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Toward Autonomous Robotic Colonoscopy: Motion Strategies for Magnetic Capsule Navigation

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***Abstract*— In this paper, a set of techniques aimed at autonomously navigating a tethered magnetic capsule for endoluminal inspection of the large bowel is presented. The manual navigation of magnetic capsules for colonoscopy can exhibit several challenges if the full control of the capsule pose is left to the clinician. Tight bends, tissue folds and large diverticula can obstruct the motion of the capsule, yielding the control system to apply greater forces and torques, with no substantial effect. For this reason, a supervisory system, capable of influencing the capsule motion to avoid obstruction and to overcome obstacles is here described. The adopted approach is based on the ”surfing” principle, where the capsule is navigated in such a way to slide on the tissue folds rather than against them. The proposed technique has been validated by means of experiments in a colon phantom, experiments have shown that the adoption of this approach allows the navigation of 350mm in the phantom, while a fully-manual teleoperation of the capsule only reaches a depth of 75mm.**

I. INTRODUCTION

Colorectal cancer is the second most common form of cancer and third cause of cancer-related mortality worldwide [1]. The gold-standard screening procedure for detection of polyps is endoluminal inspection of the large bowel, performed with flexible endoscopes. Such devices enable reliable diagnosis and effective therapies such as polipectomy, but the ability to steer the tip is usually achieved by embedding cable-based actuation, thus making the instrument rigid. Moreover, the advancement of the instrument is controlled by the clinician, who exerts forces and torques on the external part. For this reason, flexible endoscopes in conventional colonoscopy (CC) can induce pain and damage tissues as the scope is introduced. A less-invasive alternative is constituted by passive capsule endoscopes (WCE) [2], [14].

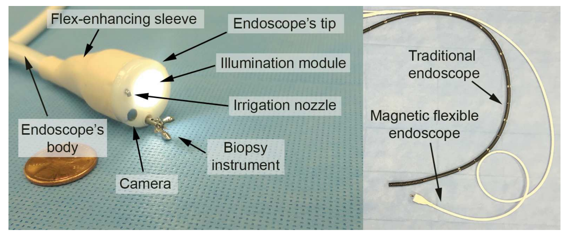

Fig. 1. On the left: Detail of the MFE capsule tip. On the right: MFE flexible tether compared with commercial colonoscope

Several examples of WCE have approached the market [4]. However, results have shown that WCE are not able to replace CC. In particular, the passivity of the capsules and the time required to travel the intestines negatively affect the performances of these systems. In order to overcome these issues, the magnetic coupling between an External Permanent Magnet (EPM) and an internal magnet, embedded in the capsule, has been extensively adopted. [6], [13]. By means of this approach, it is possible to exert forces and torques on the capsule, thus controlling its motion. In previous

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works, our group developed a Magnetic Flexible tethered capsule Endoscope (MFE), shown in Fig.1. In the MFE, the capsule is equipped with an internal permanent magnet, a camera, a light source and a channel compatible with commercial biopsy tools. The aforementioned characteristics require the presence of a soft tether, much more flexible with respect to the endoscopes adopted in CC.

The control of the driving magnetic field has been carried out by affixing the EPM to the end effector of a robotic arm, as shown by Fig. 3. In order to control the capsule position in a feedback loop fashion, a localization method has been developed, the adopted approach is thoroughly described in [7], [8].

Subsequently, a closed-loop control system based on a simple PID controller has been developed [12]. The control has demonstrated the feasibility of the capsule's teleoperation. The effectiveness of this approach has been demonstrated by guiding a capsule in a smooth and rigid environment. Moreover, autonomous retroflexion maneuvers have been successfully performed in in-vivo scenarios[9], [10], thus showing the capabilities of the system in terms of autonomy.

However, the colon is characterized by very flexible tissues and can exhibit obstacles such as folds, tight bends and anatomic flexures. These may negatively affect the performances of the closed-loop control system if the capsule is blindly navigated without considering the environment. For this reason, this approach can suffer when attempted in a more realistic scenario, like a colon phantom designed for training, where obstacles can significantly constrain the motion of the capsule.

