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Basic Mechanical Design of the Omnidirectional Vehicle Units with Magnetic Twin-Caster Mechanism for Realizing the Motion on Thin Film Walls

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***Abstract*— Moving along porous membrane walls, such as fabric or mesh, presents a significant engineering challenge for wall-climbing robots. Traditional suction mechanisms, such as suction cups, struggle to adhere effectively to porous surfaces. Additionally, if the wall is non-magnetic, conventional magnetic adhesion methods are also ineffective. While drone-based approaches offer an alternative, there is a risk of damaging the membrane with propellers, and like suction-based methods, maintaining position and posture consumes considerable energy.**

In this study, we address these challenges by proposing a robotic system designed to traverse non-magnetic, flexible membrane walls. The system comprises a vehicle equipped with three omnidirectional drive units, each with two magnetic wheels, mounted on both sides of the membrane. As a preliminary step, we conduct a fundamental analysis of the vehicle's configuration, develop a prototype, and validate its basic effectiveness through practical experiments with the physical model for future system.

1. Introduction:

1.1 Cleaning and Inspection Needs for Membrane Structure

As shown in Figure 1 and Figure 2, man-made structures with membranes include plastic greenhouses, dome membranes used in stadiums for baseball games, and solar sails with thin membranes are ever around world. The inspection and cleaning of such structures is dangerous, inefficient, and costly for humans.

Traditionally, research and development of wall-climbing robots has been highly active, ranging from magnetic-based robots(e.g. [1][7]-[11][18]) designed for ferromagnetic surfaces to systems utilizing suction cups(e.g. [3]-[5]) and adhesive mechanisms(e.g.[6]).This paper presents the basic design of the undercarriage mechanism of a robot that can move effortlessly in a membrane-type environment.

1.2 Problems with Conventional Magnetic Wall Adhesion Mechanisms

Magnetic adsorption mechanisms can be broadly classified into two types: electromagnetic and permanent. In this study, we used a permanent magnet that generates a stable adsorption force with low energy consumption instead of an electromagnet that consumes energy to maintain adsorption.

Many conventional permanent magnetic wall adsorption and power transmission mechanisms use fan-shaped N and S poles arranged alternately and radially to form a cylindrical structure, as shown in Figure 3. Such a system is capable of transmitting power through a total of three axes: two axes of translational motion along the facing plane of the magnetic transmission structure and rotational motion about an axis perpendicular to that plane. However, the nonmagnetic intermediate structure between the input and output structures is not compatible with curvature and when the intermediate structure is thin and flexible, sliding contact may damage or even destroy the intermediate structure, which is the contact target. Therefore, it is difficult to use this type of system for robots that move on the surface of a membrane wall by sandwiching the membrane between two paired units that face each other, as described above.

Figure 1: Environments with membrane structures [13].

Figure 2: Basic concept of the mobile robot for environments with membrane structures [14].

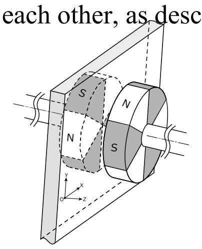
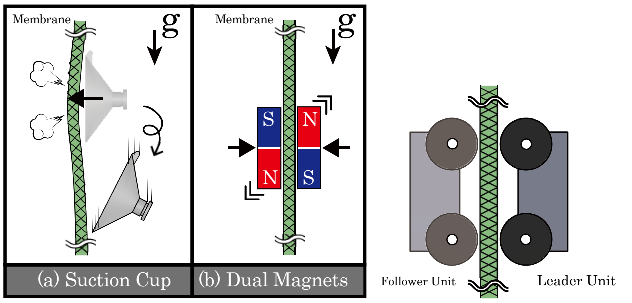


Figure 3: Example of a conventional magnetic drive force transmission mechanism.



(a) Suction Cup (b) Dual Magnets

Figure 4: Dual units adhesion method (in previous research, just only normal wheel[9])

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To address the problems described above, this paper presents a mechanism that enables three-axis power transmission while making rolling contact with an intermediate structure. We designed and fabricated an actual machine based on the presented principles and confirmed its validity experimentally.

