DESIGN AND DEVELOPMENT OF WALL CLIMBING ROBOT

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**CHAPTER 1: INTRODUCTION**

**1.1 Background:**

Wall-climbing robots (WCR) have gained significant attention in robotics due to their ability to navigate vertical and inclined surfaces. Unlike traditional ground-based robots, these systems are designed to overcome gravity, adhering to walls and ceilings using innovative mechanisms like vacuum adhesion, magnetic forces, or bio-inspired designs such as gecko-like feet. Their versatility makes them ideal for tasks in environments that are unsafe or inaccessible for humans.

In recent years, wall-climbing robots have made their way into several industries, revolutionizing how maintenance, inspection, and surveillance are conducted. Industries such as construction, energy, and infrastructure management are increasingly adopting these robots to inspect high-rise buildings, bridges, wind turbines, and pipelines. They are valuable assets for performing structural inspections, detecting faults, and ensuring safety in hard-to-reach areas. Furthermore, these robots have proven effective in cleaning operations for skyscrapers and solar panels, reducing the need for human workers to perform high-risk tasks.

The use of wall-climbing robots has enhanced industrial efficiency, minimized risks, and lowered operational costs by reducing the need for scaffolding or aerial lifts. Additionally, they offer significant advantages in precision tasks, repetitive inspections, and remote monitoring, leading to improvements in safety, cost-efficiency, and operational productivity.

This project focuses on designing and developing a wall-climbing robot equipped with a reliable adhesion system and mobility mechanisms. The goal is to create a robot capable of navigating diverse wall surfaces and performing tasks such as inspection, cleaning, and maintenance efficiently.

**1.2 Problem Statement:**

Industries and commercial buildings often require regular maintenance to ensure structural integrity, safety, and aesthetics. Processes such as cleaning, sandblasting, painting, surveillance, crack detection, and inspection are crucial for the upkeep of these structures. Traditionally, these tasks have been carried out manually, which can be labor-intensive, time-consuming, and prone to human error not to mention dangerous for the labor. However, the emergence of robotics technology has introduced significant improvements in efficiency, precision, and safety. With robotic solutions, the risk of accidents is reduced, and access to hard-to-reach areas is greatly enhanced.

Globally, tech industries are leveraging cutting-edge equipment to design advanced maintenance robots. These robots are being developed to perform tasks with precision, speed, and consistency, which is difficult to achieve with manual labor. Countries at the forefront of robotics innovation are not only building these machines but also supplying them to industries around the world. As a result, demand for such automated maintenance systems has been increasing across sectors such as construction, energy, and infrastructure.

However, one of the major challenges faced by developing countries, including Pakistan, is the high cost associated with importing these robots. Due to the fluctuating currency exchange rates, the cost of these robots often becomes exorbitant by the time they reach Pakistan. Furthermore, shipping charges and import taxes add to the overall expenses, making these high-tech robots a significant financial burden on local industries. This cost factor discourages businesses from investing in such technologies despite their long-term benefits.

Another significant barrier is the lack of local expertise to maintain and repair these imported robots. Manufacturers usually have technical teams based in their home countries, and the availability of specialized skills and spare parts is often limited in other regions. This dependence on external support makes these robots highly ineffective in terms of long-term maintenance and serviceability. As a result, the frequent need for foreign technicians and spare parts leads to delays and increased costs, diminishing the advantages that these robots offer.

For Pakistan, the way forward could involve fostering local innovation and manufacturing capabilities in robotics. That is why our team is working on building a local solution that would greatly cut costs and make it much easier to maintain the robot. This approach would not only reduce dependency on expensive imports but also pave the way for sustainable technological advancement.

**1.3 Solution:**

A promising solution to the high costs and maintenance challenges of imported maintenance robots is to develop a cost-effective wall-climbing robot using locally available resources. The focus should be on minimizing material costs, utilizing accessible electronic components, and leveraging local expertise in manufacturing and repair.

The development of a wall-climbing robot can address various maintenance tasks such as cleaning, inspection, surveillance, and crack detection in high-rise buildings and industrial plants. This robot would be capable of adhering to and maneuvering across vertical surfaces, overcoming obstacles, and carrying out tasks efficiently and safely. By focusing on a simple yet robust design, such robots can cater to industries where frequent upkeep is essential but manual access is risky and labor-intensive.

One key aspect of reducing costs is the choice of materials for the robot’s structural components. ABS (Acrylonitrile Butadiene Styrene) and wood are potential candidates due to their low cost and availability. ABS plastic, being lightweight and strong, is suitable for structural elements requiring impact resistance, while wood can be considered for non-critical structural parts, depending on the design specifications. This combination of materials can help reduce costs without significantly compromising structural integrity or performance. Moreover, ABS is easy to mold and 3D print, allowing for rapid prototyping and custom parts manufacturing.

To further cut costs and increase serviceability, the robot can incorporate locally sourced electronic components. Motors, microcontrollers, sensors, and batteries that are readily available in the local market can be used instead of expensive imported alternatives. By opting for locally produced electronics, not only will the initial production cost be reduced, but spare parts and repairs will also become more affordable and accessible. Local manufacturers and vendors will have the required stock, making maintenance easier and faster without dependence on international suppliers.

Keeping the design simple and modular is crucial to ensuring that local technicians can easily assemble, maintain, and repair the robot. A modular approach would also allow for the easy upgrading or replacement of parts without requiring complete overhauls. Training local professionals and students in designing, assembling, and maintaining these robots can create a skilled workforce, enabling the sustainable growth of this industry.

This approach of developing a locally sourced, cost-effective wall-climbing robot would lead to a reduction in costs and reliance on foreign technology. It can significantly improve the accessibility of advanced robotics solutions to industries across Pakistan, enhancing their productivity and safety. Furthermore, fostering local innovation in robotics can create new opportunities for collaboration between industry and academia, driving further advancements in the field and establishing Pakistan as a key player in the regional market for maintenance robots.

