

PhD Thesis (Graduation: 2025)

Virtual Reality-Assisted Teleoperation of Untethered and Tethered Magnetic Microrobots with A Compact and Novel Mechanism in Complex Medical Environments

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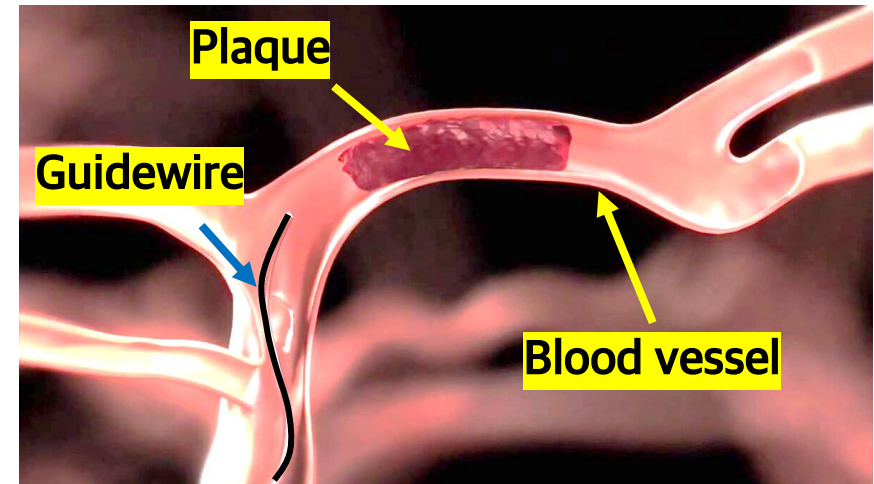
Committee members:

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3. Professor Sanghoon Lee
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5. Dr. Jinyoung Kim

Background


✓ Vascular Interventions

- ✓ Minimally invasive procedures
 - **Plaque removal**
 - **Flexible & thin instruments: Guidewires/catheters**
- ✓ Requires translation and rotation of guidewires
- ✓ Performed under X-ray
 - **Numerous health hazards**
- ✓ Robot assisted interventions
 - **Radiation protection**
 - **Reduced fatigue**



☑ Limitations of current robots: (1) complex mechanism & control (2) large size (3) heavy (4) expensive

✗




2 modules for 2 DOF
~ 15 kg, needs robotic arm
0.36 mm guidewire
~ 650K USD

✗



2 DOF - belt drive
Bulky; needs robotic arm
0.36~0.89mm guidewire
~600 USD

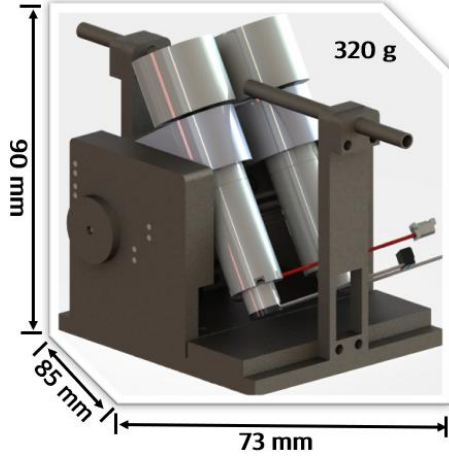
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2 DOF - robotic graspers
Bulky; needs robotic arm
0.36 guidewire
Expensive

