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WiBot 1.0: A Modular Reconfigurable Glass Cleaning Robot for High-rise Buildings

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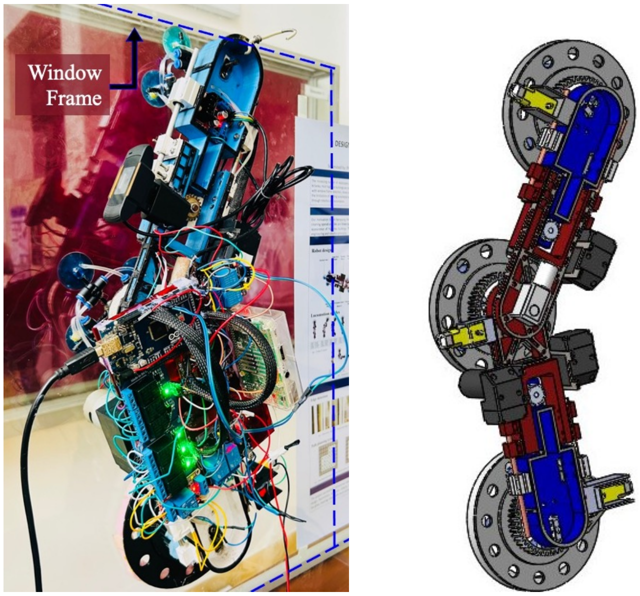
***Abstract*— Cleaning glass surfaces is a prevailing maintenance problem in high-rise buildings. In the traditional methods of cleaning windows, hanging on ropes poses significant occupational hazards to workers. Furthermore, most glass facades feature window frames to securely fasten the glass panels to the building structure, ensuring durability and elegance. In this context, existing robotic cleaning methods are limited by their capability to move-over window frames and need more flexibility to access tight corners and curved surfaces. This paper presents a novel reconfigurable glass cleaning robot called "WiBot" to address these limitations. WiBot is a kinematic chain comprising modular linkages with a prismatic joint and two revolute joints at each end. Each revolute joint has a suction unit that enables locomotion and adhesion. Window frames are detected using image processing with an onboard camera, and design optimizations were performed to improve the robot's capabilities. The prototype WiBot 1.0 was developed, and several experiments were conducted to evaluate the feasibility of the proposed system focusing on robot motion, window frame detection and move-over mechanism. The results show that WiBot can overcome the limitations of existing window cleaning solutions. Finally, several promising research directions are mentioned involving the proposed reconfigurable robot architecture in cleaning operations.**



(a) Fabricated prototype (b) 3D model

Fig. 1. WiBot 1.0 - A novel reconfigurable robot performing glass cleaning operation on a vertical window.

I. INTRODUCTION

Robotic glass facade cleaners have emerged as a prominent research topic in robotics [1]–[3]. The demand stems from the expansion of high-rise buildings featuring glass facades due to architectural requirements and the advancements in the construction industry. Consequently, the necessity to service and maintain window glasses has surged. Traditional maintenance practices primarily rely on manual labour, posing high risks in workers' lives, cost, and cleaning efficiency concerns [4]. Moreover, driven by factors like labour shortages, immigration policies, and an inefficient workforce, the glass cleaning trend in high-rise buildings now shifts toward deploying robotic systems [5]. This paper presents WiBot, a reconfigurable robot designed for glass cleaning operations in high-rise buildings (refer Fig. 1). The robot includes two main sub-systems: mechanical and control. The mechanical system combines chassis, adhesion, and cleaning mechanisms, whereas the control system has a low-level controller to control actuators and a high-level controller for window frame detection. Although WiBot 1.0 is designed to meet the minimum configuration comprising only 2 modules, it can be expanded by adding more modules that pave the way for new research directions.