**1.4 Key Design Considerations:**

After conducting thorough research about Pakistan’s climate, humidity and overall temperature changes throughout a year paired with the environment of an industry, the following design considerations were finalized to be important and countered:

**1. Sustainable and Maintenance-Friendly**

A sustainable and maintenance-friendly design is essential to ensure the longevity and operational efficiency of a wall-climbing robot. Sustainability in design emphasizes minimizing environmental impact by choosing eco-friendly materials, optimizing energy consumption, and adopting modular designs that facilitate easy upgrades or replacements. A maintenance-friendly approach ensures that key components like the adhesive mechanism, actuators, sensors, and control systems can be accessed and serviced without major disassembly. Additionally, integrating real-time diagnostic tools helps monitor component health and alert users to potential issues before they lead to significant breakdowns, thus reducing downtime and extending the robot’s lifespan.

**2. Ease of Access to Internal Drive System and Mechanical Components**

Designing the robot with ease of access to internal drive systems and mechanical components is crucial for efficient repairs and routine maintenance. This requires creating modular and accessible compartments, employing quick-release fasteners, and strategically positioning components for easier removal or inspection. Accessibility not only saves time during maintenance but also reduces the need for specialized equipment, enhancing serviceability. By simplifying component disassembly and reassembly, technicians can perform essential tasks like replacing worn-out gears, cleaning the adhesive systems, or upgrading control modules without affecting the robot’s overall integrity.

**3. High Durability of Design and Material**

The durability of a wall-climbing robot depends significantly on the choice of materials and the design approach. Given the mechanical stress, friction, and varying surface conditions these robots encounter, using high-strength alloys, corrosion-resistant metals, and impact-resistant polymers is essential. Additionally, the structural design must distribute the load evenly to avoid localized stress points that could cause failures over time. Durability considerations also extend to the adhesive mechanisms, where the choice of high-performance magnets, vacuum suction pads, or other gripping elements should ensure reliable operation over prolonged use without significant wear or performance degradation.

**4. Ability to Withstand Changes in Temperature and Pressure**

A key design consideration is the robot’s ability to operate under varying environmental conditions, such as changes in temperature, humidity, or air pressure. Wall-climbing robots used in industrial settings like power plants, chemical facilities, or tall building exteriors must endure fluctuating temperatures and exposure to elements like rain or wind. Therefore, it is crucial to incorporate materials with low thermal expansion and high resistance to corrosion. The robot’s electronics and adhesive systems must also be shielded and sealed against moisture, dust, or corrosive chemicals. Incorporating adaptive systems that adjust to pressure variations, such as self-adjusting suction pads or dynamically controlled magnetic adhesion, can ensure stable operation even in harsh environments.

**1.5 Aims and Objectives:**

Through this research, we aim to:

* Introduce an in-built wall climbing robot prototype for industry usage
* Build a cost-effective solution for companies looking for wall climbing robots with various purposes
* Create a sustainable structure for prolonged usage while remaining cost-friendly

**CHAPTER 2: LITERATURE REVIEW**

**2.1 Background Study**

The development of wall-climbing robots has its roots in addressing the challenges of performing tasks on vertical and inclined surfaces, which are typically hazardous and labor-intensive for humans. The initial exploration into wall-climbing robots began as part of a broader effort to enhance automation and safety in industries such as construction, maintenance, and infrastructure inspection. The primary challenge in designing these robots lies in achieving reliable adhesion to surfaces while maintaining the flexibility to navigate various materials and geometries. Early designs focused on leveraging simple suction mechanisms and magnetic adhesion to maintain stability on smooth or ferromagnetic surfaces. Over time, advancements in robotics, materials science, and control systems have spurred the development of more sophisticated adhesion mechanisms inspired by nature, such as bio-inspired adhesives mimicking the foot structures of geckos and insects. These biomimetic approaches have expanded the capabilities of wall-climbing robots to traverse complex and uneven surfaces, significantly increasing their versatility.

In parallel, the rise of lightweight and high-strength materials like carbon fiber composites and advanced polymers has enabled the construction of robots that are not only lightweight but also structurally robust. The integration of these materials, combined with compact and efficient motors, has been crucial in developing robots that can maintain strong adhesion without compromising mobility or maneuverability. Furthermore, advancements in sensor technology and control systems have allowed these robots to achieve higher levels of autonomy and adaptability. Modern wall-climbing robots are equipped with cameras, infrared sensors, laser scanners, and even machine learning algorithms to detect and analyze surface conditions in real time. This adaptability enables the robots to adjust their adhesion mechanisms dynamically based on changes in surface roughness or material type, thus ensuring stability and performance.

Wall-climbing robots have been successfully commercialized by several companies, leading to the deployment of these robots in real-world applications. For instance, GE Inspection Robotics has commercialized robots like the LIMBOT and BIKE ROBOT, which use magnetic adhesion to inspect large steel structures such as storage tanks, bridges, and pipelines (Nvabury Kenneh et al., 2022). These robots are equipped with sensors to detect corrosion, cracks, and other structural anomalies, providing real-time data to operators and reducing the need for human inspectors in hazardous environments. Similarly, Serbot AG’s Gekko Facade Robot uses vacuum-based suction mechanisms to autonomously clean glass facades of high-rise buildings, making it a safer and more efficient alternative to traditional window-cleaning methods. Another notable example is the VERTIGO robot, developed by Disney Research in collaboration with ETH Zurich, which uses steerable propellers to generate thrust and counteract gravitational forces. This innovative approach allows the robot to transition seamlessly between ground and wall surfaces, enabling dynamic tasks such as surveillance and inspection in complex environments.

