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Autonomous Locomotion of Capsule Endoscope in Gastrointestinal Tract

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Abstract—**Autonomous locomotion in gastrointestinal (GI) tracts is achieved with a paddling-based capsule endoscope. For this, a miniaturized encoder module was developed utilizing a MEMS fabrication technology to monitor the position of paddles. The integrated encoder module yielded the high resolution of 0.0025 mm in the linear motion of the paddles. In addition, a PID control method was implemented on a DSP to control the stroke of the paddles accurately. As a result, the average accuracy and the standard deviation were measured to be 0.037 mm and 0.025 mm by a laser position sensor for the repetitive measurements. The locomotive performance was evaluated via ex-vivo tests according to various strokes in paddling. In an in-vivo experiment with a living pig, the locomotion speed was improved by 58% compared with the previous control method relying on a given timer value for reciprocation of the paddles. Finally, the integrated encoder module and the control system allow consistent paddling during locomotion even under loads in GI tract. It provides the autonomous locomotion without intervention in monitoring and controlling the capsule endoscope.**

I. Introduction

A flexible fiber-optic endoscope is a common medical instrument to diagnose diseases in gastrointestinal (GI) tracts. Nevertheless, it can bring about discomfort or even pain to patients due to the limited flexibility of the fiber-optics and air insufflation during operation.

As an alternative, pill-type capsule endoscopes have been developed since they are small enough to swallow and do not yield any discomfort [1]. Once a patient swallows the capsule endoscope, the capsule wirelessly transmit images of inside organs to outside a data receiver while travelling along GI tracts from an esophagus to an anus. However, the current capsule endoscopes are only able to passively move by peristalsis of organs and gravity on the capsule in the GI tracts. This causes several problems in clinical practice in terms of the limited frame rate on imaging devices and lack of an active diagnosis such as a biopsy and therapeutic functions [2].

Therefore, active locomotion in the capsule endoscope is required in order to mitigate the problems. For this, various types of locomotive mechanisms have been proposed platforms to advance in slippery and viscoelastic GI tracts exploiting robotic platforms: using the multiple legs [3], mimicking inchworm motion [4], and paddling [2], [5]. For realizing any kind of active locomotion, a locomotive capsule endoscope should employ actuators internally or externally. Then, these actuators should be also appropriately controlled. However, most of the locomotive capsule endoscopes lack feedback sensors for control due to the small dimension.

Among the capsule endoscopes, the paddling-based locomotion is one of the promising mechanisms since it provided the fast locomotion speed and the long travel distance as demonstrated in the colon of a living pig [2]. This capsular robot also includes a small-sized DC motor (so called micromotor) for the active locomotion. At the beginning of the development, it was manually controlled by switching the direction of the rotation of the motor since there was no sensor to monitor the status of the robot. Due to the inconvenience of switching every cyclic motion, a timer-based control method was implemented on an external microprocessor, which enables to control the stroke of paddling for the pre-assigned time [2]. Although it contributed to increase the locomotive performance and alleviate operator's burden, it was still required to set the appropriate time to maintain the stroke that varied on external load or pressure on the robot and even by robots themselves. Moreover, it was necessary to rely on external monitoring equipment such as a fluoroscopy (C-arm) for re-tuning the time. As a result, a position based control scheme was introduced utilizing a miniaturized encoder module [5]. Although it was available to monitor the position of paddles internally, the resolution of the encoder module was still so poor for the PID control of the DC motor that in-vivo experiments could not be performed.

Therefore, a new type of a miniaturized encoder module exploiting a MEMS fabrication technology is introduced in this paper. In addition, the high precision and the accuracy are accomplished based on a PID control. Finally, the enhanced locomotive performance is verified in ex-vivo and in-vivo experiments.

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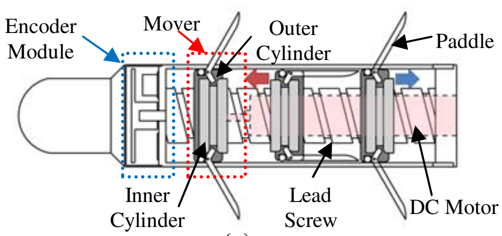
II. PADDLING-BASED LOCOMOTION IN GI TRACT

A. *Principle of the paddling-based locomotion*

The paddling-based capsule endoscope consists of a main body, multiple paddles, a mover embodying the paddles, and the combination of a lead screw, and a brush DC motor of 6 mm diameter. The overall length of the endoscope is 43 mm and the diameter is 15 mm. The length of the slit for extruding the paddles is 33 mm and the pitch of the lead screw for a linear motion is 3 mm.

