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Design and Implementation of a Glass Cleaning Robot for High Facade Structures

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ABSTRACTCleaning glass facades, especially in high-rise buildings, remains hazardous, labor-intensive, and expensive. Traditional methods involve human workers operating at unsafe heights, while many robotic solutions either use suction cups, magnetic adhesion, or tracked systems that limit maneuverability, adaptability, or power efficiency. Among these challenges, reliable and energy-efficient adhesion remains a critical unsolved problem. To address this, a wall-climbing robot has been developed using vacuum adhesion for firm yet flexible attachment to smooth surfaces. A BLDC motor with a tri-blade propeller removes air between the robot and the wall, creating a low-pressure region that allows atmospheric pressure to hold the robot in place. The drive system uses rubber-padded wheels powered by N20 mini gear motors, which generate sufficient torque to overcome both gravitational pull and vacuum-induced resistance. These motors are controlled via L298N motor drivers, while the BLDC motor is regulated through an ESC. An Arduino Uno serves as the central controller, coordinating all operations, and an external SMPS provides consistent power to the system. Mechanically, the robot's chassis is 3D-printed using PLA to ensure a lightweight and compact structure suitable for vertical mobility. Experimental tests confirm strong adhesion on inclined planes and partial success on vertical glass, validating the vacuum-assisted approach as a promising solution for safe and efficient glass-cleaning automation.

INDEX TERMS Adhesion mechanism, glass cleaning robot, high-rise maintenance, vacuum suction, wall climbing robot, BLDC propulsion, ESP32 control system, façade automation.

I.INTRODUCTION

Cleaning vertical glass surfaces on high-rise buildings is a hazardous and labor-intensive task. Traditional methods rely on human workers operating at significant heights using ropes or scaffolding, which pose serious safety risks and result in high operational costs. Manual cleaning is also inefficient for large surface areas and often leads to inconsistent coverage and quality.

Several robotic solutions have been proposed to automate facade cleaning, using methods such as suction cups, magnetic adhesion, or negative pressure chambers. However, many of these robots face limitations in terms of reliable adhesion, adaptability to smooth surfaces, energy efficiency, or production cost. Among these challenges, reliable and energy-efficient adhesion remains a critical unsolved problem.

To address this, a lightweight, cost-effective, and modular wall-climbing robot has been developed for vertical glass cleaning applications. The robot uses a vacuum adhesion mechanism powered by a BLDC motor and tri-blade propeller, which creates a low-pressure zone between the robot and the wall. As a result, atmospheric pressure provides a normal force that presses the robot firmly against the glass surface. This mechanism allows stable adhesion during climbing without the use of complex suction pumps.

Locomotion is achieved using four N20 mini DC gear motors with rubber-padded wheels, providing enough torque to overcome both gravity and the vacuum-generated normal force. The chassis is 3D-printed using PLA to reduce weight and enable easy customization.

An Arduino Uno microcontroller serves as the central control unit. It operates the N20 motors via L298N motor drivers and controls the BLDC motor through an ESC.

The entire system is powered by an external SMPS unit, allowing consistent power delivery without adding weight to the robot itself. The prototype demonstrates stable adhesion on inclined surfaces and reliable movement through individually controlled motors, forming a practical foundation for safe and scalable high-rise glass cleaning systems.

II. RELATED WORK

Robotic systems for vertical surface cleaning have gained attention in recent years due to their potential to improve safety and efficiency in maintenance operations, especially on glass facades of high-rise buildings. Various climbing mechanisms have been explored, including magnetic, pneumatic, gecko-inspired, and vacuum suction systems. Among these, vacuum-based adhesion stands out as a versatile and effective technique for smooth surfaces such as glass.

The reference work [8] introduces a wall cleaning robot utilizing a vacuum suction mechanism, enhanced with a fuzzy inference system to dynamically adapt suction power based on surface conditions. Their design used a two-wheel locomotion mechanism and rotary encoders for controlled motion, targeting improved reliability and adhesion-awareness. However, the system was limited by component bulk and mechanical complexity.

