

Paper:

Development of Slime Robot Using Bridle Bellows

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Slim Slime Robot (SSR) looked like the active cord mechanism (the snake like robot) and composed of units that can stretch, shrink and bend actively, is for several tasks in the narrow space such as moving under collapsed houses and inspection of pipelines at plants.

In this paper, we propose new concept, it is named "Bridle Drive." And we developed the prototype model of the units of the SSR-II. This unit has the Bridle Bellows composed of a large caliber bellows and wire lock system. Bridle Bellows is able to change shape by controlling wire length and air pressure and produces a large power.

Keywords: articulated body, pneumatic link

1. Introduction

We are studying a robot with multiple degrees of freedom (DOF) and flexible shapechangeability called the "Slime Robot (SR)". Organisms with simple shapes in the natural world change shape flexibly to generate locomotion. Snakes are a one-dimensional example, abalones two-dimensional, and amebas three-dimensional. Introducing basic elements of these soft, flexible creatures into engineering will open the way for applications in many different fields.

Applications of one-dimensional flexible artifacts in robots include an active cord mechanism (ACM) modeled after a snake, a mobile unit modeled after an earthworm, and a manipulator resembling an elephant's trunk. A mobile unit can be used as a serpentine robot that travels in narrow spaces, such as under rubble after a disaster (**Fig.1(a)**).

Applications of two-dimensional flexible artifacts include a hand that encloses an object like a glove, and a robot that jacks up rubble after a disaster (**Fig.1(b)**).

Applications of three-dimensional flexible artifacts include an ameba-like robot that holds an object stably on rough terrain and travels with it (**Fig.1(c)**).

Machines with multiple DOF and flexible shape changeability are capable of tasks not possible for humans in different situations.

In this paper, we developed a mobile machine with a slim body called the "Slim Slime Robot (SSR)", as an

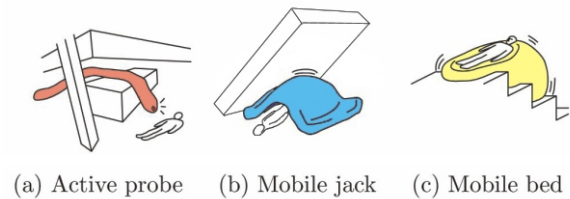


Fig. 1. Applications of Slime Robot

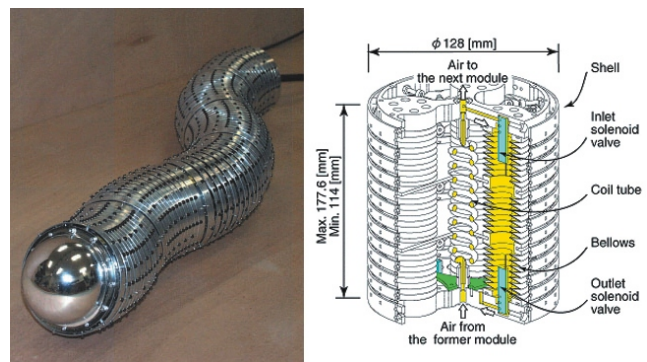


Fig. 2. SSR I

sample application of the SR. Slim mobile machines excel in stability and mobility over rough terrain, redundancy, air-tightness, and other properties, and have potential use in such fields as in-pipe inspection, disaster rescue operations, and land mine removal.

Many of conventional articulated mobile machines, generally known as snake like robots, are composed of units with bending DOF, but the most significant mechanical characteristic of this SSR is that it is composed of units that have not only bending DOF but also stretch-shrink DOF.

In this paper, we propose a new concept of mechanism to build a robot with multi-DOF and flexible shape-changing ability called "Bridle Bellows," and mechanism that applied the Bridle Drive into SSR called "Bridle Bellows," and describe the prototype of the unit of Slim Slime Robot II (SSR-II) that is composed of the Bridle Bellows. We also report the result of the experiment of the characteristics of the Bridle Bellows.