The contributions of this paper are summarised as follows,

- We present a novel reconfigurable robotic architecture for glass cleaning operations in high-rise buildings;
- Our robot system has adaptable movement abilities, enabling it to access and clean hard-to-reach areas efficiently;
- The designed robot has a unique ability to move-over window frames;
- The device is equipped with an onboard camera that employs image processing techniques to detect window frames;
- We evaluated the proposed system using a prototype of the robot: WiBot 1.0 on a vertical glass window.

The paper is organized as follows. First, Section II highlights related literature, and Section III commences by introducing the system architecture. The three motion types of the robot are included in Section IV. Section V provides

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an in-depth exploration of the move-over mechanism, and Section VI discusses the image processing technique used for frame detection. Finally, experimental results are discussed in Section VI, and Section VII concludes the paper.

II. RELATED WORK

Various research efforts have made notable advancements in domestic cleaning robots. For instance, Choi et al. [6] significantly contributed to the field by developing the first commercial window cleaning robot, known as Windoro. Additionally, Feng et al. [7] introduced a glass cleaning robot featuring a closed wiper mechanism in their work. Furthermore, a portable glass cleaning robot, designed for attributes such as lightweight, compactness, and affordability, was developed by Nazim et al. [8]. These developments have played a crucial role in advancing the field of domestic cleaning robots.

In the context of high-rise building maintenance, the Fraunhofer Institute for Factory Operations and Automation pioneered a cleaning robot that stands as the world's first curved building cleaning robot. The family of Sky-cleaner window-cleaning robots stands as a representative example of translation robots propelled by air cylinders [9]. Nansai et al. embarked on the design of a bipedal cleaning robot featuring specialized legs equipped with suction cups, and cleaning mechanisms interconnected through a parallel arrangement [1]. Moreover, Sun et al. [10] introduced an innovative approach involving a switchable UAV system, where a window-installed cleaning robot executes cleaning tasks. These collective advancements underscore the progress in the domain of cleaning robots at both domestic and commercial levels.

Most of the glass cleaning robots are designed as standalone units. However, some robots have been developed with a focus on reconfigurability and modularity. Mantis is a modular robot that can move over window frames [11]. A nested reconfigurable robot has been developed using both intra and inter-reconfigurations to increase flexibility and modularity [12].

However, the existing robots face challenges when addressing glass cleaning in high-rise buildings. These buildings equip steel or aluminium frames to support the glasses and also consist of tight glass spaces with narrow corners, which the existing robots are not capable of accessing. Reconfigurable robots come into action to tackle these situations since they are capable of altering their configurations. Considering these facts, this paper aims to propose a reconfigurable glass cleaning robot that has the ability to move-over over window frames with adaptable motion types.

III. SYSTEM ARCHITECTURE

A. Mechanical System

The mechanical system is the backbone of the proposed robot (refer Fig. 2), which incorporates chassis, adhesion, and cleaning systems. The following subsections discuss the design and optimizations of each sub-system in detail.

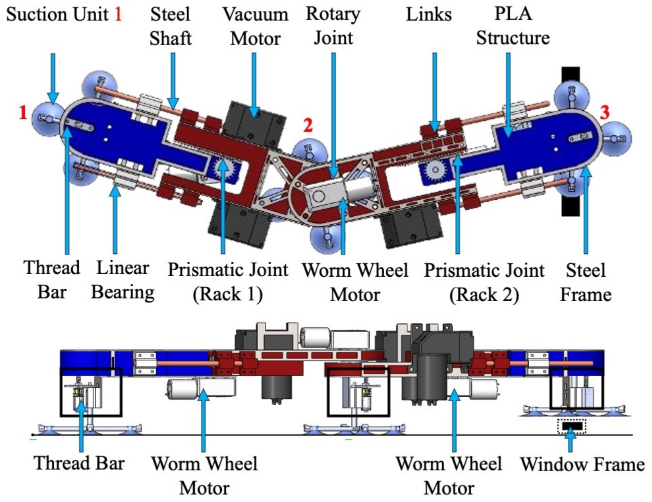


Fig. 2. Plan and Front elevation - WiBot 1.0 (cleaning pads removed to enhance the clarity). See Fig. 1 for a perspective view of the complete robot.