Commercial robots like the Sky Cleaner, HOBOT-298 (or higher version robots) TITO series have demonstrated high throughput in terms of cleaning efficiency (125 m²/h and 1500 m²/h respectively), but they are often expensive and not modular or portable. Our design aims to bridge this gap by developing a lightweight, cost-effective, and easily deployable robotic system using drone-inspired BLDC thrust for vacuum adhesion and basic DC motors for movement. Unlike previous systems, our robot uses an ESP32 microcontroller for wireless control and integrates 3D-printed modularity for customizability.

This work builds upon existing principles but targets affordability, simplicity, and ease of deployment—making it suitable for both residential and commercial glass facade maintenance.

III: SYSTEM ARCHITECTURE

The prototype of the glass cleaning robot was assembled using a combination of commercially available electronic components and custom 3D-printed parts. The implementation process involved multiple stages: component selection, electrical interfacing, mechanical integration, and software programming.

A. Hardware Components

The following major components were used in the robot:

I.Microcontroller: Arduino Uno R3, selected for its simplicity, extensive community support, and compatibility with motor driver modules and communication interfaces.

II.Motor Drivers: Two L298N H-bridge motor drivers were used to control four N20 DC gear motors (6V, 100 RPM), each driving one wheel.

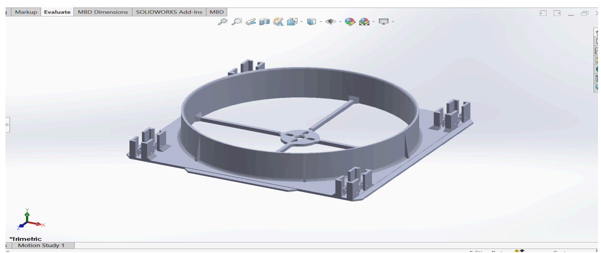
III.Brushless Motor and ESC: An RS2205 2300KV BLDC motor paired with a 30A ESC (Electronic Speed Controller) and a 6045tri-blade propeller generates vacuum suction to adhere to vertical surfaces.

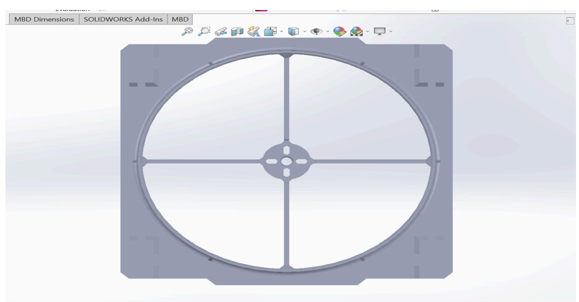
IV.Power Supply: A 12V 20A SMPS delivers power to the entire system. LM2596 buck converters are used to step down voltages for the Arduino (5V) and the N20 motors (6V).

V.Chassis: The robot's body was designed using SolidWorks and manufactured using PLA filament on an FDM 3D printer. The rectangular chassis layout was chosen for stability and effective surface coverage.

VI.Bluetooth Module: The HC-05 Bluetooth module is interfaced with the Arduino Uno for wireless manual control via a smartphone or PC.

VII.Microfiber Pad: A microfiber cloth is attached to the bottom of the chassis to clean the surface during movement.





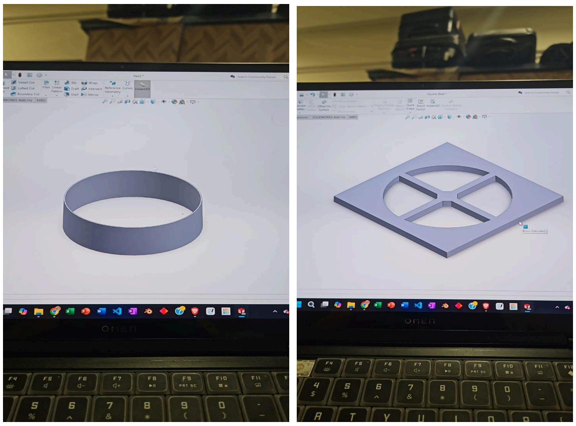


Fig. 1. CAD model of the propeller duct housing: (Top) 3D isometric view showing motor mount with airflow guide; (Bottom) top-down view highlighting circular air passage.

