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Locomotion and Steering Design of an Active Capsule Robot for Endoscopic Inspection

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***Abstract*—A new locomotion-steering mechanism of an active capsule endoscopic robotic system is designed in this paper. The locomotion and steering principles are analyzed to allow the robot to move straightly and turn around in the intestinal environment. A micro-motor is used to actively actuate the endoscope robot for straight movements and steering. Spiral outer structure is basically employed to help produce propulsive force without contacting the intestine wall. The steering head actuated by the same motor is designed to control the moving directions adapted to the curved intestines in order to further ease the discomfort of the patient. A prototype is built and experiments are conducted to illustrate the proposed design.**

Index Terms: Active endoscopic robot, Locomotion and steering, Spiral outer structure.

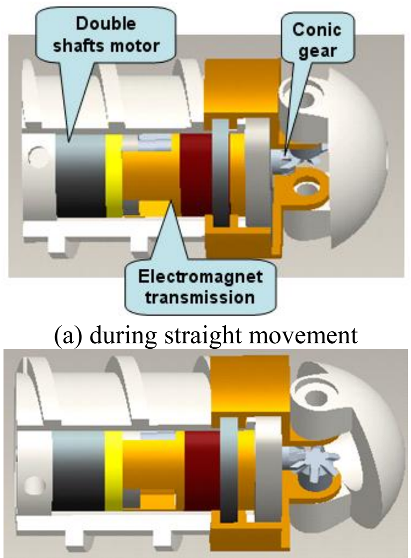
I. INTRODUCTION

Endoscopic robotic system based on the prototype discussed in this paper is expected to be used clinically in the near future to examine the Gastrointestinal tract for disease diagnosis inside the intestines and stomach. A new locomotion-steering mechanism is proposed in the paper. It consists of two parts: rotational body and steering head. A micro-motor is the main actuator for the whole system that is located at the end the rotational body. The forward and backward movements can be achieved directly by the motor and spiral outer structure of the body, Fig.1 (a). The steering head is actuated by the same motor, and a mechanism is designed to connect the steering head and the rotational body of the endoscopic robot, Fig.1 (b).

Fiber-optic bundles are widely used for Gastrointestinal tract examination since 1950s and this conventional technique has become a routine procedure in most hospitals nowadays. It can transmit the images of the stomach and upper small intestine in real time. Although the fiber-optic endoscopy is a big contribution in noninvasive surgery, it has some significant drawbacks. First, the patient has to be suffering from the bulky cables pushed into the intestine. A few percentages of the patients could not endure this discomfort every year. Another concern is the operator is required to be trained for many years in order to maneuver the endoscopic tip properly for examination. The last disadvantage is the endoscope can not be avoided to tear the inner wall of the intestines because of some abrupt movements.

Therefore, many researchers have made efforts for more than a decade to apply robotic techniques onto the endoscopic field in order to solve more-than-one of the above problems. Burdick, et al., developed a robotic endoscope in 1994 that consists of multiple segments connected through articulated joints. Inflatable balloons and rubber bellows were used as actuators to achieve the inchworm locomotion where the expanded balloon can provide the traction against the inner wall and the rubber bellows are extended to push the rest segments of the robot move forward [1]. Dario etc. also developed an inchworm robotic system for endoscopic inspection that was actuated by SMA micro-valves [2]. But the traction provided by the balloon was too low and the sliding along the intestine wall always happened. Then two other balloon robots mentioned in [3, 4] were able to avoid sliding using some special materials to replace the regular balloon to increase the traction.

However, these above robotic endoscopes move very slowly while they are all actively actuated. The long modular structure still requires the operator to push the whole bundle into the human body before the inspection. Plus, the robot always contacts the inner wall of the intestines in order to move that would result in the discomfort of the patient in some degree. Additionally, they have no steering mechanism to adapt to the curved intestines. The patient might therefore



(a) during straight movement

(b) during steering

Fig.1. Diagram of the active capsule robot for endoscopic inspection.

