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ORIGINAL ARTICLE

URARAKA VI: multi-legged robot with suckers to climb walls and pipes

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Abstract

In our previous works, we focused on the advantages of a passive mechanism in realizing autonomous robots, and we developed a multi-legged robot that climbs unknown vertical walls with uneven surfaces. In this study, we improve on our previous robot to broaden its workable area to include vertical pipes and corner walls. To demonstrate the effectiveness of the developed robot, experiments that included climbing uneven walls, corner walls, a large pipe, and parallel small pipes were conducted. Our results confirmed that the developed robot could climb in these environments. We conclude that the proposed mechanism is effective for climbing such unknown complex environments. The proposed robot is expected to be used in the inspection of large-scale infrastructures.

Keywords Climbing robot · Suckers · Infrastructure inspection · Flexible mechanism · Multi-legged robot

1 Introduction

Recently, streamlining the maintenance and inspection of old infrastructure, such as buildings, bridges, and tunnels, has become an important issue. To address this issue, the application of robots is anticipated. In addition, in the event of large-scale disasters, inspection robots are also expected to be employed in search and rescue missions [1–5].

The function of climbing a vertical wall is an important ability for robots, and various robots have been developed for this task, such as wheeled robots [6], legged robots [7], and drones [8].

The most important feature of legged-type robots is their wide application area. They can move across uneven surfaces, such as those having small dents and bumps, by employing legs with suckers. However, as the degrees of freedom of a multi-legged robot is quite high, controlling the robot involves high computational cost, and in general, it is difficult to give the robot autonomous control.

However, in inspection tasks, often many robots are operated simultaneously, therefore, the lack of autonomy is a challenge in practical use.

To solve this problem, in our previous works [9–11], we focused on a passive mechanism and developed various robots that operated in unknown complex environments by utilizing interactions between the robot body and the environment [4, 5].

In this study, we improve on our previous robot to broaden its workable area to include vertical pipes and corner walls. To demonstrate the effectiveness of the developed robot, experiments that involve climbing vertical uneven walls, crossing-walls, and climbing large pipes and small parallel pipes are conducted.

2 Task and environment

In this study, we assume the exterior of a building and pipes in an industrial plant as the work area. We use the experimental environment shown in Fig. 1.

Figure 1a shows an uneven vertical wall composed of tiles and wood boards. Figure 1b shows corner walls and (c) shows parallel pipes (left: 300 [mm] diameter, middle: 200 [mm] diameter, right: 200 [mm] diameter).

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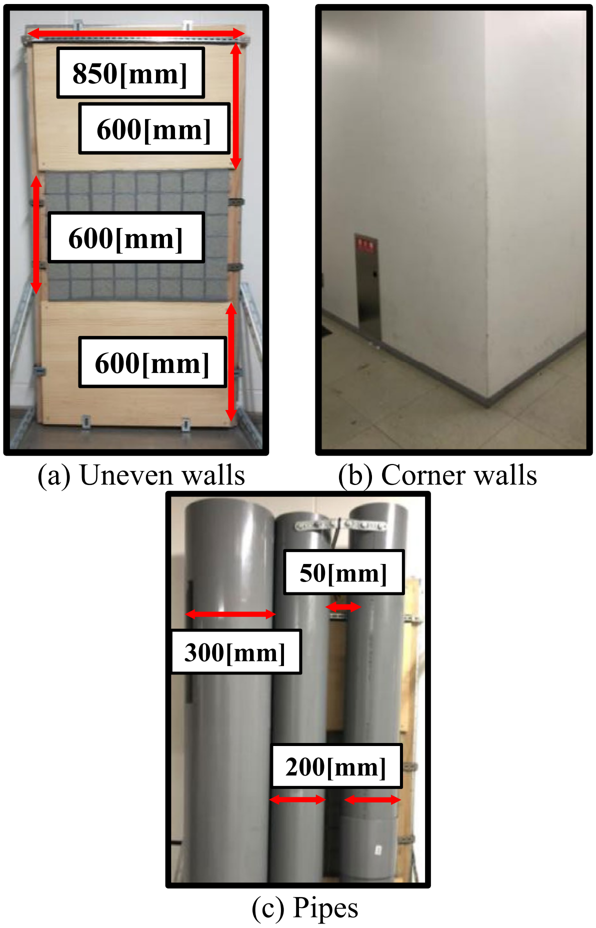


