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Active Hose: an Artificial Elephant's Nose with Maneuverability for Rescue Operation

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Abstract

This paper proposes both the design concept and the driving mechanism of a flexible robot with multiple degrees of freedom to dive into debris.

Up to now, several kinds pneumatic robots with flexibility have been developed, however, they couldn't perform multiple degrees of freedom with high bending moment.

Then a new type of robot, called "Active Hose," is proposed here, which has multiple degrees of freedom by connecting units of two degrees freedom in series and has high bending moment by introducing the spine structure and using the deformation of the spiral tubes. "Active Hose" with these performance can be expected to apply to rescue operation such as searching the victims under debris just after the earthquake, supplying fresh air and drinking water for victims, and carrying the air jacks so as to make a room for the victims to go out.

1. *Introduction*

It is said that the victims buried alive under the collapsed buildings must be saved within 72 hours after a big earthquake occurs, while no equipment has been realized which can rescue them as efficiently as we expect. In order to improve such unfavorable conditions, we have tried to develop a desirable robot to perform efficient rescue operation with referring to the report of Hanshin Big Earthquake hitting Japan in 1995 and concluded that the functions of an elephant's nose are extremely effective, because i) it has multiple degrees of freedom with flexibility, ii) it can curve and grasp the object with small curvature, and iii) it can carry the fluid just like a hose. The robot with these functions would be expected to perform the following operations as shown in Fig.1, which are (1)getting into debris to search the victims by installing the camera, (2)supplying fresh air or water to keep them alive, (3)carrying the air jacks to let them out, and so on.

In order for the robot to pass through such a narrow space, it is requested to have structural flexibility with large output force, which can be achieved by pneumatic energy with simple control. However, the compressor is unable to work when the electricity lines are suspended by the big earthquake. Therefore, we started developing a human-powered pneumatic pump with high energy transform efficiency as the practical power source, which takes advantage of the bicycle[1] driven by rescue parties or onlookers, shown in Fig.2. And this kind of pedaling style pump is considered to be helpful for the robot we aim to develop, too.

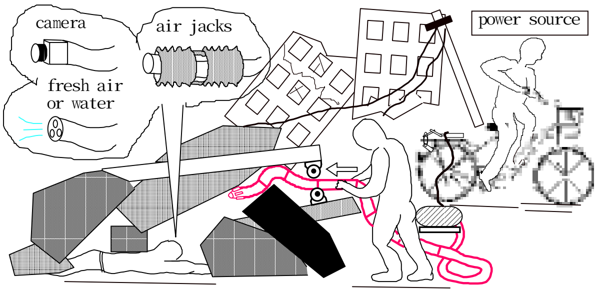

Fig.1 Image of rescue operation by way of the artificial elephant nose, whose power source is manpower transformed into pneumatic power.

Fig.2 Developed human powered pedaling pump which could pushed up the automobile in 30 [cm] in 60[s].

As for the propulsion under debris, roughly two methods can be considered. Those are the method of obtaining the thrust from the external force and one of generating the thrust by its own twisting motion. Of course, the latter seems to reduce the burden for the operator, but to simplify the story as the first step, it is assumed here that the robot is propelled by being pushed by the operator, as shown in Fig.1. If the head unit of the robot forms the posture to avoid the obstacles after detecting them, the next unit tries to follow the posture of the head, while the whole robot is pushed into debris. If such following is repeated from the head to the rear and its insertion quantity is measured at the entrance at the same time, the robot is expected to pass through the small and curved space smoothly. So as to realize the above motion, it is necessary for the robot to be partially curved with flexibility and to possess multiple degrees of freedom. This paper proposes the appropriate driving system for the robot to realize the above operation and discusses its driving performance with the result of the developed model.

