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A Comprehensive Review on Climbing Robots: Mechanisms, Adhesion Techniques, and Applications

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ABSTRACT

Robots that climb have recently emerged as an important class of mobile robots; they are capable of negotiating vertical or inclined surfaces and therefore have a great advantage in hazardous or hardly accessible environments for humans. Such robots will find critical applications in the inspection of infrastructures, the maintenance of nuclear plants, search and rescue operations, and space exploration. This review undertakes an exhaustive survey of climbing robot technologies by emphasizing the locomotion mechanisms and adhesion techniques available as well as their practical applications. The climbing strategies such as wheeled, tracked, legged, and hybrid systems are considered together with adhesion methods of magnetic, vacuum suction, dry adhesion, electro adhesion, and mechanical gripping. It gives the comparative advantages and limitations of each method in different environments. The present challenges in control, energy efficiency, and surface compatibility are discussed. Further advances in the integration of soft robotics, and adaptive designs are highlighted. This review tries to point out where future research should go by indicating opportunities for improving the performance and generality of climbing robots.

1. Introduction

In recent years, the climbing robots have gained more attention because of their specialty in moving on vertical and inverted surfaces where the journey many times so difficult or dangerous for humans to accomplish or even impossible [1]. This kind of robot finds great applicability in such tasks as inspection of bridges and buildings, maintenance work at nuclear power plants, aerospace missions, and disaster response operations. Such a robot needs wall and pipe climbing abilities, as well as scaling other complex structures where these abilities required by machines meant to work in unstructured environments.

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Climbing robots represent an attractive compromise between wheeled or tracked robots, which are limited to movement on planar spaces, and aerial robots (drones), which are limited by payload and flight time. Climbing robots have the advantages of being able to remain attached to surfaces indefinitely, carrying sensor or tool payloads, and working safely and reliably in the task space. However, vertical locomotion introduces challenges that are fundamental to robotic design, including: adhesion to various surfaces in a reliable way, as well as the scaled individual robot operations when constrained; efficiency of locomotion in confined task spaces, safety, particularly when maintaining attachment against gravitational and inertial forces of movement along the incline or face; and robustness, including adaptability to different types of surfaces and surface geometries [2].

This review aims to document the technologies related to climbing robots. The review will first establish a classification system based on locomotion and adhesion mechanism, followed by a detailed examination of the technologies. The review will discuss applications, and identify challenges in climbing robots and emerging research areas. The hope is to document current crawling robotics, and highlight forward progressions.

2. Classification of Climbing Robots

Climbing robots can be broadly categorized by locomotion and adhesion mechanisms (i.e., how they move and adhere to a vertical and/or angled surface) [3,4]. The movement mechanism describes the robot's mobility, stability and ability to adapt to different terrains including providing mechanisms as the adhesion method provides means for the robot to adhere on different surfaces while it operates. Locomotion mechanisms include wheeled, tracked, legged and hybrid mechanisms, all with distinct pros for task such as aerial manipulator. Similarly, an adhesion system is either passive (sustained via mechanical design and gravity) or active (sustained by external influence or power, ie magnet, suction or electrostatic forces) as distinguished in Table 1.