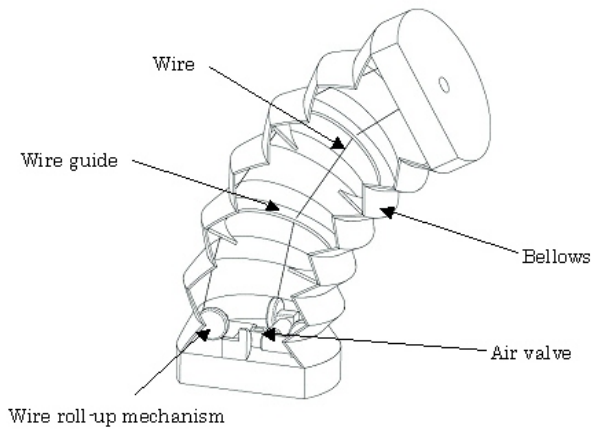


Fig. 3. Bridle Bellows

2. SSR I Overview

The SSR-I (Fig.2) we are working on consists of six units with bending DOF in two dimensions and stretch-shrink DOF. The unit has three circular bellows at equal 120-degree intervals between two disks. It bends and stretches and shrinks by controlling the three bellows and is capable of several locomotions. Since the bellow's cross-section is small compared to the total cross-section, thrust does not work efficiently, and the cross-section complexity makes it difficult to reduce weight further.

3. Proposal of Bridle Bellows and Bridle Drive

3.1. Bridle Bellows

The Bridle Bellows we propose is a new mechanism for the SSR module (Fig.3) composed of a single large diameter bellows and the wire drives that does not back-drive. The Bridle Bellows controls the bending angle and expansion of the air-driven bellows by changing the length of three wires that connect from the wire drive along the inner circumference to the end of the bellows. To contract the bellows, the unit exhausts air to decrease inner air pressure and roll up the wire.

The characteristics of the Bridle Bellows include the following: (1) It converts all force applied by air on the body's cross section (the cross section of the bellows) into thrust. (2) It is capable of any bending angle and expansion amount by changing the wire length. (3) It can limit the power of the wire drive mechanism to roll-up only, instead of matching the expanding bellows, by using the wire roll-up mechanism that will not back-drive. As a result, drastic size reduction of the roll-up actuator becomes possible. (4) As it is

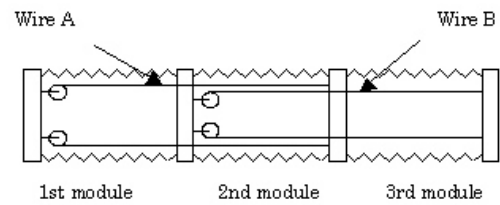


Fig. 4. Coupled Bridle Bellows

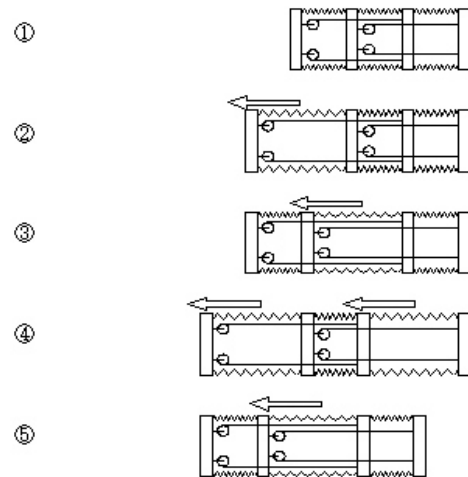


Fig. 5. Basic locomotion of Bridle Bellows

lightweight, powerful and capable of expansion and contraction, it is suitable for the driving mechanism of mobile robots that enter into narrow spaces.

3.2. Use of Coupled Drive in Bridle Bellows

We propose a coupled drive for the Bridle Bellows' adjacent modules.

In this Bridle Bellows, the ability of the wire roll-up mechanism is minimized to reduce weight. Therefore wire-driven contraction is clumsy compared with powerful air-driven expansion, as exhaust takes longer than intake.

