Inchworm-Like Colonoscopic Robot with Hollow Body and Steering Device*

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Unskillful operation and rough handling of conventional colonoscope, especially at the sigmoid colon, may lead to perforation or splitting the colon wall. Thus, it is crucial to develop autonomous or semi-autonomous colonoscopes that do not require physical force by the doctors for their motions. In this paper, we report the design and development of a colonoscopic robot system that has a locomotive function based on inchworm-like motion, with a hollow body and a steering system that consists of three pneumatic bellows of 7 mm diameter, each located 120° apart from the others at the head part. The steering device can bend up to approximately 90°. In order to evaluate the performance of the colonoscopic robot, in-vitro tests and in-vivo tests were carried out. The experimental results show the feasibility of the prototype colonoscopic robot being used for diagnosis and treatments in colon.

Key Words: Colonoscopic Robot, Hollow Body, Pneumatic Steering Device, In-Vivo Test

1. Introduction

In recent years, colon cancer becomes one of the most serious diseases and the number of people with colon cancer is growing annually due to their preference to the foods with less fiber and more fat, regardless of their ages. However, about a half of colon cancers are curable if they can be detected in early stage. Therefore, colonoscopy plays a very important role in detecting and treating colon cancers and other diseases.

A conventional colonoscope has been used for diagnoses and treatments of diseases at colon. Typically, it consists of an inserting tube of about 13 mm in diameter, a steerable tip, a camera, and a light source. It generally has two channels inside its body for biopsy and suction functions. Due to the stiffness of the tube and the channels, the conventional colonoscope causes pain to patients during its operation. Moreover, since moving the scope around the colon needs the doctor's constant attention, the doctor cannot fully concentrate on the diagnosis.

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Therefore, a new concept of colonoscope that uses an autonomous colonoscope system has been introduced. Many researches have been tried to solve the problems of conventional colonoscopes. Ikuta et al. developed an active endoscope using an SMA coil spring(1). In the field of autonomous locomotive colonoscopes, the concept of inchworm-like locomotion has been popularly employed as a bio-mimetic approach(2)–(4). It has been shown that inchworm-type devices have the capability to overcome the flexibility and the slipperiness of colons.

The authors have proposed and developed several locomotive mechanisms including a centipede-like locomotive mechanism(5), a roller-type mechanism(6), a pneumatic impulsive device(7) and a sliding clamper mechanism(8). Recently, we developed an inchworm-type robot(9) under the collaborations with Dario. It has two mechanical clamps, a retractable and flexible body, a camera and LEDs. Despite the fact that it successfully maneuvered inside a pig's colon, it lacked some essential functions necessary for normal operations of colonoscopy including steering capability, biopsy functionality and water-injection/suction function.

In the current improved version of the endoscopic robot, a locomotive functionality is introduced to the robot which now has a space to accommodate some of the essential parts including a camera, a light source for illumination, channels for biopsy and water-suction. Also, a steering device is integrated with the body of the robot so that the robot can pass through some acute bends at colon in a more efficient manner. The colonoscopic robot developed by Dario et al. does not have a steering device, and thus has limitations to passing-over acute bends in the colon. To validate the performance of the robot, in-vitro and in-vivo tests were performed.

In section 2, the design and fabrication of the proposed colonoscopic robot is covered. In section 3, the control system of the robot is explained. Experiments including in-vitro and in-vivo are dealt in section 4, which is followed by conclusions in section 5.

2. Design and Fabrication of Colonoscopic Robot

2.1 Design of colonoscopic robot

The proposed colonoscopic robot consists of a locomotive mechanism with a hollow body, a steering device, a biopsy tool, and a camera system. It is shown in Fig. 1. For the capability to expand and to retract its body for inchworm-like locomotion, its body is made of a pneumatic bellow. It has two clamps to suck colon tissue in and to grasp it to generate enough tractive force for the robot. It also has a pneumatic steering device to pass several acute bends in the colon, a miniature camera, a light source for inspection, and a biopsy channel for diagnoses and treatments.

