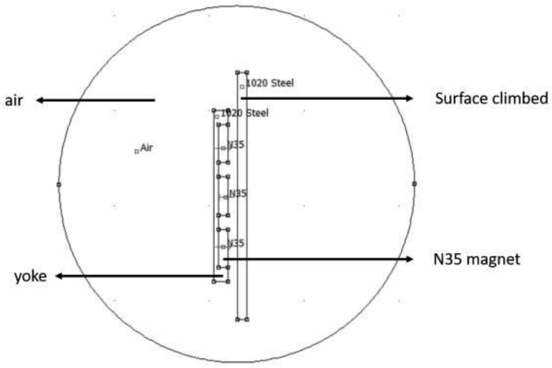


Figure 4: FEMM model drawn using preprocessing tools.

The initial processes are modelling the required geometry, and this is performed using the pre-processor tools in the FEMM. The initial step involves specifying the problem as magnetostatics and defining the depth. These tools include nodes lines and arc which can be used in building the model. The subsequent step involves the allocation of involves specifying the material by manually entering the properties or by selecting from the built-in library of FEMM.

After the materials are specified in the drawn model enclosure is built around to make the problem to be solved a finite one. The next step is breaking shown this problem which is continuing into a discrete problem. This process is called meshing and is automatically performed by FEMM. The triangular meshing algorithm is used herein.

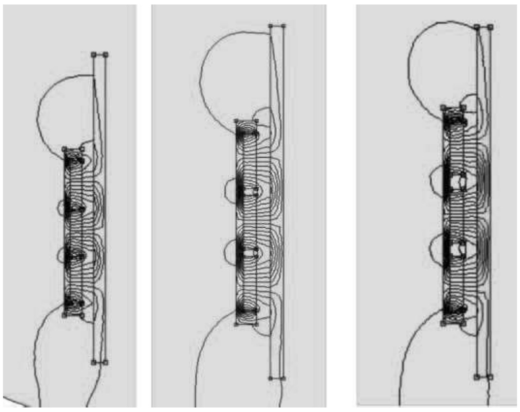
The next inline processes are running the FEM and viewing the results. This task is done, using post-processing tools.

IV. SIMULATION RESULTS AND ANALYSIS

To understand how the strength of magnetic adhesion varies with the different distances of magnets simulation studies are carried out for different distances varying from 0mm to 45 mm between the adjacent magnets inside the yoke thus increasing the yoke size as per the requirements.

The results obtained are shown in table 3. And is plotted in figure 9. Based on the results obtained the results follow a specific adhesion trend based on the flux density. This trend can be divided into three regions wherein the adhesion is comparatively low then the second region where the region where it is nearly constant and the third region where the adhesion starts to drop again.

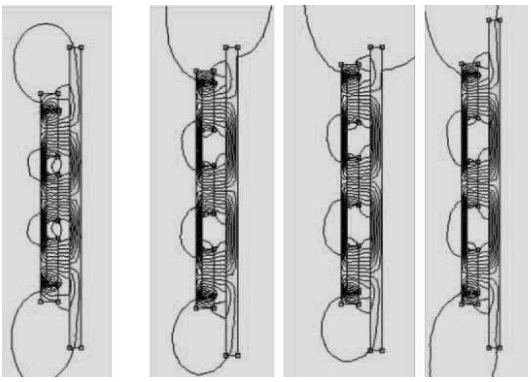
Figure 6 (a) shows the flux density of the magnets against the ferromagnetic surface that is climbed of the fist region. The initial distances that is, 0mm 5mm and 10mm, the magnets are pretty closer thus the field lines don't necessarily pass through the ferrous plate and thus produce the adhesion weaker than the 15mm-40mm range as can be seen from the figure 4 and figure 5...



a) *(b)* *(c)*

Figure 5: Field distribution for the distance between the magnets(a) 0mm (b)5mm (c) 10mm

In the second region, the field lines pass through the plates and produce better adhesion than the other two regions. When the distance has further raised the adhesion produced by the arrangement starts to drop.



(a) (b) (c) (d)

Figure 6 Field distribution for the distance between the magnets(a) 15mm (b)20mm (c) 30m(d)40mm

As the distance between the magnets crossed 40 and reached the adhesion starts to decline. This decline can be attributed to the distance required by the field lines to travel and the total no of lines passing through the ferrous surface. The field interactions start to decline and thus resulting in the loss of adhesion.

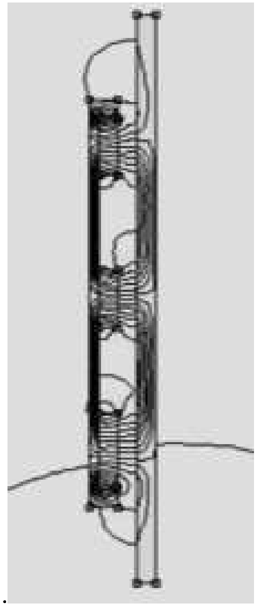


Figure 7 Field distribution for the distance between the magnets (a) 45mm

Table 3
adhesion generated in simulation and the corresponding distance between the magnets.