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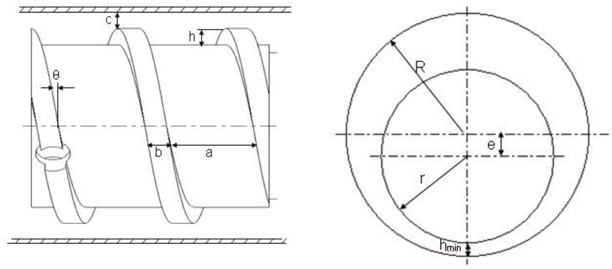
suffer from the actions on the inner wall when the endoscope passed by the corners of the curved intestines.

Other researchers proposed steering mechanisms to achieve the turn-around of robotic endoscopes. Burdick etc.[5] proposed a distal end attached at the end of their endoscope mentioned above. The robotic endoscope can bend through adjusting the air press distribution of the distal end. But the first two drawbacks mentioned in the last paragraph are still unsolvable. Suzumori etc. developed a rubber-made microactuator to achieve three degrees of freedom by controlling the internal pressure of three chambers in the microactuator respectively [6]. Fukuda etc. also proposed a micro active catheter to make two degrees of freedom movements possible [7]. Although the latter two mechanism can be potentially applied on robotic endoscopes [8], it has been far away from practical applications in the endoscope field.

Recently wireless capsule endoscope bears a milestone during the development of robotic endoscopes. It could ease the pain and discomfort of the patient greatly because the patient can swallow this “capsule” before inspection. The Israeli company, Given Imaging Limited, has shown their commercial product: wireless capsule endoscope M2A capsule [9]. According to the survey [10], Gong etc. [11] and Park etc.[12] also reported their respective prototypes similar to the M2A capsule. However, they are all passive capsule endoscopes and it usually takes more than eight hours for the complete examination. Not only the moving speed is quite slow, but also the moving direction can not be controlled.

Thus more and more research has focused on the active capsule endoscopes. In [13-15], the active legged capsule endoscopes were proposed to have relatively high forward velocity and also adapt to uneven, slippery, or flexible environment. But the moving directions can not be changed. Another kind of the capsule endoscopes could achieve their movements by the friction between the outer surface of the robot and intestine wall [16, 17]. The problem of these robots is the pain brought to the patient because of contacting and crashing with intestine wall. Therefore, the spiral-type capsule endoscopes were proposed to keep fast movements without contacting with the intestine where the intestinal mucus was functionalized to isolate the robot and the intestine [18-21], which is the baseline of this paper. However, little research has been done so far to incorporate steering into active capsule endoscopes.

Hence the main contribution of this paper involves a new locomotion and steering mechanism with high moving velocity and direction control without contacting with the intestine wall. The incorporation of the steering mechanism can make the movement smoother, further reduce the discomfort of the patients in the curved intestine and can make the view of the robot wider for more detailed examination. This mechanism can be combined with a micro CCD and a wireless communication module equipped in the steering head for a complete active capsule robotic endoscope for intestinal inspection.



(a) (b)

Fig.2. Diagram of the rotational body.

The structure of this paper follows. Locomotion and steering mechanisms are proposed and analyzed in Section II. Experiments are presented in Section III. Conclusions are described in Section IV.

II. LOCOMOTION AND STEERING PRINCIPLES

A. Straight Movement

In this paper, there are two basic modes for a robotic capsule endoscope such as straight forward and backward movements and steering movement. These two modes can be achieved when the different parts of the robot are mainly functionalized. As we mentioned in Section I, the rotational body is used to make the robot move straight forward and backward.

Spiral outer surface of the rotational body is designed to be firmly connected with a micro motor shaft to help produce propulsive force, shown as Fig.2 (a). When the motor rotates clockwise, the rotational body of the robot is compelled to rotate clockwise inside the intestine simultaneously. This rotation results in a lubricant film of intestinal mucus attached on the robot such that the robot can not contact with the intestine wall during the movement with the minimum thickness requirement of the film, $h_{\min}$, Fig. 2(b). At the same time, the rotational body pushes mucus backward. The mucus in turn pushes the robot to move straight forward. If the endoscope robot rotates faster, the mucus will produce a bigger counterforce and the endoscope robot will move forward with higher speed. Likewise, if the motor rotates counter-clockwise, the robot moves backwards.

