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Design and Basic Experiments of a Waterproof Mobile Robot Propelled by RS-Wave Mechanism*

Yu-Chun Fu, Shigeo Hirose, Gen Endo, and Edwardo F. Fukushima

Abstract— **In this research, we focus on developing a new propulsion mechanism and proposed "Rotary Surface Wave (RS-Wave) Mechanism." RS-Wave mechanism generates propulsive force from the whole body and features a simple structure with water and dust tight properties. We have verified the mechanism with a prototype in the former studies. In this paper, the first mobile robot that applied RS-Wave mechanism is introduced. The design of this mobile robot is explained, and the performance of the robot is evaluated by several experiments.**

I. Introduction

There are many tasks that are difficult or dangerous for human beings, such as rescue operation inside collapsed houses, inspection of ceilings or floors, pipeline installation, etc. For this reason, the development of mobile robots that are capable for these operations has been the subject of much research in recent years. At present, most of the mobile robots use wheels or crawlers for propulsion. Wheels and crawlers have good efficiency and stability in locomotion. However, wheels and crawlers have some defects; such as getting stuck when the mobile robot is overturned or when something tangle with their infinite rotating shafts.

Several mobile robots with different propulsion mechanism have been studied. For example, an active flexible cable that is driven by ciliary vibration mechanism [1], a snake-like robot with toroidal-skin-drive mechanism [2], earthworm robot that generate peristaltic motion [3], or pneumatically-driven robot, Slim Slime Robot [4], which is capable of generating various types of locomotion. These robots have unique and novel mechanisms; however, each of them has some defects, such as slow proceeding speed, non-waterproof or complex structure. The purpose of this research is to develop a new propulsion mechanism which has good mobility, a simple structure, and can be easily sealed against water and dust.

II. Overview of RS-Wave Mechanism

This study aims to develop a practical propulsion mechanism for mobile robot. In our previous work [5], an original propulsion mechanism called "Rotary Surface Wave (RS-Wave) Mechanism" was proposed.

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A. Concept of RS-Wave Mechanism

The idea of "surface wave" is to generate wavy motion on the surface of the mechanism as shown in Fig. 1, and the mechanism can be propelled by this motion. Fig. 2 shows the basic principle of RS-Wave mechanism. A disc is fixed on a rotating shaft with certain inclination and eccentricity. When the shaft starts rotating, the edge of the disc performs circular reciprocating motion. By connecting a series of the discs with phase difference, this mechanism provides a wavy motion that produces propulsive force.

RS-Wave mechanism has the following features:

- Generating propulsive motion from the entire body. In this case, it does not get stuck when being flipped over.
- There is no infinite rotating shaft exposed, it does not get tangled and stuck easily.
- It can be sealed against water and dust easily by wrapping up with watertight cover.
- It possesses above-mentioned advantages, but even then it still remains a simple structure and can be driven by a single actuator.

With these features, RS-Wave mechanism is suitable for mobile robot in severe environment. For example, rescue robot which search survivors in rubble, and inspection robot for narrow space that people cannot easily access.

B. Prototype of RS-Wave Mechanism

In order to verify the concept of RS-Wave mechanism, the first prototype of RS-Wave mechanism was built. The basic component of the prototype is shown in Fig. 3. It is composed of an eccentric inclined disc with a large bore bearing and a ring surrounded outward. The prototype consisted of eight component units with 90 degree phase shift between adjacent discs. In addition, all of the rings were connected by bellows which prevents the rings from rotating along with the discs and also prevents water or dust damage the mechanism. Fig. 4 shows the appearance of the prototype.