2. Magnetic Twin-Caster Mechanism

The basic design of the magnetic twin-caster mechanism developed in this study is illustrated in Figure 4. The two wheels are arranged coaxially with independent rotation on the left and right sides, and the steering axis is mounted at an offset position relative to the wheel units. The casters have a structure that is commonly used in conventional chairs with wheels. For robotic applications, an omnidirectional mobile robot that actively rotates its wheels was developed by Wada et al[2].

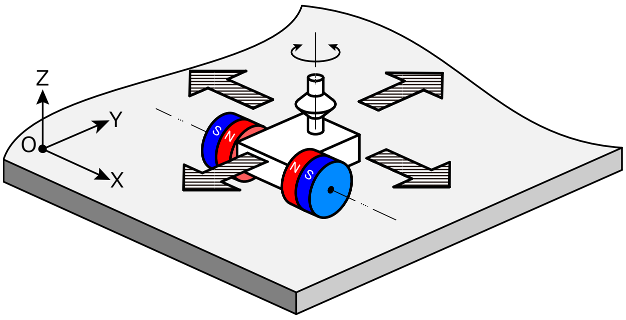


Figure 4: Basic design of the proposed magnetic twin-caster mechanism.

Because magnets with different N/S polarities are used on the front and back sides of the wheel body in this caster mechanism, the wheel does not need to be pulled off the running surface magnetically when it rotates, resulting in low resistance. Therefore, by adhering to a magnetic wall or preparing an equivalent vehicle unit on the opposite side of the wall, adsorption can be maintained, even if the wall material is nonmagnetic.

Experiments were conducted to verify the validity of these concepts after constructing a prototype machine. In previous work, we developed spherical omnidirectional wheels [15] and leg-wheel robots [16] that improved obstacle traversal by designing the mechanisms to match the size of their diameter. Building on these concepts, we are going to enhance the wrinkle-negotiation capabilities of sheet-like mobile platforms in the future. Furthermore, we anticipate that this structure will ultimately be applicable to devices with sheet-like configurations [17].

3. Prototype Construction

3.1 One-unit structure

Figure 5 presents one caster unit used in the proposed magnetic twin caster prototype. Figures 4 and 5 present an oblique view and two additional views of the prototype vehicle with three mounted caster units, respectively, and Table 1 presents the vehicle specifications.

Figure 5: A single unit of the magnetic twin-caster mechanism.

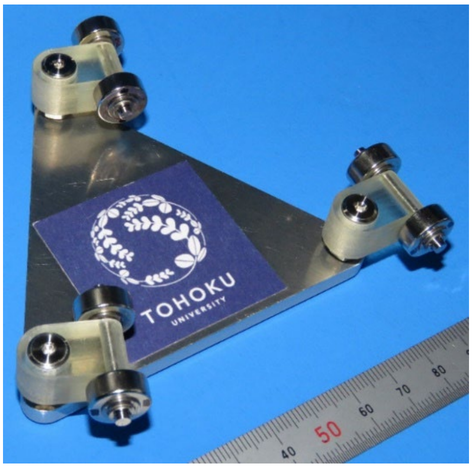
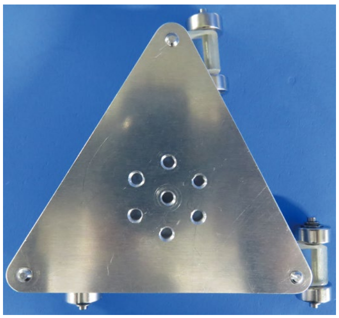


Figure 6: Oblique view of the prototype vehicle with three magnetic twin caster units.



(a) Top View

(b) Side View

Figure 7: Top and side views of the prototype vehicle.

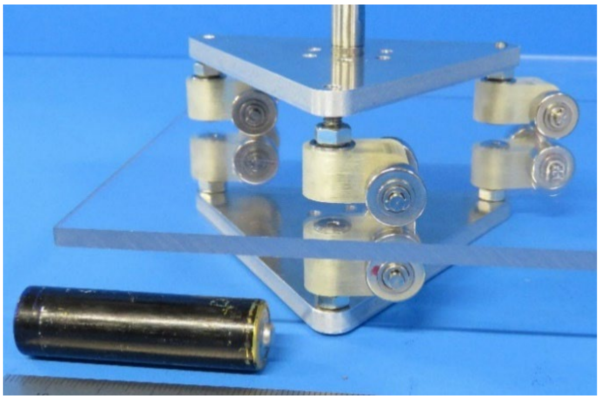
Table 1: Prototype specifications

Magnet width	5 mm
Magnet diameter	12 mm
Adsorption force (axial direction)	23.3 N
Distance between wheels	14 mm
Offset distance of the caster	12 mm
Distance between the casters	75 mm
Total mass	92 g