Distance between the magnets(mm)	Force in Newtons exerted by Yoke IFI
45	332
40	403
35	406.9
30	405.7
25	406.5
20	407
15	405
10	382.409
5	356.6
0	315.318

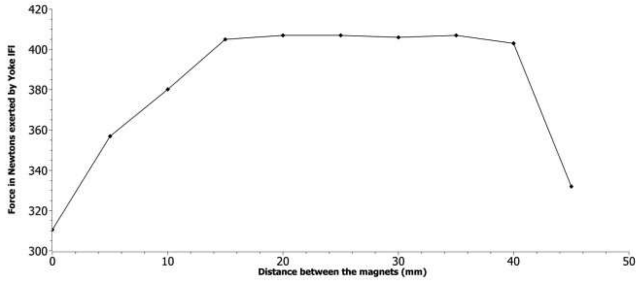


Figure 8: plot showing the variation in adhesion with respect to the distance between the magnets.

. The major inference from this result is that the adhesion remains same once the minimum distance required is achieved and this finding will help in achieving the maximum adhesion by keeping the inter-magnet distance at 15mm and this will in turn help in reducing the weight of the yoke and providing the maximum possible adhesion.

V. CONCLUSIONS

In this study, the effect of distance between the magnets inside of a yoke was studied. As per the simulation results, it was found that for a small increment in distances the adhesion improves, and it saturates after a point and when further increased the adhesion starts to drop. In the simulation conducted the distances starting from 0mm, 5mm, 10mm showed an increase in the adhesion and it saturated around 15mm and it remained the same until 40mm. beyond which the adhesion starts to drop. These results are significant as every additional length of yoke beyond the optimum point will contribute to overall weight of the climbing systems without contributing to the adhesion.

As a closing remark, it can be said the 15 mm gap is best for the given dimensions as the maximum adhesion is obtained at that particular point and any further increase in distance will not add to the adhesion. Also, from these results, it can be concluded that the weight of the yoke will be optimum at this point as any further increment will add to the overall self-weight of the robot and it's not desirable for wall climbing systems.

The work done in this paper was limited to simulations and could be further r extended by including the experimental validations. Also, further study needs to be carried out regarding the thickness of magnet and its role in optimising the yoke.

REFERENCES

[1]Smys, S. and Ranganathan, G., 2019. Robot assisted sensing control and manufacture in automobile industry. Journal of ISMAC, 1(03), pp.180-187.
[2] Jipeng, T., Neelagar, M.B., Thanuja, C. and Manjunath, T.C., 2020, June. Development of a Robotic Part Fixture Mechanism for PNP Operation in an Industrial Scenario. In 2020 5th International Conference on Communication and Electronics Systems (ICCES) (pp. 131-135). IEEE.
[3] Dong, Z., Mai, Z., Yin, S., Wang, J., Yuan, J. and Fei, Y., 2020. A weld line detection robot based on structure light for automatic NDT. The International Journal of Advanced Manufacturing Technology, pp.1-15.

[4] 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.

[5] Nansai, S. and Mohan, R., 2016. A survey of wall climbing robots: recent advances and challenges. Robotics, 5(3), p.14

[6] 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.

[7] 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).

[8] Chattopadhyay, P. and Ghoshal, S.K., 2018. Adhesion technologies of bio-inspired climbing robots: A survey. International Journal of Robotics and Automation, 33(6)

[9] 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.

[10] Carlo, M. and Metin, S., 2006. A biomimetic climbing robot based on the gecko. Journal of Bionic Engineering, 3(3), pp.115-125

[11] Balaguer, C., Gimenez, A. and Abderrahim, C.M., 2002. ROMA robots for inspection of steel based infrastructures. Industrial Robot: An International Journal, 29(3), pp.246-251

[12] 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) (Vol. 1, pp. 312-317). IEEE.

[13] Warszawski, A., 2003. Industrialized and automated building systems: A managerial approach. Routledge.

[14] 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.

[15] 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 (Vol. 1, pp. 756-762). IEEE.

[16] 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. Vol. 8, Issue 6, Dec 2018, 59-68

[17] 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.

[18]Howlader, M.O.F. and Sattar, T.P., 2016. Design and Optimization of Permanent Magnet Based Adhesion Module for Robots Climbing on Reinforced Concrete Surfaces. In Intelligent systems and applications (pp. 153-171).

[19] Hussain, S., Sattar, T.P. and Salinas, E., 2012. Parameter analysis and design framework for magnetic adhesion wall climbing wheeled robot. International Journal of Intelligent Systems Technologies and Applications, 11(1-2), pp.102-116.

[20] Sattar, T, Salman, H and Salinas, E (2011). Towards Optimum Design Of Magnetic Adhesion Wall Climbing Wheeled Robots. Khan, KM and Win, NL (ed.) 26th International Conference on CAD/CAM, Robotics and Factories of the Future 2011. Kuala Lumpur, Malaysia 26 - 28 Jul 2011 pp. 716-728

[21] Meeker, D., 2010. Finite element method magnetics. FEMM, 4, p.32.

[22] 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)