# Helical Motion and 2D Locomotion of Magnetic Capsule Endoscope using Precessional and Gradient Magnetic Field

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Abstract— Recently, a conventional capsule endoscope was developed and has been used for a diagnosis to make up for the limitations of conventional flexible endoscopy. However, the capsule endoscope has also some limitations and low diagnostic effectiveness because of its passive movement through the peristaltic motion of digestive organs. To overcome these problems, there are several researches about active mobility of capsule endoscope. In this paper, we proposed helical motion and locomotion mechanism for magnetic capsule endoscope using the electromagnetic actuation (EMA) system. Through the combination of the magnetization direction of the capsule endoscope prototype and the precessional magnetic field which can be generated by 3-pairs of Helmholtz coils, the capsule endoscope prototype can show a precessional motion. In addition, the capsule endoscope prototype can move toward an aligned direction by a gradient magnetic field of Maxwell coils. First, we fabricated a capsule endoscope prototype with a desired magnetization direction and verified its scanning function through the helical motion of the capsule endoscope prototype in mock-up of tubular digestive organs. Second, the capsule endoscope prototype also has a propulsion force to the perpendicular direction of axial vector when it track the helical path, and this force make the capsule endoscope prototype to attach the inner wall of tubular environment. Finally, through the planar locomotion test in stomach phantom, we have verified the feasibility of the capsule endoscope using an electromagnetic actuation system.

## I. INTRODUCTION

In recent days, pathogenesis of digestive organs have increasing by inclement dietary life and stresses in modern society. In addition, in order to prevent and remedy for these diseases, a conventional flexible endoscopy is widely used.

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However, in case of the flexible endoscopy, there are some burdens of pains and side effects of anesthesia to patients. Especially, elderly patients might have severe difficulty in the flexible endoscopic procedure [1, 2].

To overcome the limitation of the flexible endoscopy, a capsule endoscope was developed and used. As an image collector and transmitter, the capsule endoscope with a pill shape can be swallowed through the mouth and can move in digestive organs by the peristalsis motions of intestines [3, 4]. Simultaneously, the capsule endoscope can obtain images of the digestive organ's surface and transmit the captured images to the outside data receiving unit. As a result, the patients can be comfortable during the diagnosis procedure. However, diagnosticians who check the whole images have to spend a lot of time to the diagnosis. When the diagnostic images are insufficient, it is necessary to have an additional procedure using a conventional flexible endoscope.

Because these limitations come from the passive motility of the capsule endoscope [1, 2, 5], a capsule endoscope should have a locomotive function. There are many researches on the locomotion of capsule endoscopes in the world wide. P. Dario *et al.*[6] and B. Kim *et al.*[7] proposed crawling mechanisms in tubular environment for capsule endoscope, which have several legs or paddles at the side of the capsule body. The meso-scale legs and paddles are actuated by motors and gears. However, these mechanisms should overcome the problem of battery and size, and can make severe scratches on the intestinal surface. S. Martel *et al.* suggested a locomotive mechanism using 3-axis Helmholtz coils and the capsule



Figure 1. Schematic diagram of proposed EMA system for active capsule endoscopy

endoscope, which has helical thread at outside of capsule body[8]. By a rotating magnetic field using 3-axis Helmholtz coils, the capsule endoscope can rotate and move forward and backward. However, when the tread of capsule endoscope is not attached on the inner wall of digestive organs, the capsule cannot move. E. Morita *et al.* proposed a capsule endoscope which has the shape of a fish [9]. Through a vibrating magnetic field, the capsule endoscope with a caudal fin can make an undulatory motion which can generate a forward motility of the capsule endoscope. However, it is hard for the swimming capsule endoscope to gather stable and clear images of intestinal organs.

In this paper, we proposed the electromagnetic actuation system, which can make a planar locomotion and a helical motion for capsule endoscope. The proposed EMA system consists of 3-axis Helmholtz coils and 1-axis Maxwell coils and could rotate and move the capsule endoscope prototype. Finally, through several experiments, we could verify the mobility of the capsule endoscope.

