The Future of Surgical Robotics: Vision, Challenges, and the Science to Meet Them

CIS Guest Lecture
Baltimore, September 3rd, 2024

Axel Krieger, PhD
Associate Professor
Intelligent MEdical Robotic Systems & Equipment (IMERSE) Lab
Department of Mechanical Engineering
Affiliate Professor, Malone Center for Engineering in Healthcare
Laboratory for Computational Sensing and Robotics (LCSR)
Johns Hopkins University, 116 Hackerman Hall, Baltimore, MD

axel@jhu.edu

IMERSE

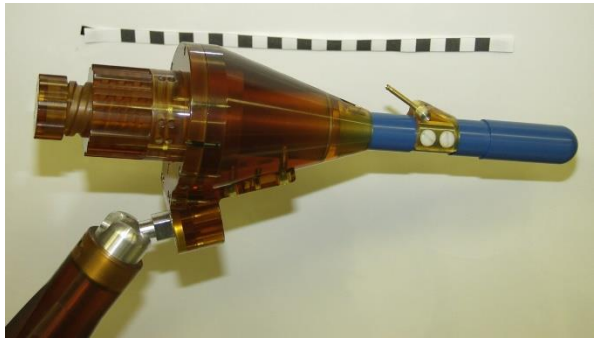
JOHNS HOPKINS
MALONE CENTER for
ENGINEERING in HEALTHCARE

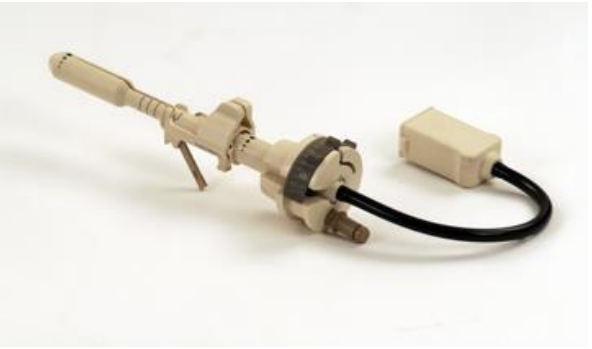
LABORATORY FOR
Computational
Sensing + Robotics
THE JOHNS HOPKINS UNIVERSITY

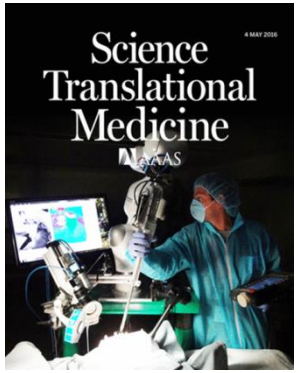
Quick Introduction

Before joining the Johns Hopkins University in July 2020:

- Undergraduate and master's degrees at the University of Karlsruhe in Germany
- PhD at Johns Hopkins
- Product Leader Sentinelle Medical Inc and Hologic Inc
- Assistant Research Professor at the Sheikh Zayed Institute at Children's National
- Assistant Professor in Mechanical Engineering at the University of Maryland





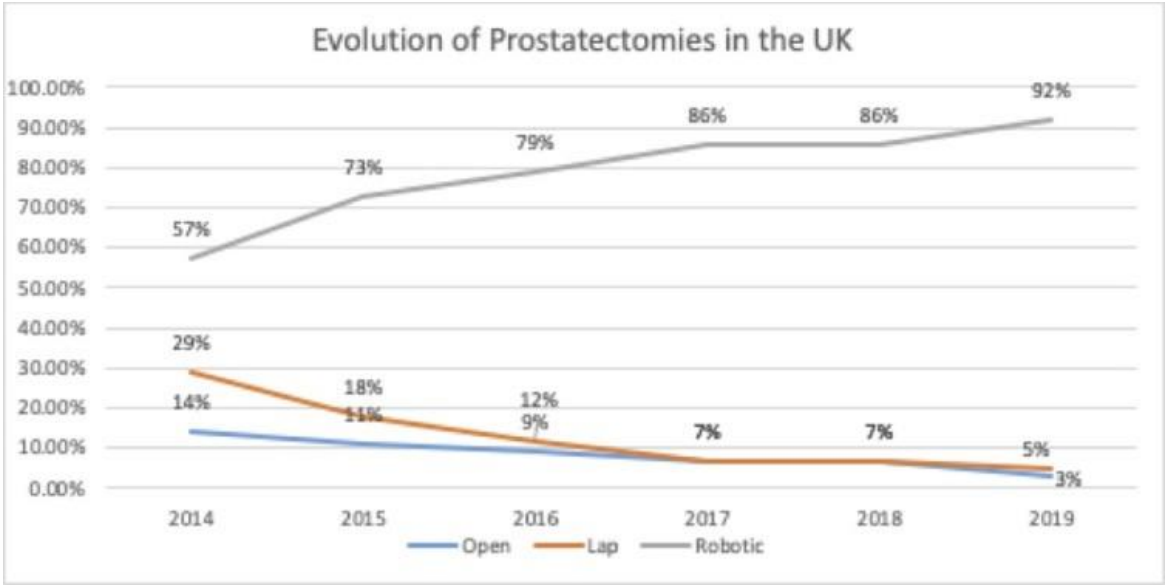


Outline

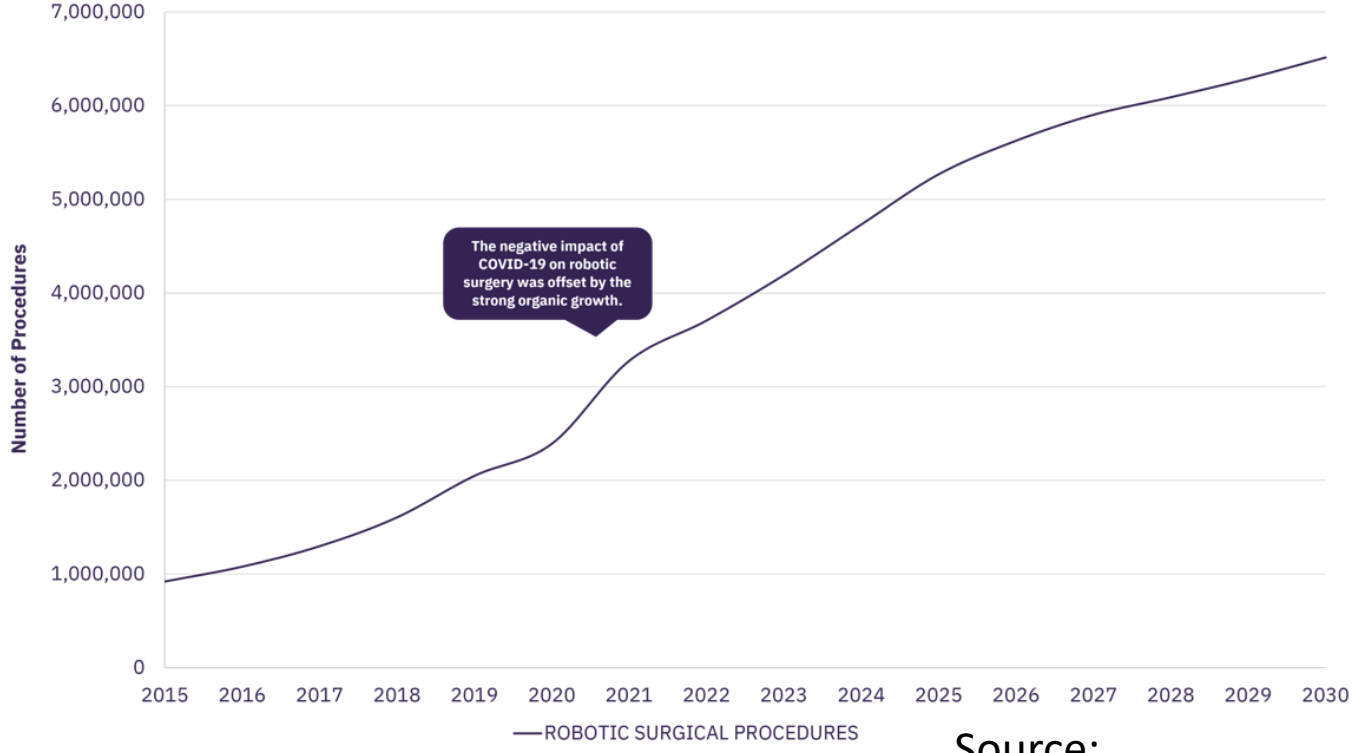
- Vision and challenges for smart and autonomous surgery and interventions
- Supervised autonomous anastomosis
- Magnetically steered robotic surgery
- Autonomous tumor resection surgery
- Learning autonomous surgical subtasks

Surgical Robotic Market

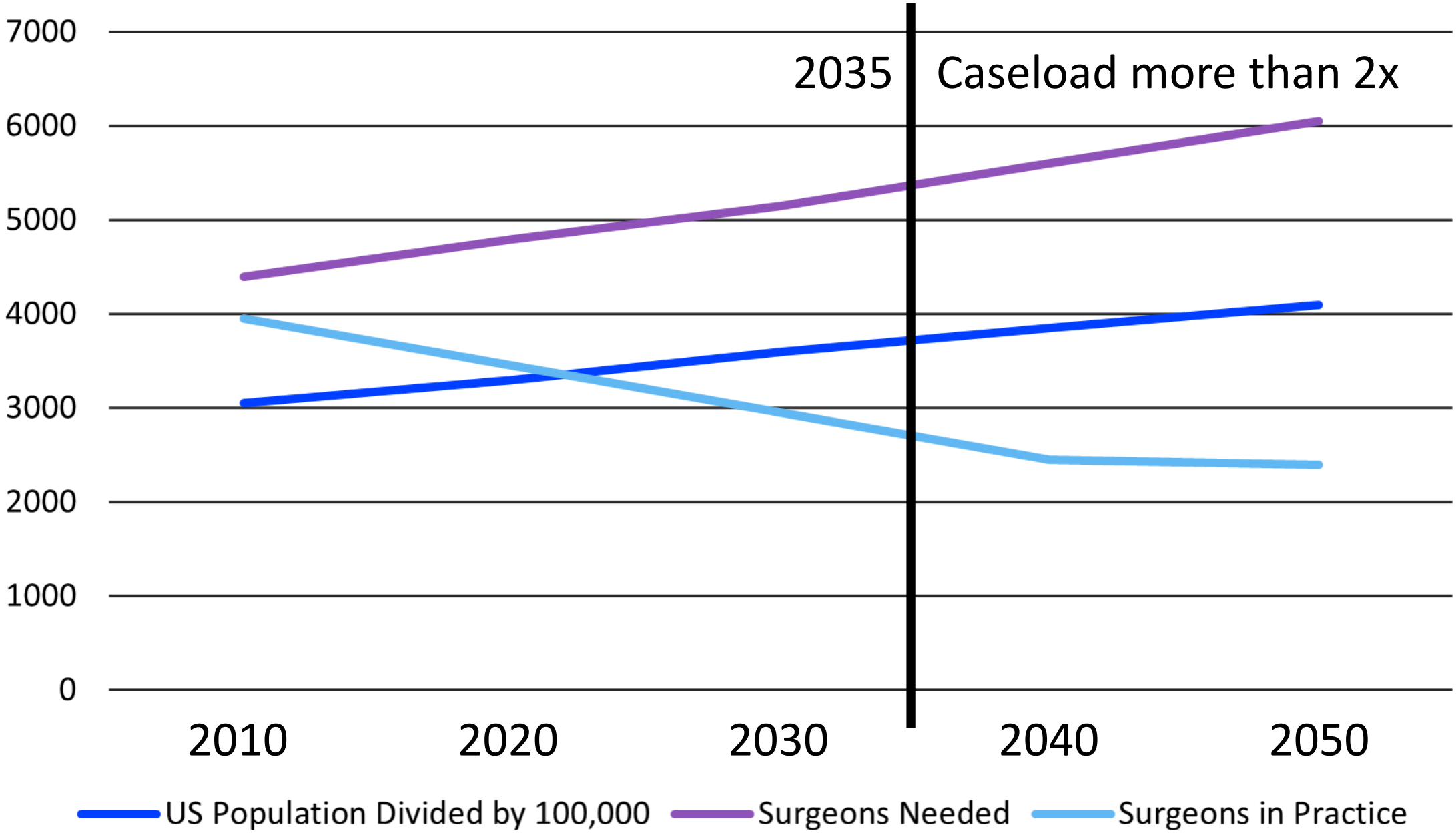
- 310 million major surgeries are performed globally each year
- In 2023 about 4 million procedures are performed with robot assistance
- Large penetration in urology and big market potential in other surgeries
- Estimated annual growth rate of 18%



Source: British Association of Urological Surgeons 2020



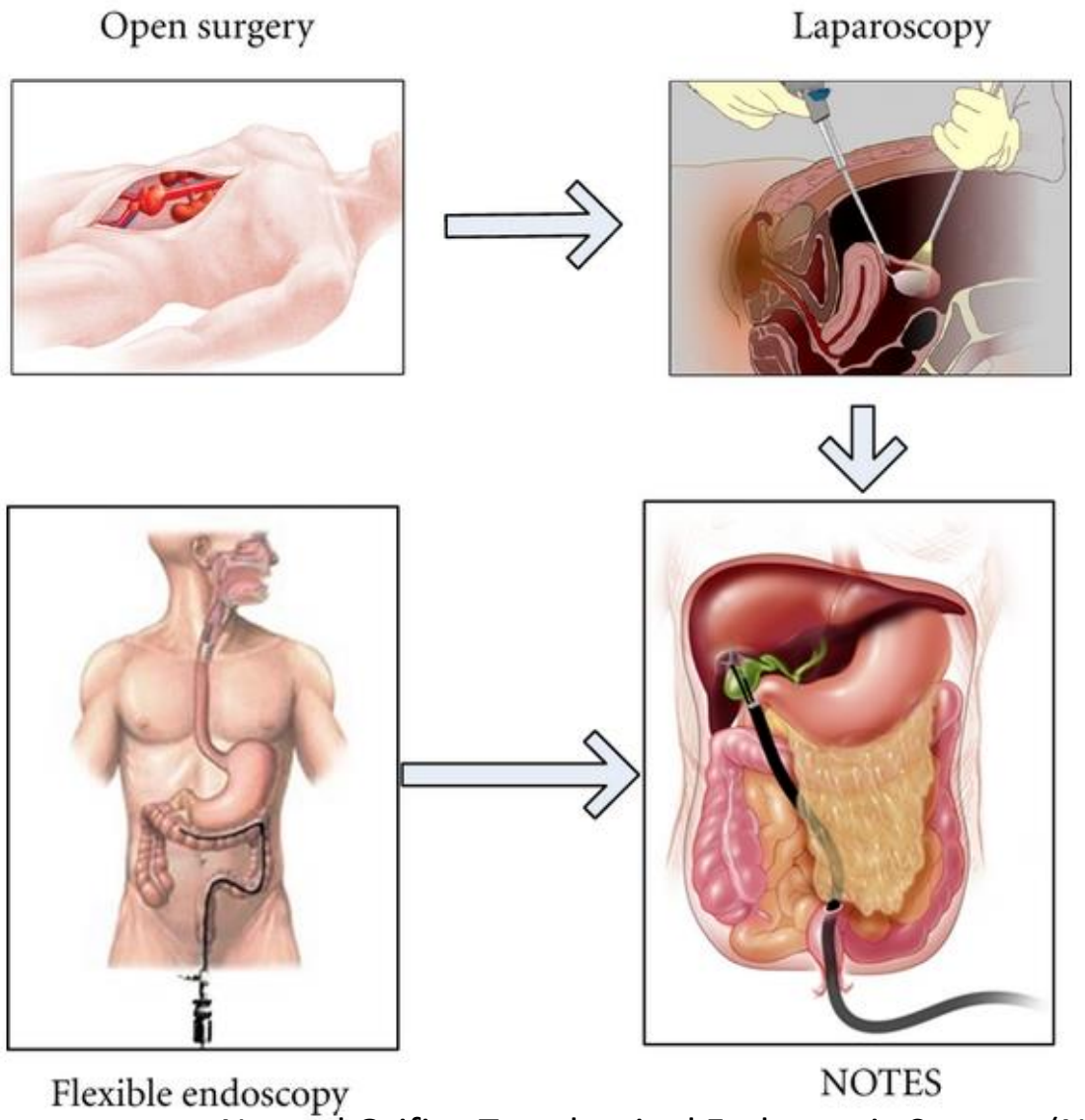
Source: globaldata.com



Susan Moffatt-Bruce, Juan Crestanello, David P Way, and Thomas E Williams Jr. Providing cardiothoracic services in 2035: Signs of trouble ahead. The Journal of thoracic and cardiovascular surgery. 155(2):824–829. 2018.

Minimally Invasive Surgery

- Blood loss, recovery time, scarring, and infections scale with the degree of invasiveness.
- Current tele-operated robotic surgery has increased minimally invasive surgeries but has not reduced complication rates
- Robotic surgery promises to further decrease the invasiveness of surgeries by decreasing tool size and enabling natural orifice approaches.

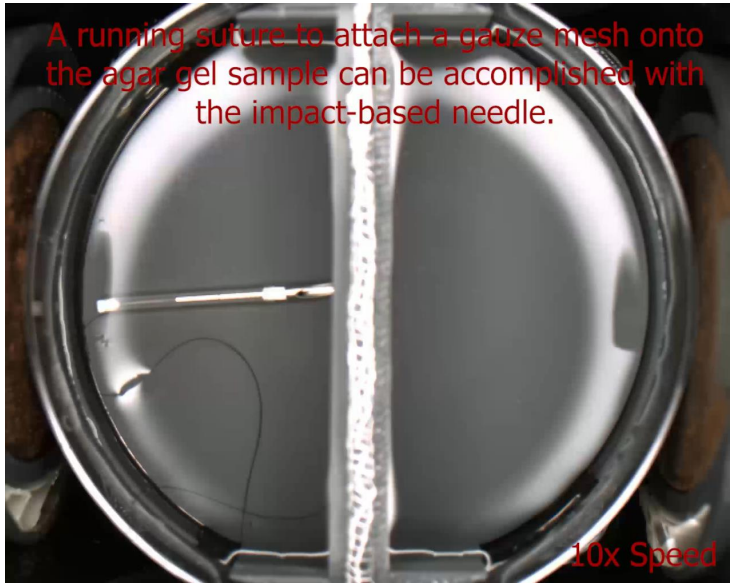


Natural Orifice Transluminal Endoscopic Surgery (NOTES)

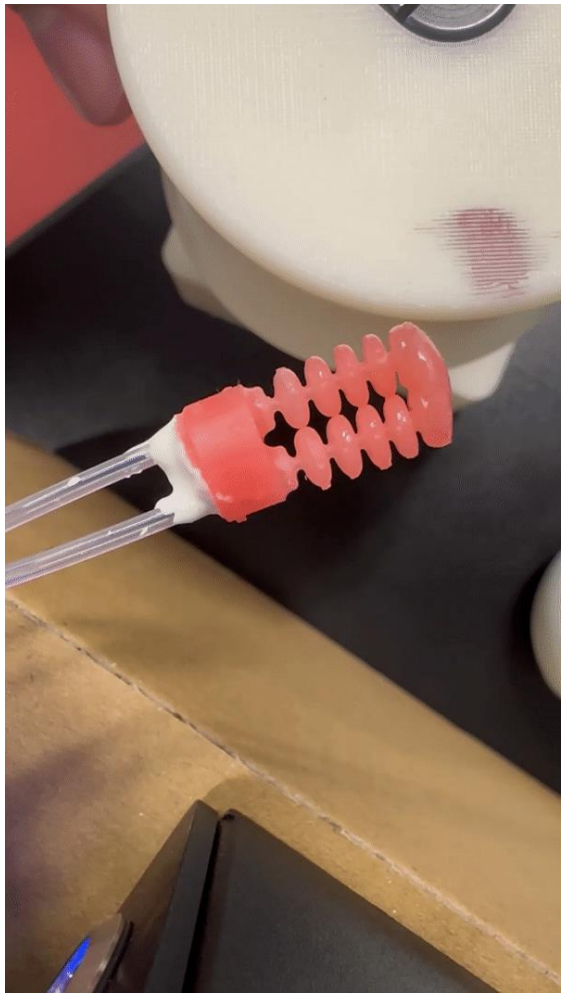
Xiaona Wang, Max Q.-H. Meng, "Robotics for Natural Orifice Transluminal Endoscopic Surgery: A Review", *Journal of Robotics*, vol. 2012, Article ID 512616, 9 pages, 2012. https://doi.org/10.1155/2012/512616

Challenges of Reducing Invasiveness

- Manufacturing complex robots at small scales introduces challenges in fabrication
- Smaller and softer robots deflect under load and are limited in force transmission.
- Less invasive approaches limit ability of camera guidance.