II. Description of the Approach

The approach described in [12] is characterised by a proportional/integral controller acting on the linearised relation between magnetic force and torque derivatives and EPM translational and rotational velocities; no strategy has been carried out in order to overcome obstacles. As a consequence, the request of the clinician to overcome an obstacle by increasing the force applied on the capsule in the desired direction can result in an undesirable

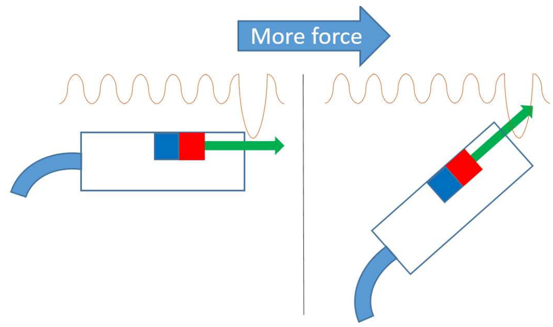

Fig. 2. Capsule stuck in a fold due to control action

situation where the capsule is embedded in the soft tissue and the movement is restricted, as demonstrated by fig. 2.

The work presented here introduces an additional layer of intelligence in the system by adopting a set of strategies which aim at simplifying the teleoperation of the capsule by adapting the behavior of the system to the environment. The situation described by Fig. 2 can be avoided by means of two fundamental actions:

- The orientation maintained during the motion must allow the capsule to slide over the tissue fold, thus significantly reducing the angle of collision between the capsule and the tissue. By adopting this artifice, the contact can occur on the upper surface of the capsule.
- In some particularly tough scenarios, the capsule can be stuck despite the surfing action. Since the feedback given to the clinician is local (i.e. the perspective of the camera), it might be very difficult to manually drive the capsule out of the fold. In these cases, an autonomous spiraling motion can be commanded to the capsule while simultaneously maintaining an applied force toward the direction of view. This can be considered as an evasive maneuver performed autonomously by the system whenever required.

These strategies, conveniently mixed, form a basic algorithm that can constitute the first step toward the autonomous exploration of the colon by means of a magnetic tethered capsule endoscope.

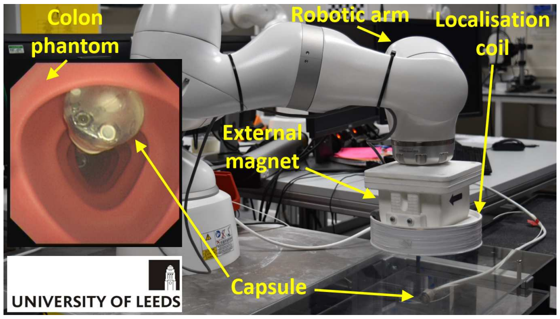

Fig. 3. Control of a magnetic capsule with external permanent magnet

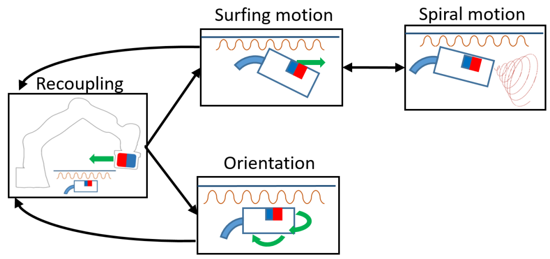

Fig. 4. Overall strategy scheme

III. Implementation

The proposed navigation algorithm is summarised in Fig. 4. The strategy is represented as a state machine where the user can request two actions, i.e. *forward motion* - to advance in the colon - and *capsule orientation* - to inspect the area surrounding the capsule by reorienting the camera. In the latter state, no translational motion of the capsule is desired and the orientation control is carried out by the feedback system described in [12]. Conversely, when *forward motion* is commanded, a hybrid control is applied to guarantee the application of a force in the desired direction of motion, while simultaneously maintaining the desired heading. This approach is necessary to overcome the restrictions arising from the dependency between applied force and capsule heading (where the closed-loop control sacrifices the desired heading in favor of the applied force). This behavior may increase the likelihood of the capsule being trapped in the surrounding tissue. The capsule heading and the applied vertical force are controlled in closed-loop by means of a proportional controller, while the forces on the horizontal plane (required for gross locomotion) are applied by means of a feed-forward velocity term, imposed on the EPM in the desired motion direction of the capsule. Eqs.(1-3) describe the control action.

$$\dot{\boldsymbol{f}} = \mathbf{K_{pf}}[0 \quad 0 \quad err_{Fz}]' \tag{1}$$

$$\dot{\boldsymbol{\tau}} = \mathbf{K_{p\boldsymbol{\tau}}}[0 \quad err_{Hy} \quad err_{Hz}]' \tag{2}$$

$$\begin{bmatrix} \dot{\mathbf{p}}_\mathbf{a} \\ \dot{\mathbf{m}}_\mathbf{a} \end{bmatrix} = J_F^{\dagger} \begin{bmatrix} \dot{\mathbf{f}} \\ \dot{\boldsymbol{\tau}} \end{bmatrix} + \begin{bmatrix} \mathbf{K_s}\bar{\mathbf{d}} \\ 0 \end{bmatrix} \tag{3}$$

$\dot{\boldsymbol{f}}$ and $\dot{\boldsymbol{\tau}}$ represent the derivatives of desired forces and torques applied on the capsule, err_{Fz} is the error between the applied and desired vertical forces, err_{Hy} and err_{Hz} are the heading errors on the vertical and horizontal planes respectively, and $\mathbf{K_{pf}}$, $\mathbf{K_{p\boldsymbol{\tau}}}$ are proportional control gains.

