Paper449

Novel Electromagnetic Actuation System for Multifunctional Capsule Endoscopes: a feasibility study

Manh Cuong Hoang[1,2], Jayoung Kim[2], Eunpyo Choi[1,2], Byungjeon Kang[2*], Jong-Oh Park[1,2*] and Chang-Sei Kim[1,2*]

[1] School of Mechanical Engineering, Chonnam National University, Gwangju, 61186, Korea;
[2] Medical Microrobot Center, Robot Research Initiative, Chonnam National University, Gwangju, 61011, Korea;
*Corresponding author Email: bjkang8204@jnu.ac.kr; jop@jnu.ac.kr; ckim@jnu.ac.kr
Telephone: +82-62-530-5230; fax: +82-62-530-5238

Abstract

For digestive organs diagnosis, wireless capsule endoscopes were developed as innovative solutions into overcoming limitations of conventional flexible endoscope such as uncomfortable procedures, pains and side effects of anaesthetic drug. Nevertheless, commercialized capsule endoscopes have been used in limited area such as oesophagus and small intestine, due to lack of active locomotive function. Though several 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. To address this problem, we propose a novel electromagnetic actuation system to achieve not only active locomotion but also multiple functions in next generation wireless capsule endoscopy. The proposed electromagnetic actuation system consists of a pair of Helmholtz coils, two pairs of rectangular coils and two pairs of Maxwell coils. In detail, the rectangular and Helmholtz coils can align a magnetized object in desired direction by generating a uniform magnetic flux and Maxwell coils, which can generate a constant gradient magnetic flux, can supply the propulsion force for a capsule endoscope. Through feasibility tests, essential endoscopic motions such as propulsion, steering, and helical motion for the diagnosis in gastrointestinal tract were verified by using the proposed electromagnetic actuation system.

1 Introduction

In recent years, there have been many gastrointestinal tract diseases that people can be suffered from, due to irregular dietary habit, lack of exercise and pressure stress working life. So, in order to achieve diagnostic and potentially therapeutic endoscopy for such kinds of diseases with more comfortably and less stressfully for the patients [1], [2], capsule endoscope (CE) was introduced and developed offering innovative solutions. With the size of a pill, it is able to examine the lower oesophagus, stomach, small and large intestine and colon and captures images continuously of gastrointestinal tract. The taken images are then sent to data storage via an external data receiver in outside of the body. Finally, the capsule endoscope is extracted and the images are utilized for analysis and diagnostic [3], [4].

However, the big disadvantage of these products is in the locomotion. Since the traditional capsule endoscopes do not have its own actuator part, they are moved along gastrointestinal tract passively by the peristaltic motions of digestive organs. Their movement is dependent on the performance of digestive organs, leading to long time in data acquisition. In addition, because the stomach and colon are large and folding structures, it is hard to overpass and reach to the target. Therefore, the capsule endoscope should have its own locomotion part so that the physician could actively manipulate it in gastrointestinal tract.

As a solution to this problem, several actuation systems were studied to control the micro-robot remotely. S. Floyd introduced two-dimensional locomotive micro-robot using EMA system which is composed of five electromagnetic coils [5]. Of these coils, two pairs of square Helmholtz coil are used to move the micro-robot made of permanent magnet in micro-meter size within plane and the other one is clamping coil holding the robot to the surface. This system could manipulate the micro-robot in a remote site. However, all paths and organs of human body have three-dimensional (3-D) shape so it had locomotive limitations for medical application. K. Ishiyama [6] and H. Zhou [7] demonstrated 3-D forward/backward motions of a spiral-type micro-robot by controlling a rotating magnetic field. The robot was propelled inside a real small intestine with rotating frequencies from 1Hz to 5Hz [7]. However, the propulsive velocity is dependent on helical angle and slip effect and it cannot move without surrounding material. In addition, S. Jeon proposed a magnetic navigation system composed of pair of Maxwell and Helmholtz coils and saddle coil to generate uniform and gradient field. The micro-robot in region of interest (ROI) can be controlled in 3-D shape [8], [9]. However, the structure of saddle coil is complex to fabricate as designed which can cause to uncontrollable errors.

