Development of an External Electromagnetic Actuation System to Enable Unrestrained Maneuverability for an Endoscopic Capsule

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Abstract— For digestive organs diagnosis, wireless capsule endoscope was developed as innovative solutions into overcoming limitations of conventional flexible endoscope such as uncomfortable procedures, pains and side effects of anaesthetic drug. Several actuation mechanisms have been studied to realize the wireless capsule endoscope with active locomotion, various motions of the capsule endoscope could not be achieved because of insufficient degree of freedom and forces. This paper presents a novel Electromagnetic Actuation (EMA) system which can maneuver endoscopic capsule unrestrainedly. The magnetic force can be controlled independently to push capsule moving without changing its orientation. The proposed system composed of eight stationary electromagnets controlled separately for producing dynamic magnetic field and gradient field in region-of-interest (ROI). The generated magnetic field and gradient field of proposed system is higher than that of our previous system. The proposed unrestrained motions are demonstrated through feasibility test.

I. INTRODUCTION

Wireless capsule endoscope (WCE) is becoming an alternative for gastrointestinal (GI) tract applications such as diagnosis, biopsy and drug delivery [1]-[6]. Passive movement, however, is the big drawback of the first-generation wireless capsule endoscope and its working area is limited in small bowel [7]. Because there is no locomotion part, the WCE is moved passively in human body by peristalsis motions of digestive organs. Therefore, in large volume organ as stomach and folding structure one as colon, the conventional capsule cannot perform visualization as clinician's desired. As the next generation of capsule endoscope (CE), active locomotion wireless capsule endoscope actuated magnetically is an upgraded version to fill the gap of the former. By adding permanent magnets to capsule body, one can control the capsule actively GI tract by external magnetic field system. The magnetic actuation systems can be classified into three groups corresponding to

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J.-O. Park and C.-S. Kim are with School of Mechanical Engineering, Chonnam National University, Gwangju, 61186, Korea (corresponding author phone: +82-62-530-5260; e-mail: jop@jnu.ac.kr; ckim@jnu.ac.kr). control strategy. The first group controls capsule by the rotational and oscillating magnetic field. K. I. Arai et al. [8], H. Takizawa et al. [9] and Jake J. Abbott [10] introduced a CE including a permanent magnet inside with spiral structure body moving by thruster force. It is explicit that this control strategy depends on the spiral structure of capsule and cannot be applied for stomach and folding positions due to lack of interaction, degree of freedom and pushing force. The second group utilizes static magnetic field to pull CE [11]-[16]. The system with a permanent magnet attached to end-effector of robot arm to navigate the capsule in the GI tract. These systems have strong magnetic field from massive permanent magnet that can control CE overpass obstacles, even U-shape folds. However, they are unable to control gradient field precisely, capsule is attracted toward the permanent magnet uncontrollably. Moreover, it has the limitation of response time and complex maneuvers. The third group includes systems composed of electromagnetic coils. R. Kuth et al. and J. Rey et al. presented a magnetic guided capsule endoscope (MGCE) system to control the capsule in the human stomach [17]. The system consisting of 12 stationary electromagnetic coils is capable of controlling capsule in 5 degree-of-freedom in which 2-DOF is for rotation and 3-DOF is to propel the capsule along desired direction. S. Park et al. presented an active locomotion intestinal capsule endoscope (ALICE) system for 3-dimensional locomotion of wireless capsule endoscope in digestive organs [18]. The system consists of 10 coils controlled by pairs to generate the uniform and gradient magnetic field separately. MCGE and ALICE is more relevant to our system; however, they use many coils. In addition,



Figure 1. The proposed EMA system prototype (a) Endoscopic capsule (b) control computer (c) Electromagnetic Actuation system (d) Power suppliers.



Figure 2. Systematic coil configuration of proposed system. 1 and 2 are Helmholtz pair coils; 3, 4, 5, 6 are rectangular coils; 7 and 8 are Maxwell pair coils. ROI is $60 \times 60 \times 60$ mm³ at center of system.