The evolution of these robots has not only addressed existing challenges but has also opened up new opportunities for industries seeking to automate high-risk and labor-intensive tasks. For instance, in the field of infrastructure inspection, wall-climbing robots are increasingly being used to assess the condition of structures such as dams, bridges, and wind turbines. Traditional inspection methods for these structures often require human workers to access difficult and dangerous areas using scaffolding, ropes, or cranes. Wall-climbing robots equipped with advanced sensors can autonomously navigate these structures, collect detailed data, and even conduct minor repairs, thus improving the efficiency and safety of maintenance operations. Similarly, in military applications, wall-climbing robots are being developed for reconnaissance missions and search-and-rescue operations in urban warfare scenarios. These robots allow soldiers to gather intelligence from vertical walls, rooftops, or the exterior of buildings, reducing the risks associated with direct exposure in hostile environments.

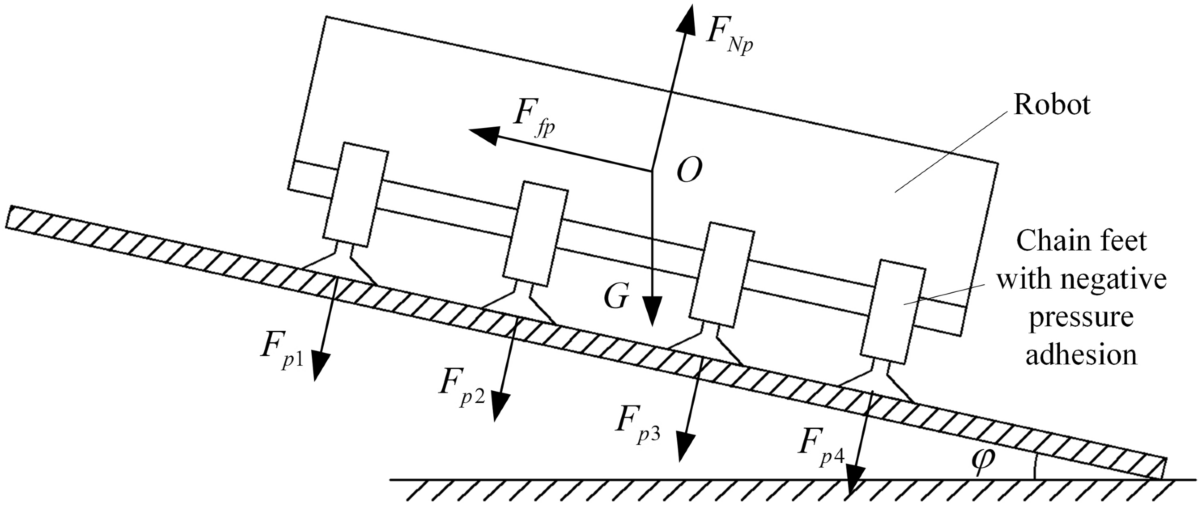
**2.2 Recent Advancements in Wall Climbing Technology**

Recent advancements in wall-climbing technologies have focused on improving adhesion mechanisms, materials, and control systems. Bio-inspired adhesion methods, such as dry adhesives mimicking gecko feet, now allow robots to traverse varied surfaces. Magnetic and vacuum-based systems have also become more efficient, enabling secure navigation on rough or metallic surfaces. Additionally, lightweight materials like carbon fiber composites and enhanced sensors have improved robot mobility and adaptability. Advanced algorithms now allow these robots to autonomously detect and respond to surface changes, leading to safer and more reliable performance in applications like inspection, maintenance, and surveillance. The technology A diagram of a robot

Description automatically generateddeployed in wall climbing robots can essentially be divided into three main categories:

**2.2.1 Adhesion Method**

**Fig 1: Technology Breakdown**

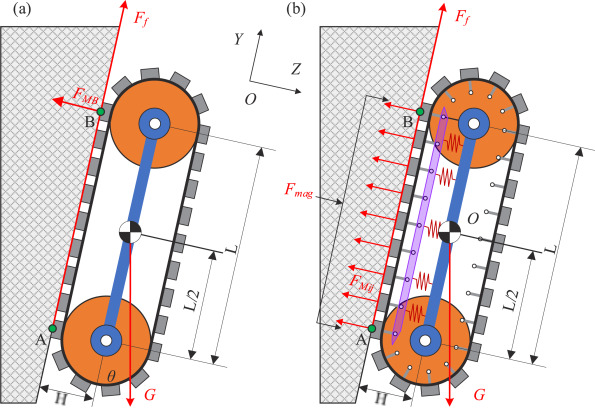
1. **Negative Pressure Adhesion**

**Fig 2: Suction Cup Adhesion**

Negative pressure adhesion methods, including suction cups and vacuum pumps, enable wall-climbing robots to adhere securely to vertical surfaces. Suction cup adhesion is ideal for smooth surfaces like glass, using vacuum pumps to generate the necessary negative pressure. Robots like the Skycleaner and those developed by Kawasaki and Yano incorporate multi-legged or biped structures with suction cups, adapting to curved and stepped surfaces through precise pressure control and mechanical designs (Houxiang Zhang et al., 2006). Variations like scanning-type cups and sinusoidal vibrations help maintain suction, addressing air leaks and surface inconsistencies.

Suction cup crawler systems integrate suction cups on rotating tracks to improve mobility, enabling faster movement. Robots by Serbot AG (GEKKO) use modular designs and mechanical valves to control pressure during motion (www.serbot.ch, n.d.). Such systems improve payload capacity but face challenges in turning due to high friction forces.

Vacuum pump adhesion provides greater mobility by incorporating wheels, reducing control complexity. Robots by Gao et al. and Zhao et al. utilize dynamic pressure regulation models to optimize stability and prevent slippage, while Miyake et al. enhance suction efficiency using liquid substances to improve sealing (Nansai et al., 2017). These advancements enable reliable, adaptable, and efficient vertical movement across various surface types.

**b) Magnetic Adhesion**

**Fig 3: Magnetic Adhesion**

Magnetic adhesion is particularly effective for surfaces with high magnetic permeability. Most prior research utilizes permanent magnets, eliminating the need for additional devices like power supplies and thereby enhancing payload capacity.

