Study of Wall Climbing Robot Having Proposition of Stable Mechanism on the Inclined Plane Based on Magnetic Force

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Abstract—**The paper studied the climbing structure and magnet selection method of exploration platform utilized for large-scale steel structures such as vessel surface. With respect to wall climbing robots, the study proposed a stable operation structure even in rapid incline change of vessel surface. Since the wheel-based operating method is hard to work flexibly in inclination changes, we employed joints and designed the robot to have a rotation joint in the center. The arrangement of wheels is an important aspect of this structure. Viewed from the side, the robot wheels should overlap with each other to have intersection points. The wheels here are ring-type permanent magnets and serve as a tool of attachment on walls. Based on the conditions identified through formula modeling, we proposed the required magnetic force. Important factors needed for magnetic force setup include platform weight, angle between ground and inclined plane, and friction coefficient. We considered only the required magnetic force for the stable adhesion of circular magnet while making not a separate mention about the necessary force for directional locomotion. The analysis results of ANSYS Maxwell are applied to magnetic attachment. Based on the final analysis results, we built a platform and found it did not slip and stayed attached on steel plate.**

Index Terms—**magnetic force, wall-climbing, mechanism, exploration robot, maxwell analysis**

I. Introduction

Robots in the initial stage were developed with the focus on human work efficiency and utilized as a means to assist human labor. They were also usually utilized on the ground. But, presently, diverse kinds of robots are researched for the purposes of use in the air, on the sea or under water [1]. The major goal of these robots in such environment is to explore and play roles on behalf of human. The purpose of developing exploration robots is not only for human work efficiency but also human work stability. Exploration robots being utilized or developed in various areas as of now, in particular, are for reduced accident rate of workers.

Most exploration robots are designed appropriately for specific types of environment. They include wall climbing robot that explores inclined planes of large-scale structures [2]. Presently developed wall climbing robots mainly rely on wheels or caterpillar for their driving operation. There is also a special case of adopting ambulation [3]. Caterpillar-based locomotion can hardly adapt to rapid topographic change and caterpillar affects the size of robot body. Ambulation-type has an advantage in changeable topography but requires a complicated control system through dynamics calculation [4].

This paper seeks to climb and explore the sides of steel structure such as vessel. To develop an inclined plane climbing robot based on magnetic force, we applied the adhesive magnet force and researched the robot's wall climbing method and structure. We also applied a mechanism for smooth locomotion at almost vertical inclination faced while moving and proposed a 4-wheel structure having ring-type magnets.

II. Mechanism of Wall Climbing Robot

The wall climbing robot is not simply for movement on walls but also for stable entry to walls as in the presented structure of this study. As shown in Fig. 1, the body is separated for front and rear-wheels drive and connected through rotation joint. The body is symmetrical based on the rotation joint so that the mass of gravity is at the center. There is an empty place inside the body to control the center of gravity. In the rotation joint, a dummy wheel was inserted, which are utilized as an assistive means for adaptation to topographic changes. The rotation joint in the platform center turns up to 40° counterclockwise and until the front wheels touch the rear wheels clockwise. Ring-type neodymium (Nd) magnets were attached to the front and rear wheels with repulsive force arranged in between to ensure they do not stick together while locomotion. Nonmagnetic material such as aluminum is utilized for dummy wheel, so it does not

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interfere in the magnetic force. The dummy wheel, as shown in Fig. 2 and Fig. 3, was employed to move vertical inclination stably. The four front and rear wheels which mounted magnet, are the ones that are actually driven by the motors. To increase the frictional force between the magnetic wheels and locomotion plane, rubber rings are used along the outer rim of magnetic wheels.