Magnetically actuated milli robot

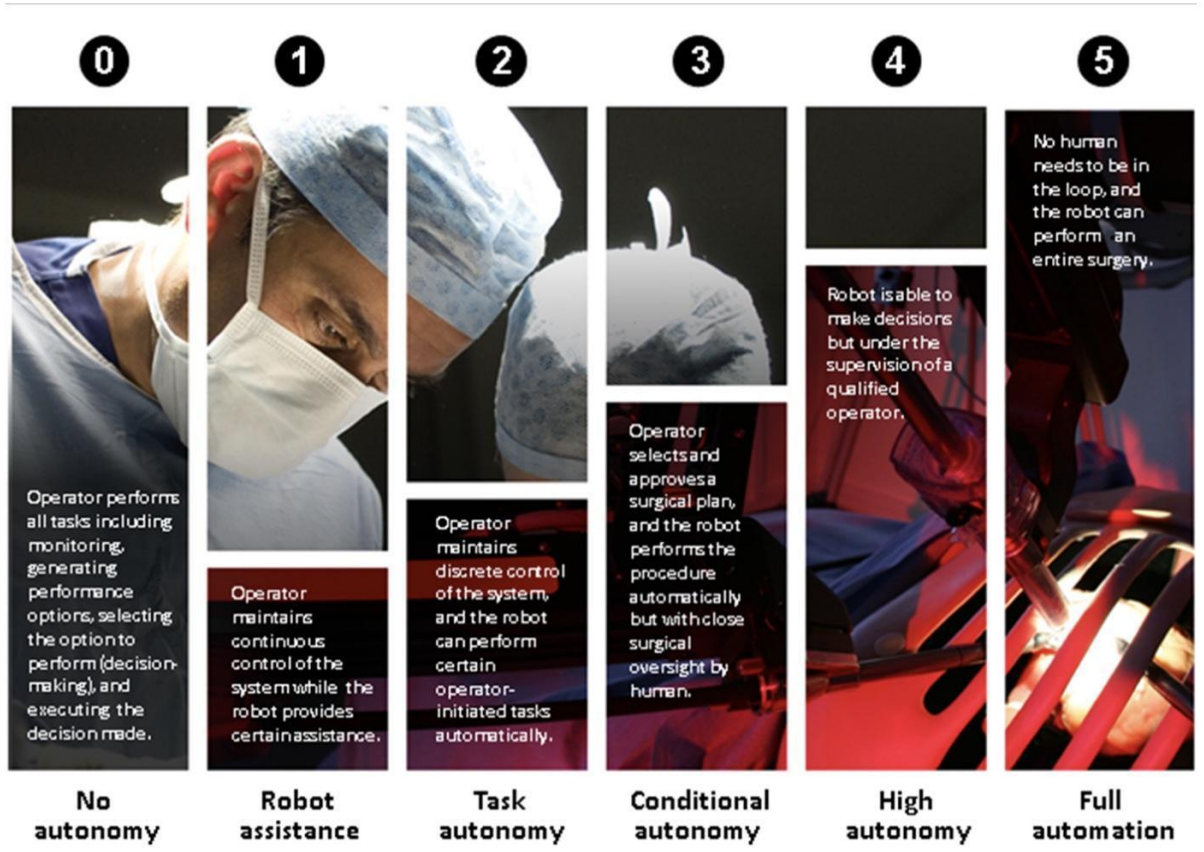


Soft robotic catheter

Erin et al. Advanced Intelligent Systems, 2022.

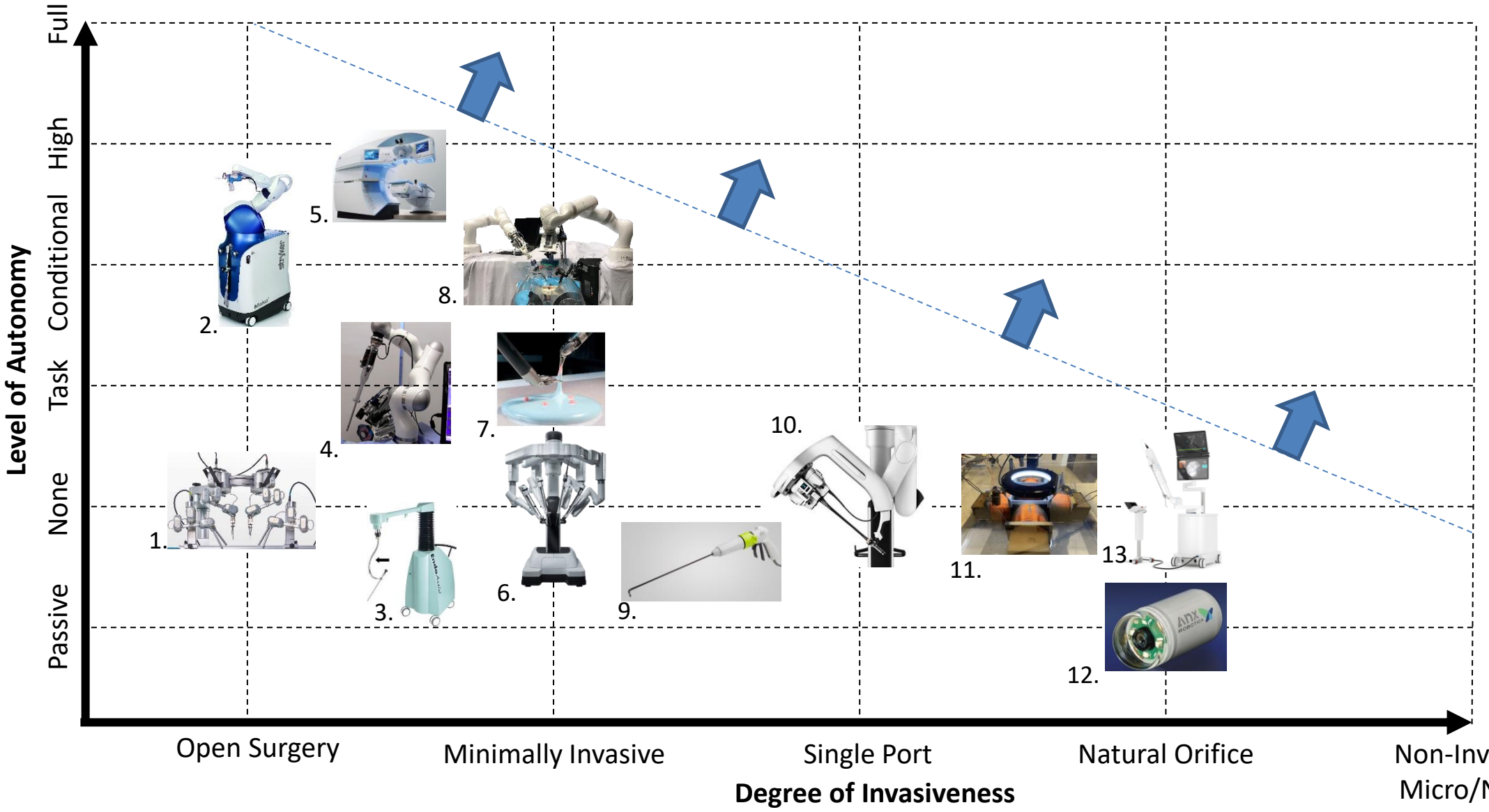
Autonomous Surgery

- Manual and robot assisted operations depend heavily on experience, skill, mental and physical state of operating surgeon
- Augment critical portions of manual surgery with robotic precision with increasing autonomy
- To reduce complications
- To democratize access to expert surgery for everyone
- To alleviate shortages in trained surgeons
- To provide essential care in environments where no surgeon is available such as trauma
- Autonomous functions limited to rigid bony anatomy and small sub-tasks



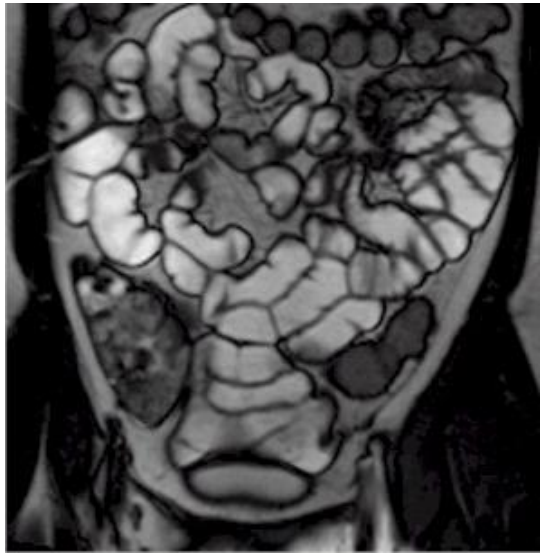
Yang et al. Science Robotics, 2017

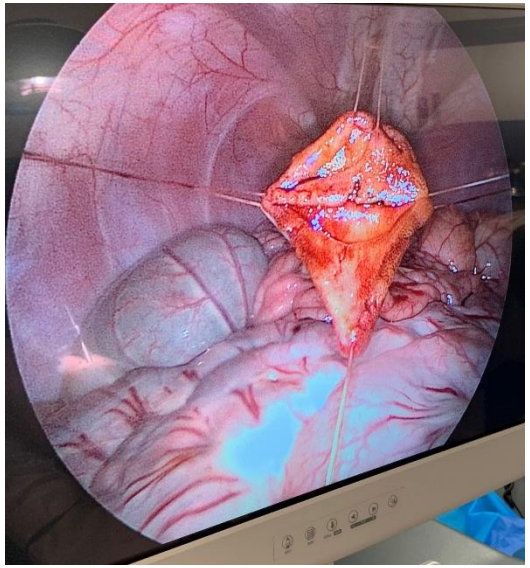
Trend in Autonomy and Invasiveness



#	Robot
1	MUSA
2	Mako
3	EndoAssist
4	STAR (2016)
5	VisuMax
6	daVinci Xi
7	DVRK
8	STAR (2022)
9	Jaimy
10	da Vinci SP
11	MagnetoSuture
12	NaviCam
13	Ion

Challenges – Soft Tissue Deformations

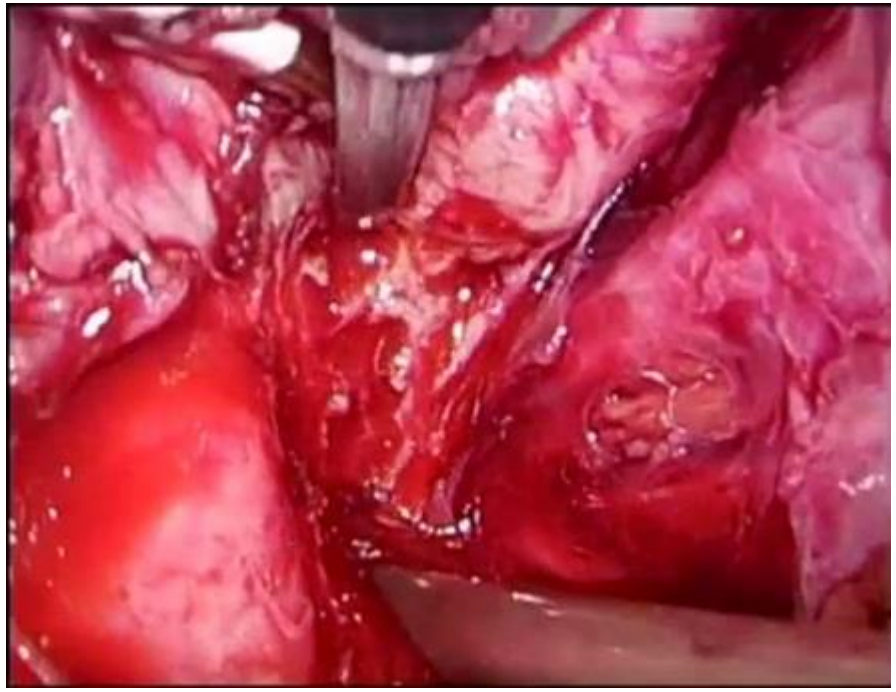




- The fundamental problems in soft tissue surgery include unpredictable shape changes and tissue deformations
- Unpredictable, elastic, and plastic changes in soft tissues pose prohibitive challenges when adapting pre-operative surgical plans
- Unlike rigid tissue surgery, autonomous surgical tasks in soft tissue must constantly adjust to unpredictable scene changes, including nonrigid deformations as a result of cutting, suturing, or cauterizing

Challenges – Perception and Tissue Tracking

- Perception is very difficult with tissues and organs all different shades of pink.
- Tissue and organs are unstructured and highly deformable.
- Tissue and organs drastically change during surgery.



Robotic prostatectomy

Autonomous Robotic Laparoscopic Surgery for Intestinal Anastomosis

Hamed Saeidi, PhD[1], Justin Opfermann, MS[2], Michael Kam, MS[2], Shuwen Wei, MS[3], Simon Leonard[4], PhD, Michael, H. Hsieh, MD[5], Jin U. Kang, PhD[3], Axel Krieger, PhD[2]

[1]: Department of Computer Science, University of North Carolina at Wilmington

[2]: Department of Mechanical Engineering, Johns Hopkins University

[3]: Department of Electrical Engineering, Johns Hopkins University

[4]: Department of Computer Science, Johns Hopkins University

[5]: Department of Urology, Children's National Hospital

axel@jhu.edu

Children's National

JOHNS HOPKINS MALONE CENTER for ENGINEERING in HEALTHCARE

LABORATORY FOR Computational Sensing + Robotics THE JOHNS HOPKINS UNIVERSITY

IMERSE

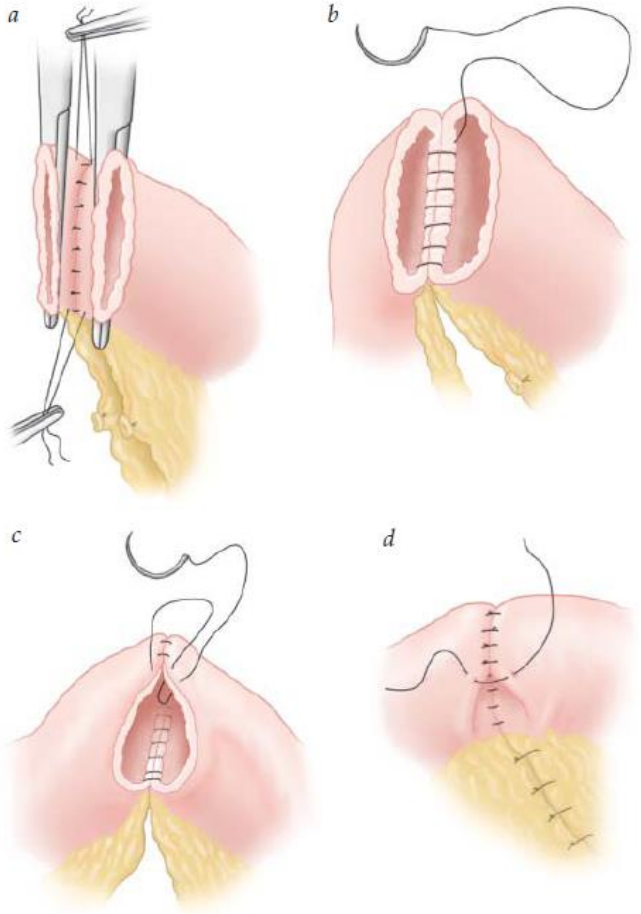
Anastomosis

- A necessary and critical part of all reconstructive surgery involving any luminal structure.

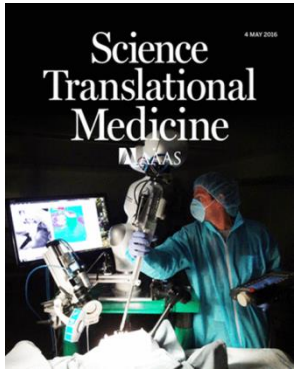
- Over **1 Million** gastrointestinal, urologic and gynecologic in the US alone.

- Significant complications exist
  - Clinical leaks
  - Late stricture
  - Adhesions

- Complication rates:
  - **25-30%** of multivisceral transplantation anastomoses
  - **19%** of colorectal anastomoses
  - **1-2%** of cardiovascular

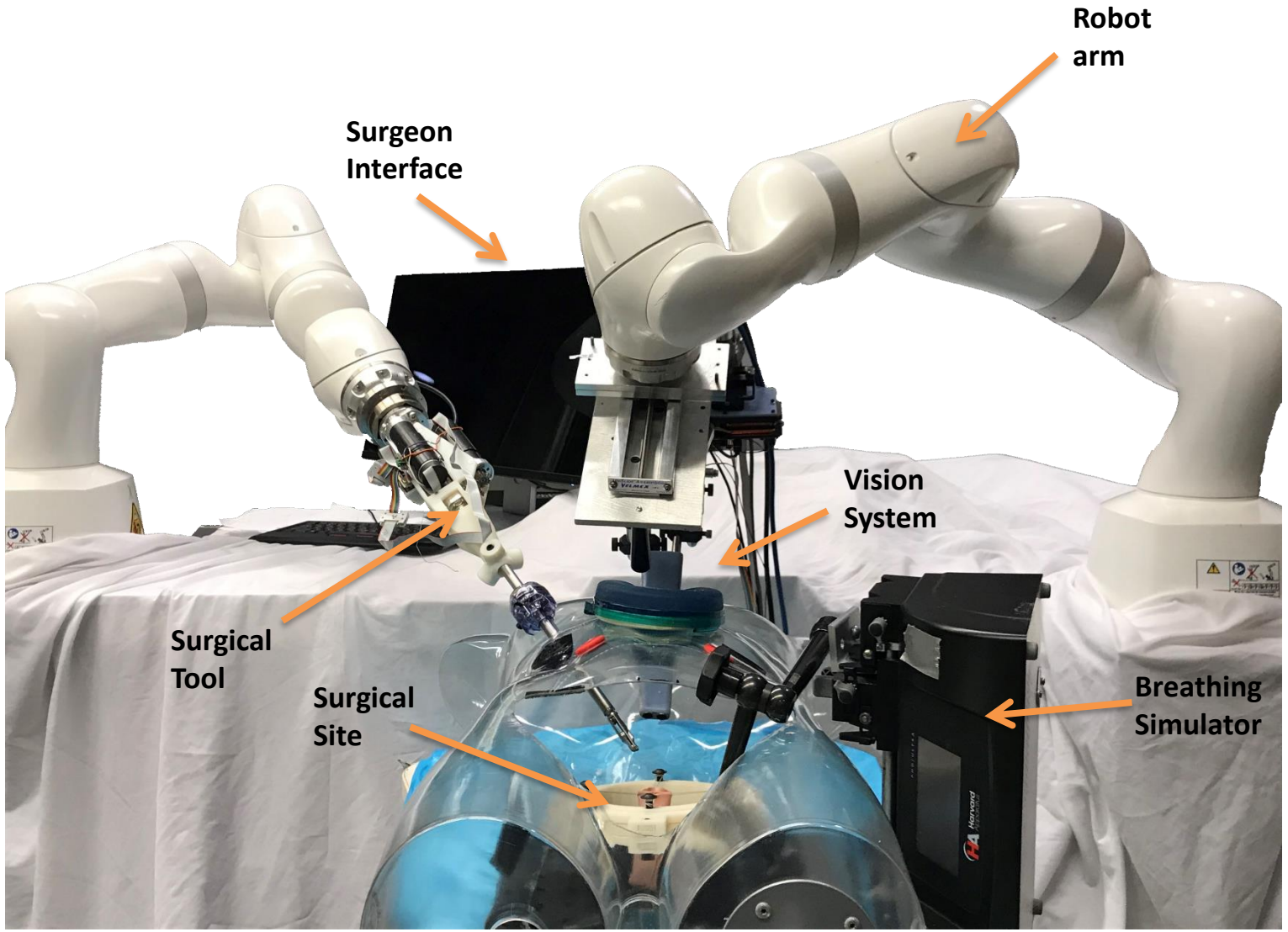


Mortensen and Ashraf (2008)



Smart Tissue Autonomous Robot (STAR)

- **Tools**: Robotic tools and systems to minimize deformations and simplify procedures
- **Imaging and Planning**: Surgical imaging system for 3D tissue tracking
- **Control**: Robot control strategies with increasing autonomy

