PhD Thesis (Graduation: 2025)

Virtual Reality-Assisted Teleoperation of Untethered and Tethered Magnetic Microrobots in Complex Medical Environments

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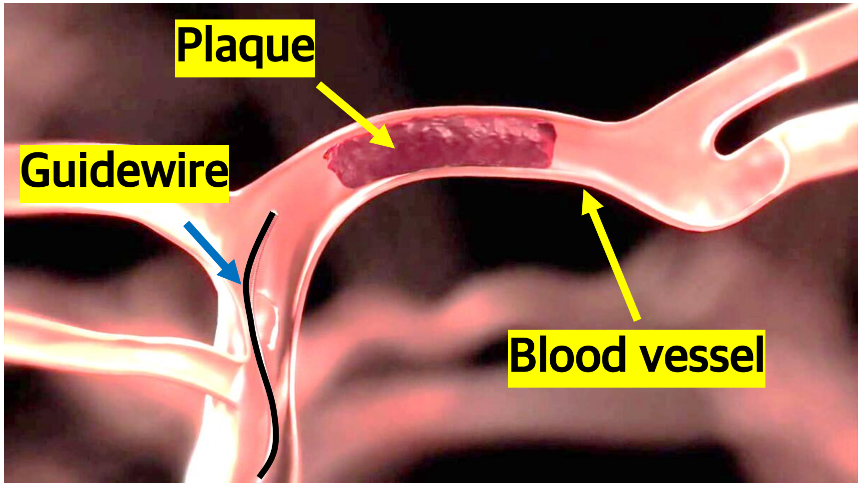
Introduction

Background

Vascular Interventions

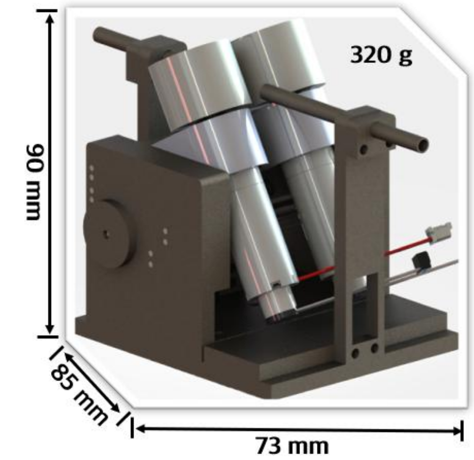
- ✓ Minimally invasive procedures
  - Plaque removal
  - Flexible & thin instruments: Guidewires/catheters
- ✓ Requires translation and rotation of guidewires
- ✓ Performed under X-ray
  - Numerous health hazards
- ✓ Robot assisted interventions
  - Radiation protection
  - Reduced fatigue



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

2 modules for 2 DOF	2 DOF - belt drive	2 DOF - robotic graspers
~ 15 kg, needs robotic arm	Bulky; needs robotic arm	Bulky; needs robotic arm
0.36 mm guidewire	0.36~0.89mm guidewire	0.36 guidewire
~ 650K USD	~600 USD	Expensive