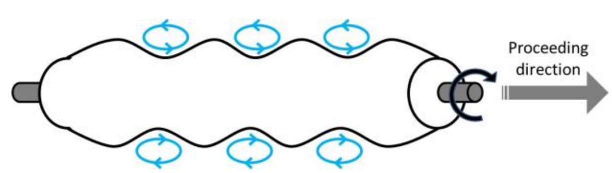

Fig. 1 Concept of RS-Wave Mechanism

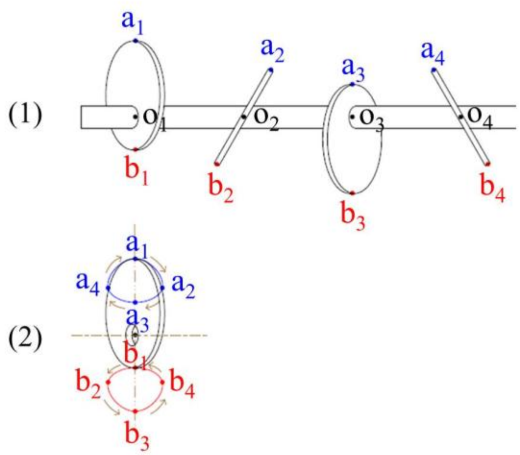

Fig. 2 Principle of RS-Wave mechanism

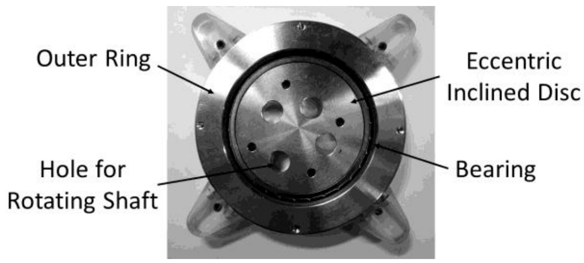

Fig. 3 Basic component of RS-Wave mechanism

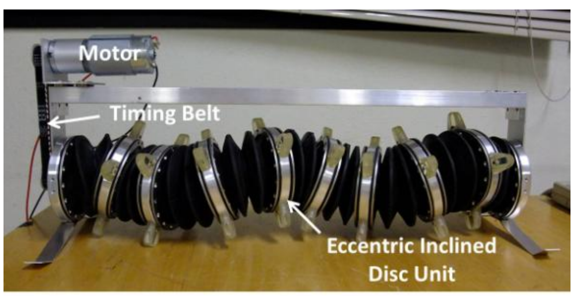

Fig. 4 The prototype of RS-Wave mechanism

The motion of the prototype of RS-Wave mechanism was confirmed experimentally. The results of the experiments validated that this mechanism can generate steady propulsive motion successfully. However, the proceeding direction was not along the axial direction, there was a certain deflected angle. The angle is affected by the design parameters of the eccentric inclined discs. The proceeding toward a deflected direction is unfavorable for the robot to enter narrow space.

The effect of variation of eccentricity and inclination of the disc were also examined by kinematic analysis and experiment. The result indicated that larger eccentricity and inclination can increase the propulsion speed, but due to large deformation of the bellows, it required lager torque while the mechanism is driven. Here exists the trade-off on selection of design parameters.

III. Design of Mobile Robot

A. RS-Wave Unit with Built-in Actuator

The first prototype of RS-Wave mechanism is driven by a motor that is fixed on an exterior frame. For a better applicability, the design should be more compact and it is better to replace the exterior frame by an interior structure and a build-in actuator.

Fig. 5 shows the modified structure of RS-Wave mechanism. The eccentric inclined discs are mounted on a rotating pipe instead of a rod. Inside of the rotating pipe, there is another pipe that connects the front and rear parts. Inside the internal fixed pipe, the motor, motor driver and controllers are placed. The motor drives the external rotating pipe through a custom made planetary gear set, which is shown in Fig. 6. The sun gear is fixed on the output shaft of the motor, and an inner gear is fixed on the rotating pipe. There are two pinion gears that transfer the power from the motor to the inner gear. Besides the pinion gears, there are four fixed supports that connect the internal pipe with the front lid of the mechanism.