Gao et al. designed a wall-climbing robot for maintaining boiler water-cooling tubes, analyzing factors that lead to slippage, and validating their approach through experiments at a thermal power plant (Yan et al., 1999). Lee et al. developed a modular wall-climbing robot with a crawler that utilizes permanent magnets, boasting high payload capacity and wall transition capabilities (Lee et al., 2014). This robot consists of six links and has undergone extensive static and dynamic analysis. A subsequent modular design included three torsos, a head-mounted arm, and a tail-mounted arm, demonstrating effective transition between wall surfaces through innovative joint configurations.

Xu et al. introduced a wall-climbing robot featuring magnetic tracks, incorporating alternating permanent magnets and metal blocks in its crawlers (Xu and Ma, 2002). An elastic torso design allows traversal over concave and convex wall surfaces, and a thorough safety analysis was conducted.

This method offers the advantage of operating without supplementary devices, relying solely on permanent magnets to generate adhesion, which increases payload capacity. However, it restricts functionality to surfaces with high magnetic permeability and poses risks of damage due to slippage on metal surfaces. The research by Gao, Lee, and Xu emphasizes understanding slippage and stability to address these challenges.

Magnetic adhesion methods in wall-climbing robots involve using permanent and electromagnets to interact with ferromagnetic surfaces. The adhesion force is influenced by factors such as magnetic field strength, contact area, distance from the surface, and magnet volume.

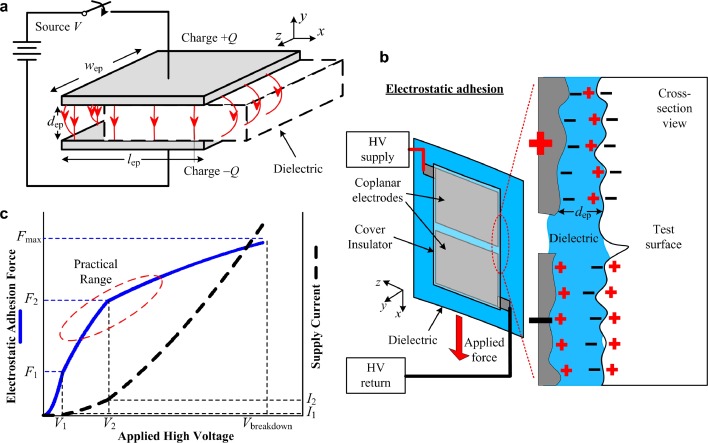
Among various magnetic adhesion designs, those combining permanent magnets with tracked mechanisms enhance stability but may lack flexibility on uneven or curved surfaces. Researchers have introduced passive suspensions to improve adaptability without sacrificing stability. While tracked mechanisms dominate, lightweight magnetic wheels have emerged to enhance agility on curved surfaces. The incorporation of bendable bodies and spherical wheels has further improved maneuverability.

Despite the advantages of magnetic wheels, they generally offer lower payload capacity due to reduced contact area. To address this, legged magnetic wall-climbing robots like MARVEL utilize electro-permanent magnets and magnetorheological elastomer footpads, allowing for easy detachment from ferromagnetic surfaces while maintaining stability (Bhaskar, Verma and Sharma, 2021).

Recent advances focus on optimizing adhesion mechanisms and understanding how various factors influence adhesion efficiency. Innovations include magnetic wall-climbing robots with suspension systems for self-compliance on curved surfaces, significantly enhancing payload capacity and maneuverability for heavy-duty applications. Comparative studies on magnet types, patterns, and configurations have highlighted ways to improve adhesion performance.

Although magnetic adhesion provides stable attachment to ferromagnetic surfaces, it limits operation to metallic environments and requires clean, smooth surfaces to maintain effectiveness. Despite these challenges, magnetic adhesion remains a crucial technology in modern wall-climbing robots across various industrial applications.

**c) Electrostatic Adhesion**



**Fig 4: Electrostatic Adhesion**

Electrostatic adhesion relies on Coulomb's law, which indicates that like charges repel and opposite charges attract. This principle is applied in wall-climbing robots (WCRs) to generate adhesion between the robot and wall surfaces by inducing charges on the robot's footpads, creating an electric field between them (Koh, Chetty and Ponnambalam, 2011). Researchers have developed theoretical models and various strategies to optimize electrostatic adhesion performance.

A critical factor influencing the effectiveness of electrostatic adhesion is the choice of materials for the robot's footpads. Typically composed of electrodes and insulating materials, electrodes can include conductive polymers, greases, carbon black, or aluminized Mylar, while silicone rubber, elastomer, polyimide, or acrylic elastomer are commonly used for insulation. These materials provide excellent elongation properties, enabling the robot to conform to different surfaces. The design of the electrodes also impacts adhesion, with structures like comb shapes enhancing electric field strength and adhesion force. Experimental studies indicate that the electrostatic adhesion force is highest on granite and lowest on tile, with performance closely linked to surface properties such as permittivity and roughness (Liu et al., 2013).

Recent research has concentrated on enhancing the adhesive capabilities of electrostatic WCRs. A popular method involves using flexible electrode panels that can conform to uneven surfaces, thereby increasing contact area. For instance, one study demonstrated a flexible electrode panel made from polyimide and aluminum foils, calculating its attractive force based on various factors such as dielectric constant, electrode area, gap length, and applied voltage.

Innovative designs include unipolar electroadhesion pads that utilize conducting electrodes and dielectric insulating films. Applying a positive voltage induces charges on the footpad, creating electrostatic attraction to the wall surface (Chen, 2015). This design is lightweight, cost-effective, and adaptable to both conductive and non-conductive surfaces. Some electrostatic WCRs employ thin electrode films to minimize weight and height; an example is the inchworm climbing robot, which features electrostatic adhesion and can navigate steep angles with a low profile.