2. Basic concepts for designing

Up to now, several pneumatic actuators with flexibility were proposed[2]-[6], however, it is unsuitable to apply them to the robot we aim to develop, due to next two reasons. One is that the number of pneumatic lines would be too large for the robot to be inserted in at its end and power density would be reduced if they were connected in series, because all the valves were situated outside of the actuators. The other is that the loss of both the bending moment and the curvature was relatively large, because one side of the actuator was passively stretched when the opposite side was pressurized to be stretched. In order to solve the above two problems, “Active Hose” with new structures is proposed here as follows.

2.1. Whole structure of “Active Hose”

Whole structure of “Active Hose” is as shown in Fig.3. It can partially curve and perform multiple degrees of freedom by connecting short units in series which have each two rotational degrees of freedom around its pitch and yaw independently. In each unit, the control valves are installed and they are connected to a tube to supply the air which is shared among all the units. Since all the units also share the signal line and the electric power line, the number of lines doesn’t increase at all even if a lot of units are connected. In addition, by divided into units, “Active Hose” can be expected to be carried easily to the disastrous site by operators. The similar concept was proposed before[7], but “Active Hose” in

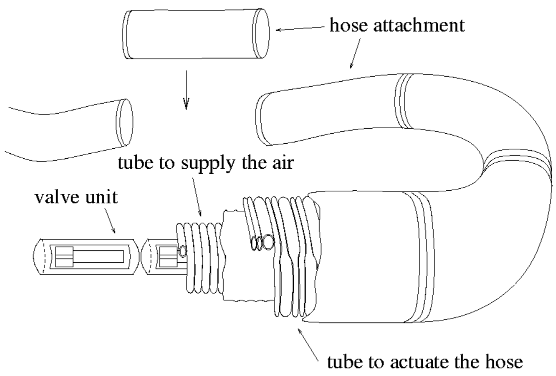

Fig.3 Structure of “Active Hose”, consisting of many units including valves in themselves. It shares a tube to supply the air among all the units.

this paper contains some novel structures and driving method as follows.

2.2. Introduction of the spine structure

It is necessary for a unit itself to possess the structure to reinforce the bending moment and to minimize curvature, considered that it must push its way in the small space under debris. Therefore, a spine structure installed to its center which helps the unit to be shrunk passively when the opposite side is stretched. The spine structure is composed of some blocks, and each block houses valves or MPU, which helps to obtain enough space for the fluid for life extension. In order to connect each block, the wire combination mechanism shown in Fig.4, is introduced, which enables units to be connected occupying smaller spaces than the universal joint.

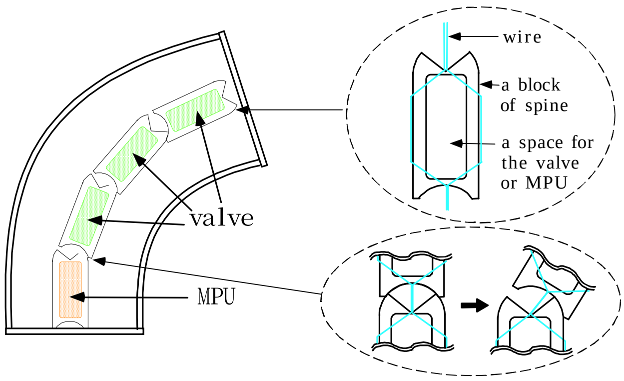

Fig.4 Spine structure and its blocks to house the valve or MPU.

3. Driving method

3.1 Proposal of Wound Tube Actuator

With regard to the driving method, it is easier for us to come up with the bellows which will be installed around the spine structure. However, they are not so much desirable driving method because of the following reason. In order to perform two degrees of freedom, yaw and pitch, at least three pairs of bellows are necessary around the spine, which tends to occupy so much space around the center to generate a large moment that there will be not enough room to be remained for carrying the water or the air for life extension.

