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Original Article

Development of a Random Walk Algorithm-based Glass Façade Cleaning Robot and its Performance Analysis

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Abstract - *Glass cleaning is one of the major cleaning tasks in malls, offices, and modern households where the human workforce is still used for cleaning. Manual cleaning on façade glasses is less safe, tedious, ineffective, and complex. With the advancement of robot technology, it is possible to use robots for glass curtain cleaning to facilitate humankind and improve cleaning efficiency. This work presents the development of a vacuum-type glass cleaning robot for façade cleaning using a random walk algorithm and its performance analysis. The developed square-shaped robot is controlled by an Arduino Mega microcontroller equipped with vacuuming and cleaning technology. An adhesion mechanism on the wheels makes the robot move forward and backwards on the glass. The robot runs on a 24-volt DC with a power rating of 75 watts. There are ultrasonic sensors to detect obstacles and help the robot navigate. The robot uses a simple, cost-effective random-walk mechanism that works effectively for 90 minutes. The robot's coverage area, repeatability, and dust collection efficiency performance have been analyzed. The result shows that the distance of 130 cm is covered in 12 sec on the vertical surface, whereas the 145 cm is covered in 12 sec on the horizontal surface. The collection efficiency was achieved at 94.06% on the horizontal surfaces and 89.134% on the vertical surfaces, showing remarkable achievement on the glass curtain cleaning.*

Keywords *- Vacuum Cleaning Robot (VCR), Façade Cleaning Robot (FCR), Random Walk Algorithm, Ultrasonic sensors and adhesion mechanism.*

1. Introduction

Robots have played a significant role in various industries and domestic service applications in this digital revolution. Many humanoid robots are simulated to perform tasks using artificial intelligence techniques [1]. In domestic applications, robot-based cleaning methodologies are becoming famous for cleaning vessels, toilets, car washing, glass doors, windows, etc. Window cleaning robots are catching the attention of the cleaning industry, focusing on windowpanes, glass tiles, and the risky job of cleaning façade glasses. Window-cleaning robots are available in different designs, and microcontroller-based robots have found a prominent place. Vacuum Cleaning Robots (VCR) can be used at homes, malls, companies, etc. This robot technology will reduce the cost of the cleaning process and increase the efficiency of cleaning and safety for humans. Typically, the VCR uses sensors, motors, and battery/electrical power with filters. It can be designed in different sizes according to the nature of the application. Hence, VCRs have more functions and have many advantages over human cleaning. This work aims to develop a VCR and analyze its performance related to optimizing the distance coverage rate and area coverage rate, minimizing the repeat coverage area, missing rate, and energy consumption rate, and improving the efficiency in cleaning. In this work, we developed and analyzed a microcontroller-based vacuum cleaning robot that can be used for glass façade in vertical or horizontal positions.

1.1. Research Gap and Novelty of the Proposed Research

Robot path planning is an essential task in robot installation, and many researchers are focusing on using different optimization algorithms to find an exact pathway to reach the destination. For example, pipe inspection and cleaning in the oil and gas industry is challenging, requiring robots with a proper path-planning algorithm. Due to the development of Industry 4.0 technologies, there is a huge demand for robots, AI-based digital gadgets, uncrewed aerial vehicles, underwater vehicles, etc. There are a lot of key challenges in these machines, from design to installation. Optimized path planning is one of the critical areas in designing an inspection robot to get an optimized result. Many algorithms are used in path planning, and still, there is a research gap in identifying the correct algorithm, particularly in glass façade cleaning robots. So, this paper addresses the requirement of a path planning algorithm when there are many obstacles during robots' vertical and horizontal travel while cleaning the vertical building glasses. The novelty of the work is to find and analyze the glass façade robot's path planning and execution using random walk algorithms to achieve better efficiency than other methodologies.