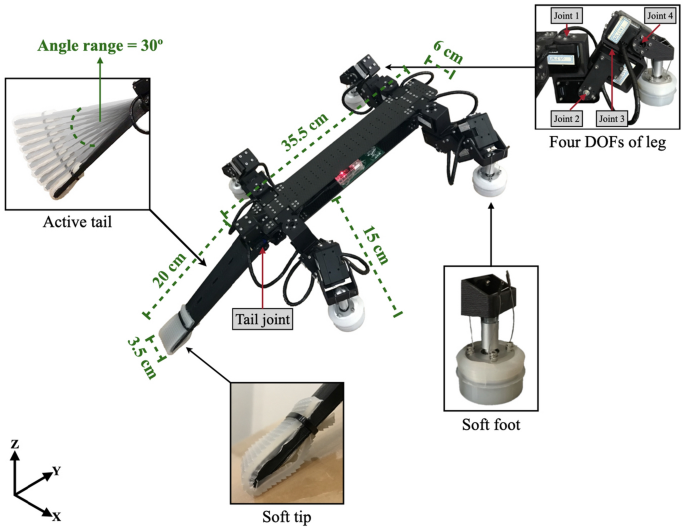
Additionally, researchers have explored integrating electrostatic adhesion with soft and micro-scale WCRs. For example, Gu et al. created a soft WCR with an electroadhesive footpad that mimics agile climbing behaviors found in soft organisms. Their design included interdigitated concentric electrodes that enhanced adhesion, with a voltage control strategy enabling effective locomotion.

Another notable design is the HAMR-E, a micro-scale WCR weighing only 1.48 g and measuring 4.5 cm. It utilizes low-voltage electro-adhesive footpads to climb on vertical and inverted surfaces, demonstrating efficient operation even in challenging environments (de Rivaz et al., 2018).

The peeling mechanism of electrostatic adhesion robots is also significant. Many utilize passive peeling, where the footpad lifts away from the surface as the robot moves, but this can increase energy consumption. An alternative approach involves a servo motor connected to strings that actively peel the footpad away, reducing energy use.

Electrostatic adhesion enables non-destructive attachment to various surfaces, making it ideal for applications requiring careful inspection, such as delicate infrastructure. This method also allows for adjustable adhesion forces by varying the voltage, enhancing adaptability to different wall surfaces. Furthermore, it simplifies robot design by minimizing the need for complex mechanisms, thereby improving mobility. However, maintaining the required voltage levels necessitates a stable power supply, which can be energy-intensive for larger or long-duration robots. Additionally, low-conductivity surfaces like glass may challenge the performance of bipolar electrostatic adhesion systems.

**d) Bio-inspired Adhesion:**



**Fig 5: Bio-inspired Adhesion**

Research has revealed that geckos possess millions of tiny hair-like structures called setae on their feet, which are further divided into smaller branches known as spatulae. These spatulae allow geckos to establish close contact with surfaces, enabling their remarkable climbing abilities (Fig. 5A). This natural mechanism has inspired the development of dry adhesives for wall-climbing robots (WCRs), harnessing van der Waals forces to facilitate adhesion to a variety of surfaces, including smooth and non-sticky materials.

Numerous innovative adhesion techniques have been derived from the microscopic fibrillar structures found on gecko feet. For instance, one gecko-inspired WCR by Murphy et al., utilizes fibrillar adhesives, enabling effective operation on smooth surfaces . The footpads of this robot are crafted from polyurethane, featuring a stem diameter of 57 μm, a tip diameter of 114 μm, and a length of 113 μm, with a soft foam layer that enhances flexibility and reduces misalignment during loading. Experimental results demonstrated a maximum payload capacity of 100 g and climbing speeds of up to 5 cm/s in any direction when unburdened (Murphy et al., 2010). The design and peeling trajectory of dry-adhesive footpads significantly impact their performance, as shown in a study that introduced a dual-layer dry adhesive system incorporating PDMS micro and macro posts, which effectively allows the robot to scale smooth and uneven surfaces over extended periods.

Another notable example is the Stickybot, developed by Stanford University, which employs directional adhesion to control attachment and detachment from surfaces by adjusting the tangential force applied through its polyurethane footpads (Sangbae Kim et al., 2008). These pads feature hairs designed to maximize contact area with a 45° tip angle, optimizing adhesion while allowing for movement. Stickybot can achieve climbing speeds of 24 cm/s on horizontal surfaces and 4 cm/s on vertical ones, thanks to its advanced actuator-driven two-stage differential system.

A significant challenge in dry adhesion is the payload capacity and the effectiveness of detachment mechanisms. Many WCRs struggle to carry loads, and ineffective detachment can hinder adhesion performance. A recent design addresses this issue with a two-stage edge peeling mechanism that reduces the detachment force, allowing for payload capacities of up to 2.8 kg for vertical climbing and 0.5 kg for inverted surfaces.

Advancements in manufacturing adhesive footpads have also been explored, such as the quadruped WCR incorporating a pressure-sensitive adhesion mechanism inspired by lizard locomotion. This design features a compliant mechanism for adhesion and peeling, enabling effective climbing on various surfaces like acrylic plexiglass, and suggests the potential for swarm applications due to its rapid prototyping construction. Additionally, a study introduced a composite design for a gecko-inspired adhesive that achieves stable and reversible adhesion.

Beyond dry adhesion, researchers are investigating wet adhesion mechanisms suitable for micro-scale robots. One study mimicked the adhesive pads of ants by leveraging water droplet surface tension, allowing a 10.2 g robot to climb vertical and inverted surfaces at speeds of 12.3 mm/s and 6.6 mm/s, respectively.

Recent explorations have also delved into alternative biological inspirations for climbing robots. For instance, a parrot-inspired tripedal robot utilizes its beak and feet to navigate structures like ladders. Similarly, a quadrupedal robot modeled after insect locomotion is designed for rapid pole climbing, employing mechanical linkages and power-dense actuators to enhance speed and stability. Another innovation is a pentapod robot designed for autonomous vertical gardening, featuring five legs with compliant joints for stability and adaptability.