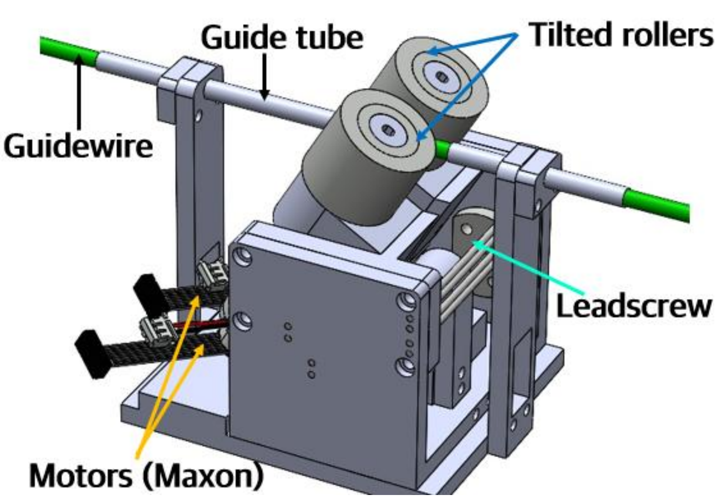
Our Solution

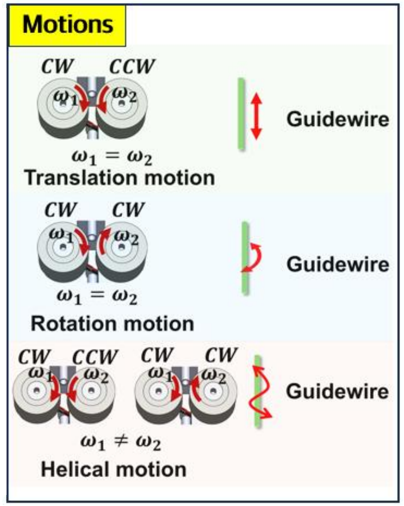


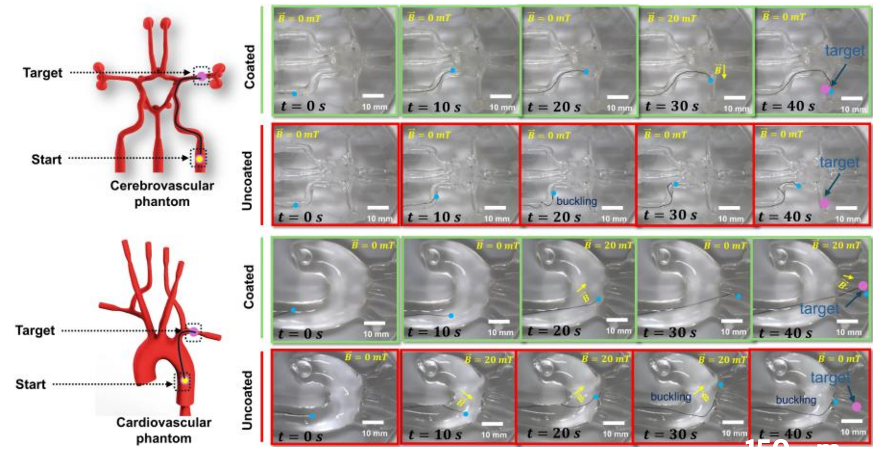
Experimental Setup

Proposed Mechanism

Dual Active Tilted Roller Actuation System

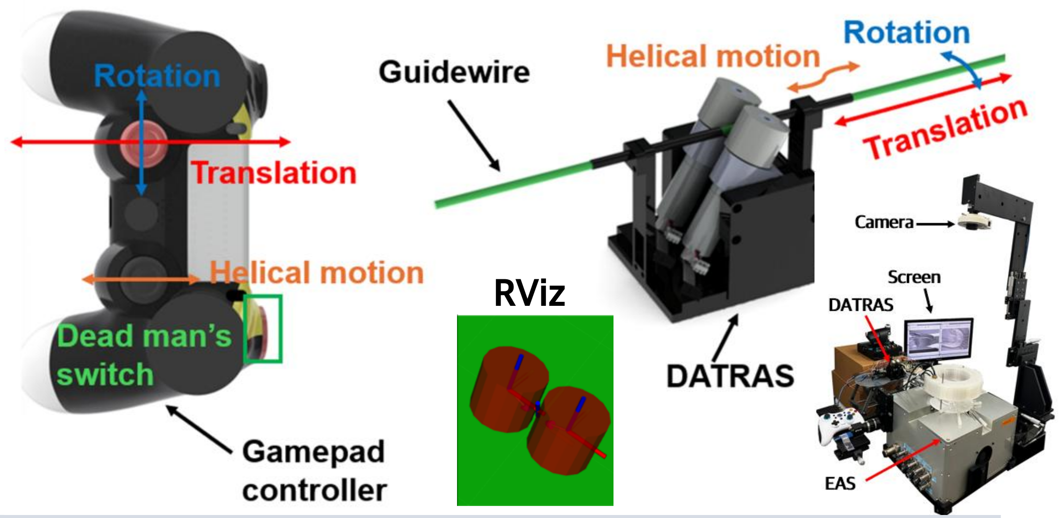






Guidewire navigation

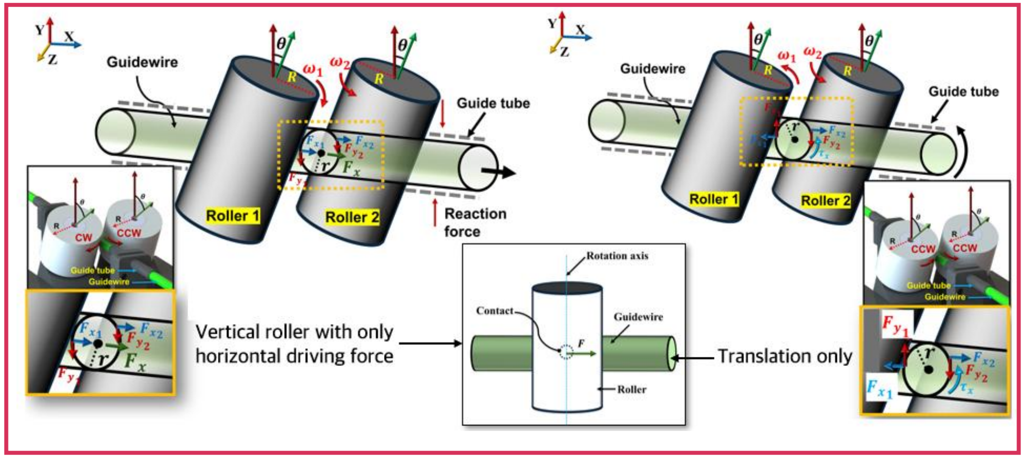
- 2 DOF in a single mechanism
  - Helical motion possible
- Dimensions: 85 mm x 73 mm x 90 mm
- Weight: 320 g
- Supports all diameter guidewires
  - Adjustable roller gap
- Cost: ~ 1k USD
- Easy integration with EAS
  - Teleoperation (ROS2 framework)

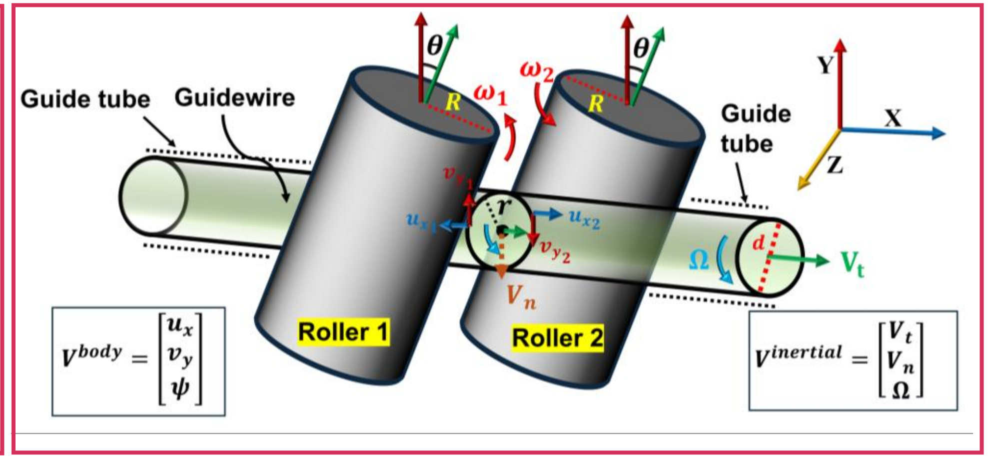


Experimental Setup

Proposed Mechanism

Working principle





$Translation{:}\ F_x = F_{x_1}cos\theta + F_{x_2}cos\theta = \mu_s N_1 cos\theta + \mu_s N_2 cos\theta$

$Rotation{:}\ F_y = F_{y_1}sin\theta + F_{y_2}sin\theta = \mu_s N_1 sin\theta + \mu_s N_2 sin\theta$

$$F_y = 0\ [guide\ tubes\ reaction\ forces]$$

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

$Helical\ motion\ when\ \omega_1 \neq \omega_2$

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

$V_t = tangential\ velocity\ (guidewire)$
$V_n = normal\ velocity\ (guidewire)$
$\Omega = angular\ velocity\ (guidewire)$