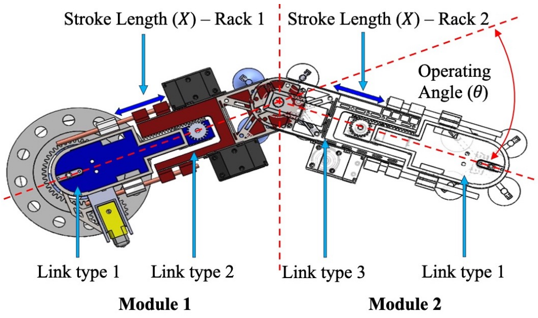


Fig. 3. Links and modules of the chassis. Each module comprises two links connected by a prismatic joint and two rotary joints and cleaning pads at both ends of the module.

1) Chassis: WiBot is designed to be a reconfigurable robot having a kinematic chain with modular linkages. A module is a combination of two links connected by a prismatic joint and two revolute joints at either end (i.e. 3 degrees of freedom per module). The revolute joint acts as the coupling joint between two modules. In this paper, the robot is designed with the minimum configuration of two modules (see Fig. 3). The robot architecture allows easy expansion by integrating additional modules. This modular approach ensures flexibility and adaptability of the robot's overall configuration.

The simplified mathematical equations for the module length calculations are provided below, showing the relationship between stroke length (X), module length (L), displacement (D), and operating angle (θ) (refer Fig. 4).

$$X = -L + \sqrt{L^2 + D^2} \tag{1}$$

$$\theta = \arctan\left(\frac{D}{L}\right) \tag{2}$$

A displacement of 200 mm was chosen to travel on the selected glass window of 900 mm × 1500 mm. The length of

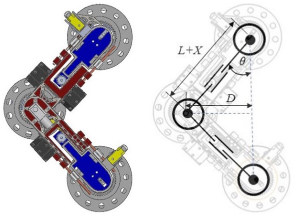


Fig. 4. Simplified kinematic model for module length selection.

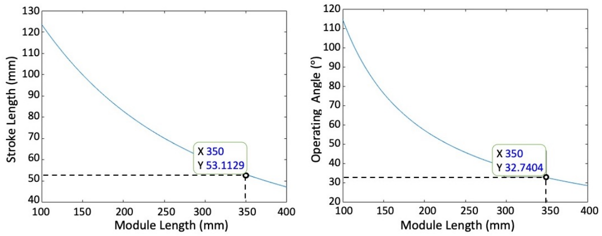


Fig. 5. Variation of Stroke length vs Module length (left) & Operating angle vs Module length (right) for a displacement of 200 mm.

the robot's link was selected to minimize the operating angle and overall system weight. The calculations determined that the module length should be 350 mm, as the stroke length of the rack joint actuator is constrained to 5 cm. The obtained operating angle of 33°is within the acceptable region for the rotary joint motor (see Fig. 5).

2) Adhesion Mechanism: Glass cleaning robots employ either active or passive adhesion systems. Choi et al. [6] demonstrated that passive methods, such as those utilizing sticky materials or permanent magnets, can operate without external power sources. On the other hand, active adhesion systems require external power and offer the advantage of adjustable vacuum pressures within suction cups, thus enhancing control during low-power operational modes. Examples of active methods include vacuum pumps, propulsion adhesion, and magnetic forces [13].

Suction unit design is crucial for maneuvering on the glass surface, thus WiBot 1.0 features three suction units, each with four suction cups. These suction units are designed as 2-DOF joints (prismatic & revolute), facilitating a move-over mechanism, *rotary* motion, and *butterfly* motion (refer to Section IV for more information regarding robot motion). The dimensions of the suction unit are selected to reduce moments upon them since the robot's centre of gravity (CG) is positioned 53 mm from the glass surface.