✓

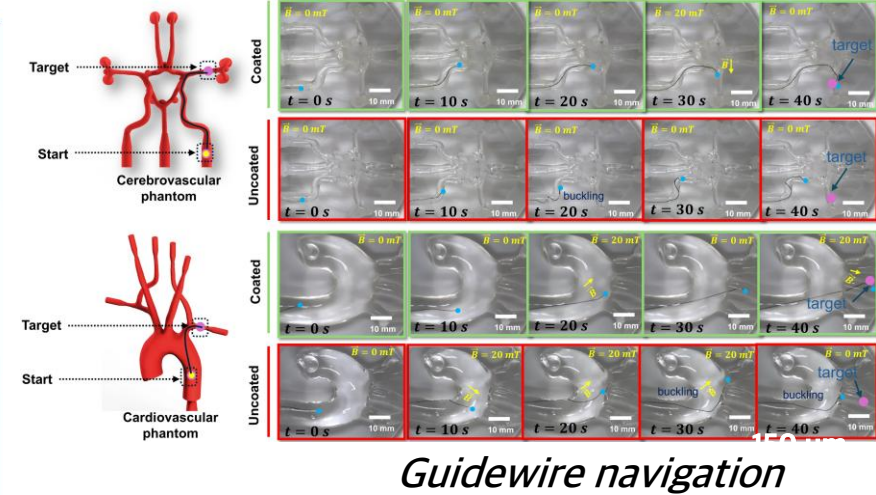
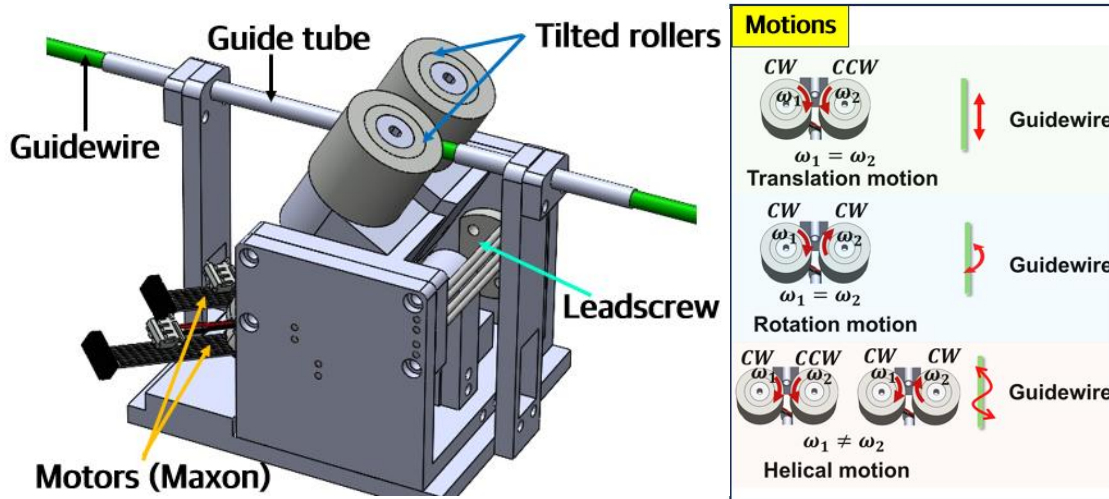
Our Solution