In this article, we propose a novel electromagnetic actuation system composed of rectangular coils and aforementioned conventional coils for multi-function capsule endoscope. In details, the system has two pairs of Uniform rectangular coils and one pair of Helmholtz coils to generate torque and align the micro-robot, two pairs of Maxwell coils to produce the propulsion force of the object. Coils of two pairs of uniform rectangular coil are placed on four sides of the square inside the Helmholtz and Maxwell coil. The basic tests of locomotion are conducted to verify the performance of new type coil and the system. With the magnetic field generated by the coil components, the capsule endoscope can perform necessary movements to the diagnosis of the gastrointestinal tract such as propulsion, steering, and helical motion.

In this paper, Section 2 explains the theoretical analysis of proposed EMA system. Details of design and fabrication of the system is introduced in Section 3. This section describes setup of experiment and the locomotion results of capsule endoscope model using our system. Finally, conclusions are given in Section 4.

Table 1: Technical specifications of proposed EMA system

Coils	***Hx***	***Mx***	***Mz***	***URC***
Radius (mm)	195	195	100	n/a
Width x Length (mm)	n/a	n/a	n/a	156 x 337
Distance (mm)	195	337.75	173.20	200
Wire diameter (mm)	1.6	1.6	1.3	1.3
Coil turns	710	1426	660	600

2 Theoretical analysis of proposed EMA system

When a permanent magnetic material is placed in a magnetic field, it could be aligned and propelled by uniform and gradient magnetic [3]. Magnetic torque and force exerting on micro-robot composed of permanent magnet in magnetic field can be expressed as the following formula:

$$\vec{\tau}=\mu_0 V\vec{M}\times\vec{H} \tag{1}$$

$$\vec{F}=\mu_0 V(\vec{M}.\nabla)\vec{H} \tag{2}$$

where μ_0, V and $\vec{M}$, $\vec{H}$ are magnetic permeability of free space, volume and magnetization value of micro-robot, magnetic field intensity, respectively. From equation (1) and (2), based on gradient magnetic field and magnetic field intensity we can get the magnetic torque and force acting on a magnetic object.

2.1 Theory of conventional Helmholtz and Maxwell coils

Generally, in order to align the micro-robot along desired direction Helmholtz coils are used because it can generate uniform magnetic field near its centre. The magnetic flux $\vec{H}$ created by a Helmholtz coils (HC x-axis in **Figure 1**) is given as following formula [8]:

$$\vec{H}_h=[d_h \quad 0 \quad 0]^T \tag{3}$$

$$d_h=0.7155\frac{n_h\times i_h}{r_r} \tag{4}$$

where i_h , r_h , n_h are the applied current, radius and number of turns of Helmholtz coil, respectively. Since the magnetic field near the centre of the coil along *x*-axis is uniform, it generates magnetic torque which tends to align the micro-robot within the effective region.

After navigating the micro-robot to desired direction, Maxwell coils are powered to produce uniform gradient field which pushes the micro-robot along determined line. The magnetic flux $\vec{H}_m$ of Maxwell (MC x-axis in **Figure 1**) coil is given as the following formula [8]:

$$\vec{H}_m=[g_m x \quad -0.5g_m y \quad -0.5g_m z]^T \tag{5}$$

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

where i_m , r_m , n_m are the applied current, radius and number of turns of Maxwell coil, respectively.

This research utilizes two pairs of rectangular coil to generate uniform magnetic field. For medical application, the inner space should be large enough to accommodate a patient. In order to get a large working space the rectangular coils are placed on four sides of the square and arranged parallel to *xy'* and *xz'* plane which conjugate with *xy* and *xz* plane an angle α of 45 degree as shown in **Figure 1**. When a current *i* is applied to pair of rectangular coil with the same direction and amplitude, the magnetic flux density along *z'*-axis is calculated as the following equation [8]:

