Omni-Directional Wall-Climbing Robot: A Novel Mechatronic System with Propulsion-Based Adhesion

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Abstract

This paper presents the design, implementation, prototype development, and qualitative evaluation of an omni-directional wall-climbing robot using a propulsion-based adhesion mechanism. The proposed system integrates a three-wheel omni-directional drive with thrust generated by brushless propeller units to maintain stable contact with vertical and inclined surfaces. Unlike conventional wall-climbing robots that rely on magnetic or suction-based adhesion, the proposed approach provides broader surface adaptability, including operation on non-ferrous and rough surfaces, without requiring surface-specific adhesion mechanisms. The robot is controlled by an Arduino Mega-based embedded architecture incorporating real-time inertial measurement unit feedback and PID-based control for locomotion and adhesion stabilization. A simplified dynamic model is developed to estimate the thrust required for reliable adhesion, while inverse-kinematic coordination of the omni-wheels enables holonomic motion and precise maneuverability. Qualitative prototype evaluation on multiple surface types indicates stable climbing performance, maintained adhesion, and smooth directional transitions under representative operating conditions. The results support the feasibility of combining propulsion-assisted adhesion with omni-directional mobility in a compact robotic platform for applications such as infrastructure inspection, high-rise maintenance, and industrial surveillance in complex environments.

1. Introduction

The advancement of robots capable of navigating diverse terrains and surfaces is increasingly vital in modern society. Wall-climbing robots have received significant attention in robotics research due to their potential for automation in hazardous and hard-to-reach environments, including infrastructure inspection, industrial maintenance, security surveillance, and rescue operations (Lou et al. 2025; Nguyen et al. 2020; Yang et al. 2024; Yu et al. 2024). The ability to traverse vertical and inclined surfaces offers substantial advantages in situations where human access is difficult, dangerous, or costly. Recent studies have also explored wall-climbing robots with omni-directional motion to improve maneuverability on complex surfaces (Jia et al. 2025).

Wall-climbing robots are commonly classified based on three core design strategies: adhesion, locomotion, and control. Adhesion methods include magnetic (Eto and Asada 2020; Wang et al. 2025), negative pressure (suction) (Hernando et al. 2021), electrostatic (Chen 2015; Yamamoto et al. 2007), and bio-inspired techniques (Wang et al. 2014), each presenting trade-offs related to surface compatibility, energy consumption, and payload capacity. Locomotion strategies include tracked (Kermorgant 2018), wheeled (Eto and Asada 2020), legged (Hong et al. 2022), and hybrid configurations (Tovarnov and Bykov 2024), which balance maneuverability and adaptability. Control strategies range from predefined motion planning to dynamic approaches that incorporate real-time sensory feedback for environmental adaptation (Zhu et al. 2024).

Despite extensive research, traditional wall-climbing robots often remain limited by surface dependency and energy inefficiency. Suction-based systems perform well on smooth surfaces but require substantial power and airtight contact, while magnetic adhesion is restricted to ferromagnetic materials. Electrostatic adhesion offers broader surface compatibility but is sensitive to environmental conditions such as humidity. Bio-inspired adhesion methods, while energy efficient, are often constrained by limited payload capacity (Zhu et al. 2024). To address these challenges, recent studies have explored hybrid adhesion strategies, including the integration of thrust-based mechanisms with conventional adhesion methods, demonstrating improved versatility and stability across diverse surface conditions (Liang et al. 2021; Tovarnov and Bykov 2024).

Building upon recent advances in propulsion-assisted climbing robots, this work presents an omni-directional wall-climbing robot that employs a

drone-propulsion-based adhesion mechanism integrated with omni-wheel kinematics to achieve holonomic motion. Unlike conventional systems that rely solely on passive adhesion, the proposed approach generates a controllable and adjustable normal force, allowing the robot to reliably adhere to vertical and inclined surfaces, including rough and non-ferrous materials. Omni-directional wheels were selected over Mecanum wheels because they provide a mechanically simpler holonomic drive configuration and can offer smoother motion with reduced vibration on flat operating surfaces, making them well suited for this application (Akkad and Almusawi 2023; Hijikata et al. 2023; Taheri and Zhao 2020).

