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Autonomous Dual-Sided Magnetic Window Cleaning Robot for Skyscraper Maintenance Applications

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Abstract: Window cleaning in tall buildings poses serious dangers and operational hazards. A dual-sided magnetic window cleaning robot that increase efficiency, safety, and usage ability is presented in this study. This apparatus consists of two synchronized units: an inner unit operated by the user from inside the building and an outer unit magnetically coupled to move parallelly. The robot is fitted with neodymium magnets that provide a powerful grip, facilitating smooth cleaning through automated movement. The cleaning mechanism integrates a microfiber pad, a rotating brush, and a cleaning solution dispenser to increase usability. The robot includes anti-fall sensors to ensure secure operation under any weather conditions. Wireless control via a remote or mobile application allows real-time monitoring and user adjustments. There is a reliable mechanism for fixing the equipment and sensors that can automatically stop the operation if hazardous environmental conditions are detected. This project aims to bring a paradigm shift in high-rise window cleaning by significantly reducing manual labour, improving safety, and enhancing operational efficiency. Why settle for less when WindowWhiz offers a smarter, safer, and more effective alternative?
Keywords: Dual sided, magnetic, cleaning robot, neodymium magnets, automated, microfiber pad, rotating brush, anti-fall, reliable mechanism

I. INTRODUCTION

In recent years, robotic systems have increasingly taken over tasks that are hazardous, repetitive, or inefficient for humans. One such application is in the high-risk domain of high-rise window cleaning, which has traditionally been performed by workers using scaffolding, ropes, or aerial lifts. These conventional methods pose significant safety risks and require strenuous physical labour under extreme conditions. According to data from the Occupational Safety and Health Administration (OSHA), over the last decade, 88 incidents related to glass cleaning have been reported, leading to 62 fatalities. A particularly alarming incident occurred in New York City in 2014 when a swing stage failed, leaving two workers dangerously on the 69th floor of the One World Trade Centre. Although the workers were eventually rescued, the event underscored the perils associated with high-rise window cleaning and highlighted the urgent need for safer alternatives.

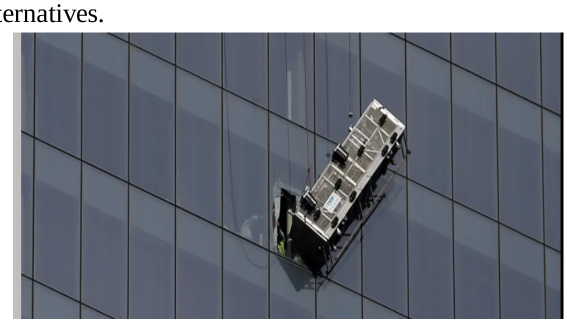

Fig 1: New York emergency crews rescued two workers trapped on a window-washing scaffold dangling

In addition to safety concerns, manual window cleaning is time consuming and inefficient. Studies have shown that human cleaners typically achieve a cleaning rate of only approximately 30 square meters per hour. In contrast, robotic systems have proven capable of dramatically improving these rates. For example, Sky Cleaner 3, a pneumatic climbing robot developed for glass wall cleaning, can clean approximately 125 square meters per hour, while TITO 500, a highly automated cleaning robot, boasts a staggering efficiency of up to 1500 square meters per hour.

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These robots not only outperform human workers in terms of speed, but also offer consistency and precision, which are difficult to achieve through manual methods. Additionally, many of these machines incorporate systems to recover, purify, and reuse water, thereby reducing environmental impact and water consumption.

Several robotic systems have been developed to address the challenges of window cleaning at a height. Sky Cleaner 3, developed by Hirose et al., uses pneumatic suction cups and a climbing mechanism that allows it to scale vertical glass surfaces. It is equipped with obstacle detection and auto-navigation features, enabling autonomous operation on flat high-rise windows. However, its operational complexity and dependency on external air pressure systems makes it more suitable for commercial-scale projects with substantial infrastructure support.