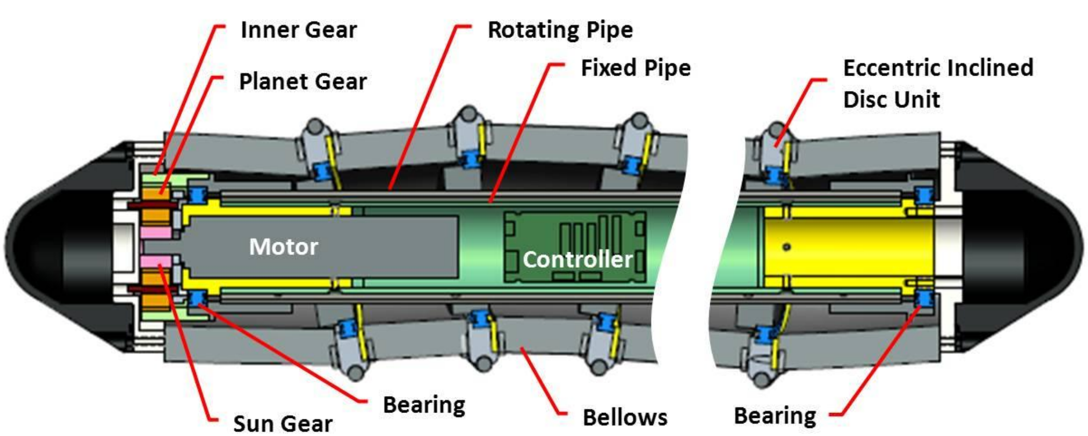

Fig. 5 Structure of RS-Wave unit

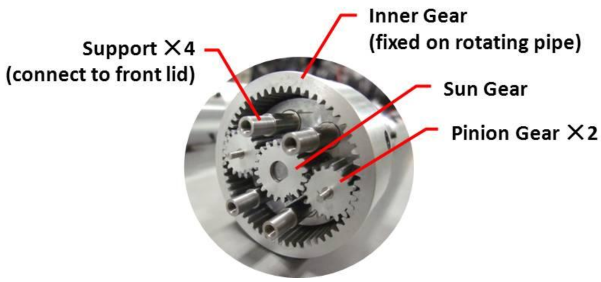

Fig. 6 Planetary gear set

Fig. 7 shows the section view of one eccentric inclined disc unit. From the center, there are the eccentric inclined disc, a large bore bearing, and an external ring. The edge of the external ring which contact to the ground is covered by rubber. There are bellows between each disc unit that protect this mechanism from water and dust. To fix the bellows, there are pressing rings on both side of the external ring, rubber bellows are clamped between the rings.

The design parameters of the eccentric inclined disc units are shown in Table 1. The radius of each external ring is 44mm, and the internal disc has an inclination of 10 degrees and an eccentricity of 3mm. One RS-Wave unit has 8 eccentric inclined discs in series. The adjacent discs are separated by 50mm and have 90 degrees phase difference. Hence, the wave length generated by this RS-Wave unit is 200mm. These parameters were decided regarding the size and energy efficiency. The space inside the internal pipe needs to be wide enough to accommodate sufficiently the motor and controllers. At the meanwhile, the total size of the robot is preferred to be miniaturized for locomotion in narrow space. Thus, small eccentricity and small incline angle of the disc were chosen. Besides, it also allows the mechanism not wasting much power on the resistance of bellow deformation. However, there is a tradeoff that the robot is unable to run fast.

A simple kinematic simulation with these design parameters was conducted. The black circular loop in Fig. 8 is the trajectory of the lowest point on the disc during one rotation cycle. In four different phases, the discs will contact the ground alternately; the period indicated in red is the period that each disc contacts to the ground and generating propulsion force. The stride length is 10.7mm. Therefore, the proceeding distance in one revolution of the rotating pipe is 42.9mm. The rotational speed of the rotating pipe is 109.4 rad/s, and thus the maximum proceeding speed is 78.2 mm/s.

