31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Development of a robotic endoscope that locomotes in the colon with flexible helical fins

M. Shikanai, N.Murai, K. Itoh, H. Ishii, A. Takanishi, K. Tanoue, S. Ieiri, K. Konishi, M. Hasizume, *Member, IEEE*

Abstract— **The purpose of this study was to develop a robotic endoscope that is low invasive, easy to operate and capable of locomotion from the rectum to the appendix in the human body. We believe that it would contribute to relieving pain in patients. We therefore developed a robotic endoscope that consists of a front and rear body with clockwise and anticlockwise helical fins, respectively. The front and rear bodies are connected via a DC motor. This robot moves forward in the colon by rotating the front body in the clockwise direction and the rear body in the anticlockwise direction. In addition, the radius of each helical fin can be changed by blowing air into a balloon implemented under each fin using an air compressor. Before experiments with animals, we performed experiments to evaluate the mechanical performance and safety of the robot. We confirmed that the maximum radius of the fins was less than the maximum radius of the colon by blowing air continuously into the balloons. We then confirmed that the robot can locomote in the colon without invasion of scratch and make short hole by performing an in-vivo experiment in live swine.**

I. INTRODUCTION

The incidence of colorectal cancer is ranked fourth in men and third in women, with over 1 million new cases occurring every year worldwide [1]. The five-year survival rate is around 50%. However, patients can recover fully if the colorectal cancers are detected early. Thus, early detection is one of the most important factors in treatment of colorectal cancers. Colonoscopic examination is one of the most reliable methods of detecting colon cancers at an early stage.

In colonoscopic examination, a doctor inserts an endoscope with a 5 mm radius into the colon from the anus and determines whether there are any cancers on the intestinal wall. However, colonoscopic examination is not easy because the large intestine is long and possesses curves and rugae. Therefore, the reliability of the result and invasiveness of the procedure are greatly affected by the skill level of the doctor. Moreover, there are also many other problems, such as overlooking the affected area, inflicting pain, punching and bleeding.

The double-balloon and capsule endoscopes were developed to solve these problems. The double-balloon endoscope consists of an endoscope, two balloons, whose size can be changed by blowing air into them, implemented at its head, and an actuator that changes the distance between the balloons. This endoscope moves forward like an inchworm by changing the size of each balloon and the distance between them. It can be inserted into the small intestine [3]. The capsule endoscope is swallowed like a tablet. It can be used to check the small intestine without any invasion [4]. However, there are some problems. For instance, the double-balloon endoscope requires higher skill than a conventional endoscope, and capsule endoscopes sometimes stay in the small intestine and overlook affected areas [5].

Various studies have been performed to solve these problems, and capsule endoscopes with legs have been developed. The legs are actuated by a shape memory alloy (SMA) [6, 7]. However, many of these robots cannot move backwards. Moreover, SMA actuators have low levels of efficiency and slow response times, more than a few seconds, because they work be heating the SMA itself[6, 8]. In addition to these colon-specific robots, a locomotive robot for pipes have also been developed [9]. However, its structure is complicated, and it is difficult to downsize. Therefore, the purpose of this study was to develop a robotic endoscope that is low invasive, easy to operate and capable of locomotion from the rectum to the appendix in the human body. We believe that it would contribute to relieving pain in patients. We therefore developed two robots with different mechanisms of movement, rotational inertia- and reverse screw-type movement. As a result of locomotion experiments in the swine colon, we confirmed that the reverse screw type is more effective [10].