Bio-inspired adhesion enables robots to securely adhere to various surface types, including smooth, rough, and uneven ones, allowing them to operate in diverse environments and perform a wide range of tasks. This approach minimizes potential damage to sensitive surfaces, making it ideal for applications in delicate settings. Additionally, bio-inspired adhesion reduces reliance on complex mechanisms, such as air pumps, enhancing the robots' adaptability and flexibility. However, this method is highly dependent on surface temperature and contamination levels, necessitating effective adaptation strategies to ensure optimal performance. Furthermore, the manufacturing processes for bio-inspired footpads, particularly dry adhesives, can be complex and costly.

**2.2.2 Locomotion Methods**

**a) Tracked Locomotion**

Tracked locomotion is a widely used strategy for Wall Climbing Robots (WCRs) due to its stability and efficient payload capacity. It distributes the robot’s weight evenly along its tracks, allowing smooth operation on both flat and curved surfaces. Common adhesion methods integrated with tracked locomotion include negative pressure and magnetic adhesion (Zhu, Sun and Tso, 2002). Innovations in this area, such as multi-body tracked designs with flexible joints, modular architectures, and suspension mechanisms, have improved adaptability and wall-transition capabilities. For instance, Park et al.'s "R-track" robot demonstrated transitions between walls, ceilings, and internal walls (Park et al., 2021). Despite the advantages, tracked locomotion can limit flexibility due to friction and weight. Recent designs aim to overcome these limitations by enhancing obstacle navigation and optimizing load distribution, as seen in a magnetic crawler WCR with a flexible skeleton and load dispersion mechanism. This approach has proven effective in navigating industrial obstacles like weld seams, ensuring stability and adhesion during operations. However, the increased friction and added weight can impede rapid movement, affecting the robot’s maneuverability in dynamic scenarios.

**b) Wheeled Locomotion:**

Wheeled locomotion is widely utilized in Wall Climbing Robots (WCRs) for its flexibility and high movement speeds. However, limited contact areas can lead to slippage, which can be mitigated by using rubber covers on wheels to increase the coefficient of friction (COF) (Oliveira, Silva and Barbosa, 2010). Magnetic wheeled WCRs face challenges with adhesion on thin surfaces due to reduced magnetic force, but innovations like triangular and omnidirectional wheel designs have improved obstacle navigation and gap crossing capabilities. For example, robots using three magnetic wheel pairs or omni-wheels can maintain adhesion and maneuver laterally along curved or cylindrical surfaces.

Curved surface adaptability is another critical area of research. Techniques like double-hinge connections or compliant suspension systems enable WCRs to adjust to surface curvatures and maintain stability. Moreover, bionic-inspired designs, mimicking climbing animals’ tarsal structures, have led to the development of spine-equipped wheels that increase gripping force. Although adding more wheels can enhance stability, it also increases the robot's weight, which can impact its mobility on various surfaces. By employing rubber tires or high-COF materials, these robots can maintain effective adhesion and stability in diverse environments.

**c) Legged Locomotion:**

Legged locomotion in Wall Climbing Robots (WCRs) involves using legs or appendages for maneuvering, offering higher adaptability compared to tracked or wheeled robots. Various designs incorporate adhesive mechanisms like magnetic feet and vacuum cups for stable climbing. For instance, the quadrupedal robot MARVEL employs magnetic feet to handle horizontal and vertical planes and navigate obstacles and gaps (Bhaskar, Verma and Sharma, 2021). Some WCRs integrate electrostatic or bionic adhesives with specialized peeling mechanisms for smoother operation, while others use grippers to cling to surfaces, enhancing climbing efficiency.

Bio-inspired legged WCRs, like those mimicking insect spine structures, latch onto small surface bumps for stability, making them effective on rough or soft surfaces. Gait planning is crucial for legged robots, involving both predefined and adaptive strategies that adjust leg movements based on real-time feedback from sensors like gyroscopes and cameras (Li et al., 2016).

Bipedal WCRs are often inspired by inchworms, utilizing electromagnetic feet for adhesion on curved and flat surfaces. Examples like the iCrawl robot demonstrate the efficiency of inchworm-like locomotion in inspecting metal pipelines (Khan et al., 2020). Recent developments also focus on multimodal locomotion, combining soft robotics and adaptive mechanisms to transition between different planes and tackle complex terrains. Flexible designs, such as reconfigurable soft robots actuated by electromagnets, further enhance mobility and adaptability. However, these advancements require sophisticated control algorithms and intricate mechanisms, increasing the complexity of legged WCRs.

**d) Hybrid Locomotion:**

Hybrid locomotion in Wall Climbing Robots (WCRs) combines multiple methods like tracked, wheeled, and legged movements. This approach enhances adaptability across various surfaces. For instance, Wang et al. designed a WCR for ship cleaning using four legs and eight wheels, combining magnetic and vacuum adhesion for stability. Bu et al. further introduced a wheel-leg WCR with magnetic omni-wheels for enhanced freedom of movement.

Recent advancements emphasize bio-inspired adhesion techniques. Dharmawan et al. developed a bionic WCR with wheel legs incorporating dry adhesive flaps for improved traction. Paper-based WCRs using electrostatic adhesion and Shape Memory Alloys (SMA) also demonstrate the potential of lightweight and efficient designs (Otsuka and Ren, 1999).

A prominent example of hybrid WCRs is Morphobot, which integrates thrusters and wheels to switch between crawling, rolling, climbing, and flying. This versatility allows Morphobot to navigate complex terrains and steep slopes, making it suitable for search, rescue, and automated handling tasks (Qin et al., 2023). Similarly, the SPIDAR robot combines walking with flight capabilities using spherically vectorable rotors, expanding WCR functionality across domains (Zhao, Anzai and Nishio, 2023).

Hybrid locomotion enhances the flexibility and maneuverability of WCRs, enabling them to traverse flat, rough, and uneven surfaces. However, these designs face challenges like increased mechanical complexity and the need for sophisticated control algorithms to coordinate multiple locomotion mechanisms efficiently.

