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Research Article

Keywords:

Posted Date: October 26th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-8389481/v1>

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Additional Declarations: No competing interests reported.

A compact multi-legged mobile robot with leg-mounted adhesion mechanisms for climbing walls in narrow spaces

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Key Words: Multi-legged mobile robot, Negative pressure, Wall Climbing, Adhesion mechanism

Abstract: The average age of infrastructure facilities in Japan is increasing steadily and relatively quickly, and the implementation of regular inspection and repair work has become a major concern. In this study, we report a compact wall-climbing robot with a set of legs that could be developed for those applications. Our results show that using a set of legs to move offers strong adaptability to uneven wall surfaces and obstacles and enables movement without dragging the adhesion mechanism. The tip of each leg is equipped with a negative-pressure adhesion mechanism to provide stable adhesion force and accommodate various materials. We describe the development of a device capable of measuring the adhesion force and discuss the design of the robot based on a mechanical model. Finally, we report the positive results of an experimental evaluation conducted to verify the feasibility of the wall-climbing task.

1. Introduction

Infrastructure facilities in Japan are aging rapidly, and the implementation of regular inspection and repair work has become a major issue¹⁾. Furthermore, due to the impact of the declining birthrate and aging population, a lack of sufficient engineers to carry out the required inspections and repairs has become a serious problem²⁾. As a result, there is a growing need for the automation of inspection and repair processes, and demand for robots designed for infrastructure inspection is increasing. Inspections of structural walls for deterioration often requires work at high elevations, which poses notable safety risks for workers. Moreover, manual inspection is difficult in confined spaces such as tunnel structures with narrow passages, ceiling ducts, or around various machinery or equipment, and visual inspections may not be sufficiently thorough. Various types of wall-inspection robots are being actively researched and developed.

Inspection robots considered for these applications include wheeled and crawling types³⁻⁴⁾, multi-legged types⁵⁻⁷⁾, and aerial types such as drone aircraft, especially quadcopters and similar hovering vehicles⁸⁾. Wheeled and crawling types require less energy to move and are relatively easy to control; however, they have limitations in environments with uneven surfaces. Although multi-legged types can traverse uneven terrain, their high degrees of freedom make control difficult. Similarly, flying types can move at high speed through most environments with few obstacles; however, they also face challenges such as requiring complex control systems, difficulties with obstacle avoidance, and vulnerability to disturbances like wind.

Adhesion methods used in wall-climbing robots include magnetic⁹⁾, viscous¹⁰⁾, and negative-pressure adhesion¹¹⁾. Although magnetic adhesion provides a stable adhesion force when the target surface is a ferromagnetic material, it cannot adhere to nonmagnetic materials and tends to increase the weight of the robot. Viscous adhesion offers some notable advantages such as easily generating adhesion force, adhering to various materials, and a compact adhesion mechanism. However, the adhesion force of these methods decreases with repeated use. Negative-pressure adhesion can adhere to various materials and maintain a stable adhesion force even after repeated use. However, some mechanism to evacuate air from the adhesion chamber is required, which results in a larger system overall. Thus, each method and type of mobility involves some unique advantages and challenges. In the design of wall-climbing robots, optimal approaches should be selected according to the intended purpose of the machine and the characteristics of the target environment. The walls of infrastructure facilities and structures are typically composed of various materials such as concrete and

metals. The robot must be able to move stably in confined space and along walls that often exhibit irregularities and obstacles.

In this study, we adopted negative-pressure adhesion to accommodate various materials with a stable adhesion force. We also chose to implement a legged design owing to the strong adaptability to uneven wall surfaces and obstacles and the capability of moving without needing to drag the adhesion mechanism.

The remainder of this study is organized as follows. In the next section, we describe the configuration of the compact wall-climbing robot along with the development of a device capable of measuring the adhesion force. We then discuss the design of the robot based on a mechanical model. Finally, we report the results of an experimental evaluation of the feasibility of wall-climbing, which verified that the task is feasible with the design considered here.

