Portable 4-DoF Robotic Catheter System for Image-Guided Percutaneous Coronary Intervention

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Motivation / Introduction

Problem Statement

- Cardiovascular disease is the #1 global cause of death, demanding improved surgical interventions.
- Percutaneous Coronary Intervention (PCI) is a common minimally invasive procedure to treat arterial blockages.
- PCI requires precise manipulation of catheters and guidewires through tortuous vasculature under continuous X-ray imaging (fluoroscopy).

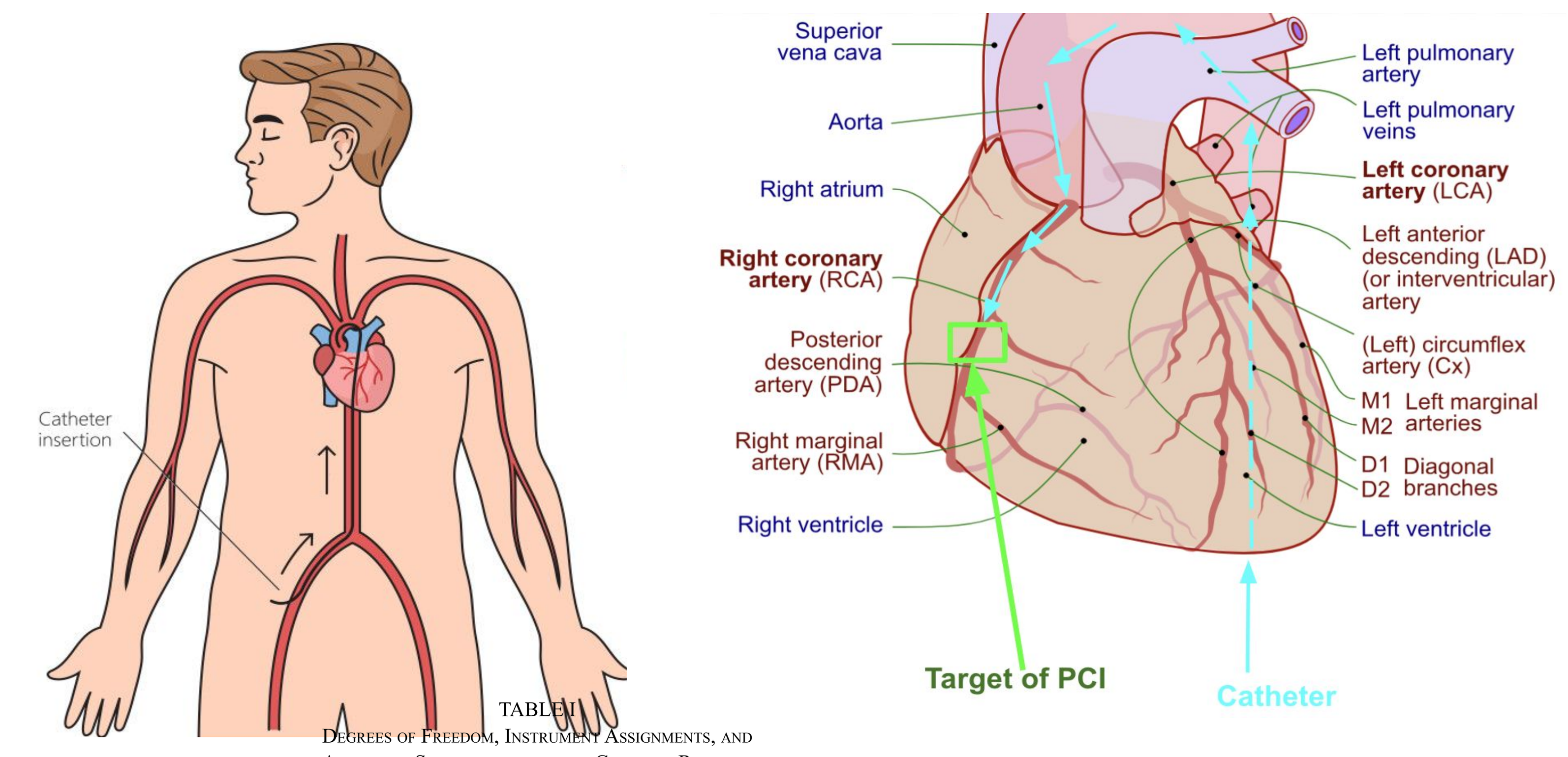


TABLE I
DEGREES OF FREEDOM, INSTRUMENT ASSIGNMENTS, AND ACTUATION SPECIFICATIONS OF THE CATHETER ROBOT

Fig. 1 & 2. Comparison of manual and robot-assisted PCI procedures and guide catheter instrumentation. The manual approach (top) involves direct hand manipulation of a guide catheter, while the robotic approach (bottom) uses a motorized drive system to control catheter movement remotely through a console. Figure generated by student authors.

Clinical & Technical Challenges

- Radiation exposure to clinicians and physical strain during prolonged procedures.
- Existing robotic systems reduce these risks but are:
  - Bulky, requiring specialized operating rooms
  - Limited in instrument compatibility
  - Expensive and non-portable

Guide Catheter Module (DoF #1 and #2)

