5-DOF Manipulation of a Magnetic Capsule in Fluid using a Single Permanent Magnet: Proof-of-Concept for Stomach Endoscopy

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INTRODUCTION

Magnetic manipulation of capsule endoscopes has the potential to make current gastrointestinal screening procedures faster, safer, and less invasive. To date, two electromagnetic systems have been developed with the ability to perform five-degree-of-freedom (5-DOF) manipulation of an untethered magnetic device such as a magnetic capsule endoscope: the OctoMag system consists of eight electromagnets arranged around a hemisphere directed toward the manipulation workspace [1]; a system has been developed by Siemens, consisting of 12 electromagnets through which a patient is positioned, for the control of a capsule endoscope in a water-filled stomach [2]. Permanent-magnet actuation systems are gaining attention for their ability to generate fields with clinically relevant strengths, inexpensively and in a compact form-factor, compared to electromagnetic systems. Previous permanent-magnet systems for capsule endoscopy have been limited to dragging and rolling capsule endoscope devices on the stomach's surface or in the large colon [3–5].

This proof-of-concept paper demonstrates magnetic 3-DOF position and 2-DOF orientation control of a mockup stomach capsule endoscope in fluid, using a single permanent magnet. 5-DOF manipulation of untethered devices has been previously demonstrated only with electromagnet systems.

MATERIALS AND METHODS

The mockup capsule is actuated in a tank of water by an axially magnetized cylindrical NdFeB magnet with dipole moment $\mathrm{M} \in \mathbb{R}^3$ (Grade N42, $\|\mathrm{M}\| = 26.2\ \mathrm{A} \cdot \mathrm{m}^2$), positioned by a Yaskawa Motoman MH5 6-DOF robotic manipulator. The capsule contains a cube NdFeB magnet with its dipole moment $\mathrm{m} \in \mathbb{R}^3$ (Grade N52, $\|\mathrm{m}\| = 0.126\ \mathrm{A} \cdot \mathrm{m}^2$) arranged parallel to the capsule's principal axis; the remainder of the capsule's volume is filled with air. The capsule's weight is 0.0153 N and the buoyancy force in water is 0.0148 N. The capsule's 3-DOF position is triangulated by two Basler A602FC cameras. The actuator magnet, capsule, and experimental setup are shown in Fig. 1.

A magnetic torque $\tau_\mathrm{m} = \mu_0 \mathrm{m} \times \mathrm{H}$ and magnetic force $\mathrm{f_m} = \mu_0(\mathrm{m} \cdot \nabla)\mathrm{H}$ are applied to the center of the capsule's magnet by the magnetic field $\mathrm{H} \in \mathbb{R}^3$ generated by the actuator magnet (μ_0 is the permeability

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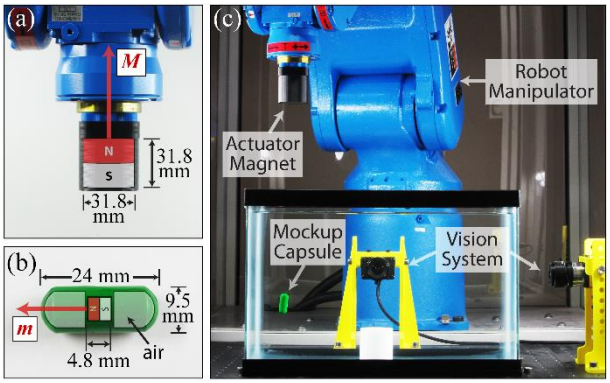

Fig. 1 The actuator magnet (a) is used to control the mockup capsule endoscope (b) in a water-filled tank, using the robotic manipulator and vision system shown in (c).

of free-space). The field produced by the actuator magnet is approximated by the point-dipole model:

$$\mathrm{H} = \frac{1}{3\pi\|\mathrm{p}\|^3}(3\hat{\mathrm{p}}\hat{\mathrm{p}}^\mathrm{T} - I)\mathrm{M}, \qquad (1)$$

where $\mathrm{p} \in \mathbb{R}^3$ is the vector from the actuator magnet's center to the capsule magnet's center, $I \in \mathbb{R}^{3\times3}$ is the identity matrix, and $\hat{}$ denotes scaling to unit length.

