A Compact Endoscopic Robot with Ultra-Steerable Catheters for Transnasal and Intraventricular Neurosurgery

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Website: http://haosu-robotics.github.io

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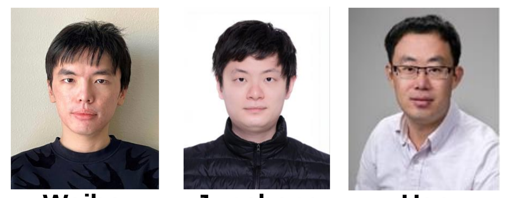
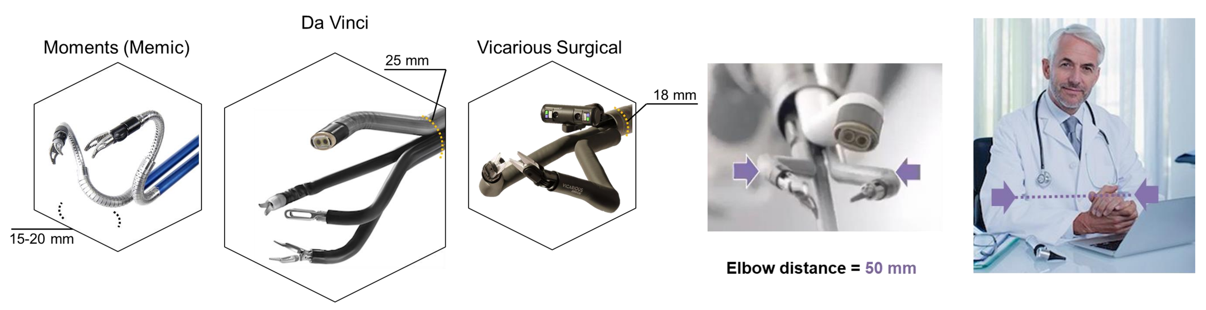
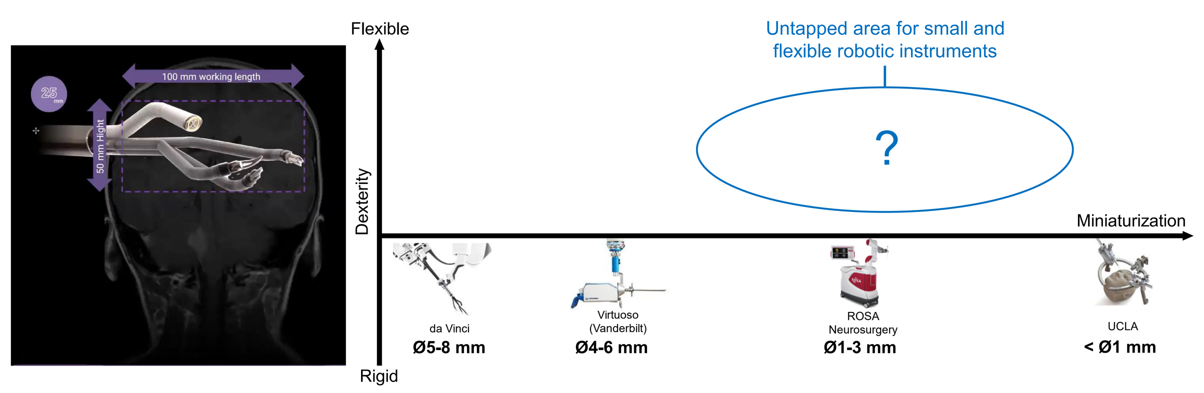


Introduction

- State of the art surgical robotics can only be used in large body cavities.
- A typical robot design with arms and elbows requires a large workspace 100(L) X 50(H) X 50 mm(W), which limits its use for abdominal and thoracic procedures.



