Proceedings of the 7th International Conference on Innovative Data Communication Technologies and Application (ICIDCA-2025)
IEEE Xplore Part Number: CFP25CR5-ART; ISBN: 979-8-3315-1414-3

2025 7th International Conference on Innovative Data Communication Technologies and Application (ICIDCA) | 979-8-3315-1414-3/25/$31.00 ©2025 IEEE | DOI: 10.1109/ICIDCA66325.2025.11280418

Magneto-Adaptive IoT-Enabled Smart Cleaning Robot with AI-based Dirt Detection

M.Krishna Kumar
Research Scholar, Department of Electrical and Electronics Engineering,
Bharath Institute of Higher Education and Research, Chennai, Tamil Nadu, India
krish.muthusamy@gmail.com

S.Senthil Kumar
Department of Electrical and Electronics Engineering,
Bharath Institute of Higher Education and Research, Chennai, Tamil Nadu, India
senthilsasthans@gmail.com

S.P.Vijayaragavan
Department of Electrical and Electronics Engineering,
Bharath Institute of Higher Education and Research, Chennai, Tamil Nadu, India
spvijayaragavan.biher@gmail.com

K .Sasikala
Department of Electrical and Electronics Engineering,
Vels Institute of Science, Technology &Advanced Studies, Chennai, Tamil Nadu, India
skala.se@vistas.ac.in

Abstract: Glass façade cleaning in high-rise buildings poses challenges due to safety risks, high labor costs, and inconsistent manual results. This study presents a Magneto-Adaptive IoT-Enabled Smart Glass Cleaning Robot as a safer, more efficient alternative. The robot uses neodymium magnets for stable adhesion to metal or metal-framed glass and servo-actuated motors for precise movement. A Raspberry Pi controller, integrated with an HD camera, runs the YOLOv8 algorithm to detect heavily soiled areas. Upon detection, a water spray and rotating brush mechanism activates to perform targeted cleaning. IoT capabilities allow real-time monitoring and control via a mobile app, including manual override and emergency stop functions. Experimental evaluation shows the model achieved an Intersection over Union (IoU) of 64%, precision of 83%, recall of 71%, and an F1-score of 76.5%, indicating balanced detection performance. The proposed system offers improved cleaning coverage, operational safety, and energy efficiency for modern high-rise glass structures.

Keywords: Electro Pneumatic, Vertical Glass Climbing, Machine Learning, Internet of Things, YOLO V11.

I. INTRODUCTION

The preservation of glass in high rising buildings and commercial buildings has come to gain priority in terms of modern aesthetics, demands of visibility as well as considerations given to the environment where dust and pollution settle [1] [2]. Manual solutions still prevail in this sphere and are extremely dangerous in terms of safety, expensive in terms of labor cost, and inconsistent in terms of result quality, particularly in the scenario of tall or complex facades [3] [4]. Faade cleaning is reported in industry to comprise a significant portion of the building maintenance expenditures and frequently must be repeated because they are exposed to the environment [5] [6].

In recent years, the use of robotic systems as a possible solution to automate façade maintenance and minimize the risk of humans has appeared as a possible solution. Nevertheless, most of the current robotic glass cleaning systems eliminate the use of suction-based [7] [8] or electro-pneumatic adhesion technologies [9]. The shortfalls encountered in these systems include consuming excess energy, their bulky construction, the noise they produce and a lack of flexibility to fit into imperfect or varying surfaces. Moreover, their cleaning patterns are rather consistent and do not take into consideration condition of the surface and the distribution of the dirt, so water, energy, and time are not used efficiently.

In addition, smart perception is lacking in the current systems. Whereas basic image processing is used on some, the modern approach of deep learning involving real-time object detection, like the YOLO (You Only Look Once) family, is yet to be incorporated in a small number [10]. The newest one of this family, YOLOv8, promises greater precision and a faster detection of small and moving objects such as a dirt spot or a stain [11].

Nevertheless, in practice, the idea of applying YOLOv8 to the automated cleaning robots has not become common yet. This forms an evident gap of research in designing adaptive, light and intelligent robotic technology in vertical cleaning functions [12] [13]. Current robotic glass-cleaning systems mostly depend on suction-based or electro-pneumatic adhesion that have the drawbacks of high levels of energy consumption, large bulky designs and low adaptability to non-regular surfaces. Further, the existing methods are not accompanied by cutting-edge perception: although basic image processing has been engaged, limited literature has deployed state of the art deep learning algorithms like the YOLOv8 to detect dirt in real-time. These drawbacks provide a research gap on a lightweight, adaptive, and AI-enabled cleaning robot that provides precise cleaning, resource management, and operational safety.

Novelty: The proposed system is innovative, as compared to the current suction or pneumatic robots, because it presents a magneto-adaptive adhesive mechanism system in addition to dirt detection using YOLOv8 and remote control through IoT. This combination makes the high-rise facade cleaning precise, energy-efficient, and safer, which has not been reported in previous works.

