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Long bending rubber mechanism combined contracting and extending fluidic actuators

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Abstract— **This study aims at development of a multi-directional bending mechanism with thin and long body driven by fluidic rubber actuators. Generally bending mechanisms with fluidic rubber actuators can have advantages of smooth and continuous motion, however because of their low stiffness it is difficult to generate high output force. To solve this problem, we have proposed a novel bending mechanism combined with contracting and extending rubber actuators. By bundling rubber actuators with different types, the developed bending mechanism can have the high stiffness. In this report, optimized extending and contracting rubber actuators are made basis on a McKibben actuator, then they are combined to be the bending mechanism. Experimentally stiffness of the mechanism is measured and is compared with a bending mechanism bundled with same motion type actuators. Resulting high stiffness can be recognized by the proposed mechanism. Additionally, a very long bending mechanism, which is 7m in length, is developed and its motion is demonstrated.**

I. Introduction

Some natural creatures have multidirectional bending mechanisms with many muscles without skeletal structure; examples are an elephant trunk, an octopus arm and so on. They can do many tasks including grasping with smooth and continuous bending motion. Such mechanisms have attracted engineers' interests because their motions are quite different from motions of general and conventional artificial mechanisms consisting of rigid actuators, joints and links. In addition artificial mechanisms mimicking them have high possibility to apply to manipulation for indefinite-shape object using in forest industry, construction industry and so on.

Actually some researchers have developed multidirectional bending mechanisms toward such smooth and continuous bending motion. Especially mechanisms configured with rubber structure and driven pneumatic/hydraulic pressure indicate high potential because originally their motions are smooth and continuous.

One of our authors has developed a bending mechanism called Flexible microactuator (FMA). This actuator is made of cylindrical reinforced-rubber having three pneumatic chamber structures. Each chamber structure extends in the axial direction by pneumatic pressure. Therefore the chamber structure, itself can be deemed extending type rubber actuator, and the FMA is assumed as a combination mechanism of three extending type rubber actuators. So the FMA can bends in any directions by balance of pneumatic pressure to each chamber [1].

W. McMahan, and et al. have also developed multidirectional bending motion by using fluidic rubber actuators. This mechanism called Octarm consists of fifteen rubber actuators arranged hierarchically. Each actuator is extending type in axial direction [2].

As above examples, in common, these multidirectional bending mechanisms are combination of same-type rubber actuators, namely extending type and extending type.

On the other hand, as other method, bending rubber mechanism can be realized by combination of extending or contracting actuators and other materials having high stiffness in axial direction and low stiffness in bending direction, examples are fibers, thin resin plates, and so on.

These rubber mechanisms can do smooth and continuous motion, however theoretically these cannot output strong force owing to low stiffness in bending direction.

Considering material mechanics, to realize high stiffness the extending and contracting actuators should be combined.

In our previous studies, a rubber mechanism of 0.5m in length generating bending motion by one extending actuator and one contracting actuator was developed, and it bended in one direction [3].

In this paper, optimization of actuators for combination realizing bending rubber mechanism is conducted, and the mechanism of 1.5m in length having one contracting and five extending rubber actuators is developed for confirmation of the validity of our concept, namely realization of multidirectional bending motion with high stiffness. Moreover a very long multidirectional bending mechanism whose length is 7m is fabricated and its motion is demonstrated.

This paper is organized as follows, in this first section, background and purpose of this research were described. In the second section, theoretical concept for highs stiffness of bending mechanism is explained. Then, in the third section, rubber actuators are optimized by simulations, and both extending and contracting actuators are fabricated. After that, in the forth section, multidirectional bending rubber mechanisms with high stiffness are developed. By a mechanism of 1.5m in length, validity of the concept of our study is confirmed experimentally. Additionally, a very long type mechanism, which is 7m in length is introduced and demonstrated. Then in the last section, this paper is summarized.