The control architecture is implemented using an Arduino Mega microcontroller and incorporates a PID-based feedback loop to ensure precise motor control and real-time stability adjustment. By integrating thrust-based adhesion with omni-directional locomotion, the proposed system expands the operational capabilities of wall-climbing robots while maintaining manageable system complexity. Furthermore, the use of a three-wheel omni-directional configuration reduces mechanical complexity while preserving full planar mobility, making the system well suited for compact robotic platforms. Related work on ground-based omni-directional robotic platforms has also demonstrated the value of holonomic mobility for maneuvering in constrained environments and for integrating sensing, perception, and embedded control within a unified mechatronic system (Yazdanpour et al. 2026).

In addition to its technical contribution, the project was developed within a senior capstone experience in Mechatronics Engineering Technology, providing a practical setting for system-level integration of mechanical design, embedded control, mechatronics, and prototype testing. As such, the work also reflects the role of applied, project-based learning in engineering technology education through hands-on system development and iterative refinement.

The primary contribution of this work is the integration of propulsion-based adhesion with a compact three-wheel omni-directional locomotion platform for wall-climbing operation on diverse surface types. In addition to the mechanical and embedded-system design, the study presents a simplified dynamic model for thrust estimation and a closed-loop control architecture based on IMU feedback and PID regulation. The remainder of the paper describes the system methodology, qualitative prototype evaluation, and key challenges identified during testing.

Although propulsion-assisted wall-climbing has been explored in prior studies, the novelty of the present work lies in the integration of propulsion-based adhesion with a compact three-wheel omni-directional holonomic drive and embedded IMU-based PID stabilization in a single wall-climbing platform. In contrast to prior systems that primarily emphasize adhesion feasibility or conventional locomotion architectures, the proposed design focuses on combining thrust-assisted multi-surface adhesion with compact holonomic maneuverability and simplified mechatronic integration. This combination enables directional flexibility, reduced mechanical complexity, and practical proof-of-concept implementation within an engineering technology capstone framework.

2. Capstone and Educational Context

This project was completed within a senior-level capstone course in the Mechatronics Engineering Technology program. The capstone required student teams to conceive, design, prototype, and validate a functional system addressing an open-ended engineering problem. The instructional structure included concept proposal, mechanical and electrical design review, prototype fabrication, iterative testing and refinement, and final demonstration, with faculty serving in an advisory role while students maintained primary responsibility for design and implementation decisions. This structure was intended to support system-level engineering competencies and reinforce disciplined engineering practice rather than ad hoc prototyping.

Educational outcomes were assessed qualitatively through milestone-based faculty review of concept selection, subsystem integration, prototype fabrication, troubleshooting, and final demonstration. Particular emphasis was placed on system integration, embedded control implementation, iterative refinement, and validation under prototype testing constraints. The project therefore served not only as a technical prototype effort, but also as an applied assessment of student competency in mechatronic system development. These milestone reviews provided the qualitative assessment basis for the educational findings discussed in Section 6.

3. Methodology

The proposed framework for the omni-directional wall-climbing robotic system integrates five primary subsystems: Mechanical Design, Propulsion System, Embedded System and Control, Software and Control Algorithms, and Dynamic Modeling. All subsystems were designed, developed, and integrated through an iterative engineering process including concept selection, prototyping, testing, and refinement.