2. Literature Review

Kuisong et al. (2017) have researched to determine the performance metrics for coverage of cleaning robots with motion capture systems [2]. The researchers have taken three popular cleaning robots, including laser-type ones. They evaluated the performance of the coverage algorithm of a cleaning robot with three metrics: coverage rate, repeat coverage area ratio, and distance traveled. Experiments were conducted with the test platform area of 9.5 m^2, and comparisons were made to identify the most efficient robot. They have concluded that laser-based cleaning robots are more efficient than randomized cleaning robots. Asafa et al. (2018) developed a disc-shaped vacuum cleaner robot controlled by an Arduino mega-controller for office and home use [3]. The robot is driven by a DC motor with four ultrasonic sensors placed 90° apart. Navigation efficiency, sweeping capacity, and power consumption were used to evaluate the performance of the developed robot. The paper reveals that the device will be deployed with fully autonomous duty for office and home use. Jinqiang et al. (2018) developed a garbage-cleaning robot using a deep neural network. Authors have mentioned that garbage cleaning on grass can be used in schools, parks, and gardens, and it will work efficiently without human intervention. This deep learning-based robot can improve cleaning efficiency by up to 95% compared to traditional methods [4]. A design and analysis of an automatic vacuum, which is a disc-shaped robot with an Arduino microcontroller and a vacuum system using the axial fan, was discussed by Harish et al. (2020). In this paper, three ultrasonic sensors were attached at the front, and the microcontroller was programmed to move along a user-defined path. The simulation was done with Coppelia Robotics software. Researchers have done obstacle avoidance and vacuum analysis in the robot simulation. They also demonstrated the velocity and pressure contour on a 2D plane with a magnitude plot using ANSYS software[5]. Zhenjing et al. (2021) surveyed window-cleaning robots, and the authors discussed various window-cleaning mechanisms, algorithms, locomotion mechanisms, adhesion mechanisms, sensors, and controller units. This paper reviews detailed window-cleaning robots' key techniques and applications[6]. Anıl and Hatice (2022) developed a vacuum cleaner robot controlled by Android smartphones. Remote control of the robot was done through a Bluetooth connection between the Raspberry Pi and Android smartphone. Random walk and snake algorithms were used as the navigation algorithm. Using a cliff sensor, the robot has been prevented from falling through spaces such as stairs[7]. Nakagawa and Date (2023) developed an autonomous blower robot for cleaning and collecting fallen leaves from trees, which can be used to clean the garden or children's park. The design has three variable speed wheel moving mechanisms. The researchers have used blowers to clean the leaves in large areas and evaluated the robot's ability to clean[8]. Nansai et al. (2018) developed a façade cleaning robot with a biped mechanism to maximize its area coverage while cleaning. The developed robot uses active suction cups to adhere to glass walls and consists of mechanical linkage to navigate the glass surface to clean it. This paper discusses the robot's control system, which consists of inverse kinematics, a fifth polynomial interpolation, and sequential control[9]. Parween et al. (2021) developed a reconfigurable Mantis-mini robot with a dry-cleaning and linear actuator-based transitioning mechanism. This robot consists of three suction elements that have independent differential drives. A structural analysis was carried out in this paper to verify the structural deformation and frequency of behavior. This paper mainly focuses on the design parameter analysis rather than the performance analysis of the robot[10]. Bisht et al. (2022) presented a unique design concept, dynamic modeling, and control strategies for efficient coverage path planning of a glass façade cleaning robot. The simulation of path optimization result of this paper shows that the robot motion for Horizontal Line Sweep (HLS) is compared to Vertical Line Sweep (VLS), Spiral Line Sweep (SLS), and Special Cell Diffusion (SCD) motion. The path is the most energy efficient [11].

The application of glass façade robots can be extended to clean photovoltaic panels. Antonelli et al. (2020) developed an autonomous robotic device for the waterless cleaning of photovoltaic panels in a desert zone using the "Arduino Due" platform[12]. Ze et al. (2024) proposed a passive adaptive wall climbing robot design based on 5 bar mechanisms. This design can be applied to curved permeable metal walls, such as large ships' outer bodies. The author claimed that the 5-bar mechanism improves the robot's adaptability by adjusting its posture so that the driving wheels can fit the wall completely. In this paper, the authors used permanent magnet wheels for vertical climbing[13]. In the requirement analysis of the glass façade robot, Shiyao Caia et al. (2020) gave six points in wall climbing and Inspection such as safe and reliable climbing mechanisms, identification of the surrounding environment and obstacles, The ability to cross or avoid obstacles, Motion control, Efficient inspection methods and the ability to record and export the inspection results[14]. Feng, Q (2024) discussed optimizing the Turing logic of a glass curtain wall cleaning robot. This research has optimized the robot path to balance spatial utilization and high average speed. The author has refined the turning path and shown that the cleaning efficiency is enhanced, achieving more overall cleaning efficiency while maintaining an exceptional ability to avoid obstacles[15]. The research gap in past literature is in cost and efficiency. The cleaning industry requires the best robot, which is low cost, high efficiency, and covers a larger area.

