Electromagnetic design for capsule endoscope navigation: a preliminary study

A cost effective and minimally invasive capsule endoscopy strategy

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***Abstract*— The gastrointestinal tract is home to some of the most deadly human diseases. Problems are related to the difficulty of accessing it for diagnosis or intervention and concomitant patient discomfort. Flexible endoscopy has established itself as the method of choice with high diagnostic accuracy, but there remain several technical limitations and the procedure is poorly tolerated by patients. The use of magnetic fields to control and steer endoscopic capsules is increasing in minimally invasive surgical applications. In fact, magnetic coupling is one of the few physical phenomena capable of transmitting motion beyond a physical barrier and allowing for a compact design of the "slave" device. In this framework, the authors present a preliminary study for the design of a magnetic coupling for magnetic endoscopic capsules considering an electromagnetic approach within the EU SUPCAM project. In particular the target was to maximize the magnetic interaction forces and torques induced by the external electromagnetic source on the endoscopic capsule embedding an internal permanent magnet, still complying with the limitations imposed by the specific applicative scenario.**

Keywords—gastrointestinal endoscopy, magnetic medical devices, electromagnets design, robotic magnetic guidance.

I. Introduction

Today, colonoscopy and gastroscopy with flexible endoscopes are the standard examination procedure for the gastrointestinal tract (GI). These techniques are fairly reliable and provide high-resolution images stream that enable accurate diagnosis. However, these techniques entail also several drawbacks [1]. First, the physician needs much practice to acquire the necessary dexterity to manipulate the endoscope. Second, movements done by the endoscope inside the body are frequently painful and traumatic and poorly tolerated by patient. Wireless capsule endoscopy (WCE) has become a useful diagnostic tool that enables clinicians to study the GI tract and reduce patient discomfort since its introduction in clinical practice in 2001 [2]. It consists of a small capsule with an embedded camera that is swallowed by the patient and transmits its images towards a storage device outside the body. Several companies produce "smart camera pills", but they still have two major limitations. As an intrinsic limitation, WCE does not allow the operator to control the navigation and the capsule proceeds by means of visceral peristalsis and gravity. This makes the trajectory of the capsule purely uncontrollable and unplanned, so that some portions of the GI surface are unlikely to be visualized. Another drawback of WCE is represented by the fact that, if areas of clinical interests are identified, the endoscopist cannot manoeuvre the capsule locally (back and forth, right and left) for detailed inspections. Therefore, solving the manoeuvring problem might significantly enhance the accuracy of the endoscopic investigation with an expected improvement of diagnostic efficacy. The use of magnetic-based systems for actuation and localization of endoscopic capsules in the GI tract has become an active area of research and it represents a good approach to solve the problem of control [3]. Magnetic forces and torques provide an efficient actuation solution whenever traditional motors cannot be integrated in medical devices for powering and size constraint [4-6]. Two different approaches, that can be used to generate magnetic forces and torques for achieving the magnetic control of a magnetic capsule, are the use of one or more permanent magnets [4, 5] or electromagnets [6]. Nevertheless, despite the growing scientific interest in magnetically controllable WCE, no effective systems with straightforward clinical applicability have been yet demonstrated. This is ascribable to a lack of reliable magnetic coupling between magnetic capsule and external magnetic source and to the difficulty to fine localize and control locomotion by means of magnetic fields. A significant example of magnetic capsule locomotion and orientation was pursued within the VECTOR project [7] that brought to the development of three endoscopic magnetic actuated capsules (Fig. 1).

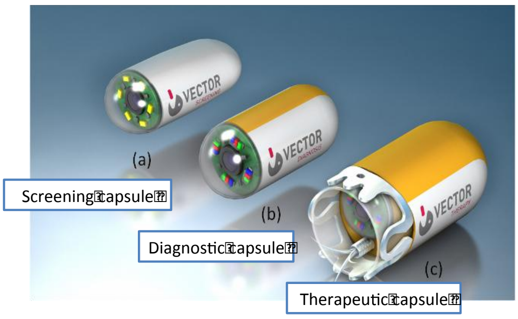

Fig. 1. VECTOR project capsule concepts, *i.e.* (a) screening, (b) diagnostic and (c) therapeutic capsule.