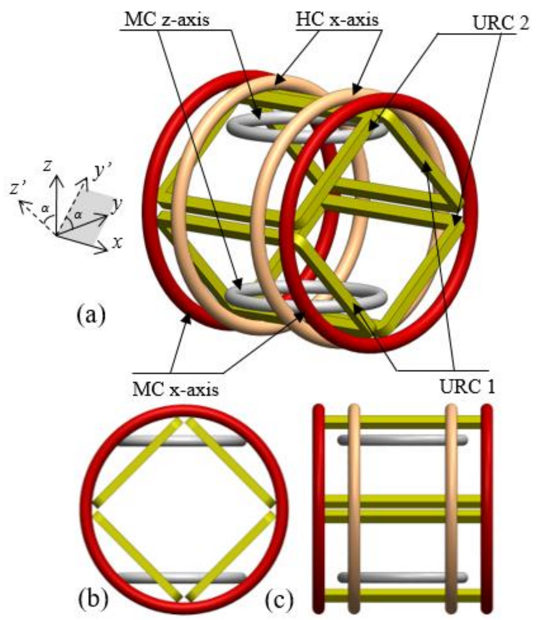

Figure 1 Schematic of proposed EMA system a) general view b) front view c) side view

$$H=\frac{ad^2 i}{4\pi}\left(\left(\left(\frac{d^2}{4}+\left(\frac{h}{2}-z'\right)^2\right)\sqrt{\frac{d^2}{4}(1+a^2)+\left(\frac{h}{2}-z'\right)^2}\right)^{-1}\right.$$
$$+\left(\left(\frac{d^2}{4}+\left(\frac{h}{2}+z'\right)^2\right)\sqrt{\frac{d^2}{4}(1+a^2)+\left(\frac{h}{2}+z'\right)^2}\right)^{-1}$$
$$+\left(\left(\frac{a^2d^2}{4}+\left(\frac{h}{2}-z'\right)^2\right)\sqrt{\frac{d^2}{4}(1+a^2)+\left(\frac{h}{2}-z'\right)^2}\right)^{-1} \tag{7}$$
$$\left.+\left(\left(\frac{a^2d^2}{4}+\left(\frac{h}{2}+z'\right)^2\right)\sqrt{\frac{d^2}{4}(1+a^2)+\left(\frac{h}{2}+z'\right)^2}\right)^{-1}\right)$$

where l, d, h, a are length, width, distance between the coils located along z'-axis and ratio l/d, i is current applied to two coils. Equation (7) can be expressed as Taylor series expansion around z'=0 [10]:

$$B_{z'}(z') \approx B_{z'}(z'=0)$$
$$+\left.\frac{\partial B_{z'}}{\partial z'}\right|_{z'=0} z' + \frac{1}{2!}*\left.\frac{\partial^2 B_{z'}}{\partial (z')^2}\right|_{z'=0} z'^2 \tag{8}$$
$$+\frac{1}{3!}*\left.\frac{\partial^3 B_{z'}}{\partial (z')^3}\right|_{z'=0} z'^3 + \frac{1}{4!}*\left.\frac{\partial^4 B_{z'}}{\partial (z')^4}\right|_{z'=0} z'^4$$

In order to obtain a uniform magnetic field, the even derivative terms should be eliminated. These conditions provide the geometrical relationship of rectangular shape coil: a and d. **Figure 2** illustrates the geometrical relationship of the proposed Uniform rectangular coil. Since, pair of coil is placed on a plane of 45 degree corresponding to xy plane, the magnetic field of near the centre between two coils in xyz coordinate can be described as the following:

$$\vec{H}_{uc}=\left[0 \quad \frac{\sqrt{2}}{2}d_{uc,z'} \quad -\frac{\sqrt{2}}{2}d_{uc,z'}\right]^T \tag{9}$$

$$d_{uc,z'}=0.373\frac{n_{uc}\times i_{uc,z'}}{d_{uc}} \tag{10}$$

where $d_{uc,z'}$ is the magnetic flux density in the ROI of the Uniform rectangular coil along z'-axis; n, i, d denote the number of turn, current and the width of the coil, respectively.