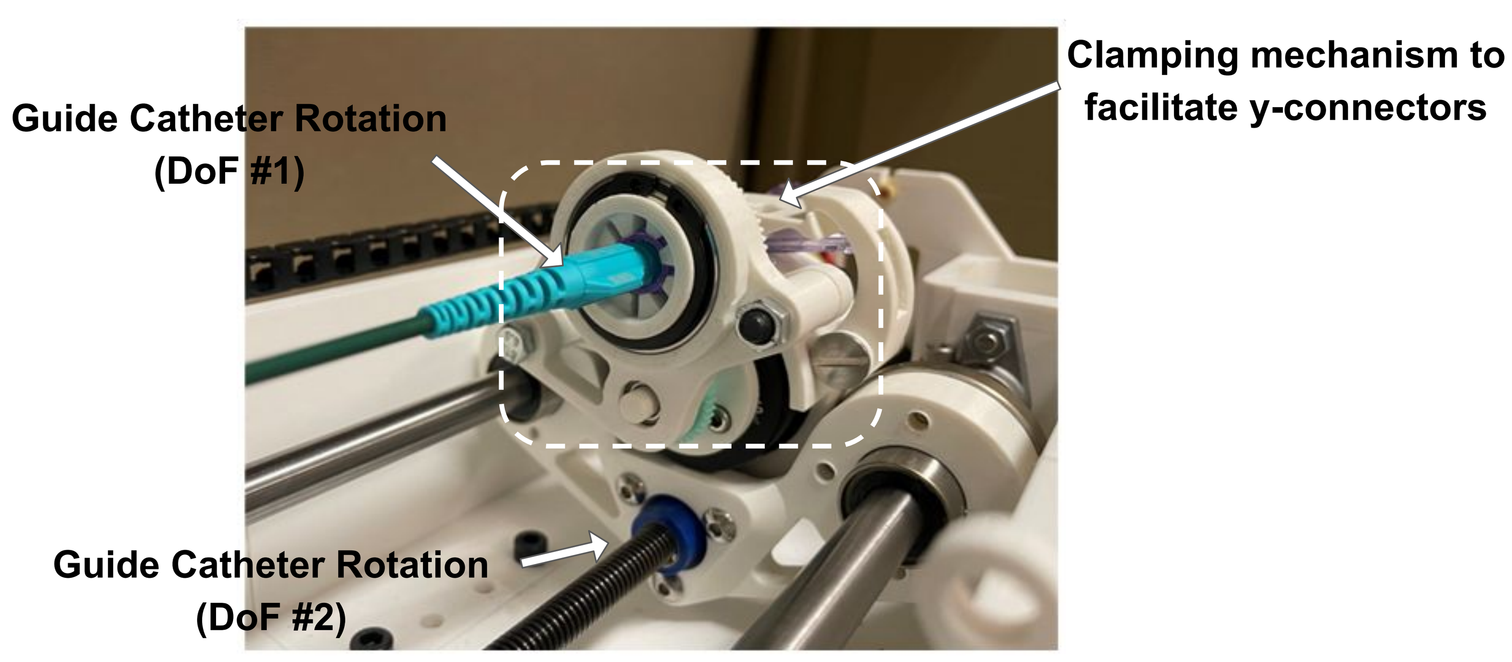


Fig. 3. Guide catheter actuation module of the robotic system. DoF #1 provides axial rotation via a direct-drive motor, while DoF #2 enables linear translation using a lead screw mechanism. A modular clamping system allows compatibility with y-connectors and off-the-shelf guide catheters.

- DoF Precision Control allows for independent axial rotation (DoF #1) and linear translation (DoF #2) of guide catheters, enabling smooth manipulation in complex cardiovascular pathways.
- Direct-Drive and Lead Screw Actuation combines a direct-drive BLDC motor for smooth catheter rotation with a lead screw platform for accurate insertion/retraction.

Experimental Result

- Developed a compact 4-DoF robotic catheter system for precise guidewire and catheter manipulation in image-guided PCI.
- Demonstrated accurate vascular navigation in a phantom heart model without slippage or vessel damage.
- Features a small footprint, direct-drive actuation, and compatibility with standard instruments.
- Offers potential for safer, more accessible robotic cardiovascular interventions.
- Future work will address sterilization methods and conduct in vivo validation.