Fig. 1 Wall used for the experiment

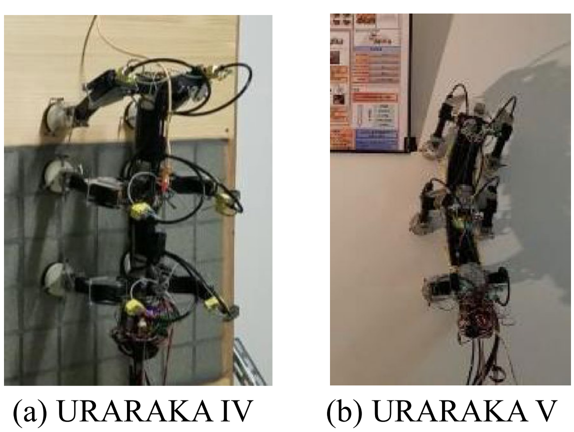


Fig. 2 Previous robot

3 Previous robots

Figure 2 shows the previous robots, URARAKA IV and V [9–11]. URARAKA IV [10] is designed to climb vertical uneven walls using a passive mechanism. For URARAKA V [11], we improved its mobility by combining passive and active mechanisms for the trunk. However, the mobility of the leg is restricted; it cannot climb a pipe or climb a corner wall. Thus, in this paper, we focus on improving the leg mechanism.

3.1 Basic mechanism of URARAKA

As shown in Fig. 3a, flexible or passive mechanisms are employed in various parts of the body, and their stiffness is set to gradually lesser values from the trunk (U7) to the sucker (U1) [9–11]. Owing to these different flexibilities, the robot can passively adapt to the unevenness and curvature of the wall surface. For example, the soft material of the sucker adapts to the small dents and bumps of an uneven surface, and the flexible trunk adapts to the curve of the wall.

To operate the suckers, we employ an air compressor, as shown in Fig. 3b–d. The positive pressure from the air compressor is converted to a negative pressure by the ejector, and the negative pressure is transferred to the sucker. Also, a pressure sensor for detecting miss-adsorption is installed for each leg.

