RV College of Engineering

Experiential Learning Report

Project-Based Learning

2024-25

High-Rise Facade Cleaning robot using Vacuum Adhesion

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1. Introduction

In the modern era of architecture, high-rise buildings are increasingly covered in glass facades for both aesthetic appeal and functional benefits such as improved natural lighting and thermal insulation. However, maintaining the cleanliness and clarity of these large glass surfaces presents a significant challenge. Over time, dust, pollutants, and environmental residues accumulate on the exterior, impacting both the building's appearance and efficiency. Traditional cleaning methods involve human labor through rope suspension or scaffolding systems, which are not only time-consuming but also extremely dangerous and costly.

Recent advancements in robotics have opened new possibilities for automating facade maintenance tasks. While some commercial cleaning robots exist, most are limited to horizontal surfaces or cannot adapt to vertical and inclined orientations due to poor adhesion systems. These limitations highlight the need for a more versatile, safe, and cost-effective robotic solution that can operate autonomously across a variety of surface angles. In particular, vacuum-based adhesion offers a promising approach to overcome the constraints of gravity and surface variability.

This project presents the design and development of a vacuum-powered robot capable of cleaning both vertical and inclined glass surfaces. The robot is engineered to use a compact suction system for strong surface attachment and a lightweight drive mechanism for movement. It incorporates a rotating microfiber cleaning module to effectively remove dust and debris as it climbs. The solution is optimized for real-world applications where safety, efficiency, and affordability are critical. Through systematic design, prototyping, and testing, the robot aims to demonstrate a practical approach to automating facade cleaning in high-rise environments.

2. Problem Definition

2.1. Problem Statement:The maintenance of high-rise building facades, particularly those made of glass, is a recurring challenge in urban infrastructure. Over time, pollutants such as dust, grime, and bird droppings accumulate on these surfaces, reducing not only the building's aesthetic value but also the effectiveness of natural lighting and energy efficiency. The cleaning of these facades, especially when positioned at vertical (90°) and inclined (30°–60°) angles, demands specialized labor and equipment. Conventional cleaning methods—such as rope access systems, scaffolding, and suspended platforms—pose serious safety risks to workers, are highly dependent on human effort, and require significant time and financial investment for setup and operation.Despite some efforts to automate facade maintenance, most existing robotic solutions are limited in scope. Many are designed only for horizontal surfaces or rely on magnetic or adhesive systems that are unsuitable for smooth, non-magnetic glass. Additionally, they often lack adaptability to varying surface angles and cannot consistently maintain stability during operation. These limitations underline the urgent need for a compact, safe, and efficient robotic solution that can autonomously clean glass facades across a range of inclinations. The project aims to address this gap by developing a vacuum-based robot that can operate on both vertical and inclined glass surfaces, providing a reliable, cost-effective alternative to traditional methods while enhancing safety and performance.

2.2.Background Information: (literature review)

[1] "Smart Surface Cleaning Robot Using Vacuum Suction Mechanism," *JETIR*, vol. 10, no. 4, pp. 351–356, Apr. 2023. [Online]. Available: https://www.jetir.org/view?paper=JETIR2304892

[2] RS2205 2300KV BLDC Motor – Datasheet. [Online]. Available: https://www.racerstar.com/

[3] Arduino Uno Technical Specifications. [Online]. Available: https://store.arduino.cc/

[4] L298N Motor Driver Module Datasheet. [Online]. Available: https://components101.com/modules/l298n-motor-driver-module

[5] LM2596 Buck Converter Datasheet. [Online]. Available: https://datasheetspdf.com/datasheet/LM2596

[6] H. Asama, M. Sato, and Y. Ishida, "Development of a wall climbing robot using negative pressure adhesion mechanism," *Proc. IEEE Int. Conf. on Robotics and Automation*, vol. 3, pp. 2777–2782, Apr. 1992. DOI: 10.1109/ROBOT.1992.219981

[7] M. L. Ruocco, G. Muscio, and M. Trotta, "Design and control of a low-cost wall climbing robot for inspection," *Mechanics Based Design of Structures and Machines*, vol. 48, no. 5, pp. 483–500, 2020. DOI: 10.1080/15397734.2020.1759422

[8] S. Hirose and A. Nakamura, "Concept and design of a wall climbing robot with permanent magnet feet," *Journal of Robotics and Mechatronics*, vol. 3, no. 1, pp. 30–37, 1991.