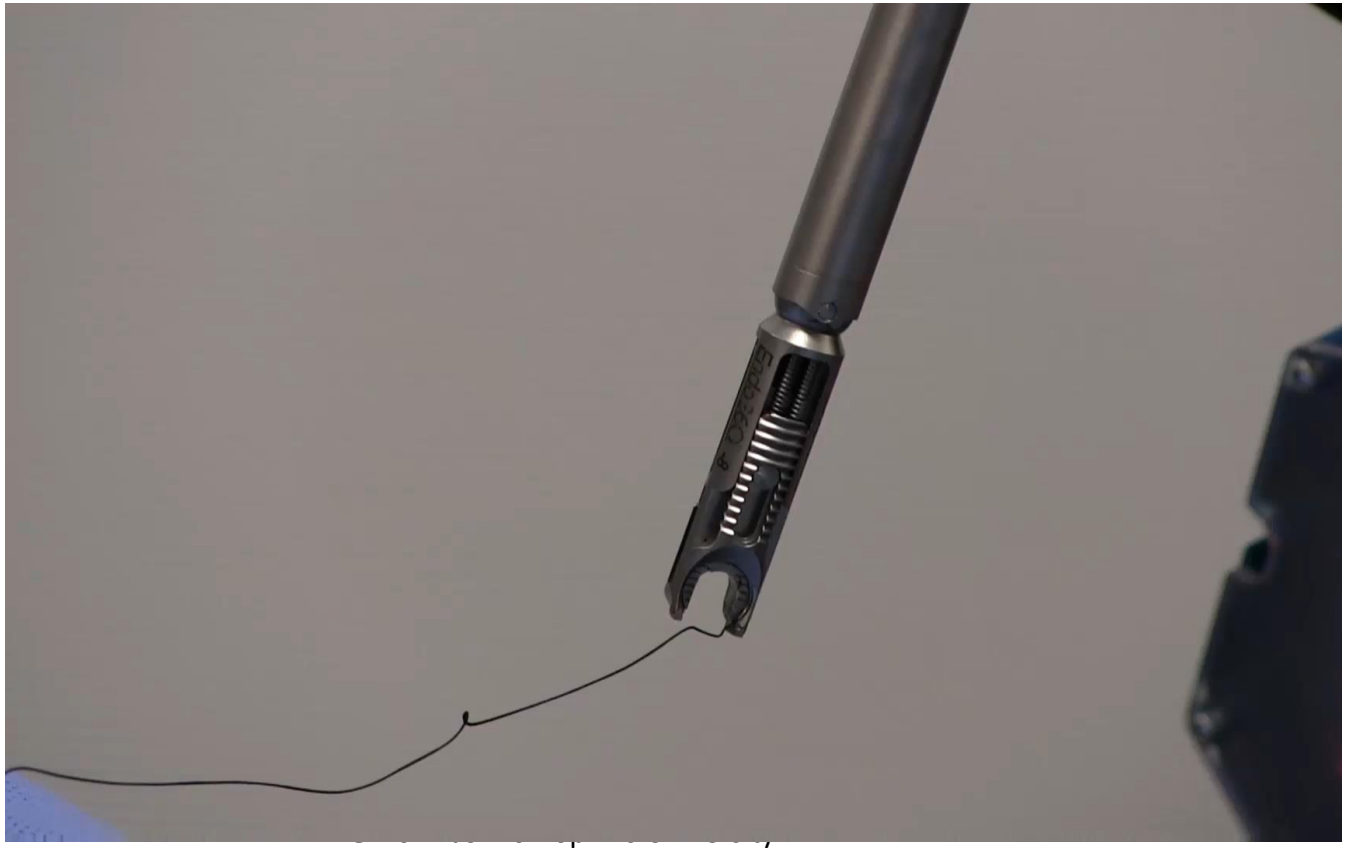


Robotic Tools - Suturing

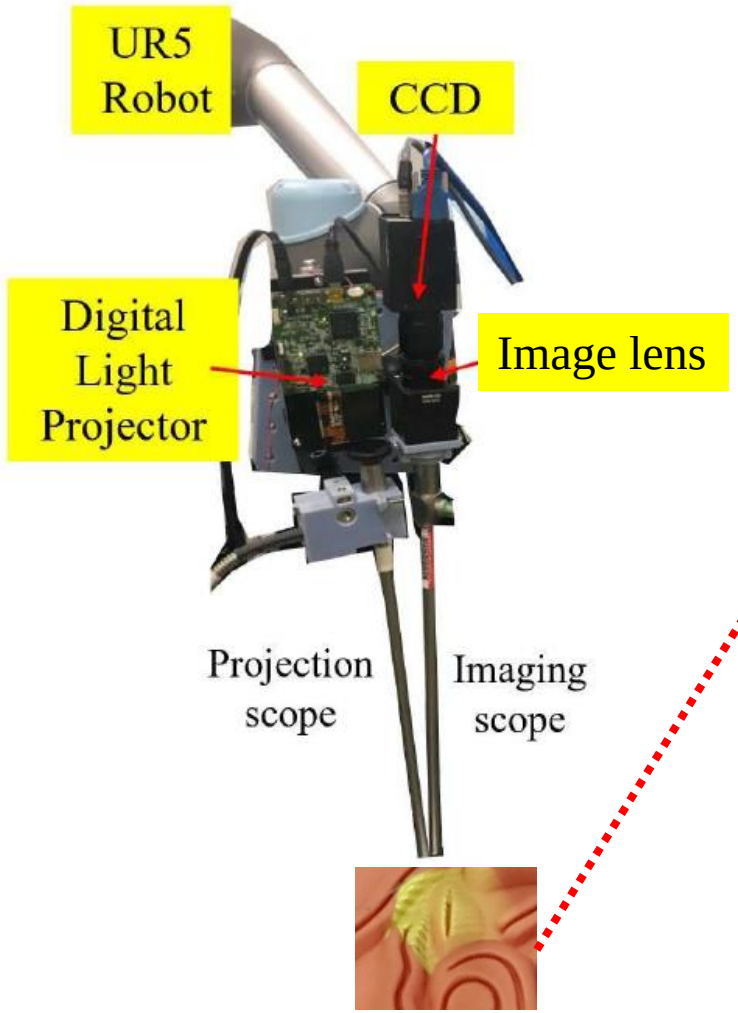
Endo360

- Circular needle drive simplifies suture motion
- Allows one-handed operation
- Additional pitch joint

Video:

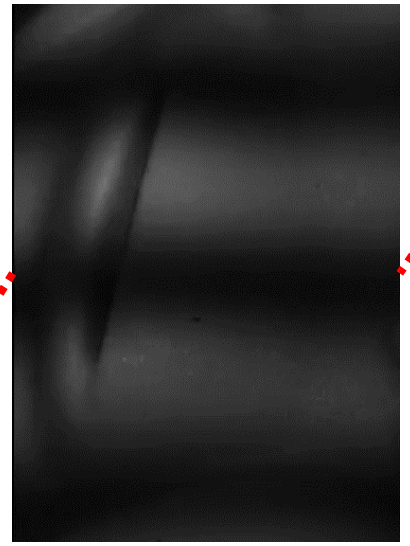


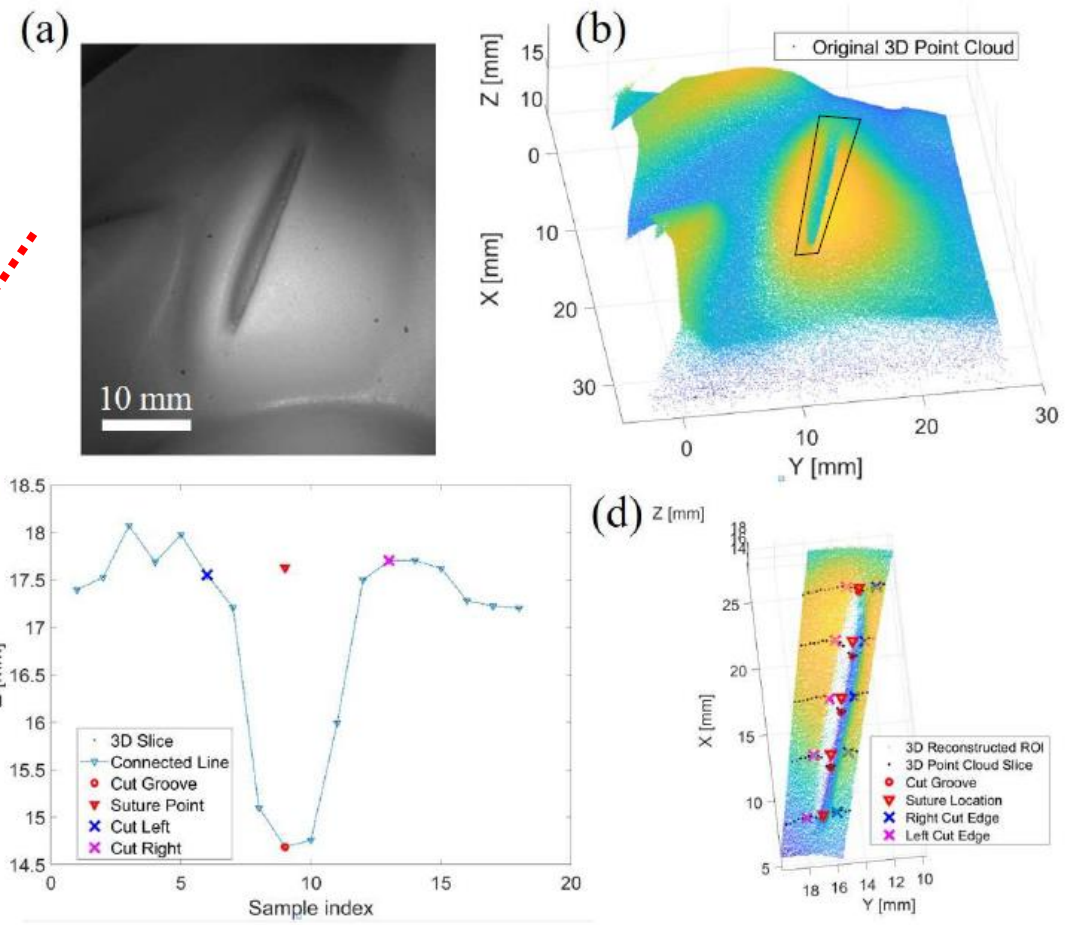
3D Imaging Endoscope & Suture Planning Strategy



Test sample

Camera view





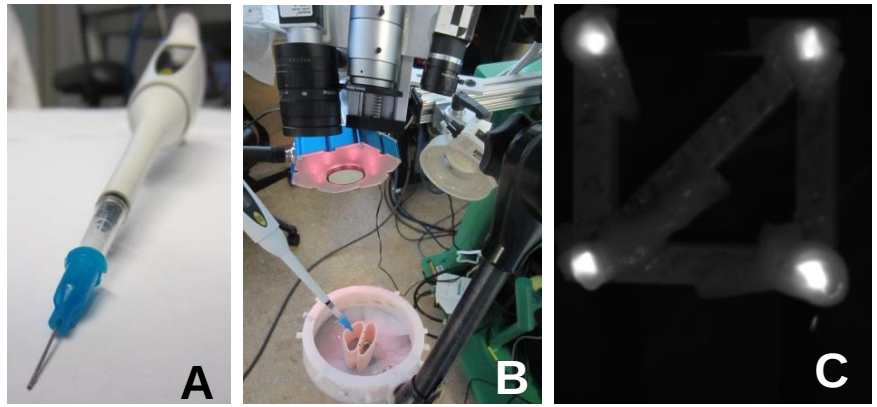
Suture planning strategy: (a) A white reflectance image of the cut sample. (b) Collected point cloud with ROI. (c) An example of calculated cut groove, left and right cut edges, and the suture point. (d) An overlay of the calculated coordinates with suture spacing of 4 mm.

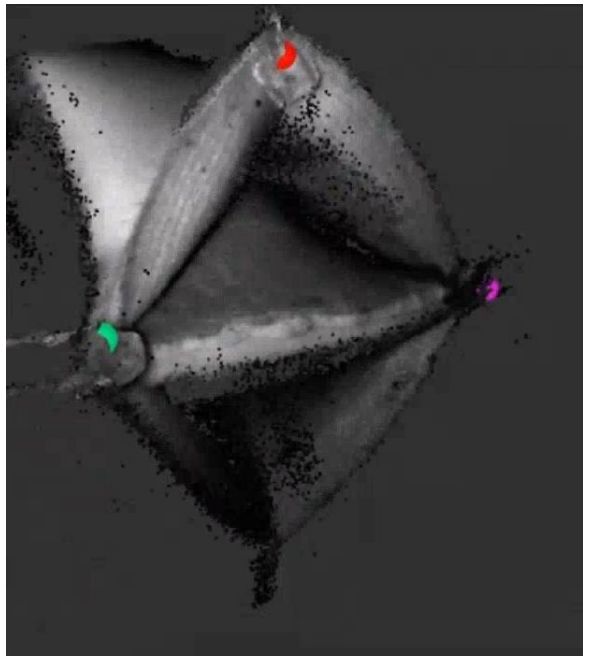
Le HND, Nguyen H, Wang Z, Opfermann J, Leonard S, Krieger A, Kang JU. Demonstration of a laparoscopic structured-illumination three-dimensional imaging system for guiding reconstructive bowel anastomosis. *J Biomed Opt.* 2018.

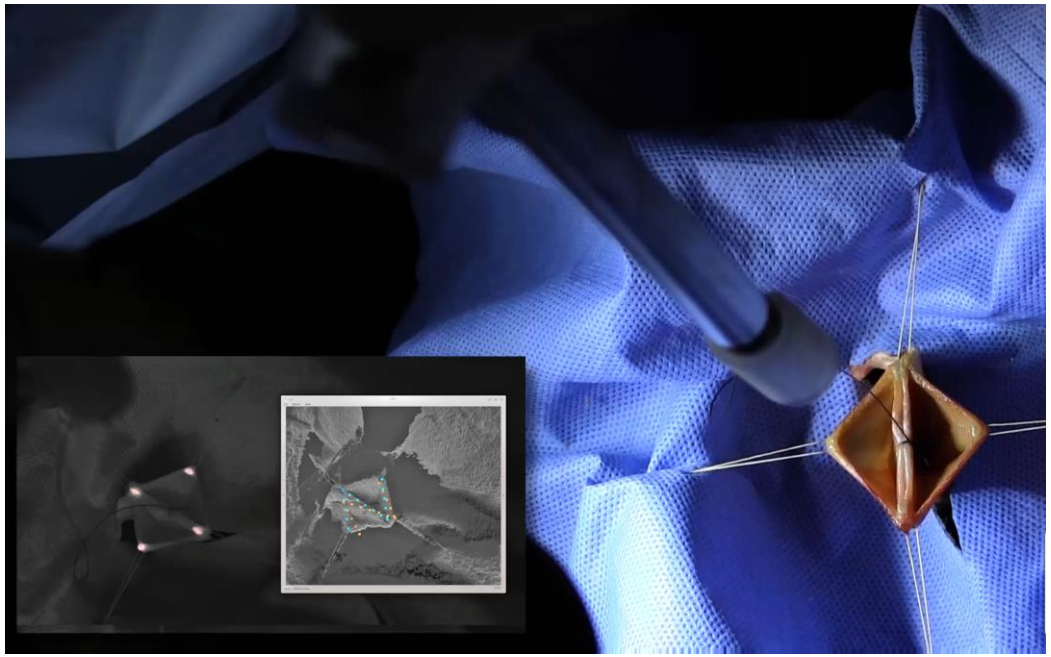
Surgical Imaging and Tracking

Near-Infrared (NIR) Camera

- Blob tracking using ViSP library
- Blobs are syringe-dispensed markers
  - Made from ICG, Permabond



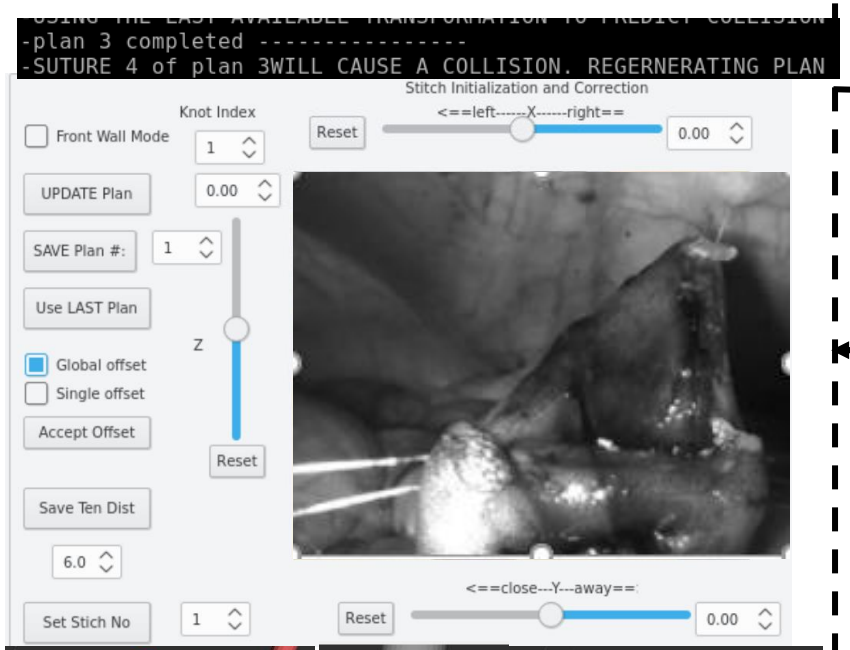




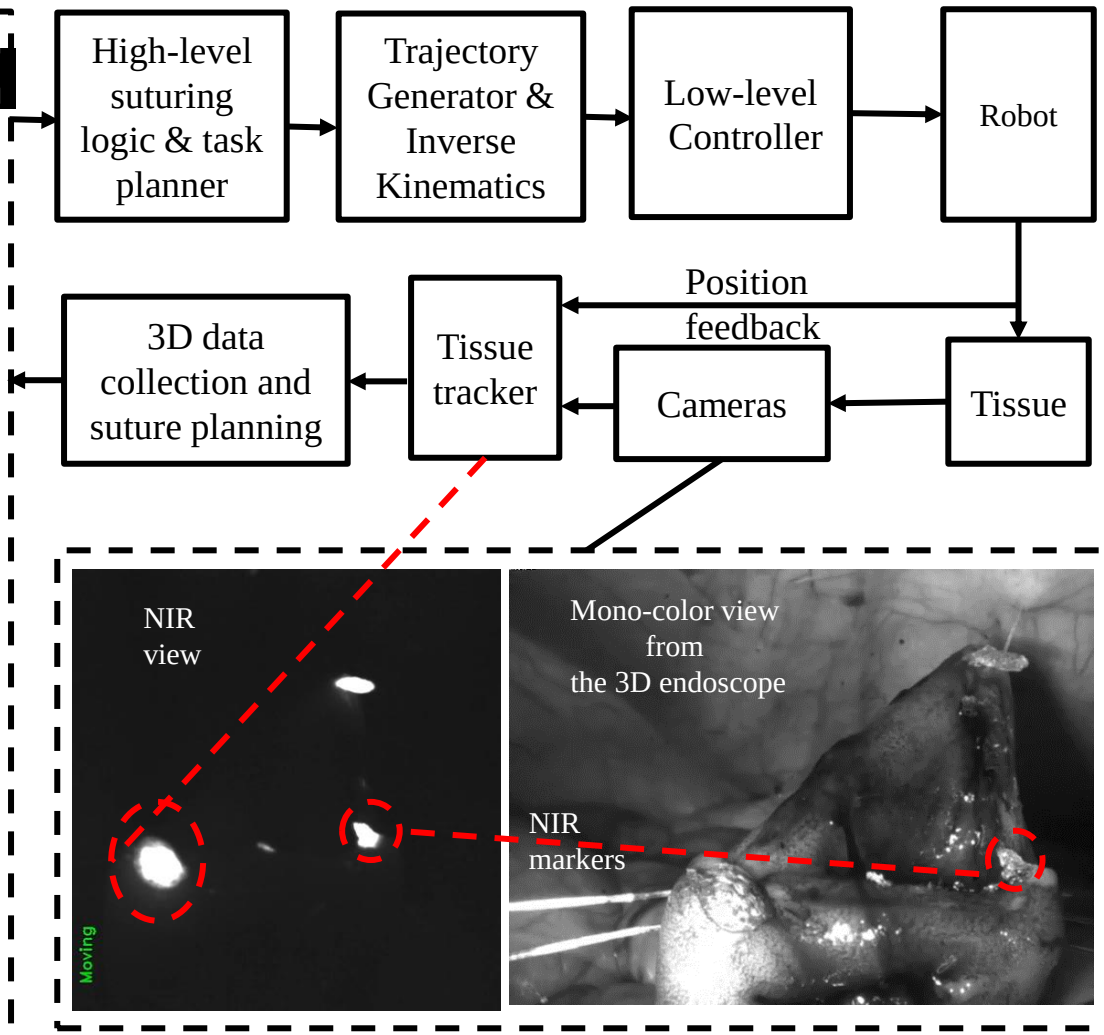
Decker RS, Shademan A, Opfermann JD, Leonard S, Kim PC, Krieger A. Biocompatible Near-Infrared Three-Dimensional Tracking System. IEEE Trans Biomed Eng. 2017 Mar;64(3):549-556.