Table 1
Classification of Climbing Robots Based on Locomotion and Adhesion

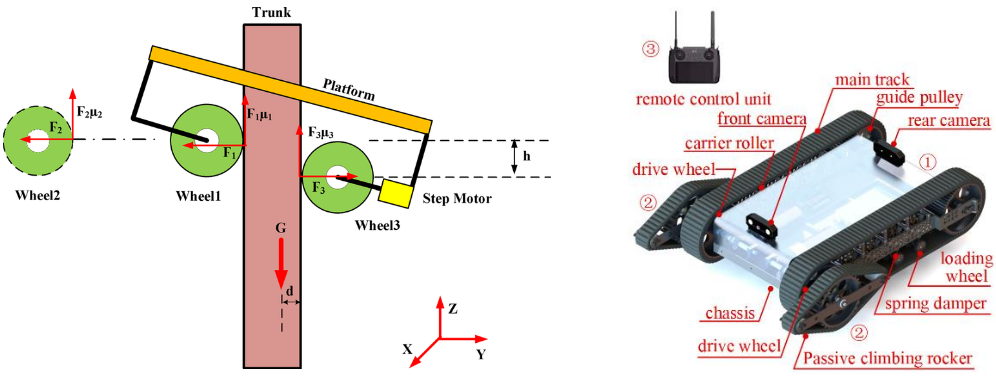
Category	Type	Description	Examples/Use Cases
Locomotion Mechanism	Wheeled Robots	Use wheels to roll along flat or slightly curved surfaces.	Pipeline inspection, flat wall climbing
	Tracked Robots	Use tracks to distribute weight and grip over a larger area.	Industrial tank inspection, ship hull cleaning
	Legged Robots	Use articulated legs for stepping and adapting to irregular surfaces.	Bio-inspired robots, rock or tree climbing
	Hybrid Systems	Combine two or more movement types (e.g., wheels + legs).	Versatile mobility in mixed environments
Adhesion Technique	Passive Adhesion	Rely on gravity, mechanical hooks, or clamps without external energy input.	Rope-climbing robots, rail-gripping robots
	Active Adhesion	Use powered methods like magnets, suction, electroadhesion, or gecko-inspired adhesion.	Wall-cleaning robots, space missions, reactors

3. Mechanisms of Locomotion

How well a climbing robot climbs is determined by the robot's locomotion mechanism that permits movement on vertical or sloped surfaces. Choosing the best locomotion method is essential to its performance, stability, and adaptability to variations in surface texture, curvature, and sloped conditions [5].The most common mechanisms used in climbing robots include wheeled, tracked, legged, and inchworm-type (robotic arm-based) locomotion. Each type offers different trade-offs in terms of speed, energy consumption, terrain adaptability, and complexity.

3.1 Wheeled and Tracked Mechanisms

Wheeled climbing robots are among the simplest designs and are suitable for relatively smooth and continuous surfaces such as walls, glass panels, or pipelines as shown in Figure 1 (a). They offer high-speed movement and low power consumption. However, they struggle on rough or uneven surfaces due to limited adaptability. Tracked robots use caterpillar-like treads that provide better grip and surface contact. Tracks can navigate minor surface irregularities and offer greater traction on metallic or concrete surfaces as shown in Figure 1 (b). They are well-suited for industrial applications like tank or ship inspection. However, tracked systems are bulkier and may have difficulty maneuvering in tight spaces or on highly curved surfaces.



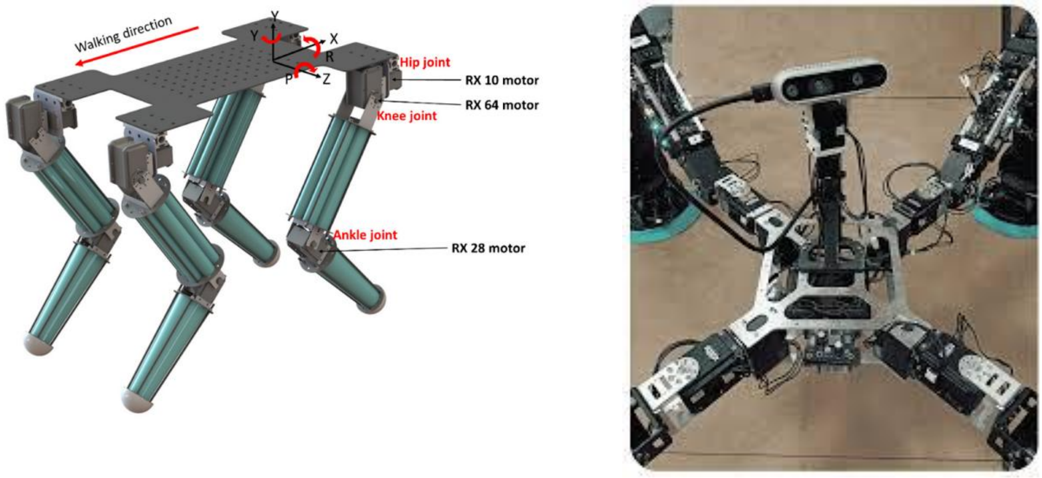
(a) Wheeled climbing robots

(b) Tracked robots

Fig. 1. (a) Wheeled climbing robot showing its basic structure and adhesion mechanism for vertical movement [6]. (b) Tracked climbing robot illustrating continuous track-based locomotion for enhanced surface grip and stability on inclined or vertical surfaces [7].