The rotation of the DC motor (RE 6 with a planetary gearhead GP 6 A, Maxon Motor AG) yields the linear motion of the mover along the lead screw while the rotation of the mover is constrained by a key groove on the main body. In addition, the mover has dual structures such as inner and outer cylinders in order to impose multi-functions such extruding and folding the paddles. For instance, the outer cylinder causes the relative phase difference to the inner cylinder since the outer cylinder experiences more drag by the main body while moving. This phase difference leads the rotation of the paddles attached to the outer cylinder by pins since the inner cylinder pushes or pulls one end of the paddles at the hinged points. Accordingly, when the mover moves backward for advancement in GI tracts, the paddles are simultaneously stretched out of the main body by pushing the end of the paddles. Similarly, when the mover retracts to the initial position (forward), the paddles are folded into the body by pulling the end in the reversed direction as described in Fig. 1 (b).

As a result, the capsule endoscope can advance in GI tracts by the reciprocating motion of the mover such like paddling. Hence, controlling the stroke and the speed of the mover plays a crucial role in the autonomous locomotion of the endoscope in the GI tracts.



(a)

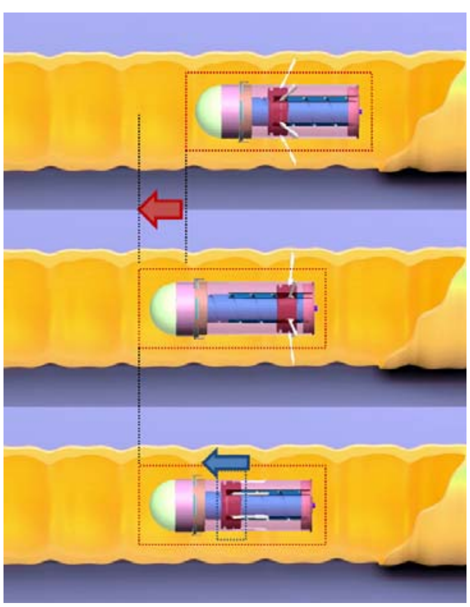

(b)

Fig. 1. A paddling-based capsule endoscope. Overall structure of the paddling-based capsule endoscope with main components (a). Locomotion principle of the capsule endoscope (b).

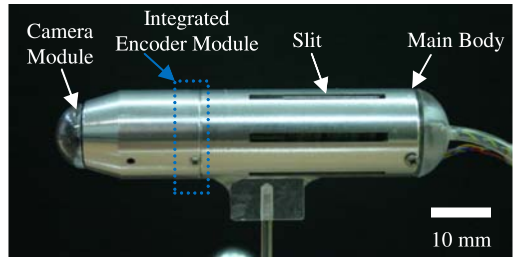


Fig. 2. Fully integrated capsule endoscope.

B. *Effect of paddling stroke in locomotive performance*

Unlike locomotion on stiff ground, viscoelastic deformation in GI tracts tends to impede the advancement of the capsule endoscope. Hence, the loss by the viscoelastic deformation should be taken into account. The effect of the loss related to the forward velocity is described in [5].

Given the linear velocity of the mover, v_{mover} by the rotation of the lead screw, the forward velocity of the capsule endoscope during one cyclic motion of the mover is derived as below.

$$v_{robot} = \frac{v_{mover}}{2} \times \left[1 - \frac{\alpha + l_{dead} + l_{ve}}{l_{screw} - (d_{front} + d_{rear})} \right] \quad (1)$$

α represents overall dragging effects induced by the kinematic relationship between the mover and the paddles and by miscellaneous tolerances in mechanical components. The length of a dead zone, l_{dead}, which does not contribute to the locomotion is included in the capsule endoscope for securing the paddles inside the main body at the initial position. l_{ve} indicates the elastic deformation of organs and the slip on the paddles when the capsule endoscope is advancing along viscoelastic tracts. An effective stroke of the mover is defined by $l_{screw} - (d_{front} + d_{rear})$, where l_{screw} is the total length of the lead screw. d_{front} and d_{rear} denote the offsets each from the front and back ends of the stroke to avoid the collision of the mover.

