



## RAIL-GUIDED MAGNETIC ADHESION FOR SLIPPAGE MITIGATION IN WALL-CLIMBING ROBOTS

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### ABSTRACT

Wall-climbing robots have a great deal of potential for checking, repairing and guarding vertical and inverted areas. Mostly of these robots faced challenges in slippage, mainly when they go over uneven or inclined walls. A new method is offered in this paper that combines rail tracking, magnetic adhesion of wheels and supporting inner tires to make sure wall climbing robots do not slip. The arrangement of joints makes it possible for the wheels to remain stable, have a better grip and make adjustments for carrying weight. There is a two-layered mechanism in the methodology where outer magnetic wheels stick to the steel rails while inner wheels are kept in the center and have constant contact by springs. Motor movement is controlled by a microcontroller and use Bluetooth to control the car remotely. Adhesion force, traction torque, relevant slippage measures and the required power were studied using different mathematical models. The models used to describe load balance, magnetic attraction and the movement of the plate during loading were all checked by running simulations in MATLAB, Solidworks and ANSYS. The prototype was constructed using fiber-reinforced plastic for car body, wheels which have permanent magnets and was tried out on surfaces that were horizontal, inclined and vertical. Results showed increased stability while moving horizontally and vertically, fewer accidents due to slipping and good load support. Rail-track designs offer a better, simpler and stronger way compared to adhesion approaches like suction and bio-adhesive systems. This research provides a useful way of moving in robotics that joins theory, making and usefulness in the real world.

**Keywords:** Wall-climbing robot, rail-track guidance, magnetic adhesion, slippage mitigation, spring suspension, mobile robotics.

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### INTRODUCTION

Due to the rapid development of urban infrastructure and industrial facilities cause significantly incremental demand for automated inspection and maintenance of large-scale into vertical and inclined structures [1-4]. Traditional manual inspection methods are often time-consuming, costly and hazardous to human life particularly in environments involving heights, confined spaces or harsh operating conditions. As a result, wall-climbing robots have emerged as a promising alternative by offering safety improvement, efficiency

and repeatability to reduce or eliminate risks to humans. A critical challenge in these applications is maintaining stable adhesion and controlled locomotion on inclined or uneven surfaces as gravitational forces and surface irregularities can induce slippage and loss of stability [5, 6].

Existing adhesion approaches including suction-based systems [7, 8], negative pressure mechanisms [9], and bio-inspired adhesives [2, 10, 11], which are often suffer from reduced effectiveness on dry or irregular surfaces and typically require high energy consumption or complex control strategies. Permanent magnetic adhesion [5, 12-16] provides a low-power and mechanically simple alternative for steel structures; however, magnetic wheel-based robots [17, 18] remain susceptible to lateral drift and slippage during transitions, load variations or changes in surface orientation. Moreover, the lack of mechanical guidance in many designs increases reliance on sensing and control algorithms thereby adding system complexity [19, 20].

Mechanical constraint through guided locomotion offers a promising strategy for improving stability and repeatability in structured environments, yet rail-assisted wall-climbing systems have received limited attention, particularly when combined with magnetic adhesion and compliant load-balancing mechanisms. Integrating passive guidance with adaptive wheel support has the potential to reduce slippage while simplifying control requirements and improving operational reliability. The main objective of this study is to design and evaluate a rail-guided wall-climbing robot that combines permanent magnetic adhesion with compliant wheel support in order to overcome slippage challenge which faced by many magnetic adhesions wall-climbing robot as analyzed by other researchers.

## 2. MATERIALS AND METHODS

### 2.1 Components Materials

The wall-climbing robot chassis prototype was fabricated using fiber-reinforced plastic (FRP) sheets due to its high strength-to-weight ratio. While permanent neodymium iron boron (NdFeB) magnets with Grade N42 and surface magnetic flux density approximate 0.5T were embedded into the outer driving wheels which rubberized in order to provide a continuous magnetic adhesion while the inner stabilizing wheels were rubberized nylon wheels mounted on compression springs with spring constant ( $k$ ) of 15 N/m. Also, the rail-guidance system consisted of a mild steel C-channel rail with thickness of 3mm and it is rigidly fixed to the test surface to constrain lateral motion.