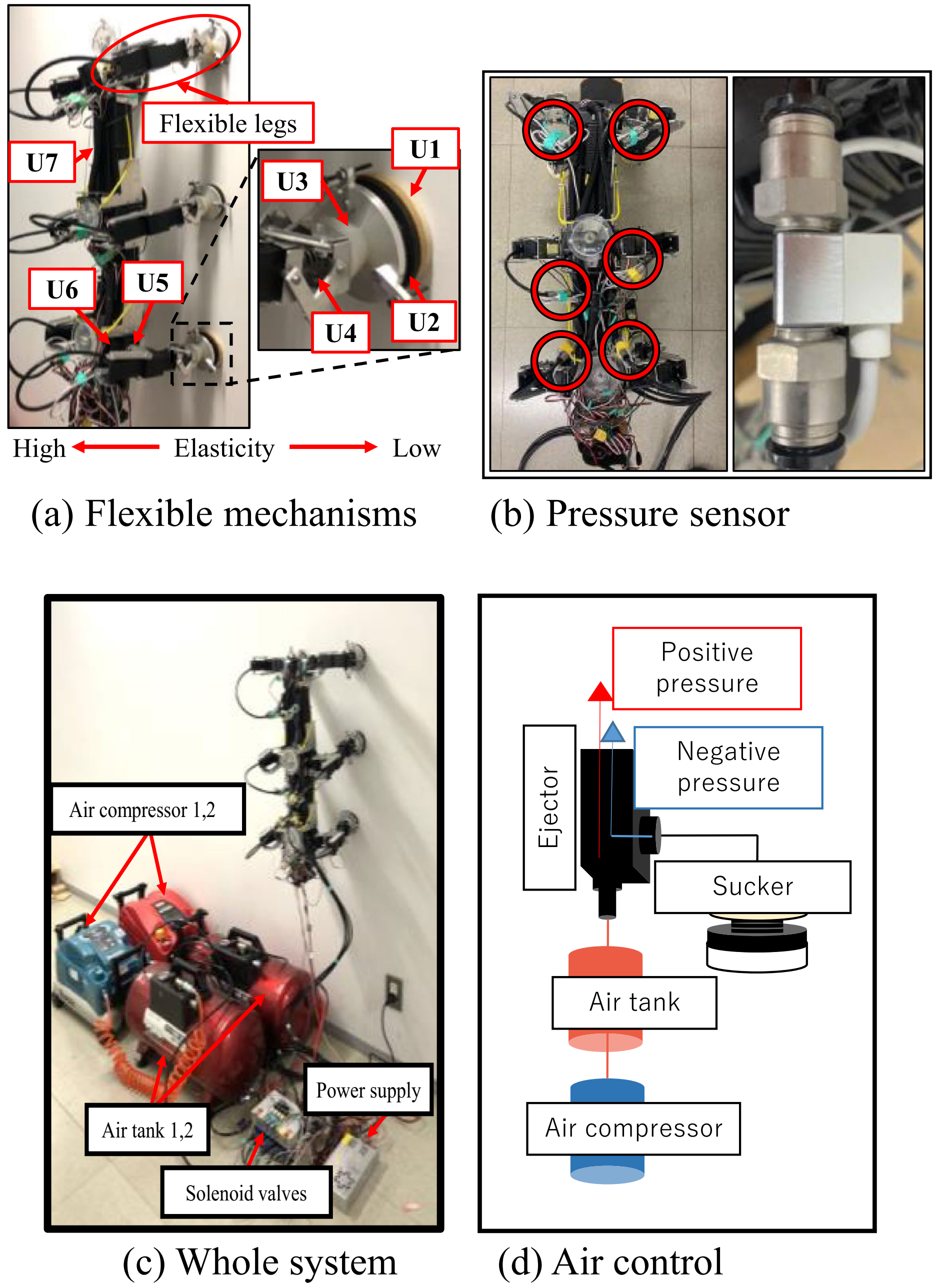
3.1.1 Legs

Figure 4 shows the leg mechanism. Two servomotors are employed for each leg, and translational movement is realized by the link mechanism (U5). In addition, as shown in Fig. 4, to passively adju10st the length of the leg based on the distance between the body and the wall, a small parallel link mechanism (U4) is employed [9–11].

3.1.2 Sucker

Figure 5 shows the sucker [9–11]. The sucker is connected to an ejector and negative pressure is applied. To seal the sucker to the wall, soft sponge (U1) is employed, and because of the softness of the sponge it can adapt to small bumps and dents on uneven surfaces such as the joints between the tiles and the surface of rock wall and the wooden board. In addition, three pins are employed to realize three-point mounting, and

Fig. 3 Mechanism (URARAKA V)



the adsorption force is converted to a vertical force to hold the weight.

Moreover, the sucker has a flexible joint (U3), and it adapts to the slope of the wall passively, using reactive force from the wall as shown in Fig. 5b.

3.1.3 Trunk

The trunk (U7) is composed of flexible bellows, as shown in Fig. 6 [9, 1110,], and it also passively adapts to the curve of the wall. The URARAKA V has a mechanism to turn the trunk to the left or right using a wire-driven mechanism [11].

4 Developed robot: URARAKA

4.1 Outline

In this study, we improve the link mechanism (U5) to make the robot able to climb a large pipe or a corner wall. Figure 7 shows the developed robot URARAKA VI, and U1 to U7 show each of its mechanisms. Table 1 lists the specifications of the robot.

We employ an air compressor with 8L air tank and 38L additional air tanks, and we employ two types of servo

