IOSR Journal of Computer Engineering (IOSR-JCE)
ISSN: 2278-0661, ISBN: 2278-8727, PP: 63-68
www.iosrjournals.org

Robotics in Biomedical

Mr. Patil Rahul M.[1], Mr. Sanadi Rajesh A.[2], Mr. Patil Abhijit N.[3]
Mr.Chougule Pradip A.[4]

[1](Department of Information Technology, Dr.J.J.Magdum College of Engineering, Jaysingpur ,India)
[2](Department of Information Technology, Dr.J.J.Magdum College of Engineering, Jaysingpur, India)
3(Department of Information Technology, Dr.J.J.Magdum College of Engineering, Jaysingpur, India)
[4](Department of Computer Science & Engineering, Dr.J.J.Magdum College of Engineering, Jaysingpur,)

ABSTRACT: *The aim of this paper is to describe the architecture and report a preliminary testing of a robotic magnetic navigation system that may serve to enable accurate GI endoscopic explorations with magnetically controllable video capsules. The robotic system considered here was recently developed for completely different (cardiovascular) applications, in order to safely maneuver endocardial catheters. The potential suitability of this type of system even for GI explorations, and in particular for controlling endoscopic capsules, was previously suggested, but never demonstrated. Following this suggestion, this paper describes the first investigation on the potentialities (and also the limitations) of the considered robotic system for such a possible new application, studied from both a theoretical and an experimental point of view.*

Keywords- *Capsule, Endoscopy, Magnetic Maneuvering*

I. INTRODUCTION

In its original sense, the term navigation applies to the process of directing a ship to its destination. This process consists of three repeating steps (a)the navigator determines the ship's position on a chart as accurately as possible; (b) on the chart, he relates his position to the destination, reference points and possible hazards; (c) based on this information, he sets the new course of the vessel.

The nautical practice of navigation has entered almost unchanged into the domain of robotics. For instance, Levitt and Lawton define navigation as a process answering the following three questions: (a) "Where am I?" (b) "Where are other places with respect to me?" (c) "How do I get to other places from here?". Applied to robot navigation, this means that the robot's sensory inputs are used to update a single global representation of the environment, from which motor actions are derived by an elaborate inference procedure. This view of navigation has not only been adopted in standard robotics textbooks but also forms the basis for many robot navigation systems.

None of these systems has yet reached the flexibility and navigation performance of bees or ants, let alone migrating birds or fish. This has motivated robotics researchers to look for biological navigation mechanisms that can be implemented on an autonomous mobile robot. Out of the large number of biomimetic approaches to navigation, we have chosen a subgroup for this review, namely those that (i) were implemented on a real mobile robot, and (ii) mimic actually observed navigation behavior of animals or humans.

II. THE NAVIGATION HIERARCHY :

The navigation hierarchy is based on the classification scheme of Trullier et al. Which we have modified and extended. In this hierarchy, navigation behavior is classified according to the complexity of the task that can be performed. Thus, each level is characterized by a certain navigation competence which can be tested experimentally. Local navigation behaviors are divided into four levels: search, direction-following, aiming and guidance; way-finding behaviors into three levels: recognition-triggered response, topological and survey navigation.

1.1. Search

An agent navigating by search alone shows no active orientation towards the goal (Fig. 1(a)). The goal can only be found by chance if the agent hits it while moving around. This simplest form of navigation requires only the basic competences of locomotion and goal detection, without the need of any type of spatial representation. Search requires a large amount of time compared to other navigation methods. Since the direction towards the goal needs not to be known, search can serve as a backup strategy when the agent cannot find its goal.

2.1. Direction-following and path integration

For this type of navigation behavior, the agent must be able to align its course with a locally available direction to find the goal. The goals itself need not to be perceivable during approach. An example of this behavior would be a ship setting its course along a fixed compass direction leading to the goal. Direction information may be extracted either from allothetic (based on an external reference) sources such as the magnetic field, celestial cues or odor trails, or from idiothetic (based on an internal reference) sources such as an inertial compass or proprioreceptive signals. Whereas direction following is more effective than search, it allows the agent to find the goal only when it moves on the trail defined by the direction.