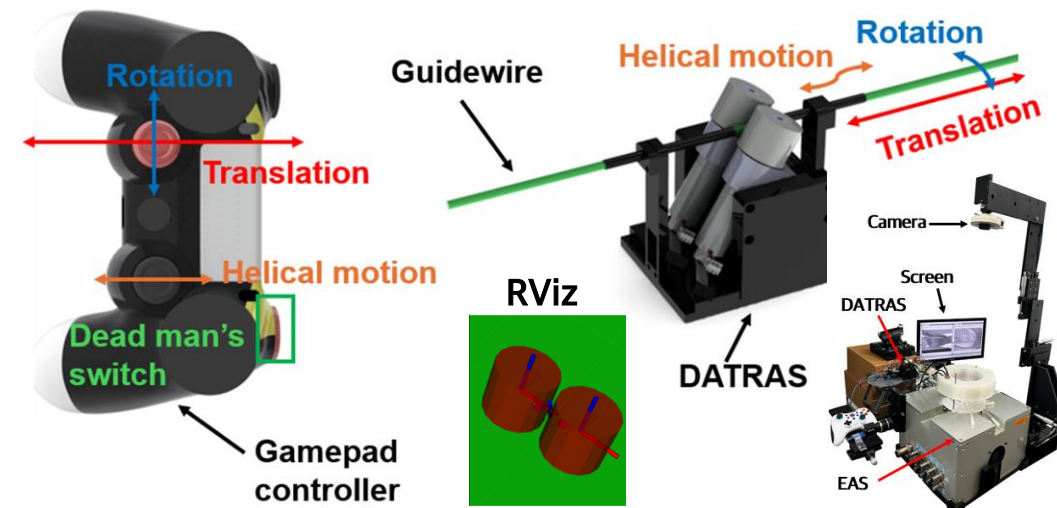
Experimental Setup

Proposed Mechanism

✓ Dual Active Tilted Roller Actuation System

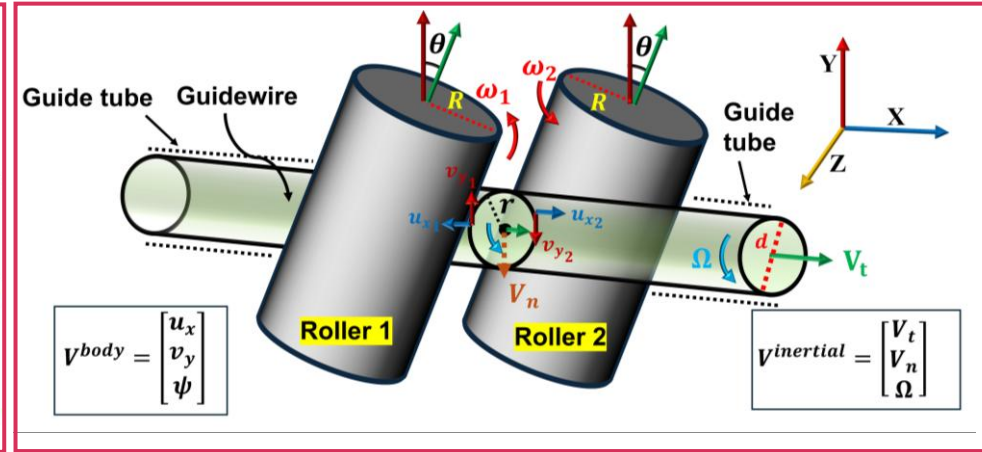
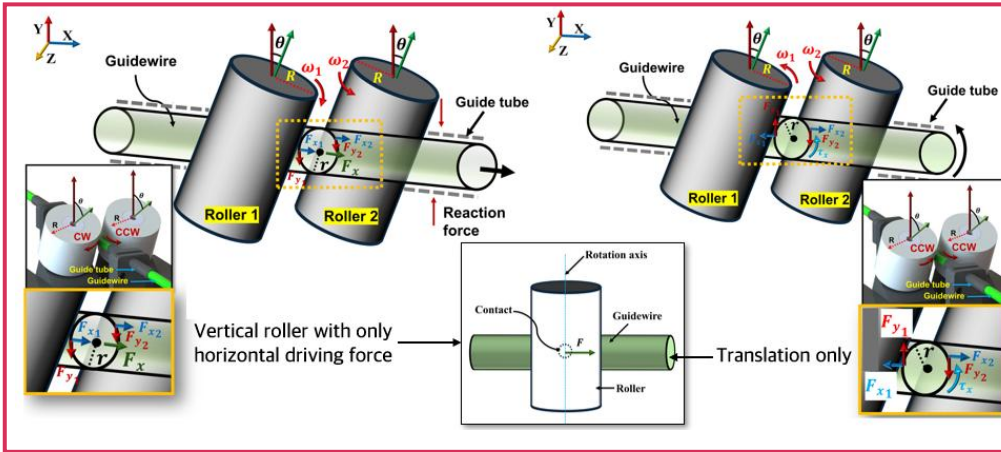


- 2 DOF in a single mechanism
 - Helical motion possible
- Dimensions: 85 mm x 73 mm x 90 mm
- Weight: 320 g
- Supports all diameter guidewires
 - Adjustable roller gap
- Cost: ~ 1k USD
- Easy integration with EAS
 - Teleoperation (ROS2 framework)



Proposed Mechanism

Working principle



Translation: $F_x = F_{x1} \cos \theta + F_{x2} \cos \theta = \mu_s N_1 \cos \theta + \mu_s N_2 \cos \theta$

Rotation: $F_y = F_{y1} \sin \theta + F_{y2} \sin \theta = \mu_s N_1 \sin \theta + \mu_s N_2 \sin \theta$

$F_y = 0$ [guide tubes reaction forces]

$M_y = 0$ [$\omega_1 \neq \omega_2$; infinite lateral resistance from guide tubes]

Helical motion when $\omega_1 \neq \omega_2$

$$\text{pitch}(h) = \left\{ \frac{\text{linear speed } (V_t)}{\text{angular speed } (\Omega)} \right\} \quad h = r \left\{ \frac{\cos \theta (\omega_1 - \omega_2)}{\sin \theta (\omega_1 + \omega_2)} \right\}$$

V_t = tangential velocity (guidewire)

V_n = normal velocity (guidewire)