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II. CONCEPT OF MECHANISM

A. *Stiffness*

Figure 1 illustrates the cantilever structure. Here concentrated load *F* is assumed, then compressive stress and tensile stress leading to compressive strain and tensile strain are loaded on the lower half and the upper half of the cantilever, respectively.

In this case, the stiffness comes from resistance force against these stresses. It means that if extending force and contracting force are generated actively in the lower half and the upper half of the cantilever respectively, it represents high stiffness.

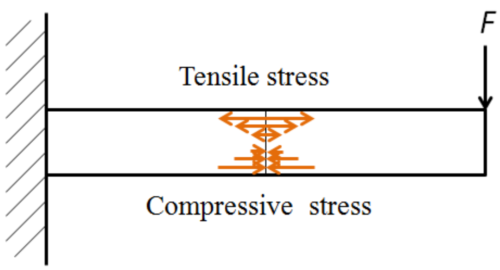
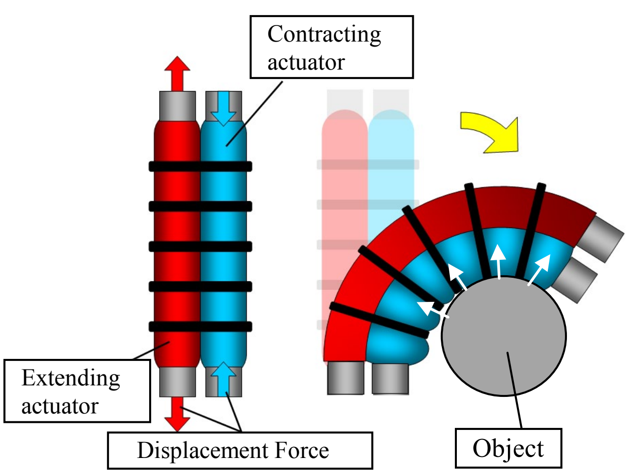


Fig. 1 Generating stress of cantilever

This indicates that a bending mechanism with high stiffness cannot be achieved by the combination of extending type actuators as refereed mechanisms mentioned above. But it can be realized by adding a contracting type actuator to extending type actuators.

B. *Concept of mechanism*

Figure 2 (a) illustrates a basic configuration of our bending rubber mechanism. As shown in the Fig.2 (a), it is bundle of extending actuator (Actuator A) and contracting actuator (Actuator B). By driving both actuators, it bends due to the different directions of strains of two actuators as shown in Fig.2(b) .



(a) Configuration (b) Driving condition

Fig.2 Concept of bending mechanism with high stiffness

When the mechanism grasps an object, the mechanism is received drag force from the object as shown in Fig.2 (b), and the compressive stress and tensile stresses are loaded in Actuator A and Actuator B respectively. However Actuators A and B generate the forces against them actively. So, the mechanism has high stiffness leading to high output force.

III. EXTENDING AND CONTRACTING ACTUATORS

A. General discussion of McKibben actuator

In this study, extending and contracting actuators have been realized by referring a McKibben actuator. The McKibben actuator is a typical fluidic rubber actuator, which was developed in 1950s [4].

Figure 3 shows a configuration of the McKibben actuator. Components of this actuator are a rubber tube, a sleeve which is knitted fibers, two end plugs, and an air tube. The rubber tube is covered with the sleeve, and the end plugs are connected to the both ends of the rubber tube for sealing. The air tube is embedded in the one end plug to apply fluidic pressure into the rubber tube.

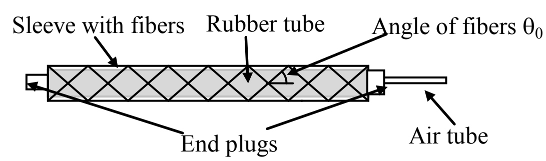


Fig.3 Configuration of McKibben actuator

The McKibben actuator generates contraction force and displacement in general, and its characteristics are expressed by equation (1).

$$F = \frac{\pi}{4} D_0^{\,2} P \left(\frac{1}{\sin \theta_0}\right)^2 \{3(1-\varepsilon)^2 \cos^2 \theta_0 - 1\} \qquad (1)$$

F, D_0, *P*, θ_0, and ε are the contraction force in axial direction, the diameter of the actuator, the applied pressure, the initial angle of the knitted fibers of the sleeve, and the contraction ratio in axial direction, respectively [4].

