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Design, Development and Trials of a Miniature Whegs Wall-climbing Robot for Ferrous Structures

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Abstract

The present work reports the development of a miniature wall-climbing robot for ferrous structures. The robot uses a combination of wheel and legs (whegs) locomotion mechanism and permanent disc flexible magnetic strips for continuous adhesion as required for vertical wall climbing. The adhesion force, gait planning and power consumption analyses confirm the concept design of the proposed robot. The design analysis and experimental trials validate the proposed wall-climbing concept using a developed miniature prototype using a 3D printing facility. The developed wall-climbing robot uses different experimental set-ups for adhesion force and power estimation during various climbing motions. The experiments of robot motion during vertical wall climbing and plain wall-transitions established that it can easily adapt to ferrous structures. After laboratory trials, the proposed robot concept can be further tested in the actual environment and other material surface applications by design modifications and experimental prototyping.

Keywords

Wheel-spokes, Flexible magnetic strips, Whegs mechanism, Design analysis, Wall-climbing robot

Introduction

There are numerous ferrous structures such as tanks, ship-hulls, bridges, towers, vessels etc. worldwide which require periodic inspection and maintenance for their long service life and continuous operations. The safety assessment of various above-ground ferrous structures is critical to reduce the effect of the disaster, which frequently leads to loss of life and property. Inspection tasks mainly include detecting surface and sub-surface damage, corrosions, and connecting joint failures for subsequent maintenance procedures. Maintenance tasks include repair of joint failures, cleaning, and painting, etc. to restore damaged structures. Conventional manual procedures to work in unreachable locations, including climbing on vertical, ceiling, and wall-transitions lead to inefficient and costly affairs.

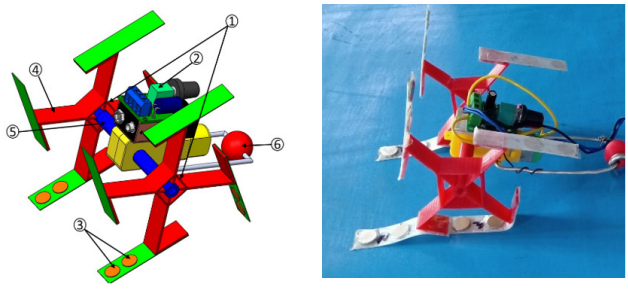
Working in these hostile environments requires wall-climbing robotic solutions for repetitive, labor-intensive, and hazardous jobs. Wall-climbing robotic system requires locomotion and adhesion techniques along with carrying inspection and maintenance payload tools. Wall-climbing robots mainly use wheel [1], leg [2], track [3] and cable-driven [4] locomotion techniques. Hybrid locomotion i.e., combined locomotion (wheel and leg, wheel and track, track and leg) is also being explored in the literature [5-7]. Wall-climbing is not possible without any suitable adhesion technique. Various adhesion techniques such as suction [3], magnetic [5], electro-adhesive [8], and gecko type adhesion [9-11] have been

widely investigated in the recent past. However, permanent magnets are widely used for ferrous medium as it is most reliable and requires no external power to create net adhesion force for holding the robot on vertical terrains. A combination of wheel and legs (whegs) has also been explored as suitable locomotion to overcome the individual locomotion drawbacks, and whegs-robot can adapt to discontinuous and uneven terrain with continuous motion [6, 11, 12]. Smooth attachment and detachment for robot movement using permanent magnets on legged robots will have a major issue, especially when high speed is preferred with the wall-climbing robot for uneven terrain [2].

The present study deals with the combined wheel and multiple legs (whegs) configuration of wall-climbing robot for continuous attachment and detachment for smooth locomotion. A prototype of miniature wall-climbing robot has been designed, developed and laboratory trials have been successfully conducted. The robot used permanent disc magnets for adhesion and a combination of wheel and legs for locomotion. The proposed whegs configuration has better maneuverability compared to the existing system. Firstly, extensive design and analysis have been performed for developing the prototype robot hardware. Laboratory trials validate the proposed wall-climbing concept to adopt in ferrous structures.

