Proceedings of the 2017 Design of Medical Devices Conference
DMD2017
April 10-13, 2017, Minneapolis, Minnesota, USA
DMD2017-3391

Towards Recovering a Lost Degree of Freedom in Magnet-Driven Robotic Capsule Endoscopy

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1 Background

Flexible endoscopy, a procedure during which an operator pushes a semi-rigid endoscope through a patient's gastrointestinal tract, has been the gold-standard screening method for colon cancer screening (colonoscopy) for over 50 years. Owing to the large amounts of tissue stress that result from the need for transmitting a force to the tip of the endoscope while the device wraps through the bowel, implementing a front-actuated endoscopy system has been a popular area of research [1]. The pursuit of such a concept was accelerated by the advent of ingestible capsule endoscopes, which, since then, have been augmented by researchers to include therapeutic capabilities, modalities for maneuverability, amongst other diagnostic functions [2]. One of the more common approaches investigated has been the use of magnetic fields to apply forces and torques to steer the tip of an endoscope [3]. Recent efforts in magnetic actuation have resulted in the use of robot manipulators with permanent magnets at their end effectors that are used to manipulate endoscopes with embedded permanent magnets.

Recently, we implemented closed loop control of a tethered magnetic capsule by using real-time magnetic localization and the linearization of a magnetic wrench applied to the capsule by the actuating magnet [4]. This control was implemented in 2 degrees-of-freedom (DoF) in position (in the horizontal plane) and 2 DoF in orientation (panning and tilting). One DoF in position is lost owing to the tethered capsule being actuated in air and thus lacking a restoring force to counter the high field gradient. The 3rd orientation DoF is lost owing to the axial symmetry of the permanent magnet in the capsule; this prevents the application of torque in the axial direction and thus controlled roll and introduces a singularity in the capsule's actuation. Although another dipole could be used to eliminate this singularity, this would complicate both the actuation and localization methods. In this manuscript, we consider the consequences of the embedded magnet (EM) being radially offset from the center of the capsule while being manipulated by an external actuating magnet (AM).

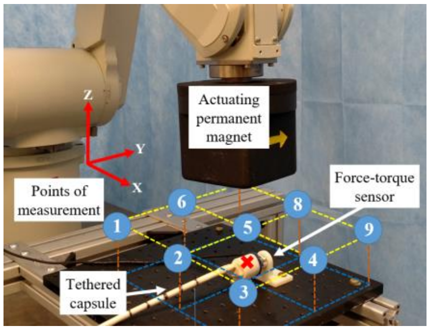

Figure 1: Experimental setup consisting of a serial manipulator with the AM at the end effector, and the capsule with the EM rigidly mounted to a force-torque sensor

We have developed a tethered capsule endoscope that contains a cylindrical EM (11.11 mm in length and diameter) with a residual flux density of 1.48 T that is offset by 1.85 mm from the center of the capsule; a distance that is less than 10% of the capsule diameter. Our investigation into the topic results from repeated observation of the capsule's preference to align such that the internal magnet is closest to the actuating magnet (AM).

The AM is a cylindrical magnet (101.6 mm in length and diameter) with a residual flux density of 1.48 T that is mounted at the end effector of a 6 DoF manipulator, as seen in Figure 1. In this manuscript, we evaluate the torqueing effects of the presence of this magnet offset with the goal of determining whether the torque effect is negligible, or impacts capsule motion and thus can potentially be used for the benefit of endoscope manipulation. A concept schematic of this effect is shown in Figure 2. A discussion of how to use this torque is beyond the scope of this manuscript. To the authors' knowledge, the use of such concept in permanent-magnet based control has not been investigated.

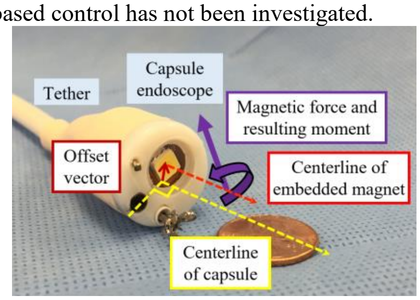

Figure 2: Conceptual schematic of force-induced torque that results from the offset of the EM in the capsule

2 Methods

To be able to utilize magnet offset information to command a desired capsule roll, a roll-torque model must be developed. To investigate the effect on capsule torque resulting from the magnet offset, we model the magnetic force that induces a moment and subsequently conduct a set of experiments to evaluate the model. We utilize a point-dipole model and a known magnet offset moment arm to compute a force-induced torque (τ_f) as follows:

$$\tau_f = {}^{w}R_c(\theta_{roll})\,{}^{c}v_m \times {}^{w}f_m \qquad (1)$$

where ${}^{w}R_c$ is a rotation matrix that maps coordinates from the capsule's local frame to the inertial frame, ${}^{c}v_m$ is the magnet offset vector expressed in capsule frame and thus doesn't change, and ${}^{w}f_m$ is the dipole induced magnetic force as can be seen in [4]. A theoretical calculation of the force-induced torque is conducted with the AM stationed at 9 pre-defined positions and with the capsule rolling about its axis. These positions were chosen for experimental convenience only and could have been any points in the capsule's workspace where enough magnetic field can be recorded physically to intuit results.