In order to generate the required adhesion force, suction cups rely on a diaphragm pump that extracts trapped air from suction cups to induce a vacuum, thus generating the required pressure difference. The selection of a vacuum pump is crucial for the robot to adhere steadily to glass surfaces, reducing the risk of accidents and guaranteeing safe operation. When compared with the other vacuum pumps, diaphragm pumps offer several advantages. They are oil-free, making them superior to rotary vane pumps [14], and they can operate quietly while allowing for adjustable vacuum levels, which sets them apart from venturi pumps [15].

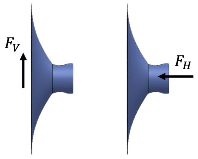
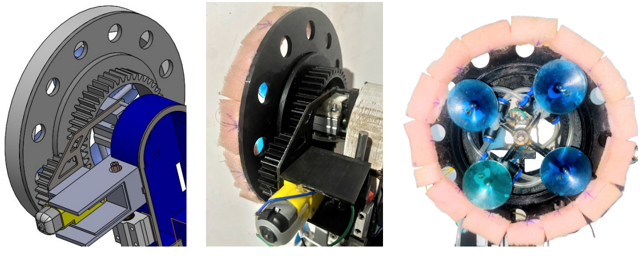
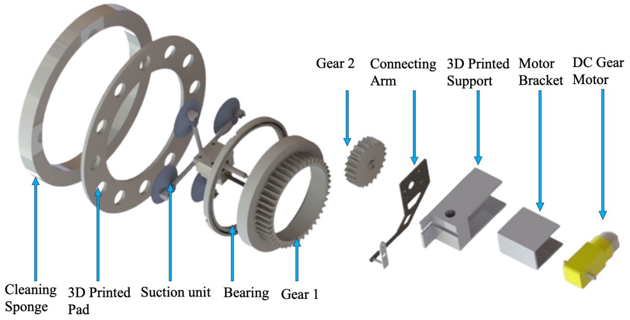


Fig. 6. Lifting forces acting on suction cup.



(a) 3D Model (b) Prototype (c) Plan view



(d) Exploded View

Fig. 7. Cleaning pad configuration.

Selection of the suction cup diameters is determined through calculations, while the number of suction cups per unit is chosen based on geometric constraints. These calculations involve a set of equations to compute the theoretical lifting force (see Fig. 6) and the suction cup diameter.

Theoretical vertical lifting force is given by,

$$F_V = M \cdot (g + a) \cdot \frac{S_H}{\mu} \tag{3}$$

Theoretical horizontal lifting force is given by,

$$F_H = M \cdot (g + \frac{a}{\mu}) \cdot S_V \tag{4}$$

where M represents the robot mass, a is the acceleration of the robot, μ is the friction coefficient, S_H is the horizontal safety factor, S_V is the vertical safety factor, and g stands for the gravitational constant.

The suction cup diameter is given by,

$$d_{\text{req}} = \sqrt{\frac{4 \cdot F_H}{\pi \cdot P \cdot N}} \tag{5}$$

where P represents the vacuum pressure inside the suction cups, and N is the number of suction cups in a single suction unit.

From the calculations and geometry constraints, it determined that the robot requires four suction cups, each with

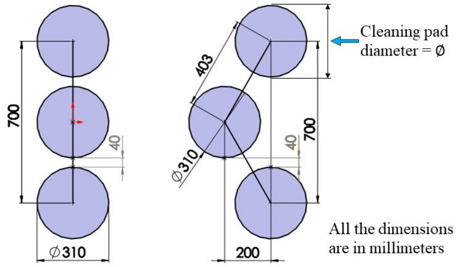


Fig. 8. Cleaning pad diameter selection is constrained by the dimensions and motion types of the robot (ϕ - 310 mm).