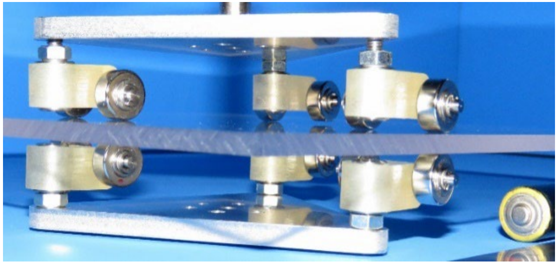
3.2 Prototype implementation: structure with three cater units

The center of the vehicle body contained holes for connecting an input/output shaft. In the first prototype, the magnetic wheel was not active and was rotated passively, acting as a power transmission mechanism. Considering the influence of magnetism, the greater the distance between the twin-caster units, the better the performance, as long as there is no deflection of the vehicle body. In the prototype constructed in this study, the distance between twin-caster units was 75mm.

the future, we plan to integrate this caster mechanism into a unit by incorporating two actuators for the two active rotational axes. This will allow the mechanism to adapt to variations in the distance between caster units.



(a) Oblique view of the mechanical prototype model



(b) Side view of the mechanical prototype model

Figure 8: Prototype implementation with three magnetic twin-cater units.

4. Experimentation using the Prototype Vehicle

4.1 Magnetic adsorption force comparison experiment

An experiment was conducted to compare magnetic adsorption forces. Figure 9 presents the testing setup used in the experiment and Figure 10 presents the experimental results. In contrast to the conventional method, where the adhesive force directly affects the surface of the object to be adhered to, the proposed method uses linear and rolling contacts, which are naturally inferior to direct contact in terms of adhesive force. However, a comparison of vehicle prototypes revealed that because an adhesive force of approximately one-third of that of the conventional design can be achieved using the same number of magnetic units in the proposed design, we believe that the proposed method should be sufficient when transmission with low-loss torque is favored over a high absolute transmission torque. We believe that increasing the value of the transferable torque can be achieved by simply increasing the number of twin-caster units and the distance between them.

(a) Conventional Configuration (b) Proposed Mechanism

Figure 9: Magnetic adsorption force measurement experimental setup.

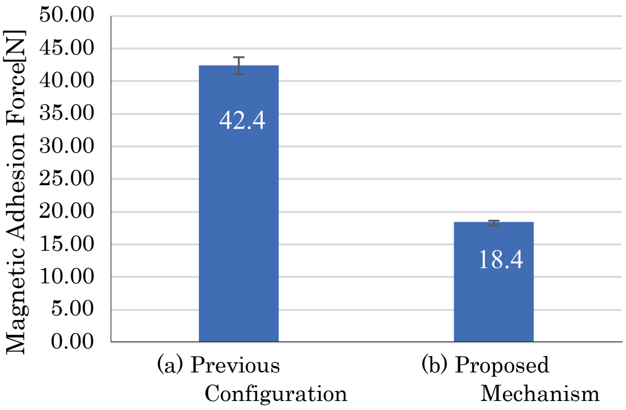
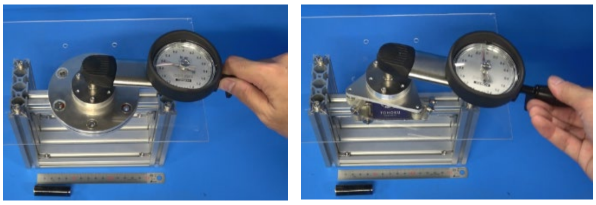


Figure 10: Experimental results for magnetic adsorption force measurement with a magnetic wall thickness of 10 mm.

4.2 Maximum transmission torque measurement experiment

As shown in Figure 11, to measure the maximum transmission torque of the conventional and proposed methods, one of the opposing units was fixed and torque was applied to the other unit until it slipped. The torque applied at the point of slippage was measured using a torque gauge and considered as the maximum transmission torque.