Experimental validation is done by mounting the capsule in a fixed position onto a mechanism that is rigidly coupled with a force and torque sensor (ATI Nano17). During each set of trials, the capsule is rotated about its radial axis in 30° increments. The true roll value is recorded using an accelerometer on board the capsule. The capsule's true position is known via manual measurement. Nine trials are performed, with 12 measurements taken during each trial for a given roll, with each trial consisting of the AM being placed in a different position on a 3 by 3 grid of points, as seen in Figure 1. The orientation of the AM does not change.

3 Results

The results obtained from both the theoretical and experimental experiments are shown in Figure 3. We take note of 3 points of interest in the result plots: (1) there exists a theoretical symmetry in the computed torque; however, this is not evident in the measured data as the magnet is not truly a dipole and geometric effects exist (2) there exists a torque magnitude error that is likely present owing to the imperfect dipole approximation, and finally (3) even small effects, such as the small bump in index 6 that results from the radial traversing of the moment arm with roll, can be predicted.

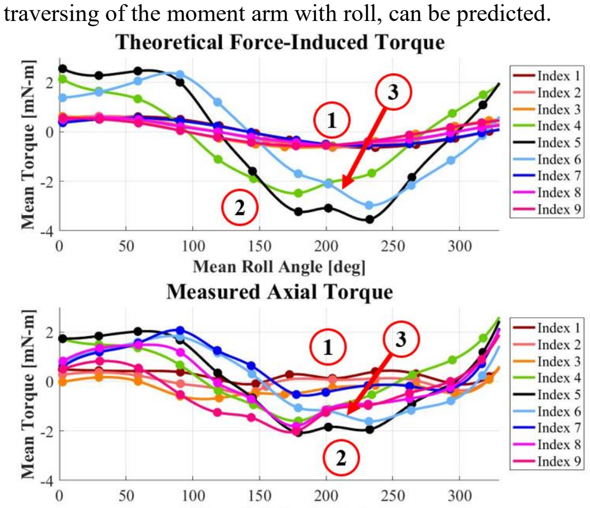

Figure 3: Theoretical and experimental results for magnitude of force-induced torque observed while rolling the capsule through a full rotation and repeating the experiment with the AM at 9 different positions

4 Interpretation

The purpose of this work is the investigation of the effect of non-concentric placement of an EM in a magnetically actuated capsule endoscope. As seen in Figure 3, the effect of the force-induced torque is greatest when the capsule and AM are aligned such that their centers are on the same plane that is also normal to both of their dipole moments. This is the typical condition observed during closed-loop controlled driving, and thus the larger magnitude results seen in the plot are the most relevant. The toque values reported here are not obtained during capsule driving, but are only obtained from miscellaneous relative positions used for model confirmation. During magnetic capsule driving, we have observed the capsule to have a preference to align such that the EM is closest to the AM; this suggests that the magnet placement offset in our device (< 10% of the capsule diameter) is sufficient to apply a relevant roll torque. During a set of 5 trials where the capsule was commanded to follow a straight trajectory, described in [4], the EM was always less than 45° from the vertical axis which is approximately where the AM was positioned, meaning that there existed an inherent preference of capsule roll orientation. Having shown that this interaction can be modeled, we suspect that the active manipulation of the position of the EM relative to the capsule's frame can result in a controlled roll degree of freedom. Although open-loop control of such degree of freedom may be sufficient, a capsule that is localized in 6 DoF may be controlled in closed-loop about this roll axis. Although we have focused discussion on roll torque, an effect in varied force magnitude exists as well as the EM is rolled around the capsule's axis. This effect can be mitigated by either feeding the closed-loop controller with the current true EM pose, or, ignoring the offset and allowing the controller to self-correct which may be sufficient.

During a gas-insufflated magnetic endoscopy, owing to the lack of restoring force, the endoscope is coupled to the wall of the colon that is, typically, nearest to the AM. If the AM is to be above the patient's abdomen, then the endoscope is constantly coupled to the anterior wall. The implication of implementing an EM offset in a passive manner, i.e. not actively rotating the EM, can be the maintaining of a constant capsule orientation during the procedure. If the EM is not rolled such that it is nearest the AM, a potential energy will exist. Actively manipulating the internal magnet may result in restoring the entire roll DoF, thus making 3 DoF orientation control possible.

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