2010 IEEE International Conference on Robotics and Automation
Anchorage Convention District
May 3-8, 2010, Anchorage, Alaska, USA

Fabrication and Basic Experiments of Pneumatic Multi-chamber Rubber Tube Actuator for Assisting Colonoscope Insertion

Shuichi Wakimoto, and Koichi Suzumori, *Member, IEEE*

Abstract— **Colonoscopy is an important medical action to detect disorders like colon cancer. However generally it is difficult to insert a scope into the colon, because the colon is flexible and complex shape.**

This study aims at development of an actuator which can add propelling ability to a colonoscope.

We focused on rubber pneumatic actuators, because advantages of them, for example, high compliance, low cost, water proof, and so on, agree with the required properties of medical devices.

In previous paper, we designed a novel rubber actuator consisting multi air chambers by using nonlinear FEM (finite element method). In this research, we fabricated the actuator employing the design; whose cross section is about 5mm x 5mm and length is over 100m, by extrusion molding method successfully. The deformation characteristics of the actuator were clarified by a motion capture system. As a result, elliptic trajectory which leads propelling motion was confirmed. In addition, transportation of a dummy scope was achieved by winding two actuators.

I. INTRODUCTION

COLONOSCOPY is very effective to detect diseases like colon cancer, however, it is difficult to insert an endoscope into the colon even by experienced doctors in some cases. While capsule endoscopes have been developed as painless inspection devices [1], [2], conventional wired endoscopes are still needed for medical procedure, for example precise diagnosis, polyp removal, and so on. From these backgrounds, several active wired endoscopes have been researched and reported [3]-[6]. However because of very complex and soft condition of the human colon, they could not be in practical usage.

We consider that realizing an assisting device which can be mounted on / removed from conventional endoscopes is very important. Because skills which currently doctors have will be utilized.

In addition, the assisting actuator is required to have following properties.

1. High compliance
2. Non-electrical drive system
3. Waterproof
4. Low cost

1 and 2 ensure high safety mechanically and electrically for human body. 3 must be realized in the colon. And 4 leads disposability for preventing infectious diseases. These requirements just agree with advantages of rubber pneumatic actuators.

Therefore we focused on development of a novel rubber pneumatic actuator generating propelling motion and assisting insertion of colonoscopes. In the past research, our research group developed some pneumatic rubber actuators to assist insertion of colonoscopes [7] [8].

The bubbler actuator is one of them and it generates travelling waves on its surface pneumatically and has propelling ability [7]. By winding it around an existing endoscope, insertion experiments into the colon model were carried out. Although the results showed some advantages, it could not work enough. The drawback was caused by inadaptability for large undulation of inner colon condition from unsatisfactory deformation of the bubbler actuator. From the results of the bubbler actuator, in the previous paper [8], we improved actuator design by using nonlinear FEM, and as its result, one efficient design with four chambers was derived. It realized very large deformation. However, because the design had very complex shape, we could not fabricate it with sufficient small cross section size and long length to wind around endoscopes, at that time, the actuator was about 10mm x 10mm in cross section area, and several tens of cm in length by molding from difficulty of fabrication.

In this paper, by extrusion molding method, we realize the actuator with about 5mm x 5mm in cross section and over 100m in length successfully. And by fundamental experiments, characteristics of the actuator were clarified. Moreover transportation of a dummy endoscope could be confirmed by winding two tube actuators around a dummy endoscope.

This research was partially supported "The subsidy to promote science and technology in the prefectures where nuclear power plants and other power plants are located", MEXT's program "Promotion of Environmental Improvement for Independence of Young Researches" under the special coordination Funds for promoting Science and Technology, and "KAKENHI Grant-in-Aid for Yong Scientists(B) (No.2070048)".

And the authors would like to thank Y. Yamamoto, Y. Nishioka and K. Ozaki for their helpful assists for some experiments.

Shuichi Wakimoto is with Research Core for Interdisciplinary Sciences, Okayama University. Okayama University, Tsushima-naka, Okayama, 700-8530 Japan

Koichi Suzumori is with Graduate School of Natural Science and Technology, Okayama University, Tsushima-naka, Okayama, 700-8530 Japan.

(corresponding author to provide phone: +81-86-251-8490; fax: +81-86-251-8490; e-mail: wakimoto@act.sys.okayama-u.ac.jp).