2.2 Actuation mechanism of a Novel EMA

The proposed EMA system consists of two pair of Maxwell coil, one pair of Helmholtz coil and two pairs of Uniform rectangular coil as shown in **Figure 1**. The magnetic field near the centre of the EMA system is expressed as the following:

$$\vec{H}=\begin{bmatrix} d_h+(g_{mx}-0.5g_{mz})x \\ \sqrt{2}/2\,(d_{y'}+d_{z'})-0.5(g_{mx}+g_{mz})y \\ \sqrt{2}/2\,(d_{y'}-d_{z'})+(g_{mz}-0.5g_{mx})z \end{bmatrix} \tag{11}$$

Firstly, in order to translate the micro-robot along determined direction θ corresponding to x-axis within an arbitrary p-plane tilted an angle φ along x-axis in **Figure 3**. From equation (4) (9) and (10), the condition of uniform magnetic field along θ direction leads to the following relation of the current of three uniform coils:

$$i_h=H\cos(\theta)\eta_h/(0.7155n_h) \tag{12}$$
$$i_{uc,y'}=\frac{1+\tan\varphi}{1-\tan\varphi}i_{uc,z'} \tag{13}$$

After aligning the micro-robot to the desired direction, the propulsion force along determined path is created by gradient field of Maxwell coils. The following conditions should be satisfied to propel the micro-robot to the target with gravitational force compensation:

$$\frac{F_p-mg\sin(\varphi)}{F_x}=\tan(\theta), \qquad F_x \neq 0 \tag{14}$$

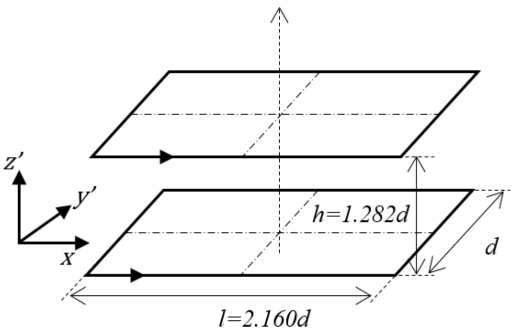

Figure 2: Pair of Uniform rectangular coil

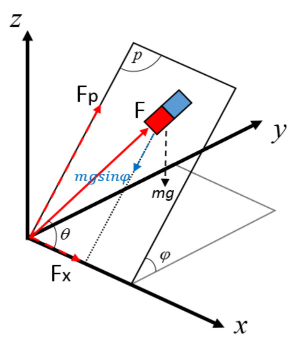

Figure 3: Schematic of 3D capsule endoscope locomotion

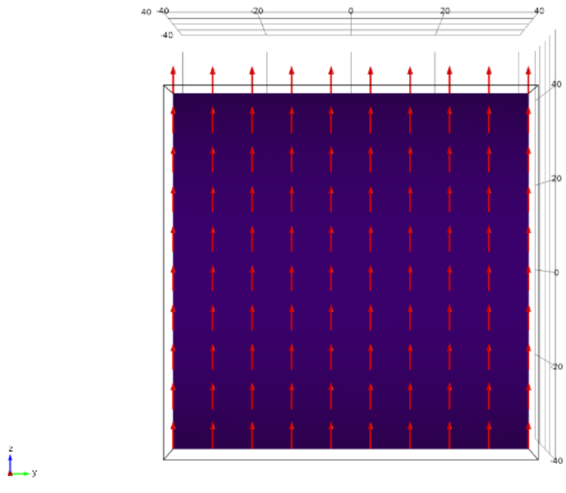

Figure 4 Magnetic field map in region of interest 40 x 40mm of Uniform rectangular coil

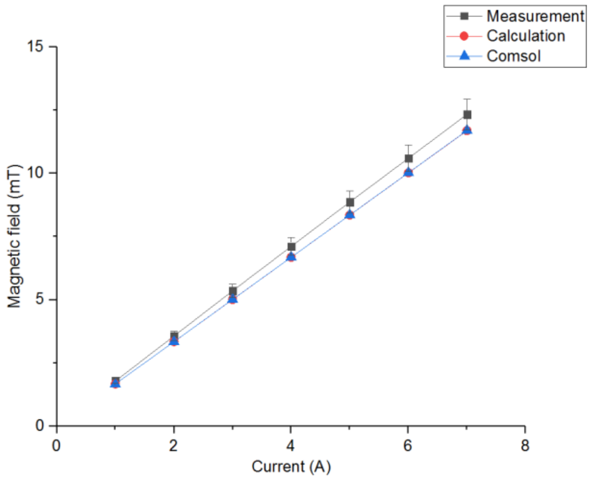

Figure 5 Magnetic field at center of Uniform rectangular coil

When the magnetic gradients, the magnetization and volume of the micro-robot is given from equation (14), the gradient magnetic field can be derived as the following:

$$\frac{MV\sin(\theta)(-0.5g_{mx}-0.5g_{mz})-mg\sin(\varphi)}{MV\cos(\theta)(g_{mx}-0.5g_{mz})}=\tan(\theta) \tag{15}$$