TABLE 1 DIMENSIONS OF ECCENTRIC INCLINED DISC UNIT

Radius r	44 mm
Inclination ϕ	10°
Eccentricity e	3 mm
Interval between discs	50 mm
Phase shift between discs	90°

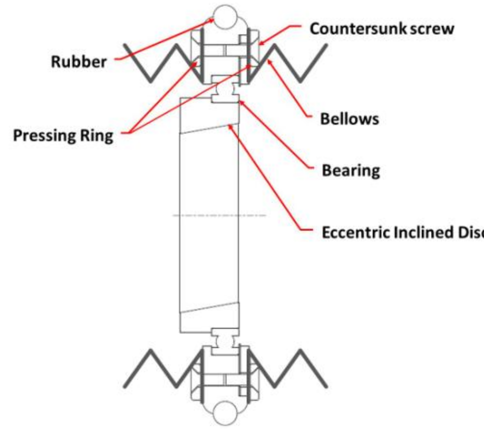

Fig. 7 Design of the eccentric inclined disc unit

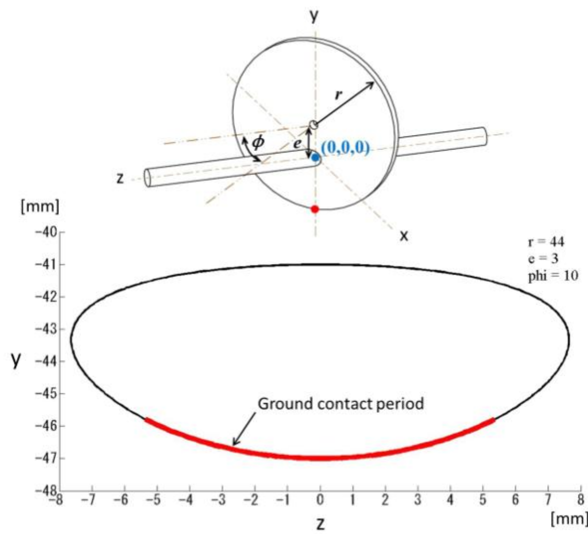

Fig. 8 Trajectory of the rim of the disc

Several RS-Wave units can be connected together in different patterns for different application purposes. For example, they can be series connected to form a snake-like robot that can inspect narrow spaces; they can be parallel connected as a mobile robot to carry other operation devices. Moreover, if we remove the bellows and let the external rings rotate freely, the mechanism can propel in axial direction and rotate freely in lateral direction. Then, they can be connected as a polygon, such as triangle or square, and it becomes an omni-directional vehicle. Images of above-mentioned connection patterns are shown in Fig. 9.

B. Structure of the mobile robot

The RS-Wave mobile robot was composed of two RS-Wave Units that were parallel connected. Fig. 10 shows the appearance of the RS-Wave mobile robot. The two RS-Wave units are mirror-symmetric. The previous prototype had the problem that it proceeded in deflected direction. Hence we design this mobile robot with a parallel structure. In this case, the cancellation of lateral propulsive forces allows the robot to move straight forward along the axial direction. The specification of this model is shown in Table 2.

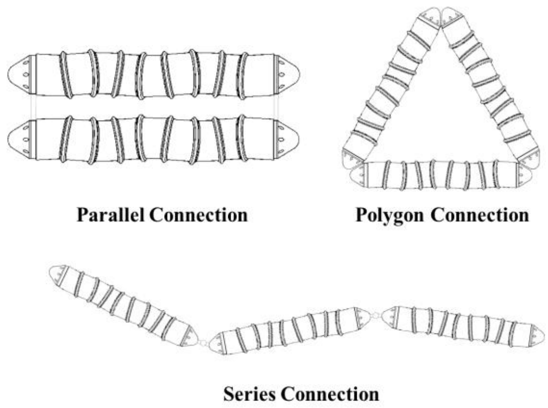

Fig. 9 Connection patterns of RS-Wave units

Fig. 10 RS-Wave mobile robot

TABLE 2 SPECIFICATION

Dimensions	592.5 mm×243 mm×88 mm
Weight	6.8 kg
Actuator	Brushless DC 90W, Gear ratio 104:1×2
Planetary Gear Set	2.7:1
Rotation Speed (disc)	109.4 rad/s
Proceeding Speed	78.2 mm/s