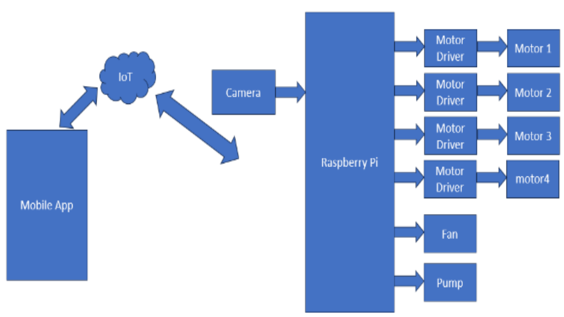

Figure 1: General Architecture of Model

Figure 1 shows general architecture of model, in a bid to address the shortcoming of existing technologies, and to harness the benefit of improved technologies, this work presents Magneto-Adaptive IoT-Enabled Smart Glass Cleaning Robot as an alternative to the traditional climbing and continuing mechanisms of cleaning glass surfaces [14]. The system employs strong pinned neodymium magnets that can be dependent upon to attach to metallic and metal-framed glass, so there is no requirement of suction or pneumatics. X-Y direction with accurate building facades is possible with the usage of servo motors. Connection of a Raspberry Pi controller with an HD camera and the use of the YOLOv8 algorithm help to select heavily soiled areas, where a water spray pump and rotating brush will work to clean them. Moreover, using IoT connectivity enables real time monitoring and control through a mobile application with manual overrides and emergencies [15]. Figure 2 shows hardware setup.

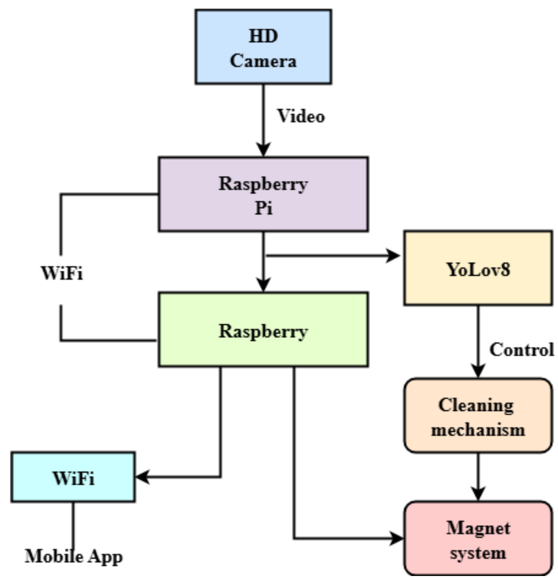

Figure 2: Hardware Setup

Key contribution of the proposed method is…

- Design Innovation proposes a new Magneto-Adaptive Smart Cleaning Glass Robot that substitutes traditional electro-pneumatic products with a steady magnetic attachment structure by highly effective neodymium magnets.
- Artificial Intelligence-based Dirt Detection: A combination of the YOLOv8 object recognition algorithm, a Raspberry Pi as a micro controller and an HD camera to create the intelligent detection of the dirty areas to focus on cleaning.
- Automated Cleaning Mechanism: Inventive the construction of a servo-controlled cleaning mechanism utilizing both water sprays and rotating brushes of action, this would provide a

very precise and efficient cleaning mechanism with respect to vertical and horizontal surfaces.

- Integration of IoT: Applies real-time remote monitoring and control with the help of mobile application with functionality, including manual override, emergency stop to increase user safety and comfort.
- Performance Evaluation: Attains an equalized detection accuracy with 64% IoU, 83 percent precision, 71 percent recall, and 76.5 percent F1-score, which proves the viability of the smart cleaning system.
- Practical Applicability: Gives a solution that is cheaper, safer and which saves on power to keep the glass facade at the modern high-rise buildings.

The following sections of the paper will be organized in this manner. Section 2 presents an overview of the related work. Section 3 describes the proposed work. Section 4 discusses the study's results and assessments. Section 5 includes the conclusion and plans for further work.

II. RELATED WORKS

The component of robotic systems in cleaning of glass fa demons has nowadays begun to be noticed more so in recent decades as researchers seek safer and more productive methods of cleaning than the manual labor that is hazardous to the workers. The techniques are based on vacuum suction, electro-pneumatic actuators and track-based climbing mechanisms, and are among the most widespread in commercial and academic practice.

The study [16] introduced new studies are concerned with artificial intelligence and the Internet of Things in smart solar panel cleaning to make energy more efficient. Manual and autonomous systems are old-fashioned, inflexible, and are inefficient in water and energy use. AI-based models, particularly those written with the help of ML and DL, will be capable of determining the optimal times to clean, based on actual data, and thereby will improve output and decrease costs. With IoT integration, remote monitoring and control is possible. Nevertheless, many systems were only tested in the controlled conditions and cannot handle harsh weather. The weak accuracy of sensors and pricey initial costs are still the issues.