Then, we propose a new kind of driving method called Wound Tube Actuator, WT Actuator for short. WT Actuator is the spiral tube surrounding the unit like a coil and its cross section forms the flat ellipse. When its inside is pressurized, the tube pushes each other to its radius direction as its cross section changes into the circle gradually. In addition to its structural simplicity, WT Actuator possesses a few advantages as follows. i) It can stretch the object easily after winding around it. So it may work as a “wearable fluid power” such as a power assist with flexibility if it is wound around an elbow or a knee. ii) It takes advantage of the force to the radius direction of the tube, not the stretch of the thrust direction, therefore a tube of high resistance to pressure can be utilized keeping flexibility. iii) It works as a virtual spring as the contact area to the next tube decreases in proportion to the displacement, while the pressure inside the tube is kept constant.

Fig.6 shows the relationship between the space ratio of actuation/cross sectional area and the bending moment. As it shows, WT Actuator, which can obtain relatively large distance from the center, needs much less space than the bellows to generate the constant bending moment. Then, how can we make the unit to the arbitrary direction by using WT Actuator?

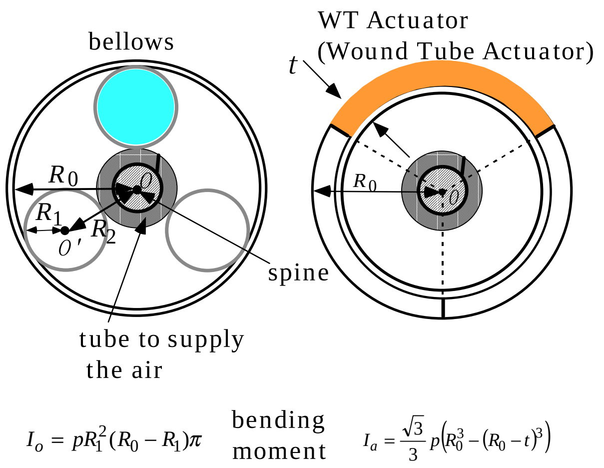

Fig.5 Comparison of the cross section between the driving by bellows and one by WT Actuators.

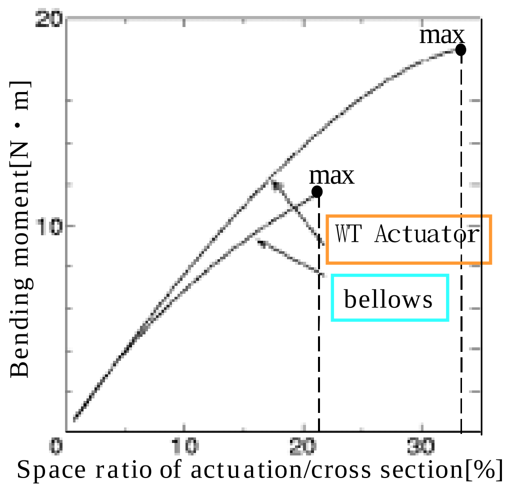

Fig.6 Simulation result of the relationship between space ratio and bending moment with regard to bellows and WT Actuator.

3.2 Driving to the arbitrary direction

Three Wound Tubes can make the unit bent to the arbitrary direction in a following way. Each Wound Tube is composed of restricted part and no-restricted part as a cycle of circumference of the unit, as shown in Fig.7. In the restricted part occupying 2/3 length of the circumference, the tube doesn't swell at all, even though it is pressurized. On the other hand, the no-restricted part occupying 1/3 length of the circumference swells until the cross section becomes circle. Eventually, only the part of 120 degrees swells when one Wound Tube is pressurized. If such three Wound Tubes are installed to the unit with the phase difference of 120 degrees, the unit can bend to the arbitrary direction.