Locomotion was driven by 11.1V DC geared motors of 100RPM and stall torque of 0.5Nm together with control electronics included an STM32 microcontroller, an TB6612FNG dual H-bridge motor driver and an HC-05 Bluetooth module which powered by a 11.1V, 2200mAh lithium-polymer battery pack.

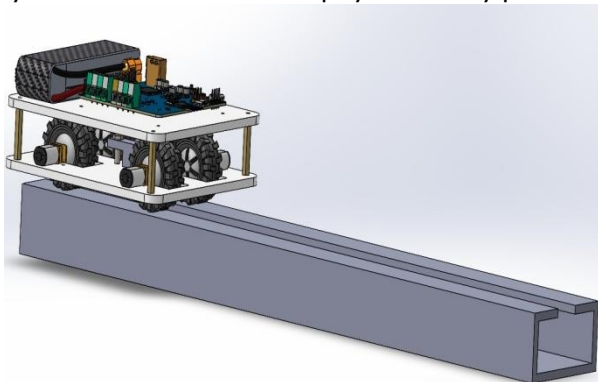


Fig 01: Front model views of structured rail-guided wall Climbing Robot

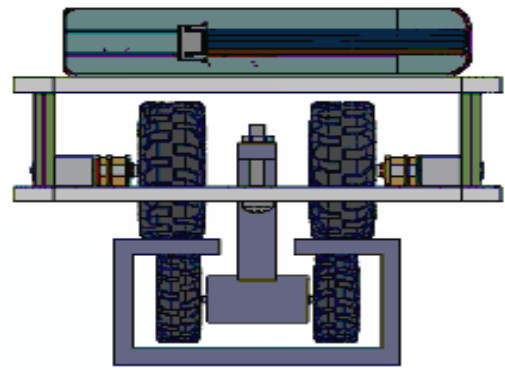


Fig 02: Rear model views of structured rail-guided wall Climbing Robot

### 2.2 Mechanical Design and Assembly

The full robot model with its rail path was designed using SolidWorks 2024 and fabricated through manual assembly. The magnetic wheels were mounted externally to ensure direct contact with the steel rail while the spring-supported inner wheels were positioned to maintain central alignment within the rail channel. This configuration enabled adaptive load distribution and minimized slippage during vertical and inclined motion.

### 2.3 Control System and Software Implementation

The STM32 microcontroller was programmed using embedded C firmware to control motor speed, direction and Bluetooth communication. Motor speed control was achieved using pulse-width modulation (PWM) while direction control was handled via digital logic signals through the TB6612FNG motor driver. Also, wireless control commands were transmitted from a custom Android application to the robot via Bluetooth using UART serial communication.

The robot responded to predefined motion commands that are forward/upward, backward/downward and stop while its control performance and stability were verified through MATLAB/Simulink simulations prior to experimental testing.

### 2.4 Analytical Modeling and Simulation

Force and stability analyses were conducted using classical mechanics equations to determine traction force, magnetic adhesion force, slippage conditions, torque and power requirements. Also, magnetic adhesion force was analytically calculated based on magnetic flux density and contact area.

#### 2.4.1 Force Analysis and Stability Equations

The analysis of forces acting on the wall-climbing rail-guided robot is crucial to ensure reliable adhesion, locomotion and stability under different operating orientations. Horizontal, inclined and vertical. The forces to consider include gravitational force, magnetic adhesion force, normal reaction forces and frictional forces.

### 2.4.1.1 Vertical Orientation (Uphill and Downhill)

Let:

- $W = mg$  be the weight of the robot.
- $\mu$  = coefficient of friction between the wheels and the rail.
- $F_m$  = magnetic adhesion force per wheel.
- $F_n$  = normal force exerted by spring-reinforced tires.
- $F_f = \mu(F_m + F_n)$  be the total frictional force Opposing motion/slippage.