2. Multi-legged robot

A comparable six-legged climbing robot¹²⁾ that relied on the effectiveness of negative-pressure adhesion was proposed in a previous study as shown in Fig. 1. The robot's structure consists of a set of adhesion mechanisms equipped with passive suction cups at the tip of each leg with motors that control the leg to make a swinging motion and perform the adhesion and detachment processes. The robot was designed to walk with a stable gait by keeping three legs adhered to the surface of the wall. However, the previous robot was not designed to climb walls. The motion of each leg was limited to swinging along a set path and performing the adhesion and detachment because a simplified control system was prioritized, which led to some notable constraints on the robot's movement while adhered to a wall. Additionally, the passive suction cups lacked sufficient pressing force and thus the entire frame exhibited inadequate adhesion strength. Furthermore, this configuration allowed only planar movement, which made it difficult for the robot to adapt to environments with multiple surfaces such as walls and ceilings.

In this study, the robot's structural design was improved to address these issues. In particular, we considered the adhesion mechanism. To that end, the range of motion of the legs was increased in terms of degrees of freedom to reduce constraints and to optimize the number of legs so as to miniaturize the entire frame and further simplify the control system. As for the adhesion mechanism, we focused on quantitatively understanding the adhesion force generated by the mechanism as a basis for design considerations. The following sections describe the development of a device for measuring adhesion force and the selection of adhesion pads using this measurement device. Furthermore, we present the newly designed four-legged robot configuration and the verification of its operation at the level of individual leg units.

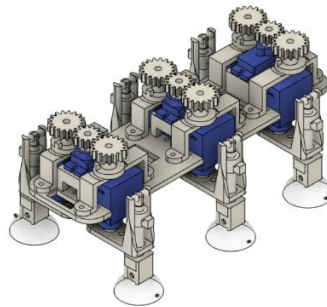


Fig. 1 Six-legged mobile robot¹²⁾

3. Adhesion force measurement

For robots designed to climb walls, the adhesion force generated by the mechanism is a critical factor directly linked to stability and mobility. In the negative-pressure adhesion method, the adhesion force enables the mechanism to adhere to the wall. Thus, we quantitatively assessed the performance of the adhesion mechanism during the design stage. To support the design of the adhesion mechanism, we assembled a dedicated experimental device to measure the

adhesion force. The negative-pressure adhesion force F is expressed by the following equation (1) based on the pressure difference ΔP inside the suction cup and the cross-sectional area A .

$$F = \Delta P \times A \quad (1)$$

Furthermore, the cross-sectional area A can be expressed in terms of its diameter D as shown in equation (2) given that a circular suction cup is used.

$$A = \frac{\pi D^2}{4} \quad (2)$$

The theoretical adhesion force was calculated from the relationship between the size of the suction cup and the pressure inside the cup.

3.1 Adhesion force measurement equipment

Figure 2 shows the device made to measure the adhesion force. Its configuration was as follows.

- **Adhesion mechanism:** We used commercially available suction pads with multiple interchangeable types of different shapes, materials, and sizes.
- **Vacuum generation unit:** The system incorporated a linear vacuum pump (vacuum level: -33,300 [Pa]).
- **Measurement sensor:** A load cell was used to measure the adhesion force as a voltage value.
- **Measuring instrument:** An oscilloscope was used to record and provide the load cell's output voltage.
- **Display unit:** This was used for real-time monitoring of adhesion force during the experiments (unit: N).

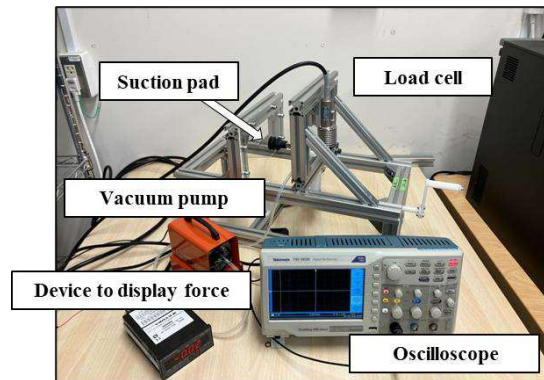


Fig. 2 Adsorption force measurement experimental system

3.2 Adhesion pad selection

The adhesion performance of a wall-climbing robot greatly depends on the shape, material, and size of the adhesion pads. For the negative-pressure adhesion method, the degree of contact with the surface and the deformation characteristics directly affect the adhesion force. Thus, the proper selection of adhesion pads is essential. To compare the performance of different pads, we measured the adhesion force under the following conditions.

- **Shape comparison:** Flat (PFG), three-stage bellows (PCG), and independent foam types (PDF, PCTK)
- **Material comparison:** Nitrile (N) and urethane rubber (U)
- **Size:** Same diameter sizes (10 [mm], 20 [mm], 30 [mm])
- **Notation for comparison:** Shape_Size_Material (Example: PFG_30_U)

Figure 3 shows the appearance of each adhesion pad.