Materials and Methods

A miniature wall-climbing robot uses whegs i.e., a combination of wheels and legs and flexible permanent magnetic strips for robust vertical climbing and plane-to-plane transitions. Figure 1a shows the computer-aided design (CAD) model and figure 1b shows the working prototype of the miniature wheg wall-climbing robot. The CAD model is prepared using SolidWorks software. It mainly consists of two whegs, an electronic unit, power supply unit, and a supporting tail. Each wheg consists of four spokes equipped with a flexible strip on each spoke, and permanent disc magnets are integrated with each flexible strip. The two whegs of the robot are connected through a dual motor shaft and an external power source is used to drive the robot for laboratory trials. A light-weight tail weighing 10 gm is used to give support to the electronic unit. All the components or parts except the electronic unit of the miniature wall-climbing robot are made by the laboratory Creality CR-10S5 3D printer. The permanent disc magnets (N48 grade) of size Φ 10 mm x 2 mm thickness are procured from the market. The design specifications of the proposed wall-climbing robot are given in table 1.



(a) (b)

Figure 1: Miniature Wheg wall-climbing robot: **(a)** 3D CAD model: 1) Whegs, 2) Electronic unit, 3) Permanent magnets on a flexible strip, 4) Spoke, 5) Connecting shaft, 6) Tail. **(b)** Working prototype.

Table 1: Design specifications of the proposed wall-climbing robot.

S. No.	Design parameters	Specifications
1	Length of robot	170 mm
2	Width of robot	100 mm
3	Height of robot	110 mm
4	Weight of the robot	150 gm

A force diagram of the miniature wall-climbing robot on inclined surface and vertical surface is depicted in figure 2. It helps to understand the concept mechanics of the motion of the wall-climbing robot. The forces and moments exerting on the robot body are the weight component of the robot ($W = mg$) acting at the robot's center of gravity (CG), normal reaction force (N) due to adhesion, traction force (f), net adhesion force (F_a) and driving torque (τ) required to move the robot. The system of equations for equilibrium during locomotion of the robot is then obtained as: $\sum \vec{F} = 0$ and $\sum \vec{M} = 0$.

Therefore,

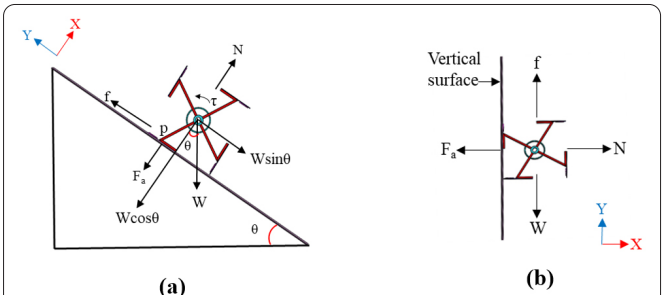
$$\sum F_x = 0 = N - \sum_{i=1}^{n} F_i - W\cos\theta \quad (1)$$

$$\sum F_y = 0 = f - W\sin\theta \quad (2)$$

$$\sum M_p = 0 = W\sin\theta \times r - \tau \quad (3)$$

Traction force (f) is given by $f = \mu N$,

Where, n is the total number of disk magnets embedded in a single flexible strip, coefficient of friction between the permanent magnet and ferrous surface (μ) = 0.4 - 0.8. Detailed force (adhesion and friction) measuring procedures can be seen elsewhere [13]. Total mass of robot (m) = 0.15 kg is obtained from the concept design. Spoke length of the robot i.e., distance from the center of wheel to tip of the leg (r) = 0.04 m.



(a) (b)

Figure 2: Free body diagram of wheg mechanisms for robot locomotion **(a)** Inclined surface and **(b)** Vertical surface.