[9] H. Lee, S. Park, and H. Park, "Development of a wall climbing robot using propeller-type adhesion," *International Journal of Control and Automation*, vol. 8, no. 1, pp. 287–296, 2015.

3. Objectives

3.1. Primary Objectives:To design and fabricate a robot capable of cleaning vertical and inclined glass surfaces using vacuum suction.To develop a robust vacuum-based adhesion system that maintains grip across varying angles (30° to 90°).

To ensure safe, stable, and reliable movement on inclined and vertical planes without slippage or tipping.

To validate the robot's adhesion and moving performance through systematic testing across multiple surface inclinations.

3.2. Secondary Objectives: To integrate a microfiber-based cleaning mechanism for efficient surface dust removal.

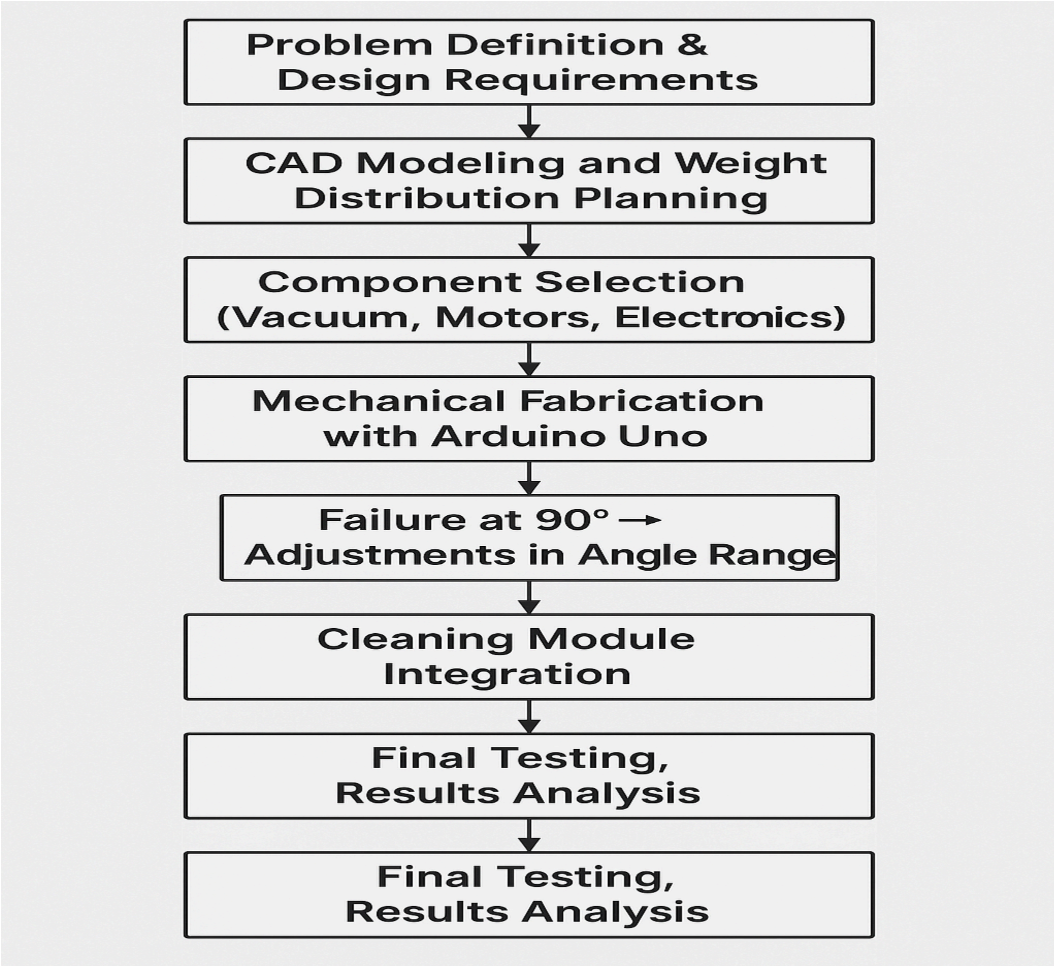
To build a modular chassis design for easy maintenance and future enhancements.

