ACTIVE CAPSULE ENDOSCOPE MICRO-ROBOT WITH BIOPSY TOOLS

HERNANDO LEON-RODRIGUEZ †

Industrial Engineering Department, Nueva Granada Military University,
Karrera 11 # 101-80 Bogota, Colombia

VIET HA LE, SEONG-YOUNG KO, JONG-OH PARK, SUK-HO PARK

Robot Reseach Initiative, Chonnam National University
160, Baekseo-ro, Dong-gu, Gwangyu, South Korea

This paper presents an active locomotive intestinal capsule endoscope as a micro-robot that travel into the digestion system with wireless control abilities. The capsule endoscope is integrating with novel micro-biopsy tools to be able to extract tissue samples from the small and larger intestine. The entirely capsule system has abilities of target random biopsies by localization method, coming to right place to take biopsy sample, take and send several hundred of pictures for further analysis by the doctor. The biopsy mechanism provides passive triggered mechanism with highly active positional accuracy to collect the biopsy tissue sample and control along the way of the intestine.

1. Introduction

Recently, medical doctors' use wired endoscope (on adults' people) and capsule endoscope (mostly in children) to deal with gastrointestinal (GI) diseases to examined on upper or lower visual endoscopy procedure have affected the small and large intestine is in a patient. Since 2002, a later version of capsule endoscope was widely commercialized as Given Imaging (Yokneam Israel), Olympus EndoCapsule (Olympus, Japan), Korean Miro Pill and PillCam, etc.[1] However, the capsule endoscopes have a similar disadvantage in terms of (active/passive) locomotion which all of them exclusively deal with peristaltic force of human digestive system. This passive locomotion will make the capsule endoscope relatively useless due to lack orientation, speed control and number of pictures in the abnormal region on the digestion track. Several alternative solutions on these difficulties has been reported by shifting to active locomotion capsule endoscope (CE) driven by external electromagnetic actuation system [2][3], developing a micro bio-inspired fish like capsule robot that mimic its motion[4], development a micro capsule submarine powers by a pair of propellers [5], and several other ideas even with wheels[6].

† Research work supported By Robot Research Initiative, Chonnam National University, S. Korea.

Several conceptual ideas for active capsule endoscopes with biopsy functions or drug delivery system (DDS) had been reported. One alternative was presented with an elastic element called magneto mechanical that can be loaded remotely by varying the magnetic field surrounding it. It is able to store and release mechanical spring energy, triggered externally. This micro-robot proposal store multiple samples large that 1 mm^3 based in one reservoir underneath its cylindrical rotating blade [7].

Other biopsy micro actuator idea for capsule endoscope was composed by a cylindrical shape of 10 mm diameter and 18 mm length. Its actuator is based in a spring locked by polymer string, when the sampling target is decide the actuations is perform by heating a SMA wire that make the polymer to meld. As a result of the trigger a micro-spike in the actuator moves forward and backward using a slider-crank mechanism [8].

One mechanically challenging micro-motor actuator was proposed as alternatives of capsule endoscope with a biopsy tool. It has the capability to stretch into to sampling point, bite and cutting off and withdrawing the sample into capsule body by doing this process automatically [9].

One promising material as actuator device in the active capsule endoscope is shape memory alloy (SMA), we had used it as alternative of active actuator connected with a razor sharp blade. This biopsy device measuring 12mm in diameter and 3mm in length was integrated into a capsule endoscope prototype. Then the electromagnetic actuation system generated a specific motion of the capsule endoscope to extract the tissue simple from the intestines. [10]

In this paper, a new conceptual platform of active capsule endoscope will be presented. The novel capsule endoscope integrated passive biopsy tools powered by external magnetic field of electro-magnetic actuation system (EMA). The new capsule endoscope can go to specific targeting lesion in the intestine and deploy the biopsy tools to extract a specific amount of tissue sample form the intestine track. The method of biopsy collected material is compatible with pill-shaped capsule endoscope which is popular commercialized. Several experiments in vitro where carry-out to test the performance of the tools and some animal test were conducted a pig stomach to show the feasibility and potential to develop proposed active locomotive capsule endoscope with biopsy tools.

