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Improvement of Locomotive Performance of Capsular Microrobot Moving in GI Tract Using Position Based Feedback Control

Kitae Park, Sungwook Yang, Jinseok Kim, Tae Song Kim and Eui-Sung Yoon

Abstract— **The position based feedback control system is proposed in order to improve the locomotive performance of the paddling based capsular microrobot moving in gastrointestinal (GI) tracts. The miniaturized optical encoder is designed and fabricated for the positional feedback of the mobile in the microrobot, which results in the precise positioning with the resolution of 0.1 mm. Moreover, the stroke of the mobile is optimized to increase the forwarding velocity of the microrobot. The control performance is verified by comparing the targeted displacement with the measured one under various loading conditions. The velocity of the microrobot is evaluated according to the various strokes and driving voltages under visco-elastically deformable and rare deformable conditions. The control system works properly with high resolution and accuracy and the velocity of the microrobot is maximized under the optimized stroke. In the in-vitro test, the velocity of the microrobot controlled by the position based feedback is increased by 73 % when the optimized stroke is applied, compared with the velocity by the time based control.**

I. Introduction

The conventional push-type endoscopies are commonly employed in order to diagnose diseases in gastrointestinal (GI) tracts. However, they bring about discomfort and even pain to patients due to somewhat stiff tubes including fiber optics and air insufflation.

Hence, the wireless capsule endoscope which is small enough to swallow through an esophagus like a pill has been developed [1-3]. Even though it highly reduces patients' discomfort and enlarges the diagnosis field such as investigating small intestines that cannot be reached by conventional endoscopies, it moves passively from an esophagus to an anus by peristaltic waves of organs and thus has difficulties in diagnosis of desired organs thoroughly.

For the reason, a locomotive capsule endoscope which is capable of exploring inside organs actively is necessary. In order to realize locomotion inside visco-elastically deformable and slippery organs, various locomotive mechanisms have been proposed for the multiple legged [4-6], inchworm-like [7-9] and paddling based [10], [11] capsule robots for advancing in GI tracts. Nevertheless, the multiple legged and inchworm-like capsule robots which adapt biomimetic legs and locomotive mechanism could be somewhat inappropriate in traveling inside viscoelastic organs effectively due to slips and the short advancing stroke during locomotion and also the low locomotion speed. On the other hand, the paddling mechanism is hardly influenced by the folding of organs and shows reliable and fast locomotion even inside intestines.

In case of the paddling based capsular microrobot, it consists of a micro-motor, lead screw, inner and outer mobiles, multiple legs and outer body mainly. Therefore, it can advance while the mobiles are reciprocating within the stroke of the lead screw, as stretching and folding the multiple legs on the mobiles. Consequently, the locomotive performance of the microrobot could depend on how to control the reciprocation of the mobiles.

In order to control the paddling based locomotion, two kinds of methods such as the manual and time based switching to the direction of the mobile have proposed so far [11]. For the manual method, the moving direction of the mobile is converted to the opposite side by operating the mechanical switch when the mobile reaches the end of the lead screw. This manual switching control not only yields inconvenience to operators but also needs external monitoring equipment such as a fluoroscopy to observe the position of the mobile inside intestines. The time based control can mitigate operator's burdens to observe and switch the position of the mobile since the mobile reciprocates continuously depending on the settled time for the cycle. However, the stroke would vary even during the fixed reciprocating time if the mobile cannot appropriately move due to loads such as pressure of organs. Thus, the external monitoring equipment is still needed to maintain the stroke of the mobile under loads.

Therefore, the position based control system to keep the stroke of the mobile consistently without external monitoring is proposed for the paddling based locomotive microrobot. For this, we design and fabricate the miniaturized encoder for the micro-motor used in the microrobot. Then, the microrobot is controlled according to the desired stroke with the position feedback to the traveling mobile. In addition, the stroke is optimized for the best locomotion and verified under various conditions.

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Kitae Park is with University of Science and Technology, 113, Gwahangno, Yuseong-gu, Daejeon 305-333, Korea

Sungwook Yang, Jinseok Kim and Eui-Sung Yoon are with Nano-Bio Research Center, Korea Institute of Science and Technology, 39-1, Hawolgok-dong, Seongbuk-gu, Seoul 136-791, Korea (corresponding author to provide phone: 82-2-958-5651; fax: 82-2-958-6910; e-mail: esyoon@kist.re.kr).