2.1.1 Locomotive body with a hollow space The developed colonoscopic robot in this paper is based on the inchworm-like locomotion principle proposed by Dario[10]. Figure 2 shows the sequence for the forward movement of the colonoscopic robot. The previous research proved that the inchworm-like locomotion is effective in colon[11]. However, due to repeated change of body length for locomotion, it is very difficult to integrate the rigid tools like a biopsy. Therefore, we allocate a hollow space in the body of the robot for integration of the tools. Figure 3 shows the design of the colonoscopic robot that uses double-layered bellows. The inner bellow guarantees the required inner space to install other tools and the outer bellow generates the necessary force for prismatic motion that is the elongation and retraction motion of the body. The advantages are its high level of air proof and the flexible body of the robot. This configuration has good locomotion capability as well as integration capability of the biopsy/water/suction function, but it increases the difficulties to assemble each component in robot body.

2.1.2 Steering device A steering device is essential to locomotion inside colon due to the existence of several severely acute bends. Without any steering system, the robot would have difficulty in passing acute bends and would simply stretch the colon without moving forward, which is called the accordion effect. A steering device is also needed to change the viewpoint of its camera during the operation. A pneumatic steering device is devised as shown in Fig. 4. Three parallel bellows are arranged between the head and the robot body, each with 120° apart from the others. The steering device has three degrees of freedom. This mechanism of the pneumatic steering device has been used for some applications like micro actuators[12],[13].

When all the bellow maintains an identical pressure level, the head tip stretches in or out in the axial direction. On the other hand, with the different pressure applied in the bellows, the head tip would bend with an angle, which

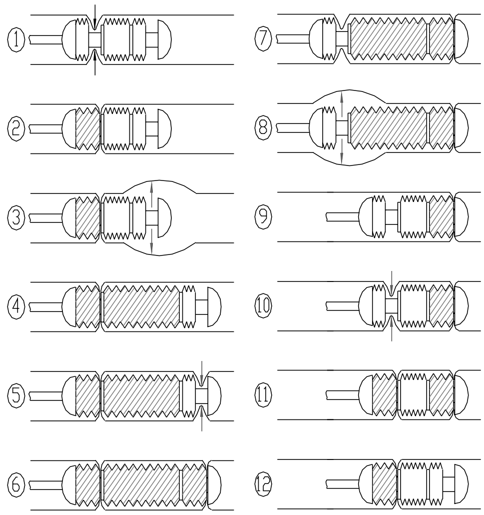


Fig. 2 The principle of the locomotion device using the inchworm-like motion and clamping mechanism