Coils	1, 2	3, 4, 5, 6	7, 8
Radius (mm)	195	n/a	100
Width x Length (mm)	n/a	156 x 337	n/a
Distance (mm)	195	200	173
Number of turn	710	600	660

TABLE I. TECHNICAL SPECIFICATION OF THE PROPOSED SYSTEM

MCGE and ALICE are not able to perform unrestrained maneuvers, which can be realized by our system, due to coil configuration and control algorithm.

The proposed EMA system was built with few requirements for a feasible system at clinical aspect as follows:

First, electromagnetic coils should be stationary for safety problem and response-time issue. The system structure is simpler and easy to be fabricated compared to our previous one, ALICE. Electromagnet air-core type was chosen due to its linear characteristic and the resultant magnetic field in ROI can be superimposed linearly from individual field from single coil. Using air-core type gives system advantage in frame design and weight. Our previous system makes use of saddle coil to generated uniform field and gradient field. These coils give a good performance; however, saddle coil with curvature part exposes the difficulty to manufacture at big scale. Hence, simple structure coil such as circular and rectangular types were considered.

Second, the number of electromagnet should be minimized while realizing the 5 degree-of-freedom (DOF) motion. Nelson et. al presented that at least eight magnetic actuators are required to perform 5-DOF control [19]. Therefore, in this study, eight electromagnetic coils were considered to form an external magnetic actuation system.

Third, to give capsule with more flexible motions, unrestrained maneuverability was put under consideration where it can move to any direction without changing posture and vice versa, capsule can move along a path with any orientation. This kind of unrestrained motion has not been presented previously due to the limitation in systematic coil configuration and control algorithm.

In this paper, we present an EMA system with novel configuration, as shown at Figure 1, to enable more flexible maneuvers for the WCE. The system has eight stationary electromagnets controlled independently to generate dynamic magnetic field and gradient magnetic field in a region-of-interest (ROI). Compared to MGCE system [17] (12 coils) and ALICE system (10 coils) [18], the proposed system could realize 3-D locomotion with less number of coils. The complex motions such as levitation task more effectively.

This paper is organized as follows. Section II introduces the proposed system with systematic coil configuration and independent force control method. The simulation results by Finite Element Method (FEM) to prove the control theory are illustrated in Section III. Section IV demonstrates experimental results of unrestrained motion using developed system. Finally, we draw a conclusion in section V.

II. SYSTEM DESIGN AND INDEPENDENT FORCE CONTROL

A. System Design

The designing attempt in this study results a novel barrel-shape EMA system. Figure 2 shows the systematic coil configuration of the system. Eight air-core type electromagnetic coils, including a Helmholtz pair coil, a Maxwell pair coil and four rectangular coils, are fixed to form a 5-DOF control system with unrestrained motions. To accommodate a patient inside system, the inner space should be maximized, given the size of outer Helmholtz coil. Hence, we fixed all rectangular coil at ±45° inclined to xy plane. By this configuration, we can utilize the magnetic field in both xand z-direction. In addition, the gradient terms $\partial Bx/\partial z$ and $\partial Bz/\partial x$ of the magnetic field from RC contribute to the. The system is capable of house a recumbent patient inside as MRI system. It is explicit that the barrel EMA with non-rotating air-core type provides the convenience for patient during operation. The technical specification of prototype system is illustrated in Table I.

Figure 3 describes the designed basic motions of capsule endoscope which has the magnetization along its axial axis. Capsule can translate along 3 basic axes in Cartesian coordinate and perform pitching and yawing to change its orientation

B. Independent force control

To move the capsule composed of a permanent magnet with dipole \mathbf{m} , one firstly needs to align it by creating a torque \mathbf{T} as follows.

$$\mathbf{T} = V \mathbf{m} \times \mathbf{B} \tag{1}$$

where $\mathbf{m} = [\mathbf{m}_x \ \mathbf{m}_y \ \mathbf{m}_z]^T$ is the magnetization vector of magnetic object, $\mathbf{B} = [\mathbf{B}_x \ \mathbf{B}_y \ \mathbf{B}_z]^T$ is the generated magnetic field and *V* is the volume of the object. x, y and z denote the