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

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

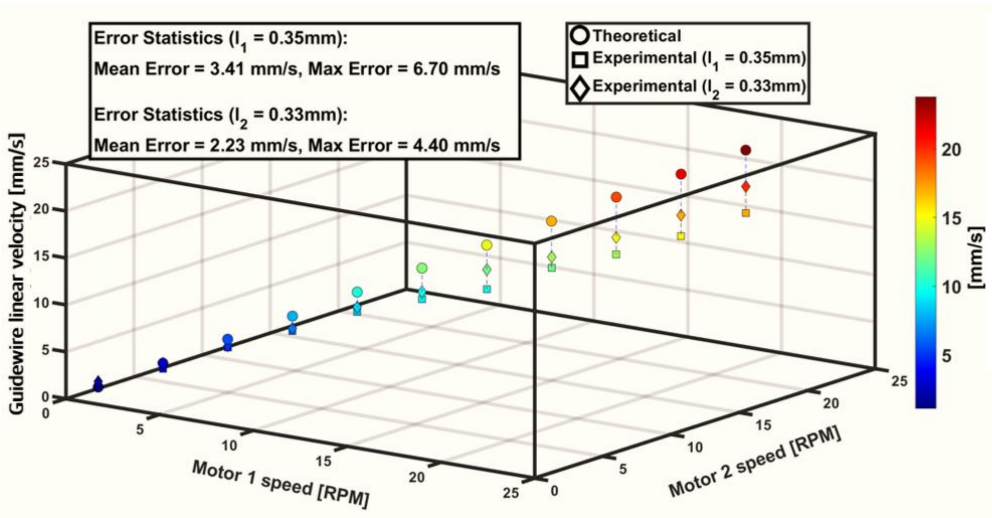
$$\begin{bmatrix} V_t \\ \Omega \end{bmatrix} = \begin{bmatrix} -\frac{R}{2}cos\theta & \frac{R}{2}cos\theta \\ -\frac{R}{d}sin\theta & -\frac{R}{d}sin\theta \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \end{bmatrix}$$

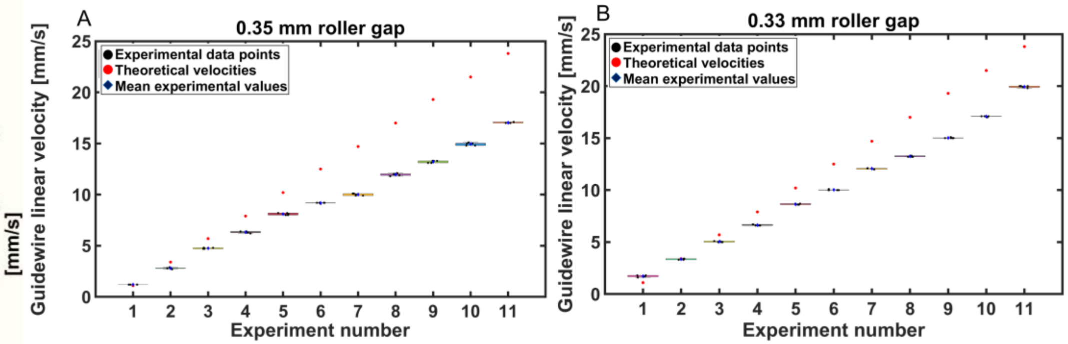
Output   Input

Experimental Results

Kinematics validation

Theory Vs Experiment

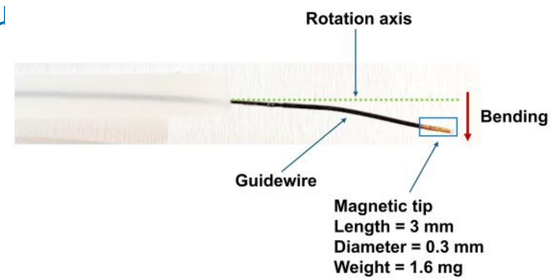




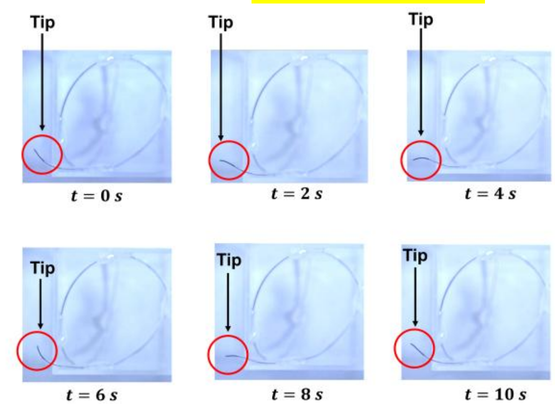
Data sparse for each experiment

- ☑ Guidewire's rotation motion was not verified due to its small diameter (0.36 mm) and flexible nature
- ☑ Error increases at elevated speed (> 12 mm/s)
  - Slip in dynamic friction regime
- ☑ Misalignments in the parts assembly (vibration) du 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