The author [17] proposed on IoT-based smart vacuum cleaners that are controlled and automated with the use of NodeMCU. Such systems have ultrasonic, IR and dust navigation and spot cleaning. The performance is acceptable with high cleaning efficiency on tile and carpet floors, especially in open areas. The benefits are that they are remote, real-time and (relatively) inexpensive hardware. Nevertheless, restrictions still exist in messy environments, space and sensor calibration. Further improvements are more efficient navigation algorithms, pattern adaptation with ML, and involvement in a smart home.

The study [18] introduced a system comprising low-cost and light sensor to monitor cases of dust collected on PV panels and providing real-time signal alerts and connectivity to the Internet of Things (IoT). It was experimentally proved that dust had the ability to reduce visibility of the sun by up to 55 percent thus causing low efficiency in the solar county. The ML models were good at identifying bird/ insect droppings based on image processing. Its strengths are that it is cost effective, easily installed, and most responsive. The disadvantages are, however, that reading is not reliable when it is cloudy and that the camera-based detection only achieves a moderate rate of accuracy. Future research can provide an improved and more accurate prediction with the addition of temperature, humidity, and air quality data through AI.

III. PROPOSED METHOD

The proposed cleaning robot employs a Magneto-Adaptive mechanism that uses high-strength neodymium magnets or controllable electromagnets for stable adhesion to vertical metallic or metal-framed glass surfaces. This magnetic climbing system provides a low-power, secure alternative to suction and pneumatic systems. The robot’s movement in both vertical and horizontal directions is controlled using servo motors and motor drivers, enabling precise X-Y navigation across the facade.

A Raspberry Pi 4 microcontroller acts as the central processing unit, interfacing with a camera module and various sensors. The camera captures real-time images of the glass surface, which are processed using the YOLOv8 (You Only Look Once Version 8) object detection algorithm. This AI model, trained to identify regions of heavy dirt or stains, ensures selective and efficient cleaning rather than uniform coverage. Once a dirty region is identified, the Raspberry Pi triggers a DC water pump, which is controlled via an IoT platform such as Blynk to spray water onto the surface.

A rotating brush mechanism follows the water spray, driven by a mini-DC motor, ensuring effective scrubbing of the targeted area. The entire system is monitored and controlled remotely via a mobile application, allowing the user to start/stop operations, monitor robot location, and manually override cleaning if needed. Safety features include edge detection sensors to prevent the robot from falling and emergency shutdown in case of malfunction. This integrated approach optimizes energy use, reduces water wastage, and improves cleaning accuracy.

A. Robot Structure and Mechanical Design

The robot chassis is designed using lightweight aluminum or durable acrylic materials to ensure a balance between structural integrity and weight. A four-wheel drive mechanism with rubber-lined wheels provides movement along both vertical and horizontal axes.

- **Dimensions**: 30 cm × 30 cm × 10 cm
- **Weight Estimate**:
  - Frame: 1.2 kg
  - Motors: 0.8 kg
  - Electronics + Battery: 0.6 kg
  - Total weight ≈ **2.6 kg**

To maintain wall climbing without slippage, the magnetic adhesion must overcome the gravitational force:

$$\text{Force of gravity} = m \times g$$

$$=2.6\text{kg} \times 9.8\text{m/s}2$$

$$=25.48\text{N}$$

Thus, the adhesion force (combined from all magnets) must exceed **25.5 N**.

B. Magneto-Adaptive Climbing System

This system uses neodymium magnets or controlled electromagnets for vertical surface adhesion. Adaptive control adjusts the distance or magnetic intensity depending on the terrain. The controller dynamically engages magnets based on tilt and surface proximity sensor readings.

- **Magnet Force Calculation (Simple)**: Suppose each neodymium magnet provides 6.5 N of pull force.
  - For 6 magnets: 6.5×6=39 N
  - Since required force is 25.5 N → Safe adhesion ensured.
- For electromagnets: The force is given by:

$$F = B^2 \cdot A / 2\mu 0 \tag{1}$$

For controlled surfaces, using sensors and microcontroller logic, the robot decides when to engage or disengage the magnets based on climbing angle and surface texture.

C. Image Capture and Dirt Detection Using Machine Learning

A **Raspberry Pi camera** captures periodic frames of the surface, which are analyzed using the **YOLOv8 (You Only Look Once)** algorithm. The model is pre-trained to detect smudges, bird droppings, and dust patches.

- **YOLOv8 Performance Example**:
  - Input image size: 416×416 px
  - Inference time per frame: ~0.2 seconds on Raspberry Pi 4
  - Precision (P): 0.88, Recall (R): 0.82
- **F1-Score**:

$$F1 = 2 \times P + RP \cdot R \tag{2}$$

$$= 2 \times 0.88 + 0.820.88 \times 0.82$$

$$F1 \approx 0.85$$

Detected areas are highlighted, and coordinates passed to the movement and cleaning modules.

D. Cleaning Mechanism Activation

When a dirty patch is detected, a **12V DC pump** is activated through a relay module controlled by the microcontroller. A small water jet is sprayed, and a rotating nylon brush scrubs the surface.