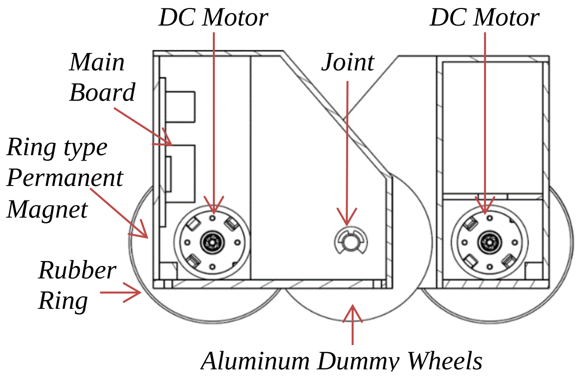


Figure 1. Structure of wall climbing Robot

Fig. 1 shows the wall climbing robot's structure, also shows magnet and dummy wheel arrangement. In locomotion robots, wheel arrangement affects their locomotive ability in obstacle overcoming. Thus, wheel arrangement is important in wall climbing robots. The wheels should look overlapped each other if looked from the side. This is because, in the case as shown on the right side of Fig. 3, the bottom of robot body should not touch the obstacle. If the robot body contacts an obstacle, it could impact its locomotion. Therefore, the intersection points created as wheels overlap should be placed closer to the robot body floor. Such a wheel arrangement determines robot body size in designing depending upon wheel size. The range of allowable weight was determined accordingly and magnet for wheels was selected

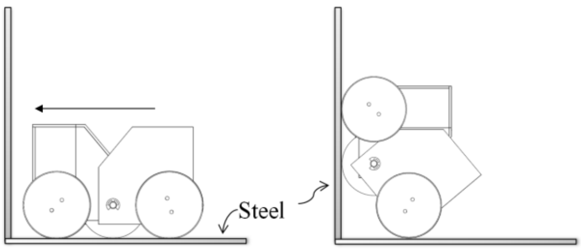


Figure 2. Adaptation mechanism by inclined plane (Up)

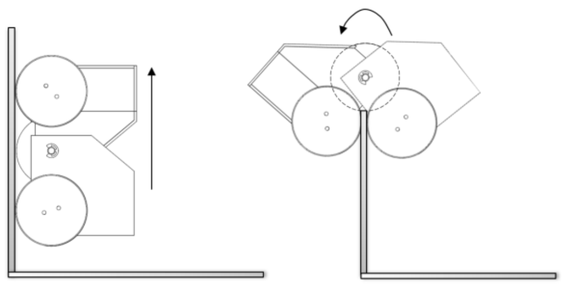
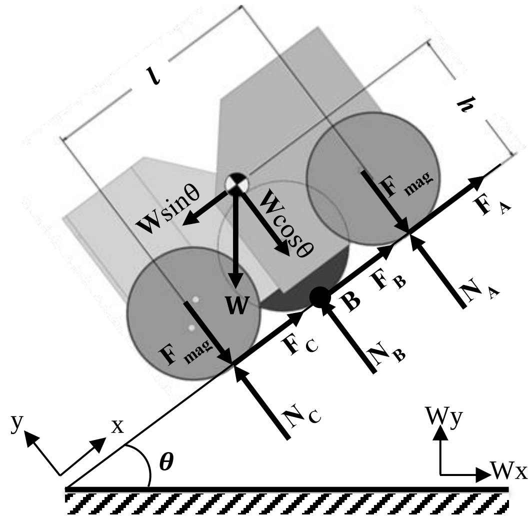


Figure 3. Adaptation mechanism by inclined plane (Down)

III. Attachable Force For Magnet

A. Modeling of Attaching Force

Stable driving of wall climbing of robot requires magnetic force to be attached to walls without slipping [5]. Fig. 2 shown free body diagram necessary to express in equation the magnetism needed in order not to be fallen or slipped off walls. Here, if the forces in the x direction and y direction achieve force equilibrium each, the robot is attached to the inclined plane in a static status. This can be defined in equations (1) and (2).



W : Weight
B : Center of Rotation
l : Wheel offset
h : Offset between **B** and CoM
θ : Slope between ground and wall
$\mathbf{F}_{\mathbf{mag}}$: Magnetic Force
$\mathbf{F}_{\mathbf{A}}, \mathbf{F}_{\mathbf{B}}, \mathbf{F}_{\mathbf{C}}$: Friction Force
$\mathbf{N}_{\mathbf{A}}, \mathbf{N}_{\mathbf{B}}, \mathbf{N}_{\mathbf{C}}$: Normal Force

Figure 4. Free Body Diagram for Wall Climbing Robot

$$\sum F_x = F_A + F_B + F_C - W\,sin\theta = 0 \quad (1)$$

$$\sum F_y = N_A + N_B + N_C - W\,cos\theta - 4\,F_{mag} = 0 \quad (2)$$

In the equation (2), $4F_{mag}$ is sum of 4 magnetic forces. It is the minimum magnetic force for robot attachment. To derive an equation to express it, the equation (3) is reorganized as in the equation (3) based on normal force and friction coefficient (μ);

$$N_A + N_B + N_C = W\frac{sin\theta}{\mu} \quad (3)$$

Finally, through the equations (2) and (3), the magnetic force necessary for wall attachment can be described in the equation (4) [1]. Based on it, the minimum necessary magnetic force can be found through the friction coefficient between wheel and wall and robot weight considered in designing.