**2.2.3 Control Methods:**

**a) Pre-defined Control Method:**

Predefined control strategies in Wall Climbing Robots (WCRs) involve assigning robots with predetermined instructions or algorithms for navigation and adhesion. This strategy is effective for simple environments, reducing the complexity of the robot’s mechanical and electronic systems. A common architecture consists of a host computer sending predefined commands to a guest computer on the robot via wired or wireless communication.

For example, Huang et al. developed a ship-inspection WCR that uses a wired remote-control system. An industrial control computer acts as the host, sending predefined instructions—like path planning, working conditions, and self-diagnosis—to a single-chip guest computer on the robot (Huang et al., 2017). The guest computer processes these instructions and converts them into signals for motors and servos, enabling precise movement and task execution.

Wireless remote-control systems are also common, where commands are transmitted using LAN or other wireless technologies. An example is the robot by Shen, Gu and Shen, which employs a hierarchical control system with four layers (tasks, actions, control, and physical) (Shen, Gu and Shen, 2006). This system interprets operator-defined actions into signals for the robot's onboard computer. Optical encoders provide position and velocity feedback, allowing force adjustments through combined static and dynamic analysis.

Predefined control strategies often involve human oversight, especially in teleoperated WCRs where the operator monitors and adjusts the robot’s actions. For robots requiring full autonomy and dynamic responses to changing environments, adaptive or dynamic control strategies are more suitable, as covered in the next section.

**b) Dynamic Control Method:**

Dynamic control strategies enable Wall Climbing Robots (WCRs) to respond and adapt in real time to dynamic environments. Unlike predefined strategies, dynamic control strategies use real-time sensing and decision-making algorithms to optimize robot movements based on the environmental conditions. This enhances the robot’s adaptability and reliability for tasks involving uncertain or complex terrains.

Researchers introduced an adaptive external force-softening strategy for legged WCRs, inspired by gecko-like climbing (Duan et al., 2023). This strategy uses admittance control, simulating a spring-like cushioning during movements on concave surfaces. The robot's foot trajectory is divided into four phases—detachment, swinging, pre-loading, and adhesion—to improve stability. Experiments showed enhanced stability of adhesive areas by 28.32% and significant improvements in the robot’s balance in all gait stages.

Advancements in sensors have played a key role in developing precise dynamic control strategies. Xue et al. proposed a spatial positioning control strategy for WCRs inspecting cylindrical storage tanks. By fusing data from ultrawideband (UWB) sensors, inertial measurement units (IMU), and encoders, they combined backstepping and sliding-mode control to handle trajectory errors (Xue et al., 2023). The results showed high precision and stability, allowing the robot to navigate cylindrical tanks efficiently.

Another example is the modular neural control strategy described with the strategy that involves a Central Pattern Generator (CPG) that uses sensory feedback to generate periodic signals. The signals undergo post-processing (PCPG) and delay line shifting before reaching the motors, adjusting the robot’s gait and motion frequency (Srisuchinnawong et al., 2019). Feedback from inclinometer and force sensors allows dynamic changes in gait and locomotion, enhancing stability.

Dynamic control strategies extend beyond motion to include path planning. Traditional models struggle with navigating robots around static and dynamic obstacles. Gui et al. proposed a method that integrates Tri-objective Grey Wolf Path Optimization (TGWPO) with Adaptive Multi-objective Particle Swarm Optimization (AMPSO) (Gui Hongfan and Zhao Zhangyan, 2023). TGWPO optimizes path length, collision risk, and smoothness, while AMPSO optimizes the robot’s gait for stability and energy efficiency. Together, these strategies allow WCRs to navigate efficiently and dynamically adapt to varying environmental conditions.Bottom of Form

**2.3 Material Consideration:**

The choice of structural materials in wall-climbing robots (WCRs) is crucial as it directly influences their performance, durability, and ability to adapt to different climbing environments. Each material brings unique properties that can enhance or limit the robot's functionality, depending on the specific challenges presented by the climbing tasks. This detailed exploration will cover various materials, including alloys, aluminum, composites, and plastics like ABS, examining their applications, benefits, and the problems they address in different situations.

**2.3.1 Alloys**

Alloys are often favored in WCR designs due to their high strength-to-weight ratio. Materials like aluminum and titanium alloys stand out for their ability to provide significant mechanical strength while remaining relatively lightweight. This characteristic is vital in robotic applications, where a lower weight contributes to improved maneuverability and reduced energy consumption during climbing tasks. In addition to being lightweight, many alloys possess excellent corrosion resistance, making them suitable for outdoor applications or environments with exposure to moisture and harsh chemicals. For example, a WCR operating in a maritime setting would benefit from the corrosion-resistant properties of aluminum alloys, ensuring longevity and reliability.

The thermal stability of certain alloys is another advantageous trait, as these materials can maintain their structural integrity across varying temperature ranges. This stability is essential for robots working in environments with extreme temperature fluctuations, allowing them to perform effectively without compromising their structural strength. However, the use of alloys is not without challenges. While they offer superior mechanical properties, the costs associated with high-performance alloys, such as titanium, can be significant, impacting the overall budget of a project. Additionally, fabricating components from alloys can require advanced machining and processing techniques, potentially increasing production time and costs.

**2.3.2 Aluminum**

Aluminum is one of the most widely used materials in WCRs, largely due to its lightweight nature combined with good strength. This combination allows robots to navigate vertical surfaces efficiently without excessive energy expenditure. Aluminum is also favored for its ease of machining; it can be easily extruded, shaped, or formed into complex designs, offering versatility in the construction of robotic components. Moreover, its relatively low cost compared to other metals makes it an attractive option for many projects.

Despite its advantages, aluminum does have limitations. Its fatigue resistance is a concern, particularly in applications involving cyclic loading. Over time, repeated stress can lead to fatigue failure, which could limit the lifespan of a WCR operating in demanding environments. Furthermore, while aluminum has good thermal conductivity, it may not be suitable for applications requiring insulation to protect sensitive components from temperature variations.