3.2 Legged Mechanisms

Legged climbing robots are specialized robotic systems that mimic the walking and climbing behaviour of animals or insects, enabling them to navigate complex and irregular terrains with greater adaptability than traditional mobile robots.



(a) Quadruped Robot with 3D Flexible Legs (b) 4-legged robotic organism

Fig. 2. *(a)* Quadruped robot with 3D flexible legs demonstrating adaptive surface conformity [8]. *(b)* Four-legged robotic organism inspired by biological locomotion for enhanced climbing agility [9].

These robots are often inspired by biological creatures such as geckos, spiders, and cockroaches, which naturally exhibit strong climbing abilities and flexible movement. As shown in Figure 2, legged climbing robots are equipped with multiple articulated limbs that can independently grip, lift, and place themselves on different surfaces, allowing for precise control and high manoeuvrability.

This design enables them to traverse uneven surfaces, corners, gaps, and obstacles where wheeled or tracked robots would typically struggle or fail. Their modular leg structure provides increased flexibility and surface conformity, making them suitable for applications in disaster zones, rocky terrain, and industrial inspection in hard-to-reach locations. However, the implementation of such systems poses several technical challenges. These include the need for sophisticated control algorithms to coordinate leg movements, maintaining balance and stability on vertical or inclined planes, and managing high power consumption due to the complex actuation systems.

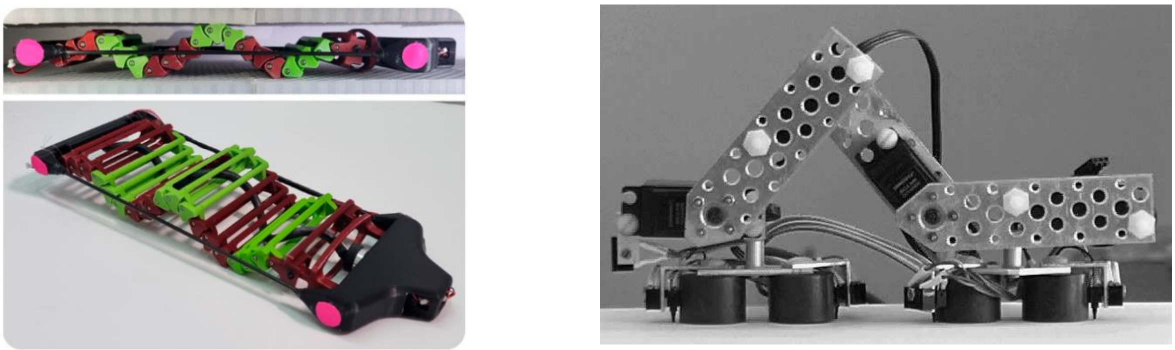
3.3 Robotic Arms and Inchworm Motion

Robots that employ inchworm-like locomotion use two or more grippers or arms that alternately attach and release, mimicking the motion of an inchworm or climbing vines. This mechanism is particularly effective in pipe inspection, space structures, and confined environments as shown in Figure 3. Although this type of movement is slow, it provides high stability and can be used in situations where other mechanisms would fail due to extreme constraints in space or orientation.

3.4 Design Considerations

Key factors in locomotion mechanism design include:

i. *Stability:* Robots must remain stable during movement, especially when transitioning between surfaces or orientations.
ii. *Control:* Precise actuation and sensor feedback are needed for smooth locomotion, particularly in legged and inchworm systems.
iii. *Weight Distribution:* Proper balance is essential to avoid slippage or detachment, especially in vertical or overhead climbs.
iv. *Energy Efficiency:* Lighter designs with low power consumption are preferable for extended operation in remote or dangerous environments.



(a) Wave-like Robotic Locomotion (b) inchworm robot

Fig. 3. (a) Wave-like robotic locomotion demonstrating continuous undulating movement for surface adaptation [10]. (b) Inchworm robot utilizing sequential gripping and extension for climbing in confined or tubular environments [11].