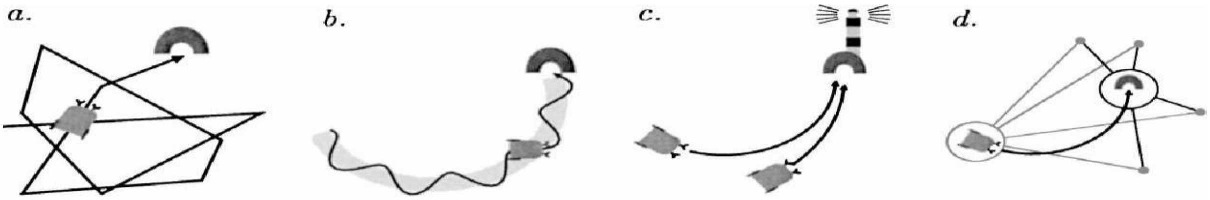

Fig. 1. Local navigation behaviors:

(a) A searching agent shows no active goal orientation. (b) Direction-following allows an agent to find the goal along a trail. (c) Aiming needs a salient sensory cue at the goal. (d) Guidance enables an agent to find a goal defined by the spatial relationship to the surrounding objects

III. INTRODUCTION TO CAPSULE ENDOSCOPY

ENDOSCOPIC explorations of the digestive tube are traditionally performed by means of probes introduced into the oral or rectal cavities. This well-established and nonsurgical technique enables detailed and reliable investigations. Nevertheless, this is achieved at the price of a considerable invasively, typically ill- tolerated by patients. In order to overcome such a drawback, endoscopic capsules, also called video capsules, were introduced in the clinical practice a few years ago. They consist of ingestible capsules equipped with miniaturized components for illumination, image capture, wireless data transmission, and power supply. Following its ingestion, visceral peristalsis and gravity transport the capsule along the digestive tube, until it is naturally expelled out of the body. During its motion, the device automatically takes pictures and sends data wirelessly to an external recorder, attached to the patient’s waist. The collected video frame sequence is viewed offline afterwards.

Capsule endoscopy is progressively emerging as a noninvasive effective tool for explorations of the gastrointestinal (GI) tube. It is particularly useful to reach inaccessible regions precluded to standard probe endoscopy, due to their excessive distance from the natural orifices. Accordingly, capsule endoscopy particularly shows a great potential for the exploration of the small bowel. Despite its demonstrated clinical value, this technique cannot be regarded today as an equivalent alternative to traditional probe endoscopy.

IV. PROPOSED TECHNIQUE

The proposed technique to control the movement, the position, and the orientation of an endoscopic capsule by means of an external magnetic field relies on a system that comprehends the following parts.

1) A magnetic component to be applied to the capsule in order to make it responsive to the magnetic field. This component could be either irreversibly integrated inside the capsule or reversibly applicable to it. In this work, a magnetic shell was applied to the capsule externally.

2) A controllable source of magnetic field in order to magnetically maneuver the capsule from the exterior of the body during the endoscopic exploration. In this work, a= robotic system for magnetic navigations was used.

3) An imaging system to monitor the navigation of the capsule. In this work, fluoroscopy (X-rays) was used, since it was already integrated within the magnetic navigation system.

V. BASIC CONCEPT OF THE PROPOSED TECHNIQUE

The video capsule used in this work was the commercial model M2A produced by Given Imaging Ltd., Yoqneam, Israel as shown in Fig. 1(a). In order to easily obtain a magnetically controllable device, an externally applicable magnetic shell for this capsule was considered as a proof-of-concept prototype solution. The structure and the magnetization configuration of the shell are presented in Fig. 1(b). In particular, the shell consists of two semi cylindrical parts, whose uniform diametral magnetizations have two main functions: they permit to secure the shell to the capsule and they provide the capsule/shell complex with a resultant magnetization (magnetic dipole moment) orthogonal to the capsule axis of symmetry, suitable for control purposes. Fig. 1(c) and (d) describes the internal parts of the capsule. As shown in Fig. 1(d), the envisaged shell covers just the cylindrical body of the capsule, while leaving uncovered not only the frontal part (to allow vision) but also the rear part (to avoid a shielding of the RF antenna). The shell dimensioning is reported in next section.