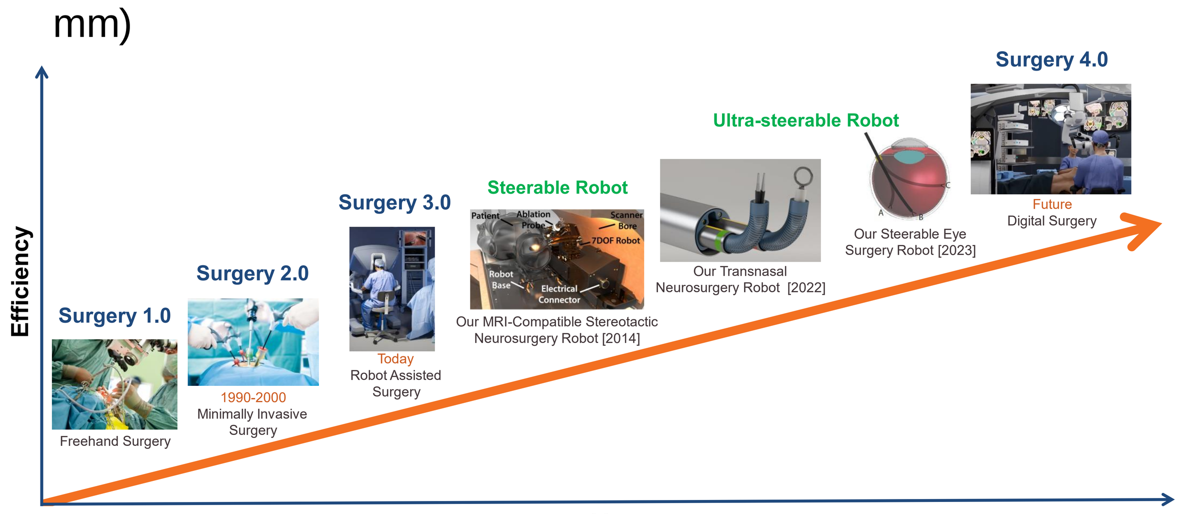
- Millions of patients undergoing "small cavity" surgery do not benefit from robotics



Small Cavities Need A Small Robot

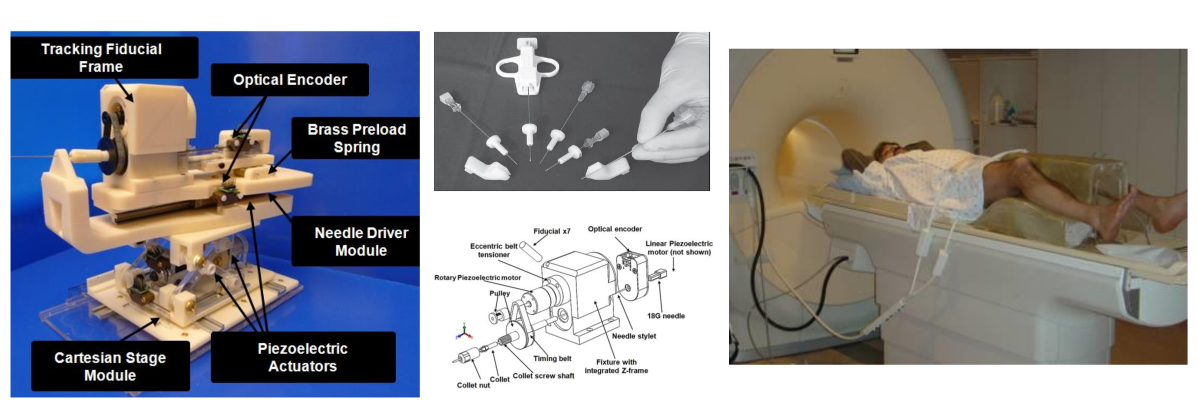
Future of Robotic Surgery

- Digital surgery: faster imaging, learning in simulation, digital twin, situation awareness
- Microsurgery: big cavities (Ø5-8 mm) to small cavities (Ø1-2 mm)