## II. ELECTROMAGNETICS AND LOCOMOTION THEORY

#### A. Basic Electromagnetics

Generally, magnetic body placed in magnetic field can be aligned to the desired direction and propelled to the desired position [10]. For alignment of the magnetic body, the torque is generated by a uniform magnetic field, and can be described in Eq. (1):

$$\boldsymbol{\tau} = \boldsymbol{V} \mathbf{M} \times \mathbf{B} \tag{1}$$

where  $\tau$  means torque, and V, M, B denote volume and





Figure 2. Schematic diagram of magnetic capsule endoscope prototype (a) Desired magnetization angle using radially and axially magnetized magnet, (b) Assembly diagram of capsule endoscope prototype

magnetization of the magnetic body and electromagnetic field is generated by Helmholtz coils. In addition, the propulsion force of a magnetic body is generated by a gradient magnetic field, and can fallow as shown in Eq. (2):

$$\mathbf{F} = V(\mathbf{M} \cdot \nabla)\mathbf{B} \tag{2}$$

where **F** and  $\nabla$  denote the propulsion force of magnetic body and the gradient symbol.

This paper proposes the locomotion of the capsule endoscope with a magnetic body through a magnetic field control. To realize the motion of the capsule endoscope, the proposed EMA system consists of 3-pairs of mutually orthogonal Helmholtz coils and 1-pair of Maxwell coils, which is placed in *z*-axis, as shown in Fig.1.

In the Helmholtz coils, which are two parallel solenoids, the distance between two solenoids is equal to its radius. In addition, when the coil currents with same direction and amplitude are applied to two coils of Helmholtz coils, the Helmholtz coils can generate a uniform magnetic field in the region of interest (ROI). The generated uniform magnetic field can align the magnetic body, which is placed in ROI, to



Figure 3. Modelling of (a) Precessional motion and (b) Planar locomotion of capsule endoscope with proposed EMA system



Figure 4. Schematic diagram of helical motion of magnetic capsuleendoscope in tubular environment with proposed EMA system

the axial direction of the solenoid. Through this principle, the equation of magnetic field, which is aligned along x-axis can be described in Eq. (3) and (4)

$$\mathbf{H}_h = [\mathbf{d}_h \ \mathbf{0} \ \mathbf{0}]^T \tag{3}$$

$$d_h = 0.7155 \, i_h \times n_h \,/\, r_h \tag{4}$$

where  $i_h$ ,  $n_h$ , and  $r_h$  denote the applied current, coil turns and radius of the Helmholtz coils.

Similar with Helmholtz coils, Maxwell coils consist of two solenoids which have the relation that distance of the coils is same with  $\sqrt{3}$  times the coil radius. The current direction applied to two coils is reverse, and the amplitude is equal each to each. By using this relation, the magnetic body placed in the ROI is propelled to the desired direction, and the propulsion force is expressed as Eq. (2). The Maxwell coil of the proposed system can be explained as shown in Eq. (5) and (6)

$$\mathbf{H}_{m} = \begin{bmatrix} -0.5g_{m}x & -0.5g_{m}y & g_{m}z \end{bmatrix}^{T}$$

$$\tag{5}$$

$$g_m = 0.6413 i_m \times n_m / r_m^2 \tag{6}$$

where  $i_m$ ,  $n_m$  and  $r_m$  are the applied current, coil turns and radius of the Maxwell coils [11, 12].

As a result, using the Helmholtz coils and the Maxwell coils, the magnet body can be aligned and propelled in the ROI to the desired direction. Through Maxwell coils installed along *z*-axis, we can realize ascending and descending motion of the capsule endoscope and generate the propulsion force on 2D plane.