2. Design Specifications

Based on a wireless capsule endoscope development the new goals is not just miniaturization of one camera and lighting system squeezed in a pill-size; the aim is to step further the capsule from passive motion to active motions through the digestive system, enables visualization of the GI tract without discomforts and the present research, deploy biopsy tools to take tissue samples without breaking the regulations and conditions.

The capsule endoscope is composed by a wireless communication unit, vision module and a power source. All of these features most be packet with external biocompatible shell, with a size of a large antibiotic pill (11mm in diameter, 26 mm in length) approved by food and drugs administration (FDA) 2001 for use in adults and in 2003 for use in children older than 10 years [11]. Recently these dimensions are been extended and approved by FDA to (12 mm diameter, 32 mm length) in 2013 for use in adults within the condition of a capsule endoscope with moderate risk [12].

Actually, the wireless communication module (receiver) is plugged with several electrodes-cups placed around the patient abdomen, similar to long-term electrocardiogram exams in order to collect the 3 or 12 pictures per seconds, with (320x 240 pixel) of real time video; meanwhile, the capsule is swallowed in the digestion system at a rate of 1–2 cm/min, where the battery last of about 10 hours. The bowel preparation procedure is similar to the traditional flexible wired endoscopy, it requires ingestion of a strong laxative to ensure adequate bowel cleanness and facilitate progression of the capsule through the GI tract to avoiding the risk of unlucky perforation, loss localization in GI track and/or retention. [11]

3. Electromagnetic Actuation (EMA) System

EMA system could be combined in 2D, 3D electromagnetic coils arranged at 90 degrees with at least one pair of Helmholtz, Maxwell, uniform or gradient coils that can generates uniform magnetic field in x, y, z axes, rotational magnetic field and oscillating magnetic field. These pair of coils generally consists of two identical circular magnetic coils, where the radius of the coils is equal to the distance between them for Helmholtz configuration and about 1.3 of the radius for the Maxwell configurations.[13] In addition, there are some other EMA configurations designed in order to obtain higher magnetic field in the region of interest (ROI) like octo-magnet coils [14] or for clear more space in the ROI like saddle coils. Basically, the EMA can generate and induce in any direction a magnetic fields that will affect any ferromagnetic material placed in the micro-robot, this micro-robot could be control and align to desired direction and thrust to the desired position [2]. For alignment of the magnetic body, torque is generated by magnetic field, and can be described in Eq. (1):

$$\tau = V\mathbf{M}\times \mathbf{B} \qquad (1)$$

Where τ means torque, and V, $\mathbf{M}$, $\mathbf{B}$ denote volume and magnetization of the magnetic body and electromagnetic field generated by Helmholtz coil.

In addition, to produce a thrust force on a magnetic body, this could be generated by gradient magnetic field and it is expressed in Equation (2):

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

Where $\mathbf{F}$,∇ are propulsion force of magnetic body and the gradient symbol.

Several alternatives of locomotion can be achieved for capsule endoscope with magnetically materials using magnetic field control by combined different pair of coils as example we presented 3-pairs of mutually orthogonal Helmholtz coils and 1-pair of Maxwell coils placed in z-axis, as shown in Figure 1.

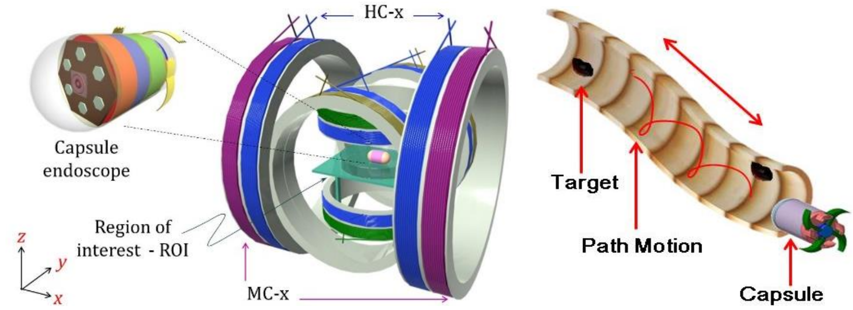

Figure 1: (Right) Schematic diagram of EMA system; (Left) path planning of capsule endoscope.

The EMA generates along x-axis uniform magnetic field that aligns the micro-robot at the same directions placed expressed as follow in Eq. (3) and (4):

$$H_h= [d_h \ \ 0 \ \ 0]^T \tag{3}$$

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

Where i_h, n_h, and r_h denote applied current, turns and radius of the Helmholtz coils.

