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A Paddling Based Locomotive Mechanism for Capsule Endoscopes

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Diagnosis and treatment using the conventional flexible endoscope in gastro-intestinal tract are very common since advanced and instrumented endoscopes allow diagnosis and treatment by introducing the human body through natural orifices. However, the operation of endoscope is very labor intensive work and gives patients some pains. As an alternative, therefore, the capsule endoscope is developed for the diagnosis of digestive organs. Although the capsule endoscope has conveniences for diagnosis, it is passively moved by the peristaltic waves of gastro-intestinal tract and thus has some limitations for doctor to get the image of the organ and to diagnose more thoroughly. As a solution of these problems, various locomotive mechanisms for capsule endoscopes are introduced. In our proposed mechanism, the capsule-type microrobot has synchronized multiple legs that are actuated by a linear actuator and two mobile cylinders inside of the capsule. For the feasibility test of the proposed microrobot, a series of in-vitro experiments using small intestine without incision were carried out. From the experimental results, our proposed microrobot can advance along the 3D curved and sloped path with the velocity of about 3.29~6.26 mm/sec and 35.1~66.7% of theoretical velocity. Finally, the proposed locomotive mechanism can be not only applicable to micro capsule endoscopes but also effective to advance inside of gastro-intestinal tract.

Key Words : Capsule Endoscope, Microrobot, Multi-Legged Locomotion, Locomotive Capsule

1. Introduction

The conventional push-type endoscope is most commonly used in most hospitals and operated by the hands of skilled individual operator. Since its tube needs some structural strength to be pushed, it has somewhat high stiffness, causing pain and discomfort to the patient. Moreover, it cannot reach to the small intestine for diagnosis. These problems caused the development of wireless capsule endoscopes. The first capsule endoscope called the M2A (Appleyard et al., 2000 ; Iddan et al., 2000 ; http ://www.givenimaging.com/) was developed and commercialized by Given Imaging Inc. of Israel. It has a dimension of 10 mm in diameter and 27 mm long and consists of a CMOS camera, an RF module, illuminating LEDs, and a battery. It can be swallowed and can transmit wireless still images (2 frames/sec) from the gastro-intestinal tract. Due to the development of wireless capsule endoscopes, it is now possible to diagnose small intestines, which can not be achieved by conventional endoscopes, and to reduce pain and discomfort of the patient.

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However, the capsule endoscopes move passively from the mouth to anus by the peristaltic waves of the digestive organ. Therefore, no active diagnosis is possible due to the lack of a locomotive capability. For doctor to get the image of the organ and to diagnose more thoroughly, a locomotive mechanism of capsule endoscopes is necessary. However, the gastro-intestinal tract consists of soft and local deformable tissues and has very slippery surfaces with the secretion of mucous. Therefore, the intestinal tract is very tough environment for a locomotive mechanism to advance.

As a locomotive robot, legged robots have been studied (Hirose, 1999 ; Pratt, 2000 ; Ryu et al., 2002) but the proposed legged mechanisms are not easy to miniaturize and thus not applied to capsule locomotion. As an example, legged locomotion in gastro-intestinal tract has been proposed (Menciassi et al., 2004). The locomotive mechanism is based on active multiple legs which have independent degrees of freedom. Since it uses multiple legs, this mechanism needs multiple actuators and controllers. Therefore, the multi-legged locomotive mechanism has the limitation of power consumption and miniaturization.

In addition, an inchworm-like microrobot comprising actuation modules and clamping modules for capsule endoscopes has been proposed (Kim et al., 2004 ; 2005 ; 2006). In order to realize long stroke of locomotive mechanism, spring type SMA actuators have been employed. But SMA actuator has very low efficiency and slow response time since it is actuated based on Joule heating. In addition, more than two actuators are required to have long stroke and strong force enough to get over resistance force due to friction and visco-elastic deformation of small intestine (Fung, 1993 ; Pioletti and Rakotomanana, 2000 ; Rosen and Hannaford, 1999 ; Tanaka et al., 2002).

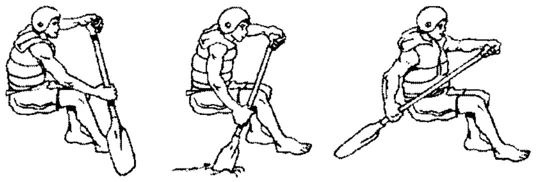


Fig. 1 Paddling a canoe

In order to solve the problems, this paper proposes a new paddling based locomotive mechanism. This locomotive mechanism is originated from paddling a canoe in Fig. 1. The paddle of a canoe is embodied as the legs of our microrobot and the canoeist is replaced by the linear actuator which is composed of a reliable commercialized micromotor and a lead screw.