Ω = angular velocity (guidewire)

$$V_t = \frac{1}{2} (-u_{x1} + u_{x2}) \quad V_n = \frac{1}{2} (v_{y1} - v_{y2})$$

$$V_t = -\frac{R}{2} \cos \theta (\omega_1 - \omega_2) \quad v_n = \frac{R}{2} \sin \theta (\omega_1 - \omega_2) \cong 0$$

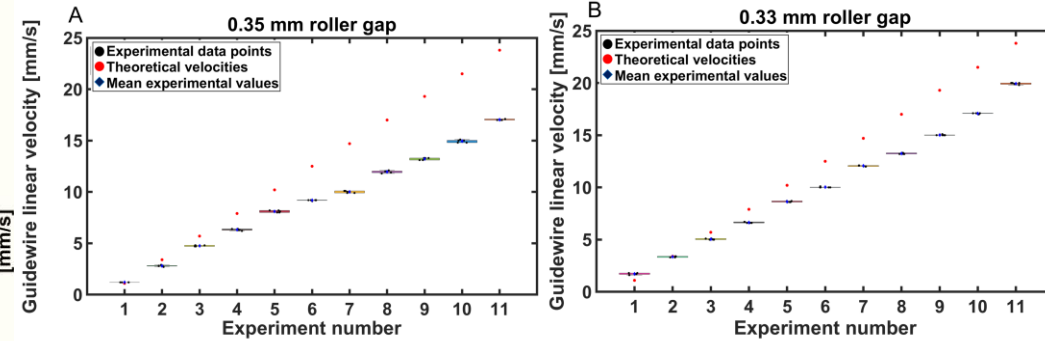
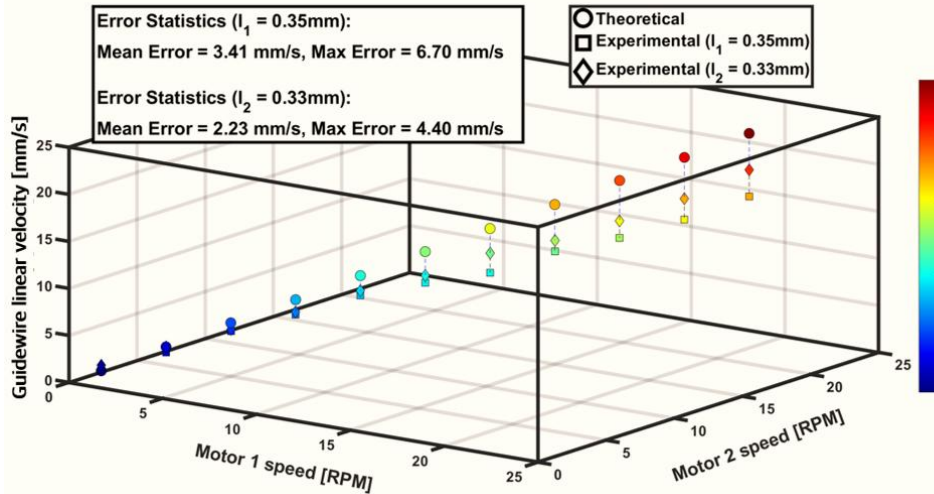
$$\begin{bmatrix} V_t \\ \Omega \end{bmatrix} = \begin{bmatrix} -\frac{R}{2} \cos \theta & \frac{R}{2} \cos \theta \\ -\frac{R}{d} \sin \theta & -\frac{R}{d} \sin \theta \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \end{bmatrix}$$