From the equation (1), the forward velocity is affected by the linear velocity of the mover as well as the effective stroke. In the worst case, the capsule endoscope would not advance in the GI tracts when the effective stroke in the denominator is the same with the overall loss in numerator. The Fig. 3 shows how the stroke of the mover affects on the forward velocity of

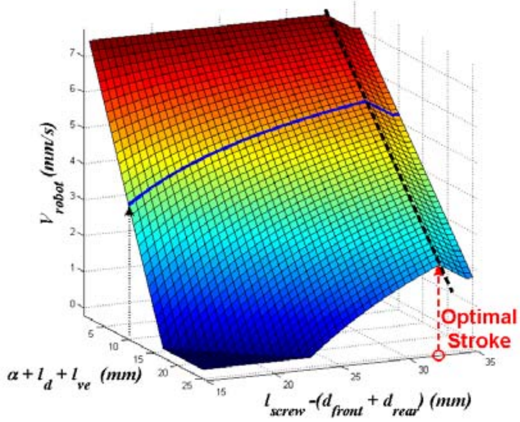


Fig. 3. Forward velocity of the paddling based capsule endoscope according to an effective stroke, $l_{screw} - (d_{front} + d_{rear})$ and overall stroke loss, $\alpha + l_{dead} + l_{ve}$.

the capsule endoscope given the lead screw of 35 mm while the loss in displacement occurs. The velocity is maximized at a certain stroke, the so called optimal stroke, which eliminates the dead zone. Beyond the optimal stroke, the velocity decreases again since it includes the dead zone during the reciprocation of the mover. The loss in displacement has been experimentally found to be 10-15 mm while locomotion in GI tracts. This could explain why such a small-sized robot which entails a short stroke has difficulty in locomotion under relatively large viscoelastic-deformation although it is available to fabricate that size of robotic platforms.

Overall, in order to maximize the forward velocity, the front and the rear offsets excluding the dead zone were found to be 2.0 mm and 0.5 mm, respectively, based on the video analysis of the effective stroke in [5].

III. Feedback Control of Paddling Stroke

A. Fabrication of miniaturized encoder

A miniaturized encoder module was designed and fabricated to control the position of the paddles since the

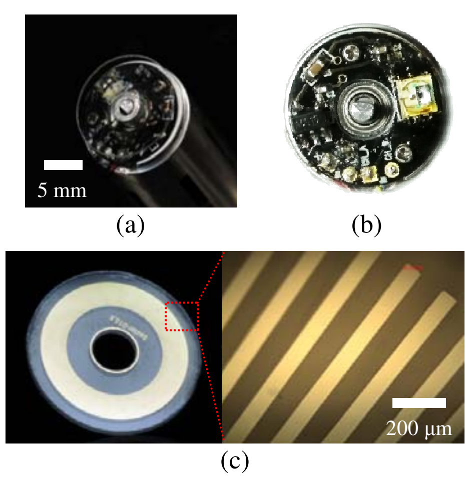


Fig. 4. Miniaturized encoder module: overall assembly on the top of the capsule endoscope (a), a PCB (b), and a codewheel with the slit of 50 µm.

position is determined by the rotation of the micromotor and the lead screw. This module is composed of a reflective surface mount optical encoder IC (AEDR 8400, Avago Technologies, 3.00 mm × 2.38 mm × 1.26 mm), a codewheel, a printed circuit board (PCB) as shown in Fig. 4. Since the optical encoder IC houses a light source and a photo-detecting circuitry in a single package, it aids to be implemented in a small dimension. For using this IC, the slits on the codewheel must be placed by 50 µm with the width of 50 µm. However, it is seldom achieved by the conventional machining technology such as metal etching.

To overcome this, MEMS (microelectromechanical system) fabrication methods were adopted to fabricate the codewheel. First, chrome and gold layers were deposited on the glass of 0.5 mm thickness for the high reflectivity of the patterns. Then, the line-shaped slits were patterned on the glass by photolithography. After wet-etching of the glass for patterning, the glass was diced to the circular disc of 13.9 mm diameter. A boss was finally attached on the disc by an instant adhesive for coupling with a shaft.