The paper is organized as follows : In the following section, the locomotive mechanism of the proposed microrobot will be explained. Section 3 will introduce the fabrication of the proposed microrobot and the control system. Through the various in-vitro and in-vivo experiments in section 4, the feasibility of the microrobot was verified and the effects of the design parameters were illustrated. Finally, concluding remarks will be drawn in section 5.

2. Locomotion Mechanism

First of all, the concept design of the microrobot is shown in Fig. 2. The proposed microrobot consists of a linear actuator which comprises micro motor and lead screw, an inner cylinder, an outer cylinder, multiple legs and robot outer body. The functions of the above components are illustrated as follows :

(1) The linear actuator moves the inner cylinder backward and forward ;

(2) The inner cylinder has grooves and there is some clearance between the grooves and the legs. Owing to the clearance, the inner cylinder makes

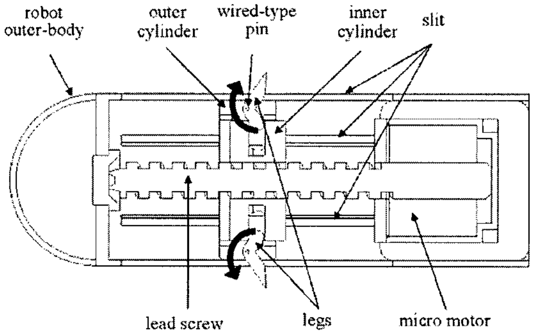


Fig. 2 Concept design of microrobot

the legs rotate and moves the legs and the outer cylinder;

(3) The outer cylinder is connected with the multi-legs by wired-type pin and is moved inside of the robot outer body;

(4) The multi-legs are protruded out of the robot body and are folded in the robot body. The microrobot has six legs which are radially positioned to contact with the intestinal surface; and

(5) Finally, in order to reduce the friction force between the robot outer body and the intestinal surface, the head of the microrobot is designed as a semi-sphere and the robot outer body is coated with lubricant such as silicon oil. And for the protruding and folding the legs, the microrobot outer body has the lateral slits.

The locomotive mechanism of the proposed microrobot is expressed in Fig. 3. First of all, step (1) shows the initial state of the capsule-type microrobot, which is inserted into the intestine. In step (2), if the actuator moves the inner cylinder right, the legs are protruded and clamp the intestinal surface. In step (3), if the actuator moves the inner cylinder further, the legs do not protrude any more and the outer body of the microrobot advance to the left. And step (4) shows the end of the stroke of actuator. If the actuator moves the inner cylinder to the left in step (5), the legs which were fixed to the intestinal surface are released and folded in the microrobot body. In step (6), the legs and the inner/outer cylinders moved to the left without the movement of the microrobot body. Finally, the robot returns to the same configuration of step (1). By this locomotion principle, the proposed capsule-type microrobot can be easily moved inside of the gastrointestinal tract.

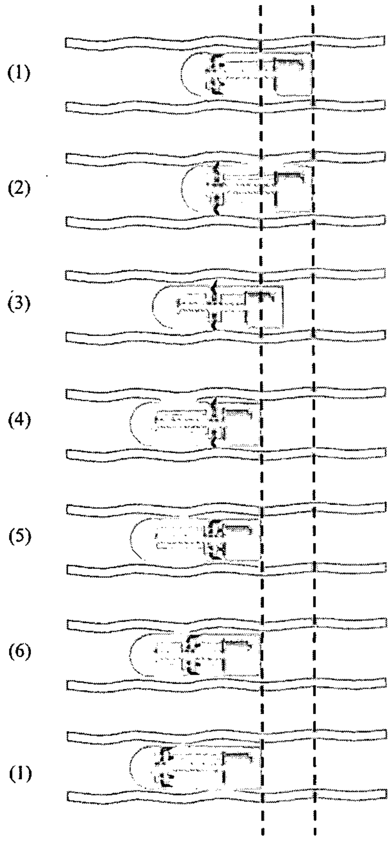


Fig. 3 Locomotion principle of the proposed capsule-type microrobot

3. Fabrication of Microrobot and Control System

The proposed locomotive mechanism is fabricated as shown in Fig. 4. The prototype uses the