The project recognizes itself as a balanced and adaptable solution. While drawing inspiration from these systems, our robot was designed to be more accessible and economically viable. It uses a lightweight frame made of an aluminium alloy and high-torque motors to ensure safe vertical mobility. Our design incorporates a suction-based adhesion system powered by vacuum pumps, allowing the robot to cling securely to various window surfaces. Unlike large-scale machines, which may require external support systems, our unit is self-contained and easy to deploy in buildings of varying sizes. Moreover, our robot includes IR sensors, ultrasonic sensors, and IMUs (Inertial Measurement Units) for smart navigation. These components help detect the edges of the window pane, prevent accidental drops, and efficiently guide the robot's movement. Additionally, the cleaning mechanism of the robot combines rotating microfiber pads with water mist nozzles to ensure thorough cleaning while minimizing water usage. The water used can be filtered and reused within the system to enhance environmental sustainability. The design was modular and scalable, making it suitable for both commercial and residential buildings.

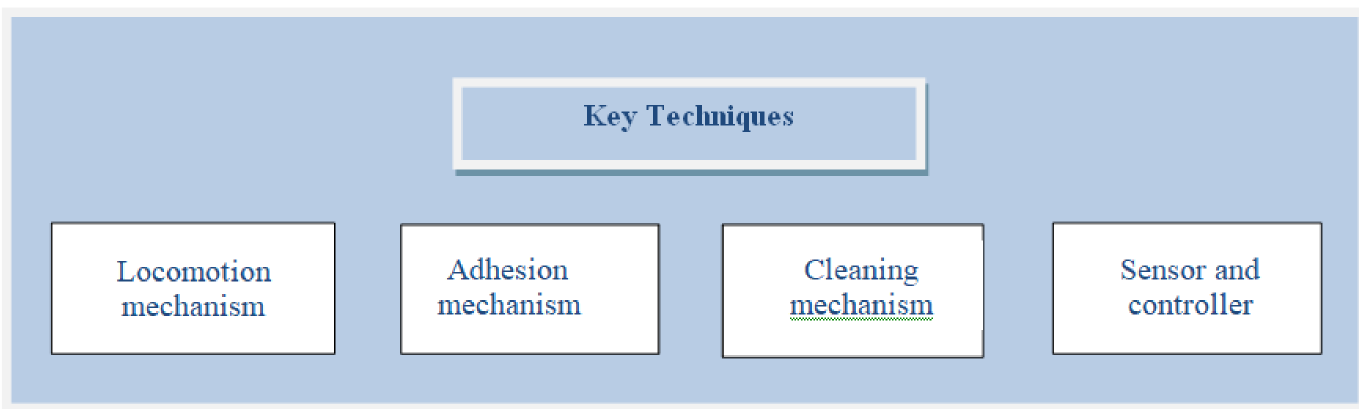

Fig 2: Mechanism of Dual Sided magnetic Window Cleaning Robot.

The working principle of the robot is based on four main subsystems: adhesion, locomotion, navigation, and cleaning. The *adhesion system* employed vacuum suction created by compact vacuum pumps mounted within the body of the robot. This system ensures that the robot remains firmly attached to vertical glass surfaces during operation, even under windy conditions. The *locomotion system* is powered by motorized wheels or tracks that enable the robot to move in both vertical and horizontal directions across the surface. These motors were synchronized to allow for smooth movement without damaging the window surface.

The *navigation system* integrated a set of sensors, including infrared, ultrasonic, and IMU sensors. IR sensors help identify the boundaries of the windows and signal the control system to reverse or turn when the edge is detected. Ultrasonic sensors assist in obstacle detection and prevent collisions with window frames and other architectural elements. The IMU ensures that the robot maintains its orientation, compensating for slight changes in the angle or tilt as it traverses the surface. The navigation algorithm allowed the robot to cover the entire surface area in a systematic path, thereby ensuring full coverage without redundancy.