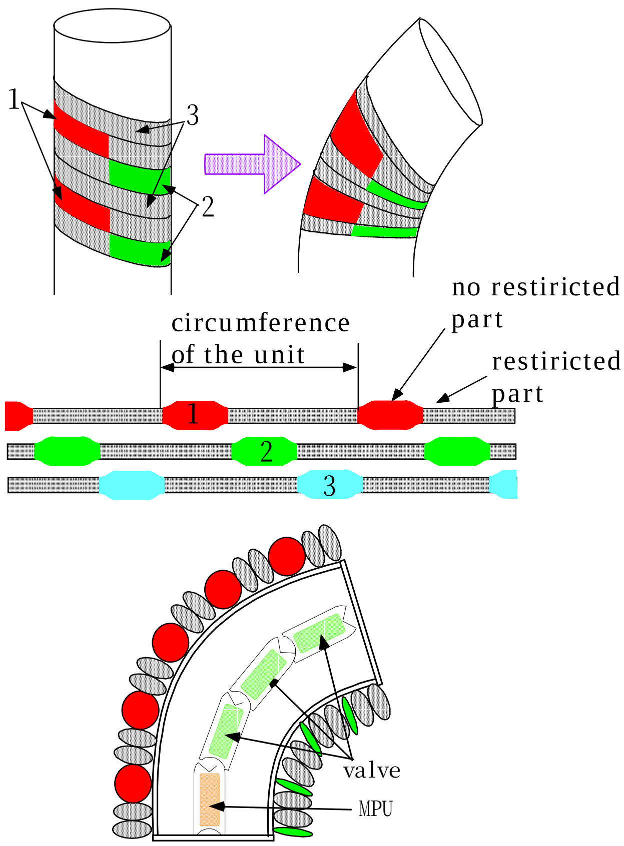

Fig.7 Driving method of a unit by using three WT Actuators.

4. Developed model

The developed mechanical model of a unit of “Active Hose” is shown in Fig.8. Its scales of the developed are 300[mm] in length, 80[mm] in diameter, and 2[kg] in weight. The diameter of the spine structure is about 25[mm]. A solenoid-actuated three-way, two-position directional control valve is installed in each spine structure. This valve is made by LEE Corp. in U.S.A. and 37.6[mm] in length, 780[mW] in its consumption power. Wound Tubes are made of urethane and their restricted part is pinched by staples so as not to swell even if they are pressurized.

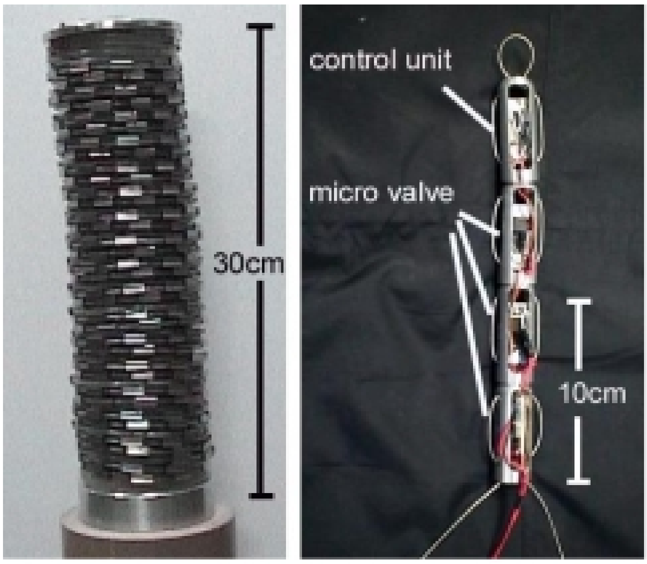

Fig.8 Overall view of the developed unit of "Active Hose" on right, and its spine structure housing valves and MPU on left.

Fig.9 WT Actuator on left which is partially restricted to swell by staplers around 240 degrees in a cycle and the hose on right which is wound by WT Actuator.

5. Experiment

5.1 Performance of the developed model

Fig.10 shows the bending action when the air pressure 0.5[MPa] was supplied to a tube. At that time, the bending angle was 45 degrees and the bending moment was 1.5[Nm], and it took about 2[s] to bend from the straight condition.

Fig.10 Bending action with a swelled tube under the pressure of 0.5[MPa].

5.2 Bending moment and bending angle

The experimental result of the bending moment is shown here. While the input pressure to the unit was kept constant, the edge of the unit was pulled by the spring measure. In this case, the bending moment can be defined as the measured force F multiplied by the distance x between the supporting point of the unit and the line of action, as shown in Fig.11. And the bending angle was measured by the camera. The result of the experiment is shown in Fig.12, which expresses the relationship between the bending moment and the bending angle.