3. Methodology

The design of the robot was done using a microcontroller energized by a DC battery with an operating voltage of 24 V and a rated power of 75W. This capacity is selected to energize the motors for movement and the pump for vacuum creation and adhesion mechanism. The higher voltage reduced the current requirements while moving the robot. The higher voltage of 24V DC will make the vacuum mechanism more effective, and the battery will last a minimum of 3 hours in the continuous cleaning operation. This is the ideal selection to reduce the overall weight and cost-effectiveness of the proposed robot. Arduino microcontroller and random walk mechanism are used in this work. Ultrasonic sensors are used to detect obstacles. An ultrasonic sensor has been used to detect the barriers, window frames, edge detection, protrusions, and uneven surfaces on the glass frame. This glass façade robot mainly uses the ultrasonic sensor to maintain a consistent distance from the glass surface during cleaning. The ultrasonic sensor has a resolution of 50 ms and a range of 30 cm, and the power supply requirement is 5V. The control system is a closed loop, as given in Figure 1. The input of 24V will be given to the locomotion mechanism, and the vacuum adhesion mechanism will make the robot hold on to the glass panels. The adhesion mechanism uses vacuum suction, a sealing mechanism, vacuum pumps, and integration with sensors. In this, the robot generates a vacuum zone using suction cups. This creates a strong adhesive force, which allows the robot to stick to the glass surface. The sealing material is rubber or silicone to hold the vacuum more efficiently for a more extended period. There are high-performance pumps to create a vacuum, and pressure sensors will monitor vacuum levels to ensure consistent adhesion in modern technologies.

The robot's movement will be decided based on the random walk mechanism. Thereby, the cleaning process takes place. The distance and detection sensors continuously give feedback to the controller to have more coverage area. The specifications for the cleaning robot are shown in Table 1. According to the software design, the controller will control the robot by adjusting the input commands through the remote. The challenge encountered in robot development is integrating hardware with software. The other challenge is adhesion during the vertical cleaning. There is a chance of the robot falling from the facade. So, a rope is attached to the robot, which can facilitate tying it with a rigid hanger as a safety measure. Other safety measures have been considered in the design, like wind stability, suction monitoring to have reliable adhesion technology, IP65,66 and 67 for dust-free and wet-free mechanisms, and weight and load management.

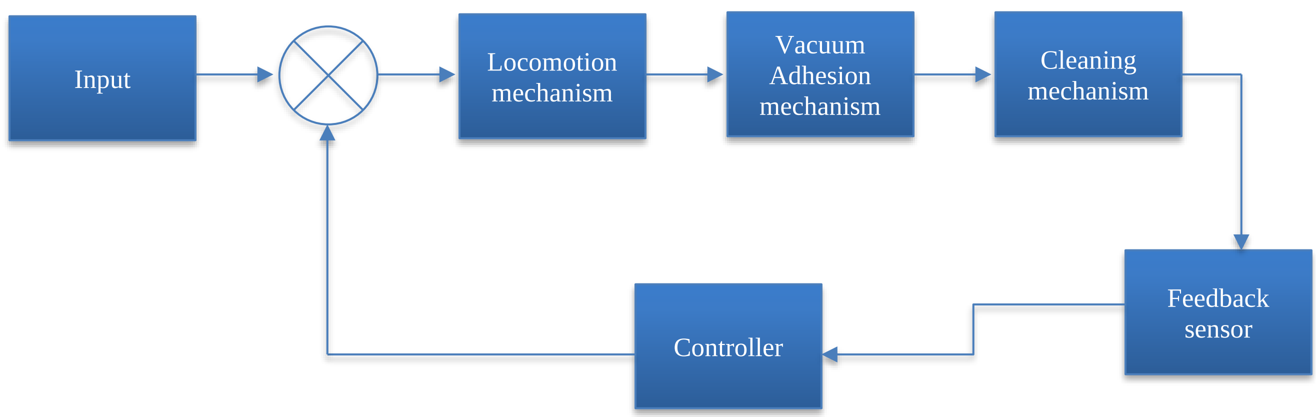

Fig. 1 Block diagram of a control system for window cleaning robot

3.1. Random walk Algorithms

The random walk algorithm is used in this robot. These algorithms are helpful in low-cost vacuum cleaner robots, and the main advantage of the algorithm is that it does not require a precise route plan. The disadvantage is that the robot passes through the same area several times.

In this algorithm, robots travel in the forward direction till any obstacle is detected by sensors. If obstacles are detected, the robot stops and changes the direction of the system according to the random number generated by the controller. The flow chart is given in Fig. 2. The random rotation time is adjusted as

$$RRT = 1\,sec + random\ time * (0 - 0.15\,sec) \quad (1)$$

The algorithms can be entirely random, and after each collision with an obstacle, the robot randomizes a new heading without considering the place where it starts. This algorithm is highly suitable for small areas or corners[16]. A random walk-based algorithm can be integrated with sensors to decide to turn left or right when there is an obstacle in the path. This way, the robot can turn without hitting obstacles. This algorithm generates a random number, and the random turn is performed afterwards. So, random movement will be based on the highly required surroundings to clean the façade.