The *cleaning system* was based on rotating microfiber rollers combined with a water-mist sprayer. The water was stored in a small onboard tank and sprayed through nozzles before the rollers passed over the glass. After cleaning, a second roller or suction squeegee collected the remaining water. The used water was filtered and collected in a secondary chamber, allowing for partial reuse and waste minimization. This closed-loop system makes the robot not only efficient but also eco-friendly.

Our window-cleaning robot is crafted to offer a practical and secure answer to a persistent issue in the building maintenance sector. While traditional methods involve significant risks and demand extensive labour, contemporary robotic solutions provide improved safety, greater efficiency, and better environmental sustainability. Specifically, our robot aims to merge the advanced capabilities of top models with cost-effectiveness and versatility.

By decreasing dependence on manual labour, reducing water consumption, and accelerating cleaning processes, it marks progress in urban automation and intelligent maintenance. This initiative illustrates how well-designed robotics can significantly address everyday human challenges, turning dangerous tasks into automated, dependable operations.

II. OBJECTIVE

The primary aim is to thoroughly examine and enhance the operational principles of the dual-sided magnetic window cleaning robot for use in high-rise settings. This requires an in-depth study of the magnetic coupling mechanism, with particular attention to the strength of the magnets in relation to window thickness and environmental conditions. User-directed navigation will be improved through sophisticated control algorithms and strong wireless communication, ensuring accurate and dependable movement.

The performance of the automated cleaning system will be made by refining the materials used for brushes, improving the dispensing of cleaning solutions, and increasing the effectiveness of squeegees to achieve streak-free results. To ensure safety, fall prevention mechanisms, such as magnetic sensors and safety tethers, will undergo thorough testing and improvements to avert accidental falls. Additionally, the integration of system components, battery longevity, and overall weight will be optimized for seamless and efficient operation. This comprehensive strategy is designed to develop a window cleaning solution that is safer, more efficient, and dependable.

III. MATERIALS REQUIRED

A. *Structural and Mechanical Components*

1) *Frame & Casing :* ABS Plastic is a durable yet lightweight material used for encasing components. This high-impact thermoplastic is renowned for its superior shock resistance and flexibility. It allows for the creation of custom-designed enclosures that securely house electronic components, provide insulation for electrical parts, resist environmental factors, and possess high impact strength to withstand minor bumps or shocks.
2) *Neodymium Magnets :* These are powerful rare-earth magnets used in the dual-sided magnetic coupling system. One part of the window cleaner is placed on the inside of the glass, while the other is positioned on the outside. The strong magnetic attraction keeps both parts connected through the glass, allowing for synchronized movement for effective cleaning.
3) *Motorized Wheels & Tracks :* Stepper motors with encoders drive wheels or tracks to enable smooth and precise movement across the glass surface. Encoders help monitor position and speed, ensuring accurate navigation and controlled cleaning patterns.
4) *Rotating Brushes & Microfiber Pads :* These are mounted on the cleaning side to remove dirt, dust, and stains. Rotating brushes dislodge debris, while microfiber pads wipe the surface for a streak-free finish. Together, they ensure efficient and thorough cleaning
5) *Cleaning Solution Dispenser & Reservoir* : A compact pump system stores and sprays cleaning liquid onto the glass. The solution helps loosen grime, making it easier for brushes and pads to clean effectively. The reservoir holds the liquid, and the spray is usually controlled automatically or via a button.
6) *Safety Tether:* A high-strength rope or cable attaches the cleaning device to a secure point, such as the window frame. It acts as a fail-safe to prevent the outer unit from falling in case the magnetic coupling weakens or detaches accidentally.