The velocities of the EPM ($\dot{\mathbf{p}}_\mathbf{a}$ and $\dot{\mathbf{m}}_\mathbf{a}$) are computed through the pseudo-inverse of the magnetic coupling $J_F^{\dagger}$. This describes the linear and local relation between the variation of the relative position of the EPM and capsule, to the variation of applied magnetic force. An additional feed-forward term is applied in order to move the EPM in the direction of the desired capsule motion $\bar{\mathbf{d}}$ on the horizontal plane. Where straight, forward motion is desired, the system enters the state of *surfing motion* by setting the desired heading of the capsule to point down on the vertical plane with an angle of 20 *deg*. A threshold on the applied force in the desired direction of motion was selected, equal to 85% of the maximum applicable force. If the applied force exceeds the threshold the capsule is considered to be stuck by an obstacle and an evasive maneuver is initiated. Several types of maneuvers have been tested. Among these, commanding a circular motion to the capsule heading and simultaneously maintaining an applied force in the desired direction of motion has been experimentally proven to be the most effective. Finally, the adopted control strategy involves a secondary task aimed at maintaining the EPM in the proximity of the capsule and to

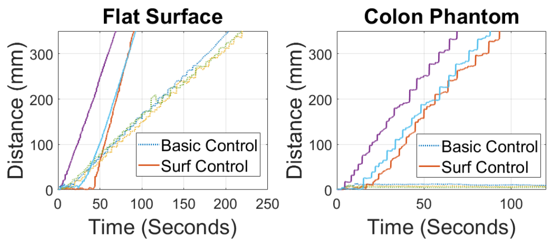

Fig. 5. Comparative distance traveled when attempting a straight trajectory (a) Along a smooth surface; (b) In a human colon phantom.

avoid large motion of the robot. When no motion is commanded to the system, the EPM moves directly above the capsule, thus minimizing the distance and maintaining the desired vertical force. This action has a beneficial influence on the subsequent motions.

IV. RESULTS

Three benchtop tests have been realised by means of the experimental platform extensively described in [12]. The capsule was placed under a flat surface with no obstacles and the motion was controlled along a straight path. Subsequently, the same capsule was placed at the beginning of a realistic phantom colon and commanded to move through a section. By using the basic closed loop system [12], an experienced operator was able to move under the flat surface. Conversely, the same operator was able to move in the colon only by adopting the strategy proposed here. Fig. 5 shows the distance traveled by the capsule over time while attempting a straight-line trajectory on a smooth, rigid surface (fig. 5a), and in a human phantom colon (fig. 5b). Experiments were repeated 3 times for each control strategy and in both environments. Results show that the proposed strategy allowed a distance of 350mm to be traveled in a mean time of 84s along the smooth surface, with the basic control achieving the same distance in a mean time of 213s. In the phantom colon, the proposed control achieved a distance of 350mm in a mean time of 83s, with the basic control only achieving a mean distance of 7.5mm in the same time.

V. DISCUSSION

The complexity of the human colon and the nature of the remote magnetic actuation arise several challenges in the development of an effective navigation strategy for capsule endoscopes. In particular, experiments have shown that feedback control of the capsule motion is not adequate to guarantee satisfactory navigation performances in phantoms. For this reason, we developed a simple yet effective strategy to support the clinician during the endoscopic procedure. The implementation of a surfing strategy and overcoming the obstacles by means of spiral motion have shown to be valid approaches to navigate in a silicon phantom characterized soft, thin walls, ridges and tight bends. In particular, the proposed approach has shown to enable the navigation of a colon phantom, as opposed to the teleoperation where this task could not succeed. Moreover, the time required to perform a simple straight trajectory in a smooth pipe has decreased from 213s. to 84 s. This constitutes an initial step toward the autonomous navigation of the colon with magnetic capsules, thus providing an intriguing starting point for the development of more advanced autonomous navigation and locomotion strategies.

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