B. Software Implementation

The software was developed using the Arduino IDE and written in embedded C/C++. The main control loop includes:

I.BLDC Control: PWM signals are generated by the Arduino to initialize and regulate the ESC for the BLDC motor.

II.DC Motor Control: The L298N modules are driven using digital I/O pins from the Arduino. Direction and speed are controlled via logic signals and PWM for each motor.

III.Bluetooth Communication: Serial communication between the HC-05 and the Arduino allows the robot to receive movement commands (e.g., forward, backward, stop, turn) from a smartphone-based interface.

C. Assembly and Wiring

During the physical assembly:

I.Motors and electronics were mounted on the 3D-printed chassis using bolts and adhesives.

II.Proper heat dissipation was ensured for the ESC using heat sinks and ventilation openings.

III.The wiring was carefully routed and insulated to avoid short circuits and minimize weight impact.

IV.Initial dry runs were conducted using external power sources before integrating the SMPS for full operation.

IV. METHODOLOGY

Wall-climbing robots developed for glass cleaning applications typically use a combination of adhesion techniques such as suction pumps, propeller-based negative pressure systems, or magnetic adhesion. While many of these systems succeed in providing stable climbing, they often suffer from trade-offs like excessive weight, energy inefficiency, and complex manufacturing. The goal of this work was to design a system that is modular, lightweight, cost-effective, and capable of adhering reliably to inclined and vertical smooth surfaces like glass façades.

The robot chassis was developed by adapting a CAD model sourced from a referenced research paper. The design was modified to accommodate our motor mounts, vacuum chamber, and wiring layout based on available components. The final chassis was 3D printed using PLA material, selected for its light weight, structural durability, and affordability. This frame serves as the base for all mechanical and electronic components, providing strength while minimizing added mass during vertical motion.

The adhesion system relies on a high-speed BLDC motor fitted with a tri-blade propeller that generates a localized low-pressure zone beneath the robot. Atmospheric pressure provides the necessary normal force that holds the robot against the surface. This suction-based method allows stable climbing on smooth, vertical glass without requiring heavy vacuum pumps, thus supporting a more compact and lightweight system.

Locomotion is achieved using four N20 mini DC gear motors attached to rubber-padded wheels in a differential drive configuration. These motors provide sufficient torque to overcome gravitational force and suction-based adhesion. Directional movement—forward, backward, left, and right—is controlled using four push buttons connected to analog pins on the Arduino Uno. The microcontroller toggles H-bridge logic via two L298N motor drivers to activate motor pairs accordingly.

Speed control for the drive motors is handled using serial commands ('1' to '4') that adjust PWM duty cycles using analogWrite() on the enable pins. Similarly, suction speed is varied by sending serial commands ('5', '6', '7') to the ESC controlling the BLDC motor, with signal generation handled through the Servo library. This setup allows for three adjustable suction intensities based on surface inclination or load.

To reduce the robot's total climbing weight, the Arduino Uno and 12V 20A SMPS power supply are both positioned at ground level. Wires are routed upward to the climbing unit, minimizing on-board weight and improving adhesion reliability. The system operates in an open-loop configuration without sensor feedback, prioritizing simplicity, cost-effectiveness, and manual control reliability during experimental testing on inclined surfaces.

V. HARDWARE AND SOFTWARE IMPLEMENTATION

The glass climbing robot was implemented using readily available electronic components, supported by a 3D-printed mechanical structure. The development process involved hardware selection, system integration, wiring, and embedded programming.