For this reason, we propose a coupled drive that uses expansion pressure of the adjacent unit to discharge air smoothly for contraction. Specifically, Wire A connects the front end of the first module with the back end of the second module (Fig.4). Wire B connects the front end of the second module with the back end of the third module. After that, each adjacent two modules are connected by wire. Fig.5 shows the basic locomotion when multiple Bridle Bellows are connected. The part that touches the ground on the module's outer circumference has a one-way claw in order to move forward using this expansion and contraction. All modules are retracted in (1), and the front module only is expanded in (2). If the length of wire A is fixed and the



Fig. 6. Bridle Drive

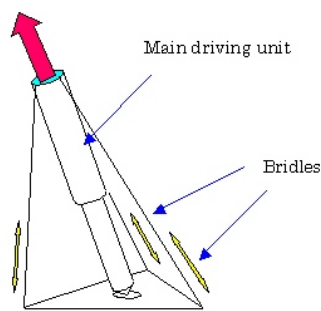


Fig. 7. Bridle Drive concept

second module starts expanding as shown in (2), the expanding pressure of the second module helps exhaust of the first module, and as a result, the first module retracts and the second module expands, as in (3). Then, from (3), if the first and third modules expand while the length of Wires A and B is fixed, the second module will retract to (4). After (5), repeat (3) and (4) and the modules will move forward.

Using this coupled drive, the Bridle Bellows is expected to travel smoothly thanks to the wire lock mechanism and pressure control, even if the ability of wire roll-up mechanisms mechanism is minimized.

3.3. Proposal of Bridle Drive

In this paper we propose a new mechanism concept named "Bridle Drive." "Bridle Drive" is, as shown in **Fig.6**, a mechanism to control a powerful moving element with the bridle.

The Bridle Drive consists of a powerful stretchable element (pneumatic or hydraulic cylinder, spring, etc.) and multiple wire roll-up mechanisms that does not back-drive (**Fig.7**). It controls the direction and amount of expansion with multiple wires operating as bridles. The Bridle Drive thus has the potential to make a lightweight and powerful actuator. The Bridle Drive adapts to different shapes by changing the arrangement of expandable element and wires. For example, it can be used in the Bridle Bellows used in the SSR, and multiple DOF systems, such as the bridle bag, which changes shape three-dimensionally.

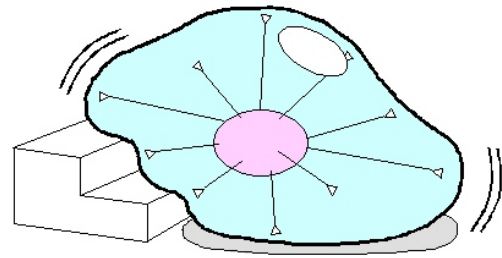


Fig. 8. Bridle bag

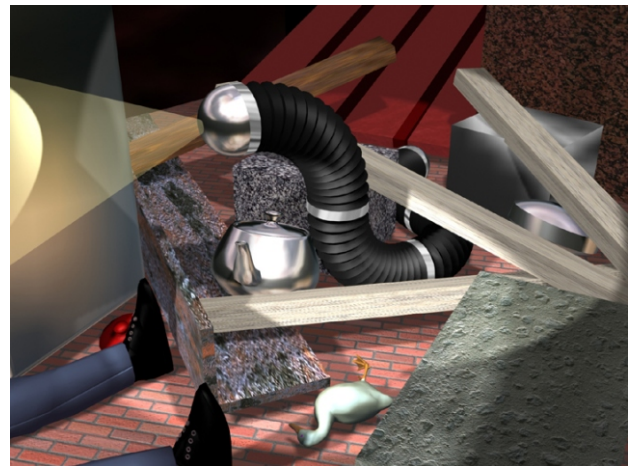


Fig. 9. SSR concept

3.4. Development the Bridle Drive Concept

The bridle bag (**Fig.8**), an air-driven bag with wires inside, is an air bag whose shape is determined by controlling the wire length.