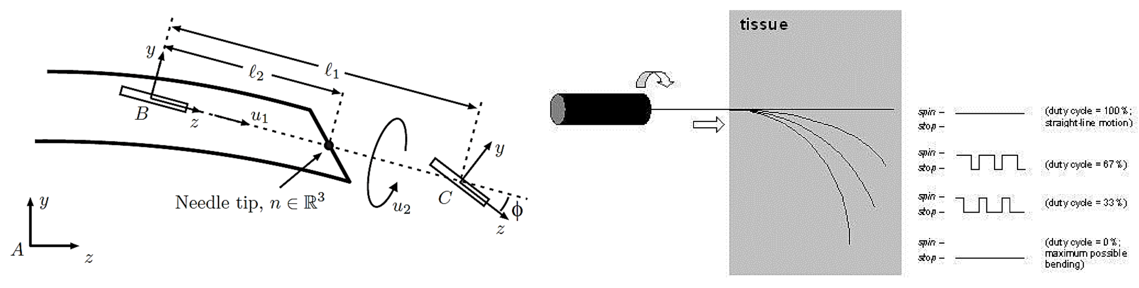


Bevel Needle Steering Robot System

- 3-DOF Needle Driver: Needle insertion/rotation , cannula retraction
- 3-DOF Cartesian Stage: x-y-z gross positioning
- 30RPM rotation velocity
- Integrated passive fiducial tracking frame localizes the device



6-DOF piezoelectric actuated needle placement robot (left); fiducial frame and rotary motor fixture, an exploded view of the needle clamping mechanism (middle); mockup test of human inside MRI (right)



Configuration of bicycle model parameters during insertion of flexible bevel tip needle(left) and duty cycle-controlled needle steering (right)

Translation and rotation twist vector

$$V_1 = \begin{bmatrix} e_3 \\ \kappa e_1 \end{bmatrix} \text{ and } V_2 = \begin{bmatrix} 0_{3x1} \\ e_3 \end{bmatrix}$$

Translation and rotation velocity profile

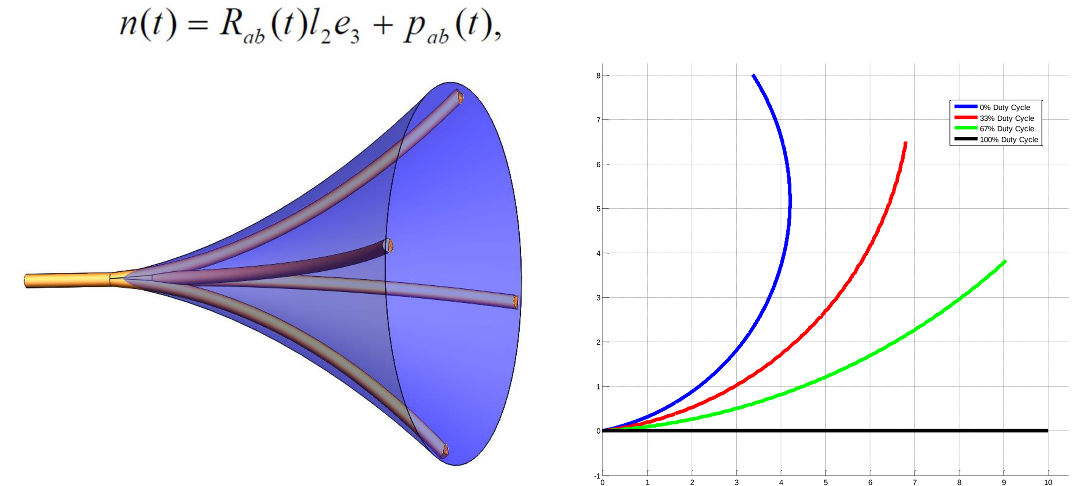
$$u_1(t) = \sigma$$

$$u_2(t) = \begin{cases} \omega, & jT \le t < T(j+D),\ j = 0,1,2,\ldots \\ 0, & else \end{cases}$$

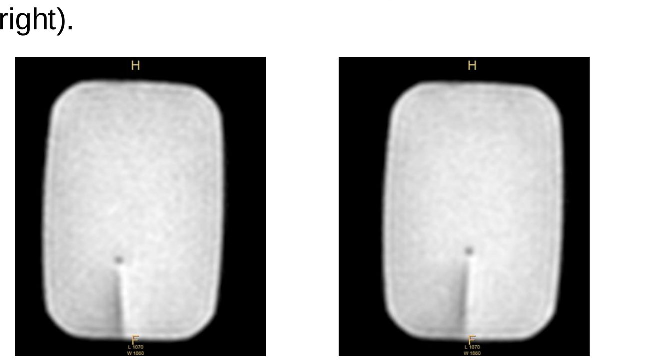
Kinematics of nonholonomic bevel tip needle