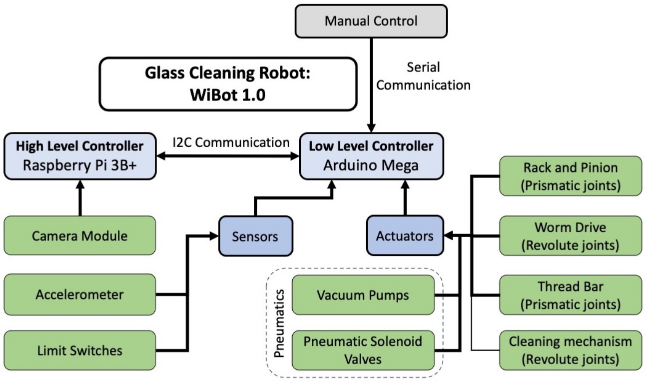


Fig. 9. Control architecture - WiBot 1.0.

a diameter of 40 mm and a vacuum pressure of 31 kPa, to ensure proper adhesion [16]. A diaphragm pump was selected with a maximum vacuum pressure of 66 kPa, and a safety margin of 50% is incorporated to guarantee secure operation.

3) Cleaning Mechanism: The design of the cleaning mechanism, as shown in Fig. 7, is based on the primary objective of maximizing cleaning coverage while minimizing system weight, and the dimensions of the mechanism are chosen based on the robot's motion modes (refer Fig. 8). A spur gear system having a 2:1 gear ratio is used to obtain the rotation speed of 150 rpm in the cleaning pad [17]. The required motor torque has been calculated as 0.5 Nm and is a critical parameter for design considerations and a DC gear motor is selected as the rotary actuator. Additionally, the cleaning mechanism is designed to be lifted by the move-over mechanism when the robot approaches the window frame (check Section V for more details).

B. Control System

The control architecture of the robot integrates high-level and low-level control functionalities as shown in Fig. 9. The low-level controller is dedicated to actuator controlling and sensing tasks and is effectively managed by an Arduino Mega development board. The Raspberry Pi 3B+ operates as the top-level controller for the high-level system, which is used for complex image processing tasks, including window edge detection from the robot's perspective. The I2C communication protocol is used to communicate between the low-level and high-level controllers.

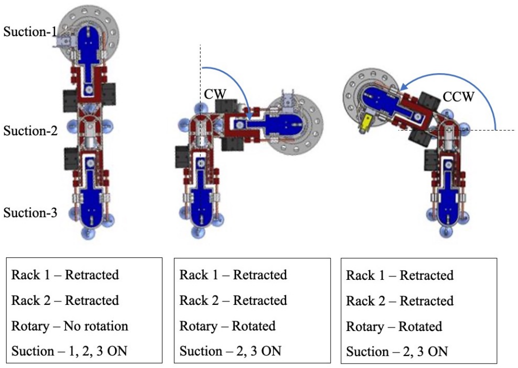


Fig. 10. *Rotary* Motion actuation sequence.

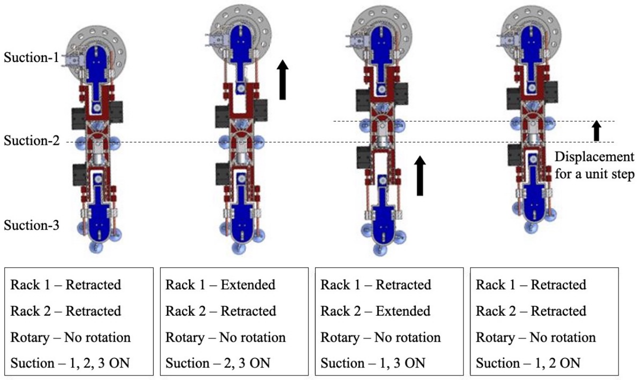


Fig. 11. *Worm* motion actuation sequence.

IV. ROBOT MOTION

The robot motion features three distinct motion types: *worm*, *butterfly*, and *rotary* to enhance flexibility and adaptability. These motion types can be used to achieve fast movement and to travel in tight spaces. The robot is equipped with three mechanisms to achieve the required movements.