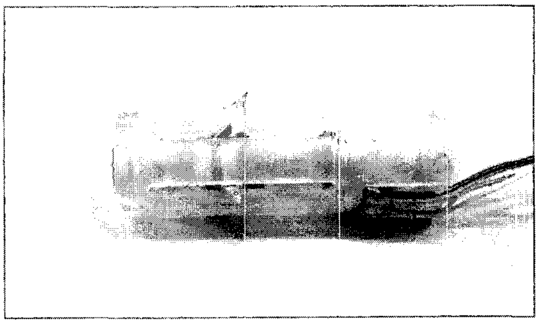
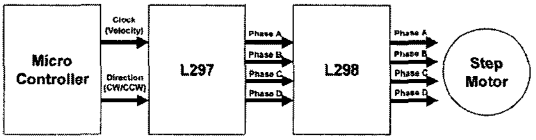


Fig. 4 Fabricated legged microrobot

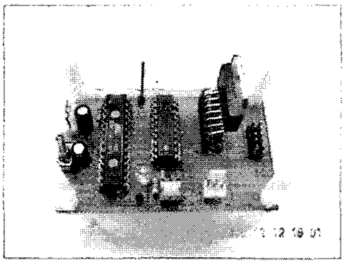
Table 1 Specifications of the micromotor and the lead screw

Motor Driving Voltage		5 V
Motor Diameter		10 mm
Motor Length		10 mm
Motor Torque	Pull in (800 pulses/sec)	4.6 $g_f\cdot$cm
	Pull out (1400 pulses/sec)	6.0 $g_f\cdot$cm
Lead Screw	Pitch	1.876 mm
	Complete Thread	19.15 mm

conventional micro step motor as an actuator and the lead screw for the linear motion. The specifications of the micromotor and the lead screw are described in Table 1. The outer body of the prototype microrobot is made as the capsule type and the outer diameter is about 13 mm. The outer body of the microrobot, the inner cylinder and the outer cylinder are made of the polycarbonate. The legs are fabricated with SUS 304, manufactured by EDM (Electrical Discharge Machining). Stainless steel wire of 200 μm diameters is used to fix the leg to the outer cylinder. The total length of the capsule becomes about 30 mm and the stroke of the legs is decided by the slits of the microrobot body. In this prototype, the stroke of linear actuator is adjusted to 15 mm and the theoretical moving velocity of the microrobot is about 9.38 mm/sec decided by the pitch of lead screw and the motor controller. The mass of the prototype is minimized up to 5.2 grams considering integration of other components.



(a) Motion control circuit block diagram



(b) Motion control board

Fig. 5 Motion circuit block diagram and control board for the proposed microrobot

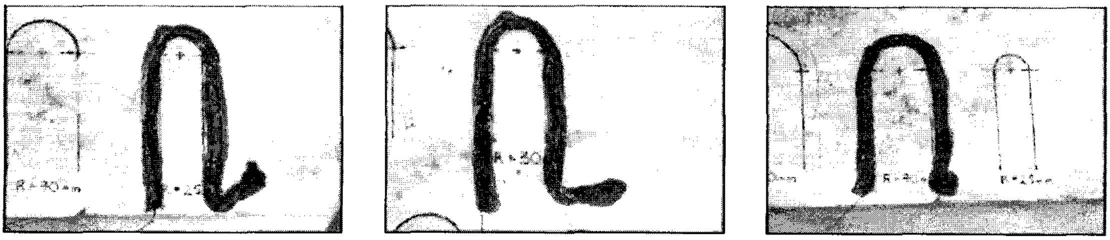
Finally, for the actuation of the microrobot, the control circuit is designed and fabricated in Fig. 5. The circuit consists of micro-controller and step motor controller (L297 and L298 of STMicroelectronics (http ://www.st.com)), where micro controller generates clock and direction commend ; L298 step motor controller IC generates four phase drive signals for two phase bipolar step motor ; and L298 is a high voltage current dual full bridge driver designed to accept standard TTL logic levels and drive inductive loads such as step motors. The circuit has the functions of position/ velocity controls and direction change of the legs.

4. In-vitro Experiments

4.1 Locomotive performance on the planar curved paths

For the feasibility test, the in-vitro experiments using small intestine obtained from live pig are executed. As shown in Fig. 6, the extracted small intestines are spread on Styrofoam and have a straight and a half circle path, the radius of about 25, 30, and 40 mm, respectively. And then paddling based microrobot is inserted into the small intestine. The microrobot can advance along the straight and a half circle path in Fig. 7.