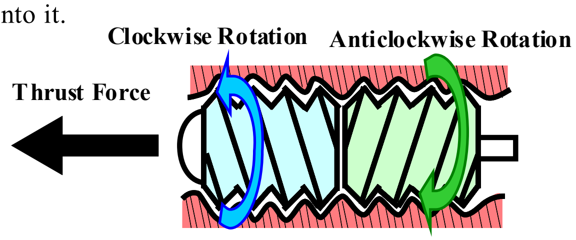
M. Shikanai is with Waseda University, Toyo, Japan (e-mail: shika-nai@fuji.waseda.jp)
N. Murai is with Waseda University, Tokyo Japan (e-mail: n-murai@takanishi.mech.waseda.ac.jp)
K. Itoh was with Waseda University, Tokyo, Japan (e-mail: k-itoh@takanishi.mech.waseda.ac.jp)
H. Ishii is with Waseda University, Tokyo, Japan (e-mail:h-ishii@takanishi.mech.waseda.ac.jp)
A. Takanishi is with Waseda University, Tokyo, Japan (e-mail: takanisi@waseda.jp)
M. Hashizume is with Kyusyu University Hospital, Fukuoka, Japan (e-mail: mhashi@dem.med.kyushu-u.ac.jp)
K. Tanoue is with Kyusyu University Hospital, Fukuoka, Japan (e-mail: tanoue_k@dem.med.kyushu-u.ac.jp)
S. Ieiri is with Kyusyu University Hospital, Fukuoka, Japan (e-mail: satoshi@molcar.med.kyushu-u.ac.jp)
K. Konishi is with Kyusyu University Hospital, Fukuoka, Japan (e-mail: konizou@surg2.med.kyushu-u.ac.jp)

978-1-4244-3296-7/09/$25.00 ©2009 IEEE

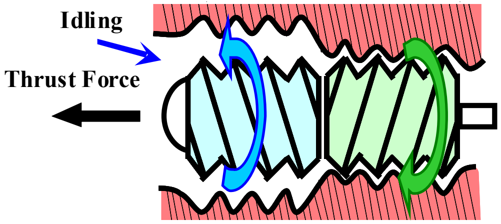
In this paper, we report the developed locomotive mechanism for a robotic endoscope. Its safety and low invasiveness are evaluated by both in-vivo and in-vitro experiments.

II. LOCOMOTIVE PRINCIPLE

The locomotive principle of our proposed robotic endoscope is presented in Fig. 1. The robotic endoscope consists of a front and rear body with clockwise and anticlockwise helical fins, respectively. The front and rear bodies are connected via a DC motor. Fig. 1 (a) shows the robot locomotion in the colon with the front body rotating in the clockwise direction and the rear body rotating in the anticlockwise direction. However, when the radius of the intestine is larger than that of the helical fins, the robot idles and cannot generate thrust force. This is shown in Fig. 1 (b). To solve this problem, the radius of each helical fin can be changed by blowing air into a balloon implemented under each fin. Fig. 1 (c) shows that this mechanism can provide appropriate frictional force between the robot and intestinal wall. Furthermore, the robot can also passively bend along bends in the colon because of the universal joint built into it.



(a) Robot locomotion in a colon with a small radius



(b) Robot is idling in a colon

(c) Robot locomotion in a colon with a large radius

Fig. 1. Hardware principles

To get the thrust force of this robot, simplify this mechanism for screw. This is shown in Fig. 2. The thrust force of a screw is derived as

$$Q = \frac{2 \cdot T}{D \cdot \tan(\alpha + \theta)},$$

where *tan α* and *tan θ* are derived as

$$\tan\alpha = \frac{p}{\pi \cdot D} \quad , \quad \tan\theta = \frac{\mu}{\cos\beta} .$$

Therefore, the thrust force is derived as

$$Q = \frac{2 \cdot T(\pi \cdot D \cdot \cos\beta - p\mu)}{D \cdot (p \cdot \cos\beta + \mu \cdot \pi \cdot D)}$$