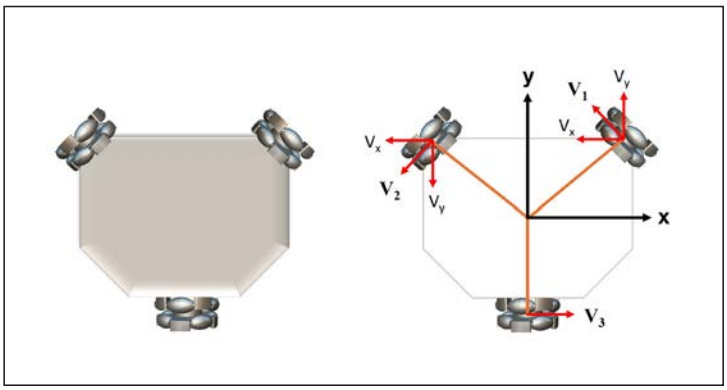


Figure 1. Robot chassis and the omni-directional wheel configuration.

3.1 Mechanical Design

The robot chassis was fabricated using 3D-printed Polyethylene Terephthalate Glycol (PETG) material, selected to provide a practical balance of structural strength, durability, and low mass. The frame accommodates the locomotion, propulsion, sensing, and control components while maintaining a compact configuration suitable for vertical operation. Three omni-directional wheels are arranged at 120° intervals, as shown in Figure 1, to provide holonomic planar motion.

The symmetric wheel arrangement allows the individual wheel-velocity vectors to be combined for translational and rotational motion. Integrated mounting features accommodate the drive motors, propulsion units, and sensors while minimizing the overall system footprint. The corresponding wheel kinematics and motion modes are described in Section 3.4.

3.2 Propulsion System

A thrust-based adhesion mechanism was implemented using Readytosky 2212 920KV brushless motors, each driving a propeller to generate a controlled normal force toward the climbing surface. The motor–propeller assemblies were mounted at an inverted angle to direct the generated thrust toward the surface while limiting undesirable torque disturbances on the chassis. To improve aerodynamic performance, a custom propeller shroud was designed and fabricated to enhance airflow directionality and reduce thrust losses due to turbulence. The propulsion units were selected to provide sufficient thrust margin for vertical and inclined operation while maintaining a compact system configuration. Propulsion output can be adjusted using orientation feedback from the onboard inertial measurement unit (IMU), allowing the adhesion force to respond to changes in robot orientation. The force-balance basis for propulsion-system sizing is presented in Section 3.5.

3.3 Embedded System and Control

The Arduino Mega microcontroller serves as the central processing unit, managing real-time sensor feedback and executing control commands. The drive system is powered by Greartisan 12 V DC motors controlled through a BTS7960 motor driver, which supports high-current operation and bidirectional motor control. Wireless user control is implemented using an FS-i6 transmitter and an FS-IA6B receiver. An onboard IMU continuously provides orientation and motion data for PID-based feedback control. The principal hardware components and key design specifications of the prototype are summarized in Table 1.

User commands from the RC transmitter define the desired platform motion and are processed by the Arduino Mega to generate wheel-drive and propul-

Table 1. Main hardware components and design specifications.

Component/Parameter	Specification / Model	Function
Chassis Material	Polyethylene Terephthalate Glycol (PETG)	Structural frame
Wheel Configuration	3 Omni-wheels at 120°	Holonomic locomotion
Microcontroller	Arduino Mega	Central control
Drive Motors	Greartisan 12 V DC motors	Wheel actuation
Propulsion Motors	Readytosky 2212 920KV brushless motors	Adhesion thrust
Motor Driver	BTS7960	Drive motor control
IMU	Onboard inertial measurement unit	Orientation feedback
RC Transmitter	FS-I6	User control input
RC Receiver	FS-IA6B	Wireless signal reception
Propeller Shroud	Custom fabricated	Airflow guidance/thrust efficiency

Table 2. The different motions of the omni-wheels.

Movement	Omni-Wheel Motion Principle
Forward	Wheel velocities are coordinated according to Equation (1) to generate forward translation
Backward	Wheel velocities are coordinated to generate backward translation
Rightward	Wheel velocities are coordinated to generate rightward translation
Leftward	Wheel velocities are coordinated to generate leftward translation
Diagonal Motion	Translational components are combined to generate the desired diagonal motion
Clockwise Rotation	Wheel velocities are coordinated to generate clockwise rotation about the robot center
Counter-Clockwise Rotation	Wheel velocities are coordinated to generate counterclockwise rotation about the robot center

sion commands. Real-time IMU feedback is used within the PID loop to correct orientation deviations by adjusting wheel velocities and propulsion thrust, thereby supporting stable wall contact and controlled motion. This embedded architecture coordinates sensing, actuation, and feedback regulation within a compact robotic platform.