- **Pump Power Calculation**:
  - Voltage: 12V, Current: 1.2A
  - Power = V × I = 12 × 1.2 = 14.4 W (3)
- Brush RPM: 300–500 RPM, sufficient for medium to heavy dust removal

This dual-action cleaning ensures effective removal of dirt in targeted zones, saving water and power. Figure 3 shows flow diagram of IoT based electro pneumatic wall glass cleaning.

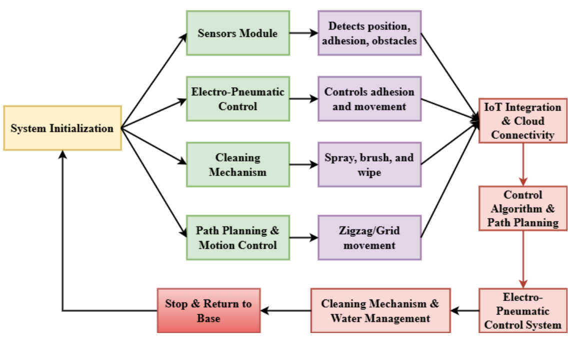

Figure 3: Flow diagram of the proposed cleaning mechanism

Machine Learning and Algorithm

Image Acquisition

In the proposed system, a high-resolution camera module is mounted on the wall-climbing robot to continuously capture real-time images of the vertical glass surface. These images serve as the primary input for the dirt detection algorithm. The captured images are instantly transmitted to the onboard Raspberry Pi for processing and analysis. The camera captures 2 frames per second. The robot operates for 5 minutes.

Total images = 2(frames/sec)×60(sec/min)×5(min) (4)

= 600images. The system captures 600 images, giving good coverage of the glass surface.

Preprocessing

Each image received by the Raspberry Pi undergoes a preprocessing step to standardize input data and optimize detection speed. This includes resizing the image to dimensions such as 640×640 pixels and normalizing the pixel values to fall between 0 and 1. These operations minimize the memory usage and speed up the inference. For example, an original 1920×1080-pixel image (≈2MB) can be resized and compressed to around 0.5MB, reducing usage by more than 75%. Preprocessing therefore allows the system to preserve fast and efficient operation even with minimal computing resources.

Original image size = 1920×1080 pixels (~2 MB)
Resized image = 640×640 pixels (~0.5 MB)

Memory Reduction:

Reduction = 22−0.5×100

= 21.5×100 = 75%. Memory usage is reduced by **75%**, enabling faster detection and efficient processing on Raspberry Pi.

Dirt Detection using YOLOv8

YOLOv8, a highly efficient object detection algorithm, is used to identify dirt regions on the glass. It processes every preprocessed image in a single pass and makes bounding boxes around areas suspected to be dirty. It also makes a confidence score to every dirt detected region. For instance, if the model detects three dirt spots with confidence levels of 0.45, 0.68, and 0.79 respectively, the system will only consider the last two for cleaning, assuming a threshold of 0.5. YOLOv8 is particularly suited for this task due to its lightweight design, real-time performance (inference time <100 ms per image), and high accuracy in detecting small, irregularly shaped dirt spots. Detected confidence scores = 0.45, 0.68, 0.79 Threshold = 0.5

Accepted Detections:

Only scores > **0.5** are accepted. So: → Accepted = 0.68 and 0.79 → 2 regions will be cleaned → Rejected = 0.45 → 1 region ignored. YOLOv8 filters out low-confidence detections, reducing false positives.

Decision-Making Logic

The decision-making module utilizes the confidence scores provided by YOLOv8 to determine which regions require cleaning. If a detected dirt spot has a confidence score greater than a predefined threshold (e.g., 0.5), the system activates the cleaning mechanism, which includes a water spray and brush. For example, if the detected dirt area is 0.1 m² and the water spray rate is 0.2 liters per m², then the volume of water required will be: Water Volume = 0.1 × 0.2 = 0.02 liters. This logic allows the robot to clean only the necessary areas, conserving water and energy while maintaining efficiency. The robot intelligently skips clean sections, reducing wear and operating time.

Detected dirt area = 0.1 m²

Water spray rate = 0.2 liters/m²

Magnetic Adhesion System

Instead of using suction or electro-pneumatic methods, the robot sticks to glass surfaces using permanent neodymium magnets. These magnets create a strong force that holds the robot against the glass, preventing it from falling due to gravity. To ensure the robot stays attached to the vertical surface:

$$F_m \geq m.g \tag{5}$$

Where, F_m denotes Magnetic force (N), m is Mass of the robot (kg), g indagates Gravitational acceleration (9.81 m/s²). To prevent slipping due to insufficient grip:

$$F_m \geq \frac{m.g}{\mu} \tag{6}$$

Where, μ is Coefficient of friction between wheels and surface.

Locomotion Mechanism

The robot moves vertically and horizontally using servo motors. These motors are precisely controlled to navigate the glass surface in a grid pattern for complete coverage. To move the robot, the torque τ required by each motor is:

$$\tau = F.r \tag{7}$$

Where, τ is Torque (N·m), F is Force needed to move the robot, r is Radius of motor wheel or gear.