For Maxwell coils, composed by two solenoids has the relation that distance of the coil (d) is same to √3 times the coil radius (r). The current direction applied to two coils is reverse, and the amplitude is equal each other. By using this relation, the micro-robot is powered to 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)

$$\mathbf{H}_m=[-0.5g_mx \ \ -0.5g_myg_mz]^T \tag{5}$$

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

Where i_m, n_m, and r_m are applied current, turns and radius of the Maxwell coils.

As a result, by combined these expressions the micro-robot can align, propel and rotated in the ROI to desired direction. Along z-axis, the capsule endoscope can produces ascending, descending motion with propulsion force on 2-D plane.

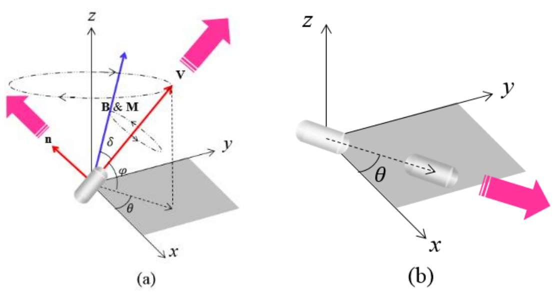

Figure 2: Diagram of (a) helicoidally and (b) Planar motion of the capsule endoscope.

The figure 2 is showing a schematic diagram of helicoidally motion and planar motion of the capsule endoscope place in ROI into the EMA. The desired magnetization direction (φ) from the axial direction generates the spiral motion using the revolution of alignment vector; as a result, the EMA system create 3-D alignment vector of the capsule endoscope by applying the equation expressed as follow:

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

As a result, by generating the spiral motion the capsule endoscope moves upward or downward of the digestive track allowed to stick in the inner wall of the larger and small intestine generated better images results and accurate diagnosis by the endoscopy doctor. (See figure 1 left).

4. Micro-robot capsule endoscope design

The capsule endoscope is a micro robot with active and complex motion to extract biopsy sample; it has to reproduce enough force and torque on the wall surface of the intestines. Based in other experimental researches the given design of capsule endoscope most generates a minimum cutting force to successfully extract biopsy tissue (larger than 2N) [10]. With circular shape of the coil and current intensity of i, we can use the following formulas to calculate the magnetic field along the axis of the coils, equations (1) (2). By alignment the magnetic field the torque acts on the permanent magnet and became the cutting force of the biopsy tool; in addition, the relation between cutting force and alignment torque can be estimated by equation (8) and the diagram is showing in figure 3.

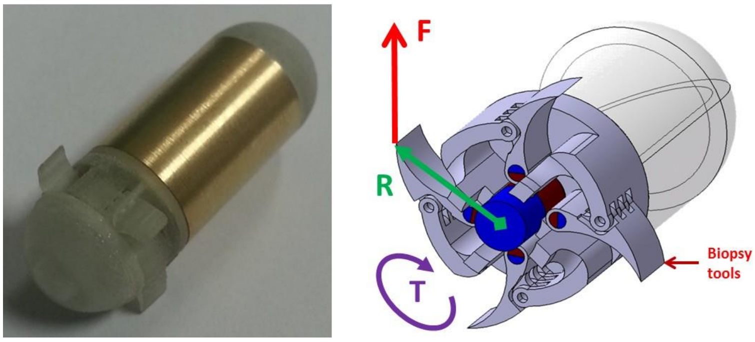

Figure 3. (Left) capsule endoscope prototype; (right) diagram of biopsy cutting tool force analysis

$$F = \tau/R \qquad (8)$$

Where F is the cutting force of biopsy tool razor on wall tissue and R is distance from the center of permanent magnet to the out part of the tool razor.

Based, that EMA parameters depending of above conditions and applied voltage and current into the micro-robot and also the capsule endoscope has restricted dimensions due to FDA regulation; the incognito relied in the permanent magnet size to be place to generate the cutting force. Considering to uses a neodymium magnet NdFeB with cylindrical shape, radius R, thickness h and magnetization (M) of 955000 A/m. By computing these analyses the results are evaluated with relation between current supplied by EMA system, dimension of permanent inside the CE and the maximum cutting force. As a results the desired dimensions for cylindrical neodymium magnet is 10mm in diameter and 15mm of length with a cutting force produced of around 3N. These results showing that the cutting force can be generated and the dimension meet the requirement of FDA regulations and would be integrated into capsule endoscope.