**2.3.3 Composites**

Composite materials, such as carbon fiber reinforced polymers (CFRP) and glass fiber reinforced polymers (GFRP), have gained popularity in the design of WCRs due to their exceptional strength and stiffness relative to their weight. These materials provide robust structural support while allowing for significant weight savings, which is crucial for maintaining climbing efficiency. The tailored properties of composites enable designers to engineer materials specifically for their applications, optimizing mechanical and thermal performance in various scenarios.

In addition to their mechanical advantages, composites often exhibit superior resistance to corrosion and environmental degradation, making them suitable for diverse operating conditions. For example, a composite structure might be ideal for a robot climbing in an area exposed to chemicals or high humidity, ensuring durability and functionality. However, high-quality composites can be costly to produce, requiring advanced manufacturing techniques such as lay-up processes or autoclave curing. The complexity of these techniques necessitates specialized knowledge and equipment, which may not be readily accessible to all manufacturing facilities.

**2.3.4 Plastics (e.g., ABS)**

Plastics, particularly ABS (Acrylonitrile Butadiene Styrene), serve as a lightweight and flexible option for WCRs, especially in non-load-bearing applications. ABS is known for its impact resistance and ease of fabrication, which allows for quick production and prototyping of robotic components. This thermoplastic can be easily molded, 3D printed, or machined, providing designers with flexibility in creating custom parts. As such, ABS is often used for protective casings or housings that shield sensitive components from environmental factors without adding unnecessary weight.

However, while ABS is beneficial for specific applications, it does have limitations. Its load-bearing capacity is relatively low, making it unsuitable for structural components that must support significant weight. Additionally, ABS is sensitive to high temperatures; prolonged exposure to elevated temperatures can lead to warping or degradation, making it less appropriate for environments with extreme thermal conditions.

**2.3.5 Situational Considerations**

When selecting materials for WCRs, several situational factors must be considered. The type of climbing surface significantly influences material choice. For robots designed to climb rough or uneven surfaces, materials with high strength and durability, such as composites and alloys, are preferred to ensure structural integrity under stress. Conversely, robots operating on smooth surfaces may prioritize lightweight materials like aluminum and ABS, focusing on optimizing mechanisms for enhanced adhesion without the need for extensive structural support.

Environmental conditions also play a critical role in material selection. For outdoor applications exposed to moisture, humidity, or harsh chemicals, materials with good corrosion resistance, such as certain alloys and composites, are crucial to ensure reliable operation over time. In contrast, indoor applications with lower load requirements may find that lighter plastics like ABS are adequate, offering cost savings and simplicity in production.

Load-bearing requirements further dictate material choice. WCRs intended to carry heavy payloads during inspection or maintenance tasks necessitate stronger materials, such as aluminum alloys or composites, to maintain stability and safety. On the other hand, robots designed for exploratory tasks or minimal load requirements may effectively utilize plastics like ABS, focusing on weight reduction while maintaining necessary functionality.

**Chapter 3: System Architecture and Component Design**

**3.1 Mechanical Design**

The **mechanical structure** of the system is engineered to be compact and lightweight, prioritizing ease of mobility and durability. The design incorporates a combination of materials to balance weight and strength, with **aluminum** providing structural support and **plastic** components for non-load-bearing parts to reduce overall weight. Aluminum is chosen due to its **high strength-to-weight ratio** and **resistance to corrosion**, while plastic is utilized for its flexibility and lightweight properties.

The chassis and outer body are carefully designed to house and protect all internal **electronic components**, ensuring they remain secure during operation. The design also focuses on **weatherproofing** to shield sensitive electronics from environmental factors like dust and moisture. This involves sealing joints and using weather-resistant materials, making the robot suitable for outdoor or harsh environments.

**3.2 Electrical Components**

The **electrical system** is centered around an **Arduino board** acting as the main controller, facilitating communication and control. The **Motor Driver L298N** is responsible for driving the **DC motors**, enabling precise control of motion. The use of **omnidirectional wheels** allows the robot to achieve greater maneuverability, enabling it to move seamlessly in multiple directions with ease.

The power system is **battery-operated**, offering portability and operational independence. A **wireless module**, such as **Bluetooth** or **ESP32**, is integrated into the system to facilitate **remote communication and control**, allowing commands to be sent and monitored wirelessly. This setup ensures reliable, real-time operation and control, even from a distance.

**Chapter 4: Conclusion**

**Conclusion**

In conclusion, this project has successfully integrated advanced mechanical and electrical designs to create the idea of a highly functional and efficient wall-climbing robot (WCR). The mechanical structure, characterized by its compact and lightweight configuration, is designed to optimize mobility while ensuring durability. The strategic use of materials such as aluminum and plastic not only contributes to the structural integrity of the robot but also enhances its adaptability in various environmental conditions. The weatherproofing measures implemented ensure that the robot can operate effectively in outdoor settings, safeguarding sensitive electronic components from potential damage due to dust and moisture.

On the electrical side, the choice of an Arduino board as the central controller provides a robust platform for programming and control. Coupled with the Motor Driver L298N and DC motors, the robot exhibits precise movement capabilities, essential for navigating complex surfaces. The incorporation of omnidirectional wheels significantly enhances maneuverability, allowing the robot to traverse a variety of surfaces with ease.

Moreover, the implementation of a battery-operated power system and a wireless communication module—either Bluetooth or ESP32—enables remote operation and monitoring, making the robot both flexible and user-friendly. This wireless capability opens up possibilities for real-time data transfer and control, which is crucial for the effectiveness of the WCR in performing tasks such as inspection, cleaning, and maintenance.

The development of this wall-climbing robot showcases a significant step forward in robotics, demonstrating the potential for hybrid locomotion systems that can adapt to diverse surfaces and conditions. Future work may explore further enhancements in the areas of sensory feedback and autonomous decision-making, expanding the robot’s capabilities and operational efficiency. Overall, this project not only illustrates the successful integration of mechanical and electrical components but also highlights the potential applications of WCR technology in various industries, paving the way for more innovative solutions in robotic systems.

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