Tae Song Kim is with Intelligent Microsystem Center, Korea Institute of Science and Technology, 39-1, Hawolgok-dong, Seongbuk-gu, Seoul 136-791, Korea.

II. Position Based Control System

A. Design and Fabrication of Position Encoder

For large scale motors, various embedded encoders are widely used for measurement of the number of rotation, speed and torque. However, for small-sized micro-motors that have the small diameter less than 6 mm, the embedded solution is not commercially available yet due to the difficulties in miniaturization and assembly [12].

Hence, we designed and fabricated a miniaturized encoder inside the paddling based capsular microrobot(the length of 43mm, the diameter of 15 mm, the weight of 13.9 g and the power consumption of 1 W) in which the micro-motor of the diameter of 6 mm is employed. In the design of the miniaturized encoder, the optical type of the encoder is preferred since permanent magnets of a magnetic encoder could interfere with magnetic fields of the micro-motor during rotation. Moreover, torque loss by unbalanced weight of magnets is relative significant, compared with total torque generated in a small-sized micro-motor.

The optical encoder is composed of a photodiode (PDB-C152SM, Advanced Photonix Inc.), a LED, a graduated disc with radial gratings and stationary gratings on the emitting LED as shown in Figure 1 (a). In addition, it includes the amplifying circuit that converts analog signals from the photodiode to digital signals to prevent distortion by external noise. The graduated disc is designed with 30 slits and the width of 0.3 mm in the diameter of 10 mm as shown in Figure 1 (b) when the operating rotation speed (655 rpm at 6 V) and the response time (5 μs at 5 V) of the photodiode are considered [13].

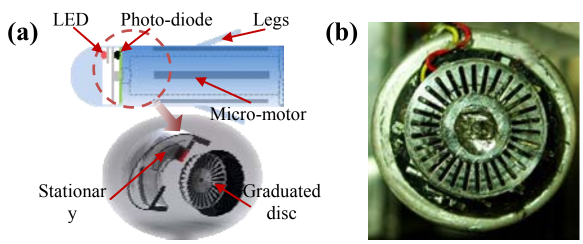

Fig.1. (a) Design of the optical encoder on the paddling based capsular microrobot, (b) Fabricated optical encoder

Accordingly, the positional resolution of the mobile is defined as 0.1 mm since the mobile advances by 3 mm per one revolution of the micro-motor and the slits are sensed 30 times with the encoder.

B. Position Based Control System for Locomotion

The multi functional control system was designed to manage an appropriate stroke for the mobile and provide reciprocating motion automatically by closed loop control with the position feedback as shown in Figure 2 (a). Hence, the control system has the following functions: the adjustment of the mobile stroke based on either the number of encoder pulses or duration for reciprocation, manual switching for change of moving direction, alteration of driving voltage, and the display of current state information including power consumption. Finally, the fabricated controller of Figure 2 (b) allows the microrobot to move while maintaining the desired mobile stroke under loads.

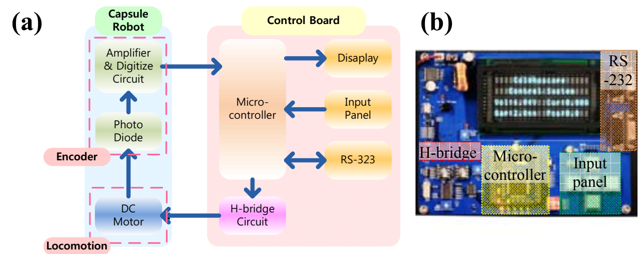

Fig.2. (a) System control flow, (b) Fabricated controller for locomotion

III. Optimization of Mobile Stroke

The paddling based capsular microrobot advances while the mobile moves backward as stretching the legs to clamp intestinal surfaces. Then, the mobile retracts to the initial position as folding the legs for the next advancement.

Consequently, the locomotive performance such as the forwarding velocity and displacement of the microrobot is highly related to the velocity and stroke of the mobile.