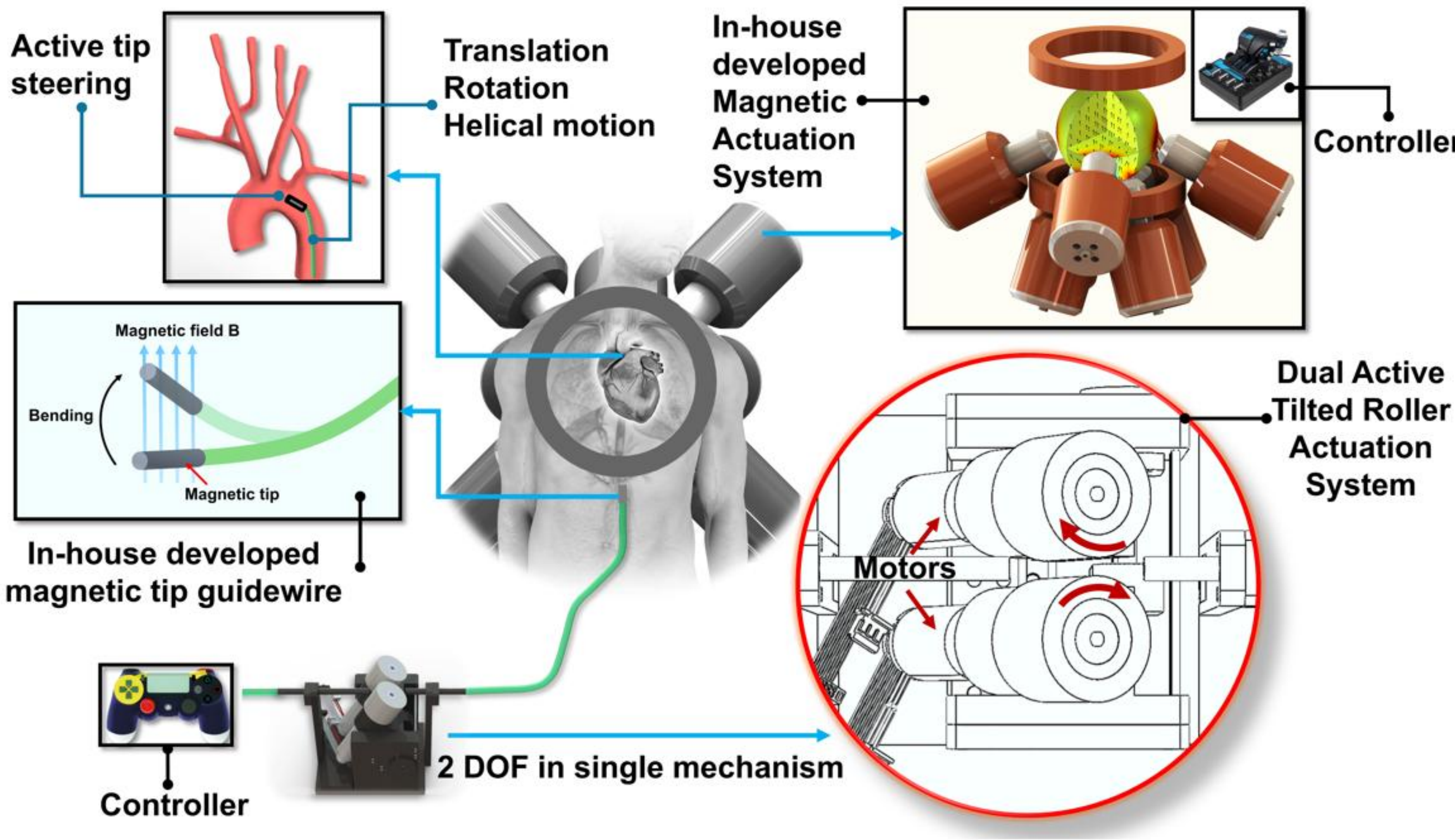
Floppy motion



Experimental Results

Guidewire Actuator Integration with Electromagnetic Actuation System

System Integration