$$g_{ab}(t) = \begin{cases} g_{ab}(0)e^{(\sigma \hat{V}_1 + \omega \hat{V}_2)t}, & jT \le t < T(j+D),\ j = 0,1,2,\ldots \\ g_{ab}(0)e^{\sigma \hat{V}_1 t}, & else \end{cases}$$

$$n(t) = R_{ab}(t) l_2 e_3 + p_{ab}(t),$$

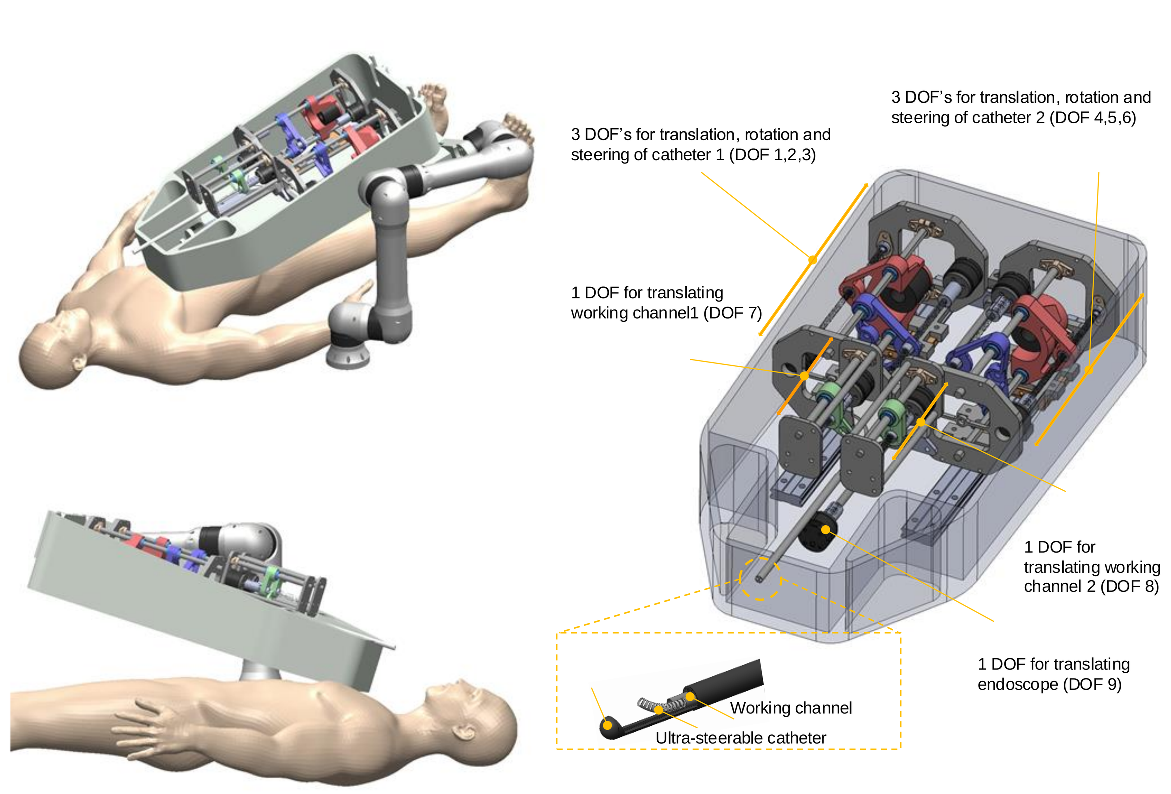


Needle steering in four directions of 3D space within the cone bounded by the maximum curvature (left) and simulated trajectory of a flexible bevel tip needle at various duty cycles (right).