To optimize the system for low power consumption and extended battery life.

To record and analyze performance metrics like suction time, climbing speed, and cleaning coverage.

4. Methodology

4.1 Approach: The methodology adopted in this project was structured around a modular and test-driven design approach. The robot was developed to adhere and climb on inclined glass surfaces, targeting angles from 30° to 75°, using a vacuum suction mechanism. Although the design aimed for operation at a full vertical angle (90°), testing revealed instability and suction loss at that angle due to gravitational pull exceeding the holding capacity of the current vacuum system. As such, the practical operating range was redefined during the project execution phase.The robot integrates mechanical components for locomotion, an embedded vacuum chamber for suction-based adhesion, and a microcontroller (Arduino Uno) for control. The climbing and cleaning mechanisms were developed as separate modules to allow independent testing and future upgrades. Iterative testing was conducted to evaluate stability, suction strength, and cleaning efficiency at various inclinations.



4.2 Procedures: The project execution involved the following steps:

I. Step 1: Design & CAD Modeling

   A. Requirements were defined considering inclined facades.

   B. CAD models were created using SolidWorks for optimal weight placement and suction layout.

II. Step 2: Component Testing

   A. Individual components like the vacuum pump, motors, and driver modules were tested.

   B. Suction tests were done at flat and inclined surfaces. Suction was unstable at 90°, but held effectively up to ~75°.

III. Step 3: Fabrication & Assembly

A. Chassis was 3d printed and assembled with the motor drive system and suction base.

B. Components were securely mounted to maintain balance during inclined climbing.

IV. Step 4: Circuit Integration

A. Arduino Uno was programmed to control motor direction and suction.

B. Electronics were integrated using L298N driver modules and powered by a 12V Li-ion battery.

V. Step 5: Inclination Testing

A. Robot was tested at 30°, 45°, 60°, and 75°.

B. At 90°, adhesion failed consistently due to insufficient negative pressure and lack of surface sealing.

C. Operational angle was finalized up to 75°.

VI. Step 6: Cleaning Module Integration

A. A rotating microfiber brush module was added and tested independently.

B. Cleaning performance was evaluated in terms of dust removal in a single pass.

VII. Step 7: Final Testing & Evaluation

A. Data was collected on adhesion time, surface coverage, suction duration, and motor heating.

B. Minor refinements were made based on observed limitations.

5. Project Execution

5.1 Planning and Design: The project began with identifying a need for an automated, safe, and efficient solution to clean glass surfaces on high-rise buildings. Initial brainstorming led to exploring various adhesion methods, including suction pumps and magnetic systems. Since the robot needed to work on non-magnetic, smooth glass, the team selected a propeller-based suction system to generate the required negative pressure using a BLDC motor with high-speed fan blades.

CAD models were developed using SolidWorks to define component layout, airflow channels, and weight distribution. Special attention was given to ensure that the center of gravity was kept low, aiding stability on inclined surfaces. The robot was designed to accommodate cleaning hardware (microfiber pad) and compact electronics while minimizing weight.

5.2 Implementation: A custom-designed acrylic frame was fabricated to house the components. Instead of a commercial vacuum pump, a BLDC motor with a propeller fan was used to generate suction by rapidly pulling air and creating a pressure differential between the base of the robot and the surface. This fan-based vacuum system was lighter and more cost-effective, though it provided limited suction strength, especially for vertical applications.

Initial tests showed that the robot could adhere and move reliably on inclined glass surfaces (30°–75°). However, it was unable to maintain stable adhesion at 90° due to insufficient negative pressure. To enhance functionality, a microfiber cleaning module was attached to the underside of the robot, allowing it to wipe and collect dust as it moved.

The system is powered by a 12V SMPS, with all electronics controlled via an Arduino Uno and an L298N motor driver. The fan and motors are activated simultaneously for movement and suction. While the vertical climbing goal remains a future enhancement, the current implementation performs well on inclined surfaces and proves the feasibility of fan-based adhesion for facade cleaning.