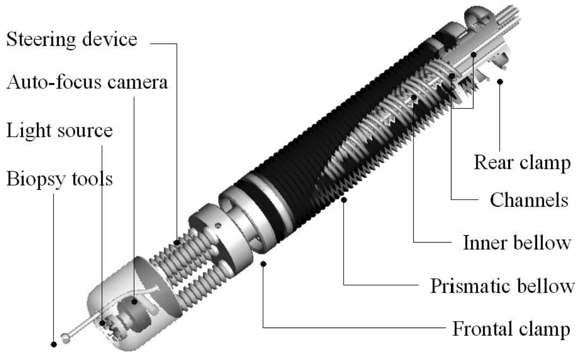


Fig. 1 Design for a colonoscopic robot

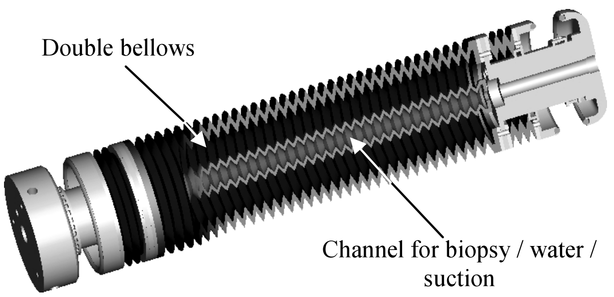


Fig. 3 Sectional view of the proposed hollow bodies

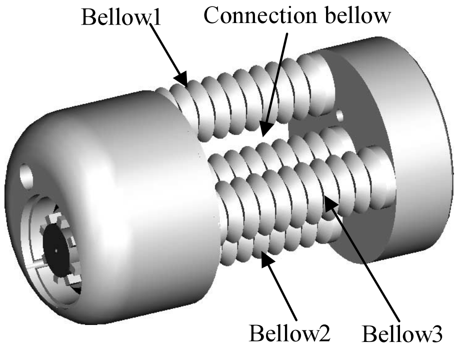


Fig. 4 Configuration of the pneumatic steering device

is determined by the magnitude of the pressure difference.

2.2 Fabrication of the prototype

The prototype robot consists of a head part, a steering part, a body part and clamping devices, as shown in Fig. 5. Its total weight is about 50 grams and the diameters of the outer and inner bellows are respectively 24 mm and 3 mm. The hollow space between the two bellows is to contain a biopsy, a water injection channel and a suction channel. The length of the robot becomes 148 mm with its full retraction and 255 mm with its full extension. The stroke of the robot is about 107 mm. Such a large stroke increases the speed of locomotion, and apparently help itself overcome the accordion effect caused by a large strain of the colon near an acute band.

The prismatic body was embodied with a soft bellow. A thrust force of about 8.28 N is generated when the pressure inside the below is maintained at 0.2 bar. The clamping devices of the front and rear parts are covered with a soft silicon material to prevent any possible severe damage to the tissue of the colon during clamping.

Figure 6 shows the head part and the steering part of the prototype robot. The steering part consists of three bellows with a 7 mm diameter. In order for the bellows to have their optimal stiffness, they are coated with parylene. When all the steering bellows maintain an identical pressure level, the length of the steering part ranges from 21.5 mm to 39.5 mm depending on the pressure level. When fully steered, its steering angle becomes about 90°. Each bellow generates a thrust force of about 1 N when its inside pressure is 0.8 bar. The silicon bellow located at the center of the steering device offers a space to house a biopsy tool and the channels for water injection or suction. A home-made micro CMOS camera and an SMD-type LEDs are integrated at the head part.

The integrated components in the prototype are shown in Fig. 7. Figure 7 (a) shows a biopsy tool used to take some parts of the organ for a detailed diagnosis or a simple treatment of tumors. Biopsy tools are tendon-driven and typically made of stiff materials. This makes it very difficult to integrate a biopsy tool to the robot body. Thanks to its hollow body, it is somewhat easy to integrate a biopsy tool to the proposed robot. Another important device for the diagnosis and the maneuver of the robot is a micro camera shown in Fig. 7 (b). This camera has the dimension of 11.8 mm in diameter and 9 mm in length. Its resolution is 510×492 and a pin-hole lens is combined with the micro camera. The pin-hole lens whose depth of field varies from 8 mm to the infinity, reduces the length of the camera and results in good quality images. Figure 7 (c) shows the light source for the camera, composed of four white LEDs, which provides the brightness of about 600 Lux at the distance of 50 mm.