The Bridle Bag consists of an air bag, a wire drive in the bag that does not back-drive, and a valve to take in and exhaust air to control pressure inside the bag. The bag provides high power brought by the air drive used for travel and work, and potential weight reduction since the shape of the air bag is controlled by wires. It can compose a system with multiple DOF.

4. Prototyping of Slim Slime Robot

The Slim Slime Robot II (SSR-II) is a one-dimensional SR. While most conventional articulated mobile machines, generally known as serpentine robots, have only bending DOF, this SSR-II consists of units with bending DOF and stretch-shrink DOF. SSR-II consists of pneumatic-driven Bridle Bellows to ensure ultra multiple DOF and maneuverability.

The SSR-II is a flexible mobile machine with a slim body and excels in stability, traveling ability on rough terrains, redundancy, air tightness and other properties. So it can be used in the environments inaccessible for



Fig. 10. SSR II units

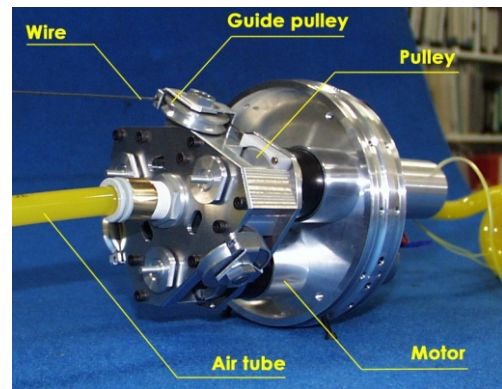


Fig. 12. Wire roll-up mechanisms

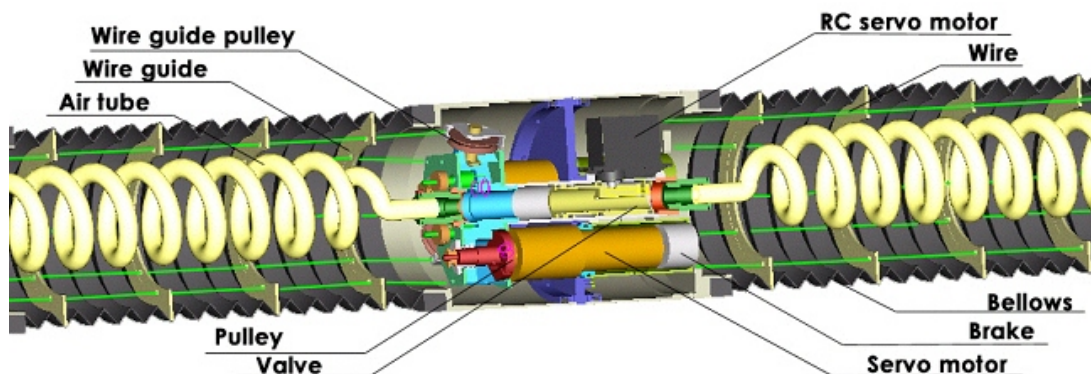


Fig. 11. SSR-II drive

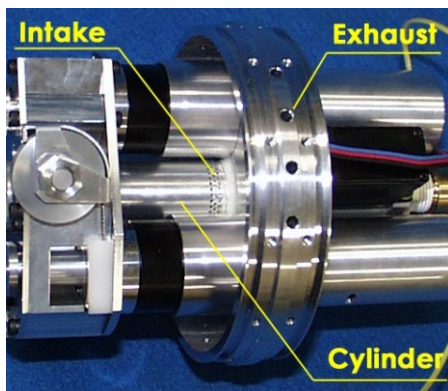


Fig. 13. Intake and Exhaust

Table 1. Specifications of SSR-II module

Length		511mm
Diameter		124mm
Mass		3.7kg
Withstand pressure of the bellow		0.1MPa (differential pressure)
Displacement of shrink		Min 150mm >>max 300mm
Actuator	Wire rolling-up	DC servo meter >> 3
	Valve	RC servo meter >> 1

humans, such as traveling in narrow spaces under the rubble to search survivors trapped in collapsed buildings after a disaster, as shown in **Fig.9**. It also can be used in inspections in pipes or under the floor or roof.