B. *Electronics and Control System*

1) *Microcontroller (ESP32) :* The microcontroller functions as the robot's central processing unit, orchestrating all its activities. The ESP32 is a perfect fit due to its integrated Wi-Fi and Bluetooth features, small form factor, and energy efficiency, making it ideal for embedded systems like this one. The microcontroller's duties include interpreting user instructions, handling sensor data, executing movement sequences, regulating motor speeds, and ensuring the robot operates safely.
2) *Motor Drivers (L298N or TB6612FNG)* : Motor drivers serve as intermediaries between the microcontroller and the motors. Since microcontrollers cannot directly provide the current needed to power motors, these drivers convert low-current control signals into higher-current outputs suitable for motor operation. The L298N motor driver modules manage the robot's motion system, enabling it to move forward, backward, and turn. They also control the rotation of cleaning brushes or rollers, allowing for dynamic and adaptive cleaning actions.
3) *Battery Pack (Rechargeable Li-Ion Battery) :* The battery pack supplies power to the entire robot, including the microcontroller, motors, sensors, and any onboard pumps. A 7.4V or 12V Li-Ion battery is commonly used for its high energy density, rechargeability, and ability to deliver consistent power over long periods.

Efficient power management is essential to ensure the robot completes its cleaning cycle without interruption. The microcontroller can monitor battery levels to issue alerts when recharging is necessary, helping maintain operational reliability and user safety.

4) *Wireless Module (ESP32 or HC-05 Bluetooth) :* For wireless communication, the ESP32's built-in Wi-Fi and Bluetooth eliminate the need for external modules. This allows seamless connectivity with a smartphone or remote-control app, enabling users to control the robot, track its progress, and receive real-time updates. In systems using microcontrollers without built-in wireless capabilities, external modules like the HC-05 Bluetooth are used to establish Bluetooth communication. Wireless connectivity enhances user convenience and allows remote operation without physical interaction with the robot.
5) *Obstacle Sensors (Ultrasonic or IR Sensors) :* Obstacle detection is crucial for smooth and safe navigation. Ultrasonic or infrared (IR) sensors detect objects or edges around the cleaning area, such as window frames or protrusions. These sensors continuously scan the environment and send data to the microcontroller, allowing it to adjust the robot's path and avoid collisions. They play a vital role in ensuring full surface coverage without damaging the robot or the window structure.
6) *Magnetic Strength Sensor (Hall Effect Sensor)* : The Hall effect sensor monitors the magnetic coupling strength between the robot's inner and outer units. This sensor detects the magnetic field intensity and alerts the system if the force weakens beyond a safe threshold. In such cases, the robot can immediately stop operations and notify the user, preventing accidental detachment and fall of the outer unit. It is a critical component of the robot's safety system.
7) *IMU Sensor (Gyroscope/Accelerometer) :* An Inertial Measurement Unit (IMU), typically consisting of a gyroscope and accelerometer, measures orientation, tilt, and movement. It helps maintain stability and balance while the robot navigates vertical or inclined glass surfaces. The IMU data allows the microcontroller to detect abnormal motions or misalignments and make real-time corrections, ensuring smooth operation and preventing slippage or loss of alignment between the two magnetic units.