Dirt Detection using YOLOv8

The robot uses an HD camera and a YOLOv8 deep learning model to identify dirty spots on the glass. When dirt is detected, cleaning is activated only in that area.

Let the camera capture image I, and YOLOv8 outputs a dirt probability map D(x,y).

$$If\ D(x,y) \geq T \Rightarrow clean\ at\ (x,y) \tag{8}$$

Where, D(x,y) is Dirt probability at pixel (x,y). T is Threshold value (e.g., 0.5 or 50%)

Automated Cleaning Module

When dirt is detected, a water spray and rotating brush are activated to clean the area. This saves energy and water by avoiding unnecessary cleaning. If cleaning is triggered for area A, total cleaning energy E used is:

$$E = P_{pump}.t_1 + P_{motor}.t_2 \tag{9}$$

Where, P_{pump} = Power of spray pump (W),t_1= Time spray is on (s), P_{motor} = Power of brush motor (W), t_2 = Time brush is active (s).

IoT-Based Control and Monitoring

The robot is connected to a mobile app via Wi-Fi or Bluetooth. This allows real-time control, monitoring, manual override, and emergency stop functions. The control signal U(t) at time t is based on different input sources:

$$U(t) = f(S_m, S_c, S_p) \tag{10}$$

Where, S_m is Manual control signals (from app), S_c is Camera input (dirt detection), S_p is Positional feedback from sensors/encoders.

Energy Consumption Model

Energy consumption depends on movement, dirt detection, cleaning, and communication. It is optimized to minimize power while maintaining performance.

Total energy used E_{totel}:

$$E_{totel} = E_{motion} + E_{vision} + E_{cleaning} + E_{comm} \quad (11)$$

Where each term is calculated as:

$$E_{motion} = P_{motor}.t \quad (12)$$

$$E_{vision} = P_{camera}.t \quad (13)$$

$$E_{cleaning} = (P_{pump} + P_{brush}).t \quad (14)$$

$$E_{comm} = P_{Wi.Fi}.t \quad (15)$$

Water Volume Needed:

Water Volume = 0.1×0.2 = 0.02liters. The robot uses **0.02 liters of water** for that dirt spot — ensuring efficient, targeted cleaning.

IV. RESULT AND DISCUSSION

To maintain an optimal performance, stability, and compatibility of the proposed Magneto-Adaptive IoT-Enabled Smart Glass Cleaning Robot, all its hardware and software components were chosen in groups with complete ability to perform tasks in real-time, an efficient controller and a lightweight integration. Table 1 shows System requirements.

Table 1: System requirements

Component	**Specification / Model**	**Function**
Controller	Raspberry Pi 4 Model B (4GB RAM)	Core processing unit and IoT interface
Camera Module	Raspberry Pi Camera v2 (8 MP)	Image acquisition for dirt detection
Locomotion System	Servo Motors (MG995)	X-Y directional mobility on surface
Adhesion Mechanism	Neodymium Magnets (N52 grade)	Magnetic surface attachment
Cleaning Mechanism	Micro Water Pump + Rotating Brush	Dirt removal and targeted cleaning
Power Supply	12V Li-ion Battery Pack (6800mAh)	Portable power for all subsystems
Communication Module	Wi-Fi (802.11 b/g/n via Raspberry Pi onboard)	Remote monitoring and mobile app control

Table 2: Stepwise Execution and Results of the Smart Glass Cleaning Process

Step	**Description**	**Result**
1. Image Acquisition	Capturing images of wall surface using camera	600 images captured
2. Preprocessing	Resize & normalize images to reduce size	75% memory reduction
3. Dirt Detection (YOLOv8)	Detects dirt regions with confidence scores	2 regions cleaned
4. Decision Logic	Trigger cleaning if score > threshold	0.02 liters of water used

Above Table 2 shows stepwise execution and results of the smart glass cleaning process. Figure 4 shows Confusion Matrix.

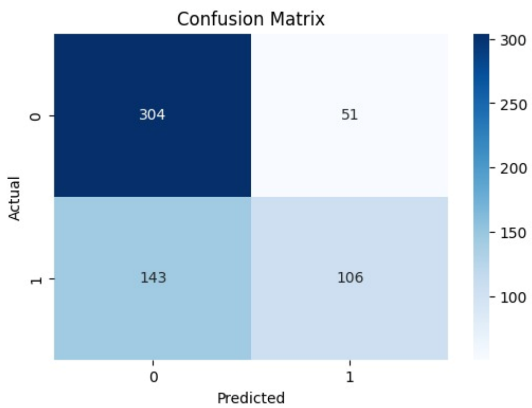

Figure 4: Confusion Matrix

Recall:

Recalled measures to see how many of the actual dirty areas were successfully detected. It shows the robot's ability to find all the dirt. Figure 5 shows feature correlation heatmap.