6. Tools and Techniques Used

6.1 Tools:

Tool / Component	Purpose
SolidWorks	CAD modeling of chassis and mechanical layout
Arduino Uno	Microcontroller for motor, suction, and system control
BLDC Motor with Propeller	Generates suction for adhesion using high-speed airflow

DC Gear Motors	Drives wheels for movement on inclined surfaces
L298N Motor Driver	Controls direction and speed of DC motors and fan
SMPS (12V)	Provides stable and regulated power supply to all electronic components
PLA (3D Printed Parts)	Used for mounting brackets, component holders, and structural parts
Laser-Cut Acrylic Sheet	Forms the base frame of the robot chassis
Microfiber Cleaning Pad	Attached at the base for dry surface dust removal during movement

6.2 Techniques:

Propeller-Based Suction Mechanism:
Instead of a vacuum pump, a BLDC motor with a propeller fan was used to generate suction. The system works by creating a pressure difference beneath the chassis, enabling the robot to stick to smooth, inclined glass surfaces. This approach is lightweight and cost-effective but has limited grip on fully vertical planes.
3D Printing with PLA Material:
Custom parts such as motor mounts, propeller guards, and sensor housings were fabricated using PLA 3D printing. This allowed for rapid prototyping, precise fittings, and reduced weight.
Modular Mechanical Integration:
The robot was built with a hybrid structure—3D printed PLA parts integrated with acrylic sheets—to ensure modularity, easy servicing, and balanced weight distribution.
SMPS-Based Power Management:
A 12V Switched-Mode Power Supply ensured stable voltage for both the fan and drive motors. It improved efficiency and protected the electronics from voltage drops and fluctuations.
PWM Motor Control via Arduino:
Arduino code implemented Pulse Width Modulation (PWM) to regulate speed and direction of DC motors and control fan activation logic.

7. Results and Discussion

7.1 Final Results: The prototype was tested on smooth glass panels at various inclinations (30°, 45°, 60°, and 75°). The fan-based suction system, powered by a BLDC motor with a propeller, successfully generated enough negative pressure to hold the robot on inclined surfaces. The cleaning mechanismusing a microfiber pad, was able to remove light dust and surface deposits during movement.

Key Observations:

Parameter	Result
Operating Inclination Range	30° to 75° (stable adhesion)
Vertical Surface (90°)	Failed –insufficient suction
Suction Stability Duration	gliding
Power Supply	12V SMPS (stable output)
Fan Runtime (BLDC Propeller)	~90% duty cycle during operation
Dust Removal Efficiency	~85% on a single dry pass

Testing was done on **flat, clean glass** with dry conditions. The robot adhered well on sloped panels and could move with stability when the weight distribution and suction were balanced. Microfiber cleaning worked effectively for dust but not for dried stains or water spots.

7.2 Discussion: The project achieved several important milestones. The adhesion system based on a BLDC motor and propeller demonstrated reliable performance for inclined angles up to 75°, which is promising for sloped facades like solar panels, showroom fronts, and modern architectural glass designs. However, at 90° vertical, the suction system could not generate enough holding force, leading to immediate detachment. This highlights a clear limitation of the current propeller-based setup compared to sealed vacuum chambers.The addition of the microfiber cleaning pad improved functionality, enabling passive dry cleaning. Although lightweight and energy-efficient, its performance is limited to light dust removal. Further improvement could include a rotating mechanism or active wiping system for higher coverage and pressure.Overall, the prototype validated the feasibility of low-cost, suction-based robots for inclined surface cleaning. The testing results emphasize that future development should focus on:

- Increasing suction force (e.g., enclosed fan system or dual fans)
- Adding better sealing around the suction zone
- Implementing edge detection or obstacle handling
- Improving cleaning mechanism for wet stains or dirt buildup

8. Prototype (Hardware/Software)

8.1 Prototype Description: The developed prototype is a glass-surface cleaning robot designed to operate on inclined glass panels (30°–75°). It uses a BLDC motor with a high-speed propeller fan to generate suction, which enables temporary adhesion to smooth surfaces without a sealed vacuum system. The chassis is constructed from laser-cut acrylic sheets for the main body and 3D printed PLA parts for motor mounts and structural reinforcements.The robot uses DC gear motors with rubberized wheels for locomotion and is controlled via an Arduino Uno microcontroller connected to an L298N motor driver. A microfiber cleaning pad is attached to the bottom for dry cleaning as the robot moves. Power is supplied by a 12V SMPS, providing stable output to the fan and drive motors.