The results are presented in Figure 12. One can see that the maximum transmission torque of the proposed method is lower than that of the conventional method as a result of the use of linear and rolling contacts.



(a) Conventional Configuration (b) Proposed Mechanism

Figure 11: Measurement of maximum transmission torque.

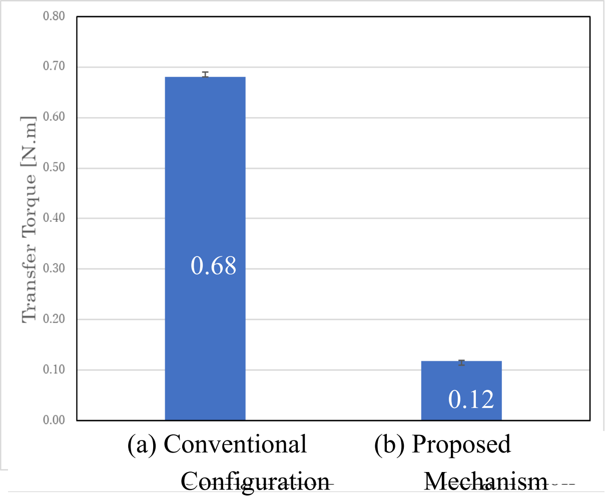


Figure 12: Results of the maximum transmission torque measurement experiment.

4.3 Torque loss comparison experiment

The experimental setup used to measure torque loss is presented in Figure 13. The purpose of this experiment was to compare the losses during torque transmission between the two designs. An acrylic plate was placed between the pairs of units and the torque loss was measured using a torque gauge. The experimental results are presented in Figure 14. One can see that the proposed method with magnetic twin casters significantly reduced torque loss compared to the conventional method

(a) Conventional Configuration (b) Proposed Mechanism

Figure 13: Torque loss measurement experimental setup.

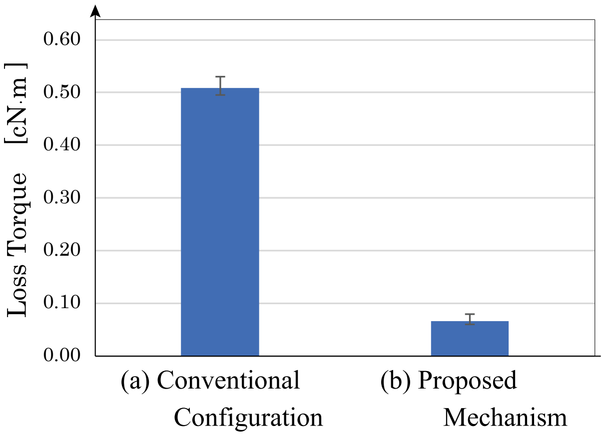


Figure 14: Experimental results for torque loss measurement.

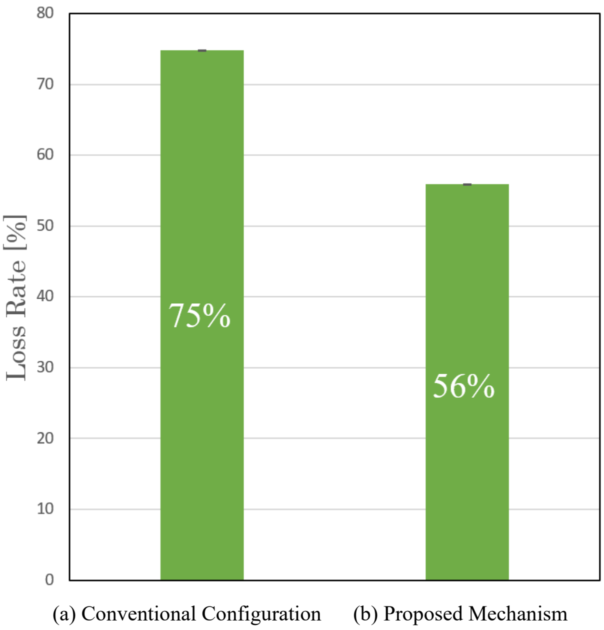
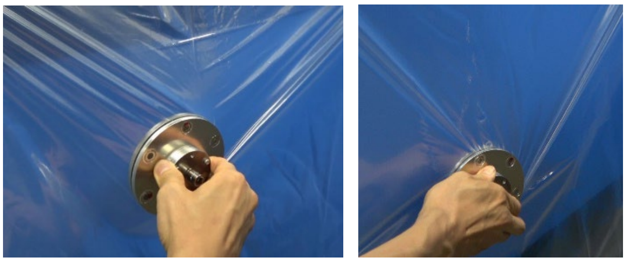


Figure 15: Comparison of loss ratios.