In this paper, we built two prototype SSR-II units composed of Bridle Bellows (**Fig.10**) to experiment the functionality of the Bridle Bellows.

4.1. Composition

The SSR-II (**Fig.11**) consists of a single large-diameter bellows, a disk-shaped joint that closes

both ends of the bellows, three wires to determine the bellows' length, wire roll-up mechanisms at the joint at 120-degree intervals to control wire length, wire lock mechanism to fix wire length, valve to control air pressure inside the bellows, and RC servo motor to drive the valve. SSR-II has an air pressure control valve at each unit to connect multiple units and provides compressed air to each unit through the coil tube in the center of the body. The unit is 124mm in diameter and 511mm (min: 351mm) long and 3.7kg in Mass. The

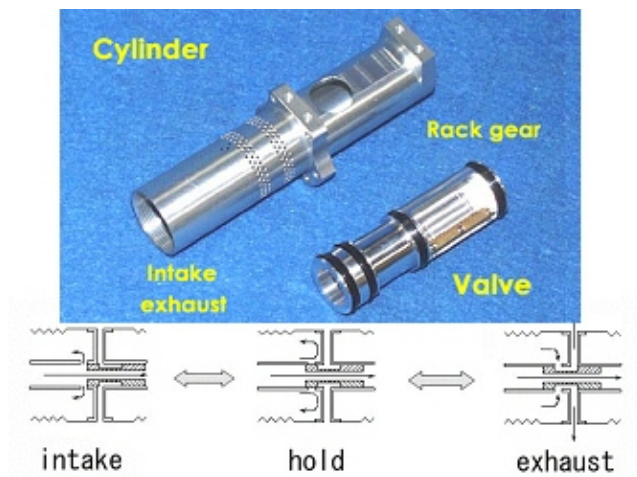


Fig. 14. Switching of intake and exhaust



Fig. 15. Bellows and wire guide

maximum power at the end of the bellows in the stretch direction is approximately 800N. **Table 1** shows specifications.

4.2. Wire Roll-Up Mechanisms

Wire roll-up mechanisms (**Fig.12**) are made of a spiral groove pulley of 30mm in diameter driven by the DC servo motor to roll up wire. To prevent wire from slipping from the pulley by sudden bellows deformation caused by external force, the roll-up pulley and guide pulley have a wire cover.

The wire lock uses an electromagnetic brake and fixes the wire length by applying the brake to the servo motor axis. Three of these mechanisms are located on the disk of the module at 120-degree intervals.

4.3. Control Valve

The air pressure control valve is a small valve. To ensure high flow rate, we developed a new mechanical valve, instead of using an existing electromagnetic valve. As shown in **Fig.11**, a cylindrical piece is placed as a valve inside of the 20mm-diameter cylinder located at