The capsule's position and heading are controlled by applying magnetic force and torque, respectively. We assume that the magnetic torque τ_m instantaneously aligns the capsule dipole moment m (and the capsule's heading) with the applied magnetic field H, and the capsule's heading can be controlled by adjusting the field direction $\hat{\mathrm{H}}$ without controlling the magnetic torque τ_m directly. The magnetic field (1) varies with the relative position p and the direction of the actuator dipole moment $\hat{\mathrm{M}}$. The total force f applied to the capsule consists of forces due to weight and buoyancy, which are both constant, and the magnetic force $\mathrm{f_m}$, which varies with p and $\hat{\mathrm{M}}$. In general, magnetic force also varies with m, however, we assume m to be aligned with $\hat{\mathrm{H}}$. The position p and actuator moment direction $\hat{\mathrm{M}}$ (controlled by the robot manipulator) are related to field direction $\hat{\mathrm{H}}$ and total force f by the nonlinear actuation function:

$$\begin{bmatrix}\hat{\mathrm{H}}\\ \mathrm{f}\end{bmatrix} = \mathcal{A}\left(\begin{bmatrix}\hat{\mathrm{M}}\\ \mathrm{p}\end{bmatrix}\right). \qquad (2)$$

Rather than explicitly inverting (2) to determine the necessary moment $\hat{\mathrm{M}}$ and position p of the actuator magnet, given the desired field direction $\hat{\mathrm{H}}$ and total applied force f, the Jacobian matrix $J_\mathcal{A} \in \mathbb{R}^{6\times6}$ is computed analytically, using the measured capsule position, and inverted using the Moore-Penrose pseudoinverse. The result relates small changes in the

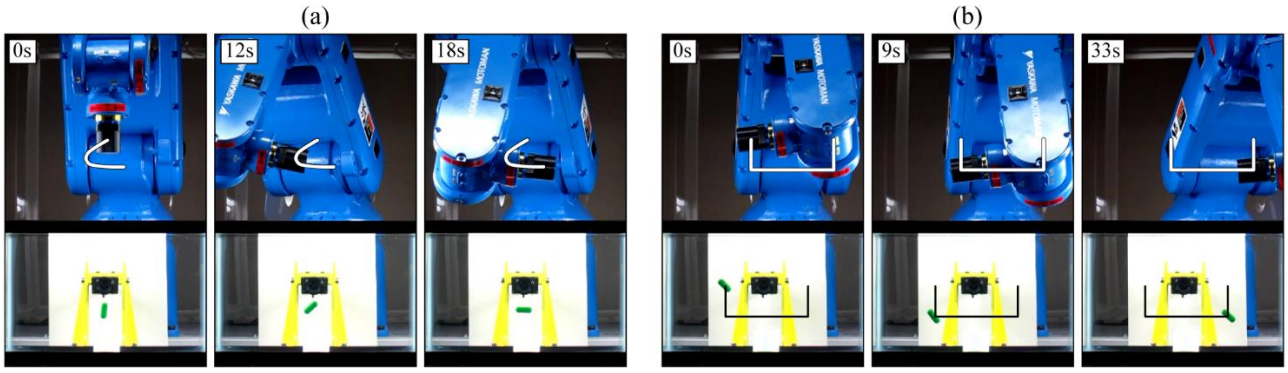

Fig. 2 The mockup capsule can be holonomically controlled with five degrees-of-freedom. In (a), the capsule is controlled to adjust its heading while remaining stationary in space. In (b), the capsule follows a U-shaped trajectory while maintaining a constant heading. The path taken by the actuator magnet is shown in both examples. Complete video demonstrations of (a) and (b) can be found at http://www.telerobotics.utah.edu/index.php/Research/PermanentMagnet.

desired field direction and force to small changes in the actuator moment and position:

$$\begin{bmatrix} \Delta\widehat{\mathrm{M}} \\ \Delta\mathrm{p} \end{bmatrix} = J_{\mathcal{A}}{}^{\dagger} \begin{bmatrix} \Delta\widehat{\mathrm{H}} \\ \Delta\mathrm{f} \end{bmatrix}, \qquad (3)$$

which governs how the robotic manipulator moves the actuator magnet in space as the desired field heading (i.e., capsule heading) and applied force vary. The matrix $J_{\mathcal{A}}$ is always rank five, meaning that the capsule can be controlled with five degrees-of-freedom. The single uncontrollable DOF corresponds to capsule rotation about its magnetic dipole moment m.