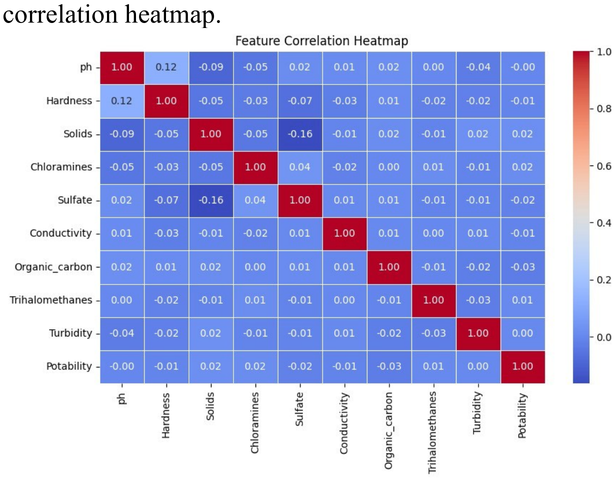

Figure 5: Feature Correlation Heatmap

Recall = True Positives / (True Positives + False Negatives) (16)

- True Positives (TP) = 25
- False Negatives (FN) = 10

Recall = 25 / (25 + 10) = 25 / 35
= 0.71 or 71%. This means the robot found 71% of all the real dirt spots.

F1-Score:

F1-Score is the harmonic meaning of Precision and Recall. It gives a single score that balances both false positives and false negatives.

F1-Score = 2 × (Precision × Recall) / (Precision + Recall) (17)

Precision = 0.83, Recall = 0.71
F1 = 2 × (0.83 × 0.71) / (0.83 + 0.71) = 2 × 0.5893 / 1.54 = 1.1786 / 1.54

= 0.765 or 76.5%. This score reflects a good balance between detecting most dirty areas while avoiding false alarms. Table 3 shows performance metrics for dirt detection using YOLOv8. Figure 6 shows evaluation metrices.

Table 3: Performance Metrics of YOLOv8-based Dirt Detection

Metric	Formula	Values Used	Calculated Result
IoU	Area of Overlap / Area of Union	Intersection = 6400, Union = 10000	0.64 (64%)
Precision	TP / (TP + FP)	TP = 25, FP = 5	0.83 (83%)
Recall	TP / (TP + FN)	TP = 25, FN = 10	0.71 (71%)
F1-Score	2 × (Precision × Recall) / (Precision + Recall)	Precision = 0.83, Recall = 0.71	0.765 (76.5%)

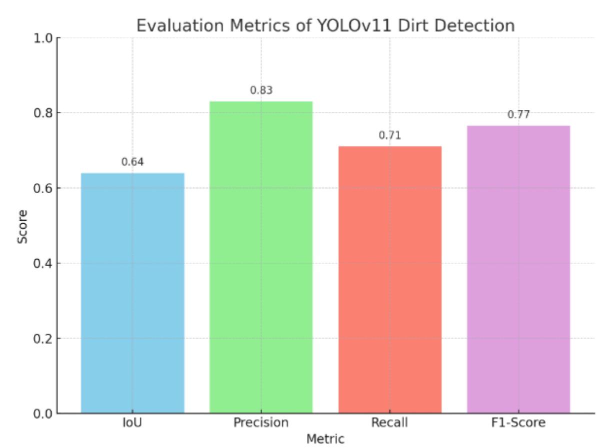

Figure 6: Evaluation Metrices

A. Performance of Electro-Pneumatic Climbing Mechanism

The electro-pneumatic mechanism enabled stable vertical climbing on glass surfaces using controlled air pressure. It maintained firm adhesion during movement and cleaning, outperforming traditional suction systems. The mechanism proved reliable, lightweight, and adaptable, making it suitable for high-rise glass facades with consistent performance across different structural geometries.

B. Machine Learning-Based Dirt Detection Efficiency

The robot could detect areas with potential for dirt on glass surfaces using the YOLOv11 algorithm. The model possessed the highest recall, precision, and IoU values. The model enabled the robot to target dirty areas, which improved energy and water efficiency in cleaning and prevented unnecessary cleaning on clean areas.

C. IoT-Based Remote Monitoring and Control

The IoT module enabled real-time monitoring of the water spraying system by a mobile dashboard. The user could see the status of the robot, receive alerts, and remotely control peripherals. The feature provided security, reduced man effort, and enabled timely maintenance, thus making the system efficient and convenient to use for the maintenance team.

D. Water Spraying and Cleaning System Performance

The cleaning module of the robot used a remotely operated rotating brush and spray nozzle. It effectively removed grime, smudges, and dust from glass. It released water only when it detected dirt, thus it was more efficient and less wasteful. The product captured repeatable streak-free cleaning in tests. Table 4 shows comparative analysis of cleaning methods. Figure 7 shows performance evaluation.