The velocities of the microrobot are measured from the video images and the locomotive performances of the microrobot are summarized in Table 2. From the results, the velocities on the straight lines are about 6.00~6.50 mm/sec and 64~69% of theoretical velocity. However, the velocities on the half circles are about 3.02~6.42



(a) R=25 mm (b) R=30 mm (c) R=40 mm

Fig. 6 Planar curved paths (R=25, 30, 40 mm) mm/sec and it is 32~68% efficiency compared to theoretical velocity. When the radius of the half circle is 40 mm, the velocity on the straight line is similar to that on the half circle. However, the velocities on the half circle with the radius of 25 and 30 mm are much slower than that on the straight line. Especially, when the radius of the half circle is about 25 mm, the velocity is only about 50% of that on the straight line. This is why the resistant force between the microrobot and the small intestinal surface is significantly increased as the radius of the half circle decreases.

4.2 Locomotive performance on a 3D curved and sloped path

For another in-vitro test, the small intestine just extracted from live pig is bridged across the two posts and thus the small intestine has 3-dimensional curved and sloped paths in Fig. 8, with the slope angle of about 34, 63, and 78 degree, respectively. And then microrobot is inserted into the end of the small intestine. As shown in Fig. 9, the proposed microrobot can advance along the 3D intestinal tract.

From the video images, the velocities of the

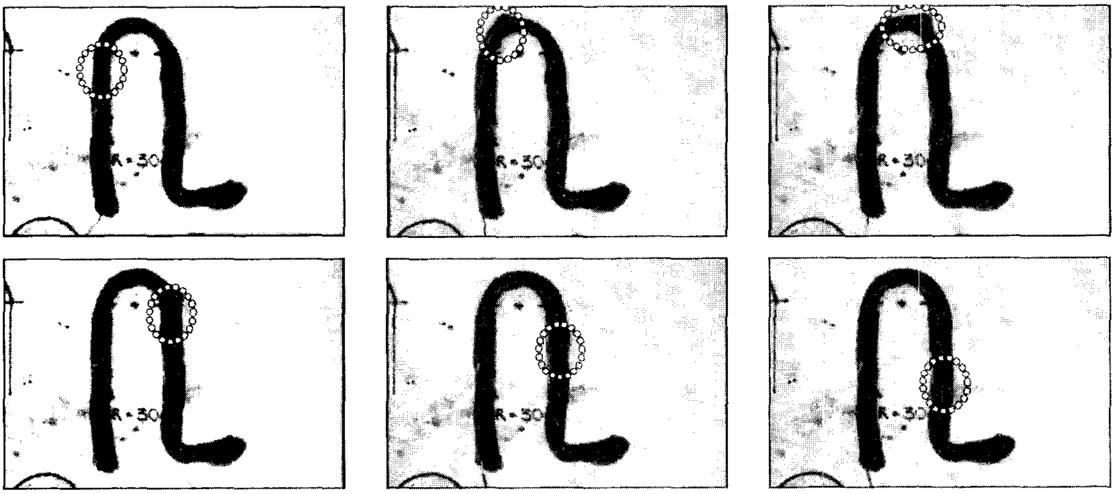
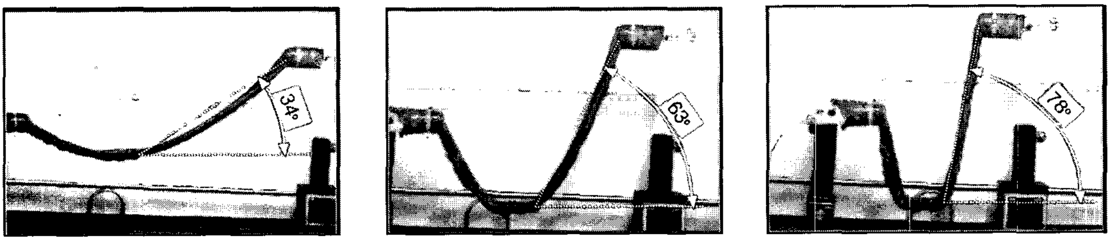


Fig. 7 Locomotion experimental results on planar curved path (R=30 mm)