Figure 3. Designed basic motion of capsule endoscope with magnetization along its axial axis



Figure 4. Remote actuation mechanism of capsule endoscope (a) Definition of magnetic field and force vector for conventional actuation control (b) Demonstration of a representative of unrestrained motion where the magnetic object moves transversely vertical orientation.

basic axes of the Cartesian coordinate system. To simplify (1), we use V as unit volume so one can easily calculate the torque by multiplying with object's volume value. However, the dipole magnet always follows the magnetic field, so it more convenient to control magnetic field **B** than torque **T**.

The non-uniform magnetic field creates gradient field which can pull the capsule with a magnetic force \mathbf{F} as the following:

$$\mathbf{F} = V(\mathbf{m}.\nabla)\mathbf{B} = V \begin{bmatrix} \frac{\partial B_x}{\partial x} & \frac{\partial B_y}{\partial x} & \frac{\partial B_z}{\partial x} \\ \frac{\partial B_x}{\partial y} & \frac{\partial B_y}{\partial y} & \frac{\partial B_z}{\partial y} \\ \frac{\partial B_x}{\partial z} & \frac{\partial B_y}{\partial y} & \frac{\partial B_z}{\partial y} \end{bmatrix} \begin{bmatrix} m_x \\ m_y \\ m_z \end{bmatrix} = V \begin{bmatrix} \mathbf{G}_x \\ \mathbf{G}_y \\ \mathbf{G}_z \end{bmatrix} \mathbf{m} \quad (2)$$

where G_x , G_y , G_z are 1×3 gradient magnetic field matrix along x, y, z direction, respectively. From Biot-Sarvat law equation, the produced magnetic field, thus its gradient field, of a single air-core electromagnet and applied current i can be described as linear equation:

$$\mathbf{B}_{k}(\mathbf{q}) = \mathbb{B}_{k}(\mathbf{q})\mathbf{i} \tag{3}$$

$$\mathbf{G}_{v,k}(\mathbf{q}) = \mathbb{G}_{v,k}(\mathbf{q})\mathbf{i} \tag{4}$$

where q is spatial location in the workspace, v = x, y, z is for the gradient component, subscript k (k = 1, 2, ...8) denotes the k^{th} electromagnet. Based on superimposed property, the resultant magnetic field and gradient field produced by eight electromagnets at point q can be described as summation of individual field:

$$\mathbf{B}(\mathbf{q}) = \sum_{k=1}^{8} \mathbf{B}_{k}(\mathbf{q}) = \sum_{k=1}^{8} \mathbb{B}_{k}(\mathbf{q}) \mathbf{i}_{k} = \mathbb{B}(\mathbf{q})\mathbf{I}$$
(5)

$$\mathbf{G}_{\nu}(\mathbf{q}) = \sum_{k=1}^{8} \mathbf{G}_{\nu,k}(\mathbf{q}) = \sum_{k=1}^{8} \mathbb{G}_{\nu,k}(\mathbf{q}) \mathbf{i}_{k} = \mathbb{G}_{\nu}(\mathbf{q}) \mathbf{I}$$
(6)

where $\mathbf{I} = [i_1 \ i_2 \ ... \ i_8]^T$ is column current vector for eight coils, \mathbb{B} and \mathbb{G}_v are 3×8 unit-current magnetic field and gradient field matrix. From (2), (5) and (6), the generated magnetic field and force equation can be described in compact form as the following:

$$\begin{bmatrix} \mathbf{B} \\ \mathbf{F} \end{bmatrix} = \begin{bmatrix} \mathbb{B}(\mathbf{q}) \\ \mathbf{m} \mathbb{G}_{x}(\mathbf{q}) \\ \mathbf{m} \mathbb{G}_{y}(\mathbf{q}) \\ \mathbf{m} \mathbb{G}_{z}(\mathbf{q}) \end{bmatrix} \mathbf{I} = \mathbf{J} \mathbf{I}$$
(7)