$$4F_{mag} \geq W\left(\frac{sin\theta}{\mu} - cos\theta\right) \quad (4)$$

B. Magnetic Force Analysis

To select the magnet having the required magnetic force, attachable force should be measured using a measuring device or analysis program. Measuring with equipment requires a lot of time and money as all kinds of magnets are needed. Thus, ANSYS Maxwell simulation program was utilized for magnetic force analysis[6]. Fig. 5 is magnetic field distribution analyzed in the given condition using ANSYS Maxwell.

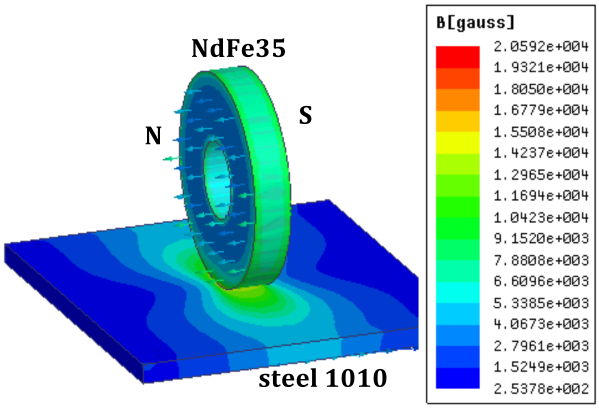


Figure 5. Analysis result for magnet

The magnet under analysis is Nd magnet in NdFe35 material. Analysis environment is Steel 1010 plate. Table 1 shows the properties of two materials. Fig. 6 is the B-H curve of Steel 1010. B and H are magnetic intensity and magnetic intensity, respectively, unit is in tesla and ampere turns/m. The B-H curve represents the magnetic flux density (B) as a result of an increase in magnetic force (H), and is saturated with no further increase in magnetic flux density when the magnetic force is reached at any point during the gradual increase in magnetic force. These saturated points are called saturating points, and Fig. 6 represents the magnetic saturation point where the magnetic flux density is about 3 Tesla.

The magnet size was set 55mm in external diameter, 20mm in internal diameter, and 10mm thickness; and the steel plate thickness was 5mm. The magnet and steel plate had 0.1mm space in between, which was the thickness of surface coating of the Nd magnet itself.

The magnet actually contacts the steel plate through lines. Of the contact lines, both ends, the N and S polar, had the largest magnetic field as in the results of Fig. 5. Here, the vertical magnetic forces upon the steel plate are in Table II. Pass is the iteration process of reducing errors during magnetic force analysis until 0.1% error. The magnetic force of final analysis was approximately 79.3 N, amounting to about 8.1kg in weight. The analyzed magnetic force was compared with that of actual magnet in a simple experiment to see how large difference they could have.

TABLE I. PROPERTIES OF THE MATERIAL FOR NDFE35 AND STEEL 1010

Material	Name	Value	Units
NdFe35	Relative Permeability	1.099778	μ
	Bulk Conductivity	625000	Siemens/m
	Magnetic Coercivity	-890000	Ampere/m
Steel 1010	Relative Permeability	B-H Curve	
	Bulk Conductivity	2000000	Siemens/m

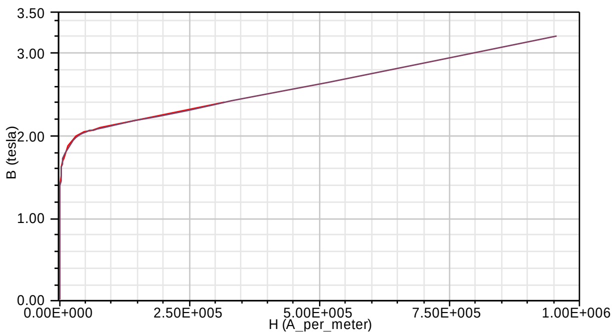


Figure 6. B-H curve for Steel 1010

TABLE II. RESULT OF ANALYSIS FOR MAGNETIC FORCE

Pass	Force [Newton]
1	82.12597689
2	81.95754124
3	81.19470342
4	80.14984792
5	79.68202436
6	79.46356609
7	79.34000133
8	79.30887027
9	79.28376087
10	79.27085013

IV. EXPERIMENT AND APPLICATION

To verify the magnetic force identified in the simulation, we made a robot and applied the simulation result and actual load on the robot. The magnetic wheels utilized in the robot were those employed in simulation.