A. Hardware Components

I. Microcontroller: Arduino Uno R3, chosen for its ease of programming, widespread support, and compatibility with motor drivers and communication modules.
II. Motor Drivers: Two L298N dual H-bridge drivers were used to control four N20 6V DC gear motors for locomotion.
III. BLDC Motor and ESC: A 2300KV RS2205 BLDC motor paired with a 30A ESC (Electronic Speed Controller) powers a 6045 tri-blade propeller to create downward thrust for vacuum adhesion.
IV. Power Supply: A 12V 20A SMPS powers the full system. LM2596 buck converters step down the voltage to 6V for the gear motors and 5V for the Arduino and Bluetooth module.
V. Chassis: The frame was designed in SolidWorks and 3D-printed using PLA. The structure is lightweight, optimized for balance and adherence, and fits within the target weight of under 700g.
VI. Bluetooth Module: The HC-05 Bluetooth module allows wireless control of the robot from a mobile device.
VII. Microfiber Pad: A microfiber cloth is attached to the underside of the chassis to passively clean the glass as the robot moves.

B. Software Implementation

I. Code was written in the Arduino IDE using embedded C/C++.
II. The BLDC motor is controlled using PWM signals generated by the Arduino, interfacing with the ESC.
III. N20 motors are managed via L298N motor drivers using digital I/O and PWM pins for speed and direction control.
IV. Bluetooth commands are received through serial communication between the HC-05 module and the Arduino, allowing remote movement commands like forward, reverse, and stop.

C. Assembly and Wiring

I. All components were mounted securely onto the PLA chassis using screws and cable ties.
II. Power connections were routed through buck converters to ensure voltage compatibility.
III. The ESC was provided with basic heat dissipation using aluminum heat sinks.
IV. Initial tests were conducted with external power before full integration with the onboard 12V SMPS.
Thus this hardware-software integration allowed the robot to achieve reliable cleaning motion on inclined and partially on vertical glass surfaces.

VI.EXPERIMENTAL RESULTS AND CALCULATIONS

To evaluate the performance of the glass climbing robot, experimental trials were conducted focusing on thrust force generation, weight support capacity, motor output, and climbing efficiency.

A. Thrust Force Generation

I. BLDC Motor Used: RS2205 2300KV with 5152 tri-blade propeller
II. Measured Thrust: 917 grams
III. Thrust in Newtons: $(917 / 1000) \times 9.81 = 8.995$ N

B. Maximum Supported Weight

To maintain adhesion on a vertical glass surface, the generated thrust must overcome the gravitational pull adjusted by the coefficient of friction.
I. Formula: $m \leq (F \times \mu) / g$
II. (coefficient of friction): ~0.8 (glass to rubber)
III. Result: $m \leq (8.995 \times 0.8) / 9.81 \approx 0.733$ kg
Conclusion: Robot can safely operate if its weight is ≤ 733 grams

C. Gear Motor Output Force

I. Motor: N20 DC Gear Motor (6V, 100 RPM)
II. Wheel Radius: 2.15 cm = 0.0215 m
III. Voltage: 12V
IV. Current: 0.07 A
V. Angular Velocity: $\omega = (2\pi \times 110) / 60 \approx 11.52$ rad/s
VI. Torque: $\tau = (V \times I) / \omega = (12 \times 0.07) / 11.52 \approx 0.0729$Nm
VII. Force: $F = \tau / r = 0.0729 / 0.0215 \approx 3.39$ N
VIII. Required Climb Force (per wheel): $8.995 / 4 = 2.25$N
Conclusion: Motors produce sufficient torque for climbing

D. Surface Test Results

I. Glass (Vertical): Partially Stable grip, clean movement
II. Whiteboard (Smooth Surface): Adequate adhesion
III. Painted Wall: Slightly reduced vacuum effect due to uneven surface and dust particles and layers of paint.
IV. Inclined Surface (45°): Fully functional and stable
V. Vertical Climb (90°): Partially achieved ,further tuning needed by using motor of higher rpm and electronic controller with higher current handling capacity.

E. Observations

I. Robot remains stable up to ~730g.
II. Beyond 750g, loss of suction observed.
III. ESC heating was noted due to lower current rating.

F. Limitations Identified

I. Single-propeller vacuum setup limits adhesion uniformity.
II. Usage of lower rpm(2300rpm/v) of motor due to cost limitations.