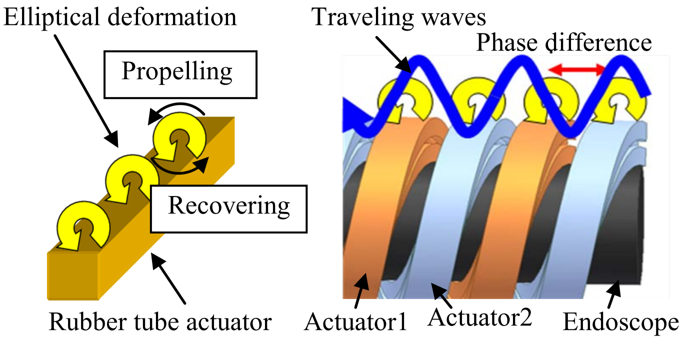
II. DRIVING CONCEPT AND ACTUATOR DESIGN

A. Driving concept

Figure 1 illustrates the working concept of assisting endoscope insertion into the colon by a rubber pneumatic actuator. The actuator is made from rubber material and it is tube shape and has some chambers. The actuator is designed to generate ellipsoidal motion on the top of the actuator by pneumatic pressure as shown in Fig.1 (a).

The ellipsoidal motion can be divided by the horizontal displacement and vertical displacement, and the former displacement affects the moving velocity during one cycle of the motion. And the latter one indicates adaptability to the bumpy colon wall. In addition, one cycle consists of two motions, one is “propelling motion”, and the other is “recovering motion”. In propelling motion, the actuator contacts with the colon wall and thrusts the endoscope. During recovering motion, the actuator dose not touch the colon wall and recovers to propelling state.

Two tube actuators are wound around a colonoscope spirally as shown in Fig. 1 (b). By driving the actuators with phase difference, traveling waves occur on the surfaces of the rubber actuators. By the traveling waves, the colonoscope can have propulsion capability. By changing direction of ellipsoidal motion, propagation direction of traveling waves can be controlled, and then the endoscope can move in both forwards and backwards.



(a) Concept of actuator (b) Assisting principle

Fig. 1 Working principle of tube pneumatic actuator for assisting insertion, (a) indicates driving concept of tube actuator and (b) shows mounting method on endoscope and assisting principle.

Additionally this actuator has following advantages,

1. It can be fabricated for low cost with long length by extrusion molding method.
2. Because of low mechanical impedance and non electrical drive, a human body is not injured.
3. It can be mounted on the conventional endoscope easily; it just winds around the endoscope using a double-stick tape manually. And it can also be removed with ease.

These agree with requirements for colonoscopy assisting actuators mentioned in section 1.

B. Actuator Design

In the previous paper [8], using nonlinear FEM, several cross section shapes of rubber actuators were analyzed. The actuators are required to generate like an ellipsoidal motion. In the analyses, actuator models were evaluated by largeness of their ellipsoidal motions.

As a result of FEM analysis, one efficient design of the actuator was derived. Figure 2 illustrates its cross section. It has four chambers inside it.

In non-driving state, the vertical size is 13 and the horizontal one is 14. Note, in the analysis, there is no unit, the size means just length ratio.

Identification number of each chamber is defined as shown in Fig.2, namely, the left lower is A, the center is B, the top is C, and the right lower is D. And the coordinate is also defined as shown in Fig.2.

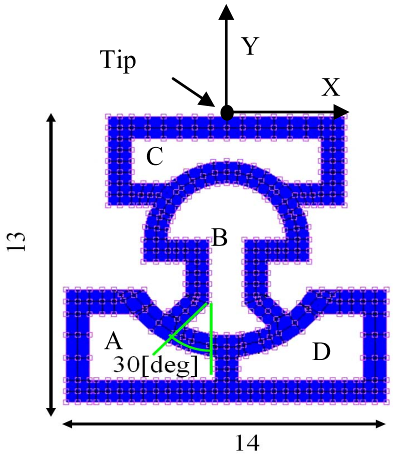


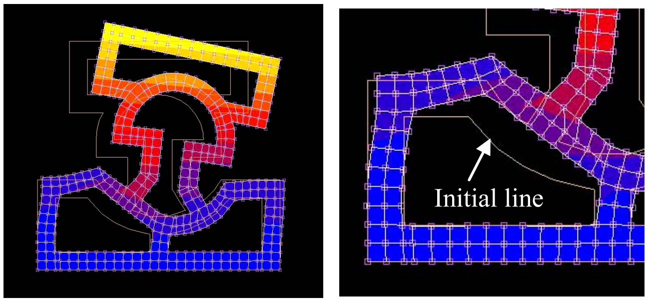
Fig. 2 Cross section design of tube actuator derived by nonlinear FEM analysis, design has four chambers.