In order to find the relationship between the axial propulsive force and the axial velocity of the rotational body, we assume that the mucus of the human body is Newton fluid at high shear speed. Thus the axial velocity of the robot and the thickness of the lubricant film of mucus can be analyzed according to the elastohydrodynamic lubrication theory [18].

Denote the axial propulsive force as F_a, the axial velocity as V_a, according to the Renault equation and the Navier-Stokes equation, F_a can be obtained as [18],

$$F_a = \frac{2\pi\mu L}{c}\left\{\frac{3\beta(1-\beta)\gamma^2 BC\cos\theta\left[r-c(1-\gamma)\right]}{(1-\beta)B+\beta r(1+\gamma)^3 C} - \frac{(1-\beta)(r-c\gamma)}{c(1+\gamma)}V_a - \beta V_a\right\} \quad (1)$$

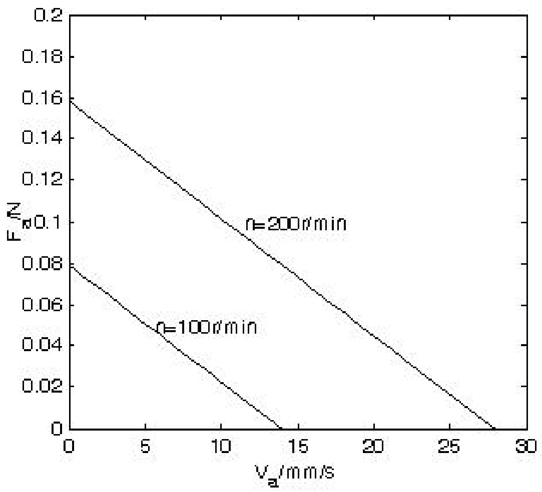


Fig.3. The relationship between the propulsive force and the axial velocity $\theta = 70°$ $\beta = 0.2$ $\gamma = 1$ $c = 1mm$ $r = 9mm$ $\mu = 5 pa \cdot s$ $L = 50mm$

$$B = (r - c\gamma)\omega r \sin\theta - V_a r \cos\theta \tag{2}$$

$$C = \omega r \sin\theta - V_a \cos\theta \tag{3}$$

where h and b are the screw height and the screw width respectively, a is the groove width, θ is the screw angle, c is the gap between the intestinal wall and the robot, $\beta = b / a$ and $\gamma = h / c$. ω is the rotational angular velocity of the motor shaft, r is the radius of the rotational body, L is the length of robot, μ is the viscous coefficient of the mucus.

The relationship between the axial velocity V_a and the propulsive force F_a is plotted given the designed parameters of the screw, Fig. 3. Apparently the propulsive force F_a decreases as the axial velocity V_a increases under a certain rotational velocity n of the motor shaft. Hence the robot speeds up when $V_a < V_{a\max}$ and reaches a constant axial velocity $V_{a\max}$ after some time. When the rotational speed of motor n increases, maximal propulsive force $F_{a\max}$ increases. The maximal axial velocity $V_{a\max}$ also increases.

B. Steering

The other important mode of the robot motion is the steering movement since the gastrointestinal tract of the human body is full of curves, Fig. 4. A steering head is designed in this paper to achieve the steering. There are two basic functions for the steering head. One is to examine some places where the view of the CCD can not reach only by straight movements. The other function is to achieve smoother movement in the curved intestine for discomfort ease.

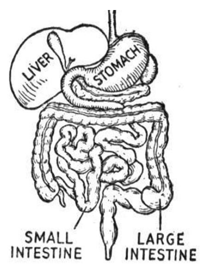


Fig.4. Curved intestines.