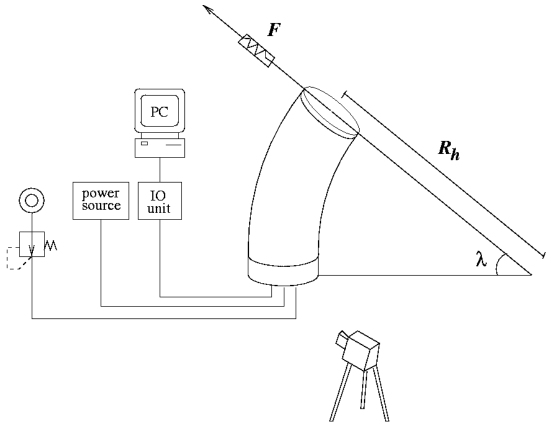

Fig.11 Experimental equipment and how to measure the bending moment.

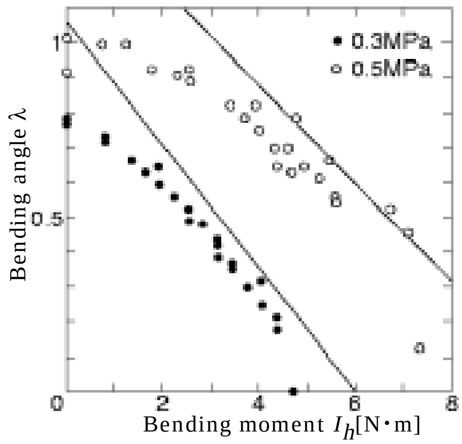

Fig.12 Relationship between the bending moment and the angle.

According to the result, it can be said that the bending moment decreases as the bending angle increases. The reason why this phenomenon happens can be explained as follows.

Let's focus on the output force of a Wound Tube F_t. When the tube is pressurized under the pressure of p, the output force F_t is composed of the pneumatic force and the elasticity of the tube and it can be expressed by the following equation, reffering to Fig.13.

$$F_t = p\pi\left(\frac{2r_i - y}{2}\right)L + F_k(y) \quad (1)$$

Here, r_i, y, L, and $F_k(y)$ experss the radius of the inner part of the tube, the height of the tube, the width of the tube and the elastic force of the tube respectively. The relationship between the height of the tube y and the elasticity of the tube $F_k(y)$ was obtained by the experiment, as shown in Fig.14. As the height increased, the elasticity decreased to the negative side, which means the shrinking force increased. However, their values were completely smaller than pneumatic force, so it can be said that the output force of the Wound Tube is almost equal to the pneumatic force, which is decided by the input pressure multiplied by the contact area. And the contact area decreases as the tube swells, which is the reason why the bending moment decreases as the bending angle increases.

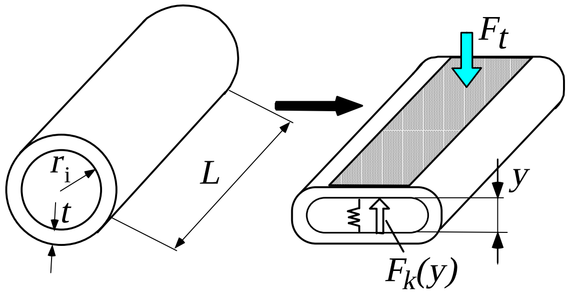

Fig. 13 Deformation of Wound Tube and its output force composed of the pneumatic force and its elasticity.