C. *Embedded Software*

1) *Microcontroller Programming: C++ using Arduino IDE or MicroPython for ESP32 :* The microcontroller acts as the brain of the robot, requiring programming to control all hardware elements and implement control logic. For the ESP32, two common programming choices are C++ through the Arduino Integrated Development Environment (IDE) and MicroPython. C++ provides excellent performance and direct hardware access, making it perfect for tasks that require precise timing, such as motor control and sensor monitoring. The Arduino IDE offers a user-friendly platform with a wealth of libraries and community support. On the other hand, MicroPython makes coding easier and is beneficial for quick development and testing. Both platforms allow developers to create firmware that determines how the robot reacts to user inputs, interacts with sensors, and manages its cleaning operations.
2) *Motor Control Algorithms: PID Control for Precise Movement :* To ensure smooth, stable, and precise movement across glass surfaces, the robot uses a Proportional-Integral-Derivative (PID) control algorithm. PID helps maintain a steady speed and direction, adjusting for external influences like glass friction, motor load, and minor misalignments. By continuously comparing actual motor performance to the desired target, the algorithm modifies power inputs in real-time to reduce errors. This level of accuracy is essential for synchronized movement between the inner and outer magnetic units, especially when cleaning in patterns like zig-zag or circular paths.
3) *Wireless Communication: Bluetooth/Wi-Fi for Remote Control :* Wireless communication is a key feature that allows users to control the robot remotely through a smartphone or computer. The ESP32 microcontroller supports both Bluetooth and Wi-Fi, enabling flexible communication options. Bluetooth is suitable for short-range, low-energy control, while Wi-Fi allows longer-range communication and advanced features like live monitoring, over-the-air updates, or cloud integration. Through a dedicated app or web interface, users can start or stop cleaning, monitor progress, change cleaning modes, receive alerts, and check battery or sensor status in real time, enhancing both convenience and user experience.
4) *Sensor Integration: Data Acquisition and Decision-Making for Safety Mechanisms :* Sensors are critical for enabling the robot to perceive its environment and make intelligent decisions. Data from ultrasonic or IR sensors, Hall effect sensors, IMUs, and temperature/humidity sensors is continuously acquired and processed by the microcontroller. Based on this sensor data, the robot can detect obstacles, monitor magnetic coupling strength, maintain stability, and assess environmental conditions. For example, if an obstacle is detected in the path, the robot can reroute itself; if the magnetic grip weakens, it can stop immediately and send an alert. This integration of real-time data and decision-making logic ensures the robot operates safely and efficiently, reducing the risk of accidents or incomplete cleaning.

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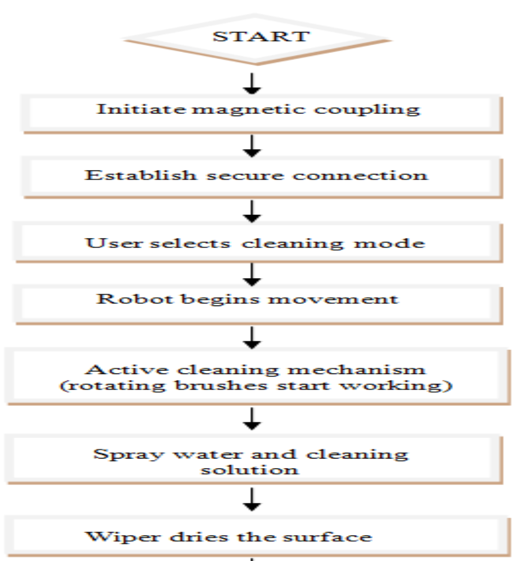
D. Mobile App / Remote Control

1) *App Development: Flutter/Kotlin for Android, Swift for IOS :* The mobile application is the primary control interface for the user, allowing seamless interaction with the window cleaning robot. For app development, Flutter is a powerful cross-platform framework that enables developers to create Android and iOS apps from a single codebase using the Dart language. This approach is efficient for development and maintenance. Alternatively, Kotlin is used for building native Android apps, offering better integration with Android OS features, while Swift is the preferred language for native iOS app development. Depending on the target user base, developers can choose the most suitable platform to build a responsive and reliable control app.
2) *Communication Protocols: MQTT or WebSockets for Real-Time Control :* To enable real-time communication between the mobile app and the robot, lightweight and efficient protocols are essential. MQTT (Message Queuing Telemetry Transport) is a popular choice in IoT systems due to its low bandwidth usage and efficient message delivery, making it ideal for remote operation and data exchange. It works on a publish/subscribe model, which ensures quick response and status updates. WebSockets provide a persistent, full-duplex communication channel over a single TCP connection, enabling continuous, real-time interaction between the app and the robot. These protocols ensure that user commands, such as movement or cleaning mode selection, are instantly transmitted to the robot and that feedback like battery status or alerts is promptly received.
3) *GUI Design: User-Friendly Interface for Monitoring and Navigation :* The Graphical User Interface (GUI) of the mobile app is designed to be intuitive, clean, and user-friendly, ensuring users can easily operate the robot without technical knowledge. It includes features such as on-screen directional controls (forward, backward, left, right), start/stop buttons, and cleaning mode selectors (e.g., linear, spiral). Real-time data such as battery level, magnetic coupling strength, current operation status, and safety alerts are displayed in an easy-to-understand format. Additionally, the app may include notifications or pop-ups for error messages or when the cleaning cycle is complete. A well-designed GUI enhances usability, improves user confidence, and makes remote operation smooth and enjoyable.

