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

- We demonstrate 5-DOF manipulation of a mockup magnetic capsule endoscope in fluid using a single permanent magnet and robot arm:
  - 3-DOF position control (up/down, left/right, forward/back) and 2-DOF heading control (pitch/yaw) for stomach endoscopy
- All prior 5-DOF magnetic manipulation systems use arrangements of electromagnets:
  1) The OctoMag for ophthalmic procedures
  2) Olympus and Siemens' system for the endoscopy of water-filled stomachs
- Permanent magnets are *cheaper* and produce *stronger* fields in a *smaller* form-factor compared to electromagnets.

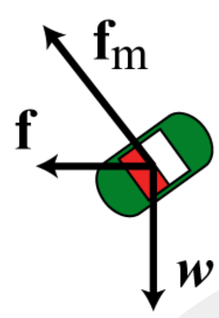
Olympus /Siemens' 5-DOF system for stomach capsule endoscopy is undergoing clinical trials.

Materials & Methods

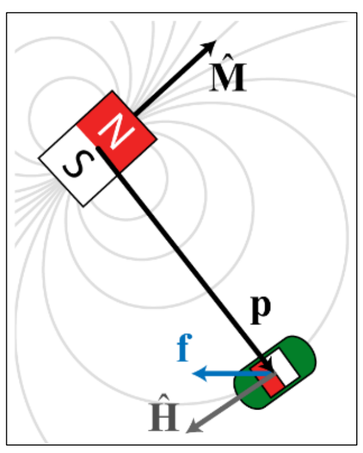
- Magnetic torque $\boldsymbol{\tau}_\mathbf{m}$ and force $\mathbf{f}_\mathbf{m}$ are applied to a magnet inside a capsule by the field $\mathbf{H}$ of an external actuator magnet (held by a robot arm):

$$\boldsymbol{\tau}_\mathbf{m} = \mu_0 \mathbf{m} \times \mathbf{H} \qquad \mathbf{f}_\mathbf{m} = \mu_0 (\mathbf{m} \cdot \nabla)\mathbf{H}$$

- **Rotation:** the magnetic torque aligns the capsule with the field heading $\hat{\mathbf{H}}$.
- **Translation:** the *total* applied force $\mathbf{f}$ is the sum of the capsule's apparent weight $\mathbf{w}$ and the magnetic force $\mathbf{f}_\mathbf{m}$.



$$\mathbf{f} = \mathbf{f}_\mathbf{m} + \mathbf{w}$$



- The robot positions the actuator magnet to adjust the total applied force and field heading.

System **inputs**:
1) actuator's heading: $\hat{\mathbf{M}}$
2) actuator's position: $\mathbf{p}$

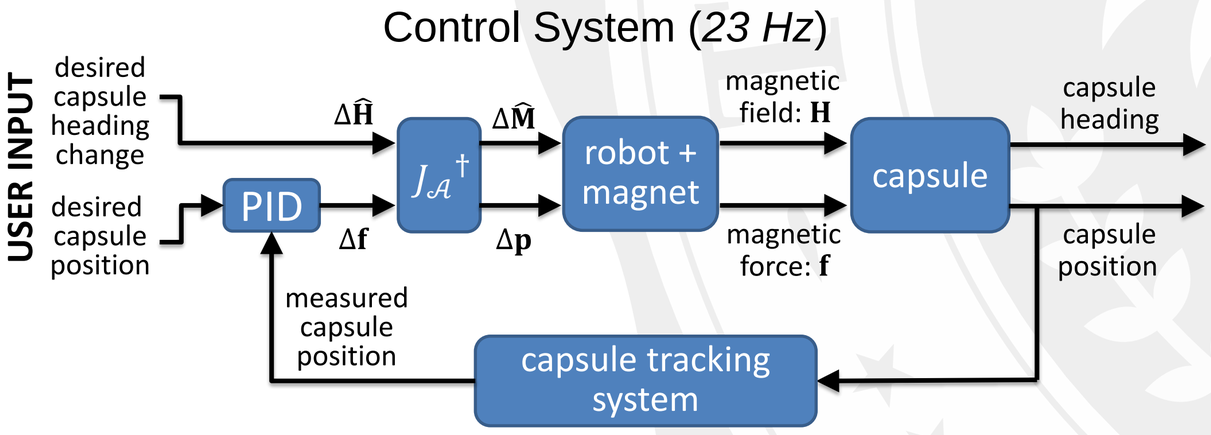
System **outputs**:
1) field heading: $\hat{\mathbf{H}}$
2) total force: $\mathbf{f}$

- The input/output mapping is linearized to relate *change* in inputs to *change* in outputs by an actuation Jacobian matrix $J_\mathcal{A}$:

$$J_\mathcal{A} \begin{bmatrix} \Delta\hat{\mathbf{H}} \\ \Delta\mathbf{f} \end{bmatrix} \approx \begin{bmatrix} \Delta\hat{\mathbf{M}} \\ \Delta\mathbf{p} \end{bmatrix} \quad \Rightarrow \quad \begin{bmatrix} \Delta\hat{\mathbf{M}} \\ \Delta\mathbf{p} \end{bmatrix} \approx J_\mathcal{A}^{\dagger} \begin{bmatrix} \Delta\hat{\mathbf{H}} \\ \Delta\mathbf{f} \end{bmatrix}$$

