Design of a Bending Module for Assembling Reconfigurable Endoluminal Surgical System

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***Abstract*—Minimally invasive surgery has been welcomed in aging society because elderly people have lower tolerance to surgical stress and the better postoperative quality of life (QOL) enhance their active longevity. Capsule endoscopy is one of the advanced techniques for painless diagnosis; however, it's not capable of interventional use. This paper presents multi-capsule surgical system aiming to overcome intrinsic limitations of single-capsule endoscopy. In this system, tiny robotic modules assemble itself within the body, build up a structure and perform surgical tasks. After the tasks are completed, the robot disassembles itself into tiny parts or reconfigures its shape to travel through the GI tract. Being modular configuration the key feature of the system, a bending module was designed and a prototype actuated by a micro brushless motor was fabricated. In addition, a motor control board was developed for the motor, which is small enough to fit in an ingestible capsule. Moreover, the overall control strategy and motor driving methods are discussed.**

I. INTRODUCTION

MINIMALLY invasive surgery has been widely accepted because of the advantages such as less trauma, less postoperative pain, faster recovery and shortened hospital stay. Especially in aging societies, these features become more welcomed because elderly people have lower tolerance to surgical stress. In addition, reduced medical expenses and better postoperative quality of life (QOL) benefit the societies. Capsule endoscopy [1] is one example of the advanced techniques for diagnosis and it has been performed worldwide with successful outcomes. This painless technique will promote frequent diagnosis to screen early cancer of the gastrointestinal (GI) tract; however, the current capsule endoscopy is only for diagnosis and a conventional surgical intervention is required afterward. In this paper, we propose multi-capsule surgical system where the capsules assemble and configure themselves and then cooperate to perform a diagnoses and interventions in the GI tract.

This paper is organized as follows. Section II describes the concept of the surgical system, target pathologies and proposed procedures. Section III reports the design of a bending module for robotic configurations and Section IV illustrates control strategy of the total system. Section V details the realization of the robotic control. Finally, the results and future work are discussed in Section VI.

II. ASSEMBLING RECONFIGURABLE ENDOLUMINAL SURGICAL SYSTEM

A. Concept of the System

A reconfigurable modular robotic system is proposed to perform screenings and interventions of the GI tract [2]. The modular design was chosen to overcome intrinsic limitations of current capsule endoscopy and allow the delivery of more components inside the body. In this system, tiny robotic modules are ingested and assembled by themselves in the stomach to configure themselves into complex structures. The robotic modules consist of different elements for structural functions, power supply, communication, diagnosis and intervention. The modules for diagnosis are equipped with a camera or a biochemical sensor while the interventional modules are with surgical tools such as forceps. The robotic configurations are planned by using preoperative diagnostic data, and then surgical tasks are performed via wireless bidirectional communication with an external console operated by surgeons. The necessary modules can be selected *in-situ* based on the diagnostic result and progress of the operation and added by ingesting extra capsules. After the surgical tasks are completed, the robot disassembles itself into tiny parts or reconfigures itself to another shape that is adequate for travelling through the GI tract.

B. Clinical Target

The possible target pathologies for the abovementioned surgical robot are the esophagus, the stomach, the small intestine and the colon. The detailed analysis of the GI tract anatomy was performed in order to identify the pathological syndrome which can benefit from the reconfigurable surgical robot. In the conclusion, the colon appears to have the largest potential of clinical impact, while a surgical robot that can reach the small intestine has the greatest novelty. Stomach seems to be the easiest part of the GI tract for the robotic system. Considering the implementation of the concept, development of a reconfigurable robot that assembles in the stomach will be a good proof.

Stomach cancer is the second leading cause of cancer death worldwide and accounts for almost one million deaths per year [3]. Because a delayed diagnosis may lead to the poor prognosis, advanced diagnostic and interventional techniques will be helpful for treating early stomach cancer. Moreover, such advanced techniques will benefit aging society: for example, the number of Japanese elderly patients with stomach cancer has been increasing even though the incidence of stomach cancer is decreasing,

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and less invasive surgery is recommended for the elderly patients [4].