IV. WORKING PRINCIPLE

The dual-sided magnetic window cleaning robot functions through a coordinated sequence of actions, ensuring it is efficient, safe, and user-friendly. The process starts with magnetic coupling, where powerful neodymium magnets in both the inner and outer units form a secure connection across the window glass. This setup allows the outer unit to mirror the movements of the inner unit without needing suction or adhesives. Once connected, the user can control the robot via a remote or mobile app, selecting cleaning paths such as linear or circular motions. The inner unit serves as the main controller, transmitting movement instructions to the outer unit, which follows due to the magnetic pull. As the robot navigates, the cleaning mechanism is engaged, utilizing microfiber pads or rotating brushes to remove dirt and dust. A built-in dispenser sprays water and cleaning solution onto the glass, loosening tough grime, while a squeegee or drying blade ensures a streak-free finish. For added safety, the robot includes an anti-fall system, with magnetic sensors constantly checking grip strength. If the magnetic force diminishes, the robot halts immediately and notifies the user.



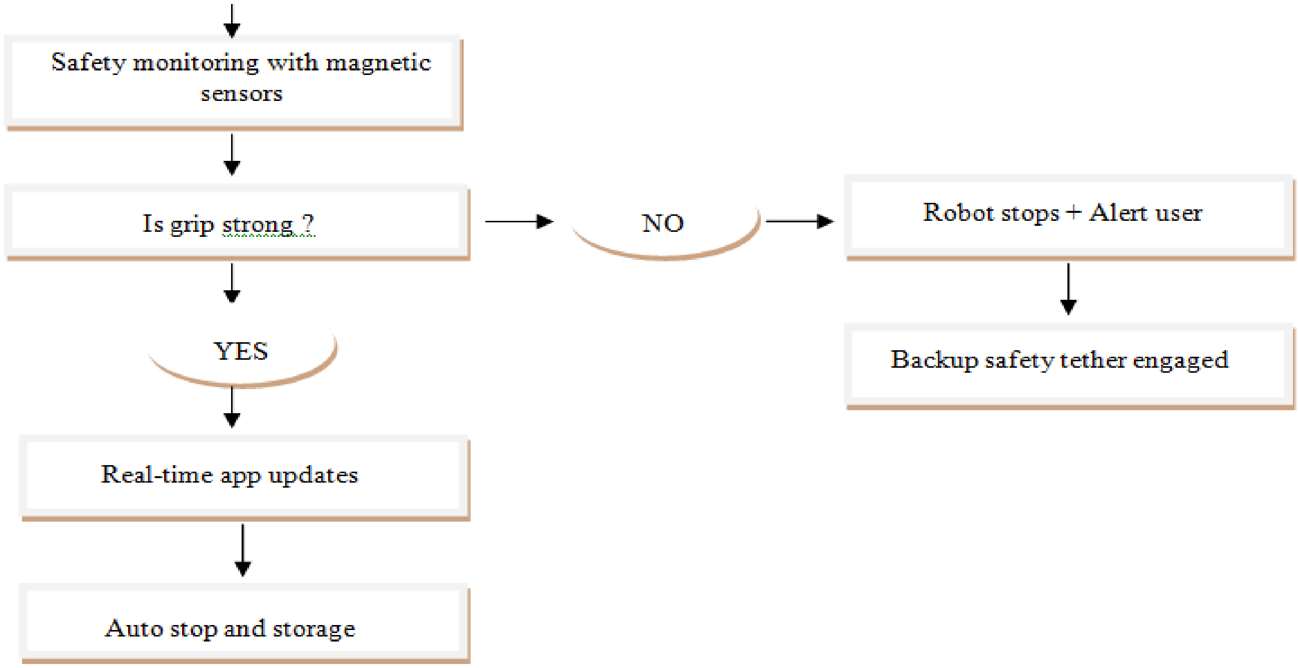


Fig 3: Flow Chart

Additionally, a safety tether provides backup, preventing accidental falls. Throughout the cleaning operation, users receive real-time updates on cleaning progress, battery status, and safety alerts through the mobile app. They can pause, modify settings, or stop the cleaning as needed. Once the cleaning cycle is complete, the robot automatically stops, and the user can detach it for storage. If the battery is low, the system sends an alert, ensuring it is recharged for future use. The above fig 3 is a simple flow chart provided to illustrate the working of the robot for better understanding.

This robotic system removes the risks associated with manual window cleaning, offering a safe, automated, and highly efficient alternative for both residential and commercial high-rise buildings. For the walls with high magnetic permeability, the magnetic adhesion method is usually adopted for the robot. Researchers have applied the magnetic adhesion method for ship welding, oil tank inspection, and other applications [7].Considering that the glass surface is a non-magnetic permeability surface, the magnetic adhesion mechanism cannot directly generate adhesion force. Hence, it is necessary to devise a special design for window-cleaning robots based on magnetic adhesion. For example, the WINDORO window-cleaning robot adopts two magnetic modules, which are placed on the inner and outer sides of the window [11]. The two magnetic modules are programmed for cleaning and navigating, respectively. The performance of WINDORO robot is further improved by replacing the circular magnet with rectangular magnet to increase the magnetic force [8]. Later, Baek et al. added an induction power generation module to the external cleaning unit, which can utilize the magnetic field change between the internal and external modules to generate electricity energy [9]. The generated electric energy can provide the required power to the extra cleaning unit continuously in real-time.