(7) shows that magnetic field and force are controlled by actuation matrix **J** and current vector **I**. Figure 4 defines the desired magnetic field and magnetic force vector for remote actuation mechanism. From input values (magnitude of magnetic field *B* and force *F*, and yawing angle γ and pitching angle φ) two desired vectors can be described as follows:

$$\begin{bmatrix} \mathbf{B} \\ \mathbf{F} \end{bmatrix}_{desired} = \begin{vmatrix} B\cos(\varphi)\cos(\gamma) \\ B\cos(\varphi)\sin(\gamma) \\ B\sin(\varphi) \\ F\cos(\varphi)\cos(\gamma) \\ F\cos(\varphi)\sin(\gamma) \\ F\sin(\varphi) \end{vmatrix}$$
(8)

where B and F are scalar input values given by operator's keyboard. (8) is based on the capsule posture in the coordinate system shown in Figure 4.

Hence, the input current to coil system can be calculated to generate desired magnetic field and force as follows.

$$\mathbf{I} = \mathbf{J}^{\dagger} \begin{bmatrix} \mathbf{B} \\ \mathbf{F} \end{bmatrix}_{desired}$$
(9)



Figure 5. Simulation results of 3D magnetic field and xz plane magnetic field in representative cases of control. (a) and (b) Conventional actuation control where the force direction is similar to magnetic field. (c) and (d) Independent force control where the force direction is independent to alignment direction. The color indicated the magnitude of magnetic field and the change of color shows the magnetic force direction. The arrow shows the magnetic field direction.

In (9), we use pseudoinverse to obtained current vector since the system is redundant type. In case there are multiple solution current vector, pseudoinverse returns the least-square solution that minimizes the power consumption and heat generation.

The actuation matrix **J** features for each system and it is different from one by one. In algebraic system, the number of independent row or column of J shows the controllability of magnetic field and force. If force submatrix of three lower rows of J has rank 1, the system is able to push the robot along aligned direction. If it has rank more than 1, we can create magnetic force along two independent directions. It means the motion of magnetic object is not restrained in heading direction. One can push the capsule moving to any direction without changing its orientation and vice versa. By using rank function in MATLAB, we found that the force submatrix of J in our system has only two cases with rank 1, which is $(\gamma, \phi) =$ $(\pm 90^\circ, 0^\circ)$. The force submatrix has more than rank 2 in the others. Therefore, the proposed system is capable of realizing unrestrained maneuvers with almost all orientation. We also examine the rank of submatrix **B** which determines the degree of steerability (DOS) of capsule. As the same manner, **B** has rank 3, giving capsule endoscope 2 DOS (yawing and pitching). The rolling motion is impossible for dipole magnet because it cannot rotate along its magnetization axis. Hence, the proposed system can perform 5-DOF in case the force submatrix has rank 3.

C. Simulation result

To establish actuation matrix J, one can derive from Biot-Sarvat law or model the system by Finite Element Method (FEM) or measure the magnetic field directly from constructed system. In this study, we use the data from a FEM model with technical parameter in Table 1 which is then calibrated to match measured values. Figure 2 shows the FEM model built in COMSOL Multiphysics Modeling 5.2 (Sweden). Firstly, we constructed a unit-current magnetic field database at origin of ROI (60 mm \times 60 mm \times 60 mm) by exciting each coil 1 A at a time. This simulation data set was then used to form actuation matrix **J** in (9). To confirm the independent force control, the calculated current from (9) with desired magnetic field and force is then used for simulation.

Figure 5(a) and (b) show two representative cases of traditional motion where the capsule moves along heading direction. Figure 5(c) and (d) illustrate the 3D and 2D magnetic field in ROI in for representative cases of independent force control. As we can see, the generated magnetic force, representing by the changing of color, is perpendicular to the magnetic field direction. This causes the capsule moving transversely without changing its orientation. This motion is likely to omnidirectional motion in mobile robot field, which has not been demonstrated previously by other EMA systems. It is explicit that our proposed system provides more flexible and complex motions than former systems, ALICE and MCGE.