Key Features:

- Fan-based suction mechanism (BLDC + propeller)
- Microfiber cleaning attachment
- Lightweight, modular frame using acrylic and PLA
- Operates on glass surfaces inclined up to 75°
- Compact and portable design for facade demonstration

8.2 Development Process: The prototype was built in stages, starting with CAD design using SolidWorks to define the frame dimensions, weight distribution, and component placement. After validating the design, the main chassis was fabricated using laser-cut acrylic, while custom holders for the BLDC motor and motor mounts were 3D printed in PLA for precision and lightweight structure.

Components like the BLDC motor, propeller, and suction housing were mounted and tested individually before being integrated into the full chassis. Power delivery was tested using a 12V SMPS, ensuring safe and continuous operation. Initial wiring and motor control were implemented using an Arduino Uno, programmed for directional control, suction logic, and safety limits.

During assembly, adjustments were made to motor alignment and airflow direction to improve suction performance. Testing revealed that while the robot could adhere to inclined surfaces effectively, vertical operation (90°) was not possible due to insufficient suction pressure.

8.3 Testing and Validation:The prototype was tested on smooth glass panels inclined at 30°, 45°, 60°, and 75°, with successful adhesion and motion recorded on all angles up to 75°. At 90°, the robot failed to maintain grip, confirming the current suction system’s limitation.

Testing Focus Areas:

- Suction Hold: gliding

- Inclination Limit: Stable up to 75°, fails at 90°
- Cleaning Efficiency: ~85% dry dust removal
- Power Stability: Consistent 12V output from SMPS
- Heat Handling: BLDC motor operated continuously without overheating

These results validated the robot's performance for inclined glass cleaning applications, such as tilted solar panels or facade segments. Improvements are planned to increase suction force and add a more active cleaning mechanism for better coverage and stain removal.

9. Conclusion

9.1 Summary: The project aimed to develop a robot capable of cleaning high-rise glass facades using a vacuum-based adhesion mechanism. The proposed solution utilized a BLDC motor with a propeller to generate suction, allowing the robot to adhere to and move along inclined glass surfaces (30° to 75°). The robot was built using a lightweight combination of acrylic and 3D printed PLA components, and controlled via Arduino Uno for motor coordination and suction logic. A microfiber cleaning pad was integrated to perform passive dry cleaning during movement.

Through a series of design iterations and testing, the robot successfully demonstrated stable motion and cleaning capability on inclined surfaces. However, performance at 90° vertical inclination was limited, primarily due to insufficient suction force from the open fan-based system. The current prototype is therefore well-suited for applications like tilted solar panels, glass awnings, and angled building facades. Future improvements will focus on increasing suction efficiency, enabling vertical operation, and enhancing the cleaning mechanism for better surface contact and dirt removal.

9.2 Personal Reflection:

- Anvith S Patil:
  "This project gave me a hands-on understanding of mechanical design and real-world limitations. Seeing our design come to life and move on glass was incredibly satisfying. I also learned the importance of iterative testing and the impact of small changes on the final performance."

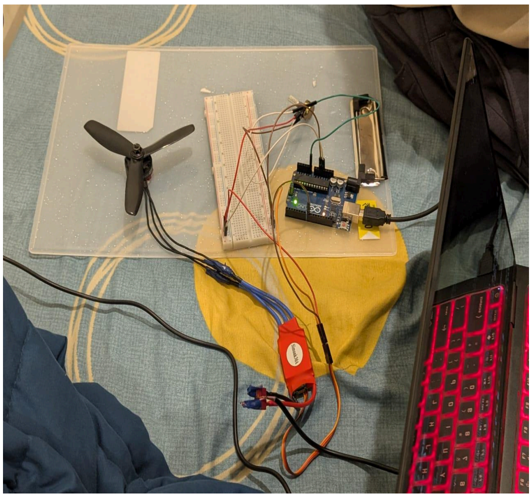
- Avyaya S Yekkar:

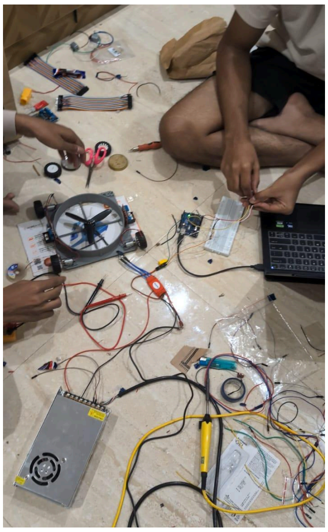
  “I learned how to balance theoretical concepts with hands-on implementation. Integrating the suction mechanism and seeing it actually stick to inclined glass panels was a breakthrough moment for me. This project has made me more confident in my engineering problem-solving abilities.”