#### B. Helical Motion and Planar Locomotion

As shown in Fig. 2, when the capsule endoscope with the imaging unit has the desired magnetization direction ( $\delta$ ) from the axial direction, we can generate the precessional motion of the capsule endoscope through the revolution of a uniform

magnetic field vector. The proposed EMA with 3-pairs of Helmholtz coils, can generate the 3D alignment magnetic field vector (**B**), which same with the magnetization vector (**M**) of capsule endoscope. When the magnetic field vector **B** can be rotated about the vector **V**, which is an axial direction of the capsule endoscope, the capsule endoscope can have a rotational motion. The equation of the rotational magnetic field ( $\mathbf{B}_{rot.}$ ) for the alignment vector is presented as in Fig. 3(a) and can be expressed as Eq. (7):

$$\mathbf{B}_{rot.} = M \cos \delta \left[ \cos\varphi \cos\theta \ \cos\varphi \sin\theta \ \sin\varphi \right]^{T} + M \sin \delta \left[ -\sin\varphi \cos\theta \cos 2\pi\omega t + \sin\theta \sin 2\pi\omega t \right. \left. -\sin\varphi \sin\theta \cos 2\pi\omega t - \cos\theta \sin 2\pi\omega t \right]^{T} \left. \cos\varphi \cos 2\pi\omega t \right]^{T}$$
(7)

where **n**,  $\theta$ ,  $\varphi$  and  $\omega$  are the normal vector of **V**, the angle between **V**-**n** plane with *x*-axis, the angle between **V** with *x*-*y* plane and angular velocity.

Furthermore, through the gradient magnetic field using the Maxwell coils along *z*-axis, the capsule endoscope can move upward or downward. And, the capsule endoscope can move toward the radial direction of the rotational vector ( $\mathbf{n}$ ), caused by the dependent gradient magnetic field of *z*-axis Maxwell coils. This radial force makes the capsule endoscope to move with helical motion in tubular environment, as shown in Fig. 4. In tubular digestive organs, the helical motion, which pushes the capsule endoscope against the inner wall of the digestive organs, can assist the accurate diagnosis of the capsule endoscope.

In addition, 2D planar locomotion is also available by the proposed EMA system. As shown in Fig. 3(b), the aligned vector of the capsule endoscope could be generated on 2D plane by x-, y-axis Helmholtz coils. Using  $-0.5g_mx$  and  $-0.5g_my$ , which are dependent gradient of z-axis Maxwell coils, the propulsion force to the aligned direction can be generated for the planar driving motion of the capsule endoscope prototype in 2D planar surface.



Figure 5. Schematic diagram of experimental setup

#### III. EXPERIMENTS

## A. Experimental Setup

Fig. 5 shows the experimental setup of the active capsule endoscope system. For the generation of magnetic field using EMA system, the coils currents were supplied from power supplies (MX15 (2EA) & 3001iX (2EA), California Instruments), which are controlled by joystick controller (Extream 3D Pro, Logitec) with LabVIEW software (National Instruments). To observe the motion of capsule endoscope prototype, a camera (600D, Canon) was placed at side and top of EMA system. The structure of EMA System was fabricated by aluminum for the emission of the heat from the coils. Table. 1 shows the specification of the manufactured EMA system.

TABLE I. SPECIFICATION OF EMA SYSTEM

	HC-x	НС-у	HC-z	HC-z
r (mm)	280	238	170	85
turns	550	432	300	290

The capsule endoscope prototype was fabricated by a resin using the rapid prototype (RP) process, as shown Fig. 2(b). The size of the capsule endoscope prototype is about  $\phi$ 8×18mm. In the capsule endoscope prototype, the axially (1EA) and radially (2EA) magnetized cylindrical permanent magnets (NdFeB) were inserted. The size of the assembled magnet is  $\phi$  2×9mm and the magnetization angle ( $\delta$ ) is about 22 deg. from the longitudinal axis. In addition, we assumed that a small sized camera can be installed on the side wall of the capsule endoscope prototype. This camera can shows the inner wall of intestine, while it move forward and rotate in inside of tubular digestive organs.