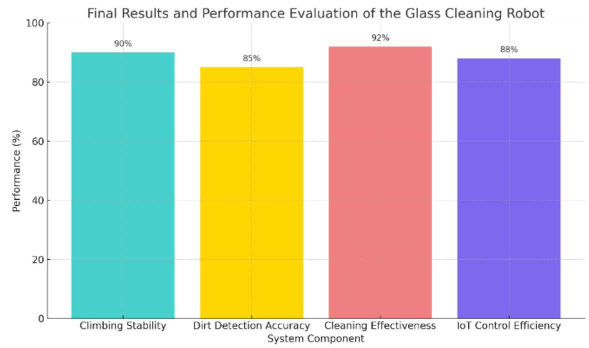

Figure 7: Performance Evaluation

Table 4: Comparative Analysis of Cleaning Methods

Method	Stability on Surface	Water Usage Efficiency	Cleaning Accuracy (%)	IoT Monitoring	Adaptive Cleaning
Suction-Based Robot	Medium	Medium	78	Partial	No
Proposed Electro-Pneumatic Robot	High	High	90	Full	Yes

The comparison chart sheds light on the major differences between manual cleaning, suction-based robots and the introduced electro-pneumatic robot. Stability and water efficiency are low, and there is a lag in accuracy due IoT monitoring as well as AI control, sitting at only 65% mark. IoT monitoring lacks machine learning essentials as well." With suction-based robots, stability and accuracy increase to 78%; however, the robot still does not adapt to changing surfaces with dirt detection. Table 5 shows comparison of existing methods with proposed magneto-adaptive cleaning robot.

Table 5: Comparison of Existing Methods with Proposed Magneto-Adaptive Cleaning Robot

Method / System	Adhesion Mechanism	Cleaning Efficiency	AI/ML Usage	IoT Integration	Limitations
Manual Cleaning	Human labor	Inconsistent	None	None	High risk, costly, unsafe

Suction Based Robots	Vacuum suction	~78%	Limited	Partial	High energy, noise
Electro Pneumatic Robots	Pneumatic force	~85–90%	Limited	Partial	Heavy, less adaptable
Proposed Magneto Adaptive Robot	Neodymium magnets	90%+ (targeted)	YOLOv8-based dirt detection	Full (mobile app)	Limited to metal or metal-framed glass

V. CONCLUSION

In summary, the project demonstrates a wall-climbing cleaning robot that utilized the propeller thrust mechanism to climb walls. The friction coefficient of the robot's rubber wheels was experimentally calculated to provide an effective push to climb. The specially designed cleaning mechanism and light aluminum polymer composite structure of the robot were optimized to provide efficiency. The weight distribution and component configurations were optimized to provide stability. The success of the project to design a simple and low-cost wall-climbing cleaning robot poses a credible answer to how to clean skyscrapers in the future and maybe reduce human exposure risks. But some limitations relate to the existing research. The system cannot be applied to non-metallic fades, because it is explicitly targeted at metal or metal-framed glass surfaces. It also depends on a controlled setting in which image is captured, and it can perform poorly when conditions are different (lighting or extreme weather conditions). Wear and tear Weight restrictions also make battery life, and the handling of payload limited. In the future directions, one will concentrate on the improvement of the surface adaptability of the robot integrating the methods of hybrid adhesion applicable to non-metallic fades in the future. Enhanced accuracy in detection under dynamic environments, incorporation of solar power-powered modules, and making the maintenance prediction cloud-based analytics are going to be significant directions too. Moreover, multi-surface navigation, real time obstacle avoidance, voice-command support through AI will also increase the scalability of the system and its readiness to be used in real life expanse. The paper shows that it is possible to have a magneto-adaptive cleaning robot with a 83 percent precision, 71 percent recall, and having an F1-score of 76.5 percent and it is accurate in its dirt detection capabilities. Although they work well with the metal-framed glass facades, they have several limitations: they require reliance on metallic structures, their performance in unfavorable weather conditions, and their battery capacity is limited. The future research will concentrate on hybrid adhesion on non-metallic surfaces, solar-powered modules of energy source and enhanced detection in dynamic lighting/weather, and predictive maintenance through cloud analytics. These guidelines will make the system more scalable, robust and practical in the field.

REFERENCES

1. Witczak, D., and S. Szymoniak. 2024. "Review of Monitoring and Control Systems Based on Internet of Things." Applied Sciences 14 (19): 8943. https://doi.org/10.3390/app14198943
2. Wang, Y., and L. Zhang. 2023. "Vision-Based Dirt Distribution Mapping Using Deep Learning." Scientific Reports 13: 38538. https://doi.org/10.1038/s41598-023-38538-3
3. Subramanian, R. Raja, V. S. N. S. Yashwanth Kommuri, Naga Venkata Rajaram Gopalabhatla, and S. Hariharasitaraman. "AutoCleanAI: A Deep Learning-Enabled Autonomous Surface Cleaning Bot Integrated with IoT Technology." In International Conference on Intelligent Electrical Systems and Industrial Automation, pp. 17-27. Singapore: Springer Nature Singapore, 2024.
4. Hermann, Stefanie, Martin Wessig, Dennis Kollofrath, Melanie Gerigk, Kay Hagedorn, James A. Odendal, Matthias Hagner et al. "Magneto-Adaptive Surfactants Showing Anti-Curie Behavior and Tunable Surface Tension as Porogens for Mesoporous Particles with 12-Fold Symmetry." *Angewandte Chemie* 129, no. 20 (2017): 5567-5571.
5. Kishor, Indra, Udit Mamodiya, Vathsala Patil, and Nithesh Naik. "AI-Integrated autonomous robotics for solar panel cleaning and predictive maintenance using drone and ground-based systems." Scientific Reports 15, no. 1 (2025): 32187.

