An Earthworm-Like Locomotive Mechanism for Capsule Endoscopes

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Abstract—A wireless capsule endoscope, M2A, has been developed to replace the conventional endoscope. However, the commercialized capsule endoscope moves passively by peristaltic waves and gravity, which has some limitations for doctors to diagnose more thoroughly and actively. In order to solve this problem, a locomotive mechanism is proposed for a wireless capsule endoscope. Based on the tests of various actuators, a piezo actuator is selected as a micro actuator for the capsule endoscope. Piezo actuators are known to have limited displacement with high voltage supply. In order to overcome the limitation of common Piezo actuator, the impact based piezo actuator is developed to realize long stroke up to 11 mm. Moreover, clammers mimicked the claw of insects are employed. A prototype of the earthworm-like locomotive mechanism integrated with an impact based piezo actuator and engraved clammers is developed. It has 15 mm in diameter and 30 mm under retraction stage and 41 mm under elongation stage in total length. Hollow space is allocated to comprise essential endoscope components such as a camera, communication module, battery, and bio sensors. For the feasibility test of proposed locomotive mechanism, a series of experiments was carried out including in-vitro tests. Based on results of the experiments, we conclude that the proposed locomotive mechanism is effective to be used for micro capsule endoscopes.

Index Terms - Capsule endoscope, clammers, earthworm-like locomotive mechanism, Impact based piezo actuator.

I. INTRODUCTION

The conventional push-type endoscope is most commonly used in most hospitals and operated by the hands of skilled individual operators. Since its tube needs some structural strength to be pushed, it has somewhat high stiffness, causing pain and discomfort to patients. Moreover, it cannot reach to the small intestine for diagnosis. These problems have drawn the development of wireless capsule endoscopes. The very first capsule endoscope-M2A[1,2] was developed and commercialized in 2001 by Given Imaging Inc. of Israel. It is 10 mm in diameter and 27 mm long integrated with a CMOS camera, an RF module, a battery, and illuminating LEDs. It can be swallowed and can transmit wireless still images from a gastrointestinal 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 patients. Recently, other wireless-type endoscopes are developed by RF System Co. and Olympus Medical System Co. respectively [3,4]. However, those capsule endoscopes move passively from the mouth to anus by the peristaltic waves. Thus, no active diagnosis is possible due to the lack of a locomotive mechanism. Therefore, Dario et al. has proposed a legged locomotive mechanism for diagnostic and therapeutic purposes[5] and also we have proposed an inchworm-like microrobot comprising actuation modules and clamping modules for capsule endoscopes[6]. In order to realize a high stroke of locomotive mechanism, spring-type SMA actuators instead of wire-type SMA actuators have been employed. However, the SMA actuator has very low efficiency and slow response time that is more than a few seconds since it actuates with heating SMA itself. In addition, more than two actuators are required to have long stroke and strong force enough to get over resistance force due to deformation of small intestine. Therefore, an impact based piezo actuator is developed to overcome limitations of response time and stroke length of the SMA spring-type actuator. The developed actuator is integrated with clammers mimicked claws of insects and an earthworm-like locomotive mechanism is realized. With variation of clammers’ shape and stroke length, a series of experiments is carried out under in-vitro condition to prove feasibility of the proposed locomotive mechanism. Once successful locomotive mechanism is developed, we may expect a multi-functioned capsule endoscope as shown in Fig.1[7]. Not only simple video based diagnosis but also physiological tests such as pH, temperature and specific cancers are feasible with real time manner.

Fig. 1. Concept design of the microrobot for capsule endoscope.
II. IMPACT BASED PIEZO ACTUATOR

A. Micro Actuators for Capsule Endoscope

A micro actuator is one of the most critical components to develop a successful locomotive mechanism for a capsule endoscope since it has to meet tough design specifications such as size, power consumption, generative force, displacement and safety. The proper actuator for the capsule endoscope should consume low power that can be supplied by a wrist watch battery. It needs to generate high force to overcome resistance force caused by collapse of digestive organs. High response time is essential to move through whole digestive organs within an hour. In addition, longer stroke to get over visco-elastic characteristic of digestive organs is highly required.

