Proc. of the 9th Intl. Conf. of Asian Society for Precision Engg. and Nanotechnology (ASPEN 2022)
15–18 November 2022, Singapore. Edited by Nai Mui Ling Sharon and A. Senthil Kumar
doi://10.3850/978-981-18-6021-8_OR-02-0019

Design of a Leg Mechanism with Suction Devices for a Hexapod Mobile Robot Moving around Multiple Environments

Ami Matsuura[1], Masato Mizukami[1,#], Naohiko Hanajima[1] and Yoshinori Fujihira[1]

1 Graduated School of Engineering, Muroran Institute of Technology, 27-1 Mizumoto-cho, Muroran-shi Hokkaido,050-8585 Japan
Corresponding Author / Email: m-mizukami@mmm.muroran-it.ac.jp, TEL: +81-143-46-5307, FAX: +81-143-46-5307

KEYWORDS: Hexapod mobile robot, Planes, Pipe, Wire, Winding mechanism, passive suction cups

Infrastructure facilities have been in operation for more than 50 years in Japan but are noticeably deteriorating and require effective inspections. The huge scope of inspections is a major social problem because of a decline in population and super-aging society have resulted in a shortage of skilled inspection engineers. To solve this shortage, robots have been developed that can effectively inspect piping and wall surfaces. However, most robots are for a single environment. Therefore, robots for multiple environments are needed.

We focused on moving not only on a flat surface but also inside pipes and on walls and developed a leg mechanism equipped with a removable passive suction cup. A wire and winding take-up mechanism were also used as the leg raising and lowering mechanism. The leg tips are detachable so that they can be changed when moving on a flat surface, inside a pipe, or when moving on a wall surface. We fabricated a prototype robot equipped with the developed leg mechanism and conducted four experiments. In the first experiment, we had the robot move 500 mm forward on a flat surface. In the second experiment, it turned 90 degrees left and right on the spot. In the third experiment, it moved 500 mm forward inside a plastic pipe with a 114-mm inner diameter. In the final experiment, it moved 100 mm vertically on a wall. The experimental results indicate the usefulness of our leg mechanism.

NOMENCLATURE

P_{max} = Maximum pressure $[\mathrm{N/cm^2}]$
F_{max} = Maximum suction force [N]
V_1 = Volume of suction cup $[\mathrm{cm^3}]$
V_2 = Volume of suction cup at suction $[\mathrm{cm^3}]$
d = Diameter of suction cup [cm]

1. Introduction

There are a wide variety of infrastructure facilities in Japan that were developed during the period of high economic growth from 1955 to 1973. These facilities are aging, and the number of inspection points is increasing at an accelerating rate. Due to the declining population, a shortage of workers to inspect these facilities has become a major issue. To solve this shortage due to the increase in the number of inspection points, there is a need to develop robots that can perform inspections in place of humans.

A wide variety of inspection robots have been developed to meet this challenge. Most can be classified into two main categories: those for wall inspections and those for pipe inspections. For wall-surface inspection robots, leg-type [1] and crawler-type mobile mechanisms equipped with a suction mechanism have been developed, while for in-pipe inspection robots, wheel-type [2] and mechanisms that obtain propulsive force by vibrating cilia have been developed. However, these inspection robots currently support only one environment; it is necessary to use different inspection robots depending on the work environment.

We investigated a design method for miniaturizing a mobile robot for moving on walls and inside pipes and developed a leg mechanism consisting of a combination of a wire and winding take-up mechanism to enable vertical movement of the legs. We fabricated a prototype robot equipped with the developed leg mechanism and conducted walking experiments in multiple environments to verify the usefulness of this mechanism.

2. Problems with previous research and wall movement

In our previous study, a small robot [3] was developed for a flat surface and in-pipe movement, as shown in Fig. 1. Experiments were conducted using the robot to move forward and turn on a flat surface and to move inside a pipe. We confirmed a problem of legs bending in an irregular direction during the movement inside the pipe. The cause of the bending is thought to be a change in the contact between the legs and pipe wall. The addition of a guide that allows the legs to move vertically up and down may be effective, but if the legs are too constrained, they may not be able to follow the curved surface and move forward. Therefore, we thought it would be effective to improve the shape of the leg tips.

To enable wall-surface movement, it is important to maintain a stable suction force to the wall surface. Thus, it is important to select a suction mechanism that not only has a large suction force but also does not interfere with the robot's functionality.

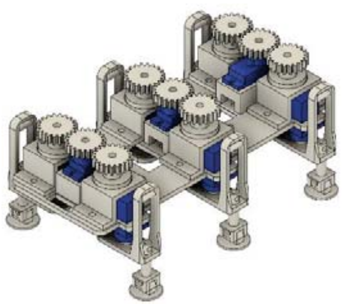


Fig. 1 Robot in our previous research

3. Suction mechanism

3.1 Examination of suction mechanism

There are various suction mechanisms, most of which can be classified into negative suction and passive suction. Negative pressure and electrostatic force are the main methods used in negative suction mechanisms, which provide strong suction but require additional actuators and energy to maintain the suction. Passive suction mechanisms, however, mainly use adhesive materials or passive suction cups and do not require an actuator to maintain suction, but their suction force is inferior to that of negative suction mechanisms.