Control System

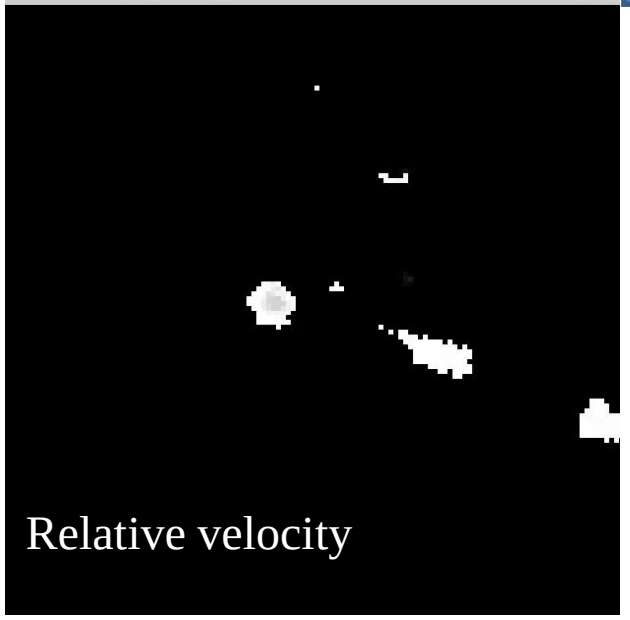
Human supervision



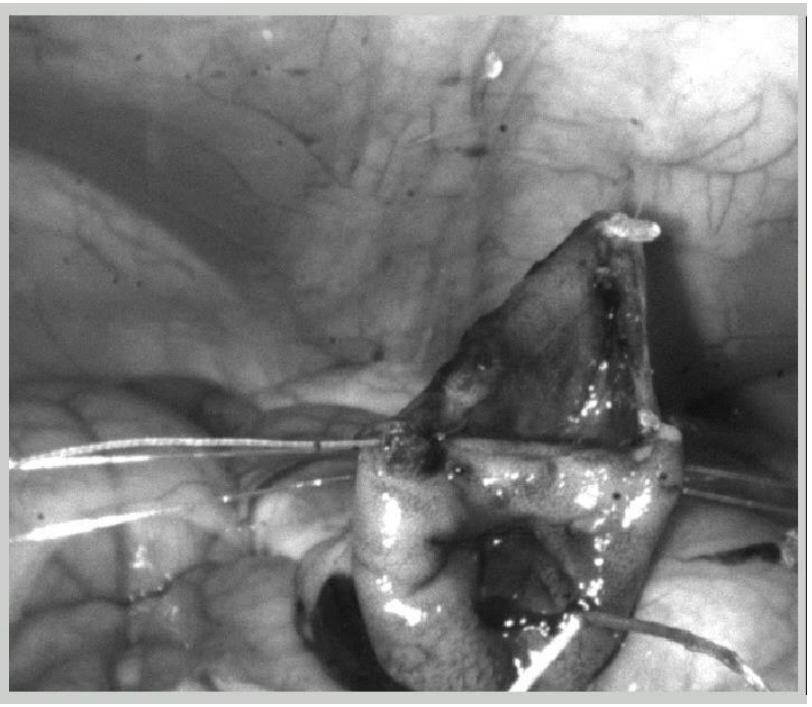
Denoising the plans, generating suture plan options, predicting the tool collision with the tissue



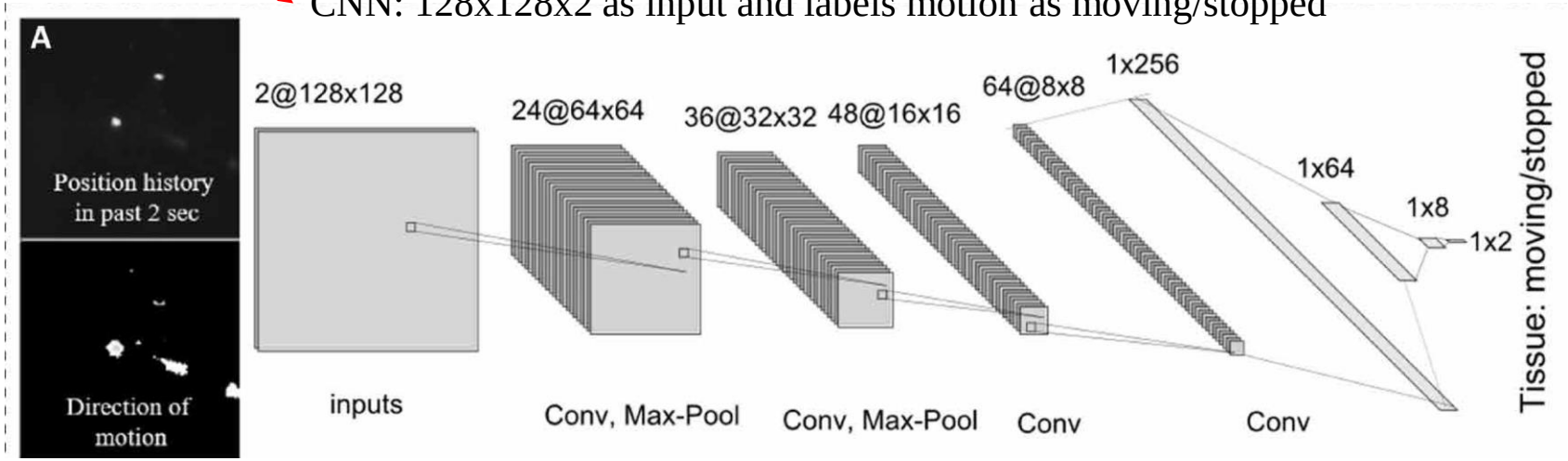
Breath/motion tracker



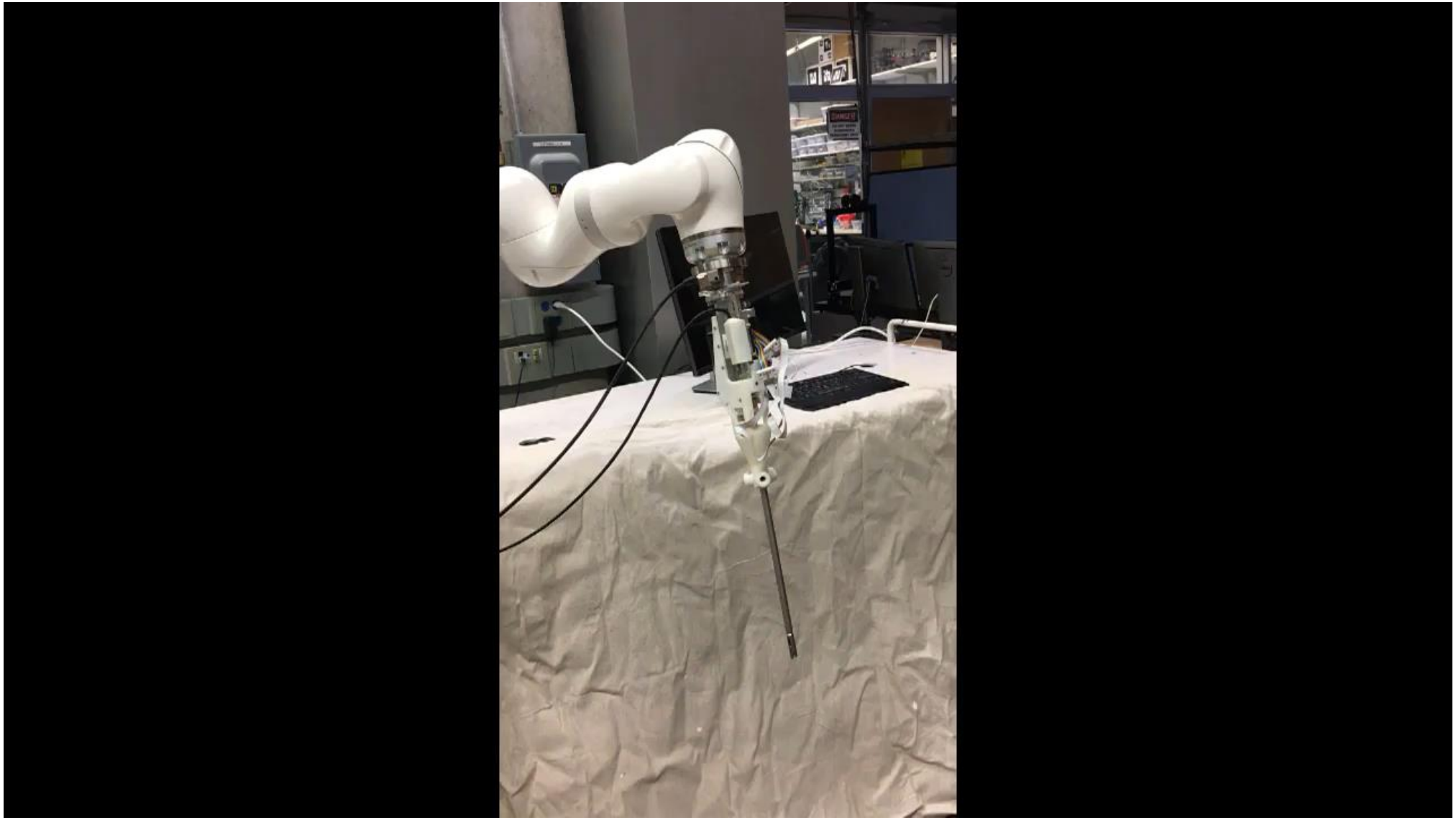
Breath tracker CNN



CNN: 128x128x2 as input and labels motion as moving/stopped



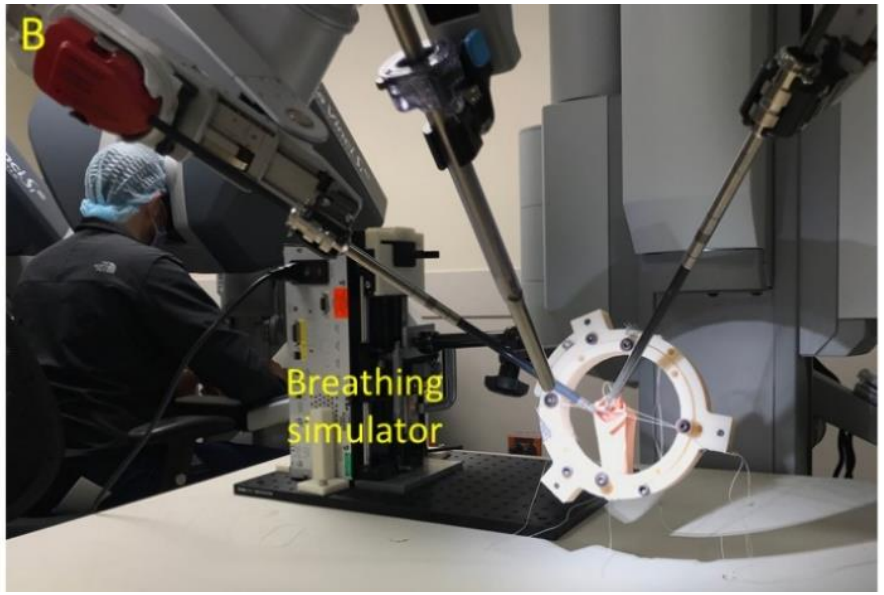
Laparoscopic Suturing with STAR

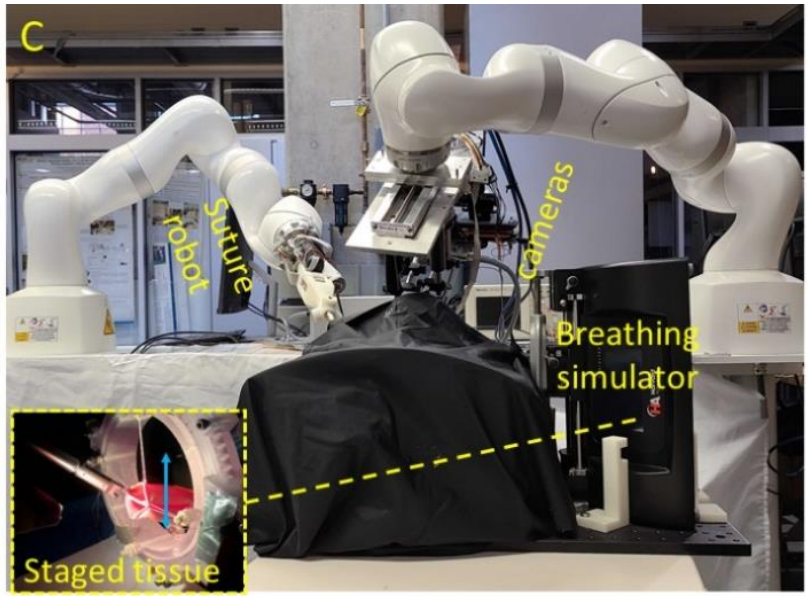


Ex-vivo Testing

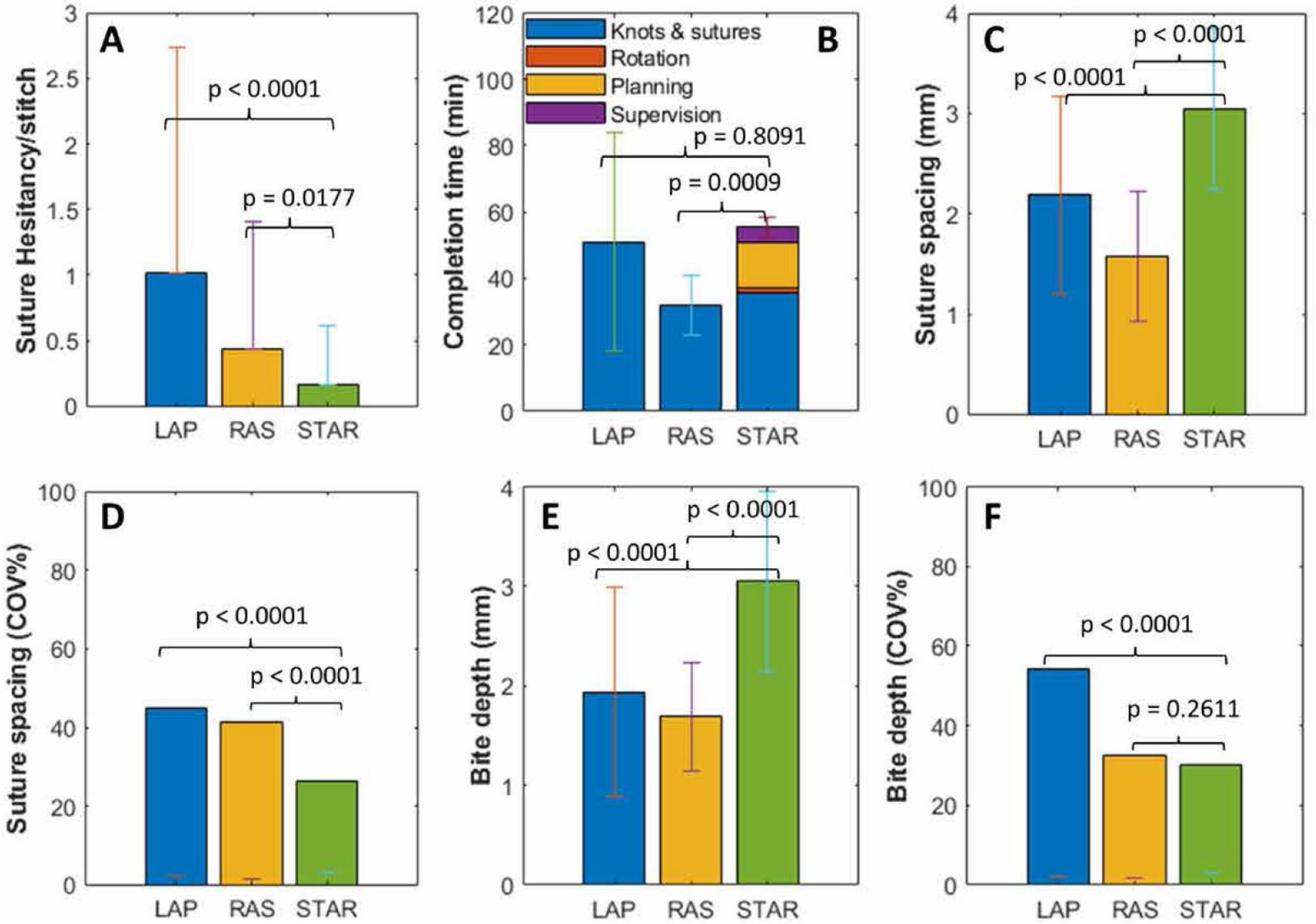
Test conditions:

A. Manual laparoscopy (LAP; n = 4)
B. da Vinci SI–based Robotically-Assisted Surgery method (RAS; n = 4)
C. Autonomous robotic anastomosis via STAR (n = 5)

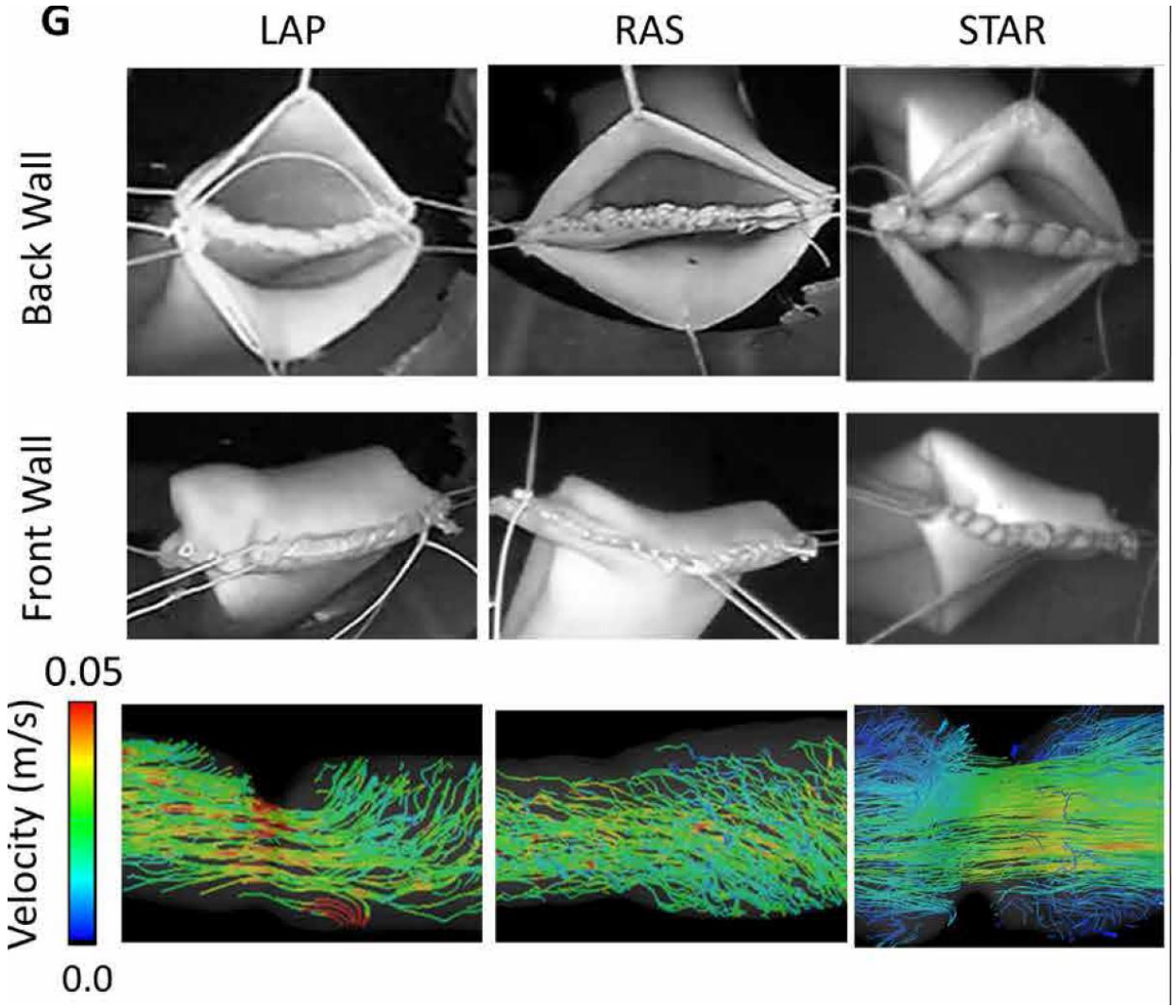




Ex-vivo Test Results



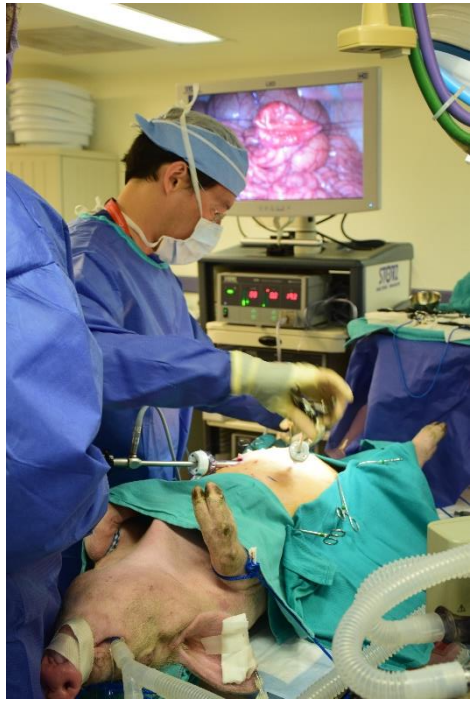
Ex-vivo Test Results

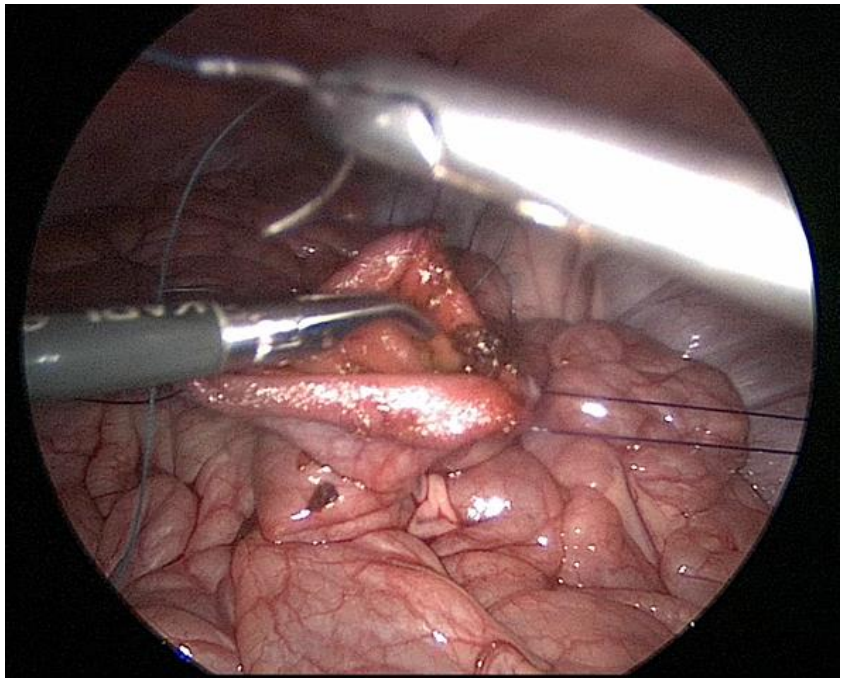


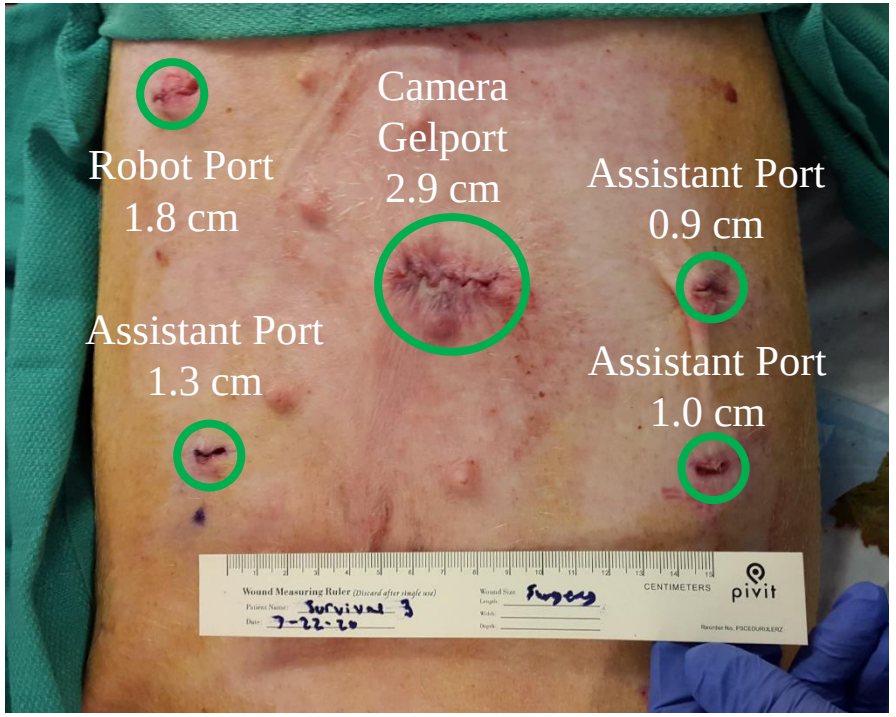
Representative examples of the phantom end-to-end anastomosis test via LAP, RAS, and STAR including 3D flow fields within each sample.