Table 1. Specification of the cleaning robot

Description	Specification
Operating voltage	24 V
Rated power	75 W
Adapter input	AC 110 – 240V, 50/60 Hz
Output	DC24V, 3.75 A
Number of wheels holding on the wall	Four vacuum type
Working temperature range	0 to 40°
Noise range	20 - 30 dB
Dust storage capacity	$0.002m^3$.
Minimum border thickness for framed glass panel	>50 cm
The minimum dimension ratio of frameless glass	60 cm x 60 cm
Sensors	Ultrasonic and distance prediction sensors
Size	22 cm X 22 cm X 5 cm

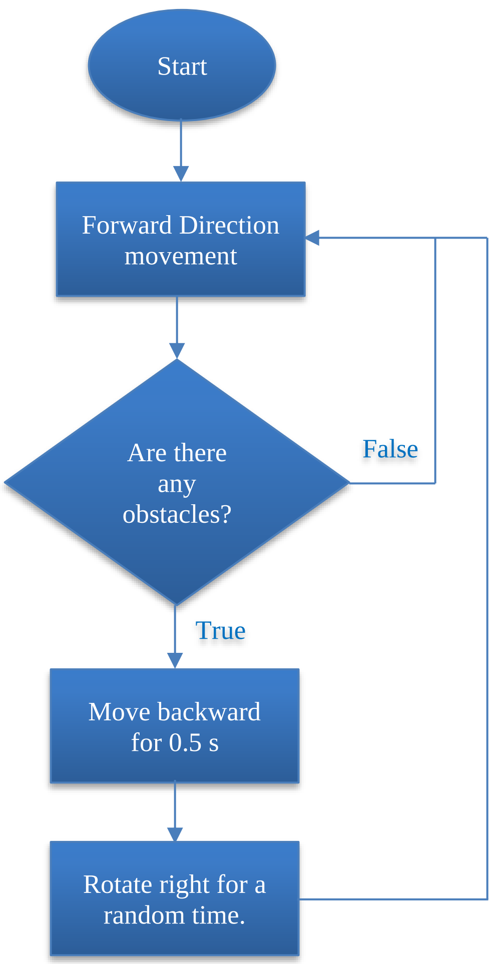

Fig. 2 Random walk algorithm

3.2. Operational Procedure of the Robot

There may be a chance to clean glasses at higher heights; a remote-based user interface system will allow one to perform tasks without unsafe conditions. The user interface is remote and has many keys for more convenience in controlling the robot's movement and improving the efficiency of the cleaning process. There are two types of keys on the remote to control the device: N–mode key and Z–mode key.

The N-mode key directs the device to move in the path of the N-shaped route to wipe the vertical surface. This allows the device to move forward and reverse during the operation. The Z-mode key instructs the device to move in a zig-zag manner to wipe the surfaces. This allows the device to move from left to right along sideways during the operations. In addition to these keys, forward, reverse, right, and left side movements can be adjusted through the corresponding up, down, right, and left arrow keys.

3.3. Operational Limitations of the Robot

- Should be used only on glasses or polished layers without broken surfaces, advertisement papers, or bumps.
- Should be used only on planar surfaces without curved or beveled surfaces.
- Preferred to use on the glass thickness without frames or with frame if the frame thickness is greater than 5 mm.
- Should be used only on non-wet surfaces to avoid slipping or risks of falling.
- The device should not be dipped in water for cleaning purposes.
- Battery charging should not be carried out in an overheating or undercooled environment. This may affect battery life.
- The device should not be placed upside-down.

4. Performance Metrics and their Calculations

The following key performance indicators are evaluated for the cleaning robot:

Area coverage rate: The area coverage rate is one of the key performance indicators used to measure the efficiency of the intelligent cleaning robot. It represents the total area covered by the robot in a given area.

$$Coverage\ rate\ = \frac{Area\ covered\ by\ the\ robot}{Area\ of\ the\ given\ space} \tag{2}$$

Repeat coverage area: There is every chance the robot will pass through the same place again during the operation. This constitutes the repetition of the area covered and should be minimized. Repeat coverage area becomes a key performance indicator. This is best achievable by defining the path of the cleaning robot.