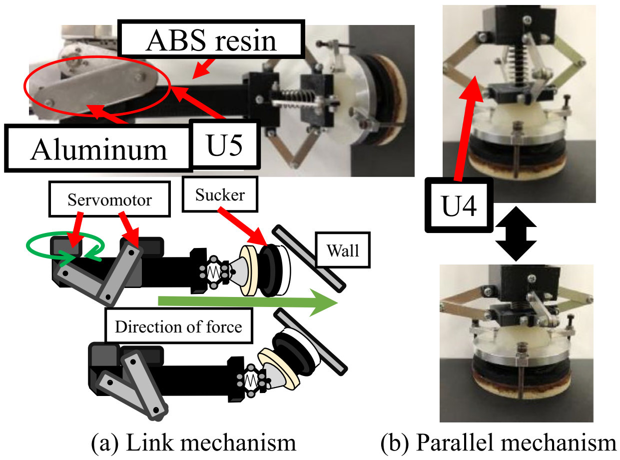


Fig. 4 Leg mechanism

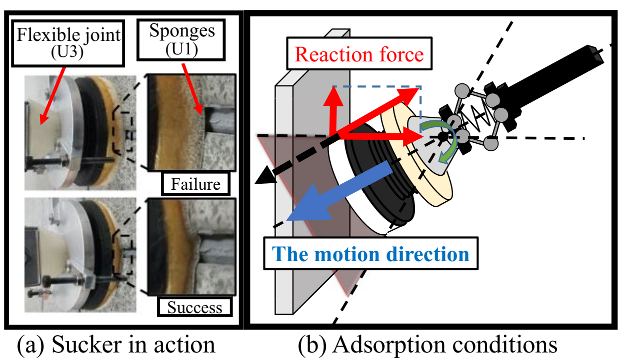


Fig. 5 Sucker

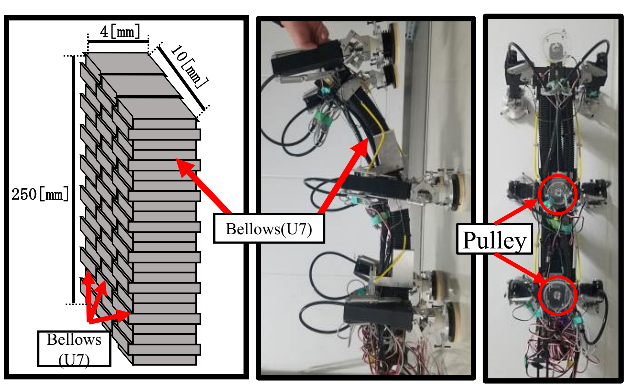


Fig. 6 Trunk (U7)

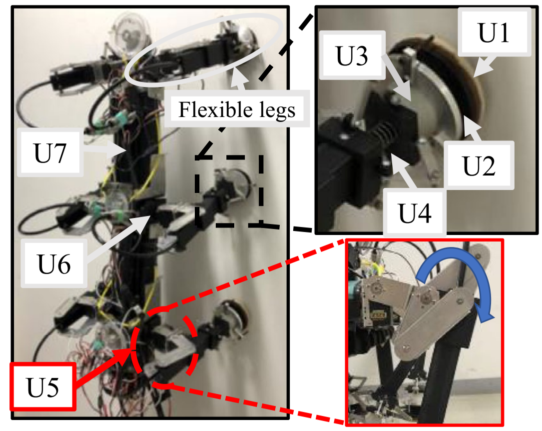


Fig. 7 Developed robot

Table 1 Robot specifications

Robot	Full length	700 mm
	Width	400 mm
	Height	250 mm
	Weight	4.5 kg
Air compressor1	Power	1.5 kW
	Discharge pressure	1 MPa
	Tank capacity	8 L + 38 L
Sucker	Width	70 mm
	Height	50 mm
	Weight	87 g
Servomotor	Model number	KRS-2572HV ICS
		KRS-4034HV ICS
	Main voltage	12 V

motor. KRS-2572HV is employed for the legs and KRS-4034HV is employ for the trunks.

4.2 Developed mechanism

Figure 8a shows the improved link mechanism (U5). This mechanism has a shoulder joint that realizes the motion shown in Fig. 4a, b. Using this mechanism, the robot can climb three-dimensional objects such as pipes and crossing-walls, as shown in Fig. 8. The angle of the shoulder joint is adjusted according to the recovery pattern presented in Sect. 4.3.