Table 2
Comparative Analysis of Locomotion Mechanisms

Locomotion Type	Speed	Surface Adaptability	Complexity	Power Use	Best Use Case
Wheeled	High	Low	Low	Low	Smooth surfaces like glass, pipelines
Tracked	Moderate	Medium	Medium	Medium	Industrial and outdoor inspection
Legged	Moderate	High	High	High	Natural terrain, irregular or rough walls
Inchworm (Arms-based)	Low	Very High	Medium	Medium	Pipes, narrow channels, space structures

This comparative understanding helps engineers and researchers select the most appropriate locomotion method for their targeted application, balancing mobility, complexity, and energy constraints as shown in Table 2.

4. Adhesion Techniques

Adhesion is the core enabler for climbing robots, allowing them to attach securely to vertical, inclined, or inverted surfaces [12]. Selecting a suitable adhesion method depends on factors such as surface material, orientation, texture, environmental conditions, and power availability. Various adhesion techniques have been developed, each with unique strengths and limitations [13, 14, and 15]. This section discusses the major types of adhesion used in climbing robots, along with their working principles, advantages, limitations, and suitable applications.

4.1 Magnetic Adhesion

Permanent magnets offer a simple and energy-efficient method for adhering to ferromagnetic surfaces [16]. They provide consistent holding force without power consumption. However, they lack flexibility for detachment or use on non-magnetic surfaces. Whereas, electromagnetic adhesion uses coils and current to generate magnetic force. It allows control over attachment and detachment but requires a continuous power supply [17]. These systems are used in industrial settings like ship hulls and storage tanks.

4.2 Vacuum Suction

Suction cups are one of the most widely used adhesion methods on smooth, non-porous surfaces [18]. A vacuum is created within the cup to form a pressure differential that holds the robot against the surface. Whereas, more advanced systems use fans or pumps to generate and maintain negative pressure. These systems can be used on slightly uneven surfaces, although they are more energy-intensive and may be affected by dust or moisture [19, 20].

4.3 Dry Adhesion

Inspired by geckos, dry adhesion uses micro-structured materials that exploit van der Waals forces [21]. These materials can stick to smooth vertical surfaces without glue or suction, and they work in both dry and vacuum environments (e.g., outer space). However, these materials are complex to fabricate and degrade over time.

4.4 Clamping and Gripping

Mechanical adhesion relies on physical gripping through claws, hooks, or clamps [22]. This method is energy-efficient and reliable on rough or irregular surfaces like mesh, wires, or natural terrain. However, it is unsuitable for smooth walls and requires surface features for anchoring.

4.5 Electroadhesion

Electroadhesion uses electrostatic forces generated by applying high voltage between electrodes and the surface. It works on a variety of materials (including glass, wood, or drywall) and is lightweight and power-efficient. However, the adhesion force is relatively low, and performance may degrade in humid conditions.

Each adhesion technique has its niche, and often hybrid methods are employed to balance performance across different environments. The choice of adhesion system significantly influences the robot’s design, energy requirements, and overall effectiveness in real-world applications as shown in Table 3.

Table 3
Comparative Analysis of Adhesion Techniques

Adhesion Method	Advantages	Limitations	Best Surface Type	Typical Application
Permanent Magnets	No power needed, simple design	Only for ferromagnetic surfaces	Metal walls, tanks	Ship hull inspection, storage silos
Electromagnets	Controlled on/off adhesion	Continuous power required, heat generation	Industrial metal surfaces	Welding robots, vertical inspection
Vacuum Suction	Strong force on smooth surfaces	Affected by leaks, dust, and high energy use	Glass, plastic, metal sheets	Window cleaning robots
Dry Adhesion	Works in vacuum, lightweight	Limited to clean smooth surfaces, material wear	Glass, plastic, polished wood	Space robotics, lab automation
Mechanical Gripping	High stability, low power	Needs edges or rough textures	Pipes, mesh, branches	Pipeline robots, tree-climbing robots
Electroadhesion	Lightweight, low energy	Low adhesion strength, sensitive to humidity	Drywall, wood, glass	Indoor inspection, wall sensors

5. Sensors and Control Systems

Effective sensing and control systems are essential for the safe and intelligent operation of climbing robots, especially in unpredictable or dynamic environments [23]. To maintain balance, orientation, and grip while climbing, these robots rely on a combination of sensor technologies and advanced control algorithms. Key sensors include Inertial Measurement Units (IMUs) for motion tracking, vision sensors for environmental perception, tactile and force sensors for detecting contact and grip force, and proximity or ultrasonic sensors for obstacle detection. These sensors feed real-time data into control systems that manage locomotion, adhesion, and path planning [24].