A rack and pinion mechanism was designed to facilitate the linear movement between the two links of the module. These modules are interconnected by a rotary joint, which enables *rotary* motion (refer Fig. 10). The *worm* motion is achieved by alternately switching vacuum pumps and allowing rack mechanism extension and retraction (refer Fig. 11). The *butterfly* motion integrates both *rotary* and *worm* motions simultaneously (see Fig. 12). The suction units are designed with passive rotary joints to acquire the rotation around the fixed suction units when the rotary joint motor actuates in *rotary* motion and *butterfly* motion.

These three joints require motors that are both powerful and lightweight to handle high joint torques and maintain position even in the event of power failure. Consequently, DC worm gear motors are chosen as their worm wheel mechanism enables self-locking the joints.

V. MOVE-OVER MECHANISM

Incorporating a move-over mechanism is crucial for glass cleaning robots to successfully navigate over window frames.

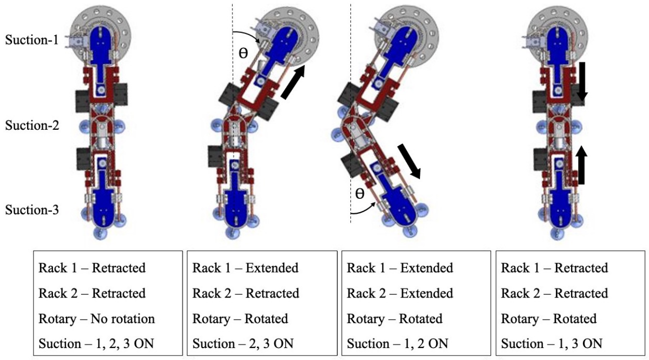


Fig. 12. *Butterfly* motion actuation sequence.

Algorithm 1: Window Frame Move-Over

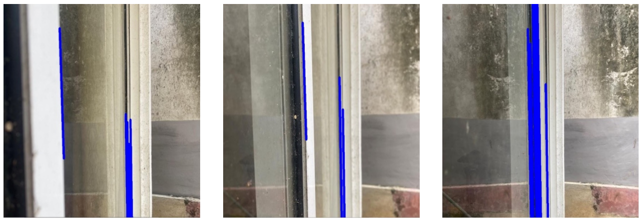
```
if Window frame detected then
    if Robot closer to window frame then
        for $i = 1$ to 3 do-
            Suction $i$ - off & Thread bar $i$ - lift;
            Rotate rotary joint;
            Thread bar $i$ - lower & Suction $i$ - on;
    end if
else
    Perform Butterfly Motion
    Perform Worm Motion
    Perform Rotary Motion
end if
```

The specific design requirement in this robotic system is to effectively move-over window frames up to 25 mm in height.

A thread bar mechanism is employed on each of the three suction units to acquire the required linear motion, and DC gear motors with an operating torque of 0.2 Nm are used to drive the mechanisms. Additionally, limit switches are used to restrict the thread bar travel distance to 25 mm. Linear bearings with an inner diameter of 6 mm are used to guide the suction units when operating. The utilization of thread bar mechanisms offers the advantage of elevating and lowering the suction units independently with lower torques compared to other mechanisms [18]. The Algorithm 1 is related to the robot's movements when navigating over a window frame.

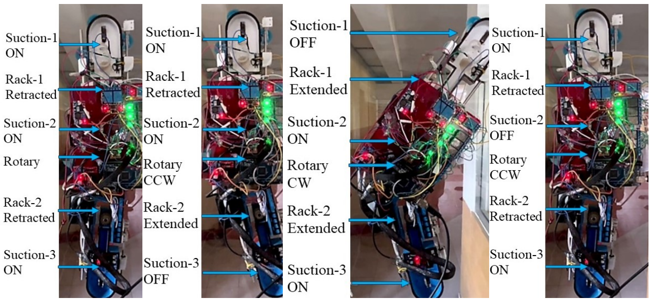
VI. WINDOW FRAME DETECTION

The robot uses an onboard camera as the sensor to identify window frames with the help of the Python open-source computer vision library (i.e. OpenCV). The camera was positioned in the middle of the robot to cover up the required field of view. The camera module captures images continuously and converts them into grayscale format to simplify processing. To reduce noise, Gaussian blur is applied to grayscale images, followed by the canny edge detection for frame identification [19]. The *HoughLinesP* function is used to detect straight-line edges. When the robot approaches an edge, frame identification information is sent to the low-controller to execute the move-over strategy.