For generating ellipsoidal motion of the tip of the rubber structure, pneumatic pressure is applied to each chamber with particular pressure pattern mentioned in the next section. Each chamber is swollen during under pneumatic pressure, and contributes actuator motion as below,

Chamber A: Displacement in the plus x direction
Chamber B: Expansion of each displacement
Chamber C: Displacement in the plus y direction
Chamber D: Displacement in the minus x direction

The structure has odd-shaped chambers including some curved lines. These leads efficient deformation when pneumatic pressure is applied. For example, chamber A has a curved line in its upper right side, and when the pressure is applied into chamber A, the curved shape part is easily swollen compared with other straight parts. Therefore it conduces to displacement in the plus x direction effectively. In this case, i.e. applying pneumatic pressure into chamber A, the analysis result is shown in Fig.3, by this figure, the large deformation of curved shape wall can be confirmed.

For the same reason, chamber D has a curved shape in upper left part to generate displacement in minus x direction. And chamber B has some bended walls and a curve wall. By this chamber shape, chamber B can deform in the longitudinal direction largely.



(a) Deformation during applying pressure into chamber A

(b) Close up around chamber A

Fig.3 Deformation of analysis model under applying pressure into chamber A; (a) shows whole cross section and (b) is close up of chamber A.

III. FABRICATED ACTUATOR AND DRIVING SCHEME

A. Fabrication

Based on the analysis result, the tube actuator was fabricated by extrusion molding method. This method has strong advantage; the tube actuator can be manufactured with very long length at one fabrication process for low cost. Therefore it is very easy to realize the arbitrary length of the tube actuator; works are just cut, attachment of air supply-tubes, and infilling on cut surfaces.

The extrusion molding method of the rubber is following steps.

1. Making a mold which determines cross section shape of the tube actuator
2. Extruding fluidized state rubber through the mold continuously
3. Vulcanizing rubber by heating during extruding

However by this method, achievement of complex cross section shape is remarkably difficult. In the process 3, rubber shape changes significantly by comparing the shape in process 2. Therefore a mold shape must be decided as considering this change.

Figure 4 shows the cross section of the first fabricated tube actuator. This actuator was realized by using a mold which is just inverse shape of the actuator design shown in Fig.2. As shown in Fig.4, the shape of cross section is quite different from the design. In black circle areas, a, b, c, and d, are stuck. And the some walls, which must be straight as the design, bend.

On the other hand, Fig.5 shows the cross section of the final fabricated actuator. Compared with the first one, this shape resembles the analysis design. The improvement was able to be achieved by changing the mold by feeding back the first fabricated shape. The four chambers can be created successfully. The cross section size is about 5mm x 5mm.

Figure 6 shows the rubber tube whose cross section is Fig.5. It was confirmed that the cross section shape of Fig. 5 can be maintained in case of more than 100m of length.

Generally extrusion molding for complex shape and soft material is very difficult technology. Establishment of this fabrication process supports our research strongly, because the tube actuator must be long length to wind an endoscope.

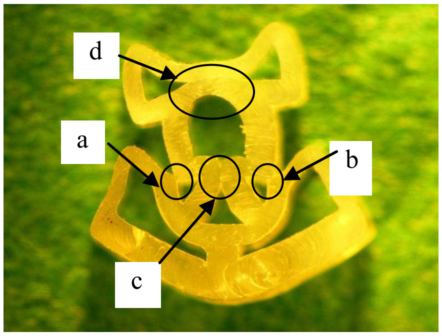


Fig. 4 Cross section of the first fabrication actuator shape; black circle areas are stuck, shape is different from analysis model.

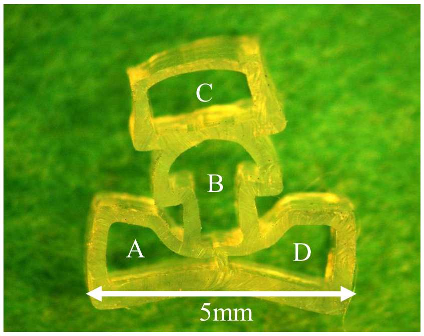


Fig. 5 Cross section of the final fabrication actuator shape; size is about 5mm x 5mm, and shape agree with analysis one almost.