5. Experiment results

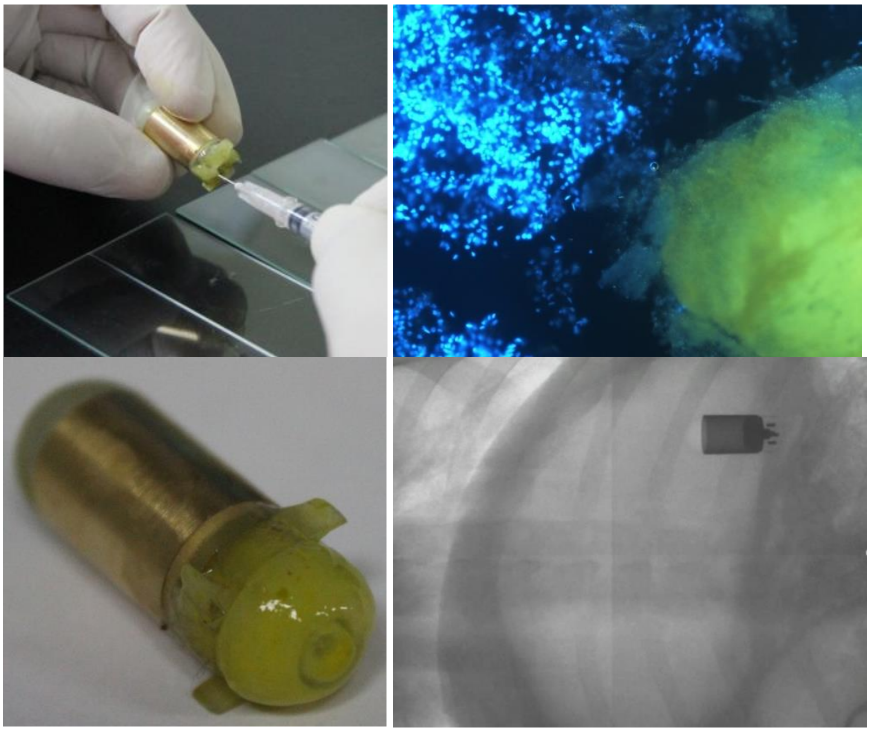

Figure 4. Capsule endoscopes performances animal test (pig digestion system) and results.

In order to demonstrate that the micro-biopsy tool can obtain biopsy samples in-vitro experiment were performed with a piece of small intestine of pig. In the experiment the EMA of figure 1 were used to drive the CE to a given target. As a result, the small intestine position and rotation of the CE in the direction simulation the biopsy tool motions successfully extract the tissue from lumen wall. Several experiments were performed to demonstrate the feasibility of the biopsy process. The tissue was cut off by the capsule and stored in the biopsy device. Several capsulate designs had been designed in other to produces one suitable concept for medical product, the entirely system and biopsy capsules had been patent in Korea in 2015. Initially the micro robot had fixed blades in order to prove the magnetic calculations and the performance in vitro and vivo tests. Further prototypes were tested in-vivo trials with successful result considering that these micro-robots are early development and many conditions needs to be solve. To insure that biopsy tools are collecting animal cells nucleic acid preparations with DAPI Stain incubate in dark space for 30 min were done on the extracted material. As a results the ultra-violate light showing on blue colour and reflex the animal's nucleus cells bright, while a vegetable cells were also reflected as presented in figure 4 (up left).

Conclusions

Several prototype of capsule endoscope integrating with fixed biopsy tools were built and tested in-vitro and in-vivo. The EMA system successfully performed the helicoidally motions in order to extract tissue sample from the intestinal wall after arriving to target lesion and increasing the magnetic field to high level the capsule is attached harder to intestinal wall and giving a rotation the biopsy process, as showing figure 4 (left down). The biopsy tools with a dimension of 3.5mm in length outside of its body can solve effectively the problem of reaction force against intestinal wall, with small amount of consumed energy. In addition, the proposed biopsy device can also be integrated into other conventional CEs without changing their telemetry module and can be triggered by external permanent magnet and/or EMA, this opens a potential revolution for an era of biopsy capsule endoscope technology.