4.4 Experiments on power transmission with thin-film flexible intermediate structures

The operation of the monitoring system used in this experiment to evaluate input and output coupling is presented in Figure 16. Experiments were conducted using a vinyl sheet material of approximately 0.09 mm in sandwiched by each mechanism. Figure 11 presents the results for power transmission using a thin-film flexible intermediate structure with the conventional method. Figure 17 presents the results of the same experiment using the proposed magnetic twin casters. As shown in Figure 11, the conventional method easily causes large deformations such as wrinkles as a result of its sliding contact, which can eventually destroy the film. In contrast, as shown in Figure 17, the proposed magnetic twin-caster mechanism has smooth omnidirectional mobility with relatively wrinkle-free motion, as shown in images (1) to (6), and can also transmit rotational motion, as shown in images (7) to (9). The same experimental results were obtained when using 0.06-mm-thick newspaper as an intermediate structure. Please refer to the video attached to this manuscript.



(a)Major deformation in the form of wrinkles

(b) Film damage caused by sliding contact

Figure 16: Power transmission through a thin-film flexible material using the conventional method.

Although there have been many proposals for moving objects with rigid intermediate structures such as window glass, to the best of our knowledge, no other methods have been proposed for thin and flexible intermediate structures. The proposed method has several potential applications, as shown in the following items.

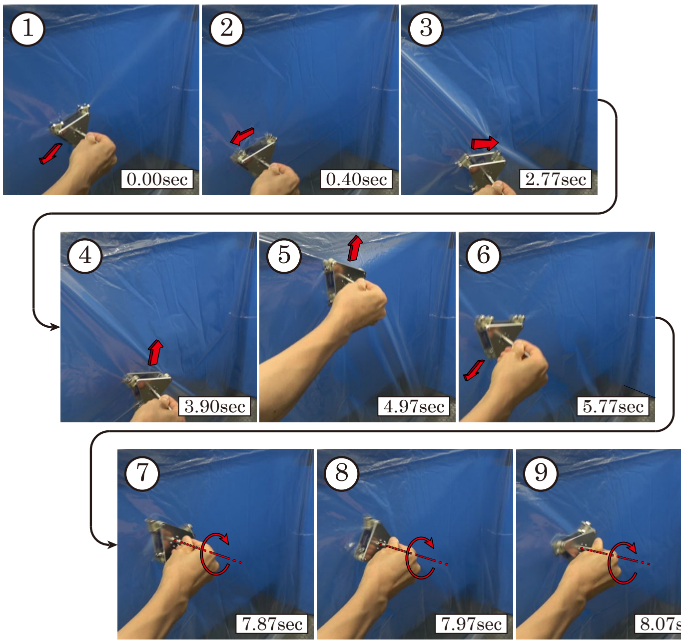


Figure 17: Power transmission through a thin-film flexible material using the proposed method (Please see the following link or the attached video file https://youtu.be/HGypPjvTpFc).

4.5 Experiments with Various Types of Thin Membrane Walls: Preliminary Studies for Future Applications

As shown in Figure 18, we constructed a frame-type experimental setup that simulates the environment of a thin membrane wall. The setup allows for clamping the membrane and adjusting its tension. In the future, we plan to incorporate a two-axis screw mechanism to precisely adjust the direction and magnitude of the tension applied to the membrane. As demonstrated in Figure 19, preliminary experiments were conducted using three types of membranes.

As a result, it was confirmed, as shown in Figure 19(b), that on the Kapton sheet, there are areas where the magnetic wheels stabilize at an inclined angle, which hinders smooth omnidirectional movement, as illustrated in Figure 20(a).