The distance coverage rate is the distance traveled by the cleaning robot in the defined path per the controller software to the least distance traveled to cover the entire area of the given space. This key performance indicator is used to calculate the cleaning robot's efficiency.

$$Distance\ coverage\ rate\ = \frac{Distance\ traveled\ by\ the\ robot\ to\ complete\ the\ task}{Least\ distance\ to\ cover\ the\ entire\ given\ area} \quad (3)$$

The cleaning rate indicates the robot's ability to clean the dust. It is the ratio of the ability of the robot to suck the dust to the total dust present in the given area.

$$Cleaning\ rate(Efficiency)\ = \frac{total\ dust\ removed}{Total\ dust\ in\ the\ given\ area} \quad (4)$$

5. Performance Analysis and Discussion

The robot was developed per the specifications in Table 1 and tested for cleaning on horizontal and vertical glass panes. The robot is tested to analyze the cleaning performance, as shown in Figures 3 and 4. In the initial performance analysis, the distance traveled concerning time is observed for both horizontal and vertical cleaning. The distance traveled in cm is noted against the 2- to 12 sec time for both cleanings. Tables 2 and 3 show the distance traveled by the robot, and Fig. 5 and Fig. 6 show the line diagram of the distance traveled against the time of 2 s to 12 s.

Fig. 3 Horizontal surface cleaning test

Fig. 4 Vertical surface cleaning test

The total distance covered on the vertical surface is 130 cm in a 12 s period. The distance covered period is increasing due to increasing height. The distance covered period increases with the increase in height. In the horizontal surface, the total distance is 145 cm in a 12s period. More distance is covered on horizontal than vertical surfaces due to the gravitational effect and the clamping effect. Overall, the result shows that vertical cleaning takes longer than horizontal cleaning. This is because the gravitational effect plays a vital role during cleaning. During testing, the seasonal effects are minimal and are not considered. So, the cleaning procedure will take longer on vertical surfaces, whereas horizontal surfaces can be cleaned in less time. The glass surface is analyzed to calculate the coverage rate of 20cm, x, 20 cm. During testing, the robot covered nearly 19cm and 19cm during horizontal cleaning, whereas 18cm and 19 cm were covered for vertical cleaning.

$$Coverage\ rate\ for\ horizontal\ cleaning = \frac{19 * 19}{20 * 20} = 0.9025$$

$$Coverage\ rate\ for\ vertical\ cleaning = \frac{18 * 19}{20 * 20} = 0.855$$

Table 2. Distance traveled concerning time on a vertical surface

Vertical Surface	
Time, *s*	Distance traveled, *cm.*
2	10
4	30
6	60
8	90
10	110
12	130

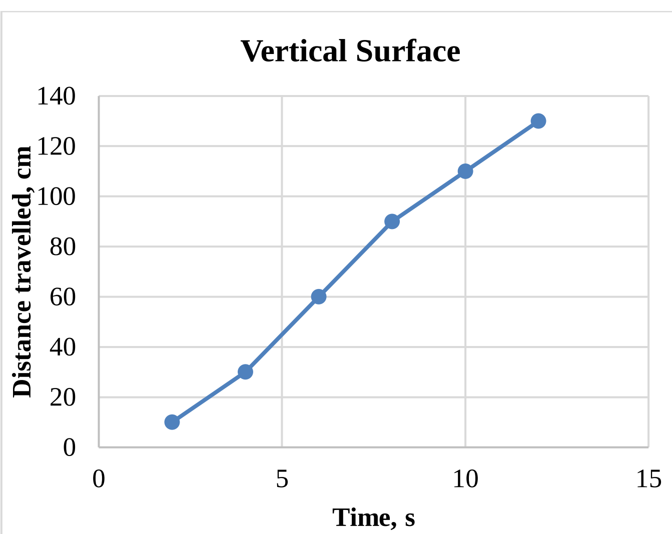

Fig. 5 Distance traveled concerning time on a vertical surface

Table 3. Distance traveled concerning time on a horizontal surface

Horizontal Surface	
Time, *s*	**Distance traveled, *cm.***
2	20
4	50
6	75
8	100
10	120
12	145