Results and Discussion

The magnetic capacity or force required to peel off the disc magnets from the ferrous surface of each strip is calculated experimentally using digital force gauge test set-up as shown in figure 3a. Figure 3b shows the fixture made by 3D

printer to hold the permanent disc magnet and perform the adhesion force measurement test. Five consecutive trials were performed for each permanent disc magnet to get accurate and precise adhesion force data. Bare disc magnet and magnet with different tape thickness were tested to determine the magnetic strength of the permanent disc magnet. Figure 4 shows the characteristics between the magnetic capacity of permanent disc magnet with the different cases of tape thickness and detachment time. The peak value of magnetic adhesion capacity 4 N, 3.3 N, 2.95 N, and 2.55 N were found experimentally using the adhesion force measurement set-up for bare disc magnet, disc magnet with tape thickness of 0.078 mm, 0.156 mm, and 0.234 mm, respectively. The results show the adhesion force decreases as the tape thickness increases. Therefore, the appropriate flexible strip thickness (0.25 mm) was chosen for the integration of disc magnets in whegs mechanisms for simultaneous locomotion and adhesion.

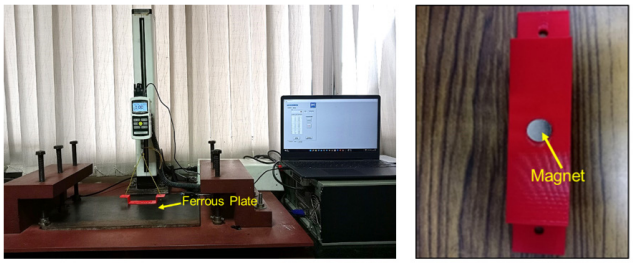


Figure 3: (a) Test set-up for magnetic adhesion force measurements and **(b)** Fixture to hold permanent disc magnet for experiments.

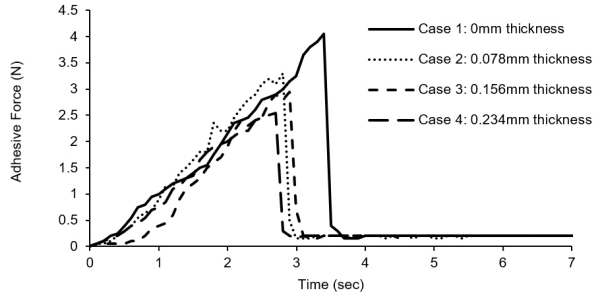


Figure 4: Adhesion force of permanent disc magnet with different cases of tape thickness.

The experimental trials conducted at laboratory on the ferrous structure were shown in figure 5. The robot performed vertical wall climbing and different plane-to-plane transitions i.e., from horizontal to vertical ferrous surface. The motion sequence of the working trials of the robot is shown in figure 5a - 5f. The power consumption during the various locomotion of the miniature wall-climbing robot is measured using the programmable DC power supply set-up as shown in figure 6a. Figure 6b shows the graphical representation of the power consumption for different locomotion of the miniature wall-climbing robot. In the vertical downward motion, the power required to drive the robot is less compared to horizontal ground and vertical upward motion, because when the robot moves in the downward direction, it moves under the sole influence of the positive gravitational force (+g). So, it requires less power compared to other wall locomotion conditions. A gait pattern has been drawn in table 2 to understand the smooth attaching and detaching sequence of the miniature wall-climbing robot, which further helps to understand the adhesion requirement for continuous wall-climbing motion. This gait pattern is for a flexible magnetic strip with single disc magnet, so continuous adhesion can be seen during locomotion.

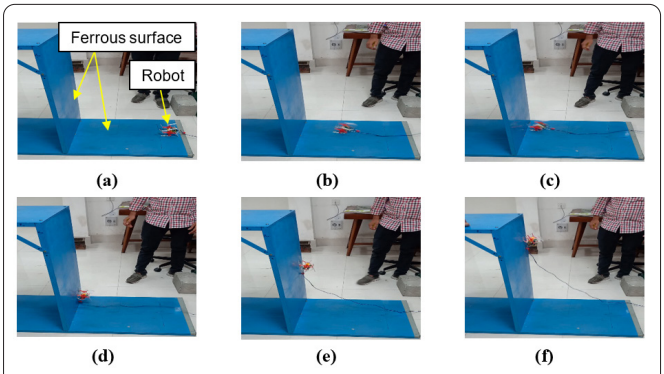


Figure 5: Experimental trials for vertical climbing and wall-to-wall transitions, where robot motion sequence is shown from steps **(a - f)**.