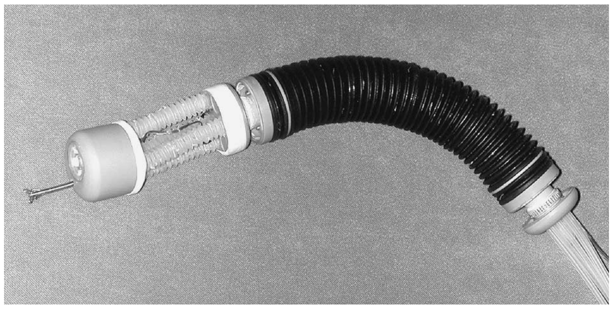
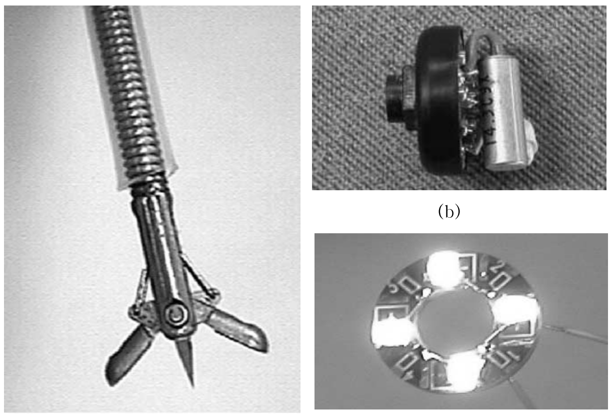


Fig. 5 Prototype of the colonoscopic robot

Fig. 6 Steering and head part of the prototype



(a) (b) (c)

Fig. 7 Integrated components in the prototype

3. Control System

3.1 Overall control system of the colonosopic robot

Figure 8 shows the control system for the proposed colonoscopic robot. A camera system is connected with the high quality image capture board and all images during the operation are recorded at a hard disk simultaneously. Two pneumatic distributors are composed of proportional valves, on/off valves, 3/2 way valves and vacuum generators. Each pneumatic distributor is also connected to a DAQ board controlled by LabVIEW software and controls all pneumatic channels related to movement and steering of the robot. At work, we can measure all of the pneumatic pressure of each channel by pressure gauge. The water injection device is also connected through the hollow space of the robot, and it is operated manually with a compressor connected outside the robot.

Figure 9 shows the overall control system designed for the doctor to conveniently handle the robot. The doctor can inspect inside of the colon precisely with the monitor connected to the CMOS camera. The control system also has a touch screen and a joystick that make doctors operate the functions conveniently with simple hits on the screen and the joystick handling. Therefore, it is very helpful for a novice doctor to operate the developed colonoscopic robot.

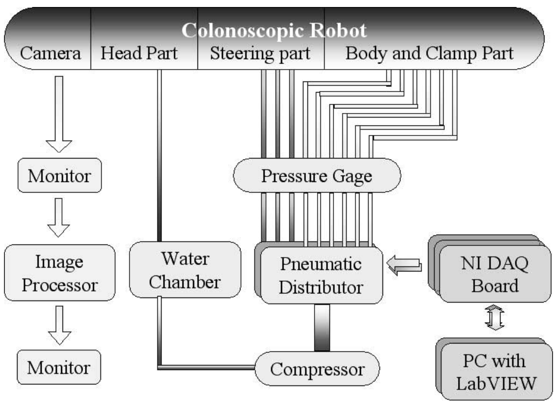


Fig. 8 The colonoscopic robot control system

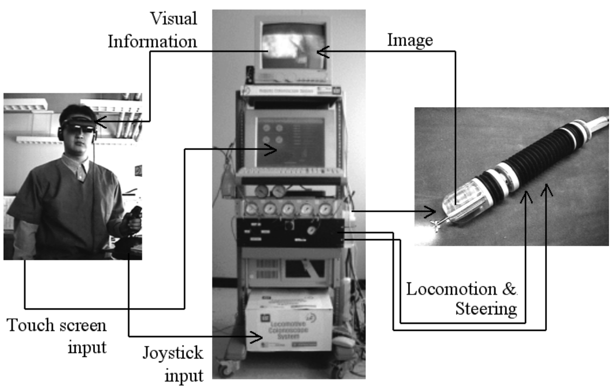


Fig. 9 Human-friendly interactive control system

3.2 Steering control system

3.2.1 Modeling of the steering device Figure 10 shows a bending geometry of the steering device composed of three flexible bellows and two plates. For simplicity in the analysis, it is assumed that the shape taken by bundles is an arc and the length at the central arc does not change and maintains the initial length, S, as shown in Fig. 10 (a). Then, the bending of the steering device can be described using two parameters: α and θ, representing the bending angle and the bending directional angle respectively. In the figure, the x-axis is defined to be the direction at which the maximum and minimum strain occur when the three bellows are modelled as a single large bellow covering all of them.