Table 4
Overview of Sensor and Control Technologies in Climbing Robots

Component	Description	Function	Application Area
IMU (Inertial Measurement Unit)	Combines accelerometers and gyroscopes to measure orientation and acceleration	Stability, posture control	Balancing during movement and climbing transitions
Vision Sensors (Camera, LiDAR)	Capture images or depth data of surroundings	Obstacle detection, mapping, surface recognition	Navigation, surface following
Tactile Sensors	Detect touch or pressure at adhesion/contact points	Monitoring grip strength and slippage	Force-controlled adhesion systems
Force/Torque Sensors	Measure force applied during contact or movement	Load distribution, stress monitoring	Legged or arm-based climbing robots
Control Algorithms	PID, fuzzy logic, adaptive and predictive controllers	Locomotion, adhesion switching, trajectory planning	Motion planning, real-time control
AI/Machine Learning	Pattern recognition, adaptive learning	Autonomous decision-making, surface classification	Dynamic environments, intelligent climbing
Remote Control	Operator-guided control via wireless interface	Manual navigation and control	High-risk or unknown environments
Autonomous Control	Onboard decision-making based on real-time sensor data	Independent pathfinding and error correction	Repetitive tasks, structured inspection missions

Modern climbing robots increasingly incorporate artificial intelligence (AI) and machine learning for autonomous navigation, adaptive movement strategies, and fault detection. Control can be either remote (teleoperated), where human operators guide robot actions, or autonomous, where onboard algorithms make decisions based on sensor inputs [25]. The integration of smart control systems enhances the efficiency, safety, and versatility of climbing robots in complex and hazardous environments.

The seamless integration of sensors and control systems enables climbing robots to operate efficiently in environments where human access is limited or dangerous. As AI technologies continue to evolve, these robots are expected to become more autonomous, intelligent, and capable of adapting to real-world conditions with minimal human intervention as shown in Table 4.

6. Power and Communication Systems

The performance, mobility, and operational duration of climbing robots are heavily influenced by their power and communication systems. A reliable power supply is crucial for driving motors, adhesion mechanisms, sensors, and processing units. Most climbing robots rely on battery-powered systems to maintain mobility and autonomy, but some are tethered, allowing continuous power delivery, especially during long operations [26]. Each power option comes with trade-offs in terms of weight, endurance, and flexibility.

In addition to power systems, communication technologies are vital for data exchange between the robot and its operator or control center. Wireless communication methods such as Wi-Fi, Bluetooth, and RF modules are commonly used but must be adapted to challenging environments like underground structures, tall buildings, or nuclear facilities where signal interference or loss is possible [27]. Lightweight and energy-efficient designs help reduce power consumption and increase robot runtime, especially for autonomous missions in remote or hazardous areas.

Table 5
Comparison of Power and Communication Systems in Climbing Robots

System Type	Option	Advantages	Limitations	Suitable Applications
Power Supply	Battery-Powered	Mobility, autonomy, no cable restrictions	Limited runtime, recharging needed	Space missions, building inspections
	Tethered Power	Continuous power, longer operation	Cable limits mobility, risk of entanglement	Nuclear plants, industrial maintenance
	Hybrid Systems	Combines battery and occasional tether	Increased complexity	Semi-autonomous inspection tasks
Design Efficiency	Lightweight Design	Enhanced climbing ability, longer battery life	May reduce payload capacity	Wall-cleaning, gecko-inspired robots
	Energy-Efficient Components	Reduced power usage, less heat generation	May sacrifice performance in speed or strength	Miniature robots, swarm robotics
Communication	Wireless (Wi-Fi, RF)	High flexibility, real-time data transfer	Signal drop in metallic or underground environments	General-purpose climbing robots
	Bluetooth	Low power, short-range communication	Limited range and bandwidth	Indoor robots, educational models
	Wired Communication	Stable, high-speed, interference-resistant	Limited mobility, used mainly in tethered systems	Research labs, controlled environments

The choice of power and communication system must align with the robot’s operational requirements, surface conditions, and environmental constraints. As technology advances, trends are moving toward compact, energy-dense power sources and robust wireless protocols that support autonomy in real-time, even in the most challenging scenarios as shown in Table 5.