STAR Anastomosis – In vivo Testing

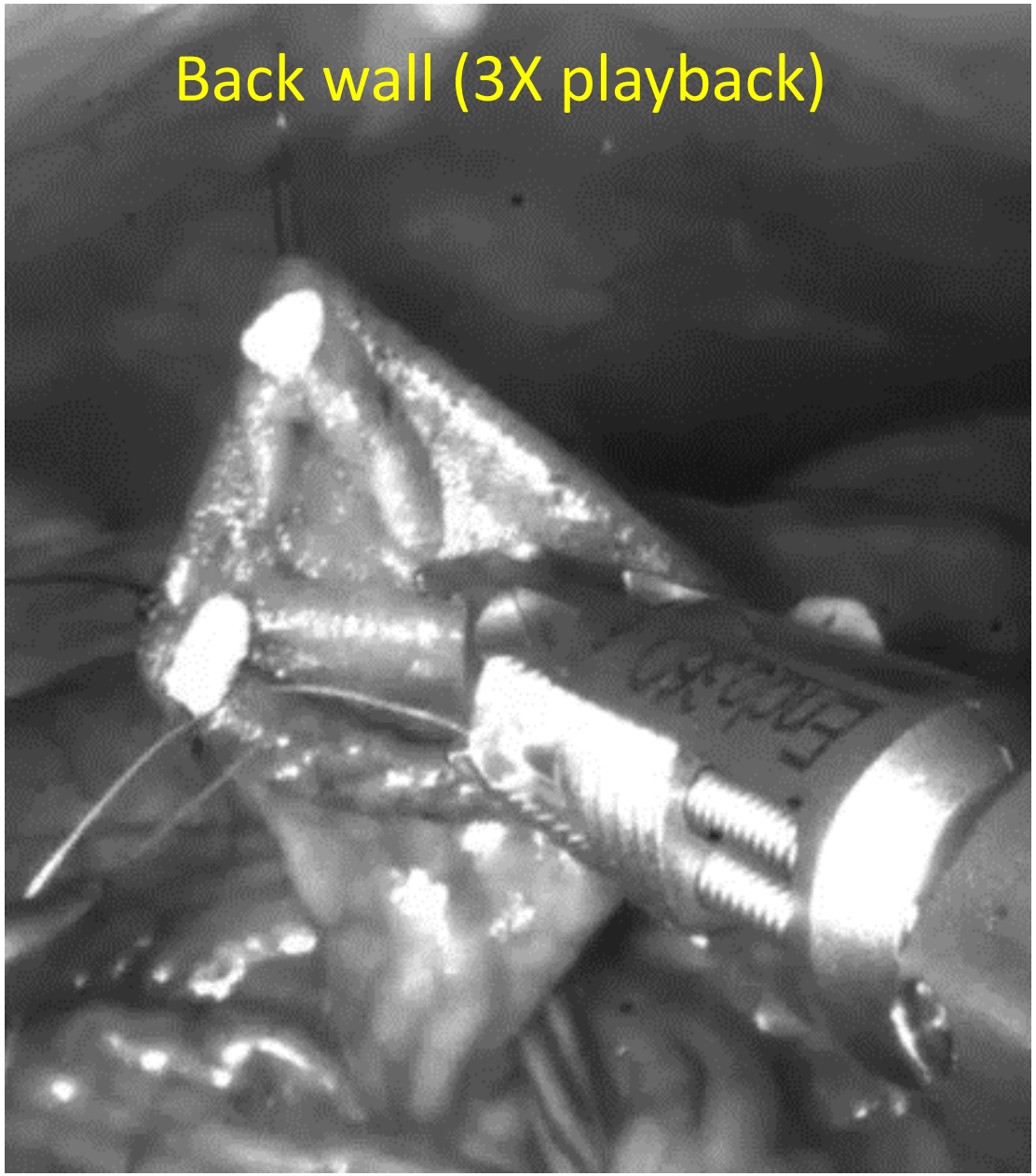
- Performed laparoscopic small intestine anastomoses in pre-clinical animal testing at Children's National

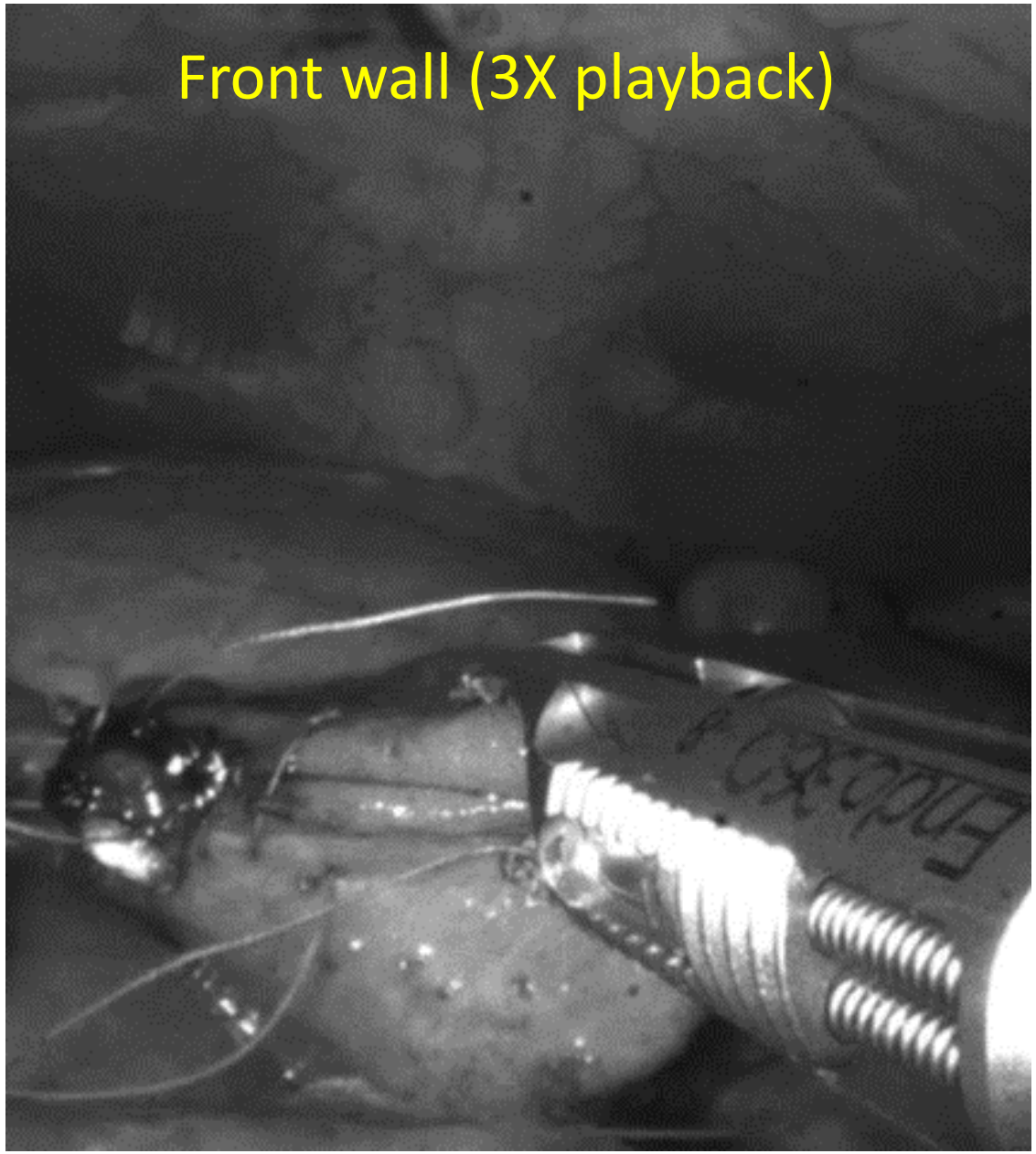




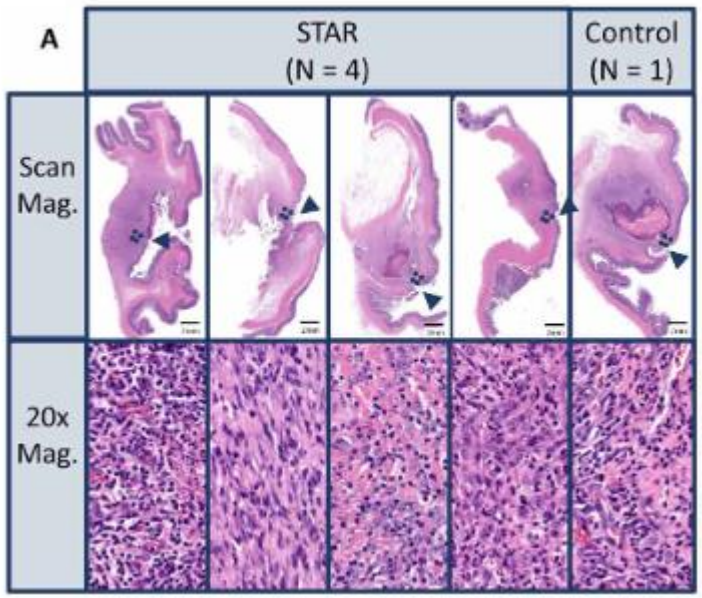


In vivo Suturing with STAR





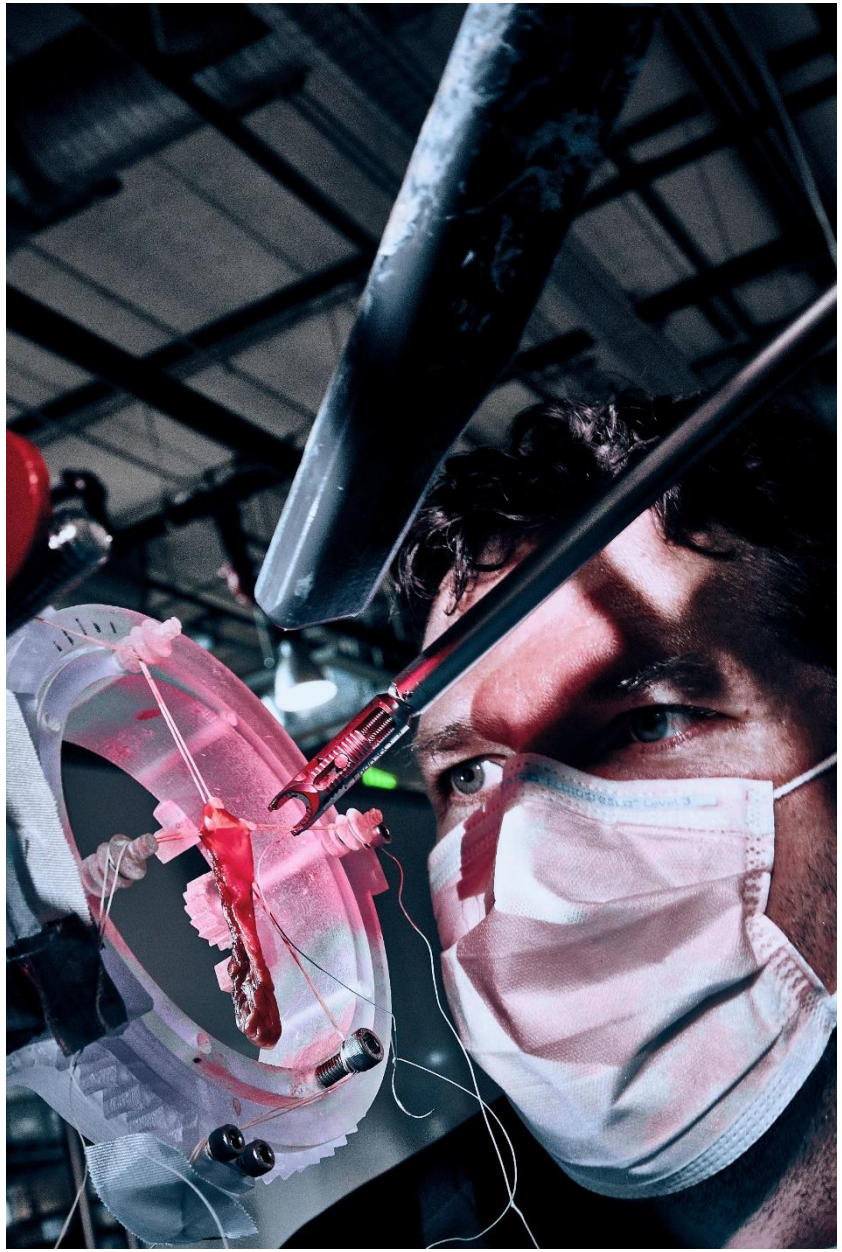
In vivo Test Results



Pig no.	Weight at surgery (kg)	Weight at sacrifice (kg)	Leak pressure (psi)	Lumen patency (%)	Completion time (min)	No. of sutures	Suture hesitancy
STAR 1	32.7	36.4	0.23	85	59.71	24	4
STAR 2	35.4	37.3	0.12	85	55.64	17	7
STAR 3	35.3	33.5	1.2	90	65.73	24	11
STAR 4	35.5	33.8	1.2	95	67.03	21	7
5 (Control)	30	32	1.2	90	25.6	21	9

Lessons Learned

- Autonomous robotics have the potential to complete surgical tasks with more accuracy and precision than MIS and RAS technique.
- Accurate tissue tracking, event detection algorithms, and novel control strategies enable autonomous surgery in soft tissues.
- Clinical testing will require technical improvements including:
  - Smaller imaging camera
  - Markerless tissue tracking
  - Improved surgical user interface



Saeidi H, Opfermann JD, Kam M, Wei S, Leonard S, Hsieh MH, Kang JU, Krieger A. Autonomous Robotic Laparoscopic Surgery for Intestinal Anastomosis. *Science Robotics*. 7, no. 62 (2022). PMID: 35080901. DOI: 10.1126/scirobotics.abj2908

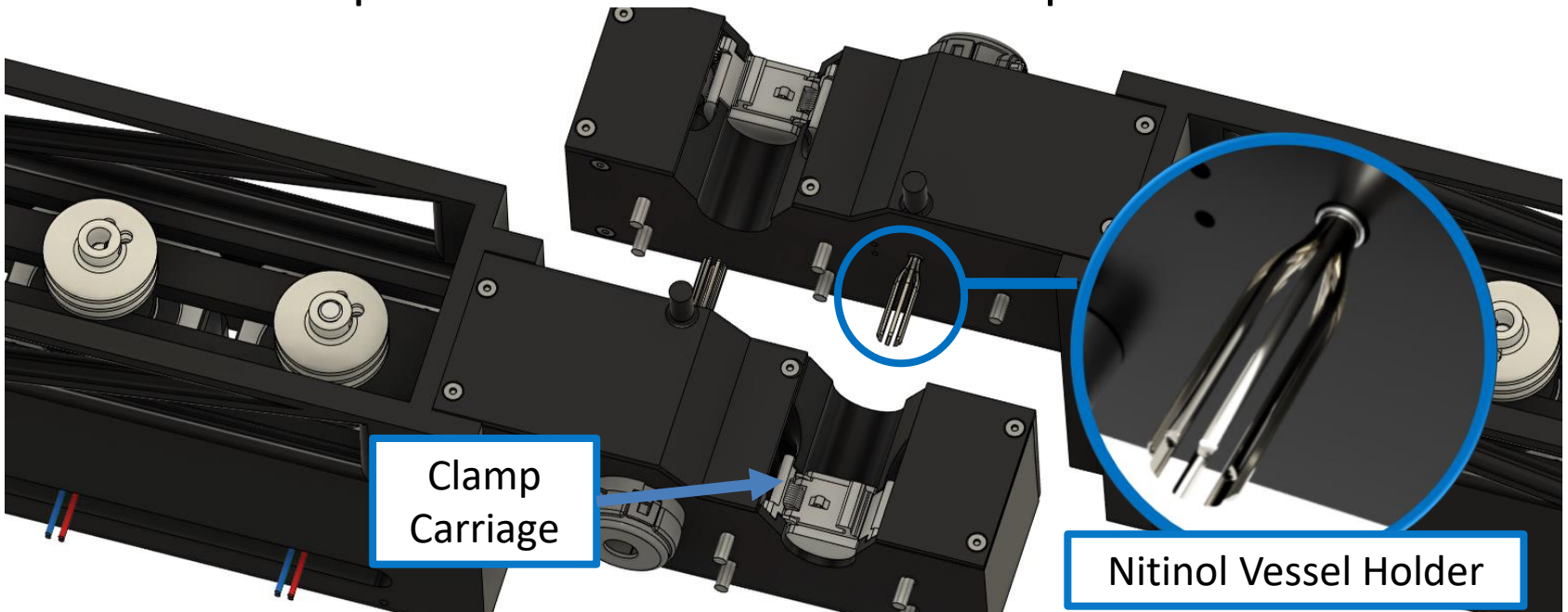
Microvascular Anastomosis Positioning System (MAPS)

Introduction

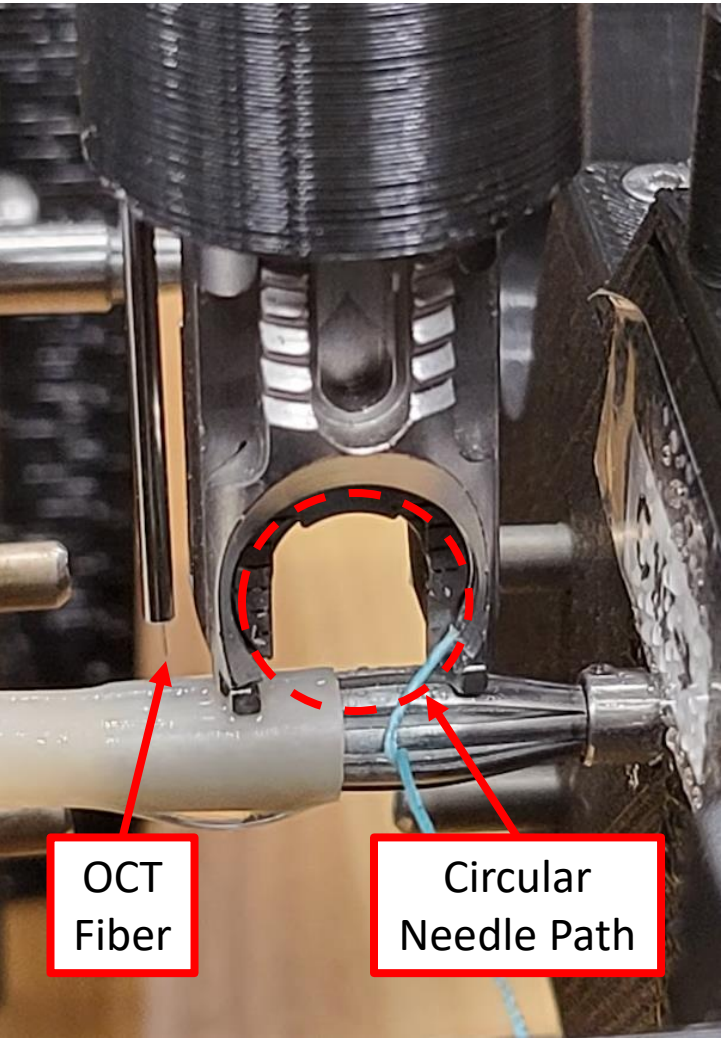
- Microvascular Anastomosis is a suturing procedure commonly done during reconstructive surgery
- STAR robot currently autonomously sutures larger structures such as intestine, but not blood vessels