According to Fig. 1 (b), the steering head is still actuated by the same micro motor as the one for the rotational body for compact design. The turning angle of the steering head is controlled by the rotational angle of a pair of conic gears. An electromagnet transmission part is designed to control the connection of the rotational body and the steering head. Motor shaft and conic gear shaft are connected or separated by turning on or off the electricity of the electromagnet coil.

Fig. 5 illustrates the steering movement of the robot in the segment of the curved intestine. The steering head aligns with the rotational body as the robotic endoscope moves straightly. Since the micro CCD would be installed in the steering head, it is easy for the operator to see the curved segment in front of the robot. So the steering head is controlled to turn at a certain angle α as the curve starts. After passing by the curved segment, the steering head is controlled to turn back and keeps the movement straight again. Notice that the turning radius of the robot, R_t, has to be less than the radius of the curve Ro to go through. To satisfy this condition, the turning angle has to satisfy the following:

$$\frac{L\phi}{l \tan\alpha} \le 1 \tag{4}$$

where ϕ is the arc angle of the curve l. Therefore the turning angle can be chosen properly to adapt to different curved segments.

III. EXPERIMENTS

A. Methods and Procedures

A prototype was built to illustrate the proposed locomotion and steering design in this paper. The prototype keeps wired because the communication and vision modules

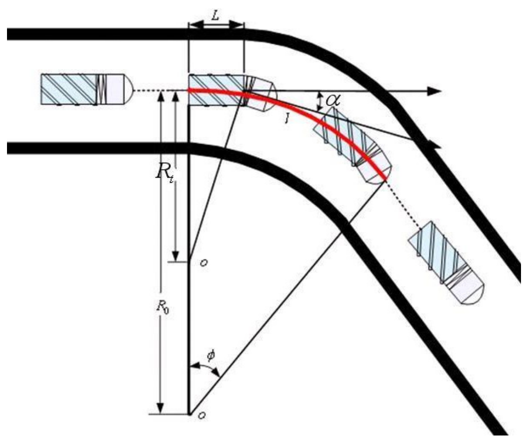


Fig.5. Illustration of the steering move in the curved intestine.

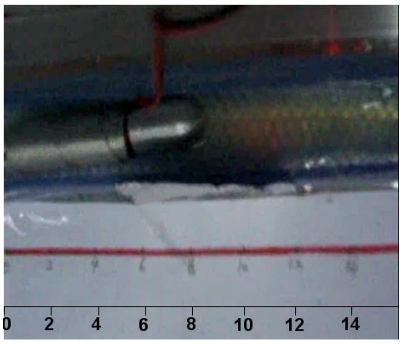
are not the main focus here. This prototype is made of steel and it is 70mm long and 18 mm in diameter which will be reduced in the next step of this research. Straight and curved cylindrical pipes were used to simulate the intestine of the human body. The upper half of the pipes was cut to facilitate the video shooting of the experiments. Mucus of human body has the properties of Casson fluid while the egg whites also have similar properties [22-24]. To simulate the intestinal mucus, egg whites were used in the experiments.

The first group of the experiments is for straight forward movements from the initial position to the position 15 mm away along a straight pipe whose inner diameter was 25 mm. The motor rotational speed is chosen as 76 rpm. The second group of the experiments is for the steering movements along an arc pipe with the same inner diameter. The arc angle of this pipe is about 18 degrees.