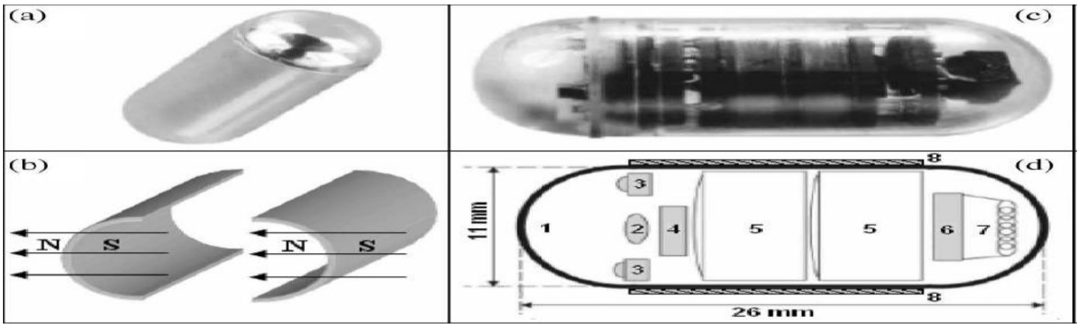

Fig. 2. Video capsule and proposed magnetic shell.

(a) Given Imaging M2A capsule.
(b) Drawing of the two semi cylindrical parts of the considered shell.
(c) Picture of the internal arrangement of the capsule.
(d) Schematic sectional drawing of the device components: 1: optical dome, 2: focal lens, 3: white LEDs, 4: CMOS imager, 5: batteries, 6: application-specified integrated circuit (ASIC) transmitter, 7: RF antenna, and 8: magnetic shell

VI. ROBOTIC SYSTEM FOR MAGNETIC NAVIGATION

The controllable source of magnetic field used in this work was the commercial Niobe magnetic navigation system produced by Stereotaxis, Inc., St. Louis, MO. This robotic system has been recently developed for different purposes, dealing with diagnosis and treatment of cardiovas- In particular, since a few years, it is employed to steer magnetically enabled catheters and other disposable interventional devices within the heart chambers or the coronary vasculature. For this purpose, it delivers a controlled field generated by two large coaxial permanent magnets, mounted on automatically operated arms. The magnets are arranged on both sides of the patient's table, as shown in Fig. 2.

The magnetic sources create a rather uniform field, whose orientation can be controlled inside a virtual sphere with a diameter of 20 cm. In fact, the magnets can be rotated inside their housings, and the housings themselves can be tilted. As a result, a magnetic element interposed between the two sources, within the control sphere, can experience 360◦ omnidirectional rotations according to the orientation of the controlled field, as schematically shown in Fig. 3. The model of the system used in this work delivers, within the control sphere, field strength of 0.08 T. The actual instantaneous position of the magnetically enabled tool being maneuvered inside the body can be monitored on demand, by means of an integrated digital scanner (Fig. 2) for fluoroscopic imaging .The clinical relevance of this navigation system and its capability of enhancing the efficiency and the efficacy of manual cardiovascular interventional procedures have been demonstrated by several works. The unique features of this instrumentation suggest its useful role as a possible platform for initial investigations on the magnetic controllability of endoscopic capsules, as described in the following sections.