From this equation, it is found that the contraction ratio and the generated force vary with the initial angle of knitted fibers. Additionally, because the maximum contraction ratio ε_{max} is achieved by *F*=0, the following equations are derived.

$$\left\{3(1-\varepsilon_{\max})^2 \cos^2 \theta_0 - 1\right\} = 0 \qquad (2)$$

then,

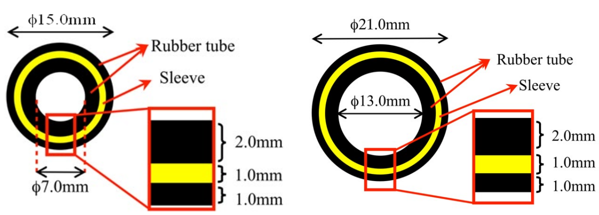
$$\varepsilon_{\max} = 1 - \frac{1}{\sqrt{3}\cos\theta_0} \qquad (3)$$

From equation (3), when θ_0 is 55 degrees, ε_{max} becomes 0. Theoretically this means that McKibben actuator with θ_0 of 55 degrees generates no motion even if high pressure is applied [5], and if θ_0 is smaller than 55degrees, the actuator contracts, and if θ_0 is larger than 55degrees, it extends.

Therefore both contracting and extending actuators can be realized by changing the initial angle of the knitted fibers of the sleeve [6].

B. Design and analysis

Figure 4 shows the cross sections of the extending and contracting actuators we have developed. The actuators are three-layer structure. Outside diameters are 21mm and 15mm, and inner diameters are 13mm and 7mm for the extending and contracting actuators respectively. In common with these actuators, the thicknesses of inner rubber layer, middle sleeve layer and outer rubber layer are 2.0mm, 1.0mm and 1.0mm respectively. Rubber material is chloroprene rubber of hardness 50. For the sleeve, p-Phenylene-2, 6-Benzobis Oxazole (PBO) fiber is used, because it is a quite strong fiber mechanically. The allowable tensile stress of PBO fiber is 5.8 GPa which is much higher than typical strong fibers, Aramid, HS-PE (high-strength polyethylene), and so on as shown in Fig.5 [6][7][8]. Therefore the actuator with PBO fibers can be expected to be applied higher pressure such as several MPa. However this fiber deteriorates due to water and ultra-violet light, so in the configuration outer layer covers the sleeve to protect.



(a) Contracting actuator (b) Extending actuator

Fig.4 Cross sectional structure; (a) is the contracting actuator and (b) is extending actuator.

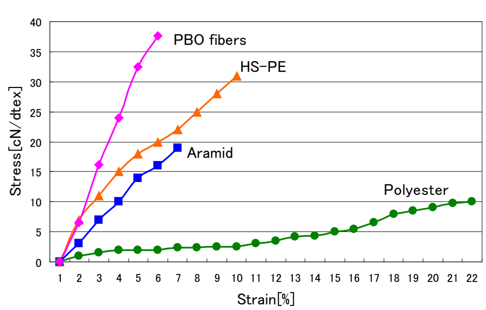


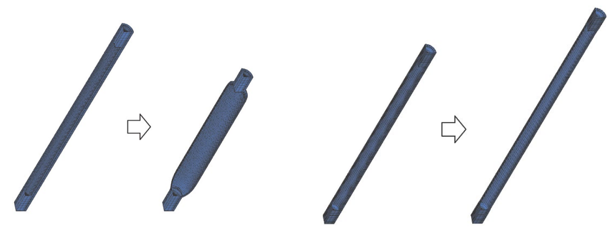
Fig.5 Strain-Stress characteristics of fibers [7]

Extending and contracting actuators are required to generate same level displacement by same level fluidic pressure. If not, they interfere their motions each other and efficiency of bending motion decreases when they are driven by same pressure, so they must be applied different pressure with consideration of different output characteristics of these actuators. This means complication of the control system.