For assembly, the PCB arranging the encoder IC and a regulator was placed in front of the main body. Then, the boss was coupled by a set screw with the shaft on the end of the lead screw. Finally, a plastic cover was securely bonded with the main body to prevent infiltration of water.

B. Characterization of control parameters for PID control

The micromotor is basically operated by a PID controller implemented on a DSP (TMSS320F2808, Teaxs Instruments) which is capable of counting encoder pulses (Enhanced Quadrature Encoder Pulse, eQEP). Based on the eQEP function, the resolution of the encoder module is improved and the direction of rotation is also detectable. Given the rotational feedback by the miniaturized encoder module, desired voltage is applied to the motor by the PID controller utilizing PWM (pulse-with modulation) signals from the DSP and an external H-bridge driving circuit.

In order to characterize control parameters for the PID control, an experimental setup simplifying the linear motion of the mover was prepared. First, the system parameters such as the moment of inertia and the damping coefficient were identified to be 1.0 × 10^{-9} kg·m^2/s^2 and 5.6 × 10^{-8} Nm·s, respectively. For this, the incremental rate of the angular velocity was analyzed upon driving voltage from -6 V to 6 V. In addition, the time constant in the step response of 10 rad/s was measured. These parameters were finally verified by comparing a simulation result with the actual measurement in the step response.

To determine P, I, and D control parameters, the Ziegler Nichols step response method [6] was adopted since the estimated system is stable enough in an operating range. From the step response of the linear motion of the mover, the P, I, and D values were initially given by 3.8, 0.05, and 0.001, respectively. For the satisfactory response without overshoot, further tuning of the parameters was executed as shown in Fig.

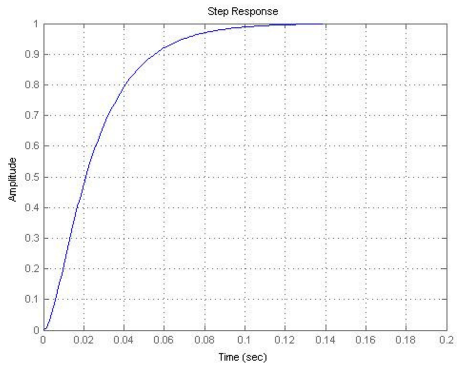


Fig. 5. Step response of the identified system model when the P, I, and D values are set by 2.0, 0.05, and 0.1 respectively.

5. As a result, the parameters were set by 2.0, 0.05, and 0.1 for the P, I, and D values.

IV. Result

A. Verification of feedback control performance

From the combination of the encoder module and the eQEP function on the DSP, the total 1192 pulse signals are acquired per one revolution, which yields the angular resolution of 0.302 degrees in rotation. Accordingly, the linear resolution is determined by 0.0025 mm when it is accompanied with the lead screw and the mover.

The controllability in linear positioning was evaluated by comparing the encoder reading with the desired displacement. The average difference between the final position and the target value was 0.005 mm. The standard deviation for 20 times measurement at each command was 0.003-0.006 mm. This demonstrates that the designed controller works well with the implemented encoder module.

For the evaluation of the accuracy, the encoder reading was compared with the actual value measured by a laser position sensor (Laser Doppler Vibrometer, Polytec Inc.). The average difference between them was 0.037 mm and the standard deviation was 0.016-0.038 mm. The directly measured values from the linear motion of the mover could be slightly different since the controller only relies on the rotational feedback from the lead screw in the absence of tolerance with the mover. Nevertheless, the stroke of the mover is still controllable in the range of 0.1 mm. The results are described in Table I.

TABLE I
Evaluation of Control Performance

Command[a]	Encoder Reading[b]	Laser Vibrometer[c]	Controllab- -ility (a-b)	Accuracy (c-b)
0.9	0.894 ± 0.006	0.875 ± 0.023	0.006	-0.019
3.0	3.000 ± 0.006	2.965 ± 0.016	0.000	-0.035
10.2	10.194 ± 0.003	10.126 ± 0.038	0.006	-0.068
15.0	14.991 ± 0.004	14.950 ± 0.029	0.009	-0.041
-0.9	-0.893 ± 0.005	-0.879 ± 0.020	-0.007	0.014
-3.0	-2.999 ± 0.005	-2.968 ± 0.038	-0.001	0.031
-10.2	10.197 ± 0.004	-10.126 ± 0.017	-0.003	0.071
-15.0	-14.995 ± 0.004	-14.980 ± 0.021	-0.005	0.015
Average	± 0.005*	± 0.025*	0.005	0.037