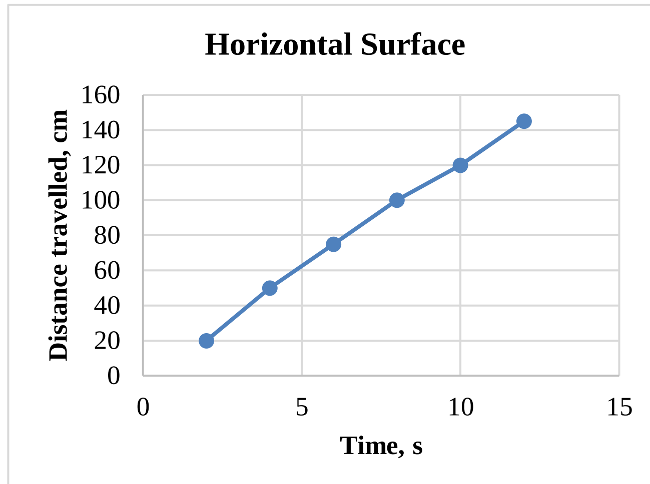

Fig. 6 Distance traveled concerning time on a horizontal surface

To understand the repeatability, the distance traveled for every 5s is observed eight times during vertical cleaning and tabulated in Table 4. The distance covered in 5 sec varies from 45 to 55 cm, which means the repeatability is inconsistent, but the distance traveled is good. The trend is shown in Figure 7. It reaches up to 60 cm in horizontal cleaning since the distance coverage is more significant than in vertical cleaning. Table 5 shows the distance traveled every 5 seconds, and the relevant line diagram is given in Figure 8.

Table 4. Distance traveled every 5 seconds on vertical surfaces

Vertical Surface	
Repetition times	**Distance traveled in every 5 seconds, *cm.***
1	48
2	48
3	50
4	50
5	45
6	48
7	47
8	55

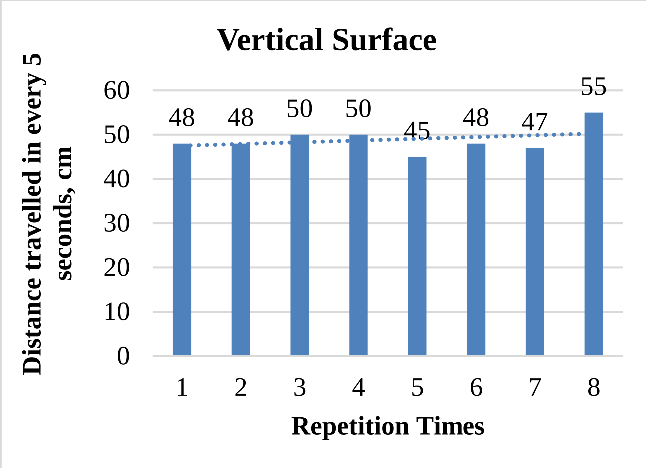

Fig. 7 Distance traveled every 5 seconds on vertical surfaces

Comparing these two-line diagrams in Figures 7 and 8, the repeatability performance line is more straight on the horizontal surface than the vertical one. The repeatability of the vertical surface cleaning varies, which means there is an effect due to gravitation and clamping time.

The dust collection efficiency was calculated by applying known dust weight to the surface. After cleaning, the collection of dust is weighted, and dust collection efficiency has been calculated. Tables 6 and 7 show the dust the robot collects during horizontal and vertical cleaning, and dust collection efficiencies are calculated. Figures 9 and 10 show the collection of dust in grams. It is noted that the average efficiency of the robot in horizontal cleaning is 94.06%, whereas for vertical, it is 89.134%. The efficiency is higher for fewer grams of dust during the horizontal and vertical cleaning process. For example, 5 gm of dust is collected ultimately, and the efficiency is 100%. However, with more dust, the cleaning efficiency decreased gradually.

It has been clear that robots work better for cleaning horizontal surfaces than vertical surfaces. However, with the evolution of recent technologies, cleaning on vertical surfaces is possible with robots where high risks are involved, and it is better than human cleaning. A limitation is that the proposed robot efficiency is higher for less dust and not for dustier and rusty surfaces.

Table 5. Distance traveled every 5 seconds on horizontal surfaces

Horizontal Surface	
Repetition times	**Distance traveled in every 5 seconds, *cm.***
1	58
2	58
3	60
4	60
5	55
6	58
7	57
8	55

5.1. Limitations of the Proposed Glass Façade

5.1.1. Cleaning Robot

Since the random walk algorithm works in randomness, it lacks a systematic coverage rate. It can be improved using hybrid algorithms combined with random walks with other algorithms or AI models using machine learning. Edge detection is difficult in the Random walk algorithm, which can be improved by integrating smart sensors. There is a scalability issue in the proposed methodology. A large surface volume may need more powerful and modern technologies in speed control of motors and suction technologies. So, the proposed method needs more sensors to improve accuracy and precision.