The actual model magnets and steel plate were utilized to measure load just before the magnet is separated from steel plate. Push-pull gauge was utilized as a measuring tool. It was fixed on the magnet and gradually pulled just before separation. Table III shows the actual magnet attachable forces measured 10 repeated times directly. The average load actual magnets could endure was found about 7.9kg, indicating about 0.98% difference from the analyzed value in Table II. By applying this analyzed result to the equation (4), we can choose the necessary magnet for robot design.

TABLE III. ATTACHING FORCE OF ACTUAL MAGNET MEASURED DIRECTLY

Count	Kg
1	7.3
2	7.9
3	8.1
4	7.5
5	7.6
6	7.9
7	8.2
8	8.0
9	8.1
10	8.3

Fig. 7 and 8 are wall climbing robots that reflect the results of magnetic analyses and attach neodymium ring type magnets to the robot's wheels. When attached to a steel plate, the robot was found not to be slipped off but stay attached with stability. By applying the structure presented in section II, we conducted an experiment of entering vertical inclination from ground and found it moving smoothly with stability. Fig. 7 shows the robot driving on the floor and in a vertical plane. Fig. 8 shows that after driving horizontally in a vertical plane, it is overcome by the opposite end of the vertical plane.

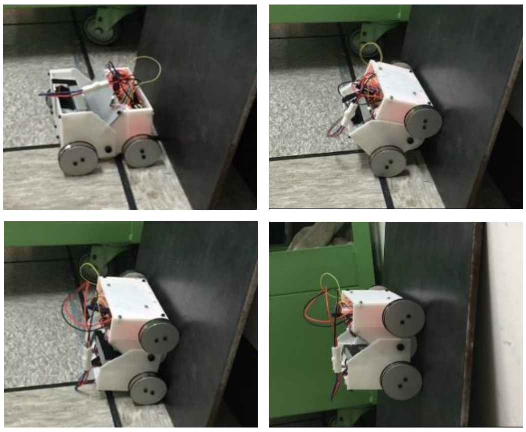


Figure 7. Application on Wall Climbing Robot

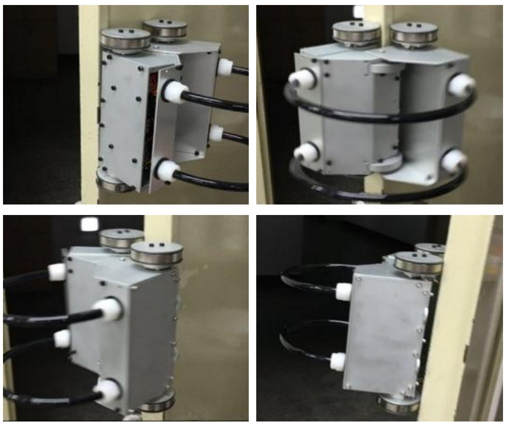


Figure 8. Horizontal Driving on Vertical Plane and Overcome Edge

V. CONCLUSION

First, we proposed a mechanism for stable locomotion in inclined plane in this study. When faced with steep inclination, the structure is capable of flexibly responding to slope angle change thanks to its joint in the center. When the robot was actually produced and experimented, we found it stably overcame structures such as thin steel plate without dropping out.

To choose the necessary magnet for wall climbing robot based on magnetic force, we proposed attaching force in equations. To achieve appropriate attaching force based on magnet, wheel torque necessary for locomotion should be considered in calculation in addition to proper magnet selection.

ANSYS Maxwell was run to analyze magnetic force. As a result of the analysis, the values approximated to the actually-measured attaching forces. Therefore, we proposed a simple method to estimate magnetic force without diverse necessary materials and equipment.

Based on those above, it became possible to run simulation analysis of diverse surrounding environments of steel structure and analyze the magnetic force between magnet and steel plate in consideration of the thickness of paint applied to steel structural surface. As magnets show noticeable loss of magnetic force even in 0.1mm distance change, the method is useful for diverse platforms based on magnetic force.

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