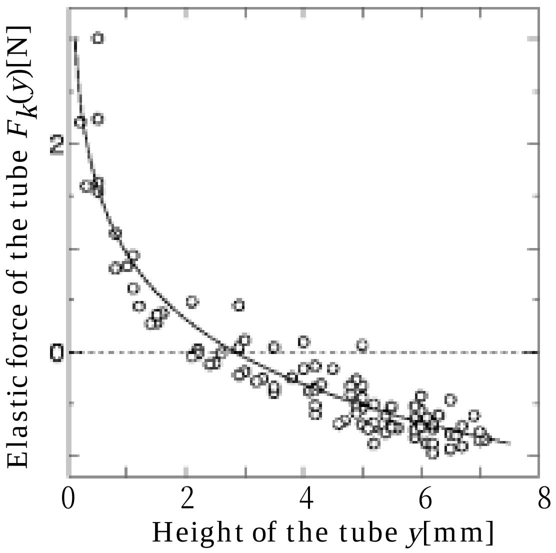

Fig.14 Relationship between the height of Wound Tube and its Elasticity.

5.3 Posture control

As for propulsion way of "Active Hose," it is assumed that the unit follow the posture of another one forward after whole units are pushed in debris. In this case, it is necessary for them to be control on the basis of posture. As the posture sensor of such flexible object as "Active Hose", the small size and the function of enlarging the slight posture change are required. Then here, a new posture sensor, called "Trimole" behaving like three moles, is proposed as shown in Fig.15. It is composed of two rings inside of the unit and three piano wires. The rings are fixed to the unit, and piano wires are fixed to one of the rings and can slide along another ring. Fig.16 shows us the structure and performance of it. By measuring the displacement of two piano wires from the ring to be slide by linear potentiometers, the posture of the unit can be estimated as follows. When the bending direction and the bending angle are expressed as θ_t and λ_t respectively, they can be given in the following equations.

$$\theta_t = \tan^{-1}\left\{\frac{-2\sqrt{3}}{3}\left(\frac{\Delta l_2}{\Delta l_1} + \frac{1}{2}\right)\right\} - \frac{2}{3}\pi \quad (2)$$

$$\lambda_t = \frac{2\sqrt{3}}{3r_t}\sqrt{\Delta l_1^2 + \Delta l_1 \Delta l_2 + \Delta l_2^2} \quad (3)$$

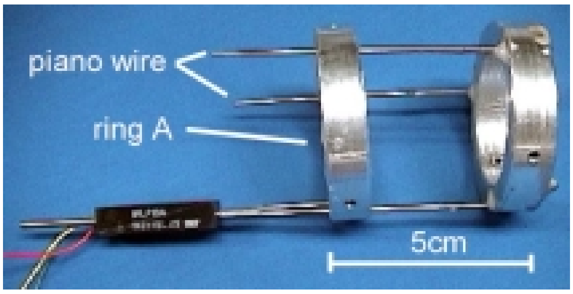

Fig.15 Developed posture sensor , "Trimole."

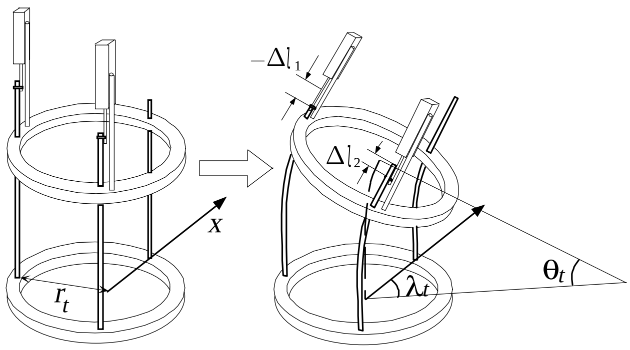

Fig.16 Structure and Performance of "Trimole."

After "Trimole" was installed to the unit, its posture was controlled from the straight condition to the bending one with the angle of 30 degrees. The result is shown in Fig.17, which tells us that the posture keeps vibrating and its reason can be explained in a following way. The valve for the tube to be stretched was connected to supply the air, while the rest of two valves for the tubes to be shrunk were opened to exhaust the air from tubes quickly. However, Wound Tubes continue to deform after the valves were closed because of viscosity and elasticity. Therefore, the valves for the tubes to be shrunk should be closed as a brake if the posture comes close to the desired one.