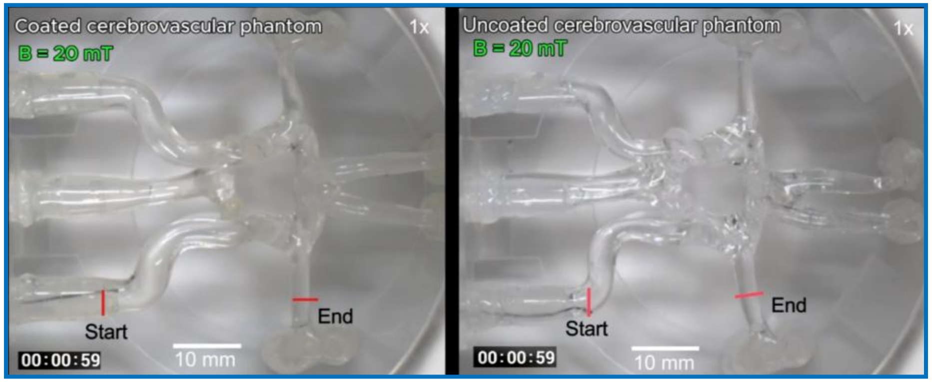


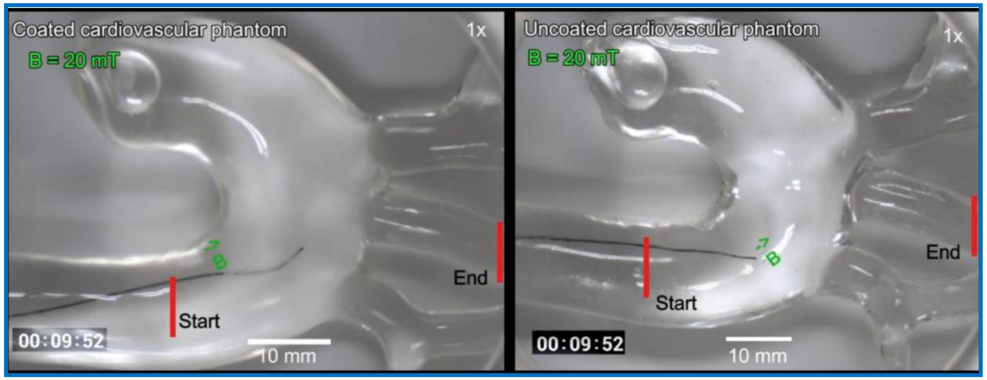
☑ In-house guidewire ☑ In-house EAS ☑ In-house guidewire actuator ☑ ROS 2 framework