Using finite element method (FEM), optimum designs of extending and contracting actuators generating same level displacement by same level pressure have been investigated by changing angle of fibers of the sleeve. Fig.6 shows examples of FEM; Fig.6 (a) is contracting actuator and (b) is extending actuator [3].

Resulting 34degrees for the contracting actuator and 67degees for the extending actuator have been derived. Fig.7 indicates the analytical results of FEM for these angles.

Positive and negative values of horizontal axis mean ratios of extension and contraction respectively. As shown in this graph, absolute values of the ratios of these actuators are almost same at same pressure value. They are about 23% with pressure of 1.5MPa.



(a) Contracting actuator (b) Extending actuator

Fig.6 Examples of FEM analysis; (a) is the contracting actuator and (b) is the extending actuator.

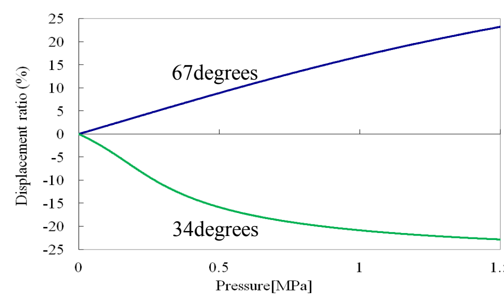
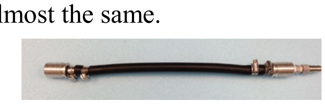


Fig.7 FEM results of fiber angles of 67degrees and 34 degrees.

C. Fabricated actuators

Following the above simulation results, actuators have been fabricated and driven by water pressure. Figs.8 (a) and (b) are initial state and driving state by 1.5MPa of the actuator with fiber angle of 67 degrees, and (c) and (d) indicate initial state and driving state by 1.5 MPa of the actuator of 34degrees. The former actuator extends with extending ratio of 19% and the latter one contracts with contracting ratio of 18%. Compared with the FEM results shown in Fig.7, both displacement ratios are small. This comes from influence of friction between the rubber and fibers of the sleeve. However the both ratios of extension and contraction are almost the same.

(a) 67degrees, initial state



(c) 34degrees, initial state

(b) 67degrees, driving state

(d) 34degrees, driving state

Fig.8 Fabricated actuators

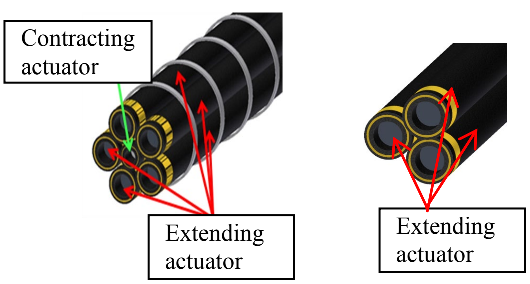
IV. MULTIDIRECTIONAL BENDING RUBBER MECHANISM

A. Configuration of multidirectional bending mechanism

Using one contracting actuator and five extending actuators, a multidirectional bending mechanism has been developed. Figure 9 (a) illustrates the configuration. One contracting actuator is center of the mechanism and five extending actuators surround it. These actuators are bundled by banding bands of plastic. This mechanism is defined as Mechanism A.

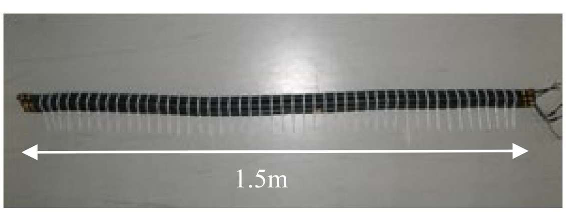
In addition, another multidirectional bending mechanism with three extending actuators bundled by banding bands has been fabricated for comparison. The configuration is shown in Fig.9 (b). This is defined as Mechanism B. Incidentally, combination of multiple contracting actuators are not easy, because contracting actuator expands in radial direction and they interferes each other so much when they are driven at the same time, so optimum interval between actuators not to interfere must be considered. Thus, simple bundling cannot be used.

Figures 10 (a) and (b) are fabricated mechanisms, Mechanism A and Mechanism B. Each mechanism is 1.5m in length of actual driving part.

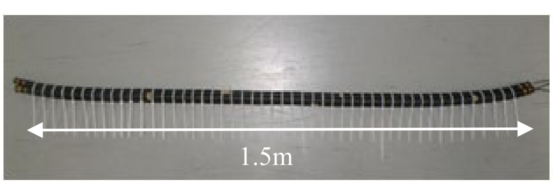


(a) Mechanism A (b) Mechanism B

Fig.9 Configuration of Mechanism A and Mechanism B



(a) Mechanism A



(a) Mechanism B

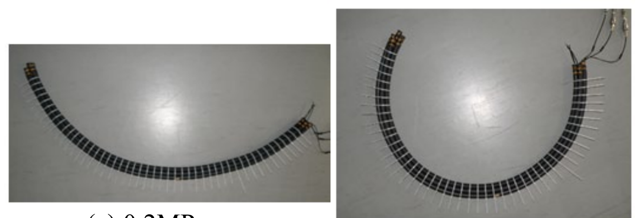
Fig.10 Fabricated mechanisms; (a) is Mechanism A, and (b) is Mechanism B.

B. Driving experiments and characteristics

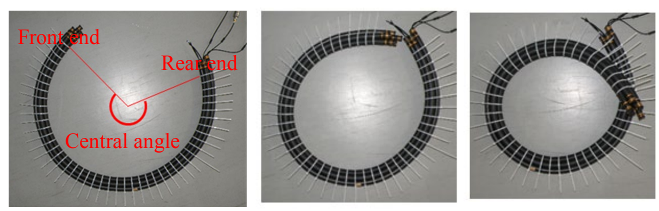
By applying water pressure, both mechanisms were driven on the floor. Considering the theoretical maximum force with 1.0MPa from equation (1), the contraction force of the contracting actuator is about twice larger than the extension force of the extending actuator. Therefore in the current experiments adjacent two extending actuators and the contracting actuator of Mechanism A were pressurized. On the other hand, two extending actuators of Mechanism B were pressurized for confirming the effect of adding of the contracting actuator.

Figure 11 shows driving states of Mechanism A. With increasing water pressure, the bending motion becomes larger. The central angle of bending defined as shown in Fig.11(c) was measured with changing applied pressure. Fig.12 indicates the relation between applied pressure and the central angle.

The relation is almost linear, and when the pressure is 1.0MPa, the central angle is about 360 degrees. In addition, curvature is almost constant through the mechanism.



(a) 0.2MPa (b) 0.4MPa



(c) 0.6MPa (d) 0.8MPa (e) 1.0MPa

Fig.11 Driving experiments of Mechanism A

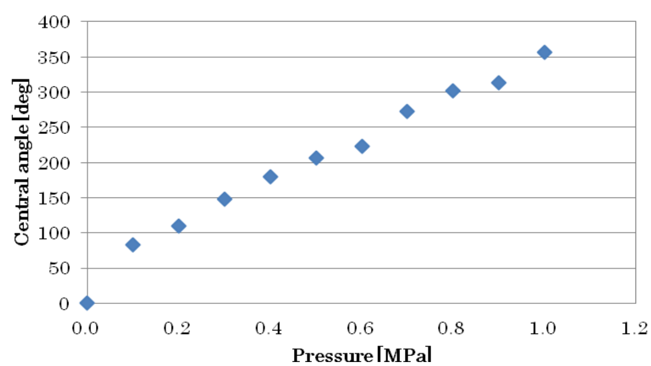
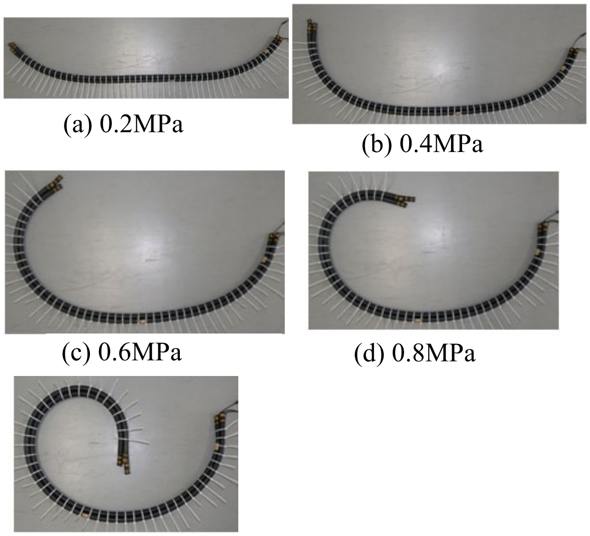


Fig.12 Relation between applied pressure and central angle of Mechanism A

Also Fig.13 shows the driving state of Mechanism B.

Compared to Mechanism A, its curvature is inconstant. For example, in case of 1.0MPa shown in Fig.13(e), the curvature of the front side is much smaller than that of rear side. This phenomenon comes from the influence of friction between the mechanism and the floor.

Unlike with Mechanism A, for Mechanism B the friction cannot be ignored because of low stiffness.



(a) 0.2MPa (b) 0.4MPa

(c) 0.6MPa (d) 0.8MPa

(e) 1.0MPa

Fig. 13 Driving experiments of Mechanism B

Stiffness of these mechanisms was measured experimentally. Fig.14 illustrates a schematic experimental setup. The rear ends of the mechanisms are fixed, and the front ends are pushed by a force gage. The force values were recorded when the front ends are thrust back by 30mm against the bending motions.

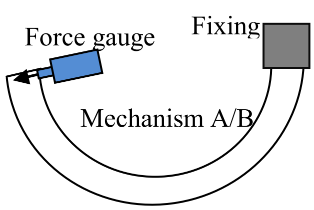


Fig. 14 Schematic experimental setup

Figure 15 shows the relation between applied pressure and measured stiffness.

It is almost constant in Mechanism B even if pressure increases. On the other hand, the stiffness of Mechanism A increases with incremental of pressure, additionally; it is much higher than one of Mechanism B.

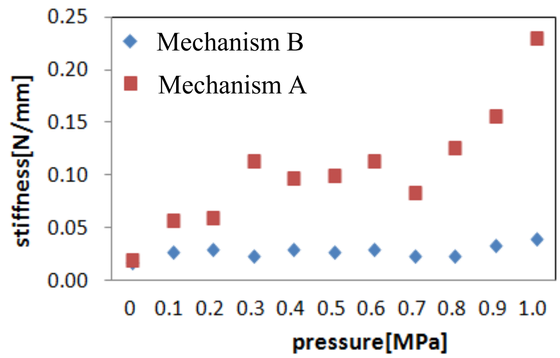


Fig.15 Relation between applied pressure and stiffness of Mechanism A and Mechanism B

From the results, clearly it is found that effectiveness of adding the contracting actuator to the extending actuators for realizing high stiffness which leads to high output force.

C. Mechanism of 7m in length

A multidirectional bending mechanism whose length is 7m has been developed. It is the longest fluidic rubber bending mechanism in the world as we know.

Likely Mechanism A mentioned above, the mechanism consists of five extending actuators and one contracting actuator.

Figure 16 shows the mechanism. Intuitively, by comparison with the human size, very long size of the mechanism can be known.

This mechanism was demonstrated in a water pool, and was driven by pneumatic pressure so as not to go down in water.