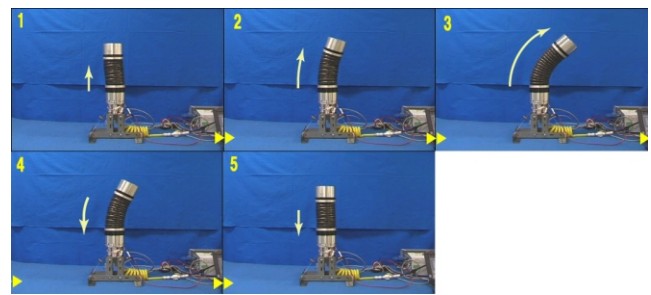


Fig. 16. Expansion and contraction

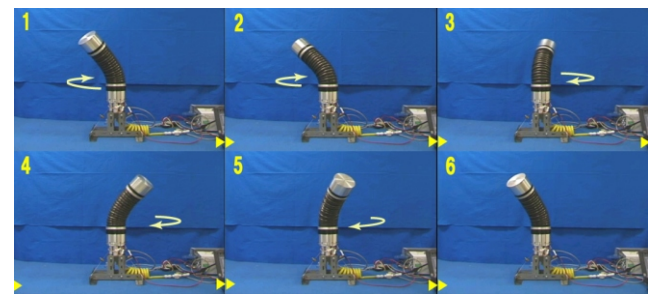


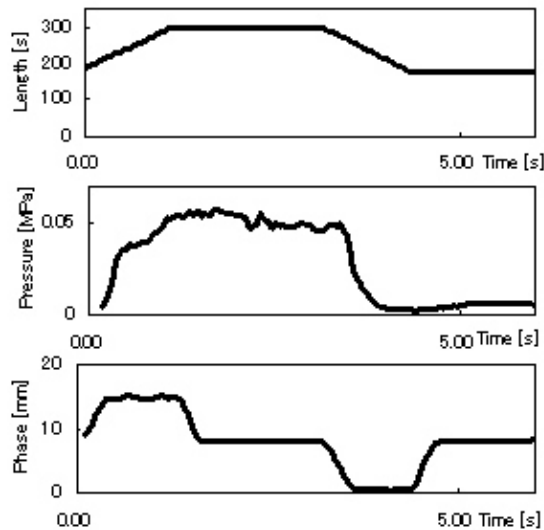
Fig. 17. Lateral rolling

the center of the disk-shaped module, which is driven by the RC servomotor via the rack gear. As shown in **Fig.13**, each module has an air intake vent on the cylinder circumference to provide air to inside the bellows and an air exhaust vent placed on the circumference of the module disk to exhaust the air to outside. The cylinder has two holes, as shown in the upper picture of **Fig.14**; one is an air intake and the other is an exhaust that goes through the module's disk to the exhaust vent on the circumference. The piece has rubber packing at four places (**Fig.14**) and switch between (1) "hold," where both intake and exhaust vents of the cylinder are closed, (2) "intake," where only the intake vent is open, and (3) "exhaust," where intake and exhaust vents are connected by the duct on the side.

4.4. Bellows

The bellows consist the most of the Bridle Bellows mechanism. It does not only stretch by air pressure, but also protects the mechanism from the outer environment. The bellows used in SSR-II is 124mm in diameter, 300mm in length and could be retracted to up to 150mm. The bellows are made of nylon lined with urethane rubber. By combining a reinforcement ring, it withstands differential pressure of 0.1Mpa from ambient pressure.

In order to make the bellows in the desirable shape, the wire that goes through the bellows can be, as shown in **Fig.15**, placed along the bellows' inside wall using the guide disk inside. SSR-II has four disks in the bellows.



Top: Length of Bridle Bellows, Middle: Internal pressure, Bottom: Phase of valve

Fig. 18. Expansion and contraction

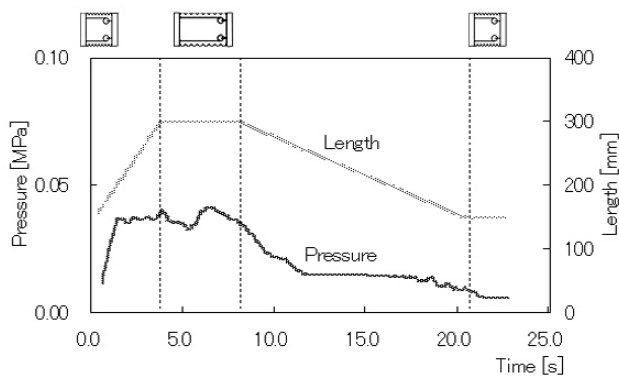


Fig. 19. Expansion and contraction of single bellows

5. Experiments

5.1. Experiment on Bridle Bellows

We conducted two experiments on behavior, A and B, on SSR-II prototype module. In these experiments, the module is fixed on the table.