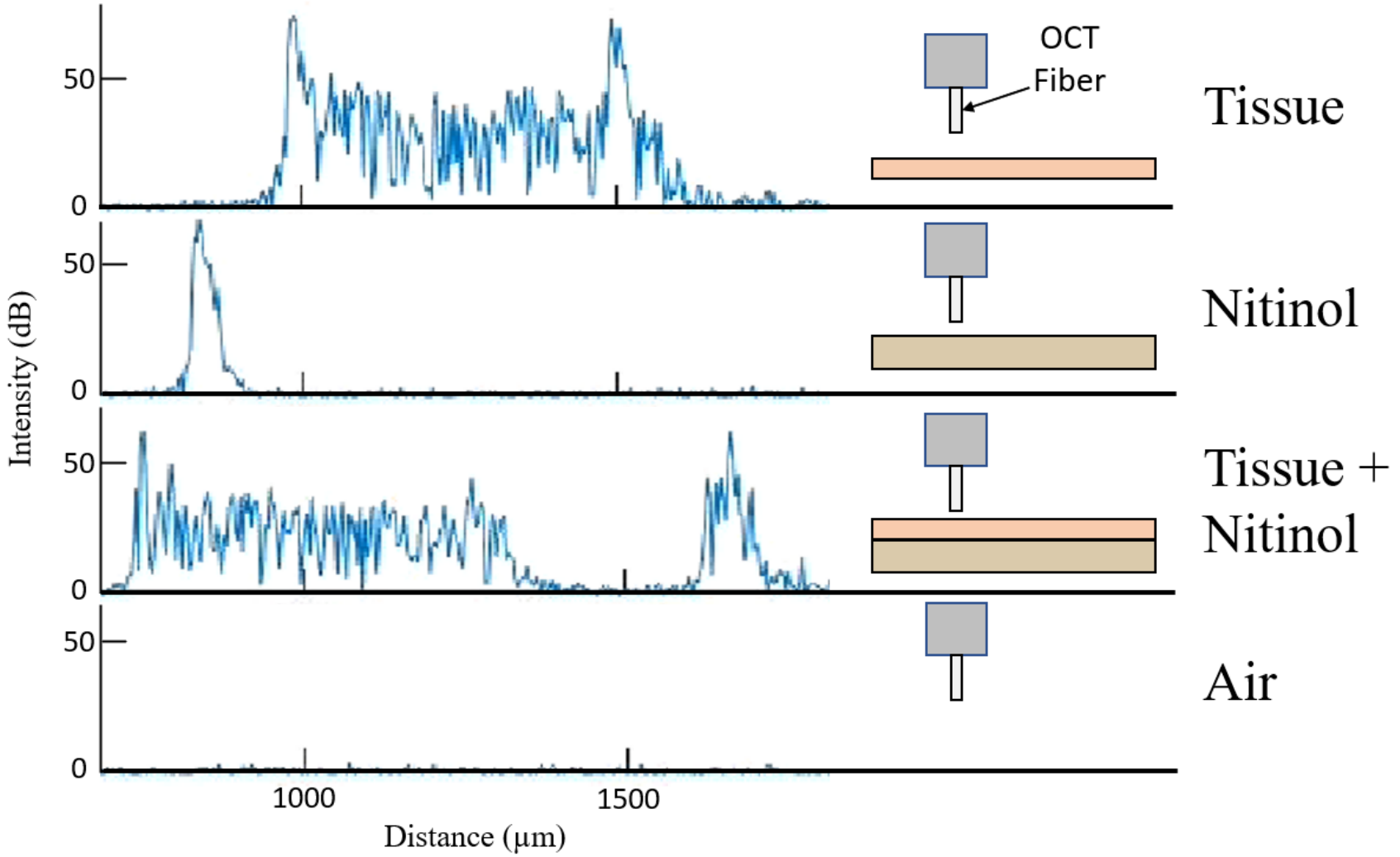
Solution

- Robotic tool positions vessels for STAR to perform anastomosis

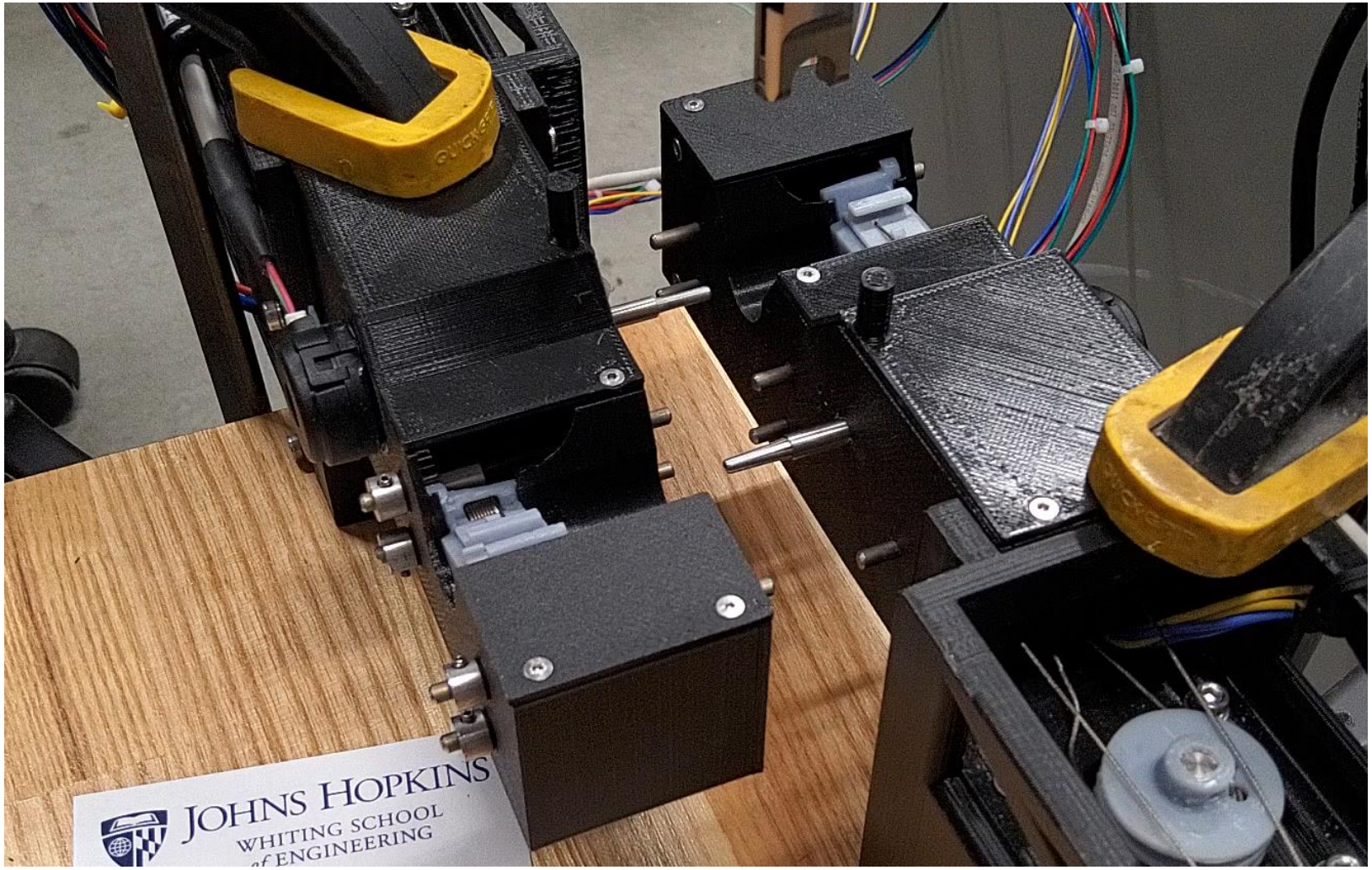


Optical Coherence Tomography (OCT) Guidance





MAPS + STAR Results



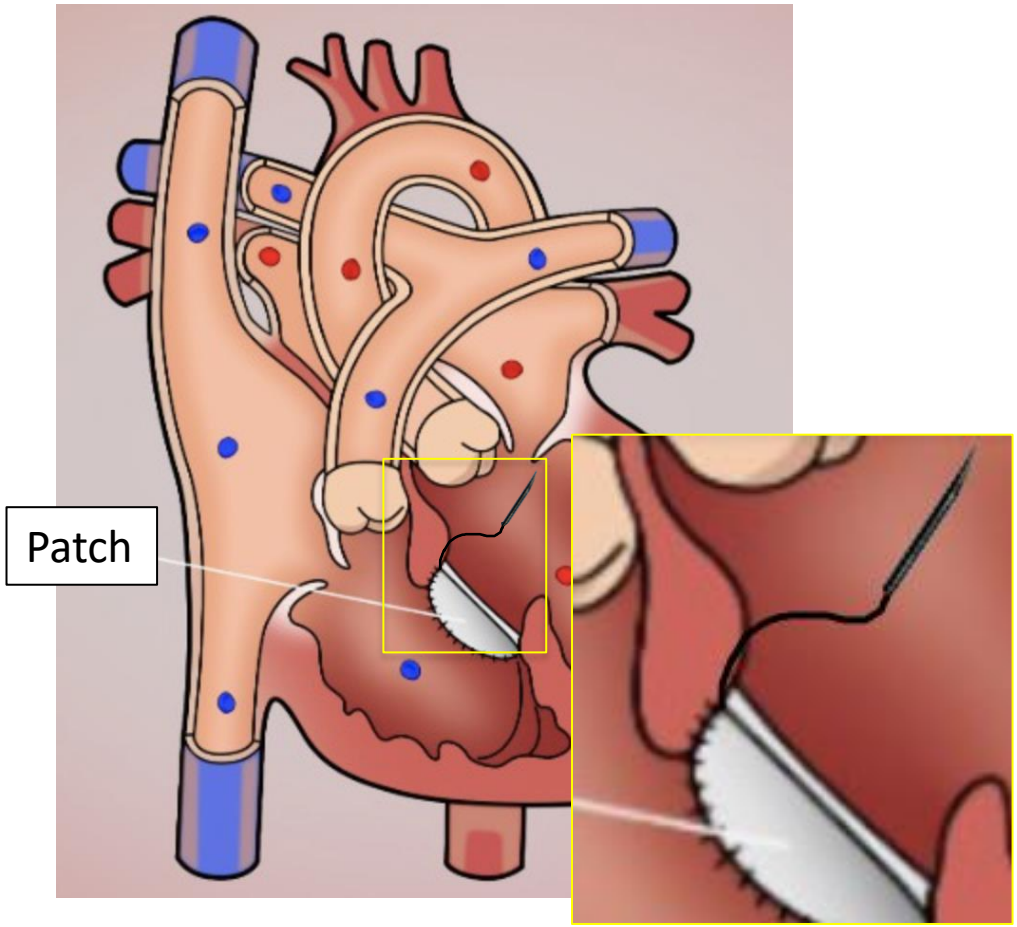
- 64/64 successful stitches, no double wall puncture
- Clinically relevant tensile strength and lumen reduction
- Similar bite depth variance to STAR alone
- Improved spacing variance over STAR alone

Haworth J, Opfermann JD, Kam M, Wang Y, Yang R, Kang JU, Krieger A. Development and Evaluation of a Robotic Vessel Positioning System for Semi-Automatic Microvascular Anastomosis. *International Conference on Robotics and Automation (ICRA), 2023.*

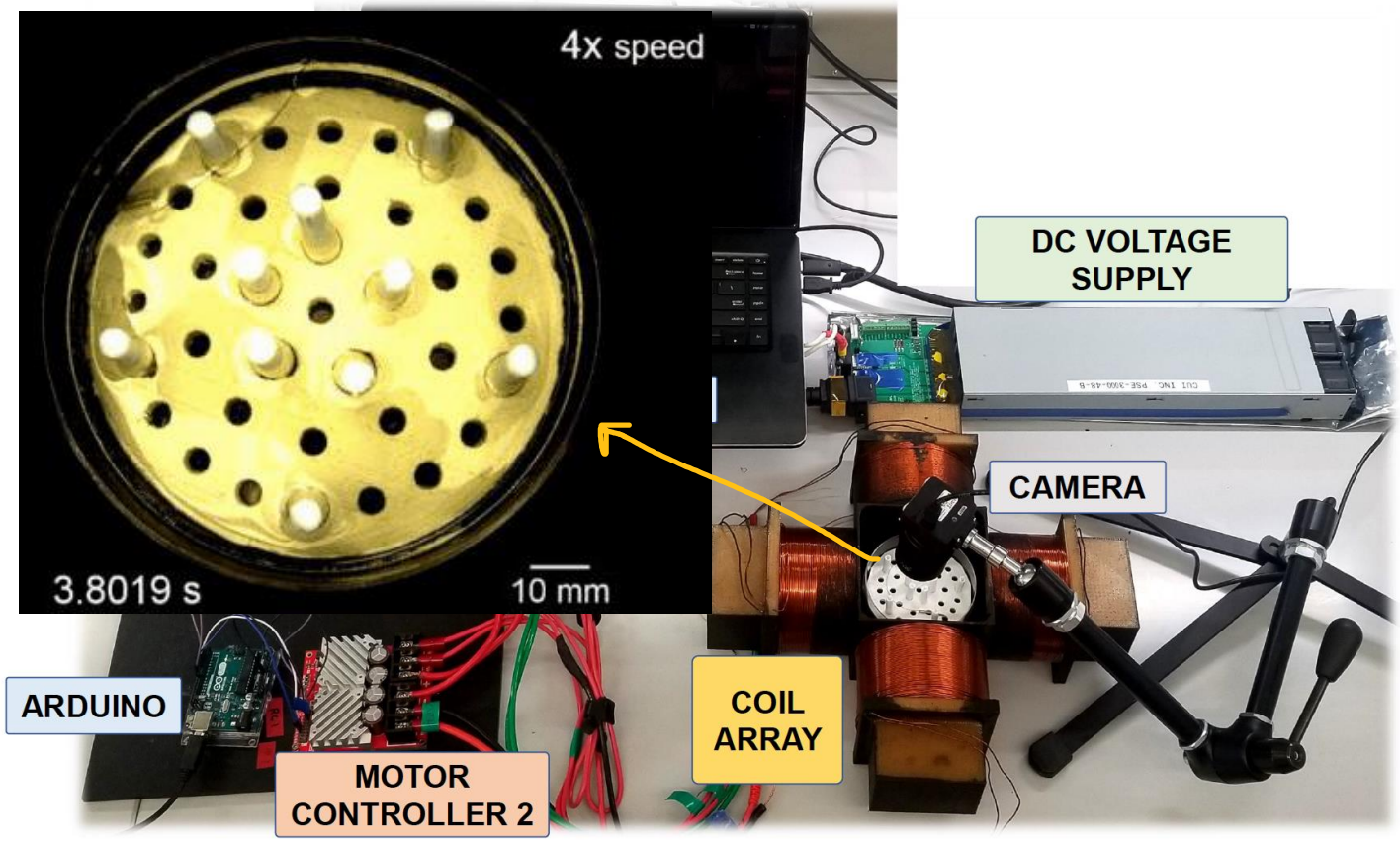
Questions?

MagnetoSuture: Concept of Untethered Suture

- Concept: ventricular septal defect repair[1]



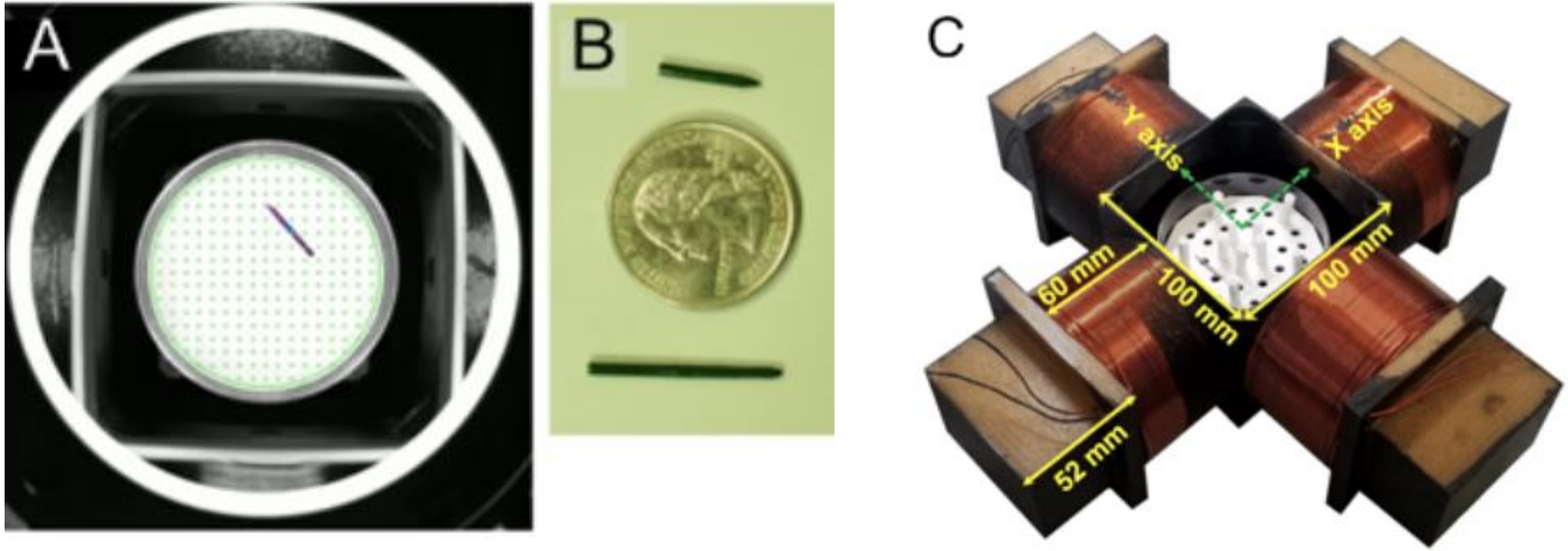
- Tele-operated magnetic suture needle[2]



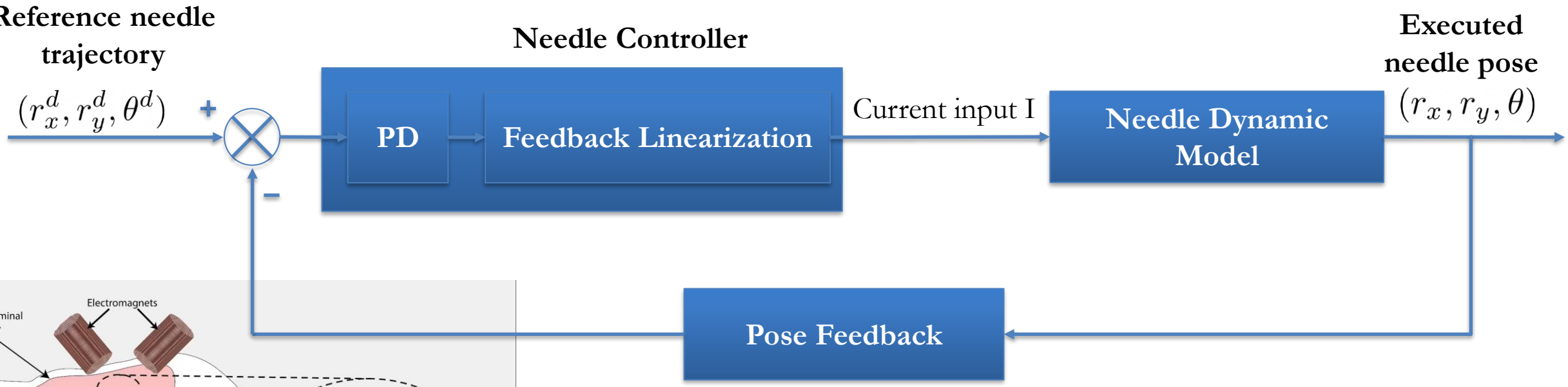
1. Image: http://childrens.memorialhermann.org/services/ventricular-septal-defects/
2. Lamar O. Mair, Xiaolong Liu, et al., "MagnetoSuture: Tetherless Manipulation of Suture Needles," IEEE Transactions on Medical Robotics and Bionics, vol. 2, no. 2, pp. 206-215, May 2020