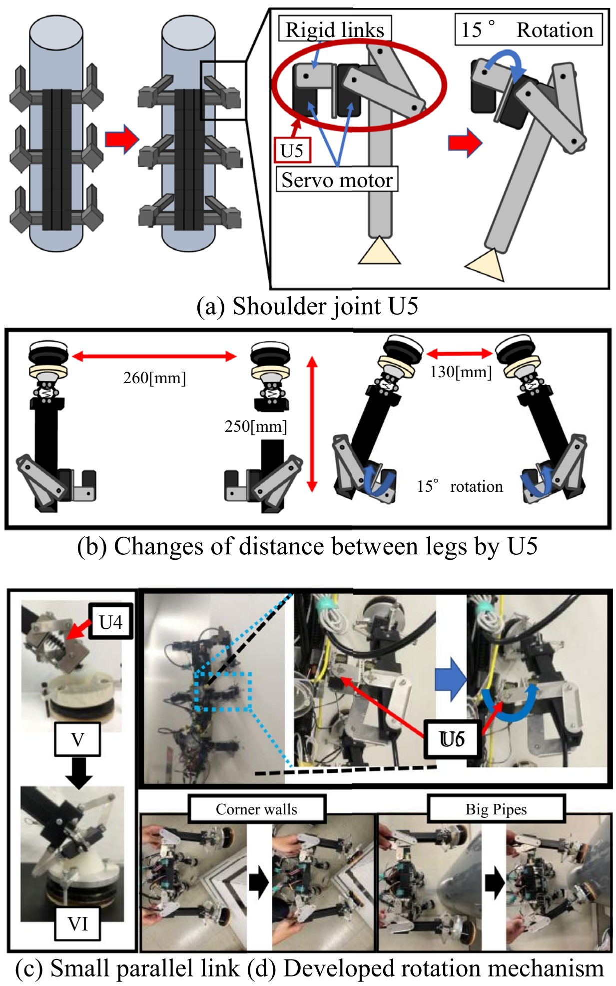


Fig. 8 Developed mechanism

The range of motion of the shoulder joint is shown in Fig. 8b. When the shoulder joint rotates 15°, the distance between the legs is 130 mm.

Figure 8c shows a comparison of the small parallel link mechanism (U4) of URARAKA V with that of URARAKA VI. By widening the link, its movable range is improved. This parallel link has two roles: one is to passively adjust the length of the leg based on the distance between the body and the environment, and the other is to passively adjust the sucker that adapts to the environment.

The developed mechanism is shown in Fig. 8d. The shoulder joint is driven by a servomotor, as shown in Fig. 8d. We find that the mechanism can adapt to large pipes and corner walls.

4.3 Developed mechanism

Figure 9 shows the locomotion pattern. The pattern is preprogrammed, and by repeating the pattern, the robot can autonomously climb walls using the passive mechanisms. The motion to adapt to an uneven surface or a curve is generated by the passive mechanisms.

In addition, to prevent falling due to miss-adsorption, the recovery pattern is as shown in Fig. 9. When a pressure sensor detects miss-adsorption, the regular pattern then changes to the recovery pattern.

5 Experiments

Figures 10, 11, 12, 13 show the results for a rough surface, corner walls, a large pipe, and parallel pipes. Number of steps and time required to climb is indicated in the caption, and the time includes recovery mode.

