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Wireless steering mechanism with magnetic actuation for an endoscopic capsule

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Abstract— **This paper illustrates the design, development and testing of a miniature mechanism to be integrated in endoscopic capsules for precise steering capabilities (Magnetic Internal Mechanism, MIM). The mechanism consists of an electromagnetic motor connected to a couple of small permanent magnets and immersed in a static magnetic field produced by an external permanent magnet or a by an electromagnetic coil. The overall steering capsule, integrating the magnetic steering mechanism and the vision system is 15.6 mm in diameter, 48 mm in length, 14.4 g in weight and can be oriented with an accuracy of 0.01°. As regards system scalability, the capsule size could be reduced down to 11 mm in diameter by optimizing some mechanical components. On the other hand, the magnets size cannot be reduced because the magnetic link between internal and external magnets at typical operation distances (about 15 mm) would be weak.**

I. INTRODUCTION

ENDOSCOPIC procedures and solutions for early cancer detection have changed dramatically in the last 10 years.

Initially, endoscopy relied on rigid telescopes and direct visualization, then the introduction of fiber optics enabled the use of flexible endoscopes. They allow reaching new areas of the gastrointestinal tract, but their efficacy relies on the physician ability. In particular the steering skill is not intuitive. Traditional endoscopes are composed by a steerable tip and a log passive tube, that is pushed in the gut, causing discomfort and pain for the patient. Some new platforms can overcome these problems. In the Colono-Sight system [1] the scope advancement is aided by a pneumatic self-propulsion system, thus reducing the force needed to push the instrument. The ShapeLock TransPort [2] allows to be inserted and steered in a flexible state and then locked into a rigid configuration conformed to the patient anatomy. In the NeoGuide system [3] the position and angle of the scope tip are encoded into a computer algorithm during the manual insertion. As the colonoscope is advanced, the computer directs each successive segment to take the same shape that the tip had at a given insertion depth.

In recent years great interest is focused towards endoscopic capsules. These devices allow wireless and painless examination, but external control by the endoscopist is not possible, thus resulting in limited therapeutic possibilities. Many researchers are working on this problem and one of the most promising options seems to be the use of magnetic fields. Olympus is developing a new navigation system based on electromagnetic fields [4], even if this is not yet available on the market.

The present paper is organized as follows: Section II illustrates the concept of the capsule steering mechanism and the dimensioning of the system, taking into account also the external magnetic field generation. Section III describes the design of the steering capsule prototype, the fabrication steps and the integration of the overall capsule including the vision system. The characterization of the device and preliminary in vitro, ex vivo and in vivo tests are reported in Section IV. Finally, conclusions and future works are outlined in Section V.

II. WIRELESS MAGNETIC STEERING MECHANISM

A. Mechanism Concept

The magnetic internal mechanism (MIM) combines one internal degree of freedom, obtained by an electromagnetic motor, with the magnetic force produced by a combination of internal and external magnets. This device allows to finely steer the capsule in a scenario of magnetic locomotion [5-6]. In fact, a rough position along an intestinal path can be achieved by dragging the capsule with the motion of an external permanent magnet, while a fine orientation (e.g. for moving the vision system) can be obtained by stopping the external magnet and by exploiting the internal capsule mechanism, as better illustrated in the next pictures.

In the current version (Fig. 1), the MIM capsule body hosts one motor (Namiki Precision Jewel Co., Japan), two small permanent magnets diametrically magnetized (N52 NdFeB, Supermagnete, Switzerland), a camera (Misumi Co., Taiwan), a battery (3.7 V, 20Ma/h, Plantraco, Canada) and an electronic circuit for control and wireless communication. The whole system includes a large external permanent magnet (N35 NdFeB, B&W Technology & Trade GmbH, China) and a PC workstation, which interacts with the

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capsule to receive and transmit commands and data in wireless mode.

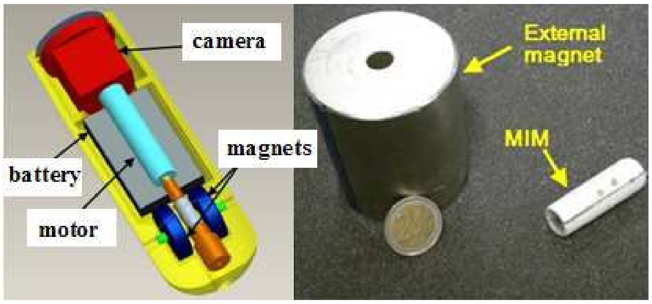

Fig. 1. The internal components of the capsule (left) and the external permanent magnet used for dragging the capsule and for generating the static magnetic field for the MIM actuation (right).