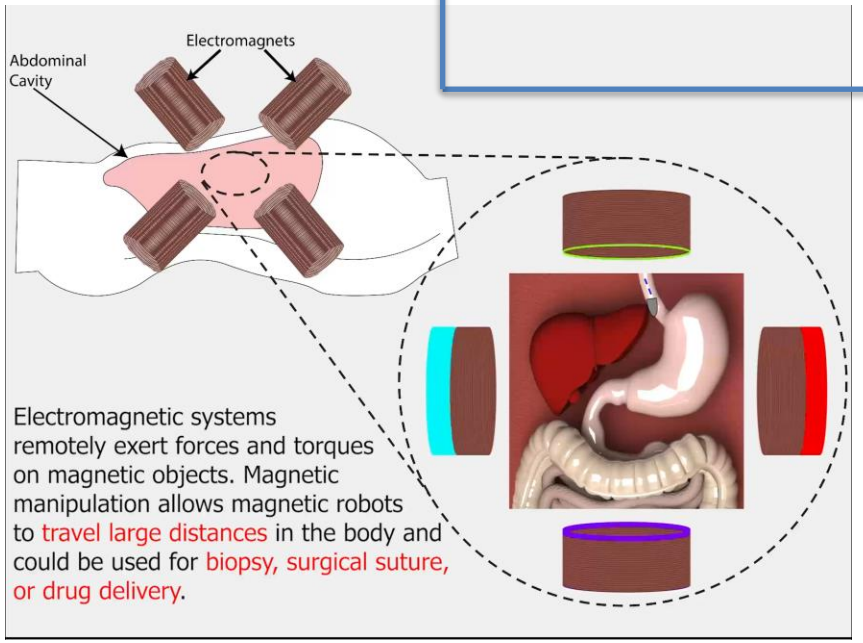
Research Problem

- Control mesoscale magnetic suture needles by using non-uniform magnetic field



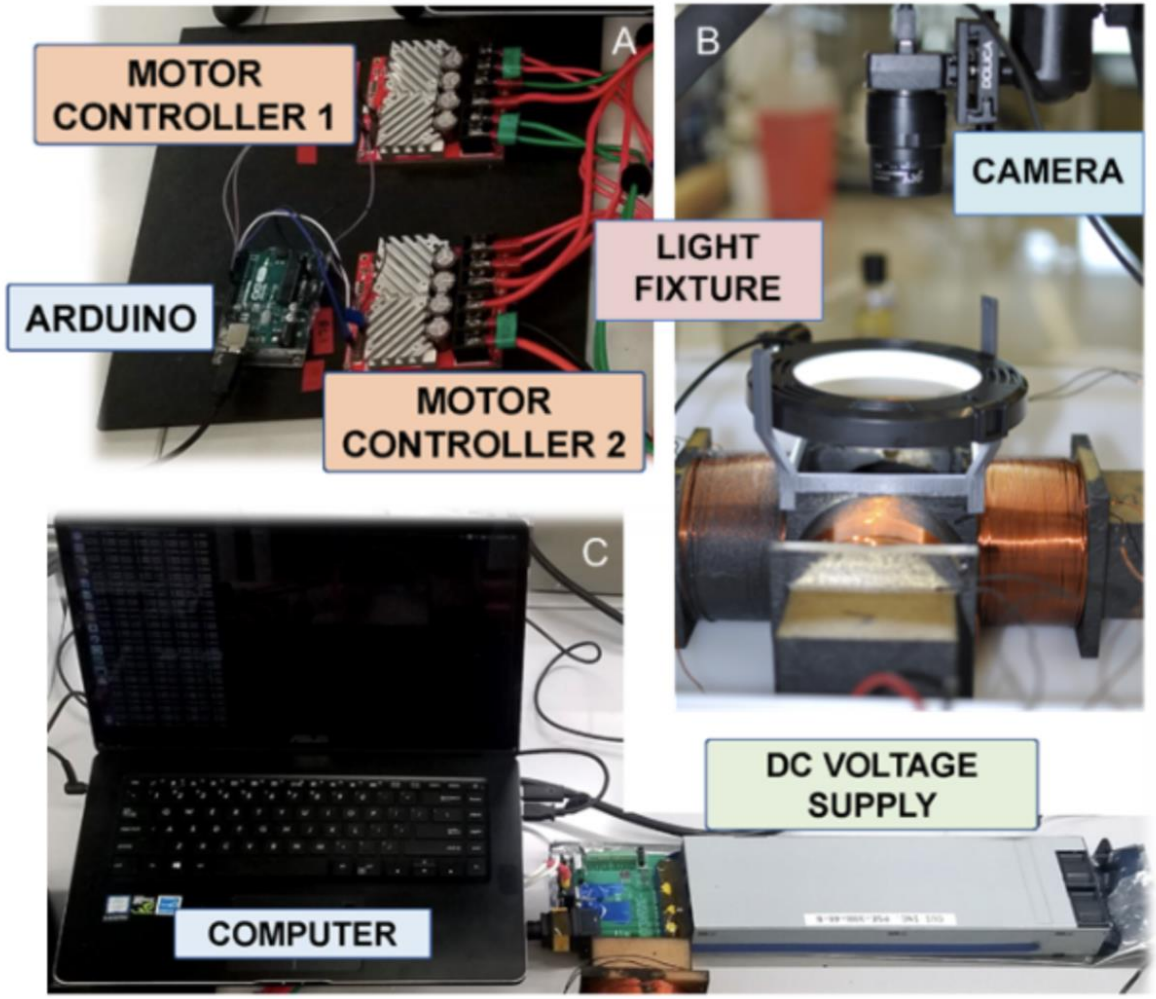
Method Overview



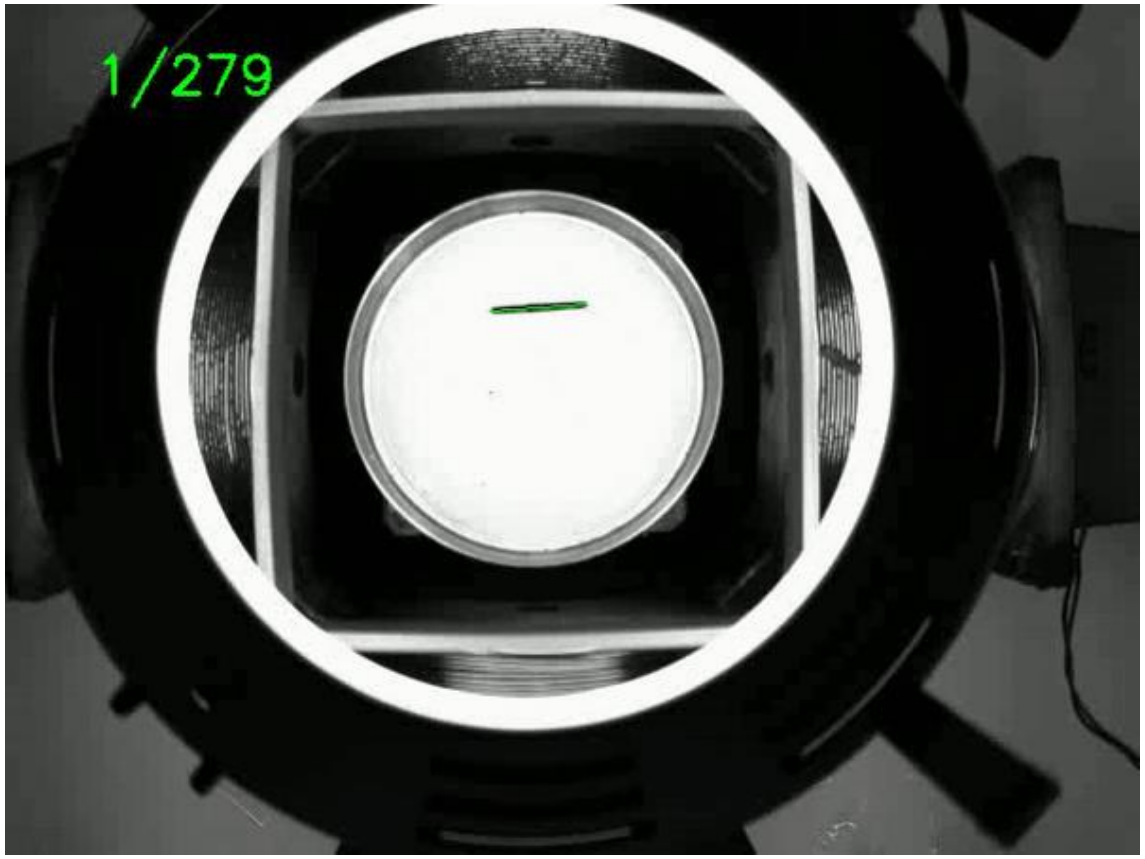


Experiment Setup and Needle Perception

Hardware configuration

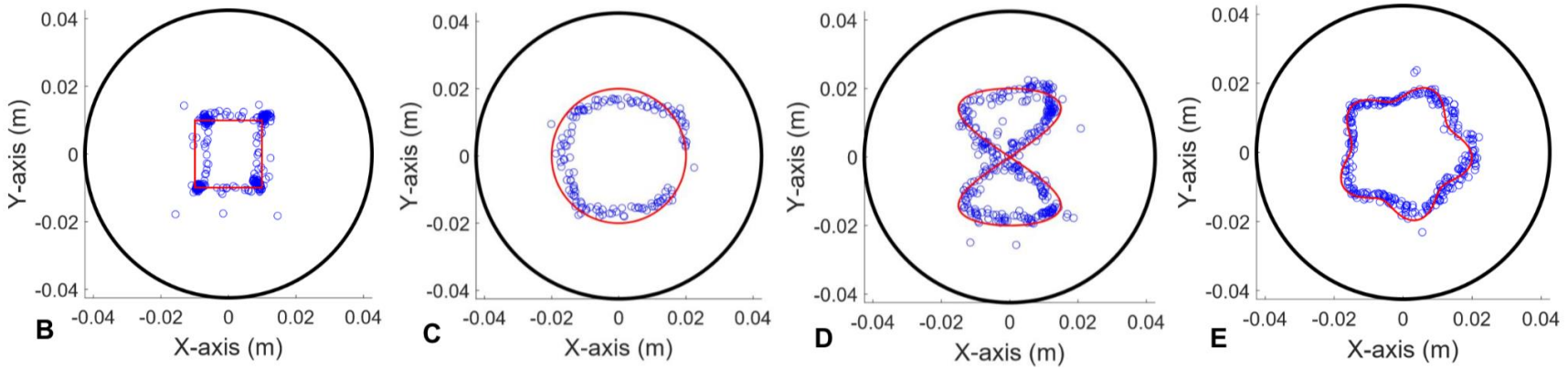


Perception of needle random movement

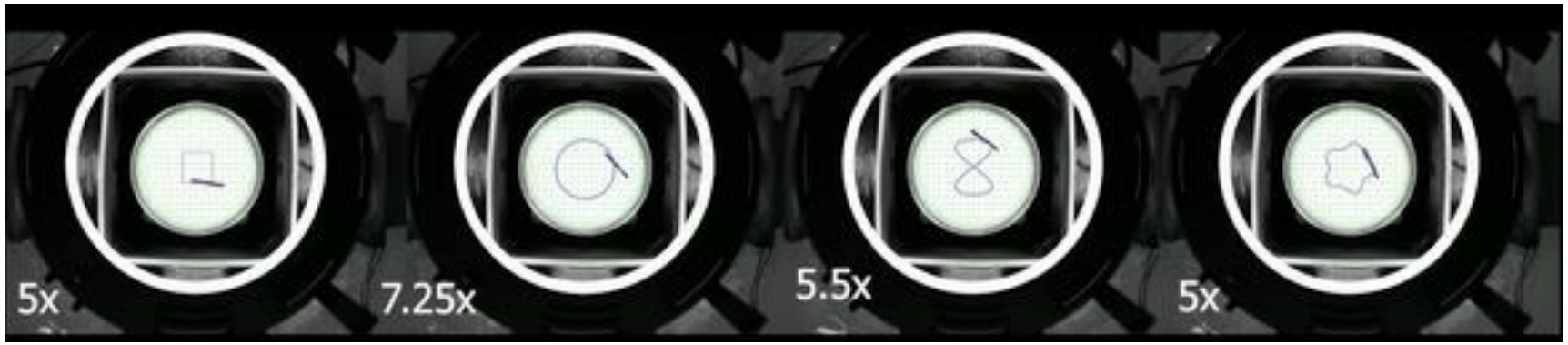


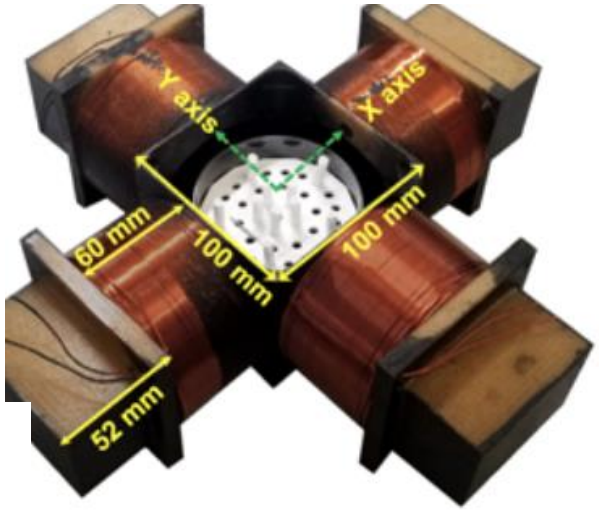
Position Control using Discretized Trajectories

$$r_{dn} = \begin{bmatrix} R\cos\left(\frac{2\pi}{N}n\right) \\ R\sin\left(\frac{2\pi}{N}n\right) \end{bmatrix} \qquad r_{dn} = \begin{bmatrix} R_x \sin\left(\frac{4\pi n}{N}\right) \\ R_y \cos\left(\frac{2\pi n}{N}\right) \end{bmatrix} \qquad r_{dn} = \left(\frac{R_{max}-R_{min}}{2}\cos\left(\frac{2\pi m_d}{N}n\right) + \frac{R_{max}+R_{min}}{2}\right)\begin{bmatrix} \cos\left(\frac{2\pi}{N}n\right) \\ \sin\left(\frac{2\pi}{N}n\right) \end{bmatrix}$$



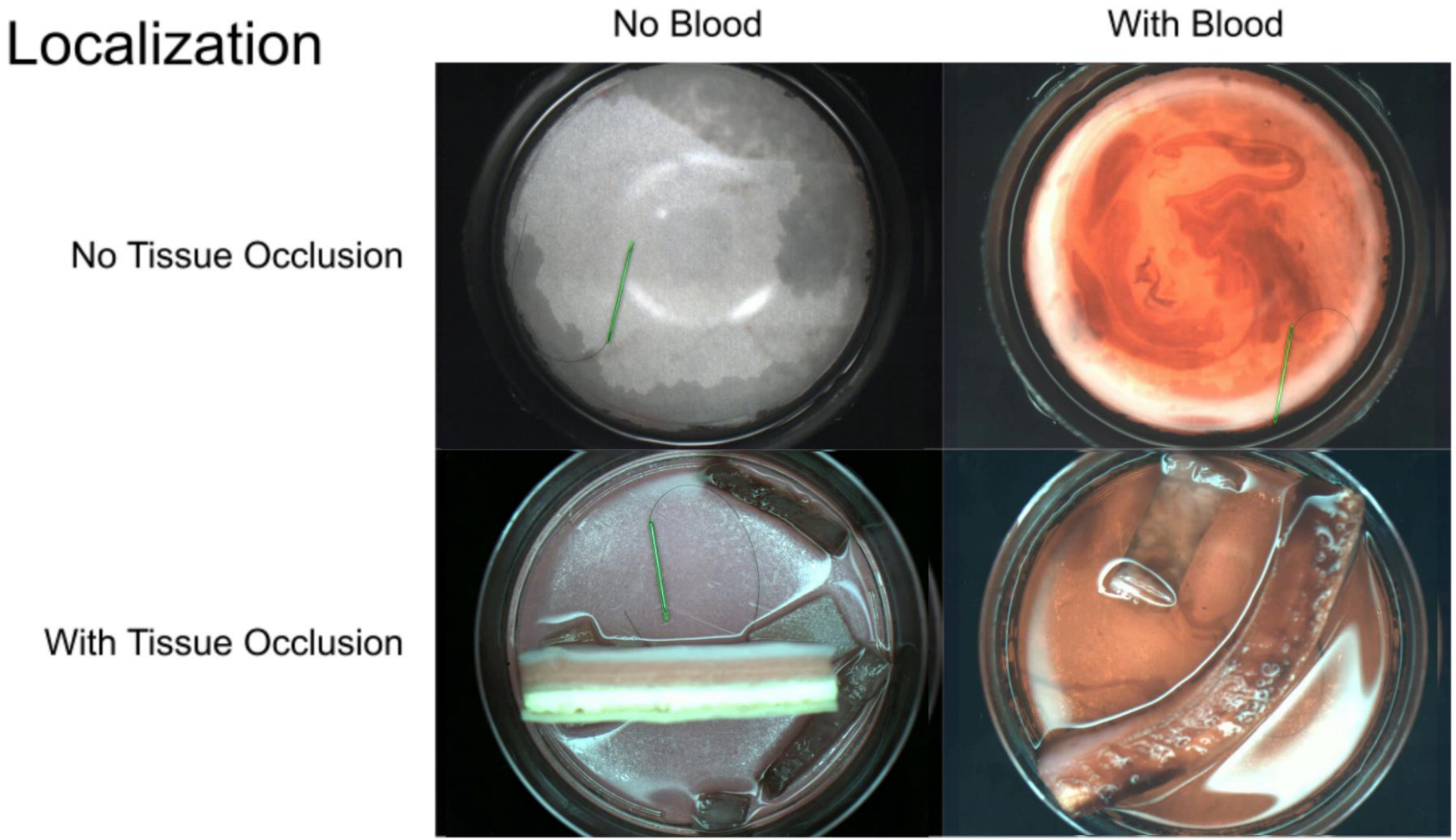
	RMS (mm)
Square	1.6
Circle	2.7
Figure-8	2.1
Purse-string	1.5





Matthew Fan*, Xiaolong Liu*, Kamakshi Jain, Daniel Lerner, Lamar O. Mair, Irving N. Weinberg, Yancy Diaz-Mercado, Axel Krieger, Towards Autonomous Control of Magnetic Suture Needles, *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Las Vegas, 2020.

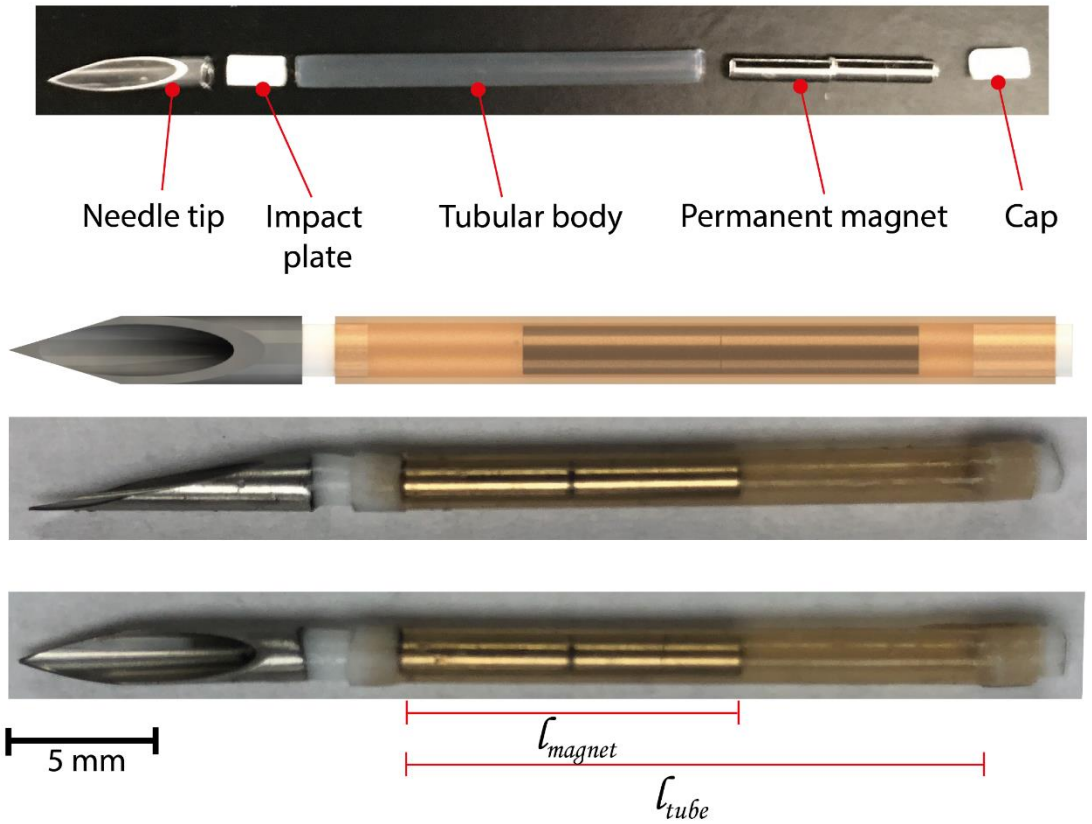
Localization and Control in Surgical Environment



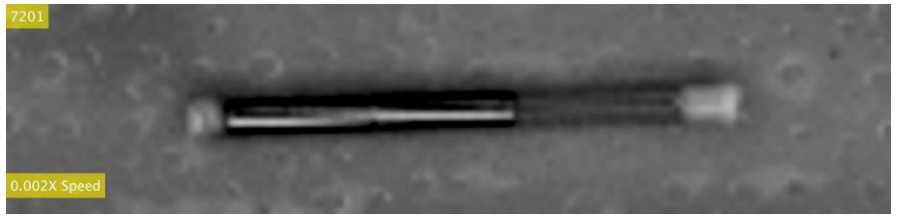
Will Pryor, Yotam Barnoy, Suraj Raval, Xiaolong Liu, Lamar Mair, Daniel Lerner, Onder Erin, Gregory D. Hager, Yancy Diaz-Mercado, Axel Krieger. Localization and Control of Magnetic Suture Needles in Cluttered Surgical Site with Blood and Tissue. *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2021

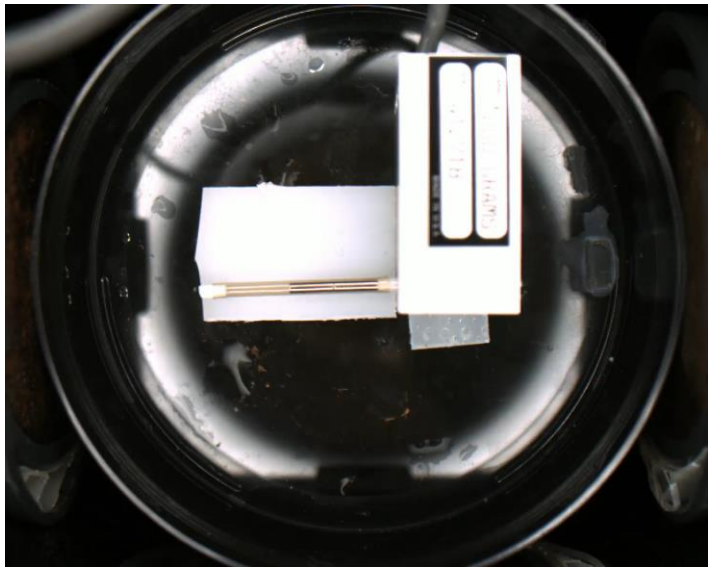
Magnetic Pulse Actuated Collisions for Tissue-penetrating Needle (MPACT-Needle)