In this paper, the authors investigated and preliminary designed the magnetic coupling for magnetic WCE considering an

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electromagnetic approach within the SUPCAM project [8]. In particular, starting from the background and knowledge of permanent magnets design, maturated within the VECTOR project, the target was to maximize the magnetic interaction forces and torques induced by the external electromagnetic controllable source on the endoscopic capsule with an internal permanent magnet, still complying with the limitations imposed by the environment.

II. MAGNETIC LOCOMOTION FOR MAGNETIC WCE

A magnetic capsule will experience both a torque and a force within an external induced magnetic field with flux density B (T). The magnetic torque τ (Nm) can be expressed as [9]:

$$\tau = VM \times B = V\begin{bmatrix} M_x B_x \\ M_y B_y \\ M_z B_z \end{bmatrix} \quad (1)$$

where V (m^3) and M (A/m) are the volume and the magnetization of the object, respectively. This torque tends to align the magnetization of the magnetic capsule to the applied external magnetic field. The magnetic force F (N) on the magnetic capsule is represented by:

$$F = V\nabla BM = V\begin{bmatrix} M_x \frac{\partial B_x}{\partial x} + M_y \frac{\partial B_y}{\partial x} + M_z \frac{\partial B_z}{\partial x} \\ M_x \frac{\partial B_x}{\partial y} + M_y \frac{\partial B_y}{\partial y} + M_z \frac{\partial B_z}{\partial y} \\ M_x \frac{\partial B_x}{\partial z} + M_y \frac{\partial B_y}{\partial z} + M_z \frac{\partial B_z}{\partial z} \end{bmatrix} \quad (2)$$

Equations (1) and (2) are based on the assumption that the magnetic capsule is small compared to the spatial changes of the applied external magnetic field's flux density B. Under this assumption, B can be considered fairly uniform within the capsule. Hence, assuming that the capsule has spatially homogeneous magnetic properties, B represents the value of the applied magnetic field's flux density in the centre of mass of the object. These torques and forces can be generated by using either permanent magnets or electromagnets. Both approaches have advantages and disadvantages to control the locomotion of a magnetic capsule. Although the first approach represents a cheap and flexible solution, adequate navigation accuracies are very difficult to achieve due to the impossibility to modulate the generated field. Since permanent magnets generate fixed magnetic fields, both precision and accuracy depend on their fine motion. The second strategy, employed within the SUPCAM project, can lead to a higher navigation precision, fine control of produced magnetic fields and consequently definition of specific forces that can be obtained by modulating the intensity of the current flowing through the electromagnet itself. Moreover, the safety of the patient and physician is increased because the magnetic coupling can be reduced or, in the case, turned off by switching off the remote power supply. However, cumbersome electromagnetic coils and high currents may be required in order to generate adequate magnetic fields and unwanted heating should also be considered.

III. REQUIREMENTS AND SCENARIO FOR MAGNETIC WCE

The SUPCAM endoscopic platform will allow performing an endoluminal medical examination through an external control magnetic system with a compact and simple manipulation structure, inexpensive, and usable in normal outpatient setting, able to ensure an accurate diagnosis of the colonic mucosa. Therefore, within the design phase of an external electromagnet, representing the locomotion external source, compactness has to be considered; the electromagnet has to be adapted to be transported and easily controlled by the physician for generating a proper link with the endoscopic device. In particular, suitable forces and torques for navigation and visualization against a high frictional deformable environment have to be generated in a narrow range of distance between the external magnet and the endoscopic device due to the abdominal thickness. Moreover, for a fine control of pitch (visualization of upper and lower wall of the colonic lumen) and yaw (visualization of right and left wall of the colonic lumen) orientations of the capsule (range of around ± 90°) specific magnetic torques have to be exerted on the capsule system.