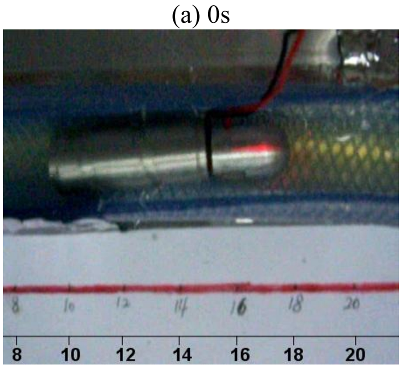
B. *Results and Discussion*

The video segments of a straight forward movement in the first group of the experiments are shown in Fig. 6. Slight vibration of the robot occurred at the beginning and then the robot quickly reached the maximum velocity. At the initial time the velocity of robot is zero, Fig. 6 (a). At t=2s, the velocity of robot becomes about 10mm/s. This was the acceleration stage. After the acceleration, the robot started to move with the constant velocity 10mm/s according to the rulers along the pipe, Fig. 6 (b)-(c). The relationship between the given motor rotational speed and the achieved axial speed of the robot is consistent with the result from the theoretical analysis in the Fig. 3. The robot moving velocity increased as the motor rotational velocity increased in the experiments, also. Hence the operator of the endoscope can easily slow down or speed up the motion from outside at any time by adjusting the rotational velocity of the motor. The rotation of the robot was not observed to result in any big impulses to the wall of the pipe.

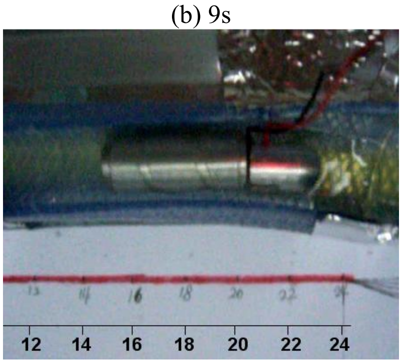
Fig. 7 shows the video segments of a steering movement among the second group of the experiments. At the initial time the turning angle of the steering head is set to 18 degrees, Fig. 7 (a). As the movement of the rotational body, the robot



(a) 0s

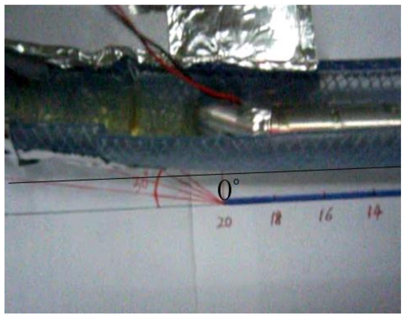


(b) 9s

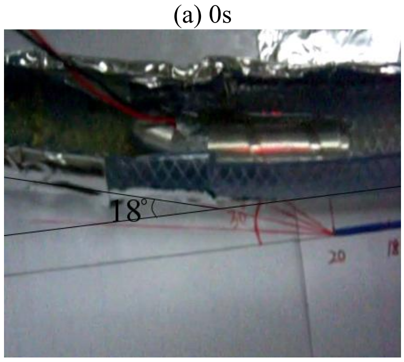


(c) 15s

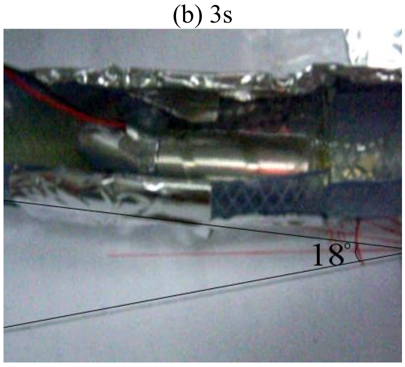
Fig.6. Video segments of the straight forward movement.



(a) 0s



(b) 3s



(c) 7s

Fig.7.Video segments of steering in the curved simulated intestine.

began to steer along the arc pipe, Fig. 7 (b), until the robot moved to the next straight segment of the pipe shown in Fig. 7 (c). Afterwards the steering angle is controlled to return to zero, which keep the straight movement in another segment of the pipe. The steering movement did not contact with the inner wall either.

C. Future Work

Future work will focus on reducing the size of this capsule robot. The expected capsule size is less than 10 mm in diameter and 40 mm long. Another topic is design of the control system which involves the integration with a micro CCD and the signal processing module. A wireless communication module is expected to be designed for easy control. This whole part will be assembled into the steering head. The intestines of pig will be used later to imitate the condition of human body intestine.

IV. Conclusions

This paper introduces a new locomotion and steering design of an active capsule robot for endoscopic inspection. The mechanisms are presented and the underlying principles are analyzed. Experiments have validated the proposed mechanism. The size of robot can be further decreased for practical application while keeping the current structure. Future work will focus on control system integration.

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