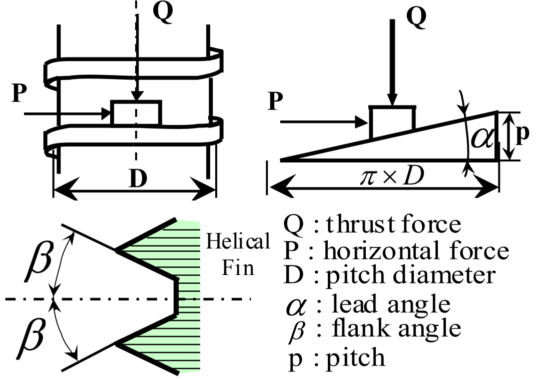


Fig. 2. Generation of thrust force

III. MECHANICAL DESIGN

An overall view of the developed hardware is shown in Fig. 3. The interior of the robot consists of a cylindrical body made of ABS resin, and the exterior of the robot consists of fins made of SEPTON, thermoplastic elastomers, pasted onto the cylindrical body. The robot is 190 mm long, and its head and fins are 30 mm in diameter. Moreover, the sizes of other parts of the front body include a 20 mm pitch diameter, 10 mm pitch, 9 deg lead angle and 36 deg flank angle. The sizes of the other parts of the rear body include a 20 mm pitch diameter, 13 mm pitch, 11.7 deg lead angle and 15 deg flank angle. The front and rear bodies are connected via a DC motor. The motor is a Maxon RE-8 DC motor with a moderating ratio of 1:221. The difference in frictional force between the front and rear units is canceled by changing the radius of each helical fin of the robot. In order to seal the pipeline which sends air as much as possible, an O-ring is used between the front and rear bodies. This prevents moisture from infiltrating into the interior of the robot. We have also developed an original connector to prevent twisting of the power source wires and air tube. The ability to generate continuous movement is a feature of this mechanism. Furthermore, even if one body cannot rotate, the other body can continue to provide thrust force.

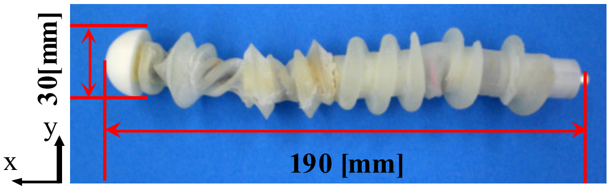


Fig. 3. Overall view of the developed hardware

IV. EXPERIMENTAL VERIFICATION

First, we confirmed the safety of the variable radius system of the robot. Part of a balloon was inserted into the colon of a dead swine and inflated. This is shown in Fig. 4. In this experiment, there was no feedback of air pressure or air flow. We also confirmed that the large intestine will not burst when the balloon is inflated to its maximum size. When air was blown continuously into the balloon, its radius swelled from 3 cm to 4 cm, but it did not inflate further because of constant outflow of air. In addition, outflow of air into the colon is safe based on the fact that doctors use air to improve insertion in large intestine endoscopy. However, air leaks cause discomfort in patients. Therefore, air leaks will be prevented completely in the future by enabling feedback of air pressure and air flow. This will make large intestine endoscopy safer, and we believe that it can be performed without discomfort.

Dead Swine Colon Extended by balloon

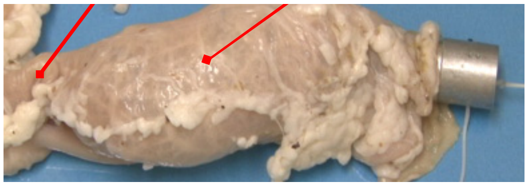


Fig. 4. Extend a dead swine colon

Second, we inspected the relation between voltage and number of rotations of the robot in air. We also investigated the changes of the number of rotations at the time of bending of the tip. The results are shown in Fig. 5.

We confirmed that there is a proportional relationship between the number of rotations and voltage and that the number of rotations does not change in air. Moreover, the robot did not rotate at less than 2.5 V because of a shortage of torque shortage.

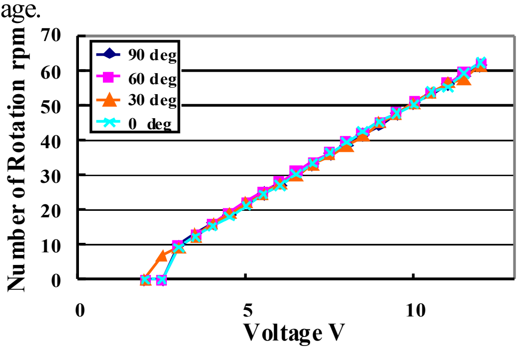


Fig. 5. Relation between voltage and number of rotations

Third, the frictional force produced by pressure from the large intestine wall enables the robot to move. We therefore measured the frictional force and tensile force in the radial direction.

The instrument used for measurement of friction force and tensile force consisted of two sticks with a load cell. To measure the friction force, a colon was clipped to them and pulled in a longitudinal direction using a ball screw. The results of experiments with four different colons from dead swine are shown in Fig. 6. To measure the tensile force, the two sticks and load cell were put into the colon and extended in a radial direction until a burst occurred in the colon. The speed of extension was fixed freely. As a result, we confirmed that the tensile force depended on speed of extension. In this experiment, separate specimens were used for each speed. The results are shown in Fig. 7.