To improve the safety of the robot, the magnetic force between the two cleaning modules needs to be monitored and adjusted to ensure that it will not fall during the movement. Wei et al. designed a magnetic force adjustment module, which can adjust the magnetic force between the two modules according to the thickness of the glass, for ensuring the stability during the movement [12]. Ryu et al. set the range of the magnetic force to ensure a safe work [10]. In particular, the magnetic force can be adjusted by changing the distance between the two modules through the control module. To realize automated operation, Choi et al. used a reducer motor to drive the magnetic gripper and adopted a strain gauge to measure the magnetic force [9]. According to the feedback of the magnetic induction module, the rotation direction of the screw drive motor was automatically controlled to adjust the magnetic force of the robot.

Usually, the magnetic adhesion robot adopts the design of internal and external modules. Hence, it can clean both sides of the window at the same time, which improves the cleaning efficiency. However, for non-magnetic permeability surfaces such as glass, such method exhibits poor barrier-crossing ability. So, it is usually adopted in domestic environments.

V. CONCLUSIONS

The paper highlights the feasibility and innovativeness of a double-sided magnetic window cleaning robot appropriate for high-rise buildings. The robot is equipped with a magnetic coupling mechanism that can tightly adhere to both sides of a glass window so that its internal and external cleaning modules can move at the same time. This offers comprehensive cleaning coverage with significantly minimized risk of conventional manual cleaning. The integration of automated cleaning devices like rotating brushes, squeegees, and spray nozzles enhances the cleaning efficiency, conserves labor, and enables the machine to operate independently or with little manual intervention. Moreover, the integration of heavy-duty safety aspects like fail-safe power devices, emergency rope tethers, and real-time monitoring sensors gives an assured performance under adverse environmental conditions like heavy rains or winds. This robot technology is not only efficient and secure but also cost-effective in the long term, thus an eco-friendly solution in contrast to common high-rise window cleaning technologies that in most instances are human resources, scaffolding, or crane-based. Future research would emphasize performance improvement with AI-driven navigation for optimal path planning and collision avoidance. Autonomous cleaning of brushes and internal parts will also be researched to improve the robot's operational independence and minimize maintenance. These developments will further improve performance, reliability, and scalability for mass commercial use in the building maintenance sector.