C. Motion Control

The control diagram of RS-Wave mobile robot is shown in Fig. 11. The microcomputer and motor driver used in this robot are TITechSH2 Tiny Controller and 1BLDC Power Module (HiBot). To drive the robot, the signals of the rotation velocity can be input through a joystick, and they are transmitted to the motors in the left and right sides respectively. The hall sensors on the motors can measure the actual rotational speed of the motor and give feedback to the microcomputer. As we are concerning to make the robot as light weight and small as possible, there is no embedded battery in this robot, and the power is supplied through a tether system.

As for the moving direction of the robot, it is simply controlled by changing the rotating direction of both motors. Since the two RS-Wave units are mirror-symmetric, when the two motors rotate in opposite direction, the robot moves forward or backward; when they rotate in the same direction, the robot turns.

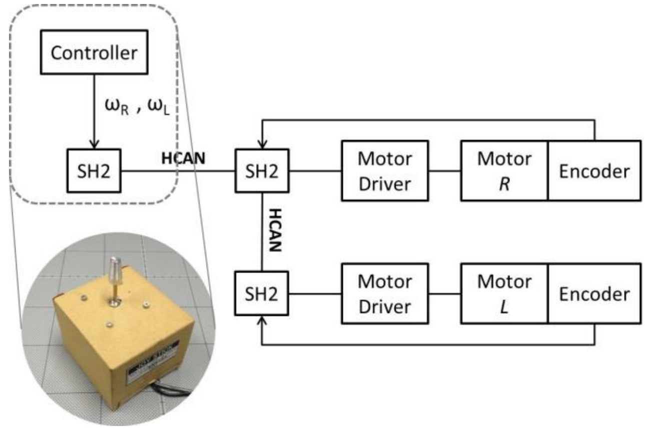

Fig. 11 Control of the mobile robot

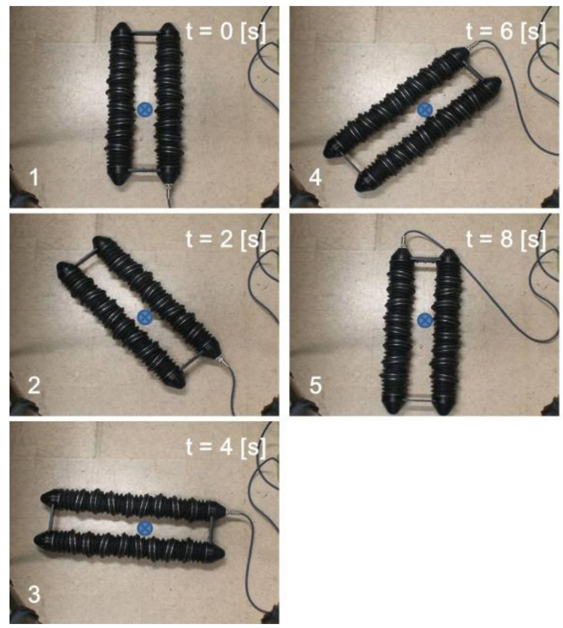

Fig. 12 Pivot turning of RS-Wave mobile robot

IV. EXPERIMENT

The mobility of this RS-Wave mobile robot is evaluated experimentally. First, the basic motions including moving forward, moving backward, making turns were confirmed. RS-Wave mobile robot is able to make a pivot turn by propelling left and right unit in opposite direction. Fig. 12 shows the robot making a left rotation for 180 degrees.

Motion experiments in several different conditions were conducted. The followings are the explanation of the experiments.