The motor is connected to a worm gear. When the worm gear rotates, it transmits the motion to a toothed gear. Being the small magnets glued with the toothed gear, they rotates with motor activation (Fig. 2).

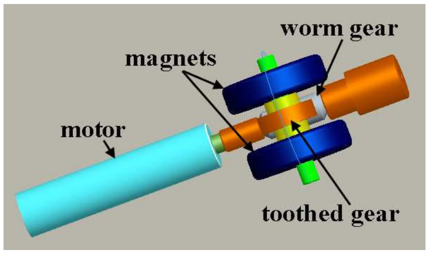

Fig. 2. The main components of the internal mechanism.

When the system is immersed in an external magnetic field **B**, the magnets tend to maintain a precise alignment with **B**, based on their position of north and south poles. If the magnetic force is enough to withstand the torque induced by the motor, thus the entire capsule rotates with the motor, while the internal magnets remain still oriented as **B** (Fig. 3 and Fig. 4).

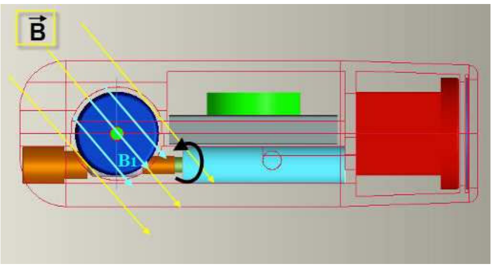

Fig. 3. The working principle of the MIM capsule. The yellow arrows represent the external static magnetic field (**B**), not necessarily uniform in the space as illustrated in the picture. The blue arrows correspond to the internal magnetic field $\mathbf{B_1}$.

In order to rotate the capsule, two options are available: either to activate the internal mechanism, or to rotate the external magnet. The second choice would require using an external big motor with a high torque. On the other hand, the use of an internal motor allows both flexibility and velocity, employing magnets that produce low magnetic fields. Moreover, in the present configuration, the external magnet does not require fine positioning: it can be moved manually or by a simple hold, thus reducing cost and space for robotic support and position control.

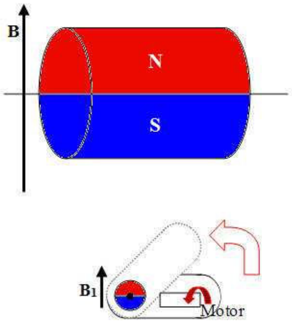

Fig. 4. The rotation of the MIM capsule with the motor activation, in relationship with the external magnet.

B. *Dimensioning of the system*

The magnetic link between the external and internal magnets was simulated through Finite Element Method (FEM) analysis software (Comsol Multiphysics). The magnetic attraction force between the external magnet and the internal small magnets at a distance of 15 cm is about 0.5 N. The magnetic flux density on both the patient and the medical operator is within the exposure limits (2 T for ceiling value and 200 mT for whole-body continuously exposure) listed in [7].

The capsule motor has to be small enough to be embedded in a swallowable capsule and should generate enough torque to move the capsule body around the magnetic link between the external magnet and the internal magnets against gravity. The torque required for moving the capsule body is 3,45 mNm, by considering a capsule mass of 14.4 g and an average distance between the capsule rotation pivot and the center of mass of 24 mm. In order to fulfill these requirements a Namiki motor with a stall torque of 5.7 mNm, 4 mm in diameter and 19 mm in length has been selected (SBL04-0829).

The residual magnetic fields of the external and internal magnets are respectively 1.2 T and 1.48 T.

III. DESIGN AND FABRICATION

The external body of the first prototype was fabricated in an acrylic resin by rapid prototyping. The motor is connected with a steel worm gear, while two cylindrical magnets (9 mm in diameter and 2.5 mm in height) are glued to the brass toothed gear (Fig. 5).

Fig.5. Half capsule body shell with the MIM.

A commercial wired camera (9 mm x 9 mm x 11 mm) was used for this preliminary prototype; it will be replaced by a smaller wireless camera (purposely developed) in the final capsule.

The minimum rotation θ that the MIM can perform depends on the driver control, the motor reduction and the gear transmission rate.