For upward vertical motion:

$$F_f \geq W \Rightarrow \mu(F_m + F_n) \geq mg$$

For downward vertical motion:

$$F_{brake} + F_f \geq mg$$

### 2.4.1.1 Inclined Orientation

Let  $\theta$  be the angle of inclination from the horizontal:

$$F_{gravity,parallel} = mgsin\theta$$

$$F_{gravity,normal} = mgcos\theta$$

$$F_f \geq mgsin\theta \Rightarrow \mu(F_m + F_n) \geq mgsin\theta$$

### 2.4.1.2 Horizontal Orientation

The gravitational component becomes perpendicular to the motion path. Here, the friction and adhesion forces are only need to overcome minor inertia or vibrations:

$$F_f = \mu(F_m + F_n) \gg 0 \quad (\text{for anti-slippage security})$$

### 2.4.1.3 Slippage Conditions

The slippage condition was derived from the imbalance between traction or frictional forces and the required driving or resisting forces.

A slippage event occurs if:

$$F_{drive} > \mu(F_m + F_n)$$

or if:

$$mgsin\theta > \mu(F_m + F_n)$$

To prevent slippage, the design must satisfy:

$$\mu \geq \frac{mgsin\theta}{F_m + F_n}$$

Additionally, for varying payloads PPP:

$$\mu \geq \frac{(m+P)gsin\theta}{F_m + F_n}$$

This ensures the system is robust under real-world load variations.

### 2.4.2 Magnetic Force Calculations

The magnetic adhesion force is provided by permanent magnets embedded in the wheels or chassis which pulling toward the steel rail. Assuming each wheel has an effective magnetic force  $f_m$  and there are  $n$  magnetized wheels in contact:

$$F_m = n \cdot f_m$$

The magnetic force required to prevent detachment is:

$$F_{m,required} \geq (m+P)g - F_n$$

Accounting for a safety factor  $S$  :

$$F_{m,required} = S \cdot ((m+P)g - F_n)$$

### 2.4.3 Torque and Power Requirements

To ensure sufficient driving capability, torque calculations must account for required traction force

$F_t$  and wheel radius  $r$ .

$$\tau = F_t \cdot r$$

Assuming no slippage:

$$F_t = \mu(F_m + F_n) \Rightarrow \tau = \mu(F_m + F_n) \cdot r$$

The power  $P$  required for motion at velocity  $v$  is:

$$P = F_t \cdot v = \mu(F_m + F_n) \cdot v$$

Including motor efficiency  $\eta$ , the actual input power required:

$$P_{input} = \frac{P}{\eta}$$

Structural integrity and stress distribution were evaluated by using ANSYS Workbench 2025 R2by assigned FRP material properties of young's modulus approximate 20GPa and density approximate 1.8g/cm<sup>3</sup> for chassis. While control dynamics and adhesion force behavior were simulated using MATLAB R2024b.

### 2.5 Experimental Procedure

The prototype was tested on a Laboratory by fixed a rail track under three surface orientations including horizontal (0°), inclined (45°–75°) and vertical (90°) and for each configuration the robot traversed a distance of 0.9m under incremental payloads ranging from 0.5kg to 2.0kg by repeated three times for each test condition to ensure repeatability.

However, measured parameters also observed included adhesion stability, wheel slippage occurrence, motor current consumption and Bluetooth response time while for the payload capacity was defined as the maximum load the robot could carry without sustained slippage.

## 3. RESULTS

This section presents the experimental and simulation outcomes obtained from evaluating the rail-guided wall-climbing robot under different surface orientations and payload conditions. Results are reported without interpretation and numerical data presented in tables are not duplicated in figures.

### 3.1 Structural and Control Simulation Results

Structural simulation results obtained from ANSYS showed that the maximum von Mises stress experienced by the robot chassis under the maximum design load remained well below the material yield limit. The maximum displacement occurred near the spring-supported inner wheel mounts and remained within acceptable mechanical tolerances that confirming structural stability under operational loading conditions.

Control system simulations conducted in MATLAB/Simulink demonstrated stable motor

response to directional commands. The system achieved steady-state speed within a short settling time with minimal overshoot and speed deviation under increased load remained within acceptable limits by indicating reliable control performance for wall-climbing operation.