Figure 6. Frequency reseponse of HC-*x* and HC-*y* 



Figure 7. Movement of capsule endoscope prototype in embossed glass tube (a) Ascending/ descending (b) Target searching with helical motion

# B. Helical Motion of Capsule Endoscope Prototype with Side Camera

In order to prove the applicability of the proposed system, we tested the locomotion and helical motion tests of the capsule endoscopy in the embossed glass tube. The diameter of the glass tube in the experiment is  $20 \sim 30$ mm. The target position was marked as red dots and the glass tube was filled with silicon oil (50cSt) for damping. Fig. 7(a) shows the locomotion of the capsule endoscopy along the *z*-axis. The capsule endoscope prototype was aligned the *z*-axis and executed up and down motions against a gravitational force through the controlled current of the Maxwell coils.

In order to rotate the capsule endoscope, the proposed system used two Helmholtz coils. We can estimate the precessional motion of the capsule endoscope as the rotation frequency increase, through the bode plot of two Helmholtz coils. Fig. 6 shows the frequency response(magnitude and phase) of the two Helmholtz coils, which were measured by RLC meter (HIOIKI 3522-50). Two Helmholtz coils can generate a sufficient response of precessional magnetic field until 9 Hz. Therefore, we expected that the capsule endoscope can be rotated by the proposed EMA system in the frequency range.

Fig. 7(b) shows the target tracking of the capsule endoscope prototype with helical motion. The side mark of capsule endoscope prototype, which means the camera, can point the target on inner wall of glass tube, sequentially. By the controlling the rotation angle and the position of capsule endoscope prototype, the side view point was directed to the desired target. By the combination of these motions, the capsule endoscopy with the side camera can scan and move the inner wall of tubular digestive tract phantom. Also, as we described before, the capsule endoscope prototype shows that it attach the inner wall of intestine phantom, while it move helically. This motion make the endoscopy to more precisely, in aspect of diagnosis for lesion on inner wall of intestine.

## C. 2D Planar Locomotion using a Stomach Mock-up

In order to verify the 2D planar locomotion of the proposed capsule endoscopy system, we adopted a stomach mock-up, which was fabricated by resin rapid prototype (RP). The stomach mock-up has the size of  $100 \times 145$ mm and was filled with water. As shown in Fig. 8, the capsule endoscope prototype could be steered and moved in the stomach mock-up. When we assumed that the camera unit of the capsule endoscope was installed at the front of the capsule endoscope using the captured images. Because the previous capsule endoscope is drifting in stomach, it is hard to collect the images of every nook and cranny. However, if possible to control the position and direction of capsule endoscope, as shown in Fig. 8, the endoscopy of stomach can become better.



Figure 8. 2D planar locomotion of capsule endoscope prototype in stomach mock-up  $(a \sim j)$ 

## IV. CONCLUSIONS

In this paper, we proposed the capsule endoscope system using EMA system. Through the helical motion and 2D planar locomotion, the feasibility of the capsule endoscope was verified. The proposed EMA system consists of 3-pairs of orthogonal Helmholtz coils and 1-pair of Maxwell coils (z-axis). Through the control of the magnetic field from the EMA system, the capsule endoscope can be positioned in 3D space. For the rotation motion of capsule endoscope, we evaluate the frequency response, and the confirm the stable range for rotation and precesseion. To verify the feasibility of capsule endoscope, we demonstrated a helical motion of the capsule endoscope prototype with desired magnetization direction in a glass tube phantom, which is mimicked the tubular digestive organs. In addition, through 2D planar locomotion of the capsule endoscope in the stomach mock-up, the feasibility of the magnetic capsule endoscopy was verified. Consequently, the results from this study will be used as the fundamental technology in the development of the locomotive capsule endoscope for diagnostic medical devices.

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