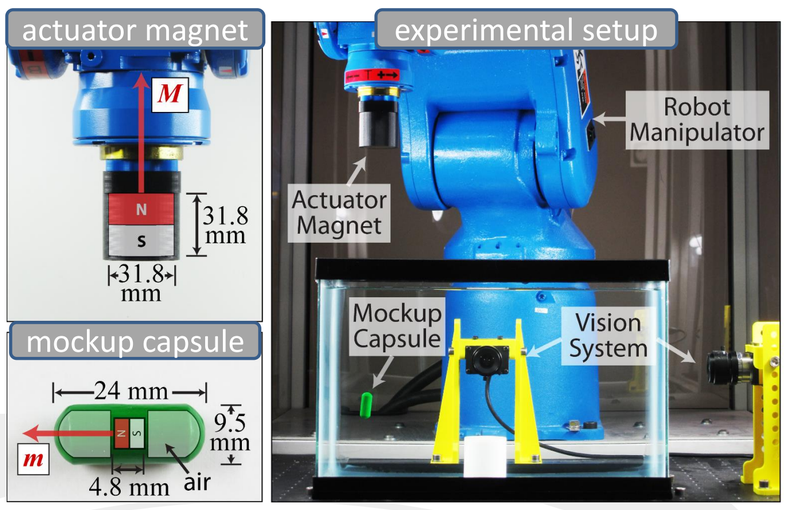
invertible with the Moore-Penrose pseudoinverse (†)

Control System (*23 Hz*)



Experimental Results

- We actuated a mockup capsule in a water tank to roughly simulate a water-filled stomach.
  - same environment as Olympus/Siemens' system

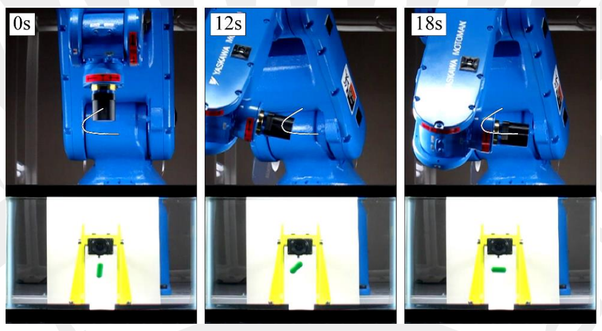


Robot Manipulator: *6-DOF Yaskawa-Motoman MH-5*
Actuator Magnet: *31.8 mm x 31.8 mm, Grade N42, NdFeB cylinder*
Capsule Magnet: *4.8 mm x 4.8 mm, Grade N52, NdFeB cube*

A vision system was used to localize the capsule for feedback control – can be replaced with a clinically relevant method.

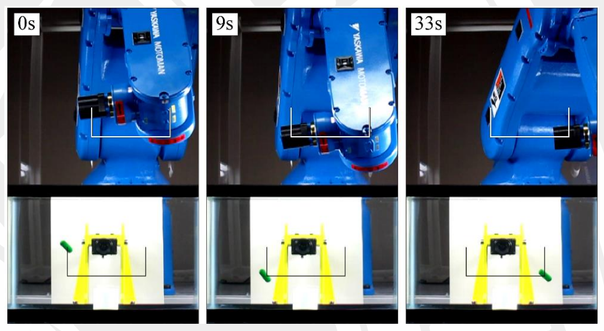
- The capsule's heading (pitch/yaw) and position (up/down, left/right, forward/back) can be holonomically controlled:

changing capsule heading only



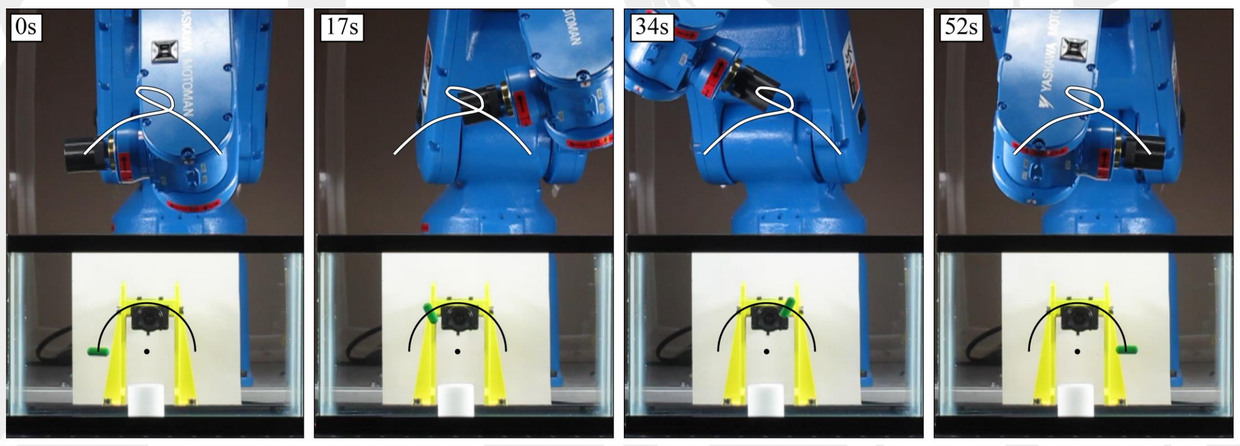
The capsule's heading is turned 90° while keeping the capsule's position stationary.

changing capsule position only



The capsule's position follows a U-shaped trajectory while its heading is stationary.

simultaneous control of heading and position



The capsule executes a remote-center-of-motion maneuver, directing its heading at the center-of-motion. Such a maneuver could be used to view a point from multiple angles.