Output Input

Experimental Results

Kinematics validation

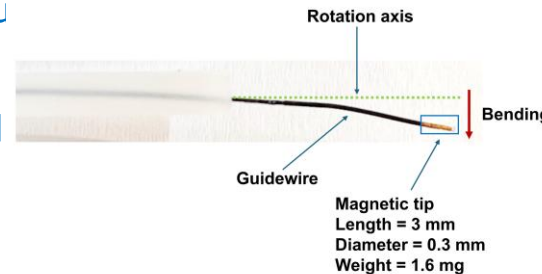
Theory Vs Experiment



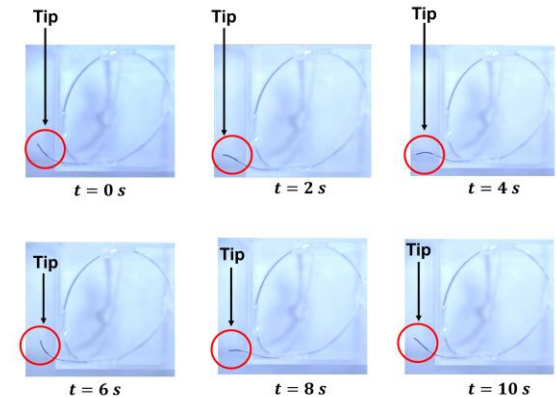
Data sparse for each experiment

- ☑ Guidewire's rotation motion was not verified due to its small diameter (0.36 mm) and flexible nature
- ☑ Error increases at elevated speed ($> 12\text{ mm/s}$)
 - Slip in dynamic friction regime
- ☑ Misalignments in the parts assembly (vibration) due to 3D printer limitations
- ☑ Elastic micro deformations at contact regions lead to non-uniform force distribution
- ☑ Smaller roller gap makes better contact with guidewire hence less error