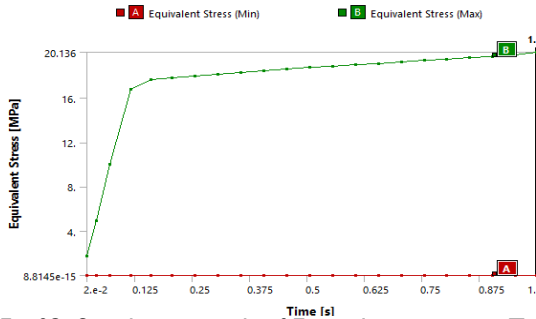


Fig 03: Simulation graph of Equivalent stress vs Time

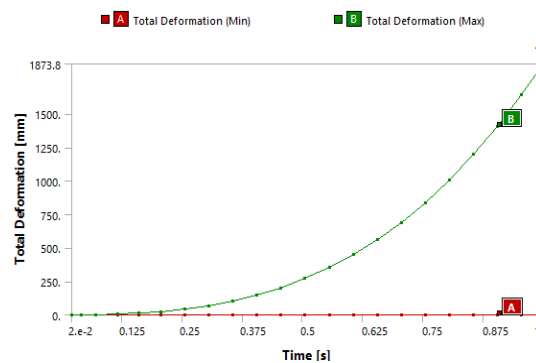


Fig 04: Simulation graph of Total Deformation vs Time

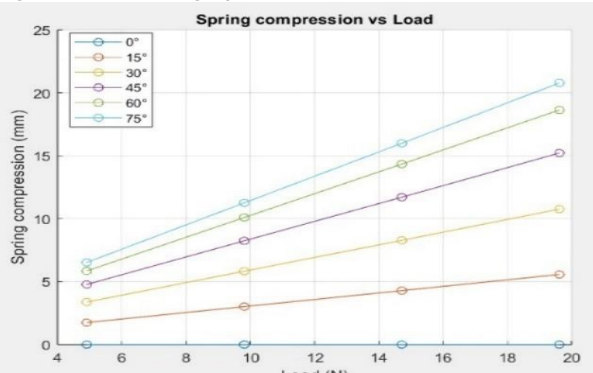


Fig 05: Simulation graph of Spring compression vs Load graph

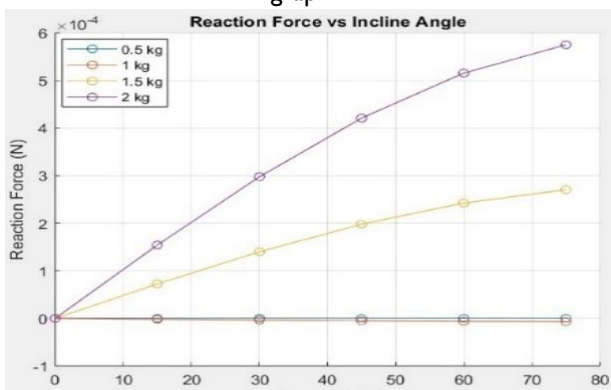


Fig 6: Simulation graph of Reaction Force vs Inclined Angle

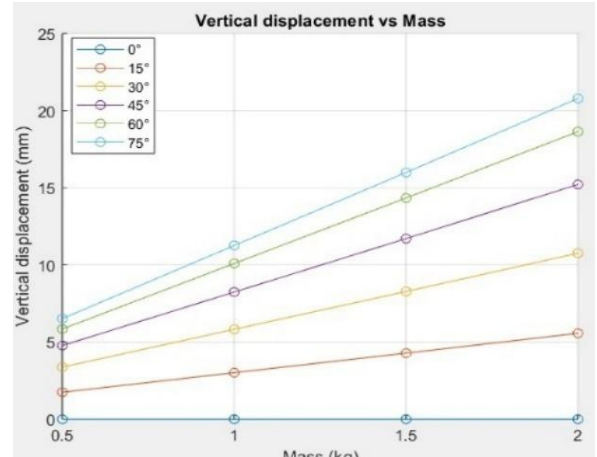


Fig 07: Simulation graph of Vertical displacement vs Mass

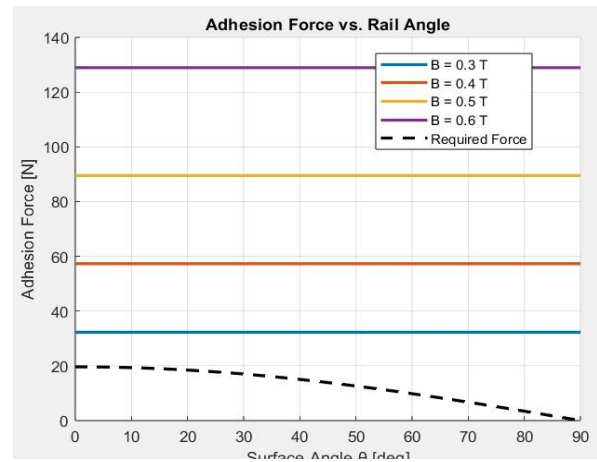


Fig 08: Simulation graph of Adhesion Force vs. Angle graph

### 3.2 Adhesion and Locomotion Performance

Experimental testing on horizontal, inclined and vertical rail-mounted steel surfaces confirmed stable adhesion and guided locomotion. The robot maintained continuous contact with the rail across all surface orientations and no lateral deviation was observed due to the mechanical constraint imposed by the rail