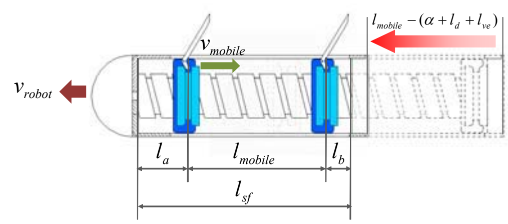

Fig.3. Define of robot velocity

The velocity of the mobile is

$$v_{mobile} = \frac{rpm}{60} \times P \tag{1}$$

where, P denotes the pitch of the lead screw.
In considering of miscellaneous drags, the settling region that enables the legs to be fully folded just for safety and viscoelastic deformation on intestinal tracts, the forwarding velocity of the microrobot is derived as

$$v_{robot} = \frac{v_{mobile}}{2}\left[1 - \frac{\alpha + l_d + l_{ve}}{l_{sf} - (l_a + l_b)}\right] \tag{2}$$

where, α denotes drags induced by the kinematic relationship between the mobile and legs and by miscellaneous tolerance in mechanical components. l_d is the dead stroke which does not contribute to advancement while the mobile is moving at the settling region. l_{ve} is described as the loss in displacement by viscoelastic deformation of tracts. l_{sf} is defined as the available maximum stroke of the mobile along the screw. l_a and l_b denote offsets at the front and rear respectively in the stroke of the mobile.

Accordingly, equation (2) represents that the forwarding velocity of the robot is affected by the velocity and stroke of the mobile and thus it would increase when the stroke of the mobile is expanded. Finally, for the best locomotion, the mobile should move as excluding the dead stroke and maximizing the effective stroke. In order to define the optimized mobile stroke, the effective strokes were measured according to various front (l_a) and rear (l_b) offsets by the video analysis while the mobile travels with fully stretching the legs. The front offset was increased from 0.0 mm to 4.0 mm with 0.5 mm stepwise and the rear offset started with 0.3 mm then increased from 0.5 mm to 1.5 mm with the same step. The measured strokes were contoured with respect to the front and rear offset as shown in Figure 4. As a result, the stroke of the mobile was optimized as 31.96 mm when the front and rear offsets were selected with 2.0 mm and 0.5 mm respectively.

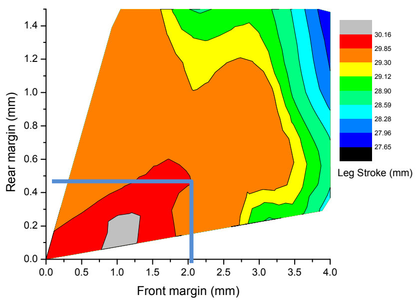

Fig.4. Experimental results with regard to the front and rear offset for the

IV. Result

A. Performance of Position Based Control System

First, in order to evaluate the accuracy of the position based control system, the displacements of the mobile were measured according to the targeted displacement of 1 mm, 3 mm, 5 mm and 10 mm through the video analysis which has the accuracy of 0.02mm/pixel. The average results on three times measurement are summarized in Table 1 and the average deviation among them is 0.038 mm. Thus, the position base control system for the paddling based locomotion works properly with the high accuracy.

TABLE I
Comparison of Controlled Displacement with Target

[a]Targeted Displacement (mm)	[b]Measured Displacement (mm)	Difference (a-b) (mm)
1.00	1.08	0.08
3.00	3.04	0.04
5.00	4.97	0.03
10.00	10.00	0.00
	Average Deviation	0.04

Second, the stability, such as maintenance of the mobile stroke under loads, was compared between the position based and the time based control. Actually, the stroke is affected and reduced by internal pressure of intestines on legs since the velocity of the mobile slows down under that condition and the stroke decreases under the fixed duration and the lower velocity. In order to simulate the condition when the velocity of the mobile decreases due to internal pressure of intestines, it was moderated by varying on the applied voltage to the micro-motor. Before the tests, the microrobot was set to have the maximum stroke at 6 V under both the time based and position based control. The each stroke of the mobile reciprocating under no external load was measured when voltage was dropped down from 6 V to 4 V without changing any control setting. The average results on three times measurement of the strokes are shown in Figure 5 and compared depending on two control methods. The stroke under the time based control was decreased with respect to the voltage drop down. On the other hand, the stroke under the position based control was maintained even the voltage changed, which means the position based control can serve uniform strokes under load condition.