In practice, values of $\Delta\mathrm{f}$ or $\Delta\widehat{\mathrm{H}}$ and certain system configurations can produce large changes in $\Delta\mathrm{p}$ or $\Delta\widehat{\mathrm{M}}$, which may be unachievable by the robot manipulator in the worst case. The manipulator's motion can be reduced by temporarily sacrificing control over the capsule's heading, without losing control over its position. This is performed by solving a constrained, weighted, least-squares minimization problem.

EXPERIMENTS

A feedback controller, using the triangulated capsule position obtained from the vision system, is used to servo the capsule to any desired position in the workspace. At every iteration, the controller produces a desired change in force $\Delta\mathrm{f}$, and the desired change in heading $\Delta\widehat{\mathrm{H}}$ is obtained from the user, which are converted into motion of the robotic manipulator by equation (3). An estimate of the capsule's heading is obtained from the measured position using (1), and is controlled in an open-loop fashion (i.e., the capsule's heading is not measured).

Fig. 2 shows two capsule maneuvers that prior actuation systems using a single permanent magnet are unable to perform. In Fig. 2(a), the capsule's heading is rotated from a down-pointing to a side-pointing configuration, while the feedback controller regulates position with no external contact. Nonintuitively, the actuator magnet does not remain directly above the capsule during the transition. In Fig. 2(b), the capsule's position follows a U-shaped trajectory while its heading remains constant. These examples demonstrate simple maneuvers. Since the system is capable of 5-DOF control, more complicated maneuvers are also possible.

DISCUSSION

The control scheme presented herein relies upon the capsule's net weight (i.e., weight minus buoyancy) to apply downward forces in the direction of gravity. When the capsule is desired to move downward, the applied magnetic force is adjusted to be less than the net weight by repositioning the actuator magnet according to (3). The maximum downward force that can be applied (without placing the actuator below the capsule) is the capsule's net weight.

When the magnetic force balances the net weight, then the capsule levitates at equilibrium and is stabilized by the feedback controller. The equilibrium distance depends on the capsule's net weight and the strength of the capsule and actuator magnets, $\|\mathrm{m}\|$ and $\|\mathrm{M}\|$, respectively. If the capsule's net weight is increased, a larger actuator magnet can be used with the same results. The closer the capsule is to neutral buoyancy, the smaller the magnetic force needed for levitation. However, since the capsule's net weight is required to apply downward force, a neutrally buoyant capsule is undesired.

In a clinical setting, the vision system used for capsule localization can be replaced by more appropriate localization methods such as RF triangulation, ultrasound, magnetic tracking, and other (potentially hybrid) approaches.

REFERENCES

[1] M. P. Kummer et al. OctoMag: An electromagnetic system for 5-DOF wireless micromanipulation. *IEEE Trans. Robot.*, 26(6):1006--1017, 2010.

[2] H. Keller et al. Method for navigation and control of a magnetically guided capsule endoscope in the human stomach. In *Proc. IEEE Int. Conf. on Biomedical Robotics and Biomechatronics*, pages 859--865, 2012.

[3] S. Yim and M. Sitti. Design and rolling locomotion of a magnetically actuated soft capsule endoscope. *IEEE Trans. Robot.*, 28(1):183--194, 2012.

[4] G. Lien et al. Magnetic control system targeted for capsule endoscopic operations in the stomach: Design, fabrication, and *in vitro* and *ex vivo* evaluations. *IEEE Trans. Biomed. Eng.*, 59(7):2068--2079, 2012.

[5] G. Ciuti et al. Robotic magnetic steering and locomotion of capsule endoscope for diagnostic and surgical endoluminal procedures. *Robotica*, 28(2):199--207, 2010.