III. No edge detection or autonomous path planning implemented.
IV. Passive cleaning only (dry microfiber, no water or scrubbing).

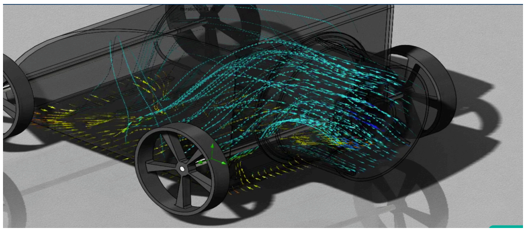


Fig.3. CFD simulation showing airflow streamlines under the chassis, indicating vacuum thrust flow pattern generated by the BLDC-propeller system.Reference[11]

VII. FUTURE ENHANCEMENTS

The following upgrades are proposed to improve the performance, reliability, and practical usability of the robot:

I. Enhanced Vacuum System

The use of industrial-grade BLDC motors along with high-current-handling ESCs would significantly improve suction efficiency. A stronger pressure differential would be generated beneath the chassis, eliminating the need for external pushing. High-quality ESCs would also provide smoother control and better thermal performance during continuous operation.

II. Wireless Control and Edge Detection

The current wired push-button interface can be replaced with wireless modules such as ESP32 or Bluetooth-based systems for remote control. Additionally, IR or proximity sensors can be integrated to detect glass edges or obstacles, enhancing safety and reducing the risk of accidental detachment during movement.

III. Advanced Chassis Material

Future designs can employ stronger and lighter 3D printing materials such as PETG, Nylon, or carbon fiber–infused PLA. These materials offer superior strength-to-weight ratios and can maintain durability even with thinner, high-density prints, reducing the robot's overall weight without compromising structural integrity.

IV. Custom PCB Integration

A single custom-designed PCB can be created to combine the functionalities of the Arduino Uno, ESC, and motor drivers. This would reduce wiring complexity, lower component count, and improve overall reliability and compactness of the system.

V. Power and Cleaning Mechanism Upgrade

Replacing the SMPS with a high-discharge-rate LiPo battery would offer improved portability and eliminate voltage drops during extended operation. Additionally, future versions may incorporate an active cleaning mechanism, such as rotating brushes or fluid spray systems, replacing the current passive cleaning approach.

VIII. CONCLUSION

The development of the glass-cleaning robot began with a detailed study of the underlying physics and mathematics behind vacuum adhesion. Calculations were performed to estimate the required pressure differential and suction force necessary to support the robot's weight on inclined and vertical glass surfaces. These estimations helped define a safe operating weight limit for the robot, which was found to be approximately 730 grams.
Once the target weight and force requirements were known, focus shifted to the mechanical design. Initially, a custom chassis was planned using SolidWorks, but after surveying open-source research, a reference CAD file was found and modified to match our specific component layout and constraints. The chassis was 3D printed using PLA for its durability and cost-effectiveness, while maintaining minimal weight.
To create the vacuum adhesion mechanism, multiple BLDC motors were tested—including 1400KV and 1800KV variants—with the RS2205 ultimately chosen for its high thrust and compact form factor. It was paired with a tri-blade propeller to generate a stable low-pressure zone beneath the chassis. For movement, different small motors were explored, but the N20 mini DC gear motors were selected for their high torque and compactness, suitable for climbing on glass surfaces.
The control system was implemented using an Arduino Uno. Four wired push buttons were used for directional movement (forward, backward, left, right), and serial terminal commands were used to adjust both the N20 motor speeds (1 to 4) and BLDC suction levels (5 to 7). ESCs like the 30A SimonK were employed for BLDC control. Although batteries such as 2400mAh Li-ion cells were tested, an SMPS (12V, 20A) proved more reliable during extended trials.
Final testing showed that the robot performed well on inclined glass surfaces between 70° and 85°. However, adhesion on fully vertical (90°) surfaces was inconsistent, primarily due to the limited vacuum pressure generated by the chosen BLDC system. Despite this, the prototype successfully demonstrated the feasibility of an affordable and modular glass-climbing robot, laying a strong foundation for future enhancements.

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