Fig. 3. Niobe magnetic navigation system developed by Stereotaxis.
It includes the following.
(a) And (b) Couple of permanent magnets. (c) Fluoroscopic scanner.
(d) Visualization displays. (e) Patient's table

VII. MAGNETIC MANEUVERING PROBLEM: ANALYTICAL BACKGROUND

7.1. Rotations of Magnetically Enabled Capsule: Magnetic Torque

The application of a static magnetic field B (magnetic induction) on the shell exerts on it a magnetic torque Tm, given by the following general expression:

$$Tm = m \times B. \quad (1)$$

This torque tends to orient the vector m along B. By designating with γ, the initial angle between m and B [Fig. 4(a)], and θ, the magnetically induced rotation angle of the device around a fulcrum O (Fig. 4(b)), the modulus Tm of the magnetic torque is obtained as

$$Tm = m*B \sin(\gamma - \theta) = M*B*\pi (b2 - a2) L*\sin(\gamma - \theta). \quad (2)$$

The occurring rotation can be described in terms of an equivalent couple of magnetic rotational forces Fmr. Each of them can be considered to be applied to the centroid of the shell's half-volume on which it acts; due to the shell homogeneity, each centroid can be assumed at the middle point between the fulcrum and the shell extremity (Fig. 4(b)). This magnetic couple should act against a couple of frictional rotational forces Ffr (Fig. 4(b)), arising from the contact of the shell with the surrounding tissue. The modulus Ffr of each frictional force is given by,

$$Ffr = \mu * N/2 \quad (3)$$

Where N is the normal force exchanged by the overall capsule/shell complex with the contact surface

(thus, N/2 is the force exchanged by each half-volume of the device) and μ is the friction coefficient between the shell and the surface. The frictional forces give rise to an antagonistic frictional torque Tf , which tends to oppose the magnetic torque. Each force Ffr is applied on the same centroid of the magnetic force, so as to generate the following modulus Tf of the frictional torque:

$$Tf = Ffr * (L/2). \quad (4)$$

The rotation θ actually achieved by the capsule/shell complex will correspond to a new equilibrium state, characterized by the balance between the magnetic and the frictional torques, according to the following equilibrium condition

$$Tm = Tf \Rightarrow M*B*\pi(b2 - a2)* \sin(\gamma - \theta) =(1/4)*\mu*N. \quad (5)$$

7.2. Translations of Magnetically Enabled Capsule:Magnetic Force

The magnetically driven orientation of the device is also accompaniedby a tendency to translation, caused by the following magnetic force Fm applied to the shell by the field:

$$Fm = -\nabla U = \nabla(m \cdot B) \quad (6)$$

Where U is the magnetic potential energy. By neglecting any spatial variation of m, simple manipulations of (6) lead to the following expressions of the space components of Fm with respect to a system of Cartesian coordinates x, y, z:

$$Fmx = m \cdot \nabla Bx$$
$$Fmy = m \cdot \nabla By$$
$$Fmz = m \cdot \nabla Bz. \quad (7)$$

Accordingly, for a field applied along a given generic direction, the modulus Fm of the magnetic force acting on the capsule/shell complex is described by the following relation:

$$Fm = m \cdot \nabla B = M\pi(b2 - a2)L|\nabla B| \cos(\gamma - \theta). \quad (8)$$

VIII. FIELD GRADIENT CONTROL: FORCE MODULATION AND SAFETY ISSUES

As clearly described by (8), in general, the possibility of controlling the field gradient delivered by the instrumentation would be a very useful feature, since it would permit to vary, during operation, the magnetic force actually impressed to the endoscopic device. This would greatly enhance the maneuvering control performance by enabling precise displacements along preferential directions. For any position of the capsule, the delivered force should respect a suitable compromise between the following needs: functional holding of the capsule and safe loading of the tissue. The latter implies a maximum magnetic force that could be applied safely in order to avoid any overloading of the GI tissues. The worst condition, corresponding to the maximum allowed

deformation of the tissue (induced by the maximum applied gradient $|\nabla B|max$), might be approximately described as follows.

In this situation, let us assume that the magnetically held capsule/shell complex deforms the GI wall so that the latter approximately covers half of the total surface Stot of the device. By assuming Stot to consist of about two semispheres (of surface Ss−sph each) and one cylinder (of surface Scyl) (Fig. 4(a)), the maximum contact surface Scon,max can be estimated as

$$S_{con,max} \sim = (1/2) S_{tot} = (1/2)*(2S_{s-sph} + S_{cyl}) = 2\pi a2 + \pi bL. \quad (9)$$

Therefore, the stress applied to the tissue in the worst case, (Stress) wor, is described by the following expression:

$$Stress_{wor} = F_{m,max} \div S_{con,max} =.(M\pi(b2 - a\div 2)L|\nabla B) \div (max \cos(\gamma - \theta)/ 2\pi a2 + \pi bL) \quad (10)$$

Accordingly, the identification of a safe threshold for the applicable stress permits to obtain an indication on the maximum allowed field gradient to hold the capsule safely.