3.4 Software and Control Algorithms

The omni-directional wheel configuration enables holonomic motion, allowing the robot to move in any planar direction without requiring reorientation. The principal motion modes associated with this configuration are summarized in Table 2. As illustrated in Figure 1 and Figure 2, the robot's movement is determined by an inverse kinematics algorithm that computes individual wheel velocities to achieve the desired translational and rotational motion.

The control system dynamically adjusts propulsion thrust based on real-time IMU feedback. To support accurate locomotion, the kinematic model for the omni-directional wheels accounts for wheel-placement geometry and the translational and rotational components of platform motion. Each wheel's angular velocity is computed as a function of the desired translational velocities and rotational rate, enabling coordinated omni-directional motion. The resulting kinematic relationship is expressed as:

$$\begin{bmatrix}\omega_1\\ \omega_2\\ \omega_3\end{bmatrix} = \frac{1}{R}\begin{bmatrix}-\sin\theta_1 & \cos\theta_1 & L\\ -\sin\theta_2 & \cos\theta_2 & L\\ -\sin\theta_3 & \cos\theta_3 & L\end{bmatrix}\begin{bmatrix}V_x\\ V_y\\ \omega\end{bmatrix} \quad (1)$$

where V_x and V_y represent the translational velocities in the planar directions, ω denotes the rotational velocity, ω_1, ω_2, and ω_3 are the corresponding angular velocities, R is the omni-wheel radius, and L is the wheel-placement radius. The angles θ_1, θ_2, and θ_3 define the orientation of each wheel relative to the robot center, according to the coordinate convention shown in Figure 1, and are spaced at 120° intervals for the three-wheel configuration. Figure 2 illustrates the principal translational and rotational motion modes associated with this arrangement.

Equation (1) describes the inverse kinematic relationship between the desired platform motion and the corresponding wheel angular velocities. It allows translational motion in the x- and y-directions to be combined with rotation about the robot center, enabling holonomic maneuvering without prior re-

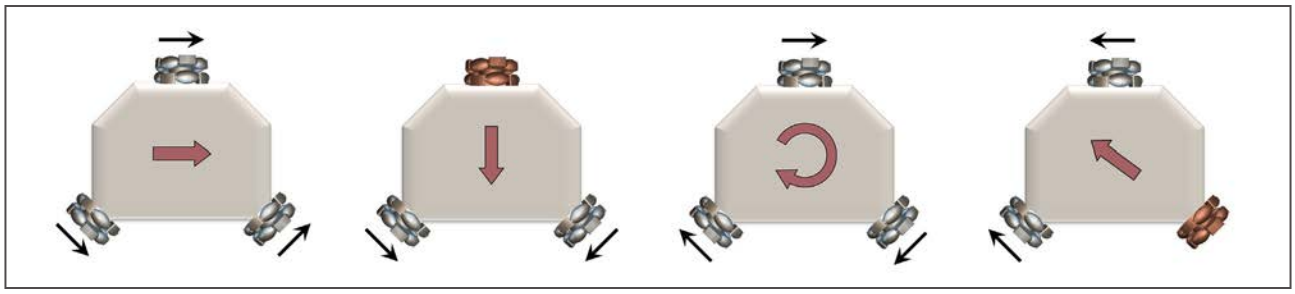


Figure 2. Moving vectors and rotation mechanisms of the omni-wheels.

orientation. The symmetric 120° wheel arrangement supports coordinated wheel-speed distribution while maintaining a compact mechanical configuration.

