Ultra-Steerable Robots for Transnasal and Intraventricular Neurosurgery

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***Abstract*—Minimally invasive neurosurgery requires precise and dexterous instrumentation, particularly in anatomically constrained regions such as the transnasal corridor and deep brain. Traditional robotic systems often lack the necessary flexibility for these delicate procedures. This paper presents an ultra-steerable neurosurgical robotic system with 9 degrees of freedom (DOF), enabling enhanced maneuverability and precision. The system integrates coaxial ultra-steerable catheters, a reinforcement tube, and an endoscope control module, providing full spatial control. Actuation is powered by direct-drive BLDC motors with high-resolution encoders, and a custom PCB with CAN bus communication ensures real-time motion synchronization. Preliminary evaluations demonstrate the developed ultra-steerable catheter has a bending radius as small as 5 mm. We envision this robotic platform to provide a promising solution for neurosurgical interventions, enhancing accessibility and precision in minimally invasive procedures.**

***Index Terms*—Neurosurgery robot, Ultra-steerable catheter, Minimally invasive surgery.**

I. Introduction

Minimally invasive neurosurgery requires exceptional dexterity and precision, especially in confined spaces such as the transnasal corridor and deep brain regions [1], [2]. State-of-the-art robotic-assisted systems (such as the MRI-guided neurosurgery robot) are often too bulky, or mechanically constrained to navigate narrow pathways effectively [3], [4]. To address these limitations, we present an ultra-steerable robotic system designed for neurosurgical interventions. This novel robotic platform features highly dexterous, small-diameter articulated arms, enabling improved access to deep-seated targets while minimizing collateral tissue damage. The system integrates digital surgery capabilities, including real-time imaging and adaptive learning-based control, to enhance precision and efficiency in complex surgical procedures.

II. Methods

The system consists of a 9-degree-of-freedom (DOF) robotic mechanism along with the compact customed control electronics, designed to provide full spatial maneuverability in constrained surgical environments. The key design components include: 1) Steerable Catheter Module (6 DOF): The robot employs a coaxial push-pull ultra-steerable catheter, where two nested tubes with geometrically patterned notches interact to achieve controlled bending. The inner and outer tubes translate independently via a motorized lead screw mechanism, generating precise curvature for steerability. A hollow-shaft motor enables 360 degrees for rotation of the catheter while allowing independent translational control, ensuring high dexterity at the distal tip. 2) Working channel Tube Module (2 DOF): The catheter is enclosed in a surgical-grade stainless-steel reinforcement tube, providing structural rigidity while allowing smooth translational motion. The reinforcement tube is actu-