3 Results and Discussion

3.1 Uniform rectangular coil

Based on the theoretical analysis in Section 2, the EMA system was fabricated with technical specifications shown in Table 1. A pair of rectangular coil 3D computer model was created in COMSOL program to verify the behaviour of magnetic field. **Figure 4** shows the uniformity of magnetic field in term of magnitude and direction within region of 40 x 40mm. Therefore, we confirm that the proposed Uniform rectangular coil could generate a uniform magnetic field in ROI of 40 x 40mm. The magnetic field at centre of Uniform rectangular coil was theoretically calculated and measured. **Figure 5** shows the results of magnetic field flux density with different values of input current from Comsol simulation, theoretical and measured values. The theoretical magnetic field values were calculated using MATLAB and the real were measured with Gauss meter (SYPRIS, MODEL 6010). The experimental results show that the generated magnetic field from uniform rectangular coil is resemble to simulated as well as calculated values.

3.2 Experiment setup

The experiment was setup as illustrated in **Figure 6** to evaluate the performance of proposed system for locomotion. A small size camera from Logitech was attached inside the EMA system for recording position of micro-robot. For the locomotion of capsule endoscope, we used a conventional joystick controller from Logitech. The power suppliers were MX12 (2EA) and 3001LX (3EA) from California Instrument controlled by LabVIEW to input current into coils. The capsule endoscope model included a cylindrical permanent magnet made of Neodymium (M = 955000A/m) with diameter of 6mm and length of 10mm. The magnetization direction of the magnet coincided with the axis of capsule endoscope model which was fabricated by 3D printer.