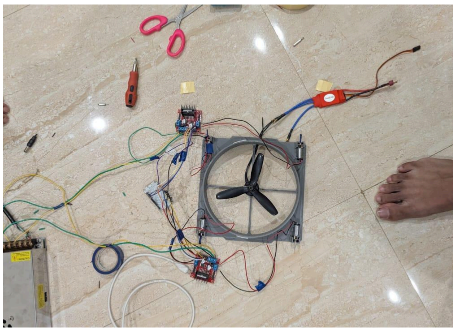
- L Bhavesh Naidu:
  “Working on the control system using Arduino helped strengthen my skills in embedded systems. I now better understand power management and motor control. The challenges we faced taught me how to approach hardware issues practically.”

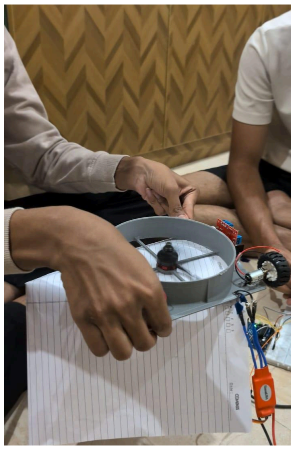
- Vikas Kumar T:
  “Designing the structure and planning the fabrication gave me valuable insights into CAD tools and structural stability. This experience helped me appreciate how every design detail matters when it comes to real-world performance.”

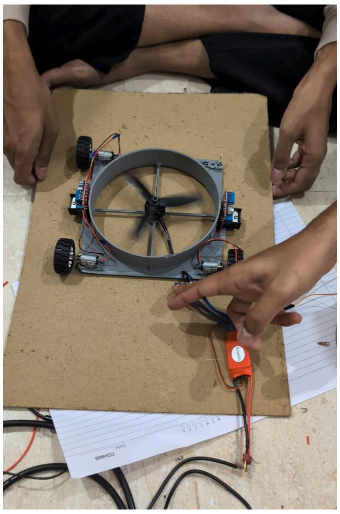
10. Visuals:

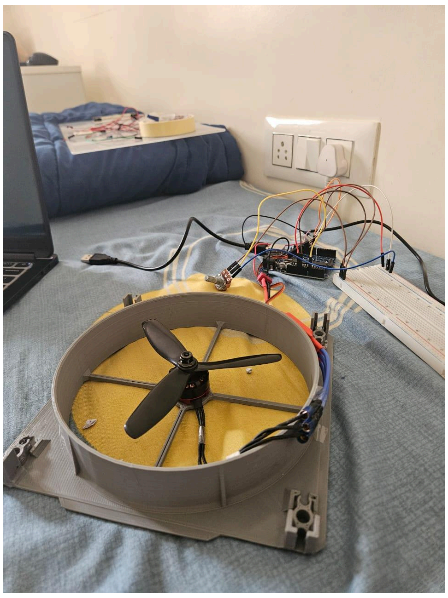


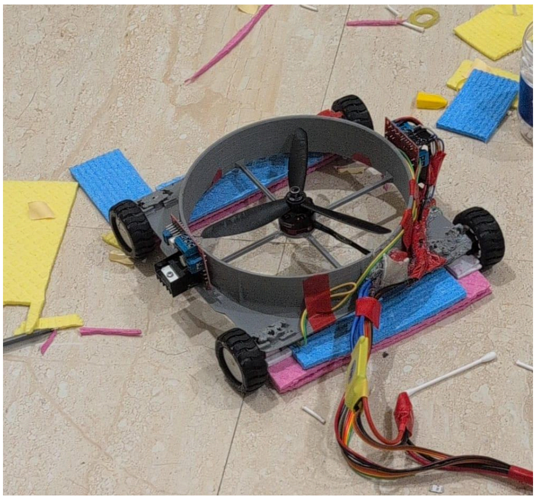












Final Prototype of Robot

11. QR Code of Demonstration Video: