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A Bending Pneumatic Rubber Actuator Realizing Soft-bodied Manta Swimming Robot

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***Abstract*— This paper shows a new design and prototyping method for a bending pneumatic rubber actuator and its application to a soft-bodied manta swimming robot. The design is based on optimal design using non-linear finite element method, in which geometrical and material non-linearity are considered and fabrication process is based on a rapid and efficient prototyping system using a CAD/CAM based rubber molding process. In this paper, the characteristics of several possible actuators are analyzed and evaluated to lead to an optimal actuator design. The actuator works very well with smooth and soft motion.**

The manta swimming robot in which the developed actuators are embedded is also designed based on non-linear finite element method. The developed manta swimming robot is made only of rubber and it swims in water smoothly as if it was a living fish. The experimental results of the manta robot motion show that good agreement with those of analytical results.

I. INTRODUCTION

Pneumatic rubber actuators have generally simple structures, high compliance, high power/weight ratio, and water-resistance, and they move smoothly as if they lived. They are expected to be one of the most promising new actuators for soft handling robots such as human-support robots, wearable power assist suits, robot hands for various works in size and shape such as fruit-harvesting end-effectors and small animal handling robots, and also expected to be a promising actuator for soft mechanisms with smooth motion like livings.

Their working principles are very simple. They consist of a rubber structure, which is often reinforced with fibers and has an internal chamber or chambers in rubber structure. Applying high pneumatic pressure to the chamber(s) causes elastic deformations of the rubber structure and it works as an actuator.

Several kinds of pneumatic rubber actuators have been developed and reported. Examples of them are MacKibben artificial muscle developed in 1950s [1], Romac actuator [2], Rubber gas actuator driven by hydrogen storage alloy [3], Flexible microactuator [4,5], Bubbler actuator [6], Pneumatic wobble motor [7], Pneumatic planar soft actuator [8], Pneumatic soft actuator [9], and colonoscope insertion actuator [10].

Pneumatic rubber actuators also interest people because of their smooth and lifelike motion and are expected to be applied to ornamental robots. We have reported several applications of pneumatic rubber actuators to animal-like robots; a small insect like robot [11], a snake-like robot [12], and pectoral fin for underwater robots [13].

While structures and working principles of them are very simple, their design processes have not been easy because elastic deformation of rubber structures have strong non-linearity coming of geometrical non-linearity for large deformation and material non-linearity of rubber. This makes the analysis and simulation of these deformations very difficult.

One effective analysis method to solve these non-linear problems is Finite element method. It is very effective to design soft mechanisms such as biomimetic underwater vehicle [14], a soft finger [15] and pneumatic rubber actuators [16], [17]. This report shows a systematic optimal design method and fabrication process of a pneumatic rubber actuator using non-linear finite elements methods, where geometrical nonlinearity, material nonlinearity, and contacting nonlinearity are taken into considerations. After that a manta swimming robot driven by the developed actuators is designed and developed also based on non-linear finite elements method. The developed manta robot swims very well in water.

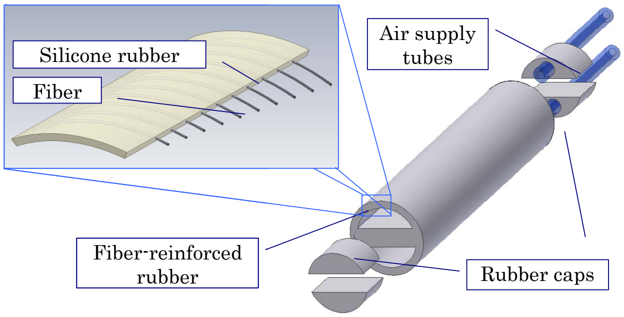

Fig. 1. Basic structure of the bending pneumatic rubber actuator with two degrees of freedom

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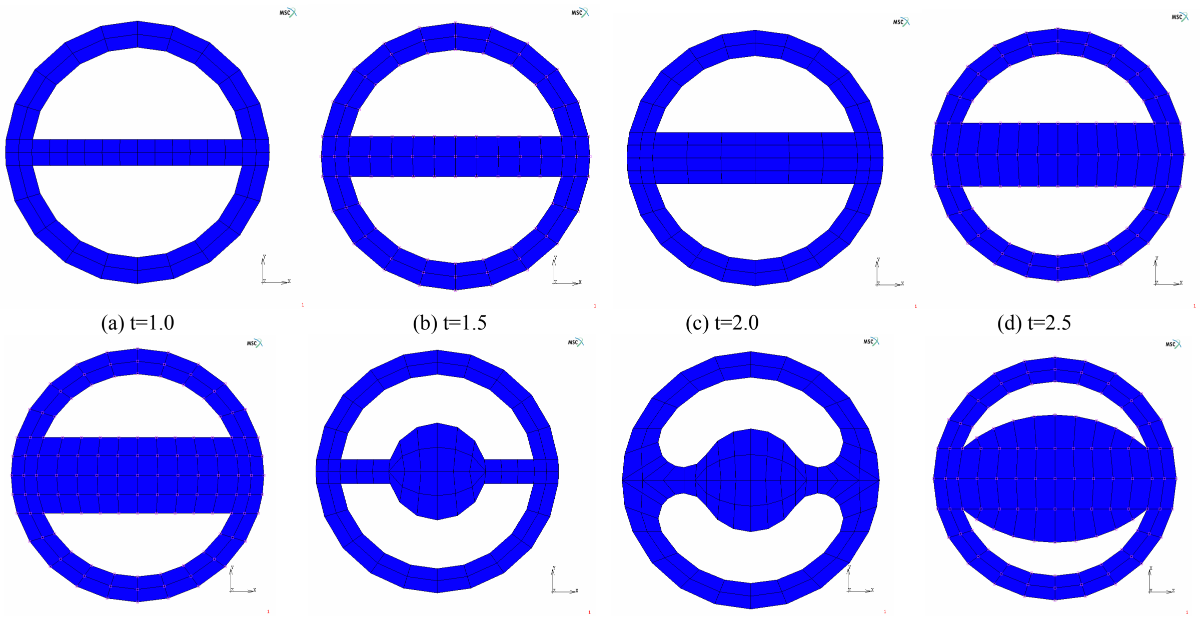


(a) t=1.0 (b) t=1.5 (c) t=2.0 (d) t=2.5

(e) t=3.0 (f) (g) (h)

Fig.2. Possible designs of cross section of bending pneumatic rubber actuators, which were simulated by FEM analysis in this research

II. FEM BASED DESIGN OF BENDING PNEUMATIC RUBBER ACTUATOR

A. Basic structure and working principle

A bending pneumatic rubber actuator with two degrees of freedom of motion is designed in this paper, while the design and fabrication method shown in this paper can be applied to designs of pneumatic rubber actuator in general.

The basic structure of this actuator is shown in Fig.1. The actuator has two internal chambers, in which the pressure is controlled independently through the pneumatic flexible tubes. The rubber is reinforced with nylon cords in the circular direction as shown in the figure to resist deformation in the radial direction.

When the pressure is increased in one chamber, the chamber stretches in the axial direction and the actuator bends in the direction opposite to the pressure-increased chamber. When the actuator is used as a robot finger, the actuator has a shape-adaptability to deform to suit to the shape and the compliance of the grasped objects. When the pressure in both two chambers is increased, the actuator extends in the axial direction of the actuator. Thus, the actuator becomes to have two degrees of freedom; bending and stretching.

As the deformation characteristics of the actuator depends on the shape of the cross section, the length of the actuator, and the elastic characteristics of the rubber, non-linear finite elements analysis is useful to design suitable actuator.

B FEM analysis method

MARC, one of the most popular commercial FEM software, is used in this research. Hyper elastic hexahedron elements are used for rubber structures and line elements are used for nylon cords in the circular direction of the outer wall of the actuator. 1168 hexahedron elements and 360 line elements are used for a typical modeling. Applied pneumatic pressures are given as hydro pressure load, which always acts in the nominal direction on the rubber walls of the internal chambers of the actuator. Contacts of the internal walls between the chambers are taken into consideration.

A three-order Mooney–Livlin model or James-Green-Simpson model is used to simulate the rubber nonlinear elasticity. The coefficients are identified through the experimental results of plane strain tension tests of the rubber.

The iteration calculation using update Lagrange method based on Newton-Raphson formula is applied. Contact problems between the actuator walls or between the actuator and grasped work are analyzed by checking geometrical interactions for each update calculation.

C Optimal design of cross section

To design optimal cross section of the actuator, static deformation analyses were carried out. The cross section doesn't change along the axial direction, because it makes the extrusion injection possible to realize very cheap actuators. The outer wall of each design is reinforced with nylon cord in the circular direction; the cord is wound in the circular direction around the outer wall of injected rubber structure and after cord-winding process the rubber coating is made around the cord, resulting in cord-reinforced rubber, in which the nylon cord is in the rubber material. Eight designs of actuators with different cross sections as shown in Fig.2 were evaluated. Models shown in (a) to (e) have different thickness of the separating wall between the chambers. The designs shown in (f) to (g) in Fig.2 are possible designs of the actuators with non-flat separating wall. Models (f) and (g) are designed to intend to prevent deformation of the separating

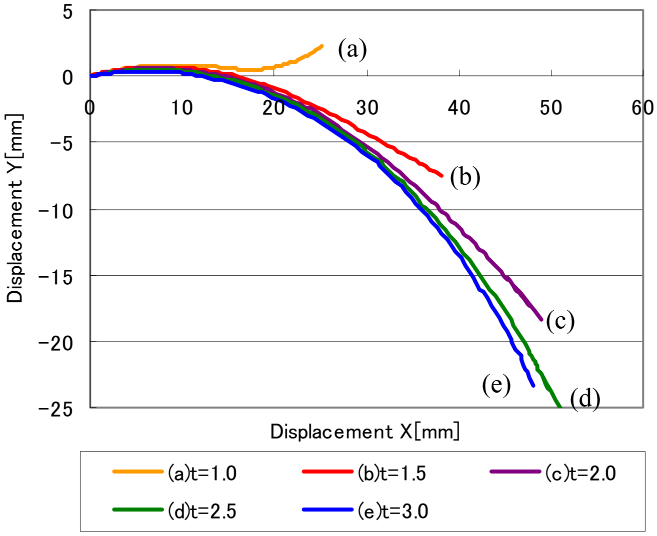


Fig.3. Analytical results of trajectories of the tip of actuators (a) to (e), the pressure is0 to 0.15 MPa

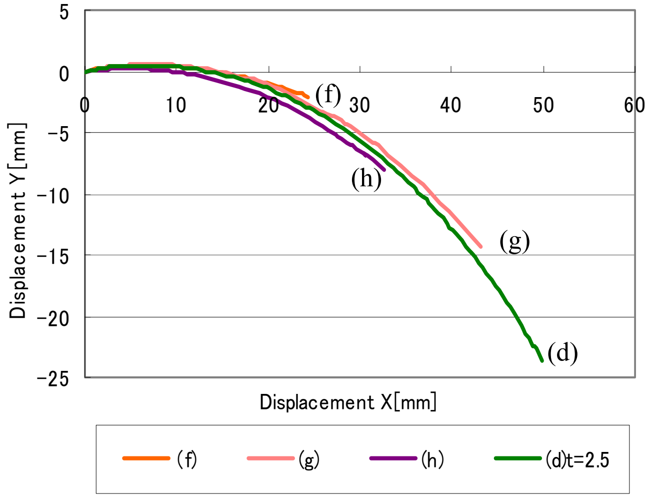


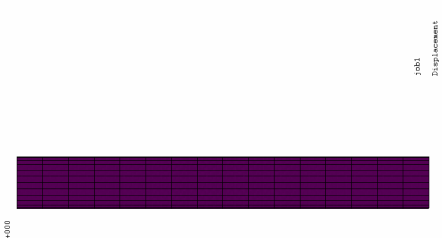
Fig.4. Analytical results of trajectories of the tip of actuators (f) to (h), and (d). The applied pressure is 0 to 0.15 MPa

wall and to make the bending angle bigger. Model (h) is designed to prevent the deformation of the separating wall especially around the center of the actuator.

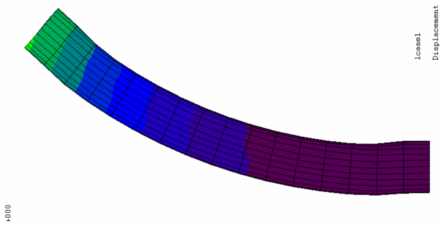
The outer diameter of the actuator is 10 mm, the thickness of the outer wall is 1 mm. The total length of the actuator is set to be 80 mm, including the end caps of both ends of the actuator, 5 mm for each; the length of the internal chamber is 70 mm.

The hyper elastic properties of the rubber are modeled as three order Mooney-Livlin model. Coefficients of the model are identified by tensile test of the rubber. The density is 1.1 x 10^{-6}kg/mm^3. Nylon cord is modeled by linear elastic model with Young modulus of 3000MP, Poisson's ratio of 0.3, and the density of 1.1×10^{-6}kg/mm^3.

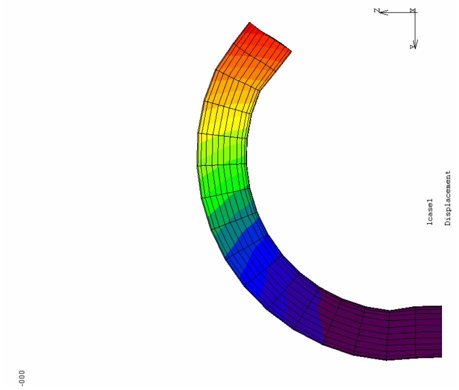
Figure 3 shows the analytical results of the displacement of the actuator tip for the models (a) to (e), where the horizontal axis, x represents the tip displacement in the bending direction and the vertical axis, y represents the tip



(a) p=0 MPa



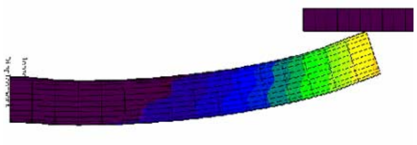
(b) p=0.05 MPa



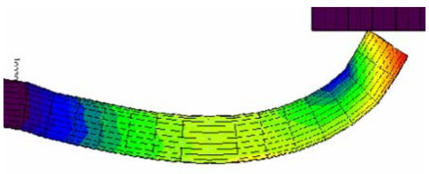
(c) p=0.12 MPa

Fig.5. Analytical results of deformations of the actuator with no load

(a) no pressure applied



(b) p=0.07 MPa, just after contacting



(c) p=0.15 MPa

Fig6. Analytical results of deformations of the actuator contacting its tip on a wall displacement in the axial direction. The figure shows the tip trajectory for the pneumatic pressure for 0 to 0.15 MPa. Pneumatic pressure is applied to the chamber located in the opposite side to the bending direction, while pressure in the other chamber is kept to atmosphere pressure. As shown in Fig. 3, the model (d) was found to show the largest displacement: the separating walls of t=1, 1.5, and 2 mm are too soft and the separating walls of t= 2.5 mm is too stiff. An interesting point in Fig. 3 is that the actuator (a) deforms in y-direction; the reason for it is that the stiffness in y-direction is very small and the deformation in y-direction is caused.

Figure 4 shows the analytical results of the displacement of the actuator tip for the models (f) to (h), and (d), where we found that the models (f) to (h) cause the deformation smaller than the model (d). The reason is that the stiffness of the rubber structure in the axial direction becomes larger for the models (f) to (h).

D Analytical results of deformation of optimized actuator

From these analytical results, we concluded that the model (d) works best. Figure 5 shows the deformations of the actuator (d) for increasing the applied pressure with every 0.2 MPa step. Figure 6 shows an example of the contact problem simulation of the actuator (d), where the tip of the actuator touches on the wall and after touching the middle of the actuator deforms.

III. PROTOTYPING AND EXPERIMENTS

Designed actuator (d) are fabricated and tested. Figure 7 shows our prototyping CAD/CAM system. The 3D CAD data, which are generated by a 3D-CADand used for the FEM analysis, are sent to a CAM system after conversion to DXL or STL formatted data. The CAM software generates tool path data of G-code and sends it to the NC machine, by which the molds are fabricated. Silicone rubbers are formed by the molds. In this manner prototype of actuators designed by FEM are easily embodied.

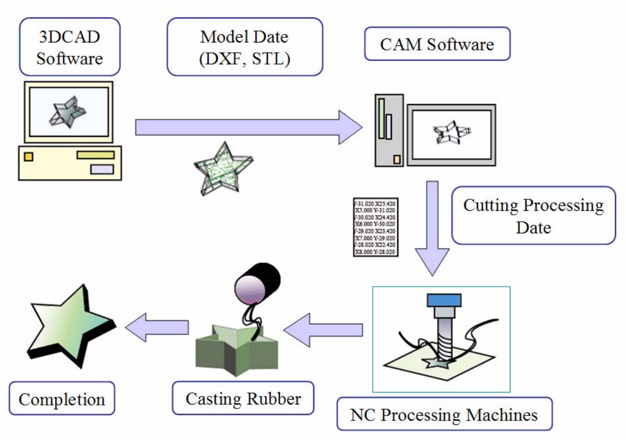
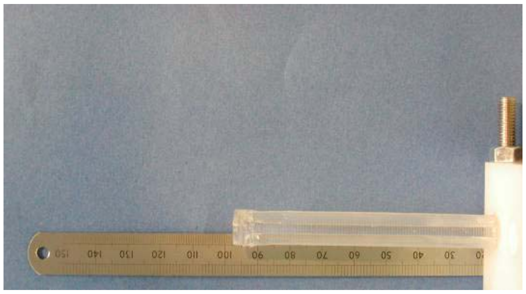
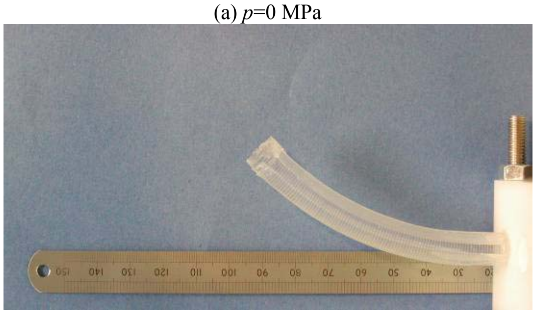


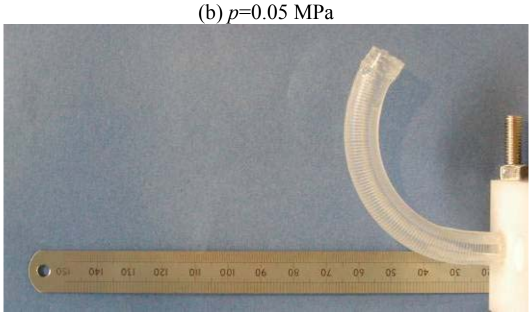
Fig.7. CAD/CAM system for prototyping actuator: CAD data transformation, mold machining by NC machine, and rubber forming with injection



(a) p=0 MPa

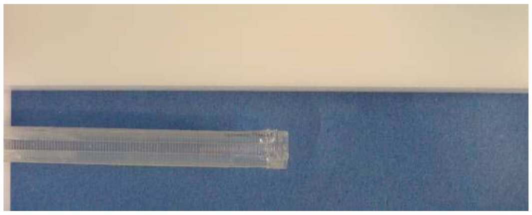


(b) p=0.05 MPa

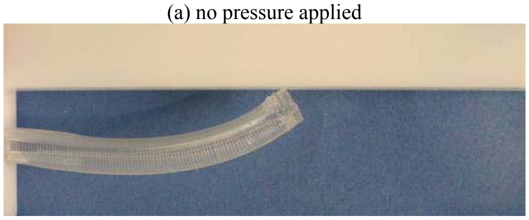


(c) p=0.12 MPa

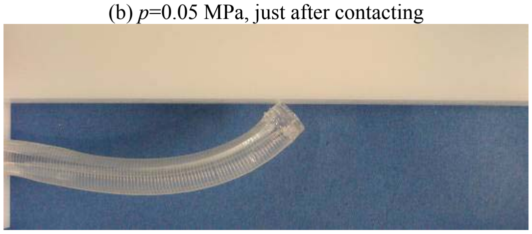
Fig.8 Experimental results of deformations of the actuator



(a) no pressure applied



(b) p=0.05 MPa, just after contacting



(c) p=0.12 MPa

Fig9 Experimental results of deformations of the actuator contacting its tip on a wall

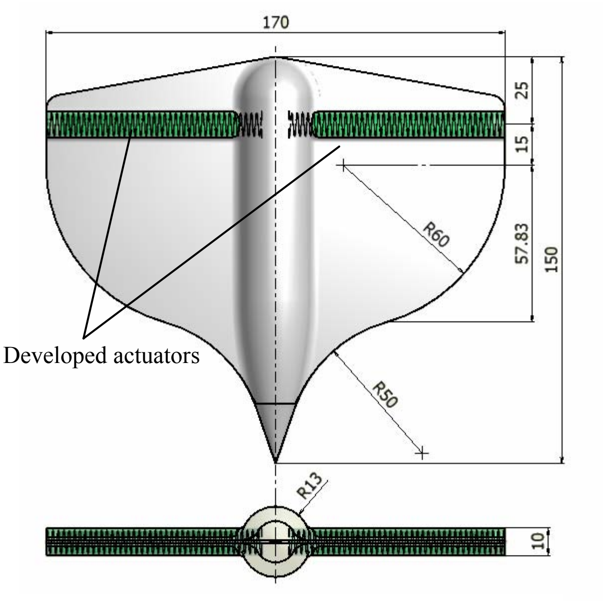


Fig10 Manta swimming robot design: two embedded bending pneumatic rubber actuators drive the manta

The motions of the prototype actuator (d) are shown in Figs. 8 and 9: Figure 8 shows the deformations of the actuator without load. It is found that the experimental results agree very well with the analytical results shown in Fig.5. Figure 9 shows the deformations of the actuator contacting the wall. They also show good agreements with the analytical results shown in Fig.6.

IV. MANTA ROBOT DESIGN

Pneumatic rubber actuators in general are suitable for underwater robots to move smoothly like living creatures because pneumatic rubber actuators have water-resistance, high power density, light weight, and high compliance to deform smoothly with interaction with water.

A manta type swimming robot is designed as shown in Fig.10. Two bending pneumatic rubber actuator, Model (d), are embedded in the robot as shown in Fig. 10. The manta robot is 170 mm in width and 150 mm in length. It is made only of silicone rubber. Two flexible pneumatic tubes are connected to each actuator, resulting in four flexible pneumatic tubes in total to drive the robot. Applied pneumatic pressure is controlled by electro-pneumatic servo valves. The robot can swim forward and also steer in any desired direction.

The shape and dimensions of the manta robot is designed to realize good motions by using non-linear FEM analysis. The simulation results of the motions of the final manta robot design are shown in Fig.11, where we find that the deformations of the flapper transmit from the actuators to rear direction working like a real manta.

V. MANTA ROBOT SWIMMING EXPERIMENTS

The manta robot shown in Fig.10 was fabricated and tested in water pool. Sequential photographs are shown in Fig.11. The robot works successfully in water with the swimming speed of 100 mm/s.

VI. CONCLUSION

This paper shows a new design and prototyping method for pneumatic rubber actuators. The method enables us to design pneumatic rubber actuators optimally and efficiently based on static analysis using non-linear finite element method, in which geometrical and material non-linearity are considered and also enables us to prototype them rapidly and efficiently by a CAD/CAM based rubber molding process. In this paper, a bending pneumatic rubber actuator with two degrees of freedom is designed and developed, where static characteristics of several possible actuators are analyzed to lead to the optimal actuator design. The experimental results of the prototype actuator shows that the developed actuator works very well and its characteristics agree well with that of analytical results.

The actuator is suitable to be applied for swimming robots

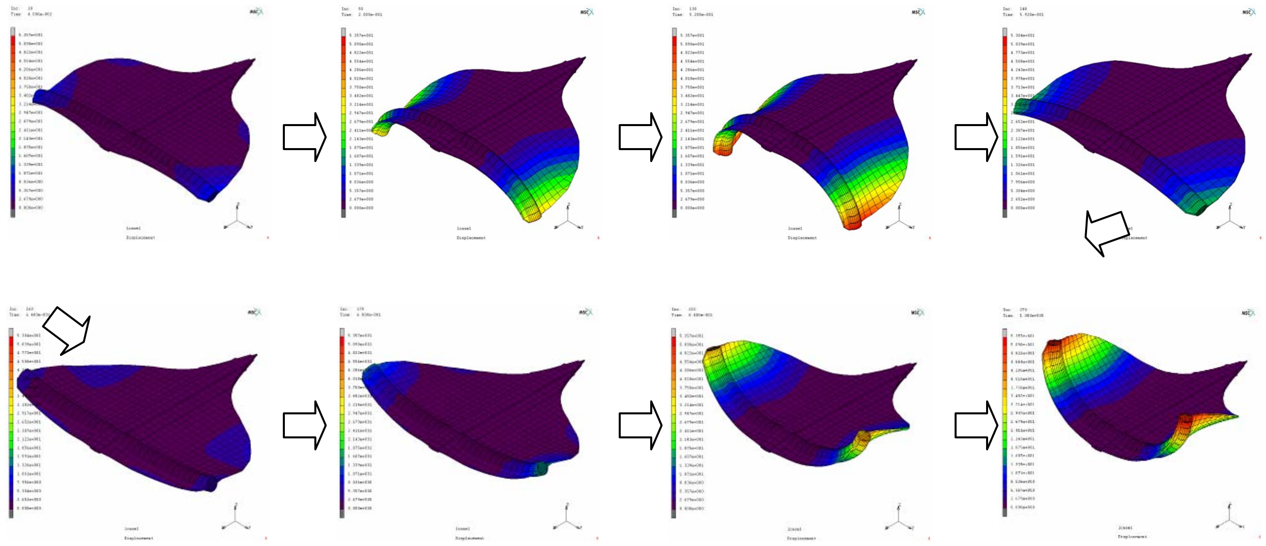


Fig10 Simulation results of Manta swimming robot motion

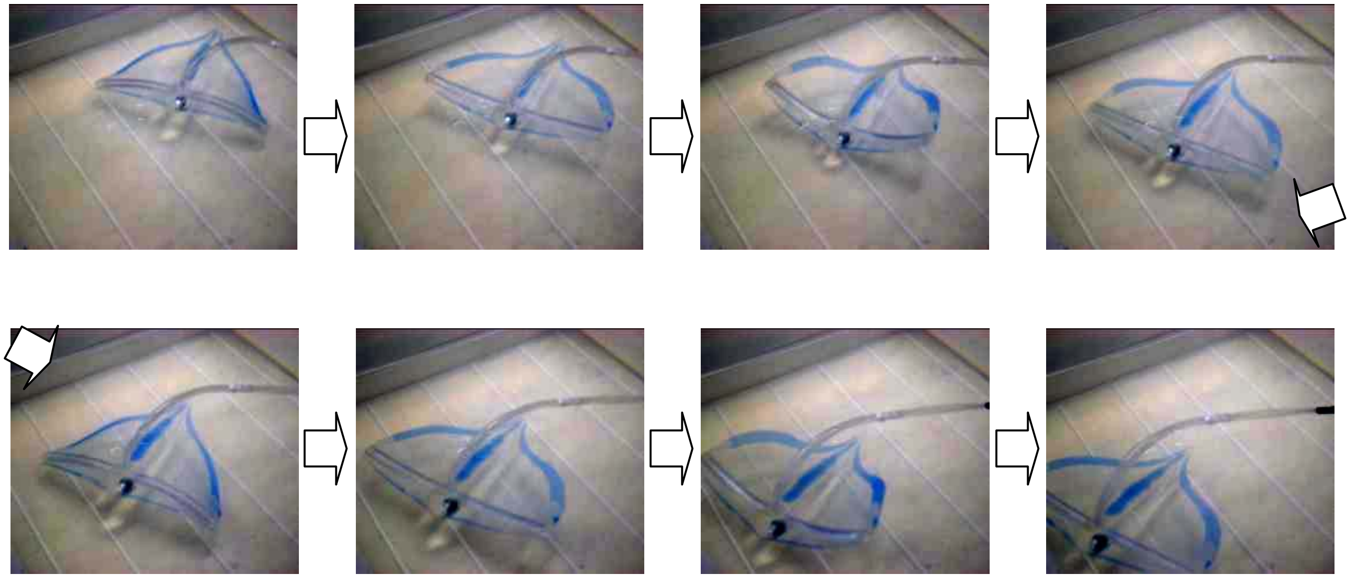


Fig11 Experimental results of manta swimming motions

in water moving smoothly like living creatures. The developed actuator is applied to a manta-type robot. The robot is made of only rubber including actuators, resulting in water-resistance, simple structure, light weight and soft mechanism. In the case of designing manta robot non-linear FEM is also very effective.

The developed manta robot works very well in water with the swimming speed of 100 mm/s.

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REFERENCES

[1] H. F. Schulte Jr., The Characteristics of the Mckibenn Artificial Muscle, *The Application of External Power in Prothetics and Orthetics*, 94-115.

[2] G. B. Immega, Romac Actuator for Micro Robot, *Proc. of Micro Roboticsand Teleoperators Workshop by IEEE Robotics and Automation Council*, (1987).

[3] T..Fukuda, et al., Rubber Gas Actuator Driven by Hydrogen Storage Alloy for In-pipe Inspection Mobile Robot with Flexible Structure, *Proc. of IEEE Int. Conf. on Robotics and Automation*, pp.1847-1852, (1989)

[4] K. Susuzmori, S. Iikura and H. Tanaka, Applying A Flexible Microactuator to Robotic Mechanisms, *IEEE Control Systems*, *vol.12*, *no.1*, (Feb.1992), pp.21-27.

[5] K. Suzumori, T. Maeda, H. Watanabe and T. Hisada, Fiberless Flexible Microactuator Designed by Finite-Element Method, *IEEE/ASME Transactions on Mechatronics*, Vol.2 No.4 (Dec.1997), pp.281-286.

[6] K. Suzumori and S. Asaad, A Novel Pneumatic Rubber Actuator for Mobile Robot Bases, *Proc. IEEE/RSJ International Conf. Intelligent Robots and Systems*, (Nov.1996), pp.1001-1006.

[7] K. Suzumori, K. Hori and T. Miyagawa, A Direct-Drive Pneumatic Stepping Motor for Robots: Designs for Pipe-Inspection Microrobots and for Human-Care Robots, *Proc. IEEE International. Conf. on Robotics and Automation*, (May.1998), pp.3047-3052.

[8] T. Noritsugu, D.Sasaki, S.Matsuo, I.Kusunoki, and Y. Mitsumine, Development of Medical Care Assist Bed using Pneumatic Planar Soft Actuator, *Journal of Robotics and Mechatronics*, *Vol.14*, *No.6*, pp.547-556, 2002.

[9] D.Sasaki, T. Noritsugu, M.Takaiwa, Development of Active Support Splint Driven by Pneumatic Soft Actuator, *Journal of Robotics and Mechatronics*, *Vol.16*, *No.5*, pp.497-503, 2004.

[10] K. Suzumori, Takayuki Hama, Takefumi Kanda, New Pneumatic Rubber Actuators to Assist Colonoscope Insertion, *2006 IEEE International Conference on Robotics and Automation*, pp.1824-1829, （2006-5）.

[11] K. Suzumori and A. Abe, Applying Flexible Microactuators to Pipeline Inspection Robots, *Trans. of the IMACS/SICE International Symposium on Robotics and Manufacturing Systems*, (1993), North-Holland, pp.515-520.

[12] K. Suzumori, F. Kondo and H. Tanaka, Micro-Walking Robot Driven by Flexible Microactuator, *Jour. Robotics and Mechatronics*, vol.5, no.6, (June 1993), pp.537-541.

[13] S. Endo, K. Suzumori, T. Kanda, N. Kato, H. Suzuki, Y. Ando, Flexible and Functional Pectoral Fin Acutuator for Underwater Robots, *The 3rd International Symposium on Aero Aqua Bio-mechanisms ISABMEC 2006*, S42, p.55, (2006-7)

[14] Y. Ando, N. Kato, H. Suzuki, K. Suzumori, T. Kanda, and S. Endo, Elastic Pectoral Fin Actuators for Biomimetic Underwater Vehicle, *Proc. of 16th Int. Offshore and Polar Eng. Conf. (CD-ROM)(ISOPE)*, 2006

[15] K. M. Lee, J. Joni, X. Yin, Compliant Grasping Force Modeling for Handling of Live Objects, *Proc. IEEE Int.Conf. on Robotics and Automation*, Vol.4, pp.3807-3812, Seoul, May, 2001, 1059-1064

[16] K. Suzumori, T. Maeda, H. Watanabe and T. Hisada, Fiberless Flexible Microactuator Designed by Finite-Element Method, *IEEE/ASME Transactions on Mechatronics*, Vol.2 No.4 (Dec.1997), pp.281-286

[17] S. Hirai, T. Masui and S. Kawamura, Prototyping Pneumatic Group Actuators Composed of Multiple Single-motion Elastic Tubes, *Proc. IEEE Int.Conf. on Robotics and Automation*, Vol.4, pp.3807-3812, Seoul, May, 2001