In this framework, to perform an effective and reliable magnetic locomotion capsule endoscopy, a modular solution was investigated: it consists in the use of a cylindrical-shape electromagnet supported by a 5 degrees-of-freedom (DoFs - 3 for translation and 2 for the electromagnet orientation) manipulator for gravity compensation and accurate remote or local control (Fig. 2a). The electromagnet will be employed in two different configurations: for an initial attraction phase of the capsule (configuration C1 in Fig. 2b - magnetization direction perpendicular to the abdominal wall) and for a locomotion and orientation phase (configuration C2 in Fig. 2c - magnetization direction parallel to the abdominal wall). For a geometric distribution of magnetic field vectors, the configuration C1, reported in Fig. 2b, allows (with the same amount of current) for a higher magnetic gradient along the attraction axis, pointing to the capsule and perpendicular to the patient abdomen, with respect to the configuration C2 in Fig. 2c. However, in configuration C1, it is not possible the yaw DoF because of the axial symmetry of the electromagnet. Therefore, the configuration C1 has to be considered only in the use at the beginning of the procedure for capturing the capsule (a target distance of 100 mm was considered for the magnetic design) but not for the locomotion and the continuous inspection of the colon. Once attracted, a ±90° pitch rotation of the electromagnet (with the magnetization direction parallel to the abdominal wall) can allow for the shift to the configuration C2, resulting in a closer capsule-electromagnet control and thus preserving for a lower amount of current needed for capsule attraction and then locomotion and orientation. In configuration C2, due to the occurred attraction of the capsule from the bottom of the colonic tract, a reduction of about 20 mm (half of the average diameter of the colonic district, resulting in a target distance of 80 mm) in the distance between the electromagnet and capsule can be considered, as a specific design hypothesis. In this configuration, the current provided to the electromagnet is sufficient to maintain the attraction of the capsule for locomotion (in C2 the capsule reaches the centre of the electromagnet for orientation purposes). In the next sections the design and the definition of the electromagnetic specifications

for the magnetic locomotion of the SUPCAM capsule are investigated and presented in details.

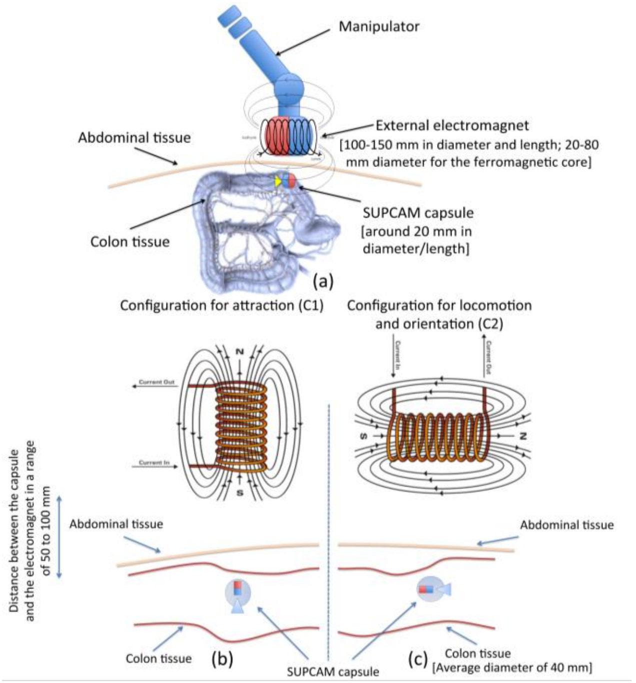

Fig. 2. (a) Schematic representation of the navigation SUPCAM platform, and (b) attraction and (c) locomotion and orientation configurations of the electromagnet.