Unit: mm
*Average of standard deviations

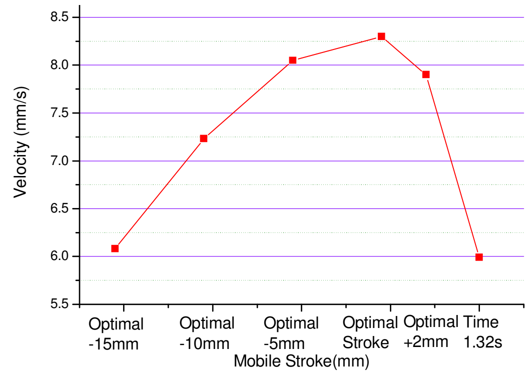


Fig. 6. Ex-vivo test result according to various strokes of the mover and a timer value for the reciprocation.

B. Ex-vivo tests

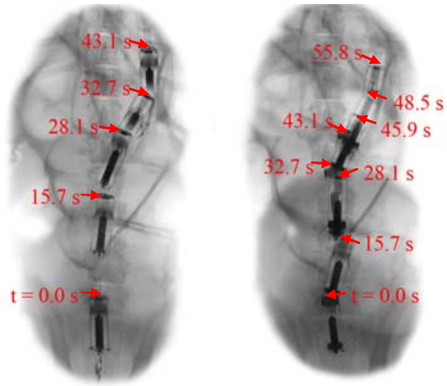
The locomotive performance under viscoelastic condition was investigated using a large intestine extracted from a pig via ex-vivo tests. The intestine was suspended between two posts and slightly inclined upward. The capsule endoscope was inserted into one end of the intestine. The strokes were set by offsets from -15 mm to 2 mm with respect to the optimal stroke that already found to be 31.96 mm as described in Fig. 6. In addition, the timer-based control method was compared by assigning the period of reciprocation as 1.32 s, which has been used in controlling the paddling based capsule endoscope [5].

As expected from Fig. 3, the velocity of the capsule endoscope was maximized at the optimal stroke as shown in Fig. 6. Moreover, as the strokes increased or decreased from the optimal stroke, the velocity decreased. Given the timer input, the velocity was almost identical with it at the stroke of 16.96 mm (-15 mm offset from the optimal stroke). This implies the timer-based control method might cause significant variations in the locomotive performance depending on the period to be set and experimental conditions.

C. In-vivo tests

In-vivo tests were performed in a living pig. During the procedure, the capsule endoscope was inserted into the rectum of the pig under anesthesia. To verify the improvement of the locomotive performance, the timer-based control method was also compared by setting the timer value to 1.9 s due to large loss in stoke inside a GI tract.

The average velocity of the feedback controlled capsule endoscope was 28.4 cm/min for travelling of 20.4 cm, whereas they were 18.0 cm/min and 17.0 cm, respectively with the timer-based control. Consequently, the locomotion speed increased by 58% with the developed control system. Moreover, the feedback control method was robust enough to surroundings of the capsule endoscope so that it did not



(a) (b)

Fig. 7. Reconstructed paths for the locomotion of the capsule endoscope in the GI tract of a living pig with respect to the elapsed time: the PID control for maintaining the optimal stroke in paddling (a) and the timer-based control for the reciprocating motion (b).

require readjustment in control setting, which had been frequently occurred in the timer-based control method.

V. CONCLUSION

Most of the locomotive capsule endoscopes have focused on feasibility of mechanisms rather than control due to relatively large dimension of sensors. To overcome this, MEMS based fabrication methods were applied to the miniaturization of the encoder module, which yields 40 times higher resolution than the previous encoder module. Such fabrication methods are expected to contribute to miniaturization of sensing parts and mechanisms in locomotive capsule endoscopes. Consequently, the autonomous locomotion is accomplished with the paddling-based microrobot in GI tracts without any intervention. In addition, minimal mucosal injuries which might occur by the edge type of the paddles will be resolved or minimized with modifications on the materials and surface structure of the paddles [7].

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