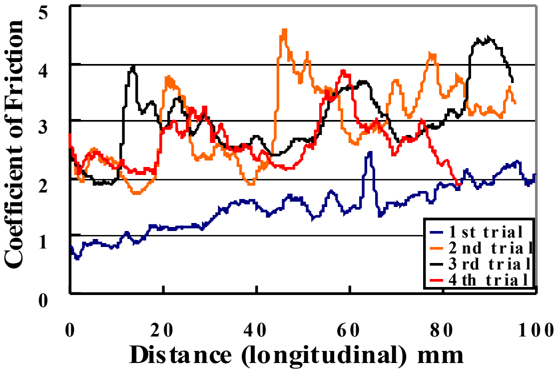


Fig. 6. Relation between distance and coefficient of friction

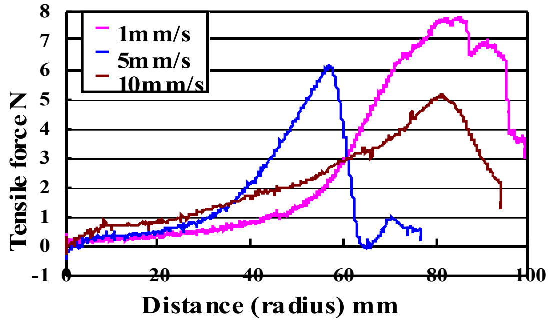


Fig. 7. Speed dependence of colon

In Fig. 7, the point at which the large intestines burst is the point at which the tensile force begins to decrease rapidly. Differences in the individual large intestines and the measurement apparatus are thought to have caused the great difference in distance to burst for 5 mm/s compared with 1 mm/s and 10 mm/s.

As a result of measuring the characteristics of the large intestine, nonlinear and speed-dependent characteristics were identified. When creating a control algorithm, it is necessary to take these points into consideration.

V. INSERTION EXPERIMENT

In order to evaluate locomotive performance, the robotic endoscope was inserted a swine colon. To estimate locomotion speed, a length of thread was attached to the back end of the robot. The speed was evaluated by measuring the distance traveled while the robot was made to rotate in one direction at 12 V. Figs. 8-9 show an image and the results of the experiment in which the robot was inserted into the colon of a dead swine colon, respectively.

Fig. 8. Insertion of dead swine colon

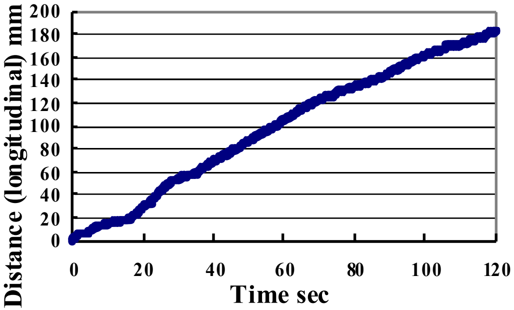


Fig. 9. Insertion into the colon of a dead swine

The results showed that the robot is capable of locomotion in both straight and bent parts of the colon. The robot's speed of locomotion was 4.8 cm/min on average. Next, experimental insertion into the colon of a live swine was performed, as shown in Fig. 10. At the time of insertion, the rotational direction and speed were manually controlled according to the situation in the colon

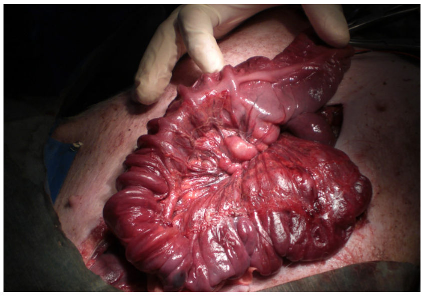


Fig. 10. Insertion into the colon of a live swine

The robot was able to run smoothly in straight parts of the colon. Moreover, temporary locomotive performance was checked in the bent parts of the colon. In this experiment, there were no large differences in the radiuses of the robot and colon because the radius of the colon of the live swine was small. Therefore, the effectiveness of the mechanism of changing the radius using balloons could not be confirmed.