system. Magnetic adhesion force was sufficient to support the robot's weight and applied payloads during static and dynamic motion. Adhesion force trends with respect to surface inclination are presented graphically in the corresponding figure while quantitative payload performance is summarized separately in tabular form.

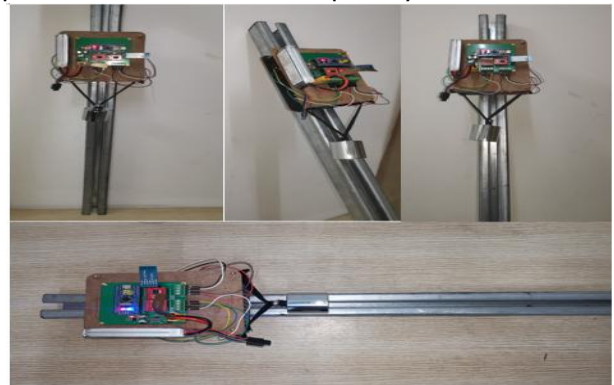


Fig 09: Experiment rail fixed into different surface angle with load of 500g

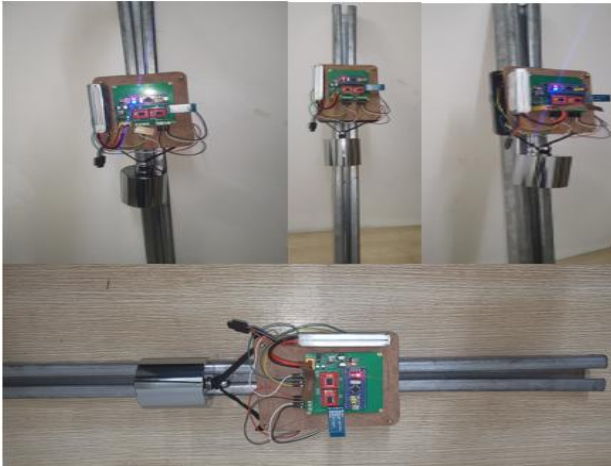


Fig 10: Experiment rail fixed into different surface angle with load of 2kg

**3.3 Payload Capacity Results**

Payload testing results are summarized in Table 1. The robot maintained stable locomotion without sustained slippage for payloads up to 1.5 kg on vertical surfaces. At a payload of 2.0kg intermittent slippage was observed during acceleration phases which indicating proximity to the adhesion limit. These payload thresholds were consistently observed across repeated trials.