Fig. 3 Suction pads

3.3 Experiments

The experimental conditions are listed in Table 1. An acrylic plate was used as the wall surface, and 10 measurements were conducted for each adhesion pad. The experimental results are presented in Table 2, and a graph of the results is shown in Fig 4.

Table 1 Experimental conditions

Number of experiments	Exhaust time[s]	Wall material
10	10	Acrylic

Table 2 Experimental Results

Suction pad	Maximum force [N]	Minimum force[N]	average force[N]
PFG_10_N	3.6	3.4	3.5
PFG_20_N	13.7	11.9	13.2
PFG_30_N	26.7	25.7	26,4
PFG_30_U	28.0	24.5	27.1
PCG_10_N	2.6	2.3	2.4
PCG_20_N	11.3	9.7	11.0
PCG_30_N	26.6	22.5	24.5
PDG_20	18.0	17.7	17.8
PCTK_30	23.5	21.9	22.5

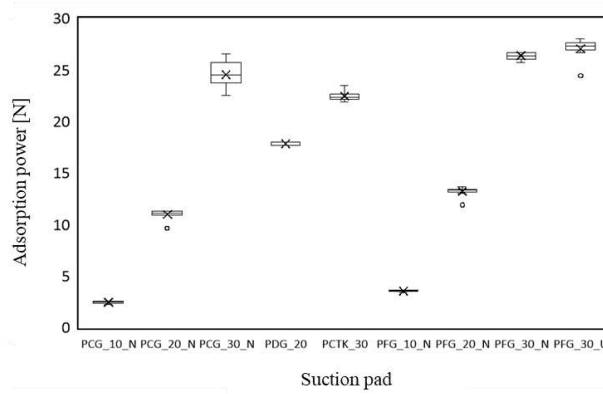


Fig. 4 Experimental results

3.4 Experimental results and discussion

The following trends were identified.

Effects of shape: The flat type (PFG) exhibited the highest adhesion force. In particular, PFG_30_U showed excellent performance, with an average of 27.1 [N], making it a promising candidate for the adhesion mechanism.

Effects of material: The urethane rubber (U) demonstrated a higher adhesion force than the nitrile rubber (N), likely because of its superior flexibility and surface conformity.

Effects of size: A clear trend was observed in which the adhesion force increased with larger diameters.

These results showed that PFG_30_U was the optimal choice for the adhesion mechanism.

In this experiment, the adhesion force was measured using an acrylic plate as the wall surface. However, the walls of actual structures comprising infrastructure facilities are often made of concrete. Concrete surfaces exhibit characteristics such as surface roughness, fine irregularities, and varying degrees of contact with the adhesion surface, which may affect the adhesion force. Experimental measurements of adhesion forces on concrete wall surfaces that simulate real environments remains as a key topic for future investigations for a more realistic evaluation of the performance of adhesion mechanisms. This would also contribute to improving the design accuracy and reliability of wall-climbing robots.

4. Four-legged wall-climbing robot

4.1 Design approach for legged robots

The following issues with the six-legged robot were identified during the design process.

- The motion of each leg was limited to swinging, adhesion and detachment, which constrained movement while adhered to the wall.
- The adhesion mechanism was passive, with insufficient pressing force and unstable adhesion.
- The 6-legged configuration tended to make the robot bulky.
- The control of adhesion and detachment was complex, which placed a heavy burden on the control system.

To address these issues, we implemented the following improvements.

- The number of legs was reduced from six to four to achieve a more compact and lightweight design.
- Each leg was equipped with four links and four joints to increase the degrees of freedom and enable more flexible movements and improved adaptability to different walls.
- An active negative-pressure adhesion system was adopted to ensure stable adhesion force through the use of a linear vacuum pump.
- Efficient forward and backward motion were realized by switching between supporting and swinging legs in a diagonal configuration.

4.2 System Configuration and Principle of Operation

Figure 5 shows an overview of the robot and a mockup prototype created to verify the operating principle. The robot primarily comprised four legs with each composed of four links and four joints. The base of each leg was connected to the main body, and the robot was able to change its orientation by performing a swinging motion. A negative-pressure suction pad is mounted at the tip of each leg as the adhesion mechanism to enable movement by repeatedly adhering to and detaching from the surface of the wall.