From the figure,

$$S = R\alpha, \tag{1}$$

$$\ell_i = (R - X_i)\alpha, \tag{2}$$

where ℓ_i and R respectively denote the length of bellow $i\,(= 1, 2, 3)$, which is bent, and the radius of the central arc, and

$$X_1 = r_e \cos\theta, \tag{3}$$

$$X_2 = r_e \cos(\beta - \theta), \tag{4}$$

$$X_3 = r_e \cos(2\beta - \theta), \tag{5}$$

where r_e and β are respectively the distance between the center of the steering device and the bellows, and the angle between the bellow 2 and the x-axis, as shown in Fig. 10 (b).

From the force-deflection relationship of the steering bellows

$$K_i \delta_i = P_i A_i \tag{6}$$

where K_i and A_i are respectively the stiffness and the effective cross-sectional area of bellow i, and extended length δ_i is defined as

$$\delta_i = \ell_i - \ell_i^0 \tag{7}$$

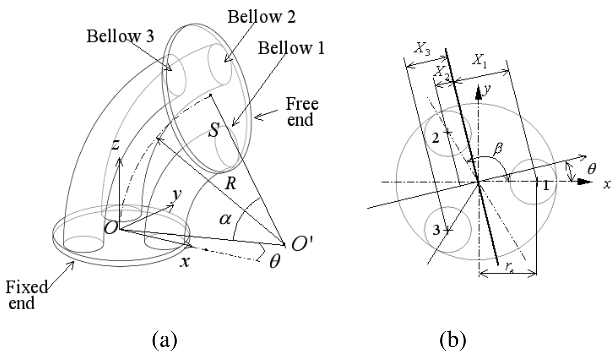


Fig. 10 Bending of the steering device: (a) a 3-dimensional view (b) a front view

where $\ell_i \ell_i^0$ denote the length of bellow i, when deformed and undeformed, respectively. Thus, the desired pressures at bellow i to have length ℓ_i becomes

$$P_i = (\ell_i - \ell_i^0)\frac{K_i}{A_i}. \quad (8)$$

3.2.2 Control system of the steering device During the operation of colonoscopy, the doctor needs to manipulate the colonoscope and diagnose the organ at the same time. Since manipulating the colonoscope effectively needs some of doctor's attention, the doctor cannot fully concentrate on the diagnosis, which results in poor performance of the operation. So, it is critical to have a transparent control system in order to enhance the diagnostic ability of the endoscopy. A human friendly user interface system is designed, which includes a joystick to manipulate a steering device.

Figure 11 shows the block diagram of the steering system. When an operator manipulates the joystick to the desired position of robot tip, its position is measured with potentiometers at each of the axes of the joystick. National Instrument's DAQ board is used to sample the joystick position. The joystick command generates reference control signals for the controllers of pneumatic proportional valves in the pneumatic distributor, which in turn generates the desired pressure of each of the steering bellows. The pneumatic distributor of steering system is composed of proportional valves, on/off valves, vacuum generators and a service unit as shown in Fig. 12. In this control panel, we can control the maximum value of the bending angle, the elongation and retraction pressure of each steering bellow. Moreover, the steering control panel shows the directional angles of the joystick and the pressure at each of the steering bellows. The overall control system is implemented by LabVIEW.