Guidewire tip bending

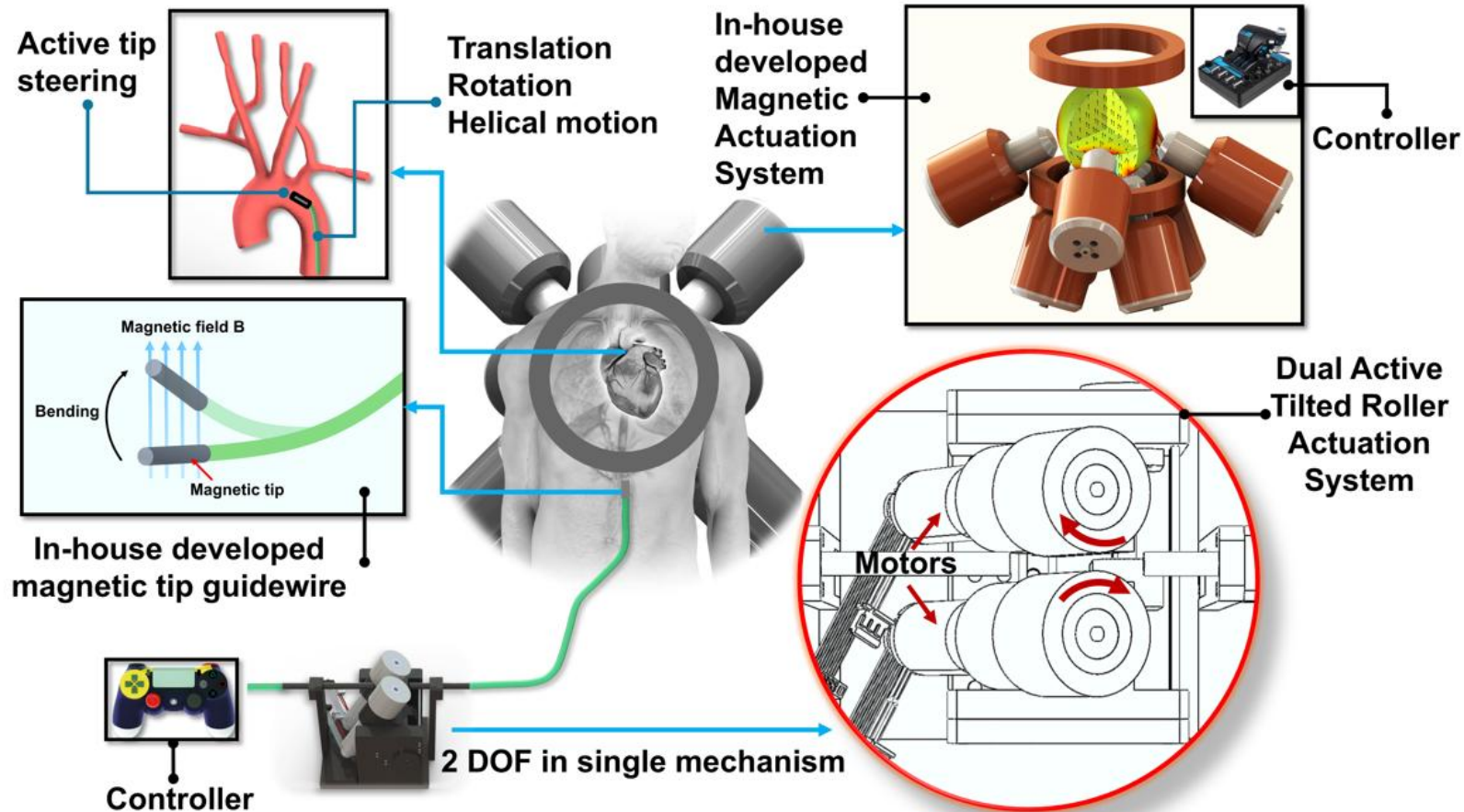


Floppy motion



Guidewire Actuator Integration with Electromagnetic Actuation System

✓ System Integration

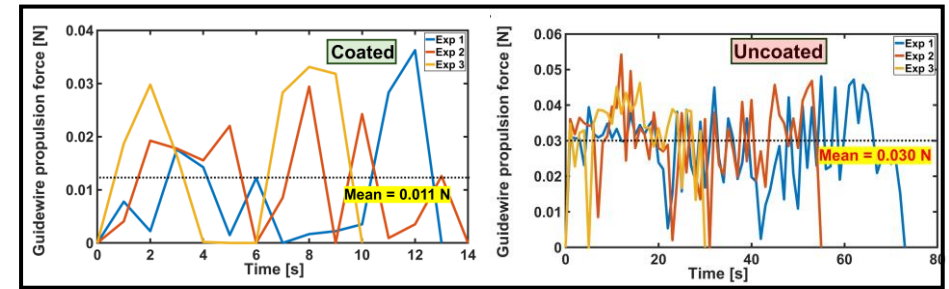
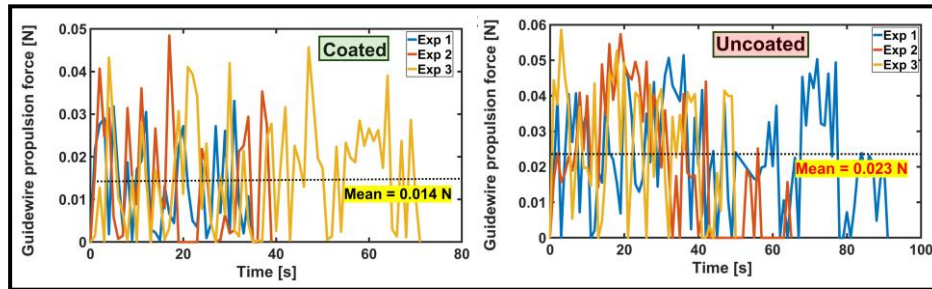
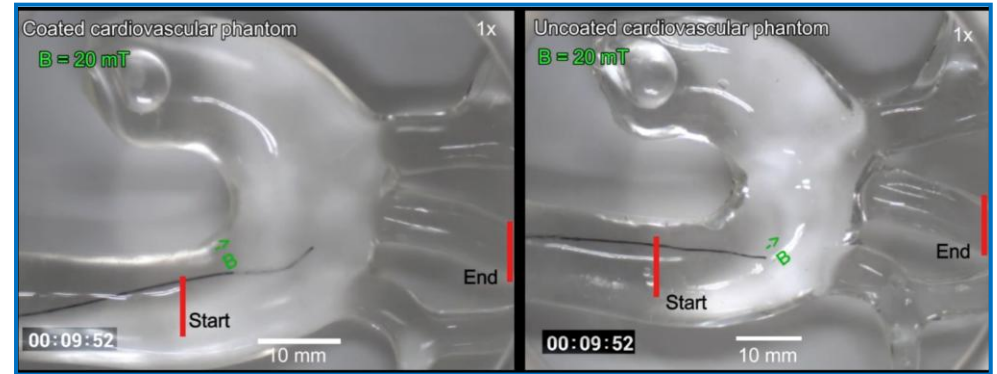
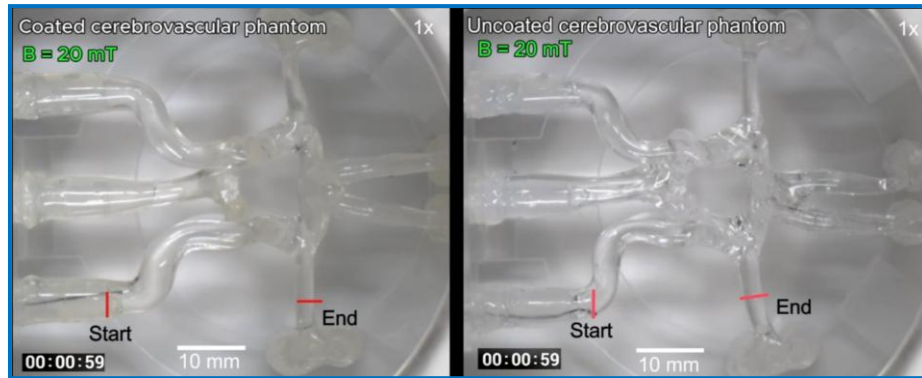