The process of walking involves designating two diagonally positioned legs as supporting legs, which remain adhered to the wall, while the remaining two legs move by swinging as the front leg shifts to a position farther from the main body and the rear leg moves closer to the body before adhering. Subsequently, the robot shifts its center of gravity to advance forward. By alternating this process between supporting and swinging legs, the robot achieves forward and backward movement on the wall surface.

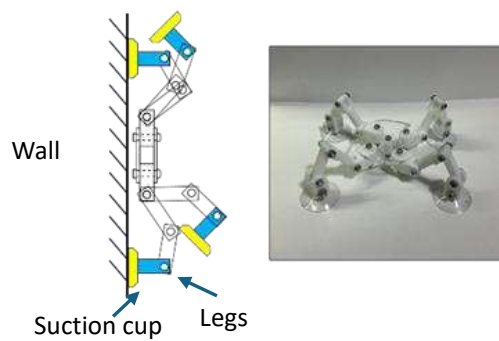


Fig. 5 4-legged robot

4.3 Motion Validation

Using the mockup, we conducted an experimental evaluation of the feasibility of mobile on both a flat surface and a wall. Figure 6 shows a simulation of the transition for planar movement, and Figure 7 shows a simulation of the transition for wall movement.

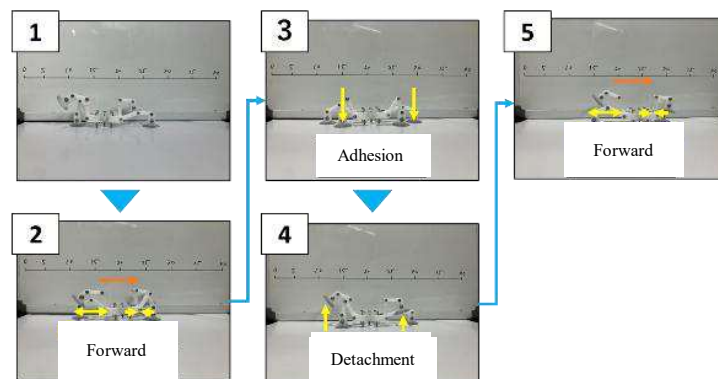


Fig. 6 Movement on a flat plane

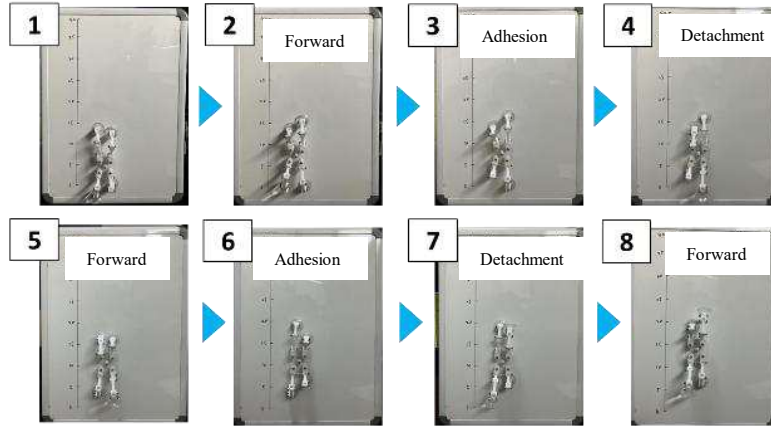


Fig. 7 Movement on a wall

The results of the evaluation verified that the robot was able to operate as intended. The mockup was able to move forward and backward flat and wall surfaces. The switch between adhesion and detachment functioned in coordination with the swinging motion of the legs, and the results confirmed that stable movement could be achieved.

5. Experimental evaluation of adhesion posture with leg unit

We also verified whether the suction pad at the tip of the leg was able to contact the surface of the wall in a parallel orientation. Parallel alignment with the adhesion surface is a critical indicator in evaluating the effectiveness of the leg design because it directly affects conformity to the surface and the stability of the adhesion force in the negative-pressure adhesion method.

The leg consists of four links and four joints, with lengths of the spans between each joint being 27.5, 96.5, 77.5, and 63.5 mm, respectively. The lengths of links 2 and 3 were designed based on the intersection point in the contact direction to ensure that the adhesion unit was able to make vertical contact during 90-degree transitions between wall surfaces. The relationship between each the length of each link and the position of the suction pad is shown in Figs. 8–10.