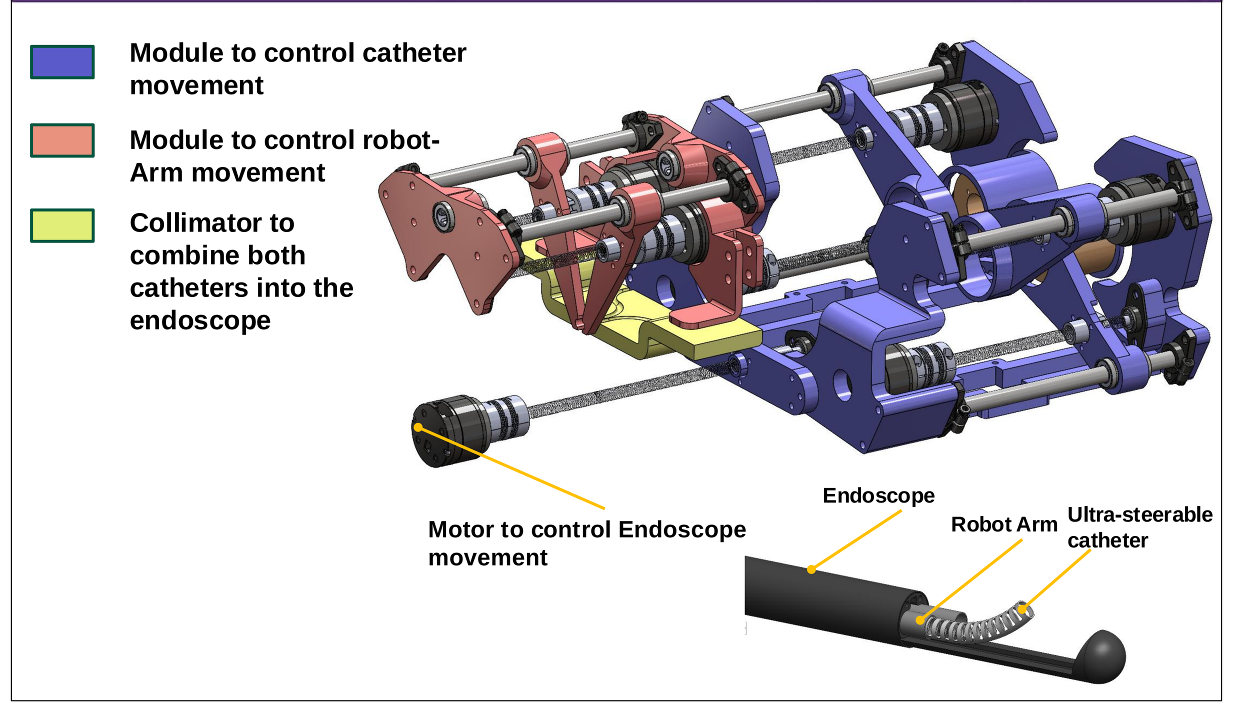


Example of needle trajectory control by steering the needle during insertion under real time imaging using the orientation of the bevel tip

Design Overview of Neurosurgery Robot (9 DOFs)