Table 2 Locomotive performances of microrobot for a planar curved path

Path	Velocity on straight linear path	Efficiency compared to theoretical velocity	Velocity on half circular path	Efficiency compared to theoretical velocity
R=25 mm	6.50 mm/sec	69.3%	3.02 mm/sec	32.2%
R=30 mm	6.42 mm/sec	68.4%	4.28 mm/sec	45.6%
R=40 mm	6.00 mm/sec	64.0%	6.42 mm/sec	68.4%



(a) Slope angle=34 degree (b) Slope angle=63 degree (c) Slope angle=78 degree

Fig. 8 3D curved and sloped paths (slope angle=34, 63, 78 degree)

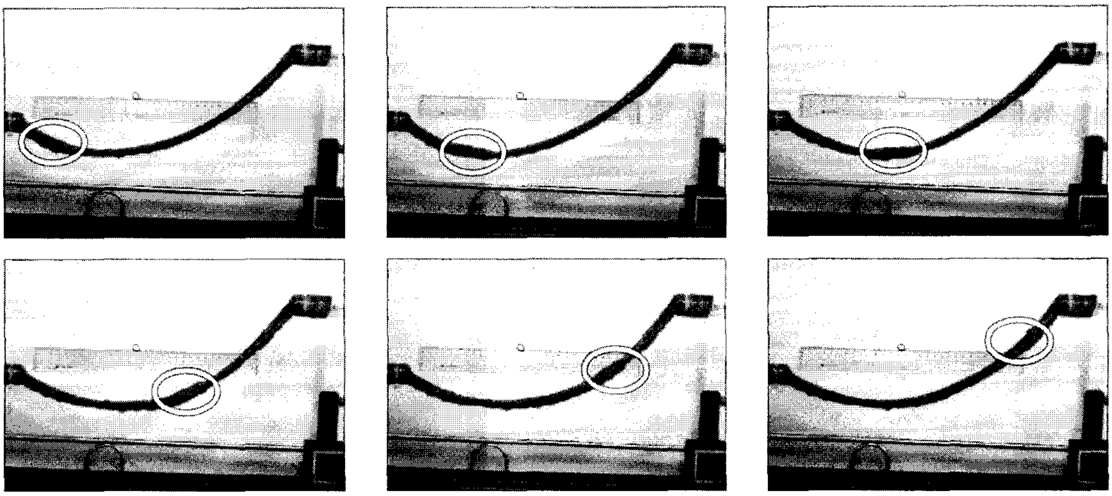


Fig. 9 Locomotion experimental results on 3D curved and sloped path (slope angle=34 degree)

Table 3 Locomotive performances of microrobot for 3D curved and sloped path

Path (Slope angle)	Velocity on 3D curved and sloped path	Efficiency compared to theoretical velocity
34 degree	6.26 mm/sec	66.7%
63 degree	3.57 mm/sec	38.1%
78 degree	3.29 mm/sec	35.1%

microrobot in 3D intestinal tract are measured and the locomotive performances are summarized in Table 3. From the results, the velocities on the 3D curved and sloped paths are about 3.29~6.26 mm/sec and 35~67% of theoretical velocity. In addition, the velocity of the microrobot is decreased as the slope angle increases due to the resistant force and the gravitational force in the 3D curved and sloped path.

5. Conclusions

This paper proposes a paddling based locomotive microrobot for capsule endoscope which has multiple legs and linear actuator. The multiple legs are sequentially unfolded and folded by inner and outer cylinder, and the inner cylinder is actuated by micro motor and lead screw. Since the proposed mechanism is actuated by the multiple legs and commercial micro motor, it has more reliable and repeatable performances and is less sensitive of the visco-elastic characteristics of the intestine. For the feasibility test of the proposed microrobot, the in-vitro tests using small intestine without incision were executed. In the locomotion test on a planar curved path, the microrobot could advance forward with the velocity of about 6.00~6.50 mm/sec on straight line path and about 3.02~6.42 mm/sec on curved path, which are 64~69% and 32~68% efficiencies compared to the theoretical velocity, respectively. From the result, the proposed microrobot on the curved half-circular path is slower than on the straight linear path due to the restriction force between the microrobot and the small intestinal surface. In addition, the proposed microrobot can advance along the 3D curved and sloped path with the velocity of about 3.29~6.26 mm/sec and 35.1~66.7% of theoretical velocity according to the angle of slope path. As the slope angle increases, the velocity of the microrobot is decreased due to the resistant force and gravitational force in the path. Consequently, the proposed paddling based capsule-type microrobot shows excellent locomotive performances inside the small intestinal tract and can be a good solution to relieve the problems of the previous capsule endoscope.

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