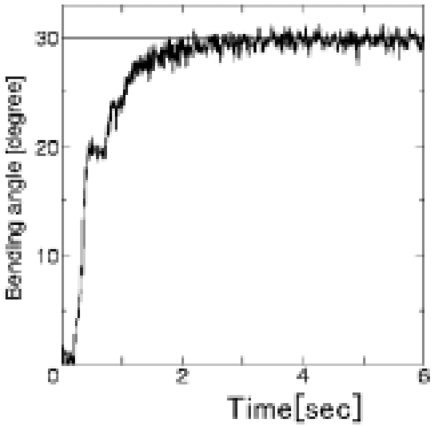

Fig.17(a) Result of the posture control from 0 degrees to 30 degrees.

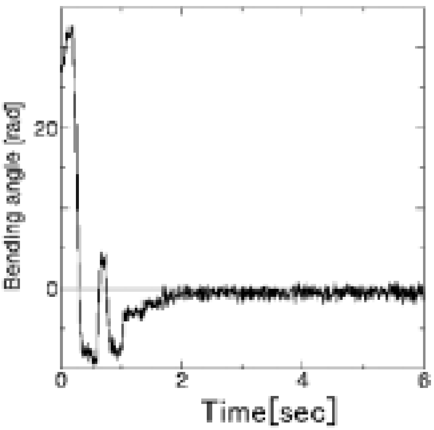

Fig.17(b) Result of the posture control from 27 degrees to 0 degrees which was unstable just after the control started.

Fig.18 shows the rotational movement around the central axis, which was realized by changing the desired posture little by little. The similar motion was also realized by just switching the valves connected to the tube for supplying, as there exists 7 combinations including all three valves are connected.

6. Conclusions

The new pneumatic robot for rescue operation in debris, called “Active Hose,” was proposed in this paper. It behaved just like an elephant’s nose with multiple degrees of freedom, which was realized mechanically by using the connective type units with valves. It was confirmed that practical bending moment could be generated by introducing the circumference expansion-type unit with the spine. For the future work, driving test in debris by transmitting the posture from the head unit to the rear one will be carried out.

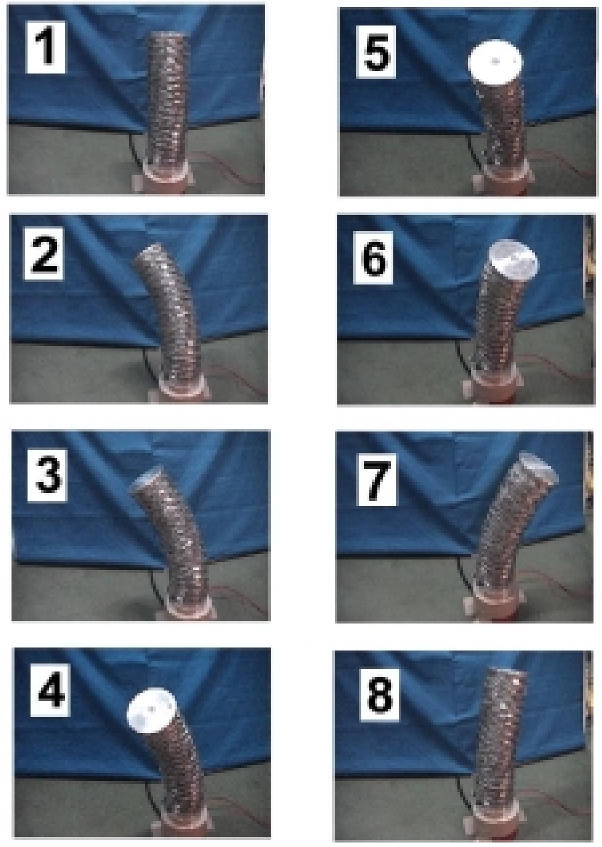

Fig.18 Rotational movement around the vertical axis of “Active Hose” under the pressure of 0.5[MPa].

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