A Compact and Versatile Catheter Robot for Invasive Cardiac and Neurovascular Interventions

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Many diseases require minimally invasive catheter-based interventions for effective treatment. Among them, cardiovascular and neurovascular diseases remain leading causes of mortality and disability worldwide. These procedures, including stenting, thrombectomy, and coiling, rely on catheter-based navigation under fluoroscopic guidance. However, manual control of guide catheters and guidewires under X-ray exposes operators to radiation risks and increases procedural complexity. While robotic catheter systems have been developed to enhance precision and reduce radiation exposure, many existing designs are bulky, require specialized facilities, and have limited compatibility with commercially available instruments, restricting their widespread adoption across both cardiac and neurovascular interventions.

To overcome these limitations, we designed and validated a compact, four-degree-of-freedom (4-DoF) catheter robot focusing on three key challenges. First, to minimize system footprint, we adopted a three-layer architecture (top, middle, and bottom) enabling catheters and guidewires to follow an S-shaped path through each module. Second, to achieve fully automated, broad compatibility without manual adjustment, we incorporated a rotating Y-connector (DoFs #1 and #2) supporting multiple catheters (1F–9F). Third, for precise, continuous guidewire insertion/retraction (DoF #4) and rotation (DoF #3), we employed a friction-roller drive mechanism accommodating various wire diameters.

We conducted benchtop tests targeting three main performance aspects. 1: Compatibility, We used commercial catheters (5F, 8F) and guidewires (0.36 mm, 0.89 mm). Motion capture at 100 Hz (via four Qualisys Miqus M5™ cameras) showed root-mean-square errors of about 0.31 mm and 10.3 for catheter movements, and 0.9 mm and 6.9 for guidewires, largely due to instrument flexibility. 2: Precision in rotation/translation. Using a six-axis Nano43™ force/torque sensor, we measured peak push forces at different motor currents. The 8F catheter reached 5.49 N (at 1.05 A), and the 5F catheter hit 3.44 N. For the 0.89 mm and 0.36 mm wires, peak forces were 0.38 N and 0.35 N, respectively. Catheter rotation torques attained 10.61 mNm (8F) and 6.55 mNm (5F), while guidewires reached 0.42 mNm and 0.22 mNm. The robot could also exert lower forces (15–40 mN) for delicate maneuvers. 3: Clinically relevant speed/bandwidth. We performed a proof-of-concept PCI simulation using a 0.89 mm$\times$450 cm Hydra Jagwire™ guidewire. Driven at about 1 mm/s, the wire navigated tortuous vessels and bypassed obstructions, demonstrating feasibility for real-world scenarios.

By routing instruments through stacked actuation layers and using adjustable modules, our compact 4-DoF robot enables a broad range of instruments to be positioned accurately within a reduced footprint. Preliminary evaluations indicate it meets typical endovascular demands for force, torque, and motion accuracy. This design offers a promising foundation for more versatile and accessible robotic platforms in neurovascular interventions.

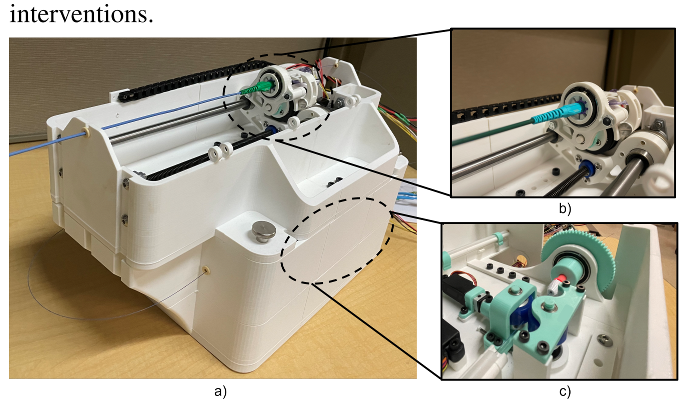

Fig. 1: 4 DoF Catheter Intervention Robot: Guide Catheter Module & Guidewire Module

References

[1] H. Su*, G. Li*, G. A. Cole, W. Shang, J. Pilitsis, and G. S. Fischer, "Robotic system for MRI-guided stereotactic neurosurgery," IEEE Transactions on Biomedical Engineering, vol. 62, no. 4, pp. 1077-1088, Apr. 2015.

[2] G. Li, N. Patel, E. Burdette, J. Pilitsis, H. Su, and G. S. Fischer, "A fully-actuated robotic assistant for MRI-guided precision conformal ablation of brain tumors," IEEE/ASME Transactions on Mechatronics, vol. 26, no. 1, pp. 255-266, Jul. 2020.

[3] H. Su, K. W. Kwok, K. Cleary, J. P. Desai, I. Iordachita, C. Cavusoglu, and G. S. Fischer, "State of the art and future opportunities in MRI-guided robot-assisted surgery and interventions," Proceedings of the IEEE, vol. 110, no. 7, pp. 968-992, Jul. 2022.

[4] S. Chang, S. Tseng, H. Su, and G. E. Francisco, "How can wearable robotic and sensor technology advance neurorehabilitation?," Frontiers in Neurorobotics, vol. 16, Sep. 2022.