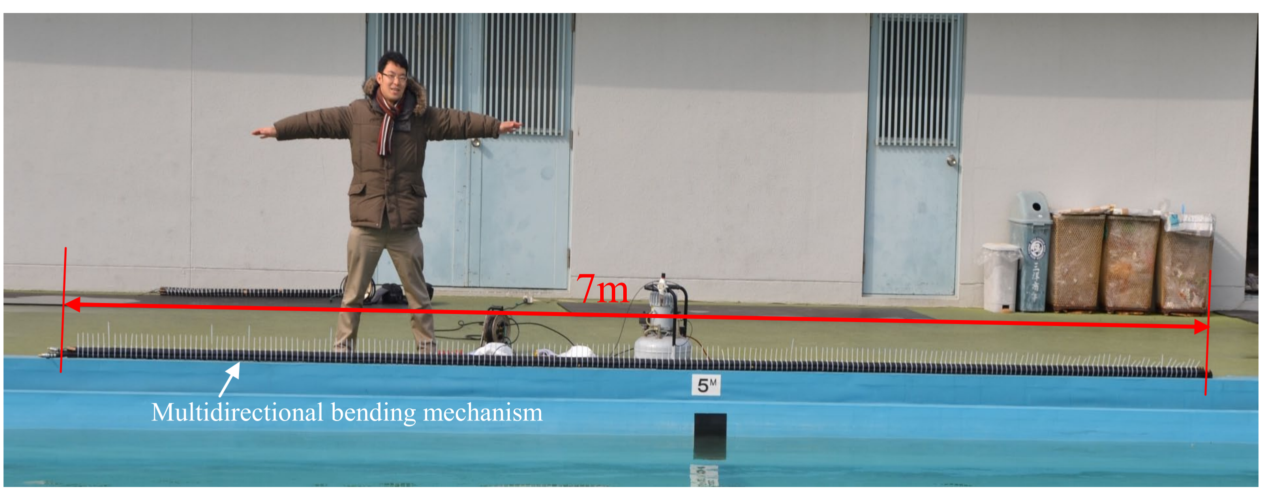


Figure 16 Multidirectional bending mechanism of 7 m in length

Figure 17 shows the demonstrations with pressure of 0.4MPa. By switching the driving actuators using the valves, successfully it generates bending motions. See the attached movie together.

V. Conclusion

In this study, the multidirectional rubber bending mechanisms combined with not only extending actuators but also the contracting actuator driven by fluidic pressure were developed.

From material mechanics, the effectiveness of the combination was confirmed theoretically. Namely high stiffness leading to high output force. Then designs of contracting and extending actuators were optimized by FEM.

A mechanism of 1.5m in length with five extending actuators and one contracting actuator was fabricated, and its motion and stiffness were measured experimentally. The results showed much higher stiffness compared to the mechanism with only extending actuators.

Moreover, a very long mechanism, which is 7m in length, was realized. It was driven on water, and could bends in multiple directions.

References

[1] K. Suzumori, S. likura, and H. Tanaka, "Applying a Flexible Microactuator to Robotic Mechanisms", *IEEE Control Systems*, pp. 21-27, 1992.

[2] W. McMahan, V.Chitrakaran, M. Csencsits, D. Dawson, I.D. Walker, B.A. Jones, M. Pritts, D. Dienno, M. Grissom, and C.D. Rahn, "Field Traials and Testing of the OctArm Continuum Manipulator", *IEEE International Conference on Robotics and Automation*, pp. 2336-2341, 2006.

[3] K. Iwata, K. Suzumori, S. Wakimoto, "Development of Contraction and Extension Artificial Muscles with Different Braid Angles and Their Application to Stiffness Changeable Bending Rubber Mechanism by Their Combination", *Journal of Robotics and Mechatronics*, Vol.23, No.4, pp.582-588, 2011.

[4] Schulte, H. F., "The Characteristics of the McKibben Artificial Muscle", *The Application of External Power in Prosthetics and Orthetics*, pp.94-115, 1961.