It can be calculated as:

$$\theta = \alpha \cdot \beta \cdot \tau \cdot 360° \approx 0.01° \qquad (1)$$

where:

$\alpha = 1/6$ motor revolutions controlled by the driver;
$\beta = 1/337$ motor gearhead reduction ratio;
$\tau = 1/18$ gear ratio.

Theoretically, it is possible to control the angle with a precision up to about 0.01°. Practically, the current PC workstation can achieve the precision of 1.8° in the angular control, which is suitable anyhow for a correct diagnosis, based on endoscopists indications. Depending on the peculiar application, the accuracy could be increased up to the theoretical limit.

The magnetic field generated by the internal magnets and by the external magnet could interact with the motor internal coils, thus compromising its efficiency. For this reason, we performed a FEM simulation (Fig. 6) of the magnetic potential induced by the internal magnets onto the motor axis. The colour areas represent the magnet poles (red = north, blue = south). The small red arrows around the magnets highlight the magnetic flux density generated by the internal magnets.

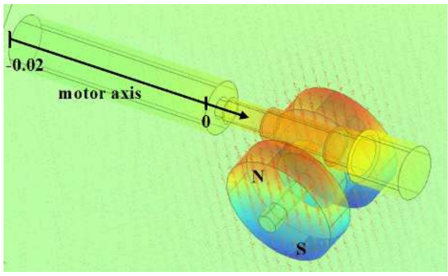

Fig. 6. Simulation of the magnetic field generated by the circular internal magnets.

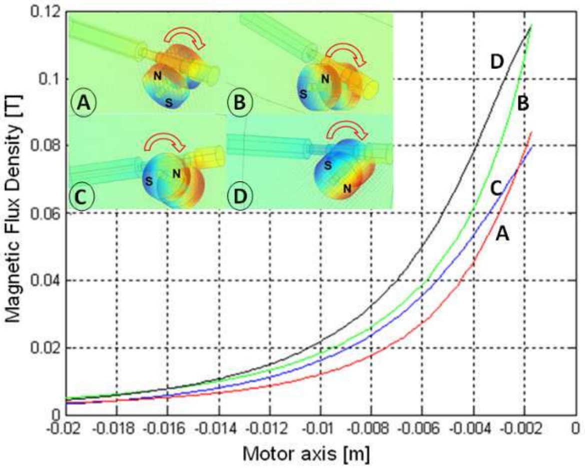

Fig. 7. Graph of the magnetic flux density generated by the internal magnets on to the motor axis.

The value of the magnetic flux density has been calculated on the motor principal axis, as illustrated in Fig. 7. The magnetic flux density decreases with the distance *d* from the magnets as $1/d^3$, yielding values ranging from 0 T to 0.12 T on the Namiki motor. When the magnets rotate, the north and the south poles approach alternatively the motor. This results in small variations in the field values for different positions: the different colour lines represent these different configurations. However, the field behaviour has the same trend for all the positions. From experimental tests it was evident that such field does not affect the motor functionality.

The effect of the external magnet onto the motor has been estimated by simulations as 12 times smaller than the effect of the internal magnets, because of the large operating distance (about 15 cm).

IV. CHARACTERIZATION AND TESTS

A first set of tests has been performed to verify the correct operation of the magnetic internal mechanism (MIM) capsule in free space, without any external forces except for gravity force and magnetic force. The external magnet was placed in the vicinity of the MIM (15 cm) and the device was operated by wireless command transmission. As represented in Fig. 8, a precise adjustment of the camera orientation was achieved.

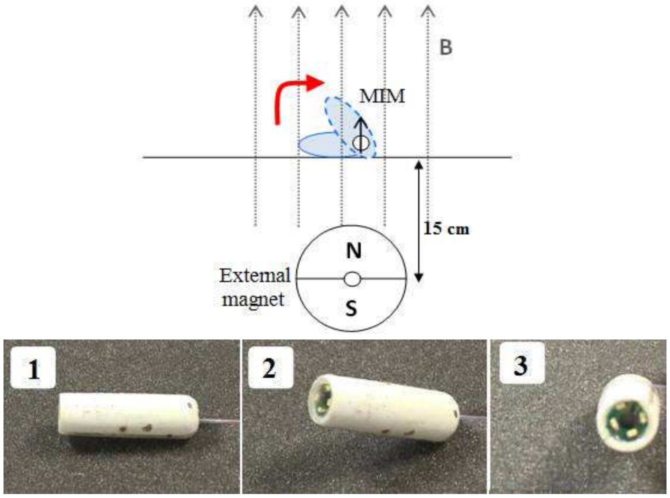

Fig. 8. MIM test on free space: three consecutive steps. The MIM and the external magnet are positioned respectively upon and under the surface of a table.