The requirements for the suction mechanism to be mounted on the robot are that (1) it must be able to be attached to the tip of the leg, (2) no additional actuator, and (3) no wiring or tubing, considering that the robot will also move inside a pipe. On the basis of the characteristics of the suction mechanism and requirements of the robot, we used a passive suction cup as the passive suction mechanism. The passive suction cup has a simple mechanism, so it is easy to change the leg end. However, the suction force of cup is affected by pressing and peeling motions.

3.2 Principle of passive suction cups

Passive suction cups are simple mechanisms, yet they can generate a large suction force by using the difference between low pressure and atmospheric pressure. The key factors are shape and material. Since the suction cups are made of soft materials such as rubber or resin, when the upper part of the suction cup is pressed, the air in the center cavity is pushed out, resulting in a very small pressure in the cavity. As a result, the difference between the cavity and external pressure increases, generating a suction force. The advantage of passive suction cups is that the peeling force is smaller than the pushing force on the wall surface. Therefore, if the pressing and peeling actions can be incorporated into the mechanism, the mechanism can be simplified. To generate a stable suction force, the suction cup must be pressed by 2 mm or more vertically against the wall surface.

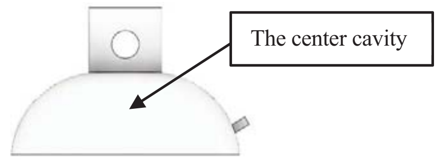


Fig. 2 Passive suction cup

When using passive suction cups, it is necessary to determine the suction force per suction cup to support the weight of the robot. We calculate the maximum suction force F_{max} obtained per suction cup [4]. Atmospheric pressure is 1.033 $\mathrm{kgf/cm^2}$. The maximum pressure P_{max} is expressed as

$$P_{max} = 10.03 \times \frac{V_2}{V_1}, \tag{1}$$

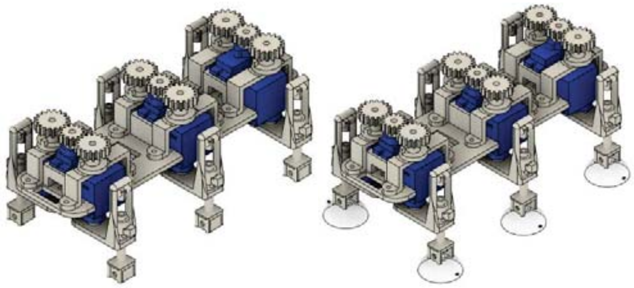
and F_{max} is expressed as

$$F_{max} = P_{max} \times \left(\frac{d}{2}\right)^2 \times \pi \tag{2}$$

4. Mechanical design and fabrication of prototype robot

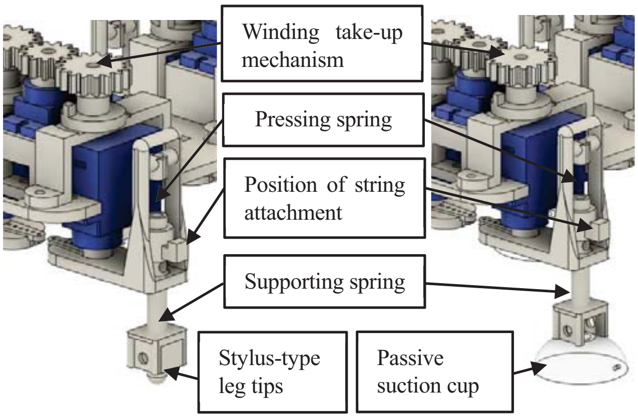
On the basis of previous research, the challenges encountered in wall surface movement, and characteristics of a passive suction cup, we designed the prototype robot shown in Fig. 3. The robot is 175 mm long, 92 mm wide, 85 mm high, and weighs 207 g. It has three legs on each side of the fuselage with a winding take-up mechanism in the center. In a normal hexapod robot, three actuators are used in one leg to achieve three degrees of freedom. In a compact robot such as this prototype, it is important to have a simple structure and reduce the size and number of actuators used. Therefore, the robot's movement direction was limited to two degrees of freedom (up/down and left/right) by using the feature of a normal hexapod robot that the contact between the leg tips and ground is a grounding point.

The legs have a simple structure, as shown in Fig. 4, with micro servo motors for left-right motion and a wire and winding take-up mechanism for up-down motion.