The characteristics of typical micro actuators are summarized in Table I. IPMC (Ionic Polymer Metal Composite) actuator has high strain with bending, however, generative force is limited to about 1g [8]. In case of a spring-type SMA actuator, we can obtain 30% stroke with 20 mm actuator. Therefore, we were able to construct inchworm-like micro robot for the capsule endoscope in dimension of diameter of 13 mm and length of 30 mm. However, it requires long actuation time more than 2 sec in case of 150 µm that can generate enough force to move the robot body. In addition, we should wait for more than 5 sec until it comes back to original shape. That means 7 sec is required for one cycle actuation. In order to overcome the problems of spring type SMA actuator, we need to find an alternative actuator that compensates the disadvantage of the SMA actuator.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>IPMC</th>
<th>PZT</th>
<th>Impact based Piezo actuator</th>
<th>SMA Spring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>Low(≤3V)</td>
<td>High(=100V)</td>
<td>Low(≤3V)</td>
<td>Low(≤3V)</td>
</tr>
<tr>
<td>Displacement</td>
<td>High bending</td>
<td>Small(0.2%)</td>
<td>High(=10mm)</td>
<td>Large(=30%)</td>
</tr>
<tr>
<td>Force</td>
<td>Low(≤1g)</td>
<td>High(=100g)</td>
<td>Medium(=20g)</td>
<td>Medium(=20g)</td>
</tr>
<tr>
<td>Speed</td>
<td>Fast(&gt;100Hz)</td>
<td>Very fast(&gt;10kHz)</td>
<td>Fast(&gt;KRPM)</td>
<td>Slow(&gt;0.1Hz)</td>
</tr>
<tr>
<td>Compactness</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Motion type</td>
<td>Bonding</td>
<td>Linear</td>
<td>Linear</td>
<td>Linear</td>
</tr>
</tbody>
</table>

B. Piezo Actuator

Generally, piezo actuators are known to require high voltage that is about 100 V although it is varied depending on size and a type of piezo. In addition, it has lower displacement than the other micro actuators such as SMA and polymer based actuators. Therefore, the piezo actuator is excluded as a micro actuator for an endoscope capsule in our previous study [6]. However, conceptually a modified piezo actuator overcomes the limitation of the piezo actuator itself. In this paper, we employed an impact-based piezo actuator. It comprises a ceramic piezo actuator, a copper base plate, PCB (printed circuit board) to fix boundary of an actuator, shaft to guide an mobile element, and a mobile element itself as show in Fig.2. The shaft is fixed on the copper plate using epoxy based bonding. The copper circular plate of 6 mm diameter with a 1.2 mm diameter hole in the center is disposed to fix the shaft. Under the copper plate, the ceramic circular plate of 5 mm is positioned. And copper plate is bonded on the circular PCB, which has inner diameter of 5 mm and outer diameter of 11 mm, respectively. Then, the shaft made of steel has dimension with diameter of 1.2 mm and length of 17 mm. A mobile element (diameter 7 mm, height 4 mm) is made of Bakelite to guarantee still condition when there is no applied voltage to an actuator. The total mass of an actuator is just 0.6 g.

C. Working Principle of Piezo Actuator

Working principle of the proposed actuator is presented in Fig. 3. An attached mobile element to the shaft is actuated with saw tooth shaped pulse (Fig.3-(b)) as an input voltage to the piezo ceramic. The ceramic actuator moves forward as much as amplitude of A during the pulse interval of a-b. On the other hand, the ceramic actuator moves backward as much as 2A when the input pulse changes from b to c and reaches to 0. At that time, only the shaft attached to the actuator moves backward and the mobile element keeps its position due to Newton’s First Law of Motion. In the pulse interval of c-d, the ceramic actuator moves forward with amplitude of 2A. At that time, a mobile element on the shaft follows the motion of an actuator due to enough friction between the mobile element and the shaft. In the range of d-e, again only the actuator comes back to base position and mobile element keeps same position. Based on repeated cycle in Fig.3, the impact based actuator works. More precise specification of the invented actuator by S. Yoon et al. is described in reference [9].

![Fig. 2. The fabricated piezo actuator.](image)

![Fig. 3. Basic working principle of the invented piezo actuator.](image)
Moving direction of the mobile element can be decided according to the shape of a pulse wave as shown in Fig. 4.