- ✓ In-house guidewire
- ✓ In-house EAS
- ✓ In-house guidewire actuator
- ✓ ROS 2 framework

Experimental Results

Performance in diverse environments

✓ Coated VS Uncoated Phantom

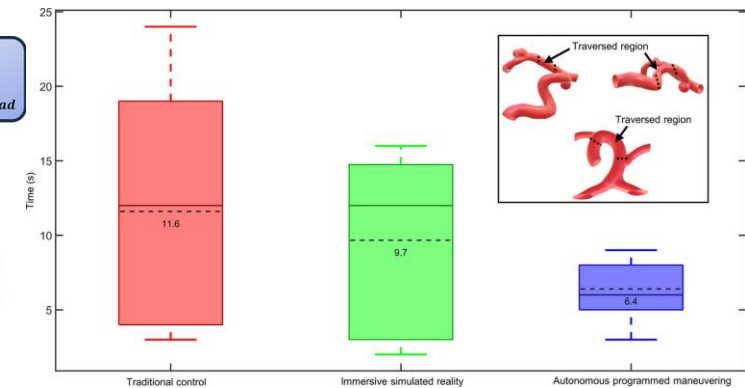
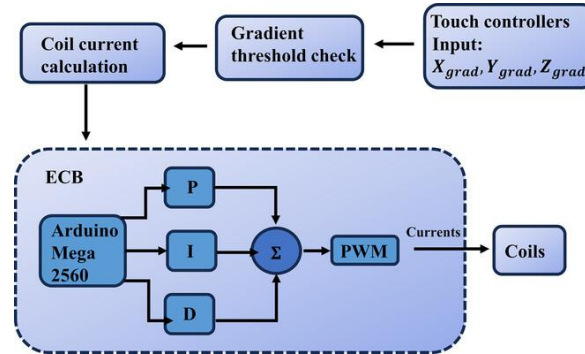
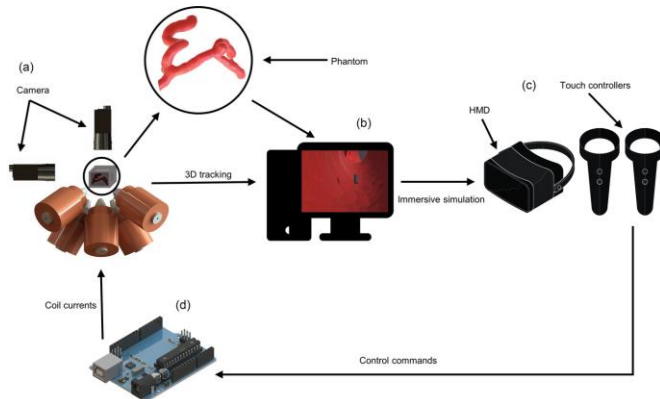


- ✓ DATRAS performs in high friction domains with higher propulsion force
- ✓ Tip navigation (yaw and pitch) controlled by electromagnetic actuation system
 - Increases total degree of freedom (DOF)
- ✓ Possibility of haptic feedback by mapping propulsion forces into gamepad vibrations
- ✓ Propulsion force increases as the resistance (friction) increases

Experimental Results

Virtual Reality (VR) Control Interface

✓ VR Enabled microrobot control



- ✓ Immersive control interface for user comfort
 - Intuitive
 - 360-degree natural movement
 - 1st person view
- ✓ Better position control; shorter operation time
 - Realistic 3D data
 - Less position error
- ✓ Can be integrated with autonomous/semiautonomous control
 - Immersive user interference when required
- ✓ Improved spatial awareness
 - Easy to navigate complex anatomies