III. EXPERIMENTAL RESULTS

A. Experimental setup

A lab-scale EMA system was constructed to evaluate the performance of the proposed method. Two small cameras C920 from Logitech was mounted inside the system at top and side position for capturing motion of micro-robot in ROI. The input parameters are changed by a keyboard and a joystick (Logitech, Extreme 3D Pro). The control software built in LabVIEW calculates the required currents for the given input parameters. Power supplies (MX12×4EA and 3001LX×4EA) are used to generate current to each coil. The capsule







Figure 7. Overlapped picture four representative cases of unrestrained motion of capsule prototype. The cyan arrow indicates the magnetic field direction and the pink arrow denotes the gradient field direction.

prototype is made of a cylindrical permanent magnet Neodymium (M = 956000 A/m) and a cover printed by 3D printer Objet 30 Pro (Stratasys Direct Manufacturing Ltd, USA) with VeroClear material. In this study, we show new maneuvers with open-loop control. The capsule motion was remotely controlled by an operator with visual monitoring via capsule's camera. Because the operator (clinician) is accustomed to intestinal anatomy and phantom model, visual



Figure 8. (a) Stomach phantom with ulcer (b) Capsule explores the ulcer (c) Capsule moves in folding structure (d) Capsule is levitated.

monitoring enables to figure out the location of the capsule in the body.

B. Magnetic field generation

To evaluate the proposed control method, we compared the generated magnetic field from constructed EMA system and the input value as shown in Figure 6. A single channel Gauss meter (SYPRIS, MODEL 6010) was used to measure the generated magnetic field at center of ROI with various values. The proposed system can generate up to 90 mT magnetic field and the maximum gradient field is up to 1.2 T/m which are much higher than our previous system, ALICE.

C. Unrestrained motion by independent force control

The unrestrained motions were realized in water environment. To observer the motion of capsule prototype, we used a transparent tank 60 mm \times 60 mm \times 60 mm filled with water. Figure 7 shows overlapped picture of the representative maneuvers. The proposed system is capable of moving capsule transversely with vertical orientation and levitating with horizontal posture. Beyond that, by utilizing buoyancy force when moving in water, one can make capsule afloat and drive it at water surface. These maneuvers for endoscopic capsule are the first time introduced.

D. Application of capsule endoscope in stomach phantom

We verified the performance of the system through feasibility test in water-filled stomach phantom from EGD (EsophagoGastroDuodenoscopy) Simulator LM-103 as depicted in Figure 8(a). The magnetic force direction was set similar to magnetic field for locomotion. Capsule was control to explore the entire stomach and visualize the environment. The movement of capsule was monitored by a conventional endoscope device. As shown in Figure 8(b), (c) and (d), capsule was controlled to reach the target to provide a closed view of ulcer for clinician. It can move easily on folding structure which may be challenge to low-magnetic-force system. And capsule can be levitated to contact to upper part of stomach in case the clinician wants to have interaction. Through feasibility test in stomach phantom, we confirm that the proposed EMA system has high potential to be applied in clinical application.

IV. CONCLUSION

In this paper, we present a novel EMA system which is able to realize unrestrained movements of the WCE. The system has eight simple-structure electromagnets without core. The coil configuration is feasible to be fabricated at big scale while maintaining the necessary uniform and gradient magnetic field by utilizing bigger sized electromagnetic coils. By applying independent force control algorithm, the developed system can generate magnetic force along with the heading-independent driving direction. The proposed method was verified through FEM simulation method. Proposed maneuvers are demonstrated through experiments. The system exposes a good performance of driving the capsule prototype in a commercial stomach phantom. More feasibility test in-vitro and in-vivo will be conducted and reported in the future. The developed EMA system has high potential to be applied for multi-function capsule endoscope such as biopsy and drug delivery.

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