3.5 Dynamic Modeling

To ensure reliable adhesion during wall-climbing operation, a simplified dynamic model was developed to analyze the balance of forces acting on the robot. The primary objective of this model is to determine the thrust force required to maintain stable contact with the climbing surface while providing sufficient frictional support for locomotion.

For a robot operating on a surface inclined at an angle α measured from the horizontal, the gravitational load can be resolved into components normal and tangential to the surface. The propulsion system generates an effective normal thrust component F_t directed toward the climbing surface, increasing the normal contact force and thereby increasing the friction force available to resist slip. Under quasi-static operating conditions, the normal force can be approximated as

$$N = F_t + mg\cos(\alpha) \qquad (2)$$

where N is the surface normal reaction force, m is the robot mass, and g is gravitational acceleration. To prevent sliding, the available friction force must be greater than or equal to the tangential component of gravity. Thus, the no-slip condition may be written as

$$\mu N \geq mgsin(\alpha) \qquad (3)$$

where μ is the effective coefficient of friction between the robot and the climbing surface. Substituting the expression for normal force gives

$$\mu(F_t+mgcos(\alpha)) \geq mgsin(\alpha) \qquad (4)$$

which shows that stable wall-climbing depends on the interaction among propulsion thrust, robot weight, surface inclination, and available friction. For vertical climbing, sufficient propulsion-induced normal force is required to provide the frictional support needed to resist downward sliding.

In addition to the no-slip condition, a safety margin F_s was included in the design-stage thrust requirement to account for surface irregularities, airflow losses, local vibration, and transient disturbances. Based on Equation (4), the required propulsion thrust can therefore be expressed as

$$F_t \geq mg\left(\frac{sin(\alpha)}{\mu} - cos(\alpha)\right) + F_s \qquad (5)$$

where F_s represents the additional safety margin used during preliminary system sizing. This relation provides a simplified design-stage estimate rather than a complete dynamic representation of the robot.

Assuming quasi-static operating conditions, the proposed force-balance model provides a first-order representation of the conditions required to maintain contact with inclined and vertical surfaces. The model relates propulsion thrust to the normal contact force and the friction available to resist sliding, while the safety-margin term accounts approximately for disturbances that are not explicitly represented. Although simplified, the model provided a practical basis for propulsion-system selection and preliminary performance assessment.

Figure 3 illustrates the principal forces acting on the wall-climbing robot. The gravitational force mg acts downward, while the propulsion thrust F_t acts toward the climbing surface and increases the normal contact force. The surface reaction force N and friction force F_f contribute to maintaining contact and resisting tangential slippage. The safety margin F_s is incorporated in the preliminary thrust estimate to account for surface irregularities, airflow losses, vibration, and other transient effects not explicitly represented in the simplified model.

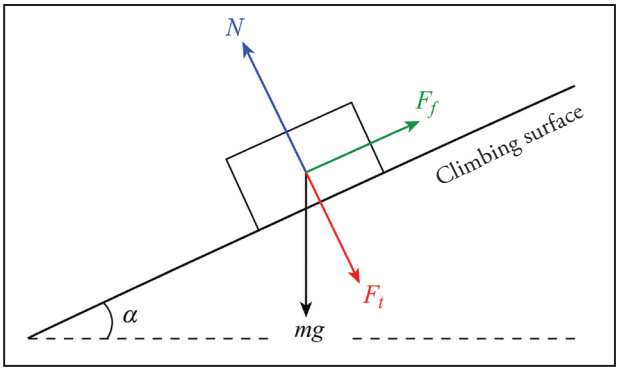


Figure 3. Force diagram for wall-climbing robot.

3.6 Closed-Loop Control System

A closed-loop control system was implemented to regulate both the robot's locomotion and propulsion-assisted adhesion. Figure 4 illustrates the interaction among user command input, IMU-based feedback, PID regulation, and actuation of the locomotion and propulsion subsystems. User inputs from the RC transmitter are processed by the Arduino Mega to generate wheel-motion and propulsion-thrust commands.