IV. ENDOSCOPIC CAPSULE

The SUPCAM endoscopic capsule integrates a permanent magnet to achieve a magnetic control for locomotion and orientation, in the interaction with the external electromagnetic source. Considering that the dimensions of the internal magnet have to be compatible with the space constraints and other embedded components (*e.g.*, battery, electronics boards, telemetry, camera, etc.), and considering the required DoFs for a diagnostic system, a cylindrical-shaped axially magnetized permanent magnet with a volume of at least $4x10^{-7}$ m^3 was preliminary selected to be incorporated into the capsule. A neodymium magnet (NdFeB, N52, magnetization equal to 1.48 T) was chosen because neodymium magnets are the strongest types of permanent magnets available and it allows reducing dimensions and/or current of the electromagnet. A rough yet conservative weight prediction for such a device may be two times the PillCam weight (around 4 g), considered a golden standard for capsule endoscopy. Considering all these issues, the targeting magnetic link should be able to navigate a device having a weight of at least 8 g in terms of attraction (at least 78.4 mN that the electromagnet must exert on the wireless device in both the configurations), dragging forces and magnetic torques for orientation. Fig. 3 reports a schematic representation of the attraction and locomotion forces relevant in the configuration C1 and C2, respectively. The equilibrium of the acting forces for allowing attraction and locomotion of the SUPCAM capsule are also reported and they were considered, subsequently, in the electromagnetic design.

V. MAGNETIC CONTROL BY USING AN ELECTROMAGNET

In this approach, the endoscopic capsule is controlled by an external magnetic source consisting of an electromagnet. The electromagnetic source is moved, supported by a robotic manipulator, by the physician in order to achieve high accuracy and reliability. With regards to the SUPCAM capsule conservative weight prediction and basing on Eq. (2), the electromagnet should produce a magnetic field gradient of at least 0.17 T/m at a distance of 100 mm in the case of the configuration C1 and 80 mm for configuration C2. In this framework, the electromagnetic system design entails sophisticated analysis and definitions of physical qualities resulting in a substantial trade-off in the parameters selection (*e.g.*, power, current, resistance and dimensions of copper wire, and number of turns). The aforementioned parameters, strictly depend on each other and system design constraints, have to be preliminary fixed with regards to the operating conditions in order to derive the electromagnetic source system performance. The magnetic field gradient is proportional to the total number of winding (N_{tot}), and it is represented by the formula:

$$\nabla B \approx \frac{N_{tot} I}{\phi^2} \qquad (3)$$

where I (A) is the current and ϕ (m) the copper wire diameter. N_{tot} can be derived by the following equation that reports also the dependence between the system design parameters:

$$\frac{\pi\varphi^2}{h} N_{tot}^2 + 2r_{\min} N_{tot} - \frac{P\pi\phi^2}{4I^2\rho} = 0 \qquad (4)$$

where P (W) represents the power, h (m) the height of the electromagnetic system, r_{min} (m) the inner hole radius, and ρ (A/m) the resistivity parameter of copper. An important parameter that was considered in the electromagnet design is represented by the maximum current density, defined as a vector whose magnitude is the electric current per cross-sectional area. In electrical wiring, the maximum current density can vary from $4Amm^{-2}$ for a wire with no air circulation around it, to $6Amm^{-2}$ for a wire in free air.

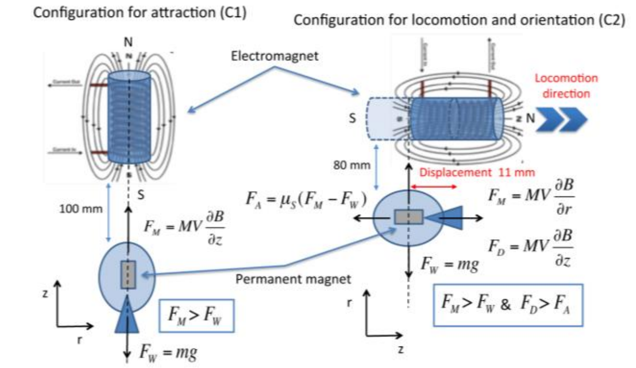

Fig. 3. Schematic representation of the attraction and locomotion forces in the configuration C1 and C2, respectively. μ_S is the static friction coefficient, F_A the friction force, F_M the magnetic attraction force, F_W the weight force and F_D the locomotion force.