(a) Flat surface and in-pipe (b) Wall surface

Fig. 3 Prototype hexapod robot



(a) Flat surface and in-pipe (b) Wall surface

Fig. 4 Leg Mechanisms

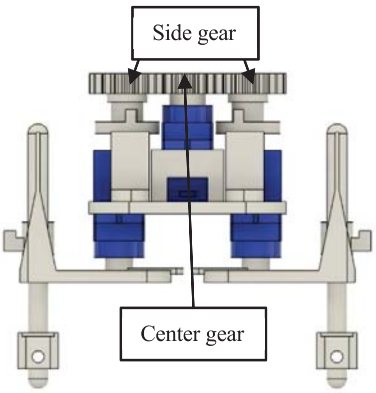


Fig. 5 Winding take-up mechanism

The leg up/down mechanism uses the winding take-up mechanism to raise or lower the leg tips perpendicular to the ground by the amount of wire taken up by the leg. By using this up-and-down mechanism, the legs can be made lighter and a small actuator can be used for the wire take-up. As shown in Fig. 5, the power of the actuator of the winding take-up mechanism is transmitted through three gears. This allows the mechanism to be shared by legs facing each other, reducing the number of actuators.

The leg part that is raised and lowered by the winding take-up mechanism is sandwiched between two types of springs. The upper spring is a pressing spring and the lower spring is a supporting spring. Since the robot in our previous research had only a support spring, it did not have enough force to keep pressing the suction cups against the wall surface when moving. Therefore, by adding a pressing spring to the upper part, a constant pressing force is exerted on the legs to press the suction cups against the wall surface. A suction cup can be easily peeled off by pulling the string attached to the protruding part of the cup.

The leg tips are detachable. When moving on a flat surface or inside a pipe, the stylus-type leg tip is attached, as shown in Fig. 4(a), and when moving on a wall, the suction cup is attached, as shown in Fig. 4(b). Therefore, the let tip can be replaced depending on the environment to enable movement in multiple environments.

The prototype robot was fabricated to confirm the drive of the devised leg mechanism. The wire portion was substituted with a string to make it modifiable.

5. Experiments

Walking experiments were conducted using the prototype robot on a flat surface, inside a pipe, and on a wall. The robot was equipped with stylus-type leg tips when moving on a flat surface or inside a pipe, and with passive suction cups when moving on a wall surface. The amount of leg movement in all experiments was ± 45 degrees to the left and right.

5.1 Forward and turning movement on flat surface

A walking experiment was conducted in which the robot walked 500 mm forward on a flat surface. The flat surface was made of carpet material, and rubber material was attached to the tips of the legs. A tripod gait was used in which three legs moved as a pair. The results of the experiment indicate that the robot was able to move forward over the target distance. The movement time was 30 seconds.

A drive experiment was conducted in which the robot was driven to turn 90 degrees to the left and right on the spot. The experimental conditions were the same as for the forward movement. The left-turning gait was based on the tripod gait. For left-turning, the right-side triad was driven from front to back and the left-side one was driven from back to front. For right turning, the right-side triad was driven from backward to forward and the left-side one from forward to backward. The results of the experiment indicate that the right and left turning movements were possible on the spot. The movement time was 12 seconds.

5.2 Forward movement inside pipe

An experiment was conducted in which the robot walked 500 mm inside a pipe. A plastic pipe with an outer diameter of 120 mm and inner diameter of 114 mm was used. Rubber material was attached to the leg tips. The gait was the same as for the forward movement. The results indicate that it was possible to move forward inside the pipe. The travel time was 30 seconds. The results also indicate that the problem of irregular bending of the leg tips, which had been a problem in moving inside a pipe, was solved.

5.3 Upward movement on wall surface

An experiment was conducted to have the robot walk 100 mm upward on a wall surface. A whiteboard was used as an uneven wall surface. All six legs were first manually adsorbed to the wall surface before moving forward. The same method was used for walking as on the flat surface in the first experiment, and the legs were driven in such a way that one pair of legs facing each other could be interchanged during winding up. To ensure stable suction and detachment of the suction cups, the take-up speed was half the speed of flat-surface movement. However, this wall-surface movement failed.

The failure could be attributed to the lack of pushing force, timing of the passive sucker detachment, and material of the string to be pulled. To solve these problems, it is necessary to examine the combination of two types of springs for the leg mechanism and reconsider the winding and yawning methods for the yawning side.

3. Conclusions

In response to the demand for automated inspection of infrastructure facilities, we studied the moving mechanism for a single robot that can handle multiple environments. We developed a leg raising and lowering mechanism using a wire and winding take-up mechanism that enables the robot to move in multiple environments and change its leg tips in accordance with the environment. We conducted walking experiments with a prototype robot to confirm the effectiveness of the developed leg mechanism.

REFERENCES

1. Saito, A. et al., “Semi-Autonomous Multi-Legged Robot with Sucker to Climb a Wall,” J. Robotics and Mechatronics. Japan, Vol.30, No.1, pp. 24–32, (2018).
2. Mikami, S. et al.,” Miniaturized omni-directional mobile mechanism for pipe inspection robots operating in a small and narrow space,” Proc.ASPEN, E22, (2019).
3. Matsuura, A. et al.,” Proposal and Basic Experiments of Improved Leg Raising and Lowering Mechanism for Small Six-legged Robot,” Proc.JSPE, J23, (2022). [In Japanese].
4. Kawasaki, S., Kikuchi, K.,” A Study of Legged Wall Climbi ng Robot using Passive Suction Cups,” Proc.JSPE Conference on Robotics and Mechatronics (Robomec), 1A2-P07, (2013). [In Japanese].