The location of the stomach cancer is known to affect 5-year survival rate [5], which shows a worse outcome of the cancer in the upper side of the stomach. The current endoscopic capsules are not capable of reaching the district, but the modular surgical robot can configure itself to perform intervention at the site. For this reason, the target location is defined as the upper side of the stomach called the *Fundus* and the *Cardia*: the fundus is rounded upper end of the stomach and the cardia is located at the gastroesophageal junction.

C. Clinical Constraints

The stomach is basically an elastic bag having a volume of 50 ml when it's empty and can distend to a volume of 1400 ml when it's full. The gastric wall is 3-5 mm thick and its inner surface is characterized by the gastric folds. The stomach can be inflated with either air or liquid as a surgical procedure to expose the internal surface.

A capsule measuring 8 mm in diameter and 16 mm in length can be swallowed by 80-90 % of people and it can pass through the whole GI tract. Meanwhile, the endoscopic capsules on the market are 11 mm in diameter and 26 mm in length [1], which can be also acceptable as an ingestible capsule.

D. Proposed Procedures

Procedures using the surgical robotic system are proposed in Fig. 1. At the very beginning of the whole processes, the surgeon asks the patient to drink a certain liquid to flood the stomach. This liquid distends the stomach and also acts as a medium for the tiny robotic modules to form a rigid structure before intervention begins (Fig.1 (b)). The liquid provides large space to allow 2-dimensional assembly of 10-15 floatable modules on its surface of 100 mm in diameter (Fig.1 (c)). The swallowed modules finish self-assembling before the liquid naturally goes away from the stomach (Fig.1 (d)). The possibility of magnetic self-assembly using permanent magnets has been demonstrated [6] and the adequate choice of the magnets are being investigated to maximize the possibility of self-assembly. Soon after the liquid goes away, surgeon may enter to interventional stage which is performed from a control panel outside the human body (Fig.1 (e)). The robot configures itself as planned based on preoperative diagnosis to perform detailed examination and intervention. After the surgical tasks are completed, the robot reconfigures itself to a snake-like shape to pass through the pyloric sphincter (Fig.1 (f)), or disassembles itself into tiny parts (Fig.1 (g)).

To ensure a total comfortable to the patient, the whole control system should be performed wireless. This will ensure a painless treatment to elderly and even minimal psychological discomfort.

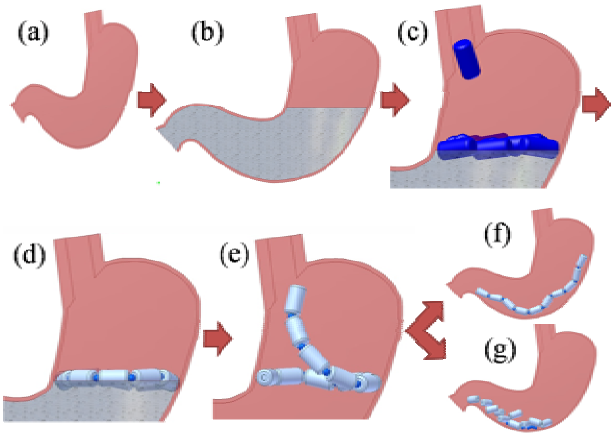

Fig. 1 Proposed Procedures: (a) empty stomach, (b) stomach filled with a liquid, (c) ingested capsules floating on the liquid surface, (d) assembled modules, (e) robotic configuration and diagnosis/intervention, (f) reconfiguration to a snake-like shape and (g)disassembled modules

III. MECHANICAL DESIGN OF A BENDING MODULE

A. Design of a Bending Module

From the characteristic viewpoint, a module used in the proposed system can be categorized as homogeneous or heterogeneous one. There are either active or passive modules regarding their functionalities and physical motions. An active module moves during assembling process, reconfiguring, and also during intervention. Hence an active motional mechanism, control board, and power are deployed within this module. Bending module is one example of the active module. On the other hand, passive modules such as extra-high capacity battery module, camera and light module and surgical tools don't have motional mechanism. All of passive modules just need to communicate and cooperate during intervention.