III. DESIGN OF LOCOMOTIVE MECHANISM

A. Locomotion Principle

Insect-like robots have been studied since they are capable of negotiating unstructured terrains such as gastrointestinal tracts in a human body[10,11,12]. Therefore, Dario et al. adopted a legged locomotive mechanism for the capsule endoscope[4]. However, it requires high power consumption to drive a robot since at least two actuators are needed to activate locomotive mechanism of the insect-like robot. Therefore, the embedded power supply in a microrobot for the capsule endoscope (11mm×28mm) is not suitable with the current state-of-the-art of actuators and batteries. In the viewpoint of fabrication, an insect mimicked robot is not easy to fabricate with conventional technology. In addition, assembling all components in the diameter and length of 11mm and 28mm is another high hurdle to realize an insect-like robot for the capsule endoscope. The above mentioned dimension is minimum requirement to pass through the zone between gastro-intestine and small intestine. Therefore, the proposed locomotive mechanism for capsule endoscopes mimics earthworm locomotion since it is easy to fabricate and to be swallowed since it has capsule shape. Moreover, it can be driven by one actuator.

The actuation module is allocated in the middle of the robot body to provide space for other components. The proposed robot consists of one actuation module and two separated robot bodys covered by insect-claw mimicked clammers. Figure 5 shows the locomotive principle of the capsule. To drive robot, frontal body slides more forward while clammers around the rear body hold contact surface. After the frontal body reaches to the maximum stroke, clammers around the frontal body hold contact surfaces. During the retraction of the linear actuator, therefore, the rear body moves forward. As this procedure is performed repeatedly, the robot can move forward. This concept, that imitates the locomotion of earthworm, enables the capsule to have the simple locomotive mechanism[13].

B. Clamping Device

For the temporary clamping of locomotion, clamping devices mimicked claws of an insect are fabricated as shown in Fig.6-(a). Type (A) is fabricated with the pitch depth of 1 mm, 14 mm outer diameter. Type (B) is fabricated with pitch depth of 2 mm, 13 mm for outer diameter. Both types of claws have slope of 45°. Type (C) is consisted of 8 sections on 1 mm by 14 mm area. Each saw-shaped claws in a section has 1 mm pitch and 45° slope. Each section is disposed with every 60° interval around the surface of the robot.

IV. FABRICATION AND EXPERIMENTAL SYSTEMS

A. Fabrication of the proposed robot

The prototype which is installed with the actuation modules using an impact-based piezo actuator is presented in Fig. 7. The prototype was made in the capsule type and made of acetylene. The outer diameter is set to 14 mm. The
robot body consists of a frontal and rear body. The length of frontal body comprised a mobile element is set to 15 mm and the rear body comprised an actuator module is set to 14 mm. The total length of the capsule under condition of retraction becomes 29.5 mm since it has 0.5 mm gap between two bodies. In stage of elongation stage, the total length of the robot is 41 mm. Therefore, the maximum stroke of once cycle is around 11 mm due to some clearance in assembly of components. The interior space except occupied by a mobile element and an actuation module remains for an integrating battery, RF module, and camera module. The weight of the prototype is minimized as 5.2 g considering integrations of other components. The theoretical moving speed is 3.92 mm/sec since the speed of the mobile element is 17.3 mm/sec and waiting time to drive the rear body is 2.15 sec.

The rear part of the robot is fixed to the base of an actuation module. The frontal part of the robot is connected to the mobile element with a snap ring to prevent loading the mass of the frontal part of the robot on the mobile element. For perfect combination between the robot body and clamping devices, groove-shaped claw is engraved around the micro robot body as shown in Fig. 7.

B. Experimental Systems

In order to control and to measure the displacement of the robot, a system is built as in Fig. 8. It comprises LabVIEW and a data acquisition board installed PC, piezo amplifier (**NF ELECTRONIC INSTRUMENTS**) to drive an actuator, vibrometer to measure displacement of the robot, and the robot itself. The saw shaped wave as in Fig. 4 is generated using piezo amplifier, that can generate up to 170V. Before feasibility test of the robot, the natural frequency of the proposed piezo actuator is found to maximize the generative force and amplitude of an actuator.