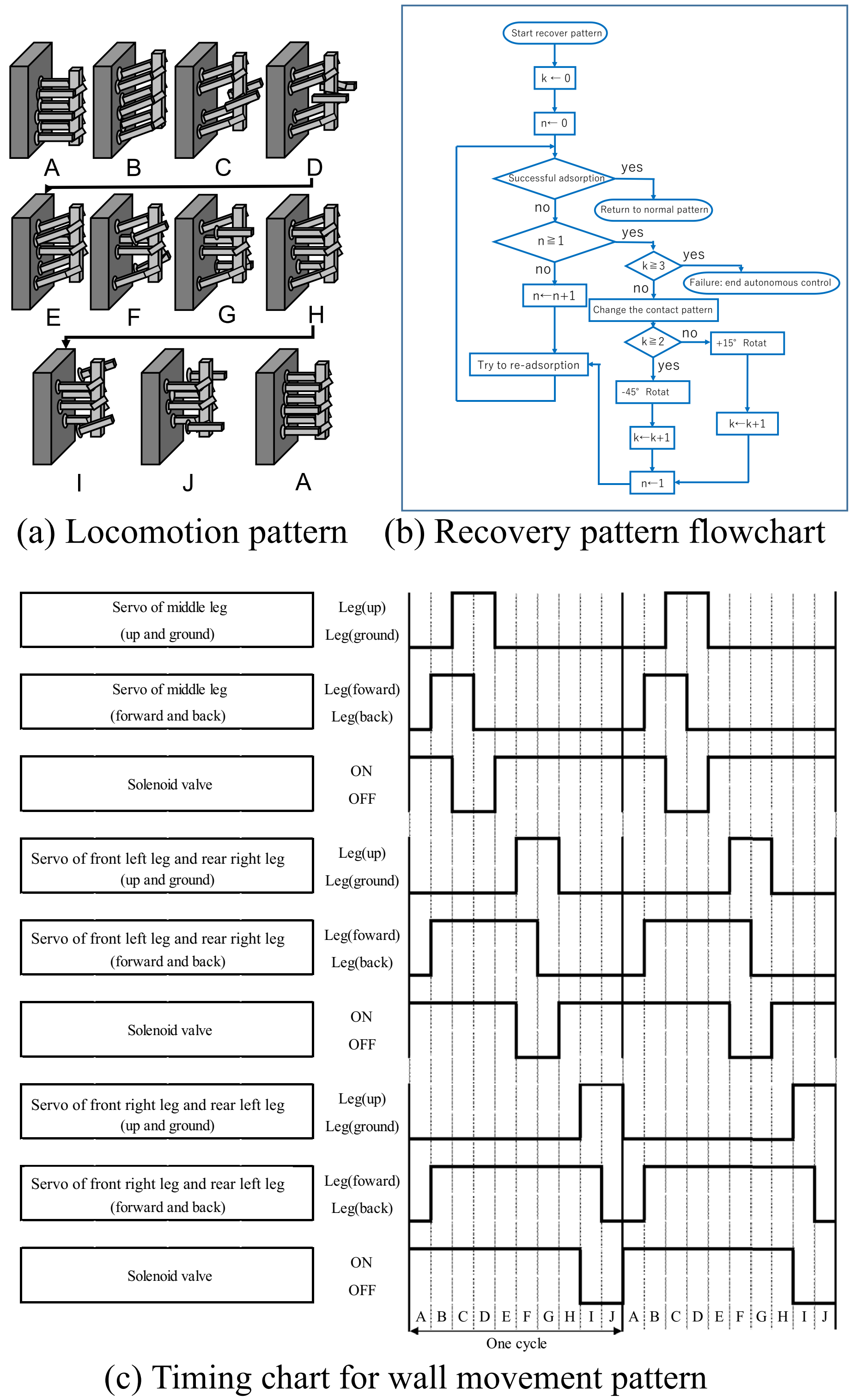
In both cases, we confirmed that the developed robot climbed the walls and the pipes by utilizing adaptive behaviors generated by the passive mechanisms. The important point is that the robot has no sensor with which to measure the complex environment, and the locomotion pattern is quite simple. The adaptive behaviors were autonomously realized by the interaction between the flexible mechanism of the body and the environment.

6 Conclusions

In this paper, we focused on the inspection and maintenance of infrastructures, and we developed a multi-legged robot that could climb various environments such as walls with uneven surfaces, curved walls, corner walls, and pipes. We conducted experiments, and we confirmed that the movable range of the robot was extended by improving the leg mechanism.

In our future work, we will combine the advantages of walking robots and climbing robots, and we will develop a robot that can operate in a broad three-dimensional environment.

Fig. 9 Locomotion pattern



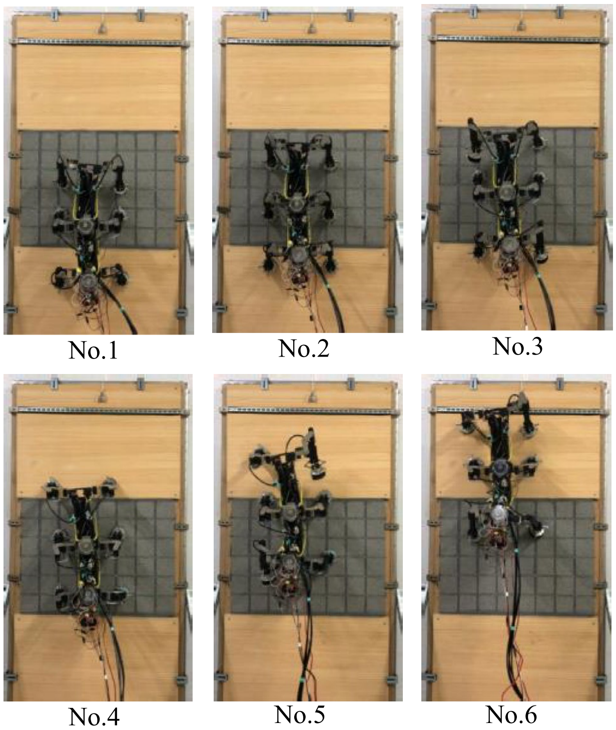


Fig. 10 Uneven walls (8 step,126 [s])