Design

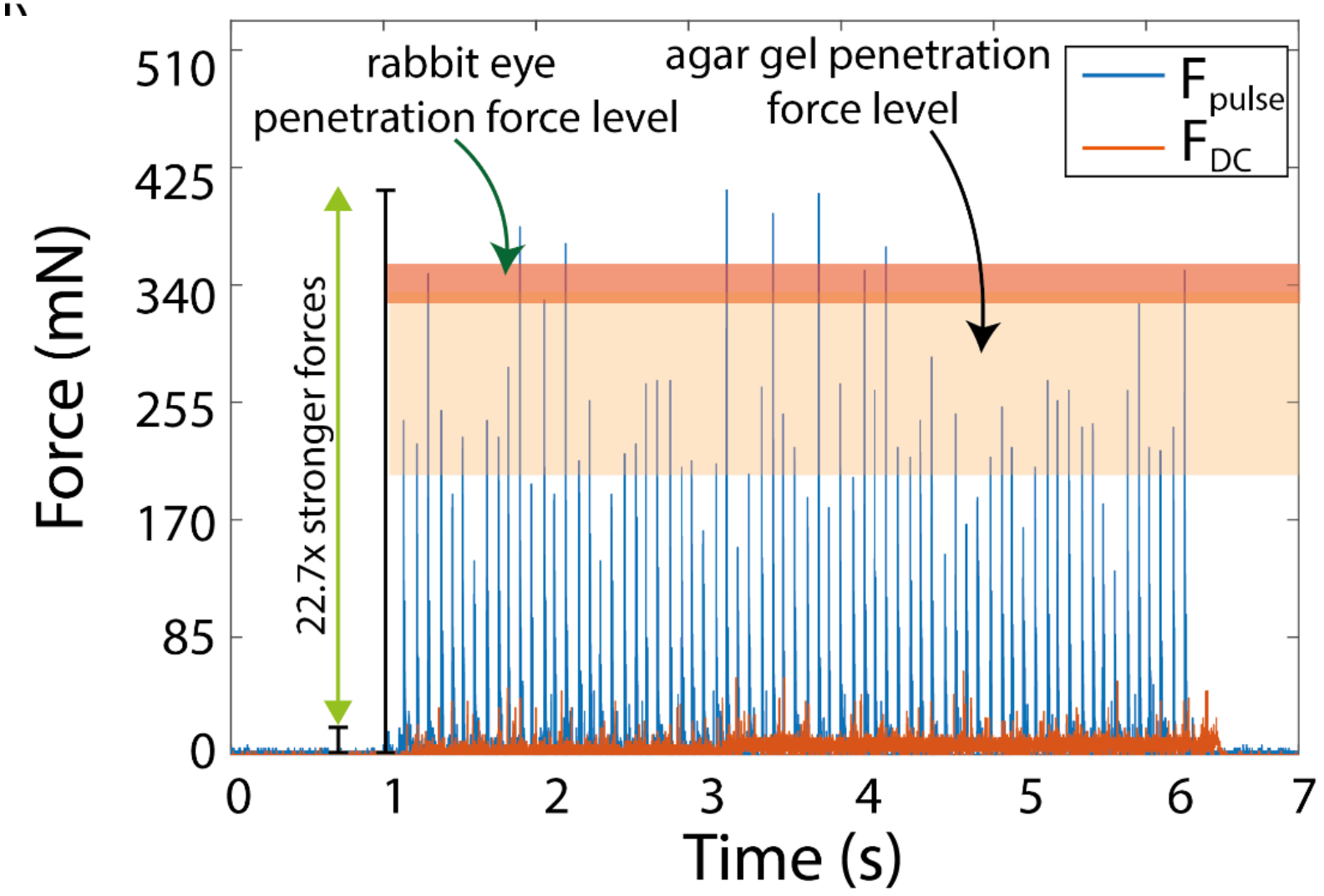


Preliminary Tests

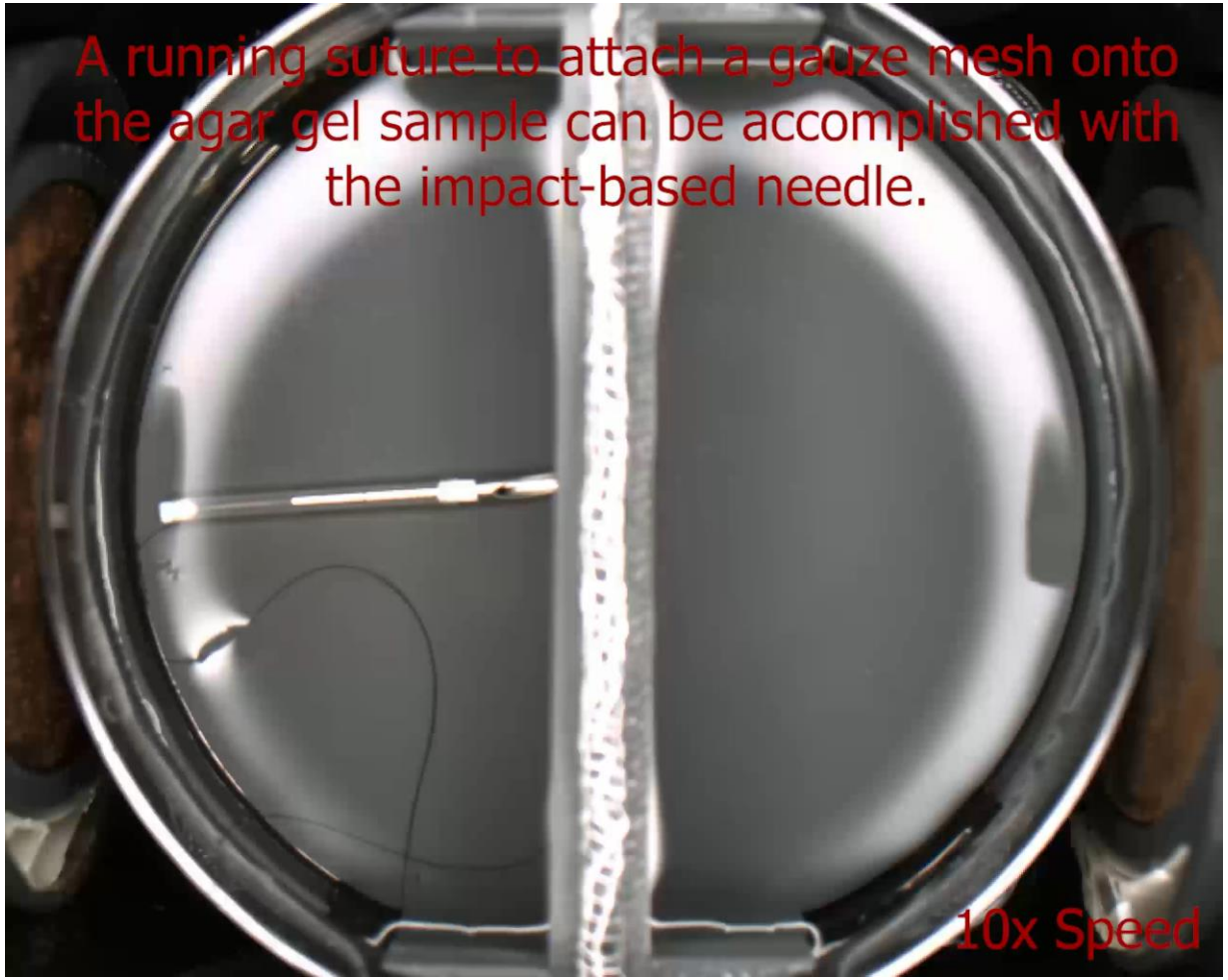


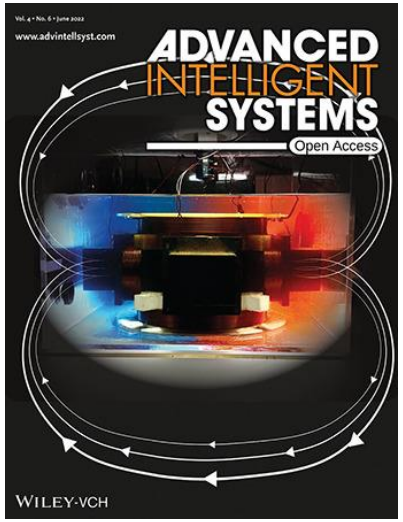


22.7 Fold Increase in the Force Generation



Suturing in Agarose Gel with Gauze Mesh



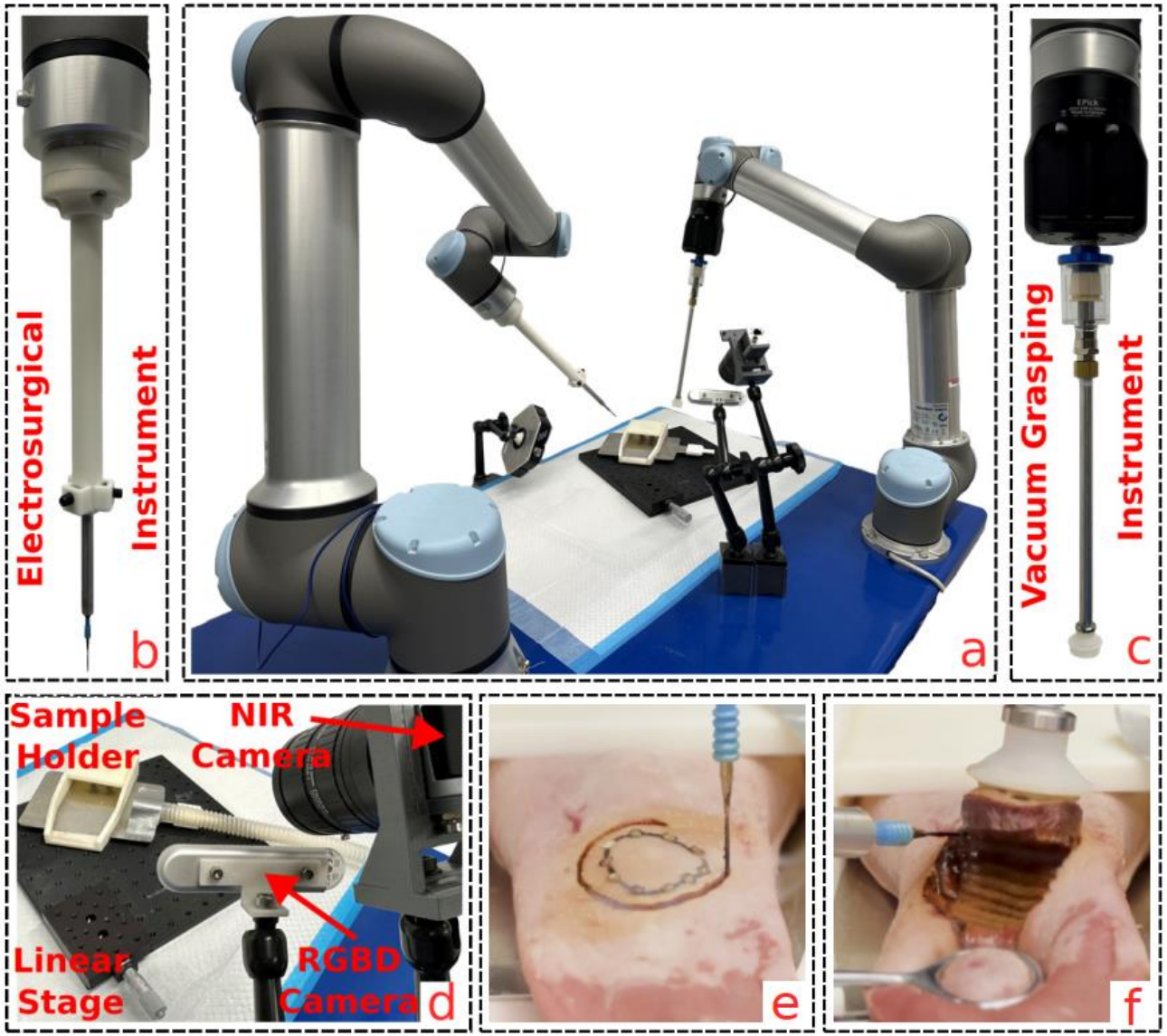


Erin O, Liu X, Ge J, Opfermann J, Barnoy Y, Mair LO, Kang JU, Gensheimer W, Weinberg IN, Diaz-Mercado Y, Krieger A. Overcoming the Force Limitations of Magnetic Robotic Surgery: Magnetic Pulse Actuated Collisions for Tissue-Penetrating-Needle for Tetherless Interventions. *Advanced Intelligent Systems*. 2022 Apr 22:2200072.

Questions?

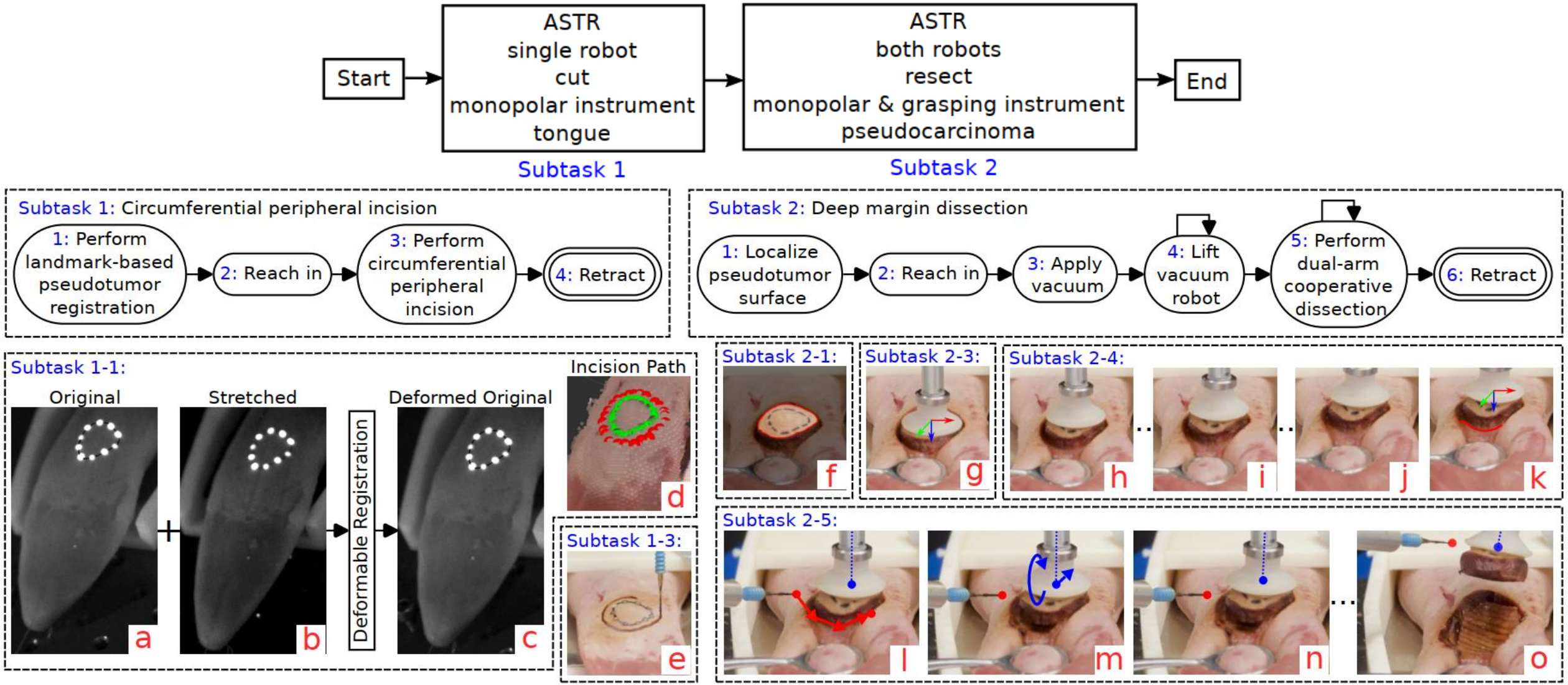
Autonomous System for Tumor Resection (ASTR)

- **Introduction**
  - Surgical resection is a primary treatment modality for many patients with head and neck squamous cell carcinoma.
- **Problem**
  - Tumor delineation difficulty.
  - No autonomy in robot-assisted surgeries.
- **Solution**
  - A near-infrared fluorescent tumor marking strategy.
  - An autonomous robot system for tumor resection.

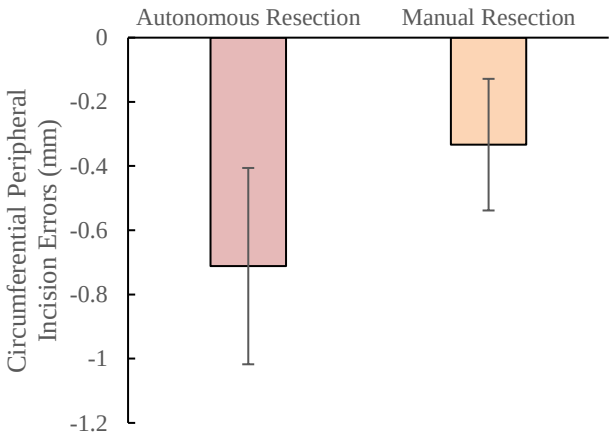


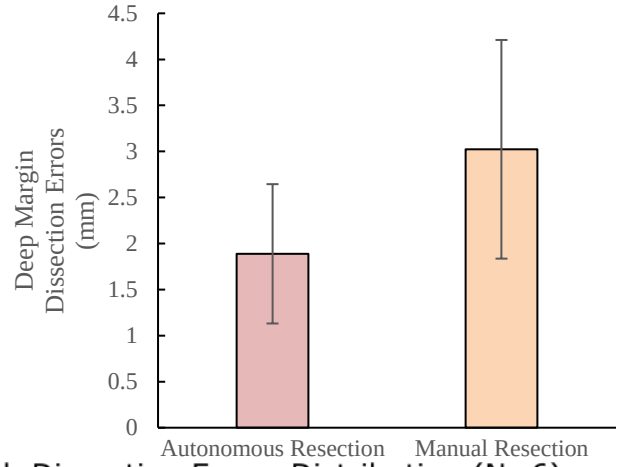
Ge J, Kam M, Opfermann JD, Saeidi H, Leonard S, Mady LJ, Schnermann MJ, Krieger A. Autonomous System for Tumor Resection (ASTR)-Dual-Arm Robotic Midline Partial Glossectomy. *IEEE Robotics and Automation Letters* (2023).

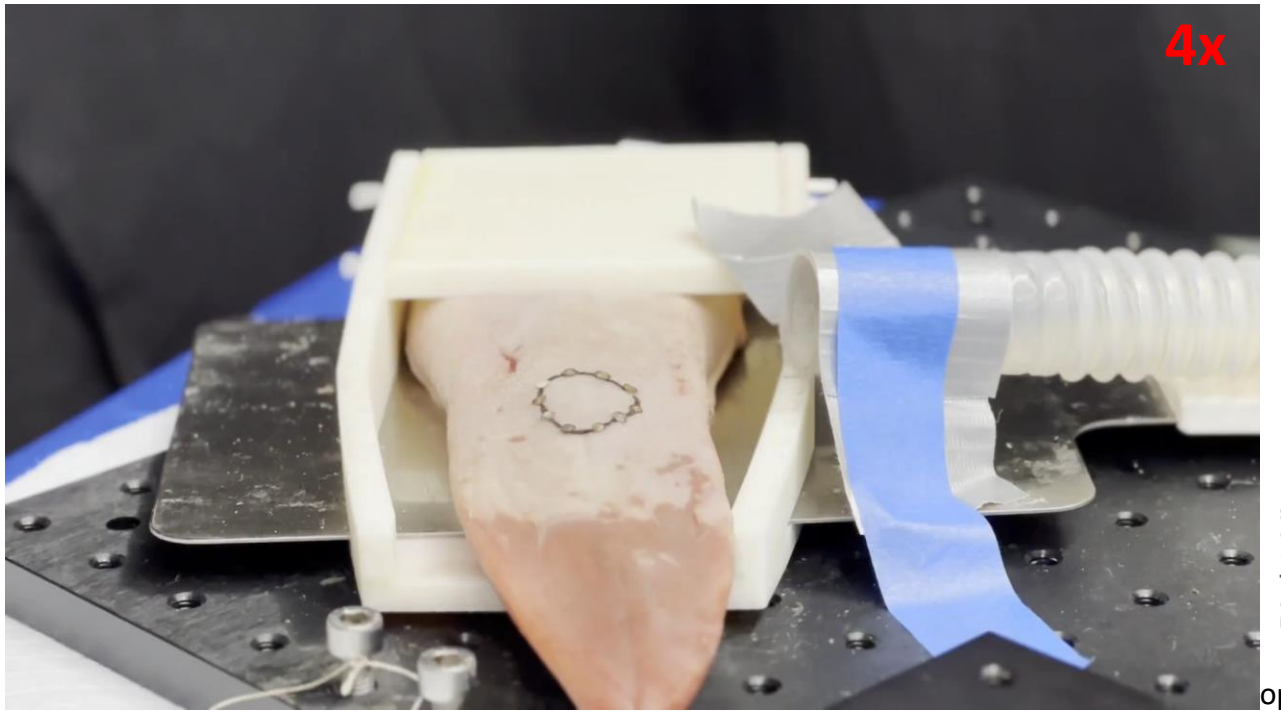
ASTR - Dual-Arm Robotic Midline Partial Glossectomy