In order to measure the displacement of the robot, the vibrometer manufactured by Polytec with capability to measure range of 81.92 mm with resolution of 20 μm is utilized. For recording of the displacement to the PC, a data acquisition board of National Instrument Co. is used. For in-vitro test, we put small intestine on a test bed after dissection.

V. EXPERIMENTAL RESULTS

The proposed microrobot is tested under various environments for feasibility tests. As a representative material of slippery and flexible material, silicone covered with oil is utilized for quantitative evaluation. And it is compared to the result on dead porcine small intestine. In order to study the visco-elastic characteristic of dead porcine small intestine and clamping loss of a microrobot, the performance of locomotion is monitored according to the variation of locomotive strokes. In addition, displacement change according to the shapes of clamping devices disposed around the microrobot is investigated. In Fig. 9, theoretical results are compared with results on silicone and on the small intestine when an actuator is driven with ±85 V and 15 KHz. Based on the speed of the mobile element, the velocity of the robot is about 3.92 mm/s theoretically. However, the velocity on silicone reaches 3.34 mm/s. It is 15% less than the theoretical result. In case of the result on dead porcine small intestine, it was just 2.23 mm/s and 57% of theoretical velocity since sometimes the clamer does not work properly due to slips between the clamer and small intestine is deformed due to visco-elastic characteristic. The zone (a) in Fig. 9 means the initial stage before movement, the zone(b) is the elongation stage to move and the zone(c) designates the retraction stage. In the zone(b), the frontal body of the robot moves to the peak, however, the frontal body of the robot moves backward in the zone (c) and stabilized after the clamping force for the frontal body is equivalent to the force to draw the rear body of the robot. For results of Fig. 9, stroke length of one cycle is 11 mm and Type (A) of the clamping device is used.

According to and stage of locomotion under same operation conditions and environment that is used for results of Fig. 9, a video clip is captured and displayed in Fig. 10. It clearly shows the frontal body bounces back to draw the rear body at (c)-start retraction stage.
In order to investigate the loss of locomotion due to viscoelastic characteristic and imperfect clamping, velocity of the proposed microrobot is measured with the variation of stroke lengths (Fig. 11). In case of 5 mm of the stroke length, there is no advance since small intestine is deformed as much as the microrobot elongates. However, the microrobot starts overcoming deformation energy and moves after it has the stroke length of 6.5 mm. Therefore, we conclude that the critical stroke is around 5 mm.

In this paper, we developed an impact based piezoactuator that can obtain more than the stroke length of 11 mm. Then, locomotive mechanism for a capsule endoscope is constructed using invented piezo actuators. The microrobot combined locomotive mechanism with clamps mimicked claws of an insect is tested on various environments such as silicone and dead porcine small intestine. When the microrobot is equipped with the clamping device that has 1 mm of pitch depth and operated with 5 mm of the stroke length, the robot does not advance because the small intestine deforms as much as the robot moves. However, when the microrobot moves with more than stroke length of 5 mm, it overcomes resistance force due to the deformation of small intestine and starts moving. With the stroke length of 11 mm, we could achieve the velocity of 2.23mm/s. It is 57% efficiency compared to theoretical velocity. Based on those experiments, we find the deformation of small intestine highly influences the performance of locomotion. More detail analysis on viscoelastic characteristic is required to construct the more reliable microrobot that can locomote under in-vivo condition.

In order to study the influence of frictional force, the performance of the microrobot is also tested under various shapes of clamps. It does not significantly affect performance of the locomotion because the change of the friction difference between the rear and frontal body according to clamp’s shapes is minor. In order to realize the wireless capsule endoscope with locomotive mechanism, we need to integrate a micro processor with a piezo amp.
Battery, and RF communication module in the microrobot body. However, still commercialized piezo actuators need 100 V level input and then it requires a voltage amplifier circuit of large dimension. Therefore, more efforts to reduce input voltage to drive piezo actuator as well as to increase the power of a micro battery are required. In addition, the stroke length for locomotion under in-vivo condition should be optimized through measurement of material property and locomotion test since resistance force will increase with sharp shape due to covering whole body of the microrobot by digestive organ.

ACKNOWLEDGMENT

This work was supported by the 21st Century's Frontier R&D Projects, under the contract number MS-02-324-01, sponsored by the Ministry of Commerce, Industry, and Energy, Korea.

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