Table 01: Payload Test Results

Payload (kg)	Adhesion Status	Motion Quality	Notes
0.5	Stable	Smooth	No wheel slip
1.0	Stable	Acceptable	Minor spring compression
1.5	Stable	Sluggish	Motor torque near max limit
2.0	Marginal	Minor Slip	Near edge of adhesion margin

**3.4 Wireless Control Response**

Bluetooth communication performance was evaluated by measuring command transmission delay between the mobile application and motor actuation. The average response time remained below 100ms across all test conditions. Communication latency increased slightly under higher payload conditions but did not disrupt control continuity or motion execution.

**3.5 Energy and Motor Load Characteristics**

Motor current measurements showed increased current draw with increasing surface inclination and payload. The highest current consumption occurred during vertical climbing with maximum payload while battery voltage remained within operational limits throughout all test durations which confirming adequate power delivery for the evaluated scenarios.

**3.6 Slippage Occurrence**

Slippage incidence was minimal across most test conditions. No slippage was recorded on horizontal surfaces while minor transient slip events occurred at

high incline angles and maximum payloads. Quantitative slippage frequencies are reported numerically in the corresponding dataset and are not duplicated graphically.

**4. DISCUSSION**

The results demonstrate that combining rail-track guidance with permanent magnetic adhesion effectively addresses slippage which remains a persistent limitation in conventional wall-climbing robots. The mechanical constraint imposed by the rail system plays a central role in stabilizing motion by preventing lateral drift which is one of a problem commonly reported in unguided magnetic wheel designs. This indicates that physical guidance can significantly reduce reliance on complex sensing or feedback-based correction strategies.

Compared with purely magnetic wall-climbing robots reported in recent studies, the present system exhibits improved motion stability during transitions and under varying payload conditions. Previous magnetic wheel designs have shown susceptibility to slippage when load distribution changes or when operating on steep inclines due to unbalanced shear forces at the wheel surface interface. The inclusion of spring supported inner wheels in the proposed design enables dynamic load redistribution which mitigates localized loss of traction and improves adhesion reliability without increasing magnetic strength or energy consumption.

Relative to suction-based and bio-inspired adhesion systems, the rail-guided magnetic approach offers a structurally simpler and more energy-efficient solution for steel environments. Suction mechanisms often require continuous power and are sensitive to surface contamination while adhesive-based systems can degrade under repeated use or environmental exposure. In contrast, the passive magnetic adhesion employed in this study provides consistent attachment with minimal power demand and the rail guidance ensures repeatable trajectory control in structured environments.

The observed payload limitations are consistent with previously reported constraints in magnetic climbing systems where shear force capacity rather than normal adhesion force often defines performance boundaries. However, by mechanically constraining lateral motion and supporting vertical load through compliant elements observed that the proposed system achieves effective payload handling within a compact and lightweight structure. This balance between mechanical simplicity and functional robustness distinguishes the present design from hybrid systems that combine multiple active adhesion mechanisms at the cost of increased complexity and mass.

Overall, the findings suggest that integrating passive mechanical guidance with magnetic adhesion represents a practical design strategy for wall-climbing robots intended for inspection and maintenance tasks in predefined rail-based environments. The approach complements offering a reliable and scalable solution

for industrial applications against the existing magnetic climbing technologies by addressing slippage through structural means rather than increased adhesion force or computational control.

## 5. CONCLUSION

This study aimed to develop and evaluate a rail-guided wall-climbing robot that integrates permanent magnetic adhesion with spring supported wheel stabilization to mitigate slippage on horizontal, inclined and vertical steel surfaces. The findings confirm that the proposed combination of mechanical rail guidance and passive magnetic adhesion effectively fulfils this objective by providing stable, controlled locomotion under varying surface orientations and payload conditions. The integration of compliant inner wheels further supports load balancing and adhesion reliability without increasing system complexity or energy demand. By directly addressing slippage through structural guidance rather than active adhesion or complex control strategies. However, the study establishes a practical and robust design approach for wall-climbing robots operating in structured steel environments. The proposed framework therefore offers a viable foundation for future rail assisted robotic inspection and maintenance systems.

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## CONFLICT OF INTEREST

We declare no conflict of interest regarding the publication of this paper.

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