In Experiment A, expansion and contraction of the Bridle Bellows was done to determine direction and expansion in advance, and calculated wire dispatch length and sent the pulley position value to the roll-up mechanism (Fig.16). This was conducted as follows: (1) Apply pressure to Bridle Bellows to dispatch wire and stretch module. (2) Close valve, fix wire length, and maintain position. (3) Exhaust air to roll up wire and contract module. The dispatch speed of each wire is controlled based on the expansion amount. Fig.16 shows that the Bridle Bellows expanded into a different form

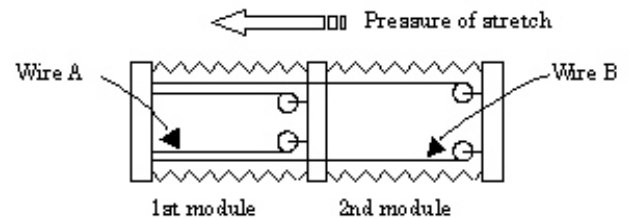


Fig. 20. Coupled bellows

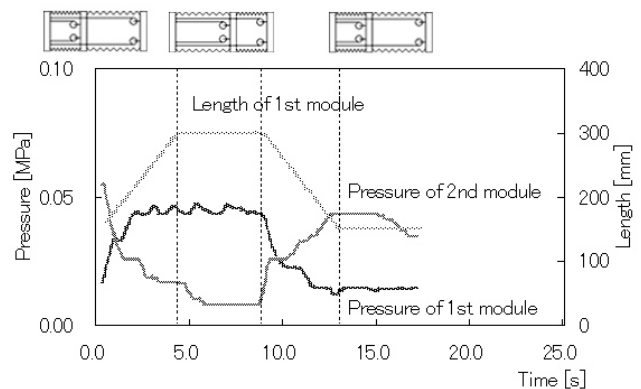


Fig. 21. Expansion and contraction of coupled bellows

and contracted back to its original shape. We confirmed that we could change the bent bellows in an arc, not linearly, by installing the wire guide inside the bellows.

In Experiment B, when the Bridle Bellows was bent, we changed wire length and maintained the same inner pressure to achieve lateral rolling (Fig.17).

We confirmed that the wire guide inside the bellows enables the bent bellows to roll while maintaining an arc (Fig.17).

5.2. Experiment

We conducted three experiments, C, D, and E, on the Bridle Bellows using prototype modules.

In Experiment C on expansion and contraction of the Bridle Bellows, expansion and contraction of the bellows, namely, (1) expand, (2) hold, and (3) contract, were done. The chart in Fig.18 shows the total length, inner pressure, and opening/closing of the valve of the bellows. The chart shows that Bridle Bellows (1) expands by pressure resulting from air intake, (2) holds the state by closing the valve, and (3) contracts by exhausting air. Power at the end of the bellows is 600N, based on calculation from inner pressure.

In Experiment D shows the course of expansion and contraction of the bellows with 20% opening of the valve. The graph in Fig.19 shows that the total length

and inner pressure of the Bridle Bellows. The sketches above the chart show the status of the Bridle Bellows at distinctive points. It shows that exhaust by wire only takes time, and the contraction speed is slower than the expansion speed.

In Experiment E, we experimented with coupled bellows that use a coupled drive with an adjacent module to achieve smooth expansion and contraction. As shown in **Fig.20**, the front end of the first module and the back end of the adjacent second module are connected by Wire B. When the length of Wire B is fixed, the contraction of the first module can use not only the roll-up force of Wire A but also expansion force of the second module, which enables smooth expansion and contraction. The chart in **Fig.21** shows the total length of the Bridle Bellows of the first module and the inner pressure of the first and second modules. the chart shows that when a single module retracts, the intake pressure of the adjacent module enables smooth exhaust, and the speed of expansion and contraction of the first module is almost the same. As shown above, we confirmed that the coupled Bridle Bellows worked effectively, and each module achieved smooth expansion and contraction.

6. Closing

In this paper, we proposed a new mechanism concept named "Bridle Drive" to realize multi DOF flexible shape changing robot "Slime Robot."

Then we built a mechanism called "Bridle Bellows" that applied the Bridle Drive to SSR, and created a prototype of SSR-II module composed of Bridle Bellows. Further, we performed experiments using the module prototypes to acquire knowledge about the Bridle Bellows.

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