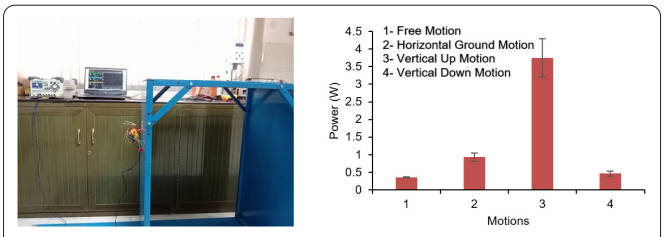


Figure 6: (a) Programmable power supply setup and **(b)** Power consumption for different locomotion of miniature wall-climbing robot.

Conclusion

The study presents a detailed investigation of whegs (wheel and legs) design configuration and flexible strips with integrated permanent disc magnets for continuous wall-climbing locomotion on ferrous structures. The design analysis and adhesion force experiments have been performed for the robot hardware development and the components are manufactured using a laboratory 3D printing facility. The robot is miniature in size with 150 gm weight, and it has 300 gm payload and peak locomotion speed of 8 m/min. The motion trials have been done and successful motion trials during vertical climbing and wall transitions have been achieved. It is established from the experimental trials that the vertical downward motion (0.5 W) requires least power compared to ground (0.9 W) and vertical upward motions (3.7 W). Future research should consider bioinspired-based design of a miniature wall-climbing robot for inspection of ferrous structures. This concept can also be further extended for other material surface applications using gecko-type bioinspired adhesive strips in place of magnetic strips.

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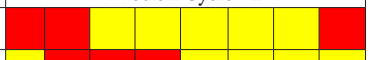
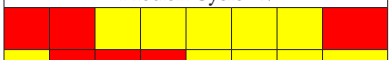
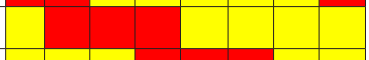
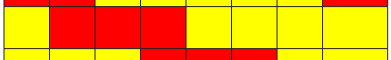
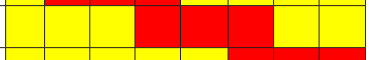
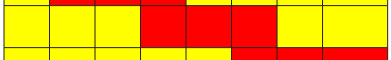
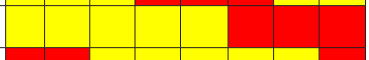
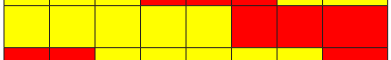
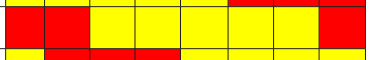
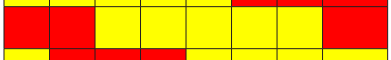
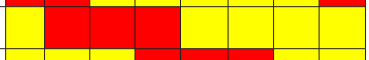
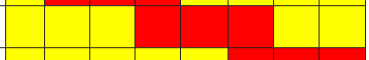
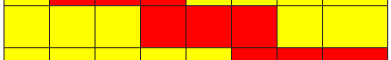
Table 2: Gait Pattern for two whegs configurations of wall-climbing robot.

	Circular disc magnet No.	Continuous attachment and detachment sequence of wheg mechanisms during locomotion	
		Motion Cycle - 1	Motion Cycle - 2
Left Spoke	1		
	2		
	3		
	4		
Right Spoke	1		
	2		
	3		
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Conflict of Interest

The authors declare no competing interests that are relevant to the content of this article.

Credit Author Statement

Nitesh Kumar Malviya: Design, Experimentation, Manuscript - original draft preparation; Ravindra Singh Bisht: Design, Conceptualization, Methodology, Analysis, Manuscript - review and editing; Kanti Lal Solanki: Design analysis, Experimentation, Manuscript - review and editing; Akhilesh Kumar Rathore: Supervision, Manuscript - review and editing. All the authors read and approved the manuscript.

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