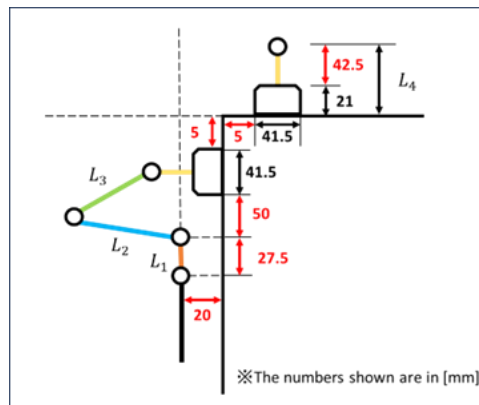


Fig. 8 Conceptual diagram

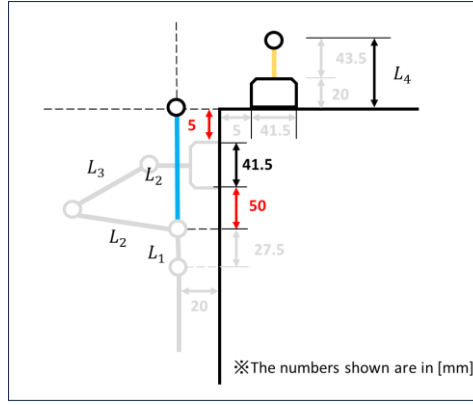


Fig. 9 Link 2 design

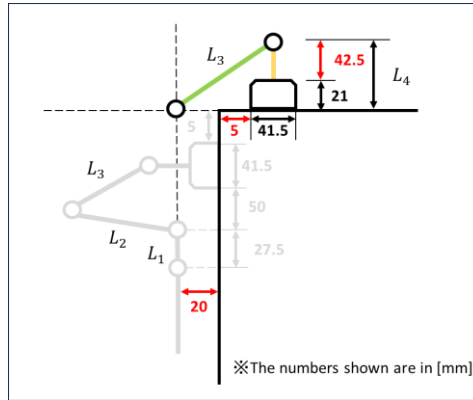


Fig. 10 Link 3 design

5.1 Static analysis of joint torque

During operation of the legs, each joint experiences loads associated with maintaining posture under adhesion and with the movement of the tip of the leg. In this study, we focused on two primary motions of the leg (1) a swinging motion of the leg relative to the base part of the structure, (2) a swinging motion from joints of the leg while adhered to a surface. For each motion, the torque applied to each joint was derived statically based on free-body diagrams. For the two motions, the calculations considered the weight of each link, the mass of the motors mounted on the joints, and the load of the adhesion mechanism. The theoretical equation for the derived joint torques are shown below (equations (3), (4), and (5)). Figures 11 and 12 illustrate the free-body diagrams for the two forms of swinging motion, respectively.

- Swinging motion from the base

$$T_0 = g \left\{ \frac{l_1}{2} m_{l_1} + \left(l_1 + \frac{l_2}{2} \right) m_{l_2} + \left(l_1 + l_2 + \frac{l_3}{2} \right) m_{l_3} + \left(l_1 + l_2 + l_3 + \frac{l_4}{2} \right) m_{l_4} + l_1 m_{m_1} + (l_1 + l_2) m_{m_2} + (l_1 + l_2 + l_3) m_{m_3} + (l_1 + l_2 + l_3 + l_4) m_s \right\} \quad (3)$$

- Swinging motion from the leg joints

$$\begin{cases} T_1 = g \left\{ \frac{l_2}{2} m_{l_2} + \left(l_2 + \frac{l_3}{2} \right) m_{l_3} + \left(l_2 + l_3 + \frac{l_4}{2} \right) m_{l_4} + l_2 m_{m_2} + (l_2 + l_3) m_{m_3} + (l_2 + l_3 + l_4) m_s \right\} \\ T_2 = g \left\{ \frac{l_3}{2} m_{l_3} + \left(l_3 + \frac{l_4}{2} \right) m_{l_4} + l_3 m_{m_3} + (l_3 + l_4) m_s \right\} \\ T_3 = g \left\{ \frac{l_4}{2} m_{l_4} + l_4 m_s \right\} \end{cases} \quad (4)$$