References

1. Zhaoshen Li, Dan Carter, Rami Eliakim, Wenbin Zou, Hao Wu, Zhuan Liao, Zhaotao Gong, Jinshan Wang, Joo Won Chung, Si Young Song, Guohua Xiao, Xiaodong Duan and Xinhong Wang; The Current Main Types of Capsule Endoscopy; Handbook of Capsule Endoscopy, DOI: 10.1007/978-94-017-9229-5_2, Springer Science+Business Media Dordrecht, 2014
2. Cheong Lee, Hyunchul Choi, Gwangjun Go, Hernando Leon-Rodriguez, Semi Jeong, Kiduk Kwon, Seong Young Ko, Jong-Oh Park* and Sukho Park*, Member, IEEE; Helical Motion and 2D Locomotion of Magnetic Capsule Endoscope using Precessional and Gradient Magnetic Field; 2014 5th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob) August 12-15, 2014. São Paulo, Brazil

3. Henrik Keller, Aleksandar Juloski, Hironao Kawano, Mario Bechtold, Atsushi Kimura, Hironobu Takizawa and Rainer Kuth; Method for Navigation and Control of a Magnetically Guided Capsule Endoscope in the Human Stomach; The Fourth IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics Roma, Italy. June 24-27, 2012
4. Gábor Kósa, Péter Jakab, Ferenc Jólesz and Nobuhiko Hata; Swimming Capsule Endoscope using static and RF magnetic field of MRI for propulsion; 2008 IEEE International Conference on Robotics and Automation Pasadena, CA, USA, May 19-23, 2008
5. Paola Dario, aranna Menciassi, Dino Accoto, Loius Phee, Cesare Stefanini; Medical Micro-robotics; ICAR 2001.
6. Anastasios Koulaouzidis, Dimitris K Iakovidis, Alexandros Karargyris, Emanuele Rondonotti; Wireless endoscopy in 2020: Will it still be a capsule?; World J Gastroenterol 2015 May 7; 21(17): 5119-5130.
7. M.Simi, G.Gerboni, A. Menciassi, P.Valdastri, Magnetic Torsion Spring Mechanism for a Wireless Biopsy Capsule; Journal of Medical Devices; pp.1-10, 2013.
8. S. Park, K. Koo, S. M. Bang, J. Y. Park, S. Y. Song and D. Cho, (2009).A novel micro-actuator for micro biopsy in capsular endoscopes, Journal of Micromechanics and Micro-engineering, pp. 1-9, 2009.
9. W. Chen, G. Yan, H. Liu, P. Jiang, Z. Wang, Design of Micro Biopsy Device for Wireless Mobile Capsule Endoscope, International Journal of Precision Engineering and Manufacturing, pp. 1-10, 2013.
10. Viet Ha Le, Leon-Rodriguez Hernando, Cheong Lee, Hyunchul Choi, Zhen Jin, Kim Tien Nguyen, Gwangjun Go, Seong-Young Ko, Jong-Oh Park and Sukho Park; Shape memory alloy–based biopsy device for active locomotive intestinal capsule endoscope; Proc IMechE Part H: J Engineering in Medicine 2015, Vol. 229(3) 255–263, IMechE 2015
11. D.Tokuhara, Wireless Capsule Endoscopy in Pediatric Gastrointestinal Diseases, New Techniques in Gastrointestinal Endoscopy, Prof. Oliviu Pascu (Ed.), ISBN: 978-953-307-777-2, InTech, 2011.
12. Chantal Beaudry/Martyna Gawrych; Given Imaging Receives FDA Clearance for PillCam® COLON in Patients Following Incomplete Colonoscopy; YOQNEAM, ISRAEL, [February 3, 2014]
13. S.T. Lin, A.R. Kaufmann, Helmholtz coils for production of powerful and uniform fields and gradients, Reviews of Modern Physics vol. 25 pp. 182–190, 1953.
14. Michael P. Kummer, Jake J. Abbott, Bradley E. Kratochvil, Ruedi Borer, Ali Sengul, and Bradley J. Nelson; OctoMag: An Electromagnetic System for 5-DOF Wireless Micromanipulation; IEEE TRANSACTIONS ON ROBOTICS, VOL. 26, NO. 6, DECEMBER 2010