The control strategy uses orientation feedback from the onboard inertial measurement unit (IMU), which provides real-time attitude information during

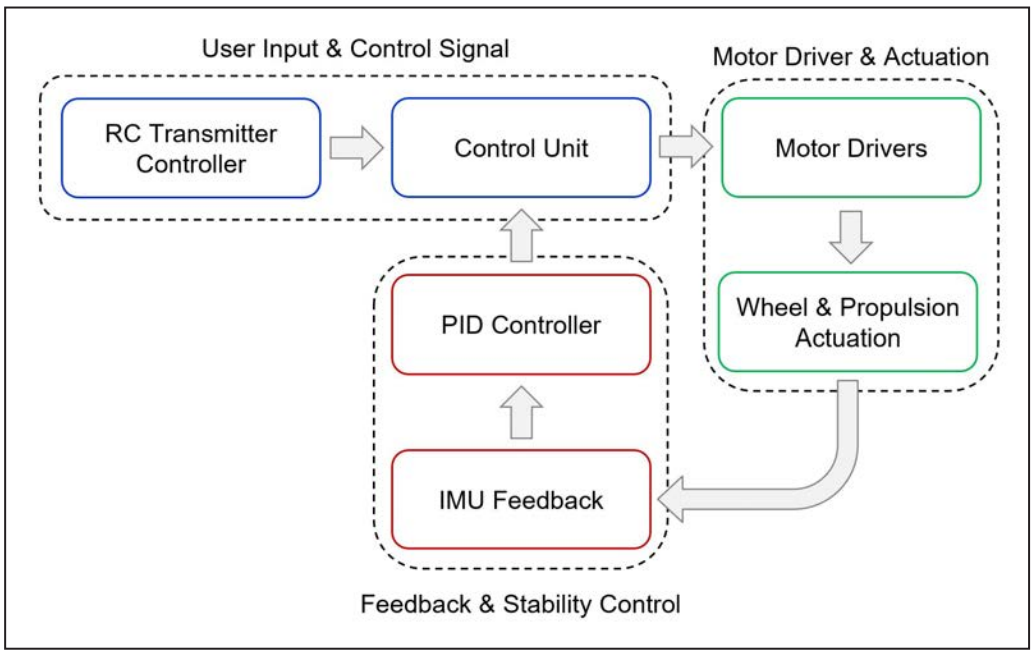


Figure 4. Closed-loop control system architecture.

wall-climbing operation. The measured orientation is compared with the desired climbing orientation to generate an orientation error, $e(t)$. The PID controller processes this error to produce a corrective control output, $u(t)$, which is applied through wheel-velocity commands and propulsion-thrust adjustments to improve stability and reduce drift.

In this control structure, the proportional term K_p provides the primary corrective response to orientation error, the integral term K_i reduces steady-state drift, and the derivative term K_d suppresses oscillatory behavior and improves transient stability. Controller gains were tuned empirically during prototype testing through iterative adjustment while observing robot behavior on vertical surfaces. The tuning process began with proportional control to establish basic corrective action, followed by derivative adjustment to improve damping and reduce oscillation. Integral action was then introduced conservatively to reduce residual drift during steady climbing operation.

Because the system was developed as a senior capstone prototype, the exact archived gain values were not preserved; however, the controller structure and tuning procedure are documented here to provide technical transparency regarding the implemented control approach. Overall, the closed-loop feedback was observed to improve balance, surface adherence, and motion stability during wall-climbing operation.