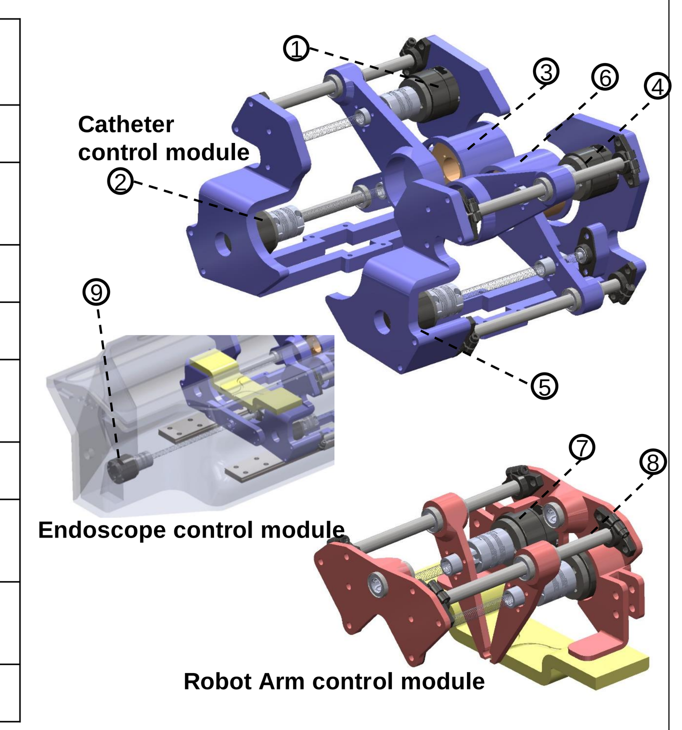


Actuation Design



Detailed Modular Design Hyperthesis

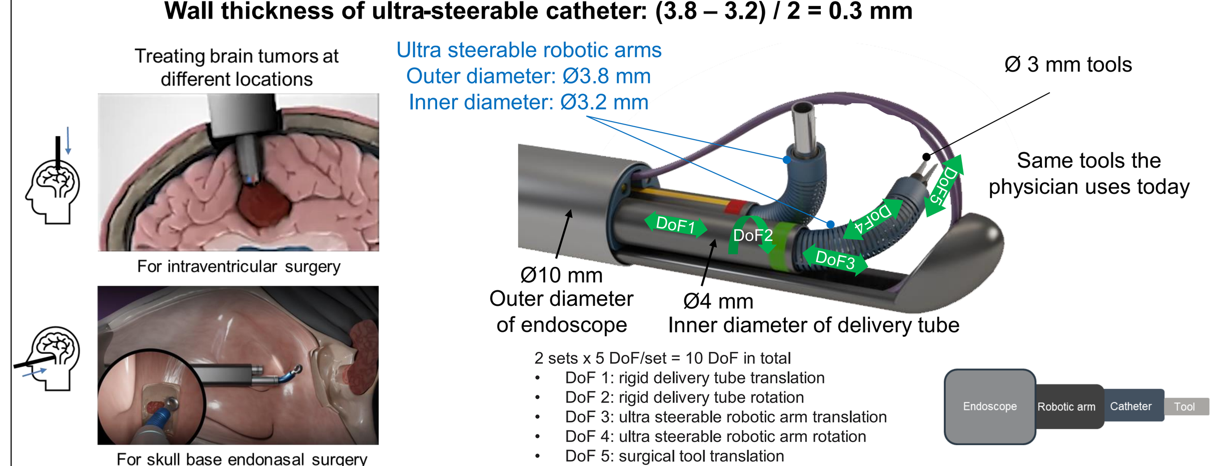
DOF	Type	Description	Range of Motion
DOF 1	Rotation	Catheter 1	± 360 deg
DOF 2	Translation	Steering of catheter 1	30 mm
DOF 3	Translation	Catheter 1	70 mm
DOF 4	Rotation	Catheter 2	± 360 deg
DOF 5	Translation	Steering of catheter 2	30 mm
DOF 6	Translation	Catheter 2	70 mm
DOF 7	Translation	Working channel 1	70 mm
DOF 8	Translation	Robot arm 2	70 mm
DOF 9	Translation	Endoscope	150 mm



Ultra-Steerable Transnasal Neurosurgery Robot

- Goals: deliver tube and surgical tools in an endoscope
- Requirements: small outer diameter, large inner diameter (thin wall for the delivery catheter)
- Superb dexterity in small corridors