7. Applications of Climbing Robots

Climbing robots have found increasing relevance across various industries due to their ability to access vertical, inverted, or complex structures that are often dangerous or unreachable for humans [28, 29]. These robots play a transformative role in infrastructure inspection, maintenance, surveillance, space missions, and disaster response. Their ability to reduce human risk, perform repetitive tasks efficiently, and operate in confined or hazardous environments makes them ideal for both civilian and defence purposes. By integrating advanced adhesion mechanisms and control systems, climbing robots can be adapted for tasks ranging from bridge inspections to satellite servicing. Some are specialized for cleaning and painting, especially on high-rise buildings and wind turbines, while others are tailored for search and rescue in post-disaster environments where rubble and vertical obstacles are prevalent [30]. Their applications continue to expand as technology evolves in mobility, autonomy, and material science.

Table 6
Key Application Areas of Climbing Robots

Application Area	Target Environments	Robot Functionality	Advantages	Challenges
Infrastructure Inspection & Maintenance	Bridges, dams, skyscrapers, wind turbines	Inspect cracks, corrosion, paint degradation	Reduces need for scaffolding and manual labor	Surface variation, environmental exposure
Nuclear and Hazardous Operations	Nuclear plants, chemical factories, reactors	Radiation measurement, leak detection, maintenance tasks	Ensures human safety in toxic/radioactive zones	Shielding from radiation, communication barriers
Military and Surveillance	Vertical walls, fences, enemy buildings	Reconnaissance, camera surveillance, perimeter patrols	Stealthy movement, high-surface access	Terrain uncertainty, power constraints
Space Exploration	Satellite exteriors, spacecraft interiors	Low-gravity climbing, tool handling, microgravity repairs	Operates in vacuum and weightless conditions	Material fatigue, extreme temperatures
Search and Rescue	Collapsed buildings, cliffs, mining sites	Victim detection, supply delivery, terrain mapping	Reaches confined or elevated spaces	Debris interference, autonomous navigation
Cleaning & Painting	High-rise windows, ship hulls, silos, wind towers	Glass cleaning, surface scrubbing, spray painting	Cost-effective and safe alternative to human cleaners	Adhesion consistency, weather impact

Climbing robots are redefining the scope of automated tasks in vertical and hazardous environments. As sensor accuracy, energy systems, and AI integration improve, their adoption is expected to grow in urban infrastructure management, defence, and extra-terrestrial exploration as shown in Table 6.

8. Challenges and Limitations

Despite climbing robotics making great strides, there remains many obstacles that prevent the large scalability of climbing robots in real-world contexts. The reliability of adhesion on a variety of surfaces [i.e. rough, dirty, wet surfaces] represents the most important obstacle to climbing robots; particularly adhesion mechanisms such as suction and dry adhesive which have much less reliability in environments with changing surfaces. Payload capacity represents another notable issue that climbing platforms must contend with, climbing robots must be light to maintain grip; the tools, sensors or batteries that a climbing robot carries on the robot, particularly when climbing, will limit the robot's operating range - along with task complexity burden.

Power and energy density remains a challenge for long term or extended operations, especially for untethered, or battery operated robotic platforms. Likewise, navigation in an unstructured or dynamic environment can be complicated - especially for climbing robots when navigating through collapsed buildings or complex industrial plants where mapping and motion control can be tedious. Moreover, climbing robot applications are often limited by the obedience of conditions such as surface compatibility as well as the climbing robot's ability to function under different weather conditions including rain, dust, and high winds which limit outdoor or all-season applications. Issues of scalable and cost remain another barrier in the economical design of climbing robots that can function in a variety of conditions, or environments without sacrificing reliability and robustness.