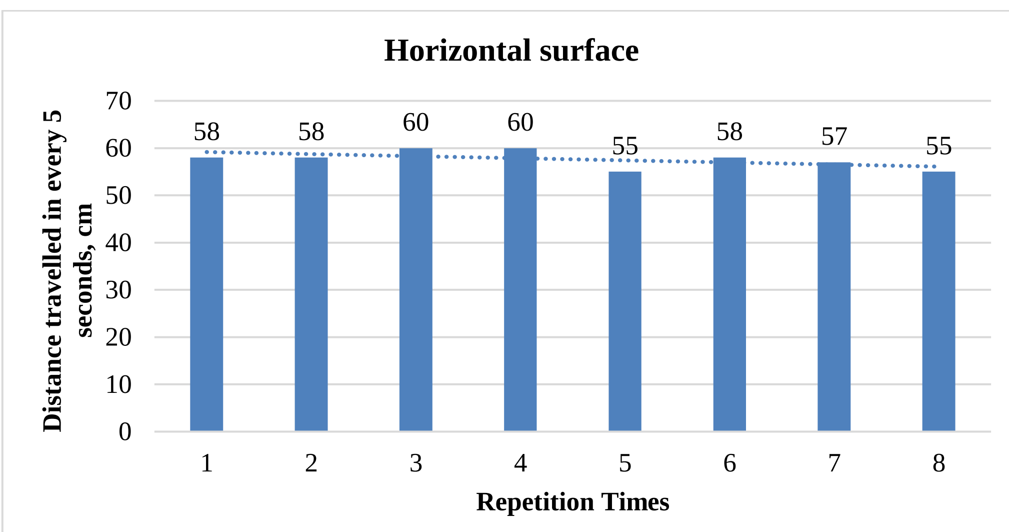

Fig. 8 Distance traveled every 5 seconds on horizontal surfaces

Table 6. Dust collection by the robot is done on a horizontal surface

Horizontal surface		
Dust is applied in grams.	**Dust collection by robots in grams**	**Dust collection efficiency %**
5	5	100%
10	9	90%
15	14	93.3%
20	19	95%
25	23	92%
Avg Efficiency		94.06%

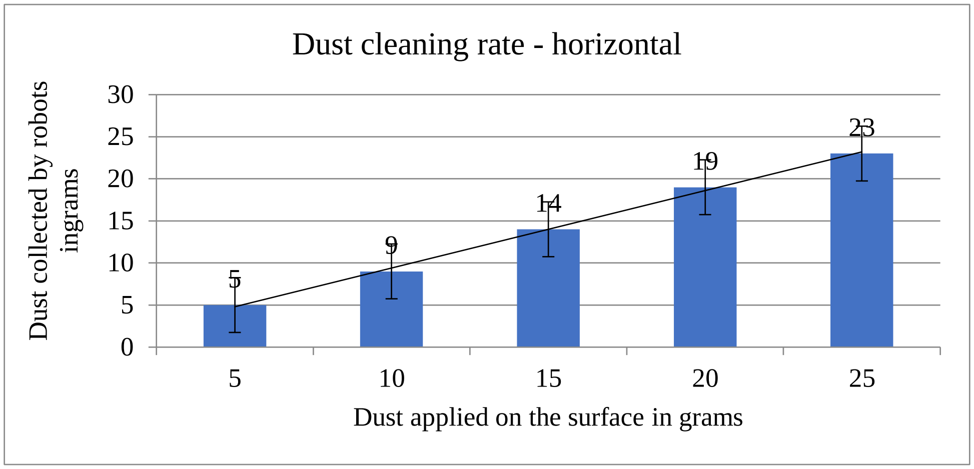

Fig. 9 Bar chart for Dust collection by the robot on a Horizontal surface

Table 7. Dust collection by robots on the vertical surface

Vertical surface		
Dust is applied in grams.	**Dust collection by robots in grams**	**Dust collection efficiency %**
5	5	100%
10	9	90%
15	13	86.67%
20	17	85%
25	21	84%
Avg Efficiency		89.134%

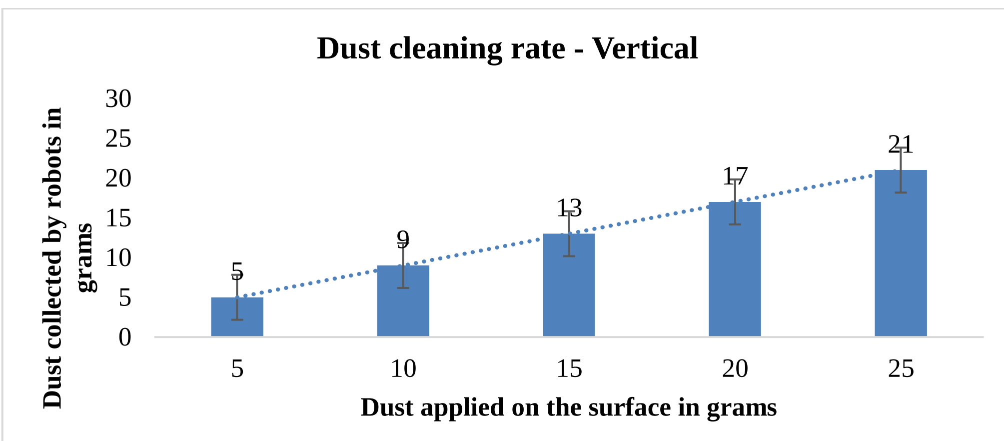

Fig. 10 Bar chart for Dust collection by the robot on the vertical surface

Table 8. Main Performances of Several Window-Cleaning Robots - Zhenjing et al. (2021)