Portable 4-DoF Robotic Catheter System Components

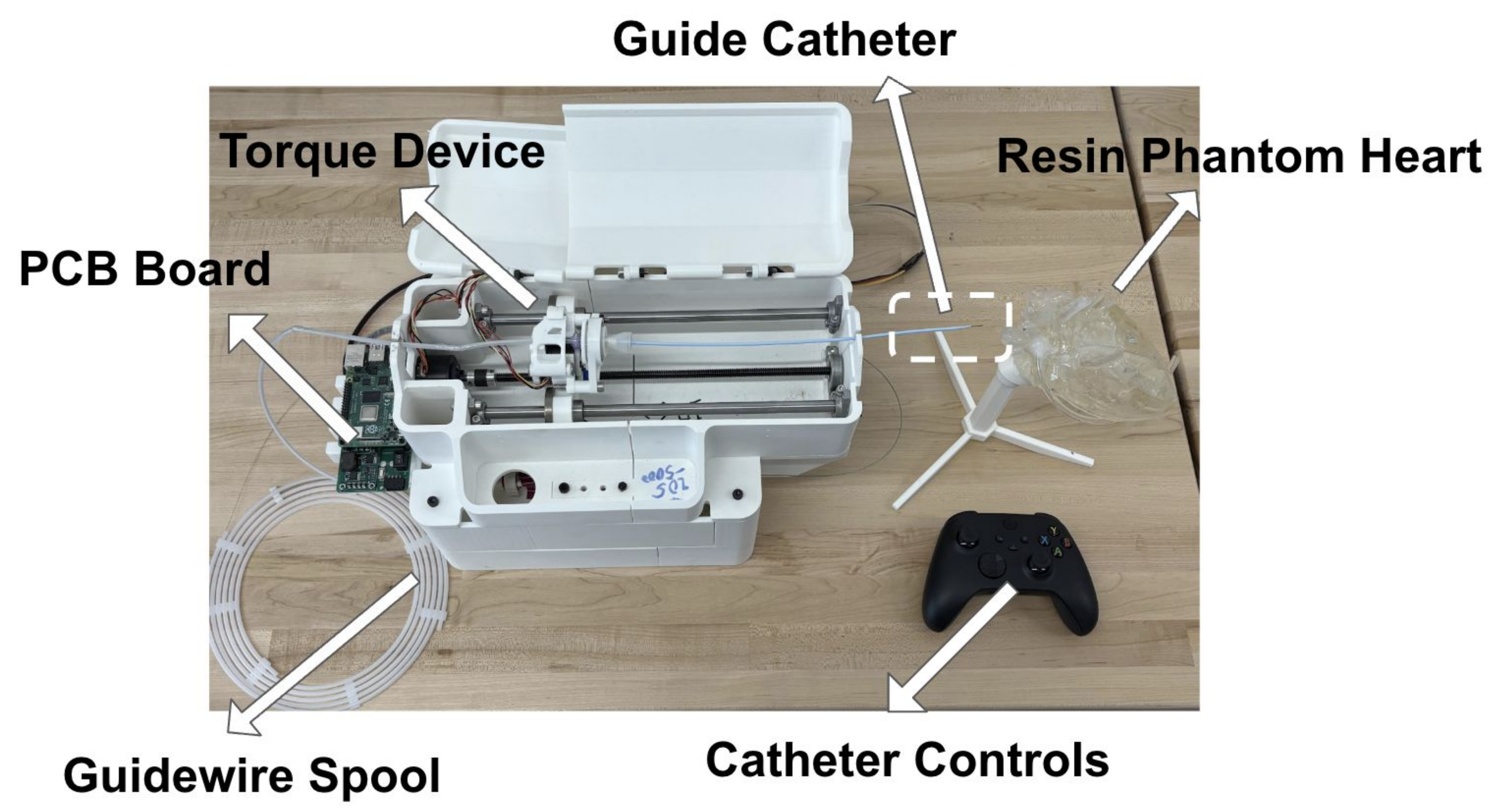
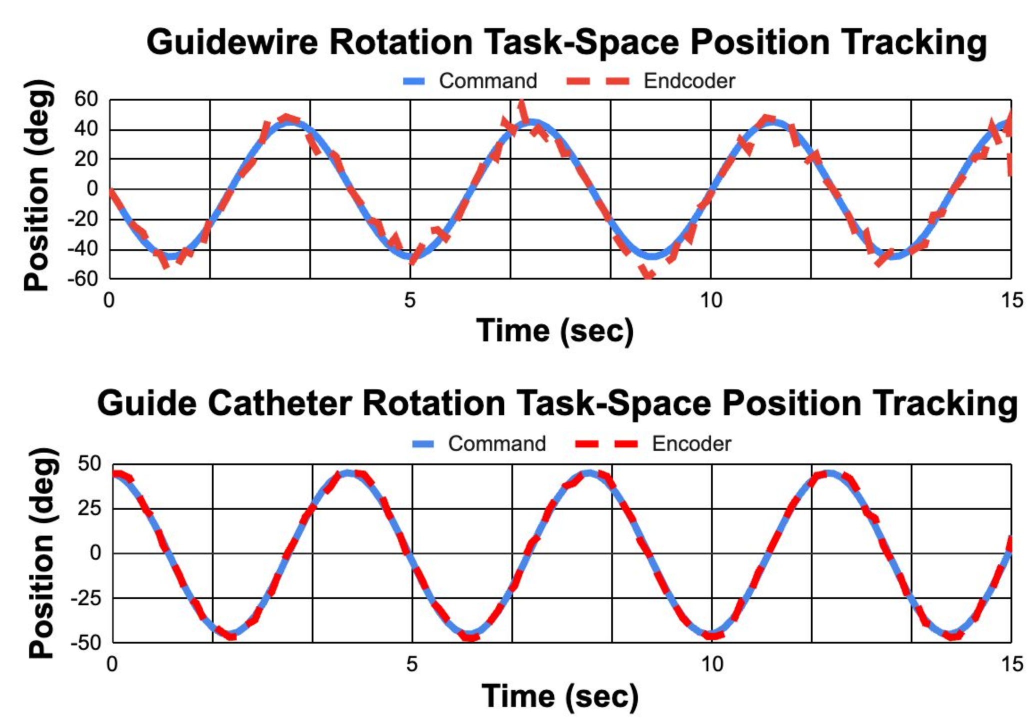