A. Underwater

To test the water tightness of RS-Wave mobile robot, it was put into a water tank. Fig. 13 shows the mobile robot moving in the water. It stayed in the water for 1 hour and it could perform proceeding and turns without any leakage. This experiment proved that RS-Wave mobile robot is waterproof, and that it is able to operate underwater as well.

B. Narrow Space

In this experiment, RS-Wave mobile robot was put in a narrow space between boards. Since RS-Wave mechanism produces same direction propulsive forces from the whole contacting surface, the mobile robot can squeeze through the narrow space easily. Fig. 14 is the image when the mobile robot escaped from the narrow interval, and Fig. 15 shows the image that it squeezed into the interval.

In a further experiment, RS-Wave mobile robot was put under an acrylic sheet, and weights were put on the top of the acrylic sheet as shown in Fig. 16. By giving the same input angular velocity, the proceeding speed and average current were recorded. Fig. 17 shows the result of the experiment. It reveals that even when the load is increased to 31.5 kg, the robot can still propel in the same speed and required current did not increase significantly. From this result, we expect that when RS-Wave mobile robot can move in rubble and can be pressed heavily by obstacles from the top, escaping and continuing the locomotion easily.

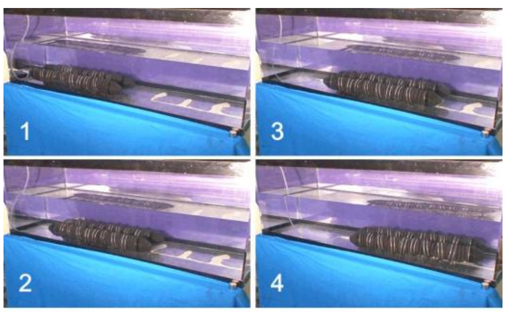

Fig. 13 Underwater experiment

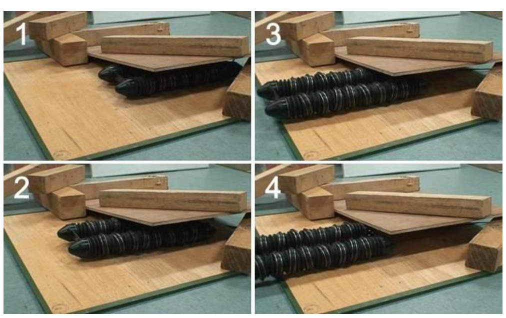

Fig. 14 Escaping from narrow space

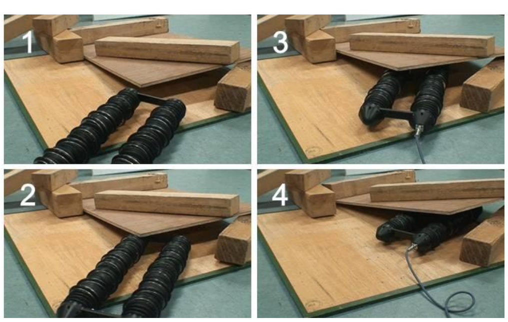

Fig. 15 Entering narrow space

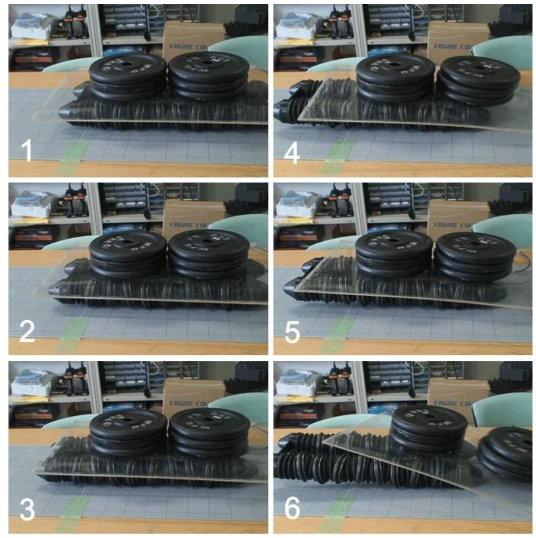

Fig. 16 Propulsion under 31.5kg load

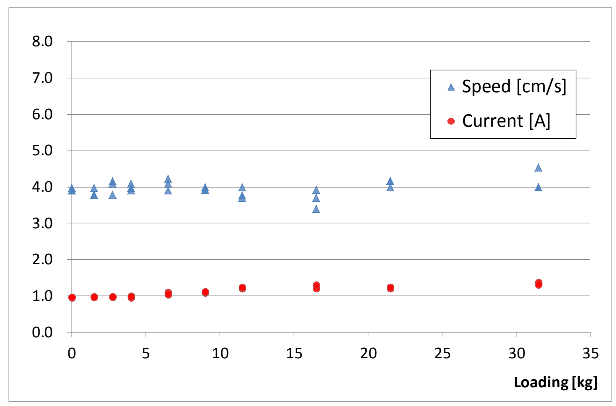

Fig. 17 Current mesurement under loading variations

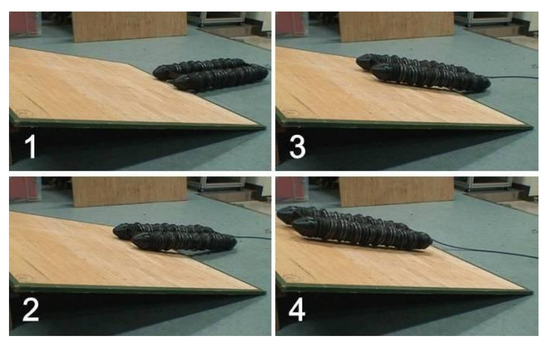

Fig. 18 Climbing up a slope

C. Slope

The purpose of this experiment is to check the ability on climbing up a slope. The angle of the slope was varied from small to large. Fig. 18 is the image of the robot climbing up the slope. The final result shows that RS-Wave mobile robot can climb up slopes under 15 degree angles. Due to its rigid body, the robot has difficulties climbing up a steep slope. When the robot comes to the transition area from level ground to the slope as Fig. 18-2, the middle part of its body does not contact with the ground and thus only the front and the rear parts are propelling. This makes it difficult to overcome steeper slope.