(a) Camera Position 1 (b) Camera Position 2 (c) Camera Position 3

Fig. 13. Window frame detection at three camera positions.



(a) Step 1 (b) Step 2 (c) Step 3 (d) Step 4

Fig. 14. WiBot 1.0 performing *butterfly* motion on a vertical glass.

VII. EXPERIMENTAL RESULTS

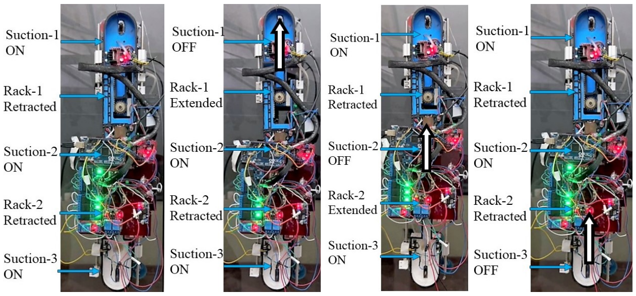
WiBot 1.0 is a prototype of the proposed glass cleaning robot and was tested to verify the main functionalities. The robot links are 3D printed with PLA material using 20% fill, and a topologically optimized 1.6 mm sheet metal frame is integrated into each link to improve the strength of the chassis. The general specifications of the robot are summarized in Table I, and several experiments were conducted for frame detection, robot motion, and move-over mechanism. The following sections are going to discuss each experiment in detail.

A. Window frame detection

The robot successfully identified the window frames through the onboard camera. To assess the robustness of frame detection, a series of tests were conducted wherein the robot was positioned at various locations on the window plane, thereby introducing distance and camera angle variations. Out of 30 attempts, the robot achieved an admirable success rate, correctly identifying window frames in 28 instances (see Fig. 13). This accurate frame identification data holds significant potential for enhancing the robot's navigation capabilities.

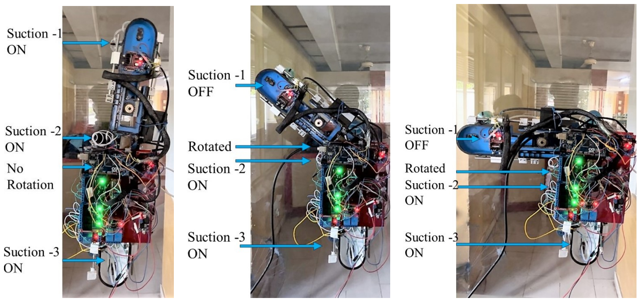
TABLE I
SPECIFICATIONS OF THE PROTOTYPE

Size ($L \times W \times H$)[mm]	800 × 70 × 150
Weight [kg]	3.5
Payload [kg]	3.5
Max frame height [mm]	25



(a) Step 1 (b) Step 2 (c) Step 3 (d) Step 4

Fig. 15. WiBot 1.0 performing *worm* motion on a vertical glass.



(a) Angle position 0° (b) Angle position 45° (c) Angle position 90°

Fig. 16. WiBot 1.0 performing *rotary* motion on a vertical glass.