After the insertion experiment, the colon was cleared to check for the influence of insertion of the robot on the surface of the colon. This evaluation was performed by visual examination by a doctor. Insertion of the robot resulted in no damage. This confirmed the low invasiveness of the robot.

VI. CONCLUSIONS AND FUTURE WORKS

A. CONCLUSIOS

We developed a robotic endoscope that has flexible helical fins and a mechanism to change their radiuses. We then evaluated its locomotive performance by both in-vitro and in-vivo experiments. The results of these experiments showed that the robot is capable of locomotion in the colon. However, the speed and direction of rotation need to be controlled in bent areas. We also measured the friction force and tensile force of the colon. Based on the frictional force of the colon, we confirmed that the large intestine wall has viscous elasticity.

B. Future Works

To enable insertion from the anus, the robot should be downsized and thinned. In addition, experimental insertion into the colon of a live swine should be performed again to confirm the effectiveness of the radius changing mechanism. Moreover, tactile sensors should be implemented in the surface of the robot to detect the situation between the robot and large intestine wall. This will enable us to control the robot in various situations. We also believe that the locomotion performance of the robot can be improved.

ACKNOWLEDGMENTS

This research was performed at the Waseda University Humanoid Institute. We would like to express our gratitude to the participating members of the humanoid consortium. We are grateful to Kyushu University Hospital for assistance with performance of the animal experiments. Finally, we would also like to express our gratitude for the cooperation of SolidWorks Japan, Inc. and the Waseda University Science and Engineering Research Center.

REFERENCES

[1] (PDF) Peter Boyle and Bernard Levin: "World Cancer Report 2008", International Agency for Research on Cancer http://www.iarc.fr/

[2] Kazutaka Yamada: "Prevention and the newest medical treatment of colorectal cancer", Ishiyaku Publishers, Inc., 2006, in Japanese.

[3] Hiroto Kita et al.: "Development of a double balloon endoscope, clinical application", Digestive Endoscopy, Vol. 17, No. 4, pp. 451-457, 2005, in Japanese.

[4] Katsuro Shirakawa et al.: "Diagnosis of the small intestine disease by a capsule endoscope", Digestive Endoscopy, Vol. 17, No. 4, pp. 473-479, 2005, in Japanese.

[5] Shu Tanaka et al.: "The present condition of a capsule endoscope and a double balloon endoscope, a view", Medical Treatment, Vol. 88, No. 1, pp. 123-132, 2006, in Japanese.

[6] Hyunjun Park, Sungjin Park, Euisung Yoon, Byungkyu Kim, Jongoh Park, and Sukho Park. "Paddling based Microrobot for Capsule Endoscopes" in Conf. *Rec. 2007 IEEE Int. Conf.* Robotics and Automation, pp. 3377-3382

[7] Byungkyu Kim and Sunghak Lee and Jong Heong Park, and Jong-Oh Park "Design and Fabrication of a Locomotive Mechanism for Capsule-type Endoscopes Using Shape Memory Alloys (SMAs)" in Conf. *Rec. 2005 IEEE Int. Conf.* ASME TRANSACTIONS ON MECHATRONICS, pp. 77-86

[8] Young Pyo Lee, Byungkyu Kim, Moon Gu Lee and Jong-Oh Park."Locomotive Mechanism Design and Fabrication of Biomimetic Micro Robot Using Shape Memory Alloy" in Conf. *Rec. 2004 IEEE Int. Conf.* Robotics and Automation, pp. 5007-5012

[9] Se-gon Roh and Hyouk Ryeol Choi."Differential-Drive In-Pipe Robot for Moving Inside Urban Gas Pipelines" in Conf. *Rec. 2005 IEEE Int. Conf. TRANSACTIONS ON ROBOTICS, pp. 1-17*

[10] Ito et al.: "Development of Colon Endoscope Robots with New Drive Mechanisms -Self-Propelled Endoscope Robots of Rotatory Inertia and Reverse Screw Types-", in Proceedings of the 25th Annual Conference of the Robotics Society of Japan 2J17, 2007, in Japanese.