IX. MAGNETIC SHELL DIMENSIONING

In order to manufacture the shell, a neodymium-based magneticmaterial was selected, according to the highly performing magnetic properties typically exhibited by this class of compounds.

The dimensioning of the shell was performed by considering the following parameters as given constants: the capsule mass mc , the shell internal diameter a (capsule diameter), the field B (allowed by the instrumentation), the mass density ρs of the shell (proper of the selected material), and its magnetization M (maximum value allowed by the adopted manufacturing process), along with the friction coefficient μ (due to the specific properties of the interface between the shell and the GI surface tissues).

The shell design was aimed at identifying the most suitable values of the remaining geometrical parameters, b and L, able to make the problem specifications satisfied. In particular, a design strategy driven by the following main specifications was considered:

(1) Minimization of the misalignment $\gamma - \theta$, for any givenapplied field min of :

$$B \sin(\gamma - \theta) = (1/4)*[Mn/ M\pi(b2 - a2) . v] \quad (11)$$

(2) Maximization of the magnetic force Fm, for any given field gradient max of :

$$F_m/ |\nabla B| = M\pi(b2 - a2)L\cos(\gamma - \theta). \quad (12)$$

The first specification is aimed at maximizing the intrinsic rotational magnetic responsiveness of the endoscopic device against the frictional resistance (regardless of strength of the applied field), for an effective alignment with the field. The second specification is aimed at maximizing the intrinsic translational magnetic responsiveness of the endoscopic device (regardless of the strength of the applied field gradient); this choice is oriented at focusing design efforts more on the shell properties than on the instrumentation capability of generating field gradients with large amplitudes (which is technically moredemanding).

Equation (12) suggests a maximization of both b and L. A maximization of b is suggested by (11) too; however, as a difference, this equation also advises a minimization of L. In fact,N is expected to increase with L; although this is rather intuitive, the following quantification for a reference case provides a useful evidence: by assuming a normal force equal to the gravitational force

$$N = (mc + ms) g = mc + \rho s\pi(b2 - a2)L g \quad (13)$$

Where mc and ms are the masses of the capsule and shell, respectively, g is the gravity, and ρs is the mass density of the shell, (6) can be rewritten in the following manner:

$$B\sin(\gamma-\theta) =(1/4)*[\mu g/M]*[mc/\pi(b2-a2) +\rho sL] \quad (14)$$

Which clearly shows the effect of L on the misalignment $\gamma - \theta$. In addition to (13) and (14), it is also necessary to take into account at least the following couple of dimensioning inputs:

1) The size and weight of the overall device should be minimized (to facilitate the ingestion and the maneuvering);

2) The shell should not hamper the capsule's functions (image capture and RF signal transmission). The latter need provides a limitation for L, which should not exceed a suitable value Lmax; according to the capsule's internal layout (Fig. 1(d)), this limiting length was assumed equal to the extension of the capsule's cylindrical body.

X. CONCLUSION

The use of a robotic system for intra body magnetic navigations was proposed here for controlling the motion of magnetically enabled endoscopic video capsules during explorations of the digestive tube. The presented maneuvering tests in a phantom provided a first proof-of-concept of the proposed technique, suggesting the feasibility of magnetically navigating an endoscopic capsule by means of a reliable robotic instrumentation. These results encourage further investigations, which should take into account some identified improvements. These are aimed at developing a new endoscopic technique that, in comparison with traditional capsule endoscopy, has the potential to combine several advantages, including improved outcomes for diagnosis, extended clinical applicability, shortened exploration times, reduced size of the battery, and possibly, of the overall capsule, along with improved safety.

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