Wall thickness of ultra-steerable catheter: (3.8 – 3.2) / 2 = 0.3 mm

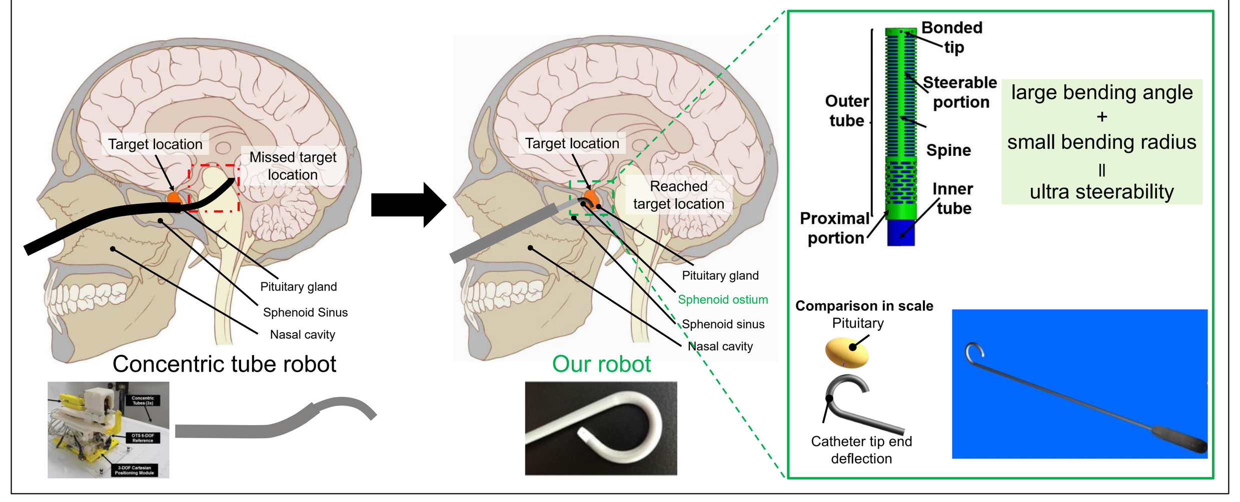


Our 10-DOF ultra-steerable transnasal neurosurgery robot can be used for both craniotomy and skull base endonasal surgery, and is compatible with surgical tools used in the operating room

Steerable robots	Concentric tube robot	Cable-drive catheter	Ultra-Steerable catheter
Groups	Dupont, Su	Webster	Ours
Robot			
Diagram			
Principle	tube interaction	line transmission (fragile)	surface transmission
Bending angle	80°	180°	240°
Bending radius	40 mm	~4.2 mm	~4.2 mm
Outer diameter	~2.39 mm	~2 mm	~ 2 mm

Ultra-Steerability Enables Dexterity in Small Cavities

- Concentric tube robot: large radius, small angle
- Our ultra-steerable robot: small radius, large angle



Benchmark with SOTA Catheters

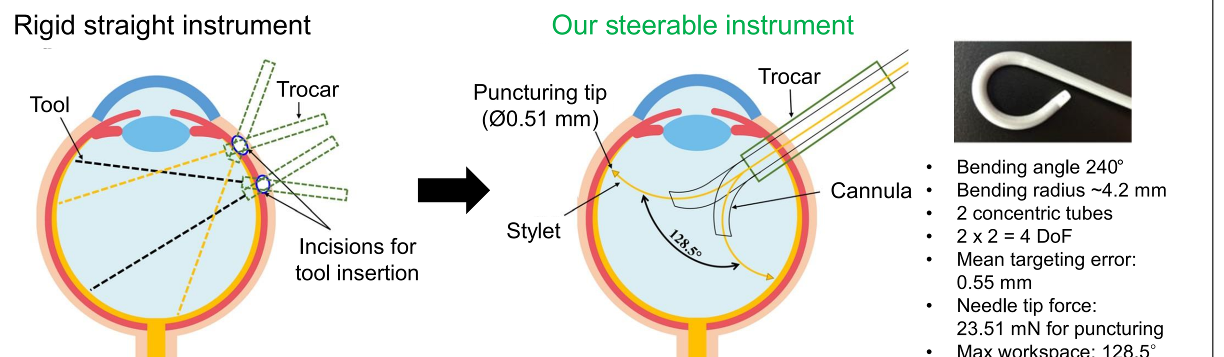
- Features of our catheter robot
- Ultra-steerable: maximum 235° bending angle with only 8.4 mm bending radius
- Small outer diameter: only around 4.2 mm for reducing incision area

Group	ROSA ONE® ZIMMER BIOMET	Dupont Harvard University	Desai Georgia Tech.	Desai Georgia Tech.	Rucker U. of Tennessee	Ours
Robot			S-Shaped Curvature	120° bend		
(Maximum) Bending angle	rigid	~ 67°	~ 90°	120°	less than 160°	235°
Bending radius	-	28 mm	-	-	45 mm	~ 8.4 mm
Outer diameter	3.5 mm	2.5 mm	1.93 mm	~ 4mm	4.02 mm	4.2 mm
Inner diameter	2.1 mm	2.3 mm	1.49 mm	> 2.5 mm	1.84 mm	3.3 mm