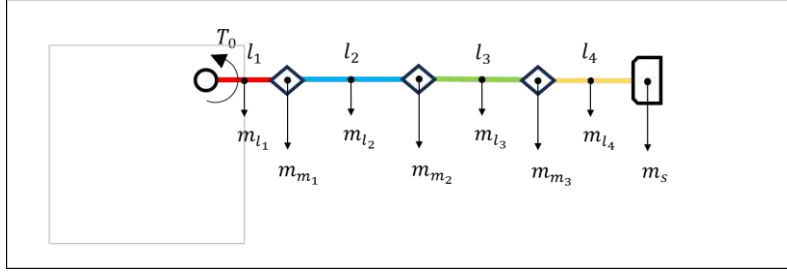


Fig. 11 Swinging motion

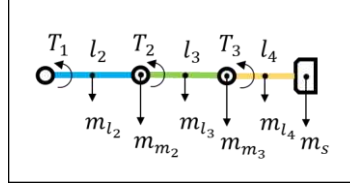


Fig.12 Swing-leg motion

5.2 Verification of operation with a single leg unit

The operation was tested using a single leg unit. The base of the leg was fixed, and rotary motors were mounted on each joint. The joints were actuated sequentially, and video recordings were taken at each state to verify whether Link 3 could perform translational motion while maintaining an orientation perpendicular to the wall surface. As shown in Fig. 13, the results of the analysis confirmed that Link 3 of the leg unit was able to move parallel to the wall surface. This indicates that the suction pad maintained constant perpendicular contact with the wall, which ensured the critical adhesion and suction force stability required for the negative-pressure suction method. These results suggest that the following design elements functioned effectively.

- **Four-link, four-joint configuration:** The high degree of freedom improved mobility along the wall.
- **Torque design based on static analysis:** The theoretical calculation of torque applied to each joint ensured sufficient driving force.

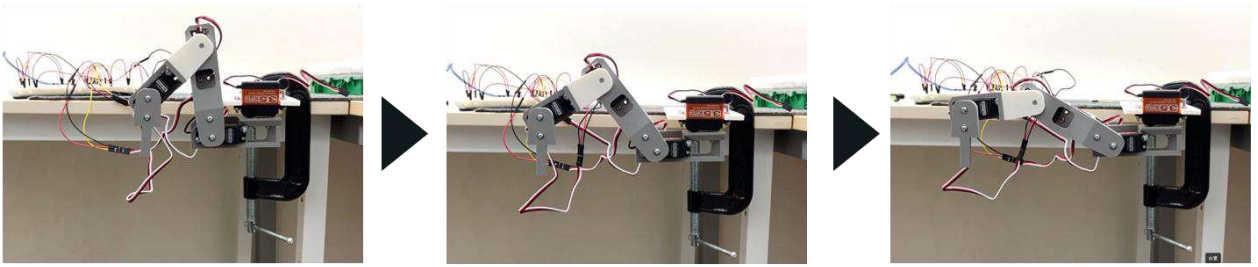


Fig.13 Experimental validation of foot-tip movement via leg mechanisms

6. Conclusions

In this study, we investigated and evaluated a leg-mounted negative-pressure suction mechanism toward the realization of a compact wall-climbing robot designed for the inspection of infrastructure surfaces. By comparing different suction methods and propulsion mechanisms, we determined that the negative-pressure suction method with multiple legs were optimal owing to their stable adhesion across a variety of materials and superior adaptability to uneven surfaces with the need to drag the suction system, respectively. We have proposed a new body configuration with four legs, each being equipped with a four-link, four-joint structure for an enhanced range of motion. This design overcomes some notable challenges with conventional six-legged robots such as excessive constraints, insufficient suction force, and complex control. We developed a device to measure

suction force given that this value is a critical factor in wall climbing and in selecting suction pad. The results of comparative experiments using commercially available suction pads demonstrated that the “PFG_30_U” pad achieved the highest suction performance in terms of shape, material, and size, which established its applicability to the leg mechanism. Furthermore, the results of an experimental evaluation of suction posture using a leg unit demonstrated that the designed link configuration enables the suction pad to maintain parallel contact with the surface of a wall to ensure stability in adhesion and effective posture control. These findings indicate that the proposed suction mechanism and leg configuration are promising for wall-climbing robots.

In the future, we plan to use the suction force measurement device to evaluate adhesion performance on concrete wall surfaces that closely resemble real environments and incorporate these findings to optimize the design of the suction pads. We will proceed with the design, prototyping, and operational verification of a four-legged robot equipped with the suction mechanism and joint-drive motors. Our objective is to develop a more practical compact wall-climbing robot by implementing control circuits and conducting operational experiments in diverse environments.

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