4. Results and Discussion

4.1 Qualitative Prototype Evaluation

Figure 5 shows the fabricated prototype used for experimental evaluation. Experimental trials were conducted on multiple vertical surfaces, including smooth walls, rough concrete, and metallic surfaces. Across all test environments, the robot successfully

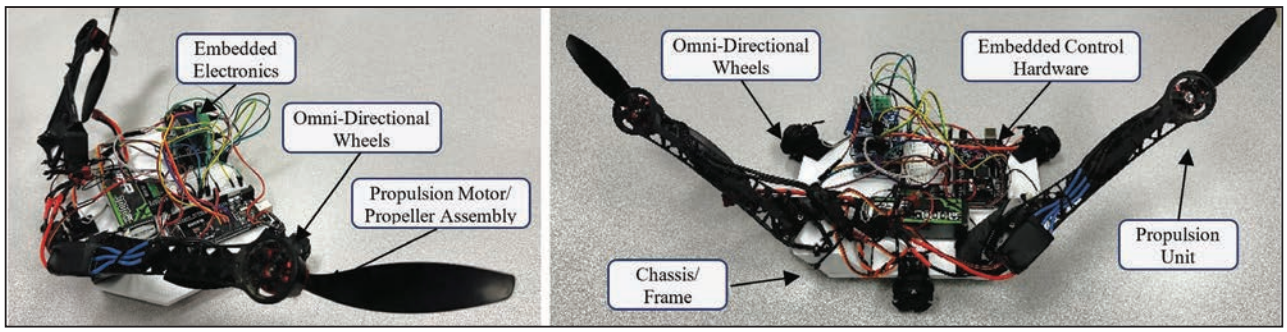


Figure 5. Fabricated omni-directional wall-climbing robot prototype: (a) Angled view showing the omni-wheel locomotion system, propulsion motor/propeller assembly, chassis, and embedded electronics; and (b) Top view showing the three-wheel arrangement, propulsion units, and integrated control hardware.

Table 3. Qualitative observations from prototype testing across surface types.

Surface Type	Orientation Tested	Adhesion Maintained	Locomotion Observed	Qualitative Observation
Smooth Wall	Vertical	Yes	Yes	Stable directional motion observed
Rough Concrete	Vertical/Inclined	Yes	Limited	Increased vibration and reduced smoothness of motion
Metallic Surface	Vertical	Yes	Yes	Stable adhesion observed during manual control

maintained surface adhesion, demonstrating the reliability and adaptability of the propulsion-based adhesion mechanism. The omni-directional wheel configuration enabled smooth directional transitions and controlled directional motion, highlighting the advantages of holonomic mobility during wall-climbing operations. Because quantitative logs were not recorded during prototype testing, the observed performance across tested surfaces is summarized qualitatively in Table 3. The table is intended to document proof-of-concept behavior under representative operating conditions rather than provide a statistical performance benchmark.

As shown in Table 3, the prototype maintained adhesion on all tested surfaces, while locomotion quality varied with surface condition. Smooth wall and metallic surface trials showed more stable directional movement, whereas rough concrete introduced increased vibration and reduced motion smoothness, likely due to increased rolling disturbance and local surface irregularities. These observations indicate that the propulsion-based adhesion mechanism was effective in maintaining surface contact across all tested materials, including non-ferrous and rough surfaces. Overall, the findings support the feasibility of combining omni-directional locomotion with thrust-assisted adhesion, while also identifying surface-induced vibration and control refinement as key areas for future improvement.

4.2 Reconstructed Quantitative Indicators

Because the original prototype testing did not include fully instrumented performance logging, limited quantitative indicators were reconstructed from archived video footage and prototype records. Based on the observed travel distance and elapsed time, the robot exhibited an approximate climbing speed of about 5 cm/s on a smooth vertical surface under proof-of-concept operating conditions. In addition, the prototype successfully completed 3 of 4 observed climbing trials under the smooth vertical surface condition, indicating partial repeatability of the prototype behavior. These reconstructed values are intended only as supplementary performance indicators and not as definitive benchmark measurements.

4.3 Experimental Limitations

Although the present evaluation is limited to qualitative prototype observations and a small amount of reconstructed quantitative evidence, the results indicate that the integrated mechatronic architecture can achieve controlled wall-climbing under multiple conditions. Future work should include quantitative measurements of thrust margin, climbing speed, power consumption, payload capacity, repeatability, and controller response to provide a more complete performance characterization.