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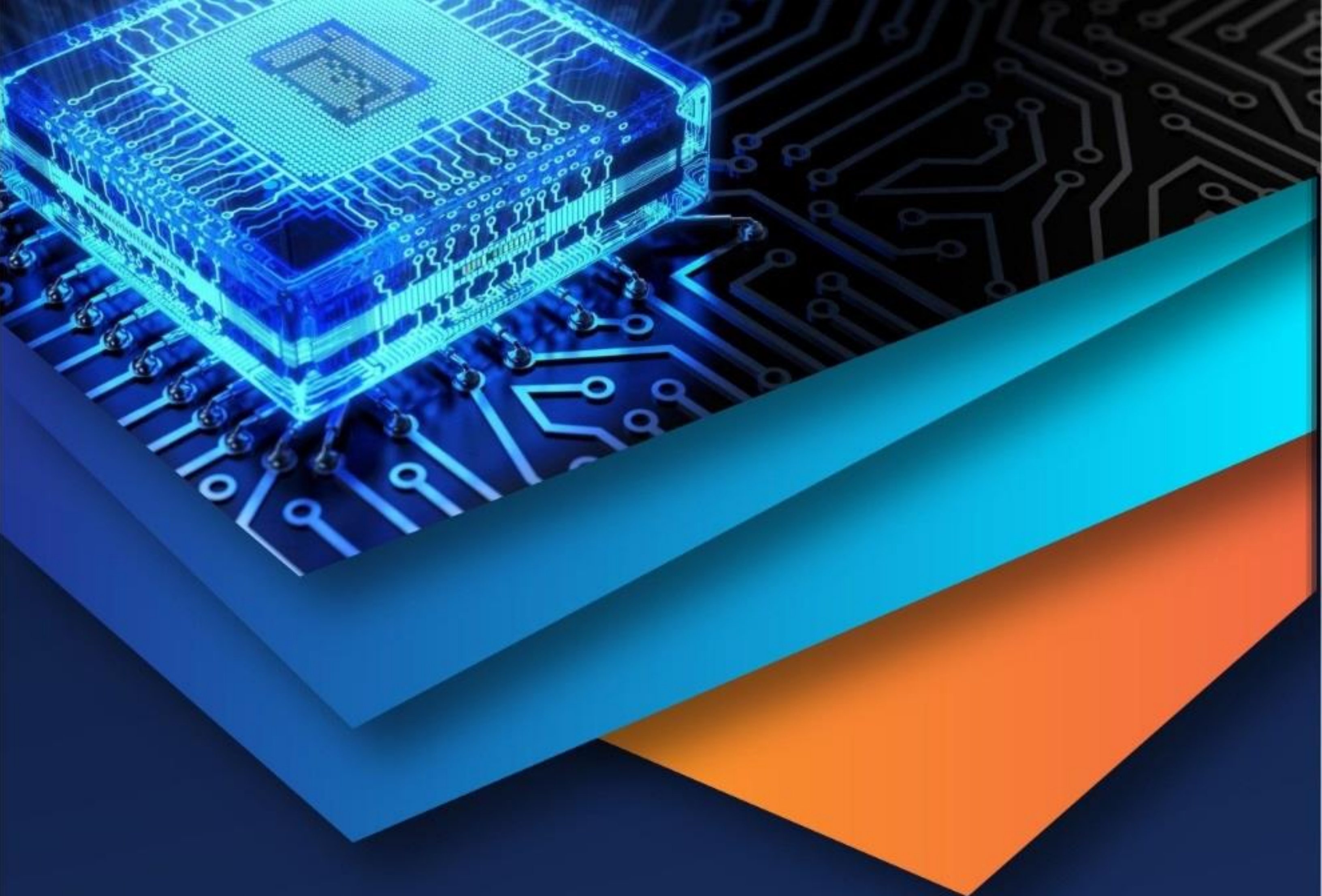

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