A possible strategy for the modular design is to use homogeneous active modules for structural construction as illustrated in Fig.1 (e). In this strategy, the modules are assembled without considering a sequential conjunction and then the specified control is allocated to each module for building up the desired configuration.

Fig.2 shows the design of the homogeneous bending module. The modules are identical and docked using a spherical magnet to have 2.D.O.F bending of 30° in any direction. Each module includes a Li-Po battery (LP2-FR, Plantraco Ltd., Canada), a motor measuring 2.4 mm in diameter (SBL04-0829PG337 from Namiki Precision Jewel Co., Ltd., Japan) and a custom-made motor control board which is introduced in the following sections. The module is 13 mm in diameter and 23 mm in height, which is almost same size as the endoscopic capsules on the market.

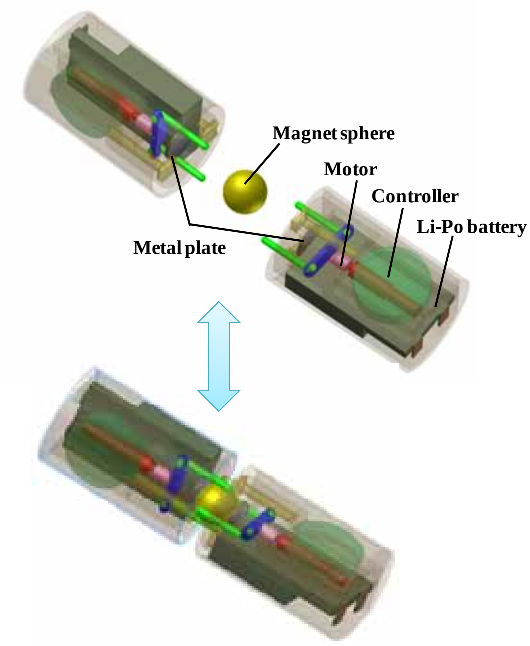

Fig. 2 Design of the bending module

B. *Bending Mechanism*

The design of the 1.D.O.F bending mechanism is illustrated in Fig.3. The joint bends around the center of O_1, which is the center of the spherical magnet. Two bars are kept parallel and moved translationally with distal ends touched on the surface of the other module. The shafts at proximal ends slide in the holes of the part that rotates around O_2. The gap between the modules at 0° bending degree is given by:

$$k = \sqrt{D_1^{\ 2} - D_2^{\ 2}} \qquad (1)$$

where D_1 is the diameter of the spherical magnet and D_2 is the diameter of the hole whose edge fits the sphere. The bar has the length of l and having semispherical shape in radius of r at its end. Therefore, the maximum distance between the modular surface and the proximal end is described as:

$$d = l + r - k \qquad (2)$$

The distance between O_2 and the proximal end of the bar is given by:

$$b = \frac{a}{\cos\theta} \qquad (3)$$

where a is the distance between O_2 and the central axis of the bar. The amount of translational movement x is given by:

$$x(\theta) = \frac{k}{2}\cdot(1-\cos\theta) + (a - \frac{k}{2}\cdot\sin\theta)\cdot\tan\theta - r\cdot(1-\frac{1}{\cos\theta}) \qquad (4)$$

where θ is bending angle of the joint. The distance between O_2 and the modular surface is given by:

$$c = d - b\cdot\sin(\theta) + x(\theta) \qquad (5)$$

The maximum bending angle is designed as 30° and then the bending angle θ is described as:

$$-\frac{1}{6}\pi \le \theta \le \frac{1}{6}\pi \qquad (6)$$

Two identical bending mechanisms need to be docked to achieve 2 D.O.F of bending that share the center of bending (O_1). To keep the all distal ends of the four bars touched on the modular surfaces, the concave part is implemented as shown in Fig.4. The curvature radius of the concave part is given by:

$$R_1 = \frac{k}{2} \qquad (7)$$

For the first prototype, the parameters of D_1, D_2, l, r and a are given and other parameters are calculated as listed in Table I. The maximum of b and the minimum of c give the dimension of the holes in which the end of the bars slide.