[5] S. Wakimoto, I. Kumagai, K. Suzumori, "Development of Variable Stiffness Colonoscope Consisting of Pneumatic Drive Devices", *International Journal of Automation Technology*, Vol.5, No.4, pp.551-558, 2011.

[6] K. Iwata, K. Suzumori, S. Wakimoto, "A Method of Designing and Fabricating Mckibben Muscles Driven by 7 MPa Hydraulics", *International Journal of Automation Technology*, Vol.6, No.4, pp.482-487, 2012.

[7] T. Hongu, "High-Tech Fibers", *Nikkan Kogyo Shimbun Ltd*., 1999, p66-127, in Japanese.

[8] TOYOBO CO.,LTD., "PBO FIBER ZYLON® Technical Information(Revised 2001.9)" http://www.toyobo.co.jp/e/seihin/kc/pbo/technical.pdf

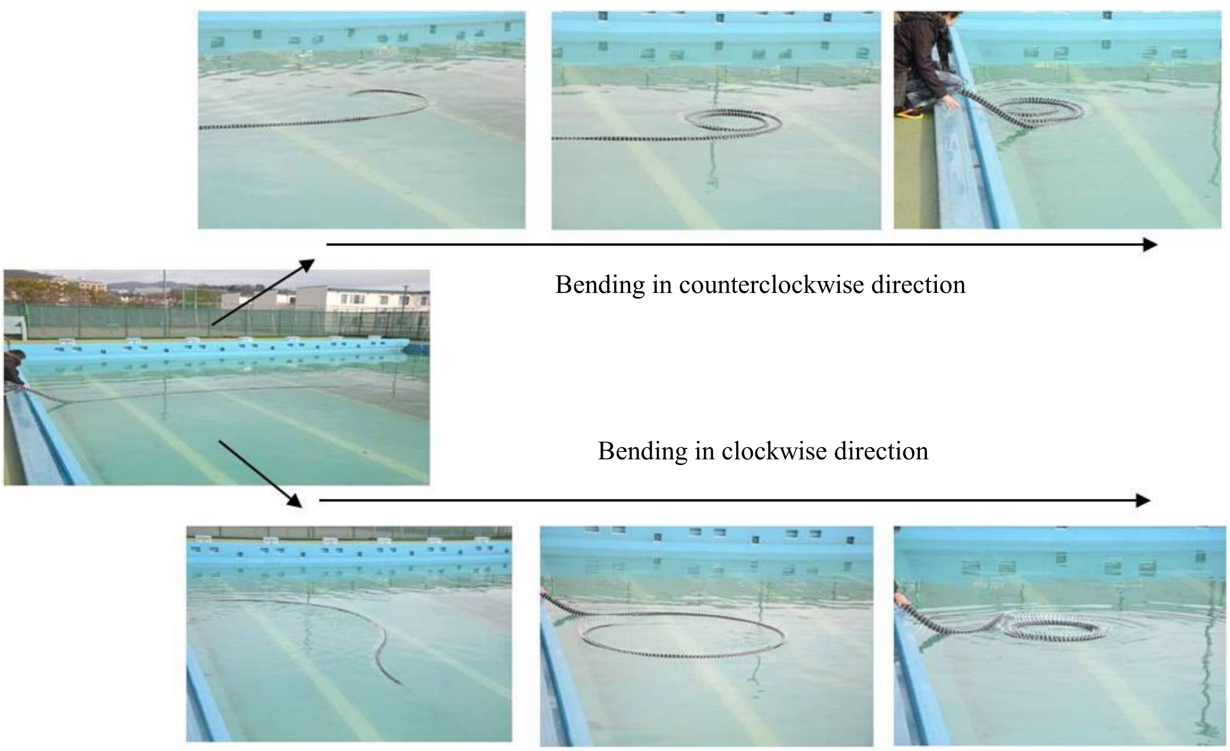


Fig.17 Driving experiments of Multidirectional bending mechanism of 7 m in length on water