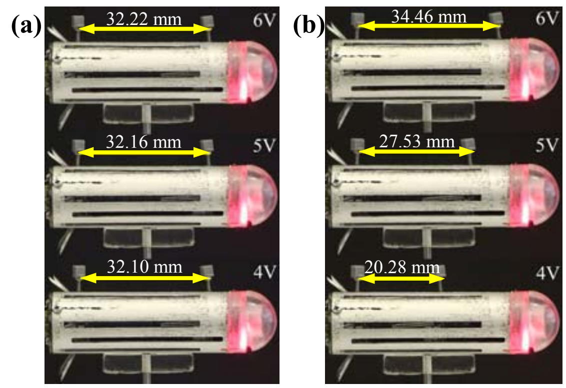

Fig.5. Mobile strokes in free space depending on the voltage drop down with Position based control (a) and time based control (b)

B. Velocity depending on Mobile Stroke

In this experiment, we measured the velocity of the robot according to various mobile strokes under deformable and non-deformable condition. A latex tube (the stiffness of 10~20 N/m) with the length of 400 mm and a silicone tube (the stiffness of 2000~3000 N/m) with the same length were employed for deformable and non-deformable conditions respectively. The average velocity was calculated with regard to various strokes including the optimized stroke (the front offset: 2.0 mm and the rear offset: 0.5 mm): the optimized stroke, the shorten strokes from the optimized one by 5, 10 and 15 mm and finally the available full stroke for the mobile. The tests were performed and compared under the applied voltage of 6 V and 5 V.

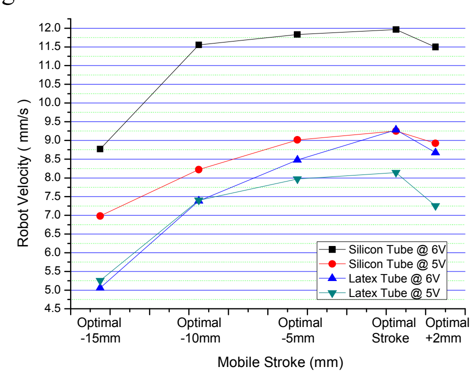

Fig.6. Experimental result according to various strokes of the mobile in the silicone and latex tubes

As shown in Figure 6, the velocity of the robot with the optimized mobile stroke was faster than others at both 6 V and 5V. The more shorten strokes from the optimized one were applied, the more declines in the velocity were yielded under both tubes. According to the equation (2), the velocity of the robot could vary on the applied mobile stroke even though the robot travels on a non-deformable surface. In addition, the velocity of the robot in the silicone tube is faster than in the latex tube since the loss in the stroke under the non-deformable condition is less than under the deformable one.

C. *In-vitro Test*

For the in-vitro test, the large intestine extracted from a pig was bridged across two posts. Thus the small intestine had the 3-dimensional curved and inclined path in Figure 7, with the slope angle of 17.7 degree. And then the robot was inserted into the end of the large intestine so that it was able to advance along the 3D intestinal tract.

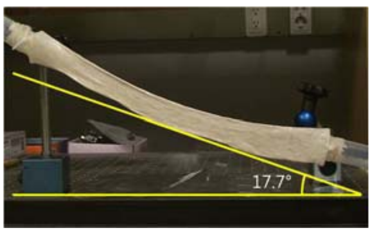

Fig.7. Inclined porcine intestine with the angle of 17.7º

Under the time based control, the duration was set as 1.27 sec. for the maximum stroke and 1.32 sec. as considering loss in stroke inside the viscoelastic intestine. This settlement was defined before the robot was inserted under no load condition. The same variation in strokes with the in-vitro test was applied under position based control. Then, the average velocity of the robot was measured when the robot advanced inside the intestinal tract of 400 mm under the time and the position based control at the applied voltage of 5 V and 6 V. As a result, it was maximized as 8.64 mm/sec when the robot had the optimized stroke as shown in Figure 8. Specifically, the velocity at the optimized mobile stroke was faster by 73% than one controlled under the duration of 1.32 sec at 6 V. Even though the mobile is set to have a full stroke in free space under the time based control, the stroke of the mobile could be reduced by change of the mobile velocity due to the internal pressure from the intestines and thus the forwarding velocity of the robot could decrease.