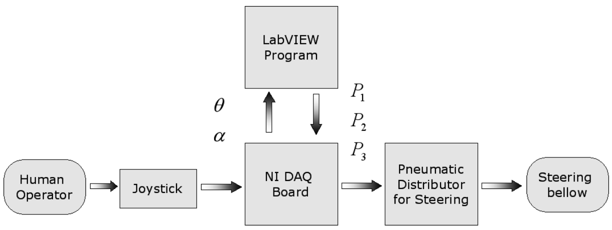


Fig. 11 Block diagram of the steering system

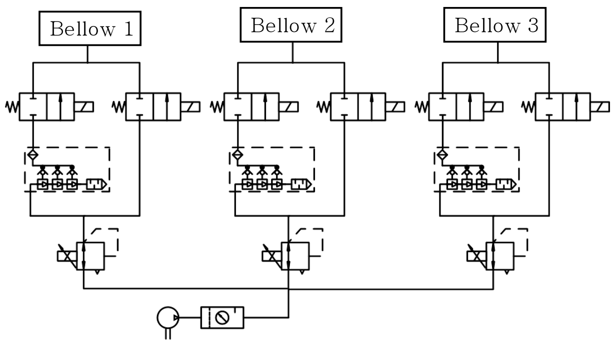


Fig. 12 Schematic drawing of the pneumatic distributor

4. Experiments

To validate the locomotion capability and the diagnostic performance of the designed colonoscopic robot, several tests were performed with its prototype. Steering tests with the steering module, in-vitro tests with the colon of a pig, and in-vivo tests with a live pig under anesthesia are described in this paper.

4.1 Preliminary test

4.1.1 Steering test To examine the characteristics of steering device, we tested linear and rotation motions of the steering device module without any load. First, while slowly changing the pressure from −0.5 to 0.5 bar, we have measured the displacement of the steering module with a laser sensor. The relation between the linear displacement the pressure at the bellow is plotted in Fig. 13. By fitting a linear curve on the experimental data, the stiffness of the bellow, K_i is empirically found.

We also measured directional angles with a video camcorder by tracing the end points of the needle that is placed and glued at the center on the free end plate. Sampling of the directional angle was done with an interval of 5° while the bending angle is fixed at 60°. The resulting directional angle as commanded by the twist angle of the joystick is shown in Fig. 14. The pneumatic steering device using a parallel mechanism showed a good performance, especially, in case of linear and rotation motions.

4.1.2 In-vitro test To obtain the proper values of some of important control parameters for robot locomotion, for example, pressure level at the bellows and the clamping devices and time periods of applying the pressure, some experiments were performed under various environments.

We used different test-beds to simulate the various parts of colon. Three test-beds were used, each with dif-