D.Step

In the above experiments, RS-Wave mobile robot were only tested on even ground. However, in real environment, there are many rough terrains. Therefore, in this experiment, we examined the robot's mobility when facing steps. Since the eccentric inclined discs only lift up 6 mm during propulsion, the height of the step is quite limited. The experiment result shows the maximum step this robot can overcome is about 25mm.

The above experiments present the mobility of RS-Wave mobile robot. It has good performance on even ground or narrow space, and also the watertight structure allows it to operate in the water as well. As for locomotion in uneven terrain, the present design is not sufficient. To improve the design, perhaps by connecting several units of this robot with lifting mechanism in between, they can overcome larger obstacles as the image in Fig. 19. Additionally, if the robot has an elastic shaft, it may have better terrain adaptability.

Fig. 19 Image of RS-Wave units connected with active joints

V. CONCLUSION

In this paper, the modification of RS-Wave mechanism and its first application on a mobile robot were introduced. The design of the structure was explained and the performance of the robot was evaluated through experiments. It is proven that this mobile robot is watertight, and it has good maneuverability that can squeeze through narrow space easily.

There are some defects in this robot such as it is not sufficient for locomotion on rough terrain with current design. In the future, we will keep working on improving RS-Wave mechanism. For example, modifying its rigid structure into an elastic one, or connecting multiple units for better terrain adaptability. Also, we are considering adding load-sensitive mechanism to improve its energy efficiency. At the meanwhile, we will continue developing other practical application that utilizing the distinguishing features of RS-Wave mechanism.

ACKNOWLEDGMENT

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