Fig. 4. Labeled components of the portable 4-DoF robotic catheter system. The PCB board houses the control electronics for motor actuation. The guidewire spool stores and feeds the sterile guidewire. The torque device provides controlled rotational input to the guidewire. The guide catheter serves as the primary conduit for device delivery. The resin phantom heart is used for simulated PCI navigation trials. Catheter controls (game controller) allow teleoperation of the system during experiments.

- Integrated electronics and catheter modules enable precise guidewire and catheter manipulation in simulated PCI procedures.
- Resin phantom heart provides a realistic vascular environment for testing navigation performance and system accuracy.

Joystick-Controlled Position Tracking Algorithm



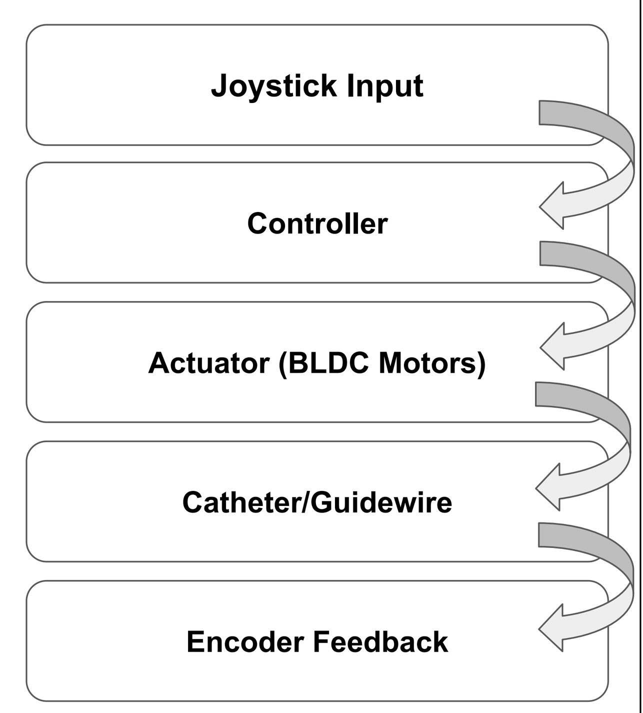


Fig. 5 & 6. Joystick-controlled position tracking performance for the guidewire (top) and guide catheter (bottom). The blue curve represents the commanded sinusoidal input, while the red curve shows the encoder-measured response. Both modules exhibit close agreement between commanded and actual trajectories, demonstrating high tracking accuracy across multiple cycles. The flow diagram on the right illustrates the control loop, where joystick input is processed by the controller, actuated via BLDC motors, and corrected through encoder feedback.

- Joystick-controlled tracking tested for both guide catheter and guidewire rotation.
- Blue curve shows commanded sinusoidal input; orange curve shows measured response.
- Results indicate close match between commanded and measured positions.
- High tracking accuracy maintained across multiple rotation cycles.

Degree of Freedom Instrument Assignments

- 4-DoF architecture allows independent rotation and translation of both the guide catheter and guidewire for precise navigation.
- High-resolution control (0.3° rotation, 0.5 mm translation) enables accurate positioning while minimizing the risk of vessel trauma.

Degree of Freedom	Instrument	Motion Type	Motion Range	Resolution
1	Guide Catheter	Axial Rotation	Rotation: ±180° (0-360°)	0.3°
2	Guide Catheter	Linear Translation	Translation: ±150 mm (0-150mm)	0.5mm
3	Guidewire	Axial Rotation	Rotation: ±150° (0-300°)	0.3°
4	Guidewire	Linear Translation	Rotation: ±180° (0-360°)	0.5mm

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