Robot	Cleaning efficiency m2/h	Dimension (mm x mm x mm)	Locomotion mechanism	Surface type
TITO 500 (Akinfiev et al., 2009) [17]	1500	1500x3500x340	Cable-drive	Vertical
BMFR (Moon et al., 2015) [18]	403.2	1600x1970x545	Winch System, Wheels	Vertical
Non-actuated glass-curtain wall-cleaning robot (Qian et al., 2006) [19]	200	1500x800x400	Cable-drive	Vertical
Autonomous climbing robot for elliptic half-shell cleaning (Zhang et al., 2007) [20]	150	3000x1500x400	Wheels	Elliptic half-shell
Sky cleaner 3 (Tokhi et al., 2007) [21]	125	1136x736x377	Transition	Vertical
SIRIUSc (Elkmann et al,.2008) [22]	120	-	Transition	Vertical
SkyBoy (Wang, 2010) [23]	95	1300x402x470	Driving belts	Reversed inclining
WINDSOR (Choi and Jung.,2011) [24]	62	200x200x50	Wheels	Vertical

6. Comparison in Terms of Efficiency

The paper by Zhenjing et al. (2021) [6] tabulated the cleaning efficiency performance of several window cleaning robots in m^2/h, as in Table 8. Compared with other robots, the proposed robot efficiency is calculated as follows, as tabulated in Table 8.

The calculation for cleaning efficiency in m^2/h on a horizontal surface:

Dimensions of the cleaning robot are 22 cm X 22 cm X 5 cm.

Distance covered in 12 s is 145 cm.
The total area covered in cm^2/s = $\frac{145 * 22}{12}$
Cleaning efficiency in m^2/hr.

$$= \frac{145 \; * 22 * 3600}{12 * 10^4} = 95.7 \; m^2/hr$$

The calculation for cleaning efficiency in m^2/hr. on a Vertical surface:

Distance covered in 12 s is 130 cm.
Cleaning efficiency in m2/hr.

$$= \frac{130 \; * 22 * 3600}{12 * 10^4} = 85.8 \; m^2/hr$$

So, compared with the robots' efficiency listed in Table 8. The efficiency aligns with the Sky Boy robot, whose dimension is 1300x402x470 mm, compared to the proposed robot, which has 220x220x50 mm. In comparison with the similar size of the robot "WINDORO," the proposed robot is more efficient in both vertical and horizontal operation (95.7 m^2/hr and 85.8 m^2/hr) where WINDORO has recorded 62 m^2/hr. So, the developed robot has achieved better efficiency in its category and is also much more cost-effective than other robots.

7. Conclusion and Future Development

In this work, a vacuum-type cleaning robot is modeled, and its performance is analyzed. An analysis was conducted to understand the Random walk algorithm-based robot's efficiency and effectiveness in cleaning vertical and horizontal glass panels. 24V DC powers the robot and has a rated power of 75W. The robot has been powered through a battery or direct electricity connections under the given conditions. Performance evaluation has been done to understand coverage area, repeat coverage area, distance coverage rate, cleaning rate effectiveness, and dust collection efficiency based on a random walk algorithm. On the vertical surface, the robot took 12 sec to reach 130 cm, whereas it covered a 145cm distance in 12 sec on the horizontal glass surface. When the robot is trailed for 5 sec, a 48.875 cm distance is covered on the vertical glass surface and 57.625 cm on the horizontal glass surface. Dust collection efficiency on horizontal surfaces is 94.06%, and vertical is 89.134%. The random walk algorithm has been used due to its accuracy and cost-effectiveness. In the future, we can say it is possible to use different algorithms, different cleaning mechanisms, and additional sensors to improve the effectiveness of the vacuum cleaning robot. More sensors and an effective algorithm can give more efficiency in cleaning. There are some disadvantages to vacuum technology, which new and effective adhesion techniques can replace in future developments. In the future, artificial intelligence-based robots can enhance efficiency and adaptability on a large scale and improve performance. AI-powered robots can be integrated with intelligent sensors, machine learning, computer vision, and IoT technologies to optimize operations.

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