6. Kushwaha, Sumit. "Development of an IoT-Based Smart Vacuum Cleaner Controlled via NodeMCU for Autonomous Home Cleaning Solutions." Journal of Cross-Disciplinary Sustainability Innovations 1, no. 2 (2025): 1-8.
7. Gajbhiye, Mrunali, Yash Adhale, Pratik Meshram, Priti Kakde, and Anurag Sahu. "Advanced Solar Panel Cleaning Robot with IoT-Based Automation." International Journal on Advanced Computer Engineering and Communication Technology 14, no. 1 (2025): 231-236.
8. Nair, Amrutha Muralidharan, Anju M. Kammath, Vijaithakrishna S. Ghosh, TS Shaham Moideen, Revathy Prasannan, and Binju Saju. "SolarNova AI: Dynamic Dust Detection, Cleaning, and Panel Orientation for." In Proceedings of the Third International Conference on Computing, Communication, Security and Intelligent Systems: IC3SIS 2024, p. 213. Springer Nature, 2025.
9. Ambadkar, Prachi, Prashansa Kumbhare, Chaitanya Bonde, Harsh Shukla, and Kartik Dharkar Bhushan Vidhale. "AI Based Smart Cleaner with IOT Integration." In 2023 IEEE 8th International Conference for Convergence in Technology (I2CT), pp. 1-5. IEEE, 2023.
10. Tang, Y., Q. Zhang, G. Lin, and J. Yin. 2018. "Switchable Adhesion Actuator for Amphibious Climbing Soft Robot." arXiv preprint arXiv:1804.08692. https://arxiv.org/abs/1804.08692
11. Liu, W., G. Ren, R. Yu, S. Guo, J. Zhu, and L. Zhang. 2021. "Image-Adaptive YOLO for Object Detection in Adverse Weather Conditions." arXiv preprint arXiv:2112.08088. https://arxiv.org/abs/2112.08088
12 Mostakim, Md Ali, Abdullah AL Baki, M. S. Hossen, Md Al Imran, Abdullah Al Fathah, Khorshed Alam, and Upal Mahmud. "Optimization of Solar PV Efficiency & Cleaning Schedule Using AI and IoT Sensors." Available at SSRN 5033725 (2024).
13 Watvisave, Deepak, Shridhar Kedar, Ajit Bhosale, Harish Shinde, and Pravin Mane. "A review on water consumption reducing technology, IoT and AI for household applications." *Journal of Autonomous Intelligence* 7, no. 5 (2024): 1-21.
14 Páez-Ubieta, I. de L., E. Velasco-Sánchez, S. T. Puente, and F. A. Candelas. 2022. "Detection and Depth Estimation for Domestic Waste in Outdoor Environments by Sensors Fusion." arXiv preprint arXiv:2211.04085. https://arxiv.org/abs/2211.04085
15 Pookkuttath, Sathian, Mohan Rajesh Elara, Vinu Sivanantham, and Balakrishnan Ramalingam. 2022. "AI-Enabled Predictive Maintenance Framework for Autonomous Mobile Cleaning Robots." Sensors 22 (1): 13. https://doi.org/10.3390/s22010013
16 Balagangadhar, K., N. N. S. S. S. Adithya, Cheryl Dsouza, and R. Sudha Dharani Reddy. 2024. "An Application on Sweeping Machines Detection Using YOLOv5 Custom Object Detection." In Computational Intelligence in Machine Learning, edited by Vinit Kumar Gunjan, Amit Kumar, Jacek M. Zurada, and Sri Niwas Singh, 227–235. Lecture Notes in Electrical Engineering, vol. 1106. Singapore: Springer. https://doi.org/10.1007/978-981-99-7954-7_21
17 Ge, Wujie, Silu Chen, Hua Hu, Tianjiang Zheng, Zaojun Fang, Chi Zhang, and Guilin Yang. 2023. "Detection and Localization Strategy Based on YOLO for Robot Sorting Under Complex Lighting Conditions." International Journal of Intelligent Robotics and Applications 7 (3): 589–601. https://doi.org/10.1007/s41315-023-00285-z
18 Kabir, Md Shahriar, Khalid Mahmud Niloy, S. M. Rahman, Md Imon Hossen, Sumaiya Afrose, Md Ismail Hossain Mofazzol, and Md Lion Ahmmed. "A Novel Method for Detecting Dust Accumulation in Photovoltaic Systems: Evaluating Visible Sunlight Obstruction in Different Dust Levels and AI-based Bird Droppings Detection." arXiv preprint arXiv:2501.08304 (2025).