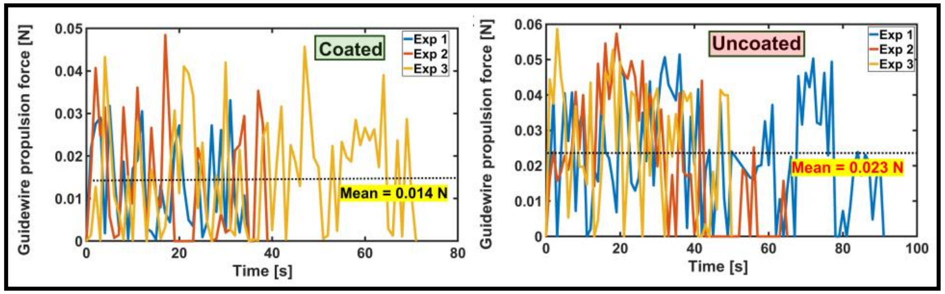
Experimental Results

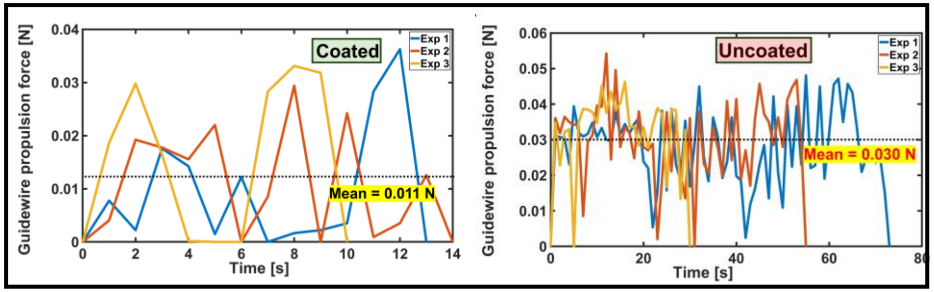
Performance in diverse environments

Coated VS Uncoated Phantom







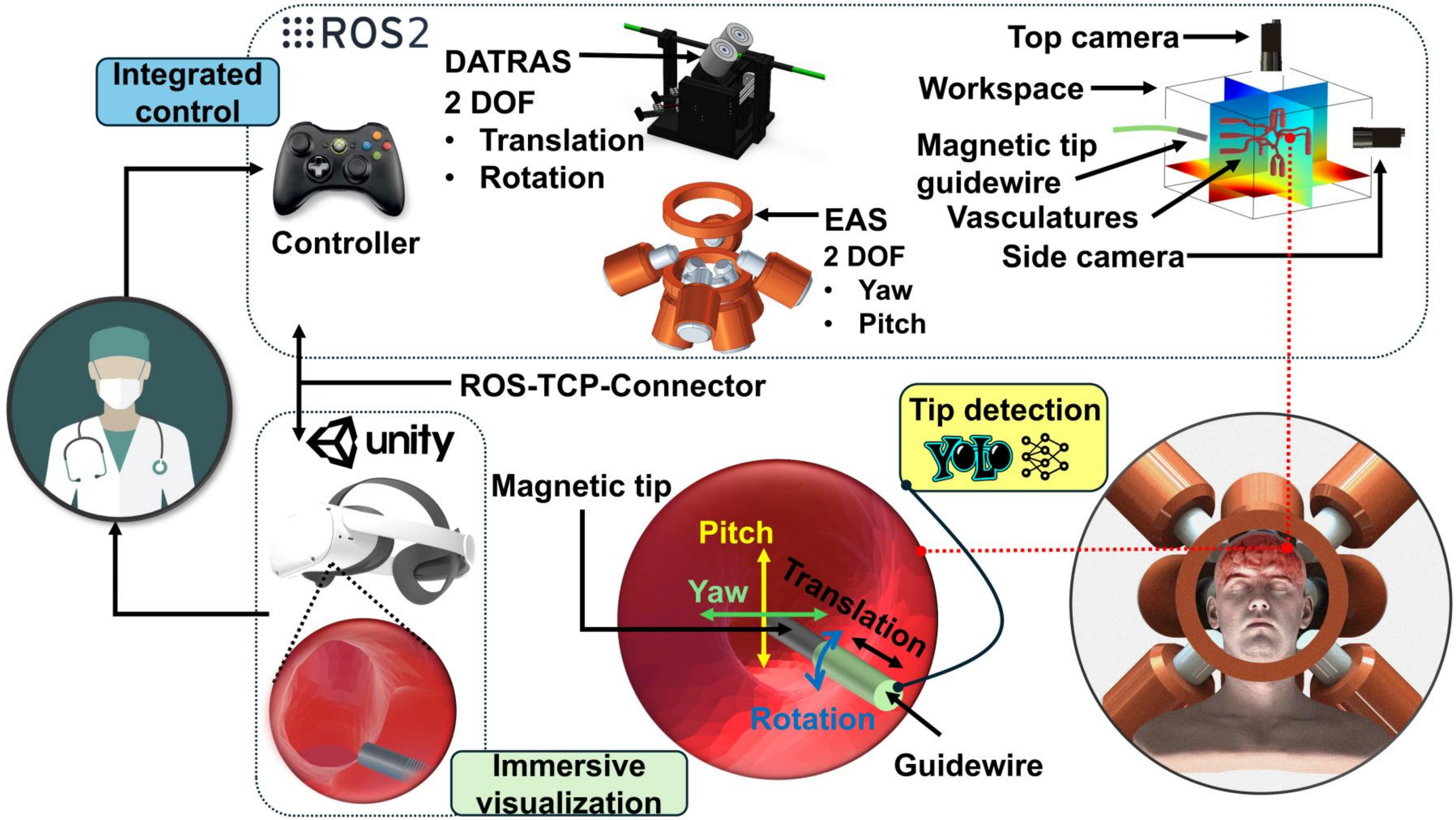


- ☑ DATRAS performs in high friction domains with higher propulsion force
- ☑ Tip navigation (yaw and pitch) controlled by electromagnetic actuation system
  - Increases total degree of freedom (DOF)
- ☑ Possibility of haptic feedback by mapping propulsion forces into gamepad vibrations
- ☑ Propulsion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