Fig. 6 Developed tube actuator whose cross section is Fig.5; by extrusion molding method, rubber tube can be achieved over 100m with maintaining same cross section shape.

B. Driving scheme

Figure 7 illustrates the driving scheme of the tube actuator. To generate assisting motion of endoscope insertion, the red point, which is the top of the actuator, must move like ellipsoidal trajectory.

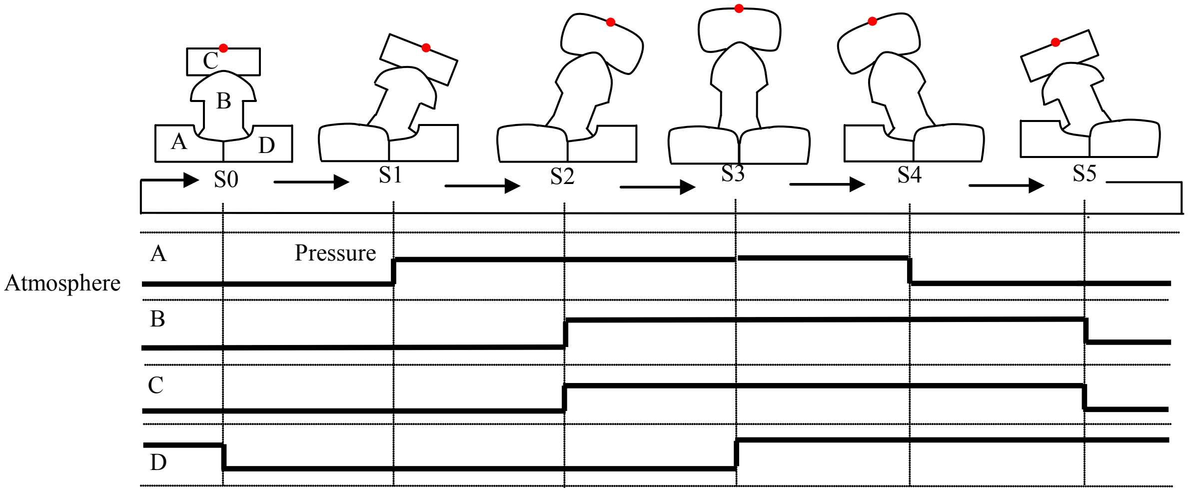


Fig.7 Driving scheme of rubber tube actuator, it consists of six states from S0 to S5, red point, which is top of actuator, move like ellipsoidal curve.

For this motion, driving condition of the actuator consists of six states from S0 to S5 as shown in Fig.7. Each state is described below.

S0: All chambers are atmosphere pressure; the red point is the initial state.

S1: Chamber A is pressured; the red point moves in the right side.

S2: Chambers A, B and C are pressured; the red pint moves in the right upper sides.

S3: All chambers are pressured; the red point moves in above.

S4: Chambers B, C and D are pressured; the red point moves in the left upper side.

S5: Chamber D is pressured; the red point moves in the left side.

By repeating the motions from S0 to S5, the red point can move like ellipsoid trajectory.

C. Simulation

By employing above scheme and actual rubber mechanical property, nonlinear FEM analysis was carried out. In the analysis, both material nonlinearity and geometrical nonlinearity were considered. For the material nonlinearity, result of material test was approximated by Mooney-Rivlin function which is one of the major functions to present rubber material characteristics.

Fig.8 shows one of the analysis results, and Fig. 9 indicates the trajectories of the tip of the analysis model in cases of 25kPa, 50kPa and 75kPa.

The horizontal axis is displacement in x direction, and the vertical axis is in y direction. By increasing air pressure, motion of the top in the model becomes widely as maintaining same trajectory form.

It is confirmed that the top of the model can generate almost intended motion, near-ellipsoidal motion, and propelling and recovering motions are generated.

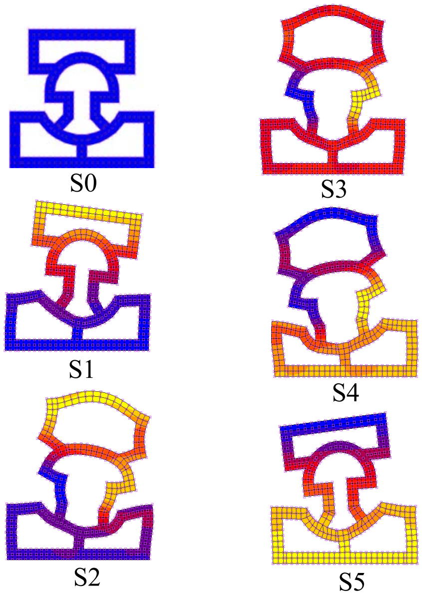


Fig. 8 Results of nonlinear FEM analysis; each figure corresponds state of S0 to S5 in Fig.7.