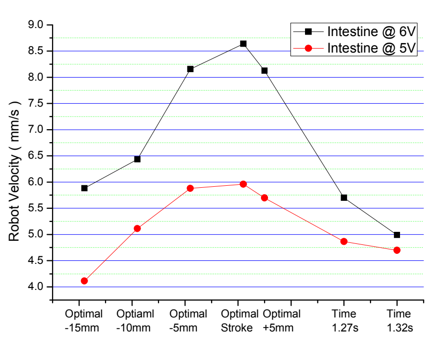

Fig.8. In-vitro experimental result according to various strokes of the

V. Conclusion

The position based control system with the optical encoder was proposed for improvement of locomotive performance of capsular microrobot moving in GI Tract. The miniaturized optical encoder was fabricated and the resolution was high enough to control the microrobot. The enhanced controllability and stability in locomotion with position feedback were verified. For the best locomotion, the mobile stroke of the microrobot was optimized through the video analysis. Finally, the locomotive performance was evaluated through the in-vitro and in-vivo experiments by comparing results under other strokes and control method. In conclusion, the locomotive performance of the microrobot is improved since the stroke of the mobile can be maintained under loads and managed to maximize the forwarding velocity of the microrobot due to the proposed position based control.

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References

[1] G. Iddan, G. Meron, A. Glukhovsky, P. Swain, "Wireless Capsule Endoscopy", Nature, Vol. 405, pp. 417, 2000.
[2] Given Imaging Co., Israel, http://www.givenimaging.com/,
[3] RF system lab., Japan, http://www.rfnorika.com/
[4] A. Menciassi, C. Stefanini, S. Gorini, G. Pernorio, P. Dario, B. Kim, J-O Park, "A Legged Locomotion in the Gastrointestinal Tract", Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, Vol. 1, pp. 937-942, 2004.
[5] M. Quirini, R. J. Webster III, A. Menciassi, P. Dario. "Design of a Pill-Sized 12-legged Endoscopic Capsule Robot", 2007 IEEE International Conference on Robotics and Automation Roma, Italy, 10-14 April 2007
[6] M. Quirini, A. Menciassi, S. Scapellato, C. Stefanini, P. Dario, "Design and Fabrication of a Motor Legged Capsule for the Active Exploration of the Gastrointestinal Tract", IEEE/ASME Transactions on Mechatronics, Vol. 13, no. 2, April 2008
[7] B. Kim, S. Lee, J.H. Park, J-O Park, "Inchworm-Like Microrobot for Capsule Endoscope", Proceedings of IEEE International Conference on Robotics and Biomimetics, 2004.
[8] Y. Lee, B. Kim, M. Lee, J-O Park, "Locomotive Mechanism Design and Fabrication of Biomimetic Micro Robot using Shape Alloy Memory", Proceedings of IEEE International Conference on Robotics and Automation, Vol. 5, pp. 5007-5012, 2004.
[9] B. Kim, S. Park, C. Jee, S. Yoon, "An Earthworm-Like Locomotive Mechanism for Capsule Endoscopes", Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005.
[10] H.J. Park, S.J. Park, E.S. Yoon, B.K. Kim, J.O. Park, S.H. Park, "Paddling based Microrobot for Capsule Endoscopes", Proceedings of IEEE International Conference on Robotics and Automation, 2007.
[11] S. Yang, K. Park, S. S. Lee, K. Na, J. Kim, J. Choi, S. Park, J. Park, E. Yoon, "Locomotive Microrobot for Capsule Endoscopes," The journal of Korea robotics society, vol. 4, pp 62-67, Mar, 2009.
[12] M. Dimmler, C. Dayer, "Optical Encoders for Small Drives", IEEE/Transactions on Mechatronics, Vol. 1, no. 3, December 1996
[13] J.G. Webster, "The Measurement, Instrumentation, and Sensors Handbook". CRC Press IEEE Press, 1999, pp.6.98-6.118