- Oliver-Butler, K., Childs, J. A., Daniel, A., & Rucker, D. C. (2021). Concentric push–pull robots: Planar modeling and design. IEEE Transactions on Robotics, 38(2), 1186-1200.
- Price, K., Peine, J., Mencattelli, M., Chitalia, Y., Pu, D., Looi, T., ... & Dupont, P. E. (2023). Using robotics to move a neurosurgeon's hands to the tip of their endoscope. Science Robotics, 8(82), eadg6042.
- Luh, H. T., Zhu, C., Kuo, L. T., Lo, W. L., Liu, H. W., Su, Y. K., ... & Huang, A. P. H. (2024). Application of Robotic Stereotactic Assistance (ROSA) for spontaneous intracerebral hematoma aspiration and thrombolytic catheter placement. Journal of the Formosan Medical Association.
- https://www.merit.com/product/swiftninja-steerable-microcatheter/
- Qi, R., Nayar, N. U., & Desai, J. P. (2023). Compact Design and Task Space Control of a Robotic Transcatheter Delivery System for Mitral Valve Implant. IEEE Transactions on Medical Robotics and Bionics.
- Chitalia, Y., Jeong, S., Yamamoto, K. K., Chern, J. J., & Desai, J. P. (2020). Modeling and control of a 2-dof meso-scale continuum robotic tool for pediatric neurosurgery. IEEE Transactions on Robotics, 37(2), 520-531

Ultra-Steerable instruments as one alternative option

- Rigid instrument: multi-incisions, limited workspace, collision with intraocular lens
- Steerable instrument: single incision, larger workspace, avoids collision



Leveraging our ultra-steerable instruments, our eye surgery robot can provide a safer and less invasive procedure with a larger workspace

References

[1] **H. Su**, K. Kwok, ... & G.S. Fischer, "State of the Art and Future Opportunities in MRI-Guided Robot-Assisted Surgery and Interventions," in Proceedings of the IEEE, Jul. 2022

[2] A. Gao, R. R. Murphy, W. Chen, G. Dagnino, P. Fischer, M. G. Gutierrez,..., **H. Su**, C. Wang & Yang, G. Z. (2021). Progress in robotics for combating infectious diseases. Science Robotics, 6(52).

[3] S. Luo, M. Jiang, S. Zhang, J. Zhu, … & **H. Su**. 2023 Learning rapid optimization of exoskeleton assistance for multimodal human locomotion, (In preparation)

[4] **H. Su**, et al. "Physical human–robot interaction for clinical care in infectious environments." Nature Machine Intelligence 3.3 (2021): 184-186.

[5] **H. Su**, et. al , "MRI-Guided Telesurgery System Utilizing a Fabry-Perot Interferometry Force Sensor and a Pneumatic Haptic Device", Annals of Biomedical Engineering, 2017

[6] **H. Su**, … & G. S. Fischer, (2016). A concentric tube continuum robot with piezoelectric actuation for MRI-guided closed-loop targeting. Annals of biomedical engineering, 44, 2863-2873..

[7] **H. Su**, et al. "An MRI-guided concentric tube continuum robot with piezoelectric actuation: A feasibility study." 2012 IEEE International Conference on Robotics and Automation. IEEE, 2012

[8] **H. Su**, W. Shang, G. Cole, ... & G. S. Fischer, (2014). Piezoelectrically actuated robotic system for MRI-guided prostate percutaneous therapy. IEEE/ASME transactions on mechatronics, 20(4), 1920-1932.

[9] W. Gao, R. Liu, I. Sanchez, J. Zhu, A. D. Lallo and H. Su, Design and Control of an Ultra-Steerable Endoscopic Robot for Neural Microsurgery Surgery. IEEE/ASME transactions on mechatronics, in preparation.

[10] Lin, F. Y., Bergeles, C., & Yang, G. Z. (2015, August). Biometry-based concentric tubes robot for vitreoretinal surgery. In 2015 37th annual international conference of the IEEE engineering in medicine and biology society (EMBC) (pp. 5280-5284). IEEE.