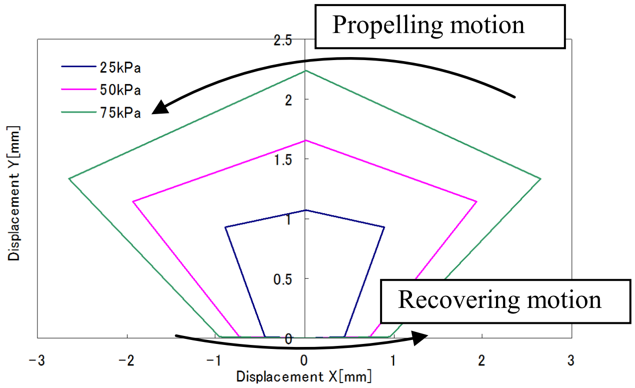


Fig.9 Trajectories of tip of simulated model; blue line, pink line, and green line are obtained under applied pressures of 25kPa, 50kPa and 75kPa respectively.

IV. DRIVING EXPERIMENTS

A. Motion of single tube actuator

Using one tube actuator, motion was measured. Figure 10 shows tested actuator. Its length is 120 mm.

Fig.10 Tested actuator (length is 120 mm)

Figure 11 shows the motion of the actuator under 75kPa. (The motion can be shown in the video clip.) In the experiments, a white mark was mounted on the middle top point of the actuator. It was used as a tracking mark in motion capture system. Performance of the actuator depends on load, however weight of the mark is quite small, it is about 0.005gf, therefore its influence can be ignored. The red point indicates center of the white mark which is calculated by the image processing software.

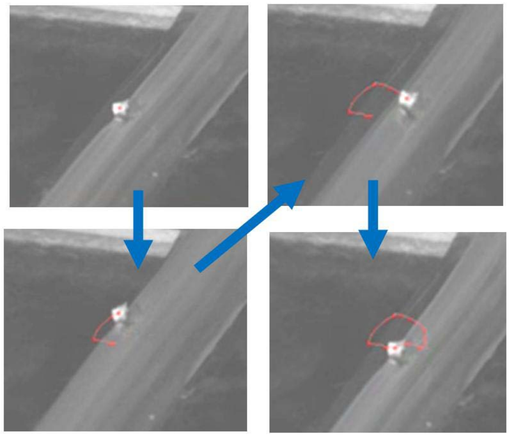


Fig.11 Experimental results of single tube actuator under 75kPa, and red point is center of the mark.

Figure 12 is the graph of the red point. In this graph, the motions were measured under 25kPa, 50kPa and 75kPa of pneumatic pressure with 1.0Hz. And like FEM results, the motion area increase with rise of pneumatic pressure. The maximum absolute displacements of x and y directions are about 5.7mm and 2.2 mm under 75kPa. Note, under repeated 100kPa of pressure, the actuator was broken; therefore the maximum pressure was defined as 75kPa.

The errors between the FEM results and the experimental results were caused by following reasons.

1. In the FEM, there is no constraint in the longitudinal direction, namely it was assumed that the length of the tube was infinity.
2. As shown in Fig.5, the shape of the fabricated actuator is not same as analysis one perfectly. Also it is not symmetric completely.
3. Experimental results may include about 5% of calibration error.

In these reasons, the second one is the most major factor. Therefore if the errors need to reduce more, the shape must be conformed to analysis model. However from Fig. 11 and Fig.12, propelling and recovering motions of the actuator can be found clearly. In addition, by considering difficulty of rubber extrusion molding, the current cross section is sufficient shape.

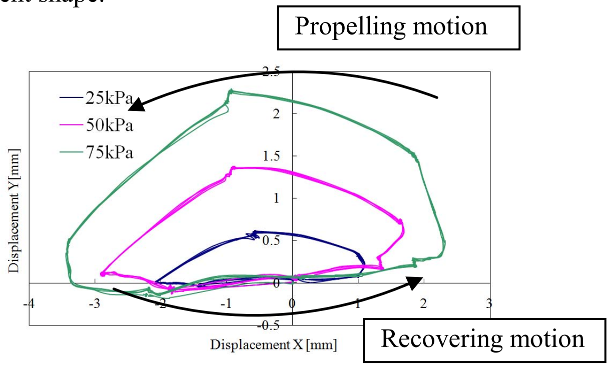


Fig.12 Experimental results of single tube actuator under 25kPa, 50kPa and 75kPa; propelling and recovering motions can be confirmed.