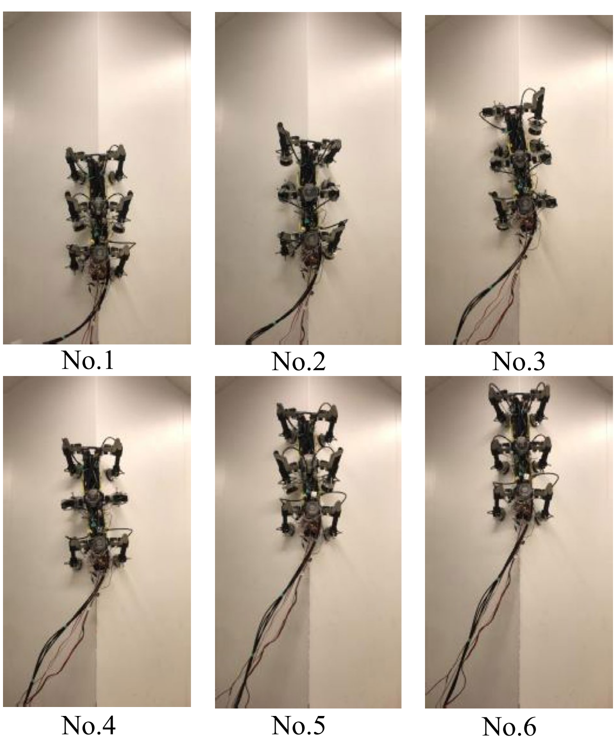


Fig. 11 Corner walls (9 steps,162 [s])

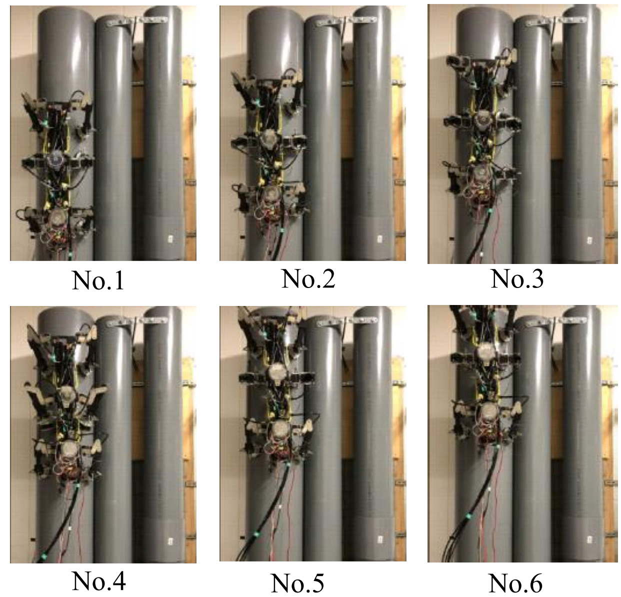


Fig. 12 One large pipe (*d*: 30 [cm], 8 steps,130 [s])

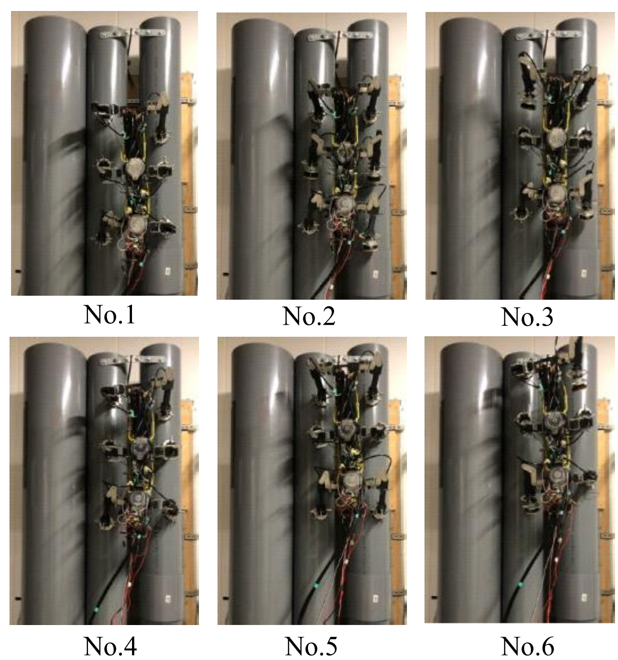


Fig. 13 Parallel pipes (Gap 5 [cm], *d*: 20[cm], 6 steps, 74 [s])

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