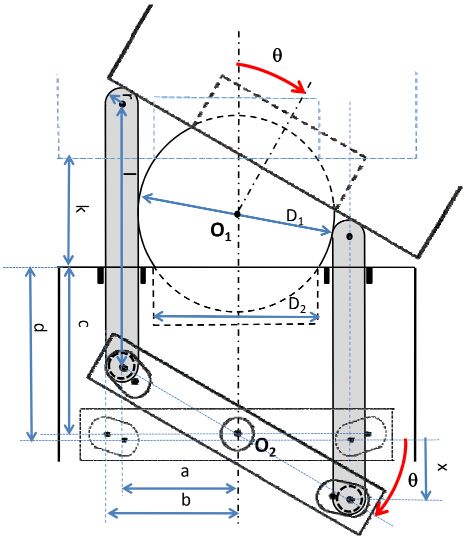

Fig. 3 Side view of the bending joint showing all design parameters for 1.D.O.F bending

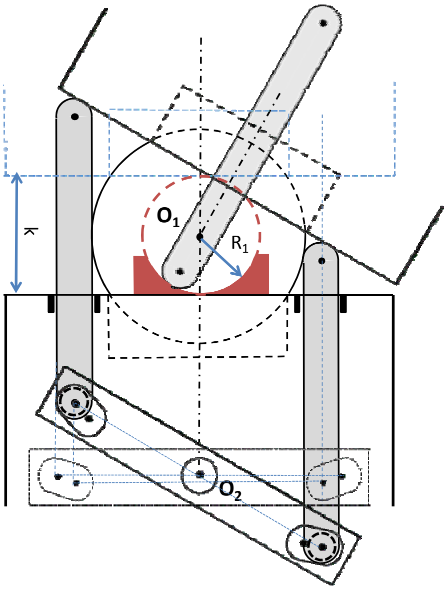

Fig.4 Side view of the bending joint showing the concave part for 2.D.O.F bending

Table I Parameters for the bending mechanism

Given parameters		Calculated parameters	
D_1 [mm]	6	k [mm]	3.32
D_2 [mm]	5	d [mm]	5.18
l [mm]	8	$b_{\max}$ [mm]	4.04
r [mm]	0.5	$c_{\min}$ [mm]	5.00
a [mm]	3.5	R_1 [mm]	1.66

C. Prototyping

Fig.5 shows the fabricated prototypes of the bending module. The bars and concave parts are made of conductive and nonmagnetic material to be possibly used for the communication between the modules. The spherical magnet is made of neodymium-iron-boron (NdFeB), having enough force to dock the modules. The experiments to evaluate the torque and the positioning accuracy are planned after the implementation of the motor control described in Section V.