For compact designs, such as windings of transformers or electromagnets, a current density value in the range of 2 to 3

Amm^{-2} is recommended; higher current density can be allowed for a short time or with the combination of a properly designed cooling system. The aforementioned formulas were exploited for the design of the electromagnet and a FEM analysis (with COMSOL Multiphysics Inc.) was performed to evaluate the magnetic field gradient (Fig. 4). In particular, based on Eq. (3) and Eq. (4), a cylindrical shaped electromagnet, 150 mm in diameter and 150 mm in length, with a copper wire section of 8.4 mm^2 (920 total windings) and an internal ferromagnetic core of 20 mm in diameter (weight of around 15 Kg) was selected as a compatible and suitable candidate for the magnetic control of the SUPCAM capsule.

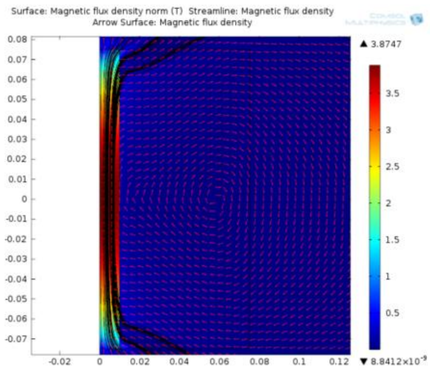

Fig. 4. 2D FEM simulation of the electromagnetic system by COMSOL.

Required magnetic forces and torques for managing the medical procedure in the applicative scenario can be generated by the electromagnetic system in order to guarantee the navigation of the SUPCAM capsule. Specific minimum electrical and physical requirements for the electromagnet are reported in Table I.

	Current (A)	Current density (A/mm^2)	Force (mN)	Distance (mm)
Attraction - C1	12.4	1.36	78.4	100
Attraction - C2	36.2	3.97	78.4	80
Locomotion - C2	37.6	4.12	85.1	80

Table I. Minimum electrical and physical requirements in terms of current, current density, force at the distances for the configurations C1 and C2.

A higher current of at least 36.2 A (current density of 3.97 A/mm^2) has to be imposed for maintaining the capsule attracted once the electromagnet is rotated of ± 90° (pitch angle) switching from the configuration C1 to the configuration C2 due to the different magnetic field profile in the operating space. In the configuration C2, a current of 37.6 A (resulting in a dragging force of 85.1 mN) has to be supplied for locomoting the capsule, displacing the electromagnet along the lumen locomotion direction half of the capsule diameter (11 mm) from the capsule itself. The current value was figured out taking into consideration the possibility to face an opposite sliding frictional force (equal to 78.1 mN) with a conservative static frictional coefficient of 1. Finally, the electromagnet in the configuration C2 allows, with a current of 36.2 A at a distance of 80 mm, a considerable magnetic torque in the order of 5 Nmm for pitch and yaw capsule orientation. These values are much larger than the system inertial momentum, therefore the dynamics of orientation could be neglected and the capsule is aligned nearly instantaneously with the magnetic field of the electromagnet.

VI. Discussion and Conclusion

Starting from the knowledge of permanent magnetic design in GI procedures maturated within the EU VECTOR project, a preliminary magnetic design of an electromagnetic system was performed for locomotion and orientation of an endoscopic capsule for diagnostic procedures in the colonic district. Target magnetic attraction/locomotion forces and magnetic torques were derived for the electromagnetic source design in order to guarantee a reliable navigation of the colonoscopic capsule. The presented electromagnetic design will bring to the development of a physical electromagnetic source; the data obtained in the modelling process will be evaluated by a direct field measurement analysis exploiting a magnetic field measuring probe for evaluating the correctness of the design model. Then, tests will be performed with the developed electromagnetic source with the SUPCAM capsule in *in-vitro* and *ex-vivo* conditions in order to evaluate the magnetic navigation principle and test the electromagnetic system in the project framework. Tests will also guarantee the potential tuning of the system and the need of a cooling system will be evaluated with regards to the real operating condition and required forces for navigation (especially for configuration C2). Due to the high weight of the electromagnetic system (around 15 Kg), a 5 DoFs robotic manipulator will be designed for holding and accurately moving the electromagnetic source by the physician. The use of a controllable manipulator and the possibility to tune the supplied currents in the electromagnetic system will bring to the implementation of an accurate navigation strategy of the SUPCAM capsule, in combination with the knowledge of the position of the device thanks to the development of a localization system [10].

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