The MIM was then tested in a phantom setup by using fresh porcine colon. The capsule was moved through the colon with the external magnet, as shown in Fig. 9. Upon stopping the capsule, the internal mechanism was activated to assess the possibility of fine adjustment of the positioning angle. The following preliminary results were obtained during the experiments:

1. The telemetric link worked properly up to 2 m [8].
2. The rotation of the internal magnets allowed a fine adjustment of the capsule between 1.8° and 360°.

3. The force generated by the magnets looked appropriate for the task.

Finally, the approach to rotate the capsule by rotating its internal permanent magnets turned out to be feasible and reliable.

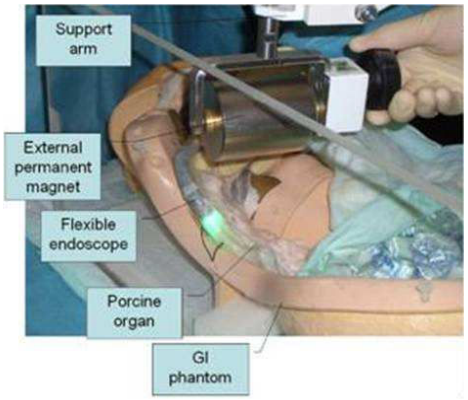

Fig. 9. The experimental phantom set-up.

We acquired a video inside the explanted colon by using a flexible endoscope introduced frontally respect to the MIM capsule. Some photo-frames taken during the MIM testing session are shown in Fig. 10. Two coloured markers (red and black) were positioned on two different locations on the lumen. The markers are 2 mm in diameter and are located at a distance of 50 mm, corresponding to an angular distance of 180°. With this setup, we tried to evaluate the ability of the capsule on-board camera to visualize in a controllable way the two markers in sequence. The first set of pictures (Fig. 10 top) reports the endoscopic view in three consecutive steps of the MIM rotation. The second set (Fig. 10 bottom) shows the same three consecutive steps recorded by the capsule video camera. We can observe that the vision angle changes, thus allowing a fine orientation for the vision module.

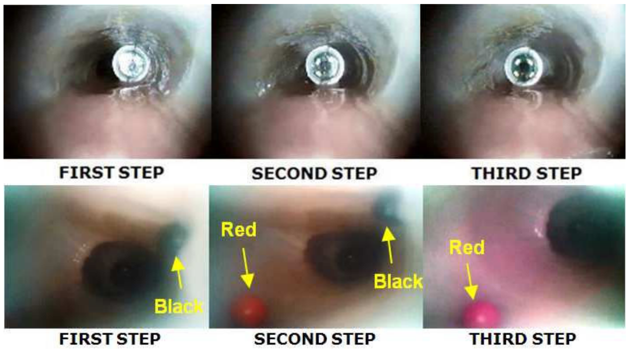

Fig. 10. *Ex-vivo* test in porcine colon. Endoscopic view (top) and on-board camera view (bottom).

After completion of the phantom trials, the capsule was assessed in an in vivo experimental session. The feasibility study was carried out on a domestic female 50 kg pig. The experiments were done in an authorized laboratory, with the assistance and collaboration of a specially trained medical team, in accordance with all ethical considerations and the regulations related to animal experiments. The capsule was observed by using a flexible endoscope, which was kept at some distance from the operative location, in order not to affect the positioning and movement of the wireless capsule. The MIM allowed a panoramic orientation of the field of view and a precise camera steering, focusing on different areas of the mucosa under operator guidance. The time required to inspect back and forward 40 cm of the colon was of about 10 minutes. At the end of the entire experimental protocol, the capsule remained fully functional and the mucosa was not damaged. The tests demonstrated that the capsule was able to work reliably also in an in vivo environment.

V. CONCLUSIONS

This paper has illustrated a smart magnetic mechanism for wireless endoscopic capsule steering, that has the potential to be integrated in many endoscopic devices. The system is precise, agile and robust, as demonstrated by many in vitro and in vivo tests.

Future efforts will be devoted to the set up of a user friendly interface for making the motor control more intuitive for physicians. A purposely developed graphic interface - showing for each motor step the simulated position of the camera - would be of great benefit for correct capsule positioning and diagnosis.

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