B. Transportation experiments using dummy scope

By winding two tube actuators spirally in parallel around a dummy endoscope which is a resin rod using double-sided tape, transportation experiments were carried out.

By driving with phase difference of the half cycle between two actuators, one actuator is in propelling motion, the other is in recovering one. Repeating the relation, traveling waves occur on the surface.

Figure 13 shows the experiment. In the experiment, the dummy endoscope was able to be transferred. The velocity, in case of 75kPa and 1.5Hz in a vinyl hose, was about 12 mm/s.

Figure 14 is close up of the tube actuators during driving. It was confirmed that propelling state and recovering state can be generated appropriately. These motions are shown in the video clip.

Fig.13 Transportation experiment using two tube actuators winding around dummy endoscope

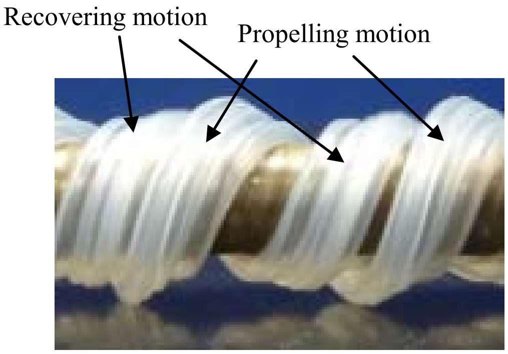


Fig.14 Close up of two actuators; one works as propelling motion, and the other performs as recovering motion.

V. CONCLUSION

In this study, we aims at development of a novel tube rubber actuator assisting colonoscope insertion. In previous work, we could derive an efficient shape of the actuator. However appropriate size of the actuator was not able to be achieved because of difficulty of its fabrication.

In this paper, successfully we realized the tube shape rubber actuator with suitable small size by extrusion molding method. The cross section is about 5mm x 5mm and over 100m in length.

The characteristics of the fabricated actuator were measured by the motion capture system. Although the errors occurred between experimental motions and analysis ones because of small shape error, propelling motion and recovering motion can be successfully generated. Moreover by winding two tube actuators around the dummy scope and driving them with phase difference, transportation of the dummy scope was achieved. The speed was 12 mm/s under 75kPa and 1.5Hz. Currently the actuator has been mounted on a conventional endoscope and insertion experiments have been carried out using the colon model.

REFERENCES

[1] Michel Delvaux, Gerard Gay, "Capsule Endoscopy in 2005:Facts and perspectives", Best Practice & Reserch Clinical Gastroenterology Vol.20, No.1 ,pp23-39, 2006.

[2] Glenn M.Eisen,"Capsile Endoscopy Indications,"American Society for Gastrointestinal Endoscopy,Vol.14, No.1 July, pp1-4, 2006.

[3] Gregory G, Ginsberg, "Colonoscopy with the variable stiffness colonoscope", Gastrointestinal Endoscopy, vol. 58, No.4, 2003.

[4] J.Peirs, D.Reynaerts,H.Van Brussel, "A miniature manipulator for integration in a self-propelling endoscope", Sensors and Actuators A92, pp343-349, 2001.

[5] H. Kita, H. Yamamoto, "Double-balloon endoscopy for the doasnosis and treatment of small intestinal disease", best Practice & Reserch Clinical Gastroenterology, Vol.20, No1, pp179-194, 2006

[6] Maria Chiara, Alberto Arena, Dino Accoto, Arianna Menciassi, and Paolo Dario, "A SMA-actuated miniature pressure regulator for a miniature robot for colonoscopy", Sensors and Actuators A 105,pp119-131, 2003.

[7] Koichi Suzumori, Takayuki Hama, and Takefumi Kanda, "New Pneumatic Rubber Actuators to Assist Colonoscope Insertion", Proc. of IEEE International Conference on Robotics and Automation, 995, pp.1824-1829, 2006.

[8] H. Onoe, K. Suzumori, and S. Wakimoto, "Optimum design of pneumatic multi-chamber rubber tube actuator generating traveling deformation waves for colonoscope insertion" Proc. of IEEE/ASME International conference on advanced intelligent mechatoronics, pp.31-36, 2008.