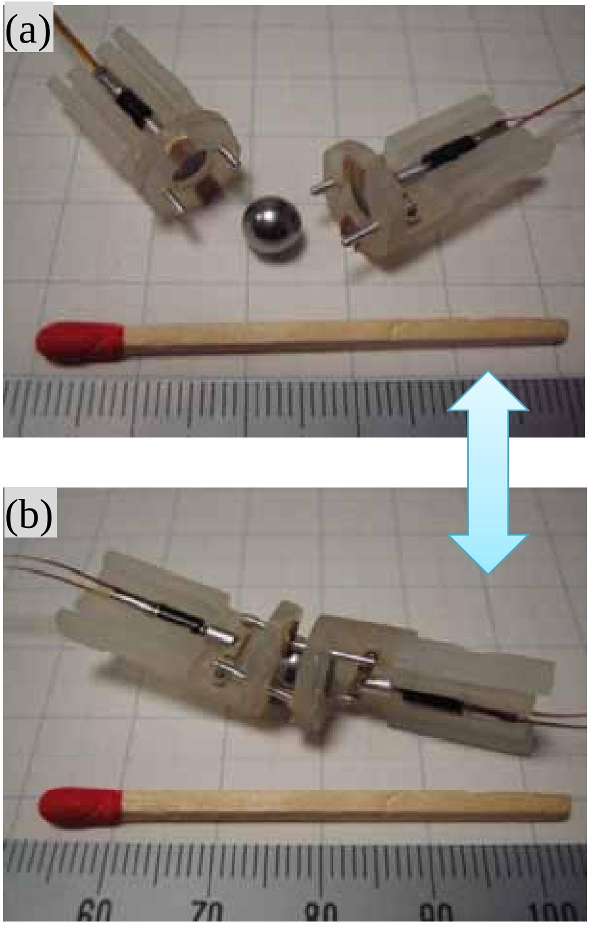

Fig. 5 Prototypes of the bending module: (a) undocked modules (b)docked modules

IV. Control System Overview

Despite the characteristic and the physical motion of each module, the same control board lies inside the modules. This in-house developed control board has a programmable microcontroller which required to be programmed depends on the type of peripherals attached to it or its function. For example, a bending module has actuators as its peripherals which are brushless micro motors (SBL02-06H1PG337). Other possible modules are a central control module and a power module. The central control module is in charges of internal communication between modules, while the power module supplies extra long lasting power and predicts the overall power consumption during intervention. All of them use the same board but different algorithm is loaded to the program memory of microcontroller.

Control strategies are different during assembling, reconfiguring, interventional stage, and disassembling process. In assembling process, active homogeneous modules such as the bending modules are self-assembled and locations of the module are recognized by internal communication to allocate different roles. Once active modules are assembled and its structure is recognized, these modules configure themselves to find a passive module such as camera and light module. Attaching a camera and light module is proposed as the next sequence here since vision could be useful as a visual feedback to operators to locate where the rest of the modules are and reach a proper configuration.

Reconfiguring process is needed when the functional modules are not in the proper position: for example, the configuration should be changed when the field-of-view of the camera module is not adequate to deliver a good visual feedback during intervention. Besides, the reconfiguration is necessary when a certain task needs to be addressed using a different structure of the robot: for example, a snake like structure is best during intervention at the lower end of the stomach. This process is basically as simple as detaching-reattaching from one end to another end until the targeted configuration or structure is reached.

During interventional stage, the robotic structure is accessible through wireless communication. As some modules receive commands from the control panel operated by the surgeon, it redirects the commands to dedicated module by internal wiring between modules.

After the intervention is done, the disassembling process is launched. Instant detaching mechanism is needed to be implemented for undocking the modules to bring the structure into total collapse. Each separated module will go through the rest of the GI tract and excreted as normal digestive process.

V. Realization of Control System

The realization of the control system started by developing the board with commercially available components on the market. The smallest brushless motor from Namiki Precision Jewel Co., Ltd. was selected as an actuator for the bending mechanism, but unfortunately the dedicated driver board for this motor comes in inappropriate size to be put inside the ingestible module. Considering the space constraint inside the capsule, a new control board was developed, optimized, and tested. Fig.6 shows the board having a round shape with 10.8 mm in diameter and 2.3 mm thickness, which fits in the capsular module. This board is the smallest one ever built using commercially available components as light as 0.27 grams in weight and using three wire to communicate to external computer by using serial communication RS232 protocol.