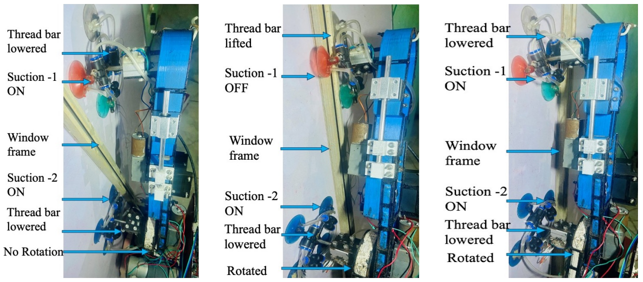
B. Robot speed and Cleaning coverage

The WiBot 1.0 provides three different modes of motion: *butterfly*, *worm*, and *rotary*. In the *butterfly* motion, it can achieve a speed of $36\,\mathrm{cm/s}$ and clean up to $11.8\,\mathrm{m^2/h}$ (see Fig. 14). The *worm* motion allows the robot to navigate through tight spaces, cleaning an area of $2.54\,\mathrm{m^2/h}$ at a speed of $8\,\mathrm{cm/s}$ (see Fig. 15). The *rotary* motion provides rotational speed at $0.3\,\mathrm{rad/s}$ with hourly cleaning coverage of $4.6\,\mathrm{m^2/h}$ (see Fig. 16). WiBot 1.0 achieved these speeds and coverage while cleaning a vertical glass surface without obstacles. The prototype was fabricated to prove the proposed concept. Thus, higher coverage rates can be achieved with fast actuation (i.e. better actuators) and tethered power.

C. Move-over window frames

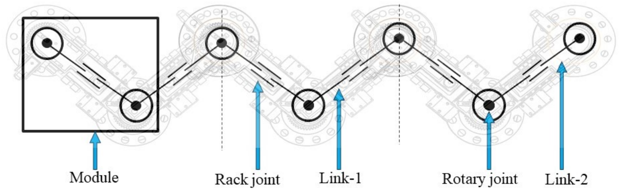
The functionality of the robot's move-over mechanism realized using thread bar mechanisms. Although the mechanism of WiBot is designed for 25 mm, alignment issues caused by fabrication defects of the prototype limited the maximum frame height to 15 mm (refer Fig. 17).

WiBot 1.0 can handle an additional weight of 3.5 kg, which can be used to carry cleaning liquids (i.e. payload). The fabricated chassis could hold a total weight of 7 kg including the payload. The developed prototype's primary limitation is the motion speed. Hence, future versions are expected to enhance its operational speeds using powerful motors and cleaning coverage can also be increased by implementing cleaning pads for each suction unit.

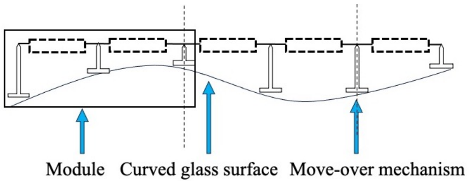


(a) Suction unit at right side of window frame (b) Suction unit on window frame (c) Suction unit at left side of window frame

Fig. 17. Move-over operation in suction unit 1 for a frame gap of 15 mm.



(a) Multi-module glass cleaning robot.



(b) Multi-module glass cleaning robot on a curved surface.

Fig. 18. Schematic diagrams which depict future directions.

VIII. CONCLUSIONS

This paper aims to elevate the building maintenance standards regarding safety and quality through the incorporation of robotics and automation. The key findings include the importance of a sturdy and lightweight chassis for mobility, the suitability of adhesion mechanisms and the effectiveness of cleaning mechanisms. Significant contribution has been made in designing and developing the robot's adhesion, chassis, and cleaning mechanisms. The lightweight chassis design ensures durability and functionality. The WiBot 1.0 has limited speed due to the lack of high-speed and high-torque motors at low cost, and the move-over capability is limited to 15 mm window frames. Future directions of the project include the integration of additional modules and curved surface moving capabilities to a future version of WiBot (refer Fig. 18). WiBot 1.0 successfully validates the ability to clean and manoeuvre on glass surfaces with window frame mover-over capabilities. In conclusion, the proposed robot has immense potential to revolutionize glass cleaning operations through its reconfigurable properties.

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