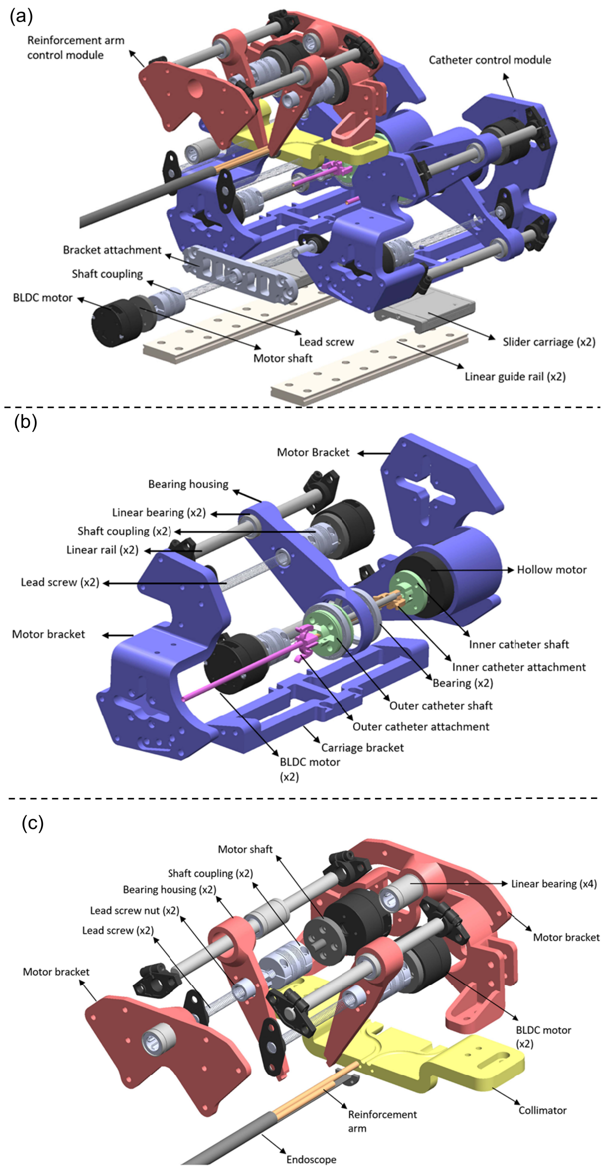

Fig. 1. (a)overview of the CAD model neurosurgery robot, which also depicts the overall modular assembly. (b) design of ultra-steerable catheter control module. (c) design of working channel tube control module

ated via a lead screw system, enabling controlled extension and retraction within the transnasal corridor. 3)Endoscope Module (1 DOF): The endoscope is affixed to a modular attachment that translates along a linear rail system, ensuring stable visualization throughout the procedure. The endoscope serves as a guiding structure for the steerable catheters and surgical tools. Collimator Assembly: This component integrates two catheters into a parallel axial configuration before insertion into the endoscope. The collimator design is optimized to maintain a minimum bend radius, ensuring seamless catheter movement without excessive mechanical stress.

The control electronics of the system are designed to enable precise real-time actuation while maintaining a compact footprint. The robot is powered by direct-drive brushless DC (BLDC) motors, each equipped with built-in motor drivers and incremental optical encoders, allowing closed-loop torque, speed, and position control. The system utilizes a Teensy 4.1 microcontroller for high-bandwidth communication with all actuation units via Controller Area Network (CAN) bus protocol, ensuring synchronized motion control. A custom two-layer PCB integrates all electronic components, minimizing wiring complexity while supporting expandability up to nine actuators. Additionally, a dedicated grip actuator with a micro BLDC motor and lead screw mechanism enables secure tool retention with sub-millimeter precision. The high-resolution position feedback (14-bit encoder resolution) ensures accurate tool trajectory execution, enhancing the system's reliability for microsurgical applications.

III. Results and Conlusion

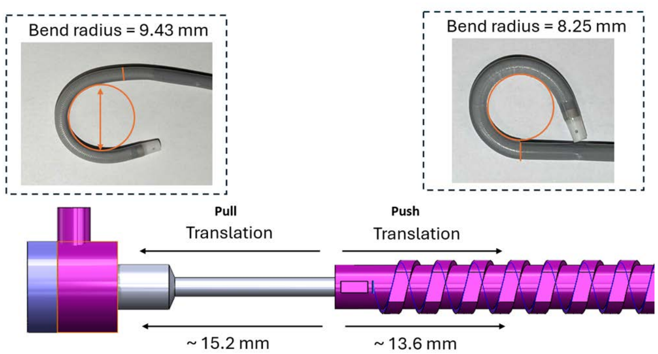

Fig. 2. Push-pull motion and the respective maximum displacement and bending radius of the designed ultra-steerable catheter.

Benchtop validation and preliminary cadaveric trials confirm the system's ability to navigate complex anatomical pathways with high precision. The steerable catheter achieves bending radii as small as 5 mm, significantly surpassing the dexterity of conventional rigid tools. The adaptive trajectory control system maintains stable motion, dynamically adjusting to anatomical shifts in real-time.

IV. Future Work

Future research will involve ex vivo phantoms and in-vivo testing, beginning with transnasal pituitary tumor resection and deep brain electrode placement. Clinical trials will evaluate improvements in procedural time, targeting accuracy, and surgeon ergonomics. Further developments will focus on optimizing system ergonomics, enhancing haptic feedback mechanisms, and integrating AI-driven algorithms for trajectory planning and navigation [5] for semi-autonomous robotic assistance.

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