5. Challenges, Optimizations, and Experimental Observations

Several challenges were identified during initial testing. Early prototypes exhibited instability due to uneven thrust distribution, which affected the robot's ability to maintain consistent adhesion on vertical surfaces. This issue was addressed through iterative refinement of propeller placement, resulting in more uniform force distribution and improved stability. Control precision also posed a challenge, as initial PID tuning led to oscillatory behavior and positional drift. Through systematic adjustment of PID parameters, the system achieved smoother motion transitions, reduced oscillations, and enhanced maneuverability. Repeated testing on multiple surface types also supported the refinement of experimental procedures and helped improve the repeatability of adhesion and locomotion trials.

Energy consumption also emerged as an important design consideration because propulsion-based adhesion requires continuous thrust generation. Because power consumption and operating duration were not instrumented during prototype testing, energy efficiency was not quantified in the present study. Future work should include measurements of power consumption, battery duration, and propulsion efficiency together with improvements in motor selection and control strategies.

Future iterations of the system could benefit from the integration of advanced control interfaces, such as semi-autonomous operation and brain–computer interfaces (Yazdanpour et al. 2024a), to improve operational flexibility and user adaptability. Prior research on autonomous omni-directional mobile robots has demonstrated the effectiveness of sensor-based stability mechanisms, including infrared sensing and AI-driven visual perception (Yazdanpour et al. 2024b). Incorporating similar sensor fusion techniques could further enhance dynamic adhesion control, enabling real-time adaptation to varying surface conditions.

6. Experiential Learning and Educational Impact

Capstone design experiences provide an important setting for integrating prior learning, addressing open-ended engineering problems, and developing competencies associated with professional engineering practice (Webster and Turner 2024). The wall-climbing robot project provided a hands-on experiential learning environment in which students integrated mechanical design, additive manufacturing, embedded systems, sensing, control, and prototype testing within a single multidisciplinary system. Rather than addressing these topics as isolated course activities, the capstone required students to make design decisions, integrate multiple subsystems, identify system-level failures, and iteratively refine the prototype based on observed performance. This process connected theoretical concepts in mechatronics and control with the practical constraints encountered during fabrication, integration, and testing, consistent with prior engineering technology work emphasizing hands-on system development as a means of connecting theoretical knowledge with practical problem solving (Ma and Pecen 2024).

Educational outcomes were evaluated qualitatively through faculty review of project milestones and observation of the students' progression from concept development to a functional integrated prototype. Evidence of learning was reflected in the students' ability to integrate mechanical, electrical, and control subsystems, identify and correct uneven thrust distribution, iteratively tune the PID controller to reduce oscillation and drift, and refine the design based on prototype testing. These activities provided evidence of developing competency in system integration, troubleshooting, iterative engineering design, and prototype validation. Because formal pre/post surveys, standardized assessment instruments, or quantitative educational measures were not administered, these findings are interpreted as qualitative evidence of student learning rather than quantitative measures of educational effectiveness.

7. Conclusion

This paper presented the design, implementation, and qualitative prototype evaluation of an omni-directional wall-climbing robot using a propulsion-based adhesion mechanism. The proposed system combines a three-wheel omni-directional locomotion platform with thrust-assisted adhesion to address limitations commonly associated with conventional suction- and magnetic-based wall-climbing robots. By integrating holonomic mobility, PID-based closed-loop control, and IMU feedback, the robot achieved stable motion, reliable surface adhesion, and smooth maneuverability on vertical and inclined surfaces. Dynamic modeling supported the estimation of thrust requirements for surface adherence, while prototype testing supported the feasibility of the overall system on multiple surface types. The results demonstrate that propulsion-assisted adhesion combined with omni-directional mobility provides a practical approach for wall-climbing robotic platforms intended for applications such as infrastructure inspection, maintenance, and industrial monitoring. Future work will focus on improving energy efficiency, extending operational duration, and incorporating more advanced sensing and autonomous control capabilities. In addition to its technical contribution, the project illustrates how capstone-based implementation can support applied engineering technology education through hands-on system integration, control, and prototype validation.

Acknowledgment

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