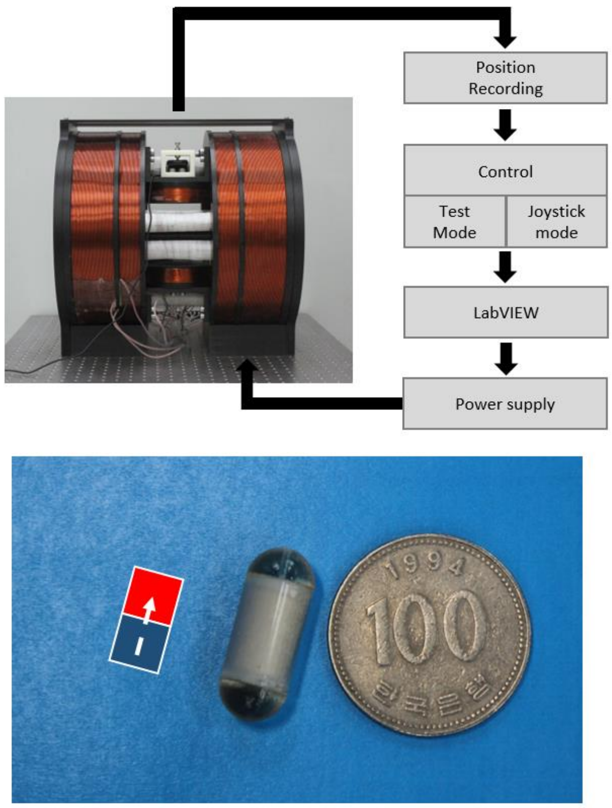

Figure 6 (Top) Experiment setup and (Bottom) prototype of capsule endoscope

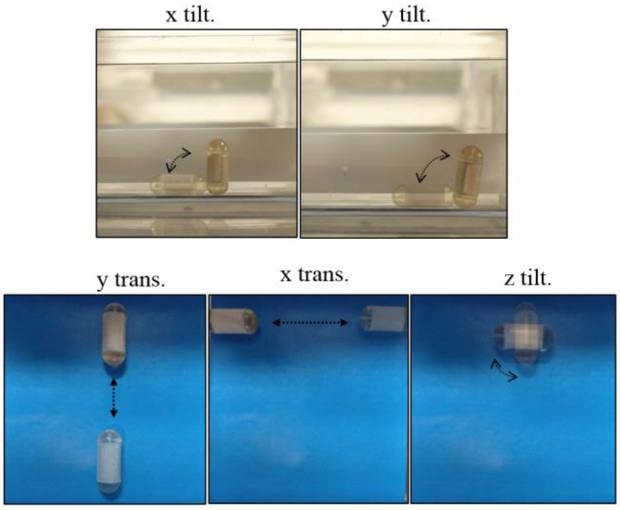

Figure 7 Basic motions test of capsule endoscope

3.3 Basic tests of the EMA system

In order to verify the performance of proposed EMA system for 5-DOF, basic motions test was conducted with capsule endoscope model as shown in **Figure 6**. Firstly, the uniform magnetic field was generated to align the microrobot along the desired direction. The uniform gradient field was then created to propel capsule endoscope along the path. The uniform field was set greater than gradient field to ensure that the propulsion direction was determined by uniform magnetic field. **Figure 7** shows the overlap pictures of translation and tilting (rotation) motions of capsule endoscope prototype along *x*-, *y*- and *z*-axis. We confirm that with these basic motions we can combine them to achieve others movements such as steering or helical.

4 Conclusion

In this paper, we introduced a new EMA system which consists of conventional coils and proposed uniform rectangular coil. The uniform rectangular coil can generate a uniform magnetic flux density within region of interest and its values are closed to the simulated as well as calculated results. The basic motion tests using a capsule endoscope model were conducted to evaluate the performance of the system. The capsule endoscope was aligned and pushed along desired direction. For 3D locomotion of capsule endoscope, we proposed an actuation algorithm with gravity compensation. In addition, we could fabricate the big rectangular coils to accommodate patients with high accuracy due to its geometrical structure. Therefore, it is expected that the proposed EMA system would be much potential to be applied in medical applications such as biopsy or active drug delivery.

Acknowledgement

This research was supported by the Next-generation Medical Device Development Program for Newly-Created Market of the National Research Foundation (NRF) funded by the Korean government, MSIP(No.2015M3D5A1065682).

5 Literature

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7月6日（星期四）Thursday，July 6, 2017， Room: M3-04

主题/Topic		类人/仿生/足式机器人，微型机器人 Biologically Inspired Robotics, Micro / Nano Robotics
会议室/Room 1		M3-04
Time	Number	Paper Title
09:40-10:00	No.87	用于基于细胞的治疗剂固定的新型永磁体阵列的模拟 Simulation of Novel Permanent Magnet Array for Cell-based Therapeutic Agent Fixation
		Kyungmin Lee
		School of Mechanical Engineering, Chonnam National University, Korea
10:00-10:20	No.84	多功能胶囊内窥镜新型电磁驱动系统：可行性研究 Novel Electromagnetic Actuation System for Multifunctional Capsule Endoscopes: A Feasibility Study
		Manh Cuong Hoang
		School of Mechanical Engineering, Chonnam National University, Gwangju, Korea Medical Microrobot Center, Robot Research Initiative, Chonnam National University, Gwangju, Korea
10:20-10:40	No.85	PLGA-PEG 基磁纳米胶囊，用于对比增强 MR 成像和聚焦超声触发药物递送 PLGA-PEG base magnetic nanocapsule for contrast-enhanced MR imaging and focused ultrasound-triggered drug delivery
		Zhen Jin
		School of Mechanical Engineering, Chonnam National University, Gwangju, Korea
10:40-11:20	Keynote Speech	生物医学微/纳米机器人 Biomedical Micro/Nano Robotics
		Prof. Jong-Oh Park
		IFR Executive Board Member Director, Medical Microrobot Center Director of Robot Research Initiative Professor of Chonnam National University, Korea
11:20-12:00	Keynote Speech	人工智能驱动智能机器人工业走向创新经济 AI Driven Intelligent Robotics Industry towards Innovation Economy
		罗仁权教授 Prof. Ren C. Luo
		Chair Professor & life distinguished professor at National Taiwan University Director of International Center of Excellence on Intelligent Robotics and Automation Research in National Taiwan University Member of EU Industrial Advisory Board, Taiwan Editor-in-Chief, IEEE Transactions on Industrial Informatics (Impact Factor 4.708)
12:00-12:50		午餐 Lunch Break

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