Autonomous Navigation of a Magnetic Flexible Endoscope

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***Abstract*— Flexible endoscopes can induce pain as the scope is introduced through the lower-gastrointestinal (GI) tract. Magnetically actuated endoscopes constitute a less-invasive alternative. However, current navigation using open-loop control is slow, ineffective and requires a high skill-set. In response, this work presents adaptive lumen-detection based autonomous navigation for the purpose of reducing procedure times as well as cognitive demand. Bench-top trials with 8 participants were conducted and showed increased autonomy to be superior when compared to open-loop control.**

I. INTRODUCTION

Magnetically actuated endoscopic devices present potential in being a less-invasive alternative to flexible colonoscopy, the current gold standard procedure for colorectal screening [1]. One such implementation - a Magnetic Flexible Endoscope (MFE) - comprises a small Internal Permanent Magnet (IPM) inside a soft-tethered, camera-equipped capsule and an External Permanent Magnet (EPM) at the end effector of a robotic manipulator (Fig. 1). Interaction between the EPM and IPM allows the MFE to be pulled and orientated through the colon via the magnetic forces and torques [2].

However, due to the unintuitive nature of controlling the magnetic fields, the tortuous pathway of the lower-GI tract and absence of a direct line-of-sight to the MFE, there is a high cognitive demand in controlling the MFE. This can be up to 3 times slower than conventional colonoscopy [3]. In response, work presented by Taddase et al [2] allows for the pose of a MFE to be accurately estimated in real time (100Hz, accuracy of 5mm positional, 6° angular), enabling the development of closed-loop control algorithms for the MFE.

Complimentary research has seen groups develop image-processing techniques to infer the direction/center of a lumen in live endoscopic images, remarking that future benefits would be found in the application of these techniques in to autonomous navigation of endoscopic devices [4], [5], [6].

We have developed high-level-autonomous navigation of a MFE using real-time pose information, combined with a robust 20Hz lumen detection algorithm. The contribution of this work is improved usability and procedure times for a MFE, with resources previously needed to obtain high-navigational skill being freed so that they can be better utilised on patient diagnosis and treatment.

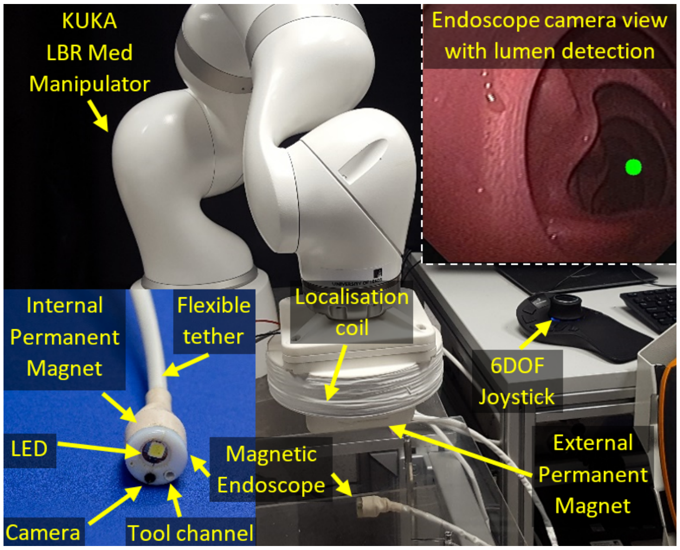

Fig. 1. Overview of magnetically actuated endoscopic system with lumen-detection-based autonomous navigation

II. CONTROL STRATEGY

We used OpenCV to implement and build upon an adaptive threshold segmentation algorithm presented by Wang et al [5]. After obtaining a segmented region from the MFE camera image that most likely contains the lumen, we apply a binary threshold with a tolerance set off of experience with the system to remove all but the darkest pixels from the region. The center-of-mass point of the remaining darkest pixels is the final coordinate estimate for the center-of-lumen. To steer the MFE, we impart a magnetic torque on the MFE via the EPM such that the error between the estimated center-of-lumen and center-of-image is minimised.

Linear velocity of the MFE is governed by a velocity term that is inversely proportional to the size of the error between the estimated center-of-lumen and center-of-image. This allows the system to give priority to steering the MFE, and only progress forwards via magnetic force when a lumen has been centered in front of the endoscope. This permits obstacles that may otherwise hinder locomotion to be circumnavigated.

There can be scenarios where no lumen is present in the image and the MFE will try to advance towards the tissue wall. For this we measure features present in the image using the FAST Feature Detector [7], with a feature being defined as a discernible edge within the image. In no lumen scenarios, there will be a low number of features and the EPM is autonomously moved away from the MFE to

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decouple the magnets. The operator is then instructed to pull back slightly on the tether so that, being free from magnetic torque imparted by the EPM, the MFE can naturally align to the lumen of the colon and autonomous control can resume.

III. EXPERIMENTAL VALIDATION

A. Method

A group of 8 operators (not trained in performing colonoscopy or using the MFE system) were asked to navigate the MFE from the rectum to the caecum of latex phantom colon (M40, Kyoto Kagaku Co., Ltd), a model commonly used for colonoscopy training. The colon was arranged in accordance with the instructions for a standard layout (Fig. 2) and lubricated. The end of the navigation task (the caecum) was placed and clamped at 9 haustral folds (300mm) from the total length (1300mm) of the colon. The colon model was covered from view in all tests to prevent the operator having direct knowledge of the location of the MFE. A test was labeled as successful upon navigating from the rectum, to the caecum in 20 minutes or less.

Each operator performed this navigation task 5 times using open-loop control, during which the operator directly commanded the pose of the EPM using a 6 DOF joystick controller (3-D SpacePilot, 3Dconnexion Inc., Waltham, MA). This was followed by 5 attempts during which the system would attempt to autonomously align and advance the MFE. When no lumen could be detected, the operator was instructed to pull back on the MFE tether to re-align the camera to the lumen of the colon. Failing this, and only when necessary, the operator could momentarily override the autonomous system using the joystick.

B. Results

Overall completion rates (percentage successfully navigated from the rectum to the caecum in 20 minutes or less) was 65% (26/40 trials) for open-loop control and 100% (40/40 trials) for autonomous control. An example of a successful trial using autonomy is shown in Fig. 2.

Fig. 2. Example of completed autonomous trajectory

Operator times of successful trials are shown in Fig. 3. Open-loop control presented the slowest median completion time of 640.35 243.30 seconds. Autonomy reduced this median completion time to 257.7 94.67 seconds. Autonomy displayed more consistent completion times across all participants. P-values indicate statistical significance when comparing times from autonomy to open-loop control.

Fig. 3. Times of sucessful repetitions: Open-loop n=26, autonomous n=40. Red bars indicate median, edges are 25th and 75th percentiles, whiskers indicate range and red crosses denote outliers. P-values computed using the Kruskal Wallis test.

IV. CONCLUSION

The introduction of autonomy when navigating a MFE system has shown great potential in reducing cecal incubation times while also improving ease-of-use. The autonomous control strategy was over 6 minutes faster on average compared to open-loop control. As the operators were not trained in performing colonoscopy and unfamiliar with the MFE system, this work shows potential of such procedures being performed by more readily available, minimally trained staff, reducing costs and procedure wait times. Further *in-vivo* work is currently underway to provide quantitative assessment of autonomous navigation using a magnetic endoscope.

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