Table 7
Challenges and Limitations in Climbing Robot Design and Deployment

Challenge	Description	Impact	Possible Solutions
Adhesion Reliability	Performance drop on dusty, wet, or curved surfaces	Risk of falling or detachment	Hybrid adhesion methods, surface-adaptive materials
Payload and Power Constraints	Limited carrying capacity and battery life due to weight restrictions	Short mission duration, limited sensor/tool integration	Lightweight batteries, energy-efficient components
Unstructured Navigation	Difficulty mapping or adapting to cluttered, unknown environments	Poor path planning, risk of collision	AI-based mapping, real-time adaptive control algorithms
Surface Compatibility	Not all adhesion methods work on all surface types or materials	Restricts robot usability to specific surfaces	Multi-material gripping systems, smart sensors
Weather and Environment	Wind, rain, humidity, or extreme temperature affect robot adhesion and function	Operational failure in outdoor/harsh conditions	Weatherproofing, environmental sensors, adaptive adhesion
Scalability and Cost	High costs of development and customization	Limited deployment in commercial or low-budget sectors	Modular designs, mass-producible components

Addressing these limitations requires an interdisciplinary approach, integrating advances in material science, AI, control theory, and robotics engineering. Future climbing robots will need to be more adaptive, durable, and cost-effective to meet the demands of diverse, real-world environments as shown in Table 7.

9. Future Trends and Research Directions

The field of climbing robotics is evolving rapidly, with several emerging trends poised to overcome existing limitations and expand the scope of applications. One promising direction is the incorporation of soft robotics and flexible materials, which can conform to irregular surfaces, absorb shocks, and reduce mechanical complexity. These materials mimic biological organisms and enable safer interactions with both structures and humans. Alongside this, the integration of AI-based adaptive control systems is enhancing the robot's ability to make real-time decisions, learn from its environment, and autonomously adjust locomotion or adhesion strategies based on surface conditions and obstacles.

Another major focus is achieving multi-surface and multi-environment adaptability, where robots can seamlessly transition between vertical, horizontal, and uneven terrains, even in harsh outdoor or space-like environments. Future climbing robots are also expected to work in cooperative systems, where they may be integrated with drones or aerial robots for tasks like aerial deployment, inspection, or hybrid navigation. The focus on human-robot collaboration is also increasing, especially in vertical construction, inspection, and maintenance tasks, where robots can work side-by-side with human workers to improve safety, efficiency, and accessibility. Collectively, these advancements will change the landscape of climbing robots as adaptable agents of intelligence in complex, high-risk domains.

10. Conclusion

Climbing robots have developed into a critical option for moving across vertical and complex surfaces in a number of different areas such as inspection of infrastructure, maintenance in dangerous environments, and space exploration. This review has introduced the critical aspects of their functionality, from locomotion types such as wheeled, tracked, legged, and inchworm, to a variety of adhesion types such as magnetic, vacuum, dry, and electro adhesion. Additionally, the integration of advanced sensor technologies and control systems, including AI-driven navigation, has significantly enhanced the autonomy and adaptability of these robots. Applications are steadily expanding, with robots now capable of performing tasks in high-risk, inaccessible, and sensitive environments with improved safety and precision.

Despite these advancements, several technical challenges remain, including limitations in adhesion reliability, power efficiency, and navigation in unstructured settings. Therefore, continued research and development is essential to improve material science, artificial intelligence integration, and energy systems. Future innovations in soft robotics, multi-surface adaptability, and collaborative operation with drones and human workers hold great promise for expanding the role of climbing robots in real-world applications. As the technology matures, climbing robots are expected to become more robust, intelligent, and accessible, making them indispensable tools in both industrial and exploratory domains.

Author Contributions

Conceptualization, S.K.S. and B.B.C.; methodology, I.D.; formal analysis, S.K.S.; resources, P.R.D.; data curation, S.K.S and S.S.; writing—original draft preparation, S.K.S. and B.B.C.; writing—review and editing, B.B.C.; visualization, S.S.; supervision, P.R.D. All authors have read and agreed to the published version of the manuscript." Authorship must be limited to those who have contributed substantially to the work reported.

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Data Availability Statement

All data are included in the manuscript. However, the reader may contact the corresponding author for more details on the data.

Conflicts of Interest

The authors declare that there are no conflicts of interest associated with this research.

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