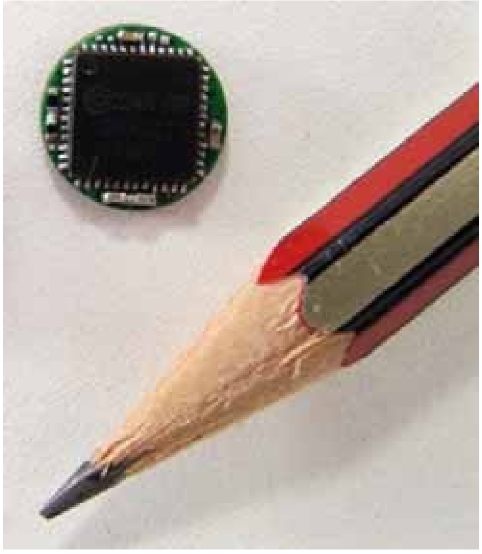

Fig. 6 Control board

A. Specifications of the Motor Control Board

The board is built using Silabs C8051F311 microcontroller as the main controller. In order to deliver high and low commutation logic to the three coil phases of brushless motor, six pieces of IRF7509 MOSFET that consists of P and N-channel are assembled. Inside one IRF7509, P and N-channel are constructed in series and are connected to each motor's phase. BEMF signals are obtained by connecting each motor's phase directly to analog inputs of microcontroller without any filter network lies between them.

Instead of using P and N-channel configuration, two N-channel MOSFETs IRFZ44 in series are used in [7], which is considered as a better configuration in term of its lower conductive resistance value. It is true that N-channel has 10 times lower internal conductive resistance than P-channel which implies in better efficiency since the voltage drop remains low. However referring to the high logic state on every port of Silabs C8051F3xx during reset [8], two N-channel combinations might lead to an excessive electric current withdrawn from the battery on every system reset. Even though this period is short, this is not exactly a safe configuration since it might lead to circuit damage, overheating problem, and explosion. Therefore P and N-channel configuration is preferred in this paper. The efficiency of this configuration is acceptable and the voltage drop doesn't significantly affect the performance of kinematic mechanism.

B. Motor Driving Method

The driving methods have been studied on how to start the motor [9, 10], to sense and manipulate BEMF [7, 9, 10], and to control the speed using Pulse Width Modulation (PWM) [9, 10]. In line with the idea of board miniaturization using fewer components, BEMF is acquired and measured relatively to the ground instead of to the neutral phase of the brushless motor. Mathematical calculations have been performed in order to avoid using this neutral phase as reference point [9, 10]. One of the methods given by [9] is using a virtual neutral point by combining three external resistors in star configuration. Yet [10] proposed to save three reference values at the very beginning in the initialization stage when the controller is turned on.

The developed board was tested to control one brushless motor and the performance was quite satisfying either for 4 mm SBL04 series and 2.4 mm SBL02 series of the brushless motors from Namiki Precision Jewel Co., Ltd. In the near future, a wireless communication feature will be embedded within the chip and its performance will be tested.

Energy consumption measurement need to be performed as soon as the complete system is ready and loaded with the latest optimized code. The latest algorithm was able to sense BEMF for every 100 µs while maintaining the speed above 90% of normal speed driven by dedicated board of the micro brushless motor.

IV. DISCUSSION AND CONCLUSION

In this paper, the assembling reconfigurable endoluminal robotic system has been introduced and its first target has been defined as a diagnosis and intervention of early stomach cancer located in the upper side of the stomach. As the first step, a bending module was designed as an example of the active modules to configure the structure and a prototype is fabricated. To make the capsule as small as ingestible, a new motor control board was developed and its driving method was investigated. The results show that the performance of the bending mechanism and the motor controller are satisfying and they are ready to be integrated.

The future work includes the miniaturization of the components such as actuators, sensors and battery, which is important because the smaller capsule is preferable especially for elderly patients as well as children. Since the microactuators have been developed as shown in [11, 12], the implementation of the actuators in the modules should be investigated. Wireless communication that has already realized painless capsule endoscopy should be implemented to the system as well, considering that the communication should be bidirectional in this system and the time delay due to the teleportation is crucial. The motion planning and control strategy has been addressed in the researches for the modular robots as reviewed in [13, 14], thus these algorithms will be integrated with the preoperative planning system considering both clinical and kinematical constraints.

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