Experimental Results

Virtual Reality (VR) Control Interface

✔ VR Enabled tethered and untethered microrobot control

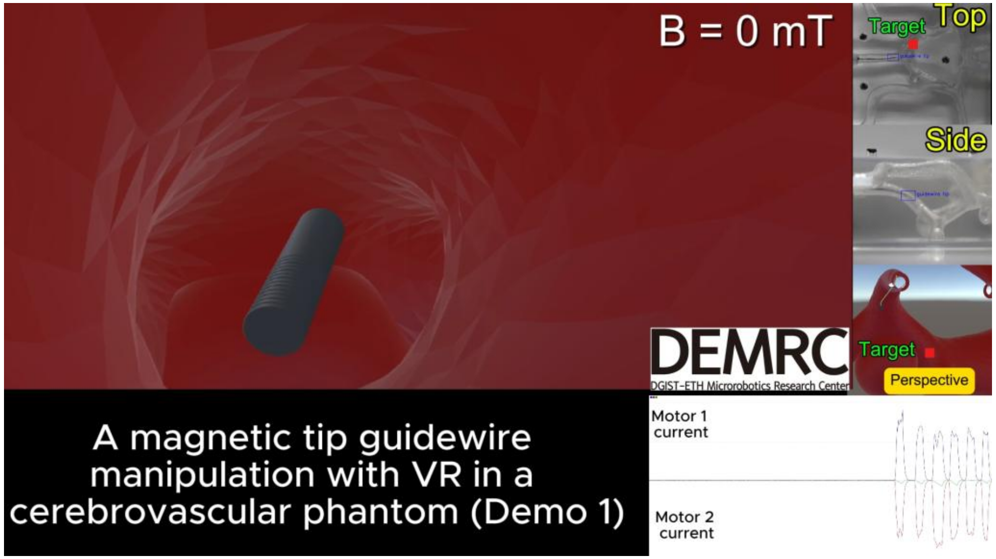


Schematic diagram of the integrated system architecture

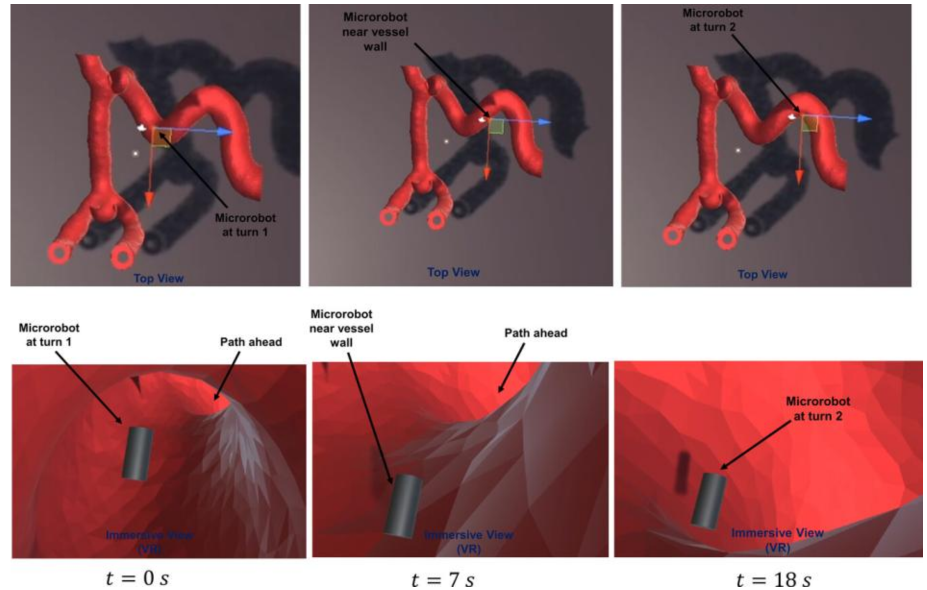
Experimental Results

Virtual Reality (VR) Control Interface

VR Enabled tethered and untethered microrobot control



Tethered microrobot (magnetic guidewire) control



Untethered microrobot (magnetic particle) 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