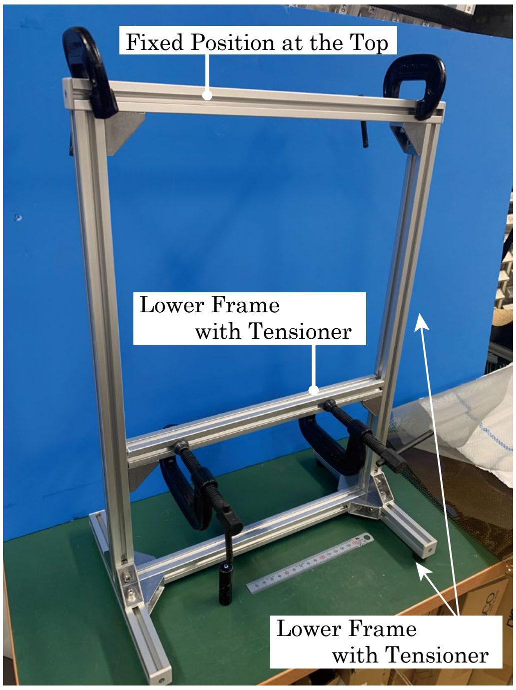
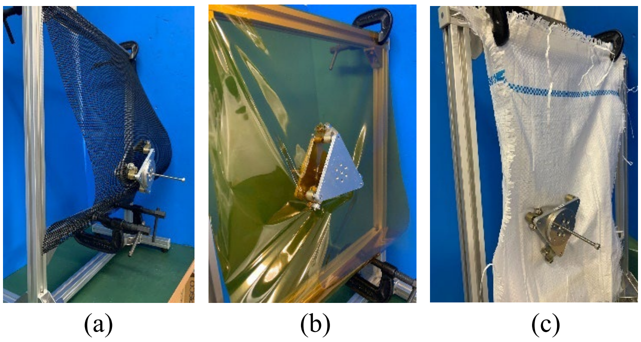


Fig. 18: Experimental Setup for Wall Climbing with Different Tensioner Sheets



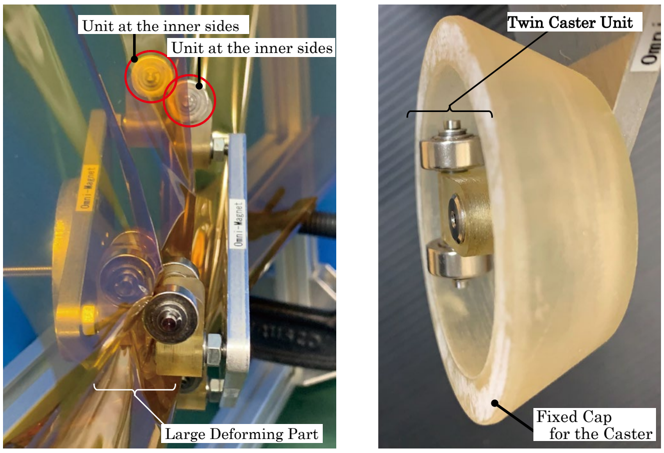
(a) Mech Sheet with 0.8mm Thickness

(b) Polyimide Film with 25µm Thickness

(c) Polypropylene with 0.3mm Thickness

Fig. 19: Wall Experimental Setup with Thin Flame

Moving forward, a new finding suggests the need for improvements, such as adding a cover around the caster mechanism that slides in contact with the surface, as shown in Figure 20(b), to prevent excessive deformation of the membrane surrounding the wheel unit.



(a) (b)

(a) Large Deforming Problem on Polyimide Film with 25μm Thickness (The two pairs of magnetic adhesion units on the outer and inner sides are not symmetrically aligned due to the deformation of the membrane wall).
(b) Cap Mechanism for Prevention of the large passive deformation of Thin Sheet

Fig. 20: Experimental Setup for Wall Climbing with Different Tensioner Sheets

5. Conclusion

In this study, we designed a magnetic twin-caster mechanism that enables three-axis power transmission while making rolling contact with a conventional thin-film intermediate structure. We designed and fabricated a prototype based on the proposed design. The effectiveness of our approach was confirmed through measurements and experiments conducted using the prototype.

Future research prospects include development of the units with cap to prevent the large deformation of the thin wall around the unit. In addition, implementing motorization will be done by integrating motors into the wheel section of the caster unit, achieving the actuation of the wheels, and realizing it as the mobility system for a wall-climbing robot.

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