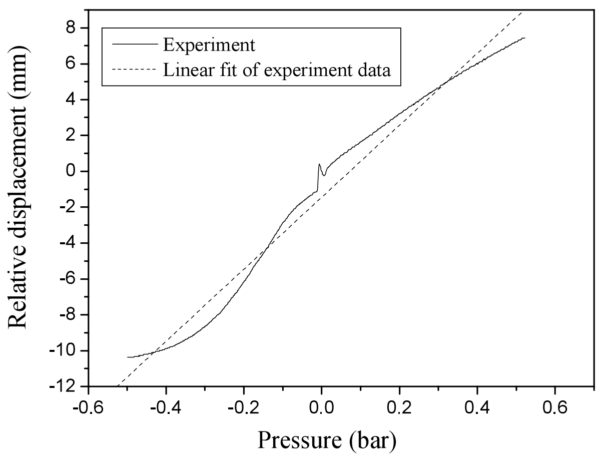


Fig. 13 Experimental result of the linear motion

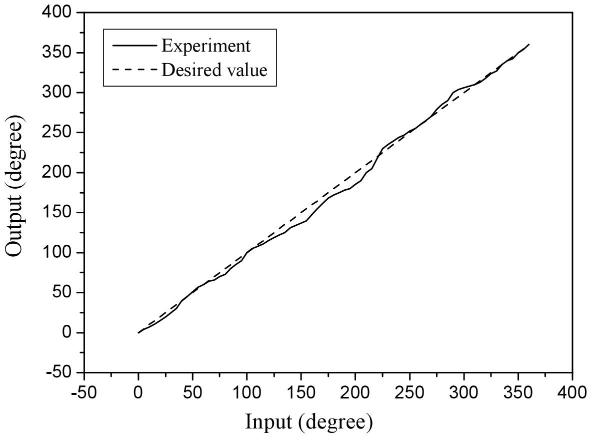
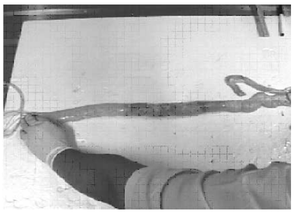
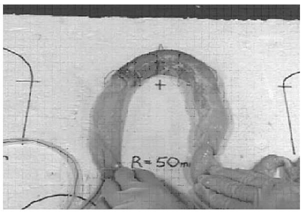


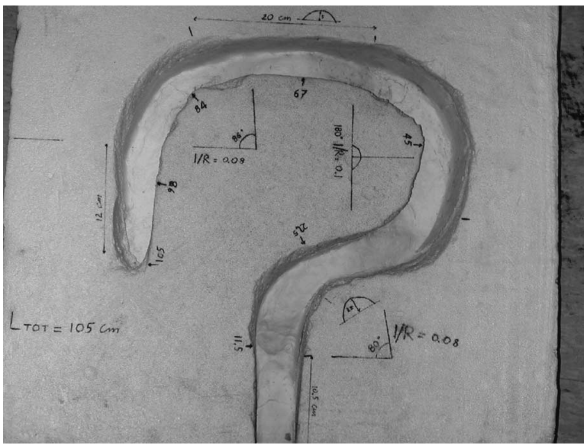
Fig. 14 Experimental result of the rotation motion



(a)



(b)



(c)

Fig. 15 Test-beds to simulate various tracks: (a) Straight path, (b) Curved path (R = 50 mm), and (c) Combined path

ferent types of a track: straight one, curved one with the radius of curvature of 30 mm, and curved one with the radius of curvature of 50 mm, as shown in Fig. 15. In addition to the test-beds for simple basic track, a test-bed for the complex track was also used, which consists of 5 basic tracks: two straight 2D tracks, a 3D curved track with a 80° bend and the radius of curvature of 120 mm, a 3D curved track with a 180° bend and the radius of curvature of 100 mm, and a 2D curved track with a 84° bend and the radius of curvature of 120 mm. The 2D tracks are flat and horizontal, and has no changes in the elevation while the 3D tracks have ups and downs with maximum hump

Table 1 Experimental result of in vitro test

Description of path	Distance (cm)	Speed (cm/min)	Efficiency (%)
Straight path	43	18.97	88.64
Curved path (R=30 mm)	24	12.1	57.94
Curved path (R=50 mm)	31	13.58	63.46
Combined path	92	15.20	71.03

of 50 mm. All the test beds were made by carving an appropriate track out of a thick styrofoam board.

The selected pressure for the bellows are 0.2, −0.3 and 0.3 bar for robot elongations, robot retractions, and clamping the sucked colon tissue respectively. The suction times for the clamps at the front and the rear were set to 10 s and 6 s respectively. A single cycle of locomotion took approximately 30 s, which yields the result that the theoretical moving speed is about 21.4 cm/min.

Table 1 is the test results under various environments. The velocity of the robot is almost the same as its theoretical velocity at a straight motion, resulting in about 88.6%-efficiency, which is the percentage ratio of the actual speed to the theoretical speed.

A single cycle of locomotion takes approximately 30 seconds and the stroke of the robot is 107 mm, which result in the theoretical velocity of 21.4 cm/s. However, since there is some slip and clamping failures, the actual velocity in the colon becomes lower than the theoretical one. The efficiency in Table 1 is the ratio between theoretical velocity and experimental velocity.

At curved regions in the colon, mainly due to the so-called accordion effect or the viscous elastic behavior of the colon along with failures in clamping at the front, the locomotion efficiency decreases further down to approximately 60%. However, the robot was able to successfully pass that region without any difficulty.

4.2 In-vivo test

To validate the locomotive and diagnostic performance of the proposed robot, an in-vivo test was performed with a pig under anesthesia. We inserted the robot into the colon through the anus. The robot was successfully able to move up to 50 cm from the anus. It turned out that the pressure loss at the bellows was negligible. Despite the fact that the device with two bellows was more rigid than a robot with a single bellow, it was flexible enough to follow the lumen. Figure 16 shows a fluoroscope image at one of the curved areas in the colon during the in-vivo test. The steering device and the flexible body design were very helpful in moving through the acute bends of the colon.

Figure 17 shows a view inside the colon during a robot biopsy. The home-made CMOS camera at the robot showed the tissue of the colon and the biopsy tool reaching at the desired area at the colon. Insertions of the biopsy tool was relatively easy when the robot was in straight

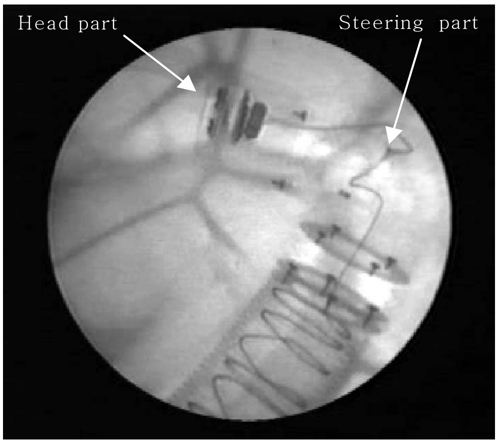


Fig. 16 Robot image through the fluoroscope

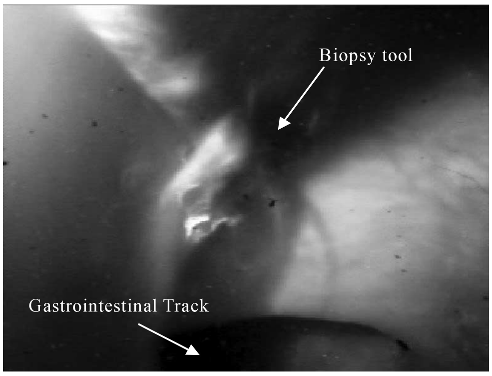


Fig. 17 Biopsy and camera test

pass. However, insertions become quite difficulty when the steering device was in acute bending. We definitely need to investigate a better way to guide the biopsy tool safely.

After completing the in-vivo test, we inspected the tissue of the colon with a conventional colonscope to see if there are any damages due to clamping. There were no visible marks from the clampings, but we found some marks on the colon wall. However, they are similar to typical marks left by typical conventional colonoscope. This test confirms that the proposed robot can be employed as a colonoscopic robot for some limited diagnoses and treatments in colon.

5. Conclusions

In this paper, we developed a colonoscopic robot that can move successfully through the slippery and flexible internal track of a colon. It is designed with a hollow body to house system integration components including a camera, a light source, a water injection channel and biopsy tools. In order to pass acute bends in colon, a pneumatic steering device is designed for the robot. In addition, a user-friendly steering control system is constructed to enhance the performance of the doctor operating the robot. In order to evaluate the performance of the colonoscopic robot, in-vitro and in-vivo tests were carried out. Especially, the robot was able to move up to 92 cm in the in-vitro test and 50 cm from the anus in the in-vivo test, showing its high effectiveness in locomotion, diagnosis, and treatment. In the test, we learned that a steering device is absolutely necessary to pass over acute bends in colon.

Further work is in progress to decrease the diameter of the robot and to enhance the bending capability of the steering device. Furthermore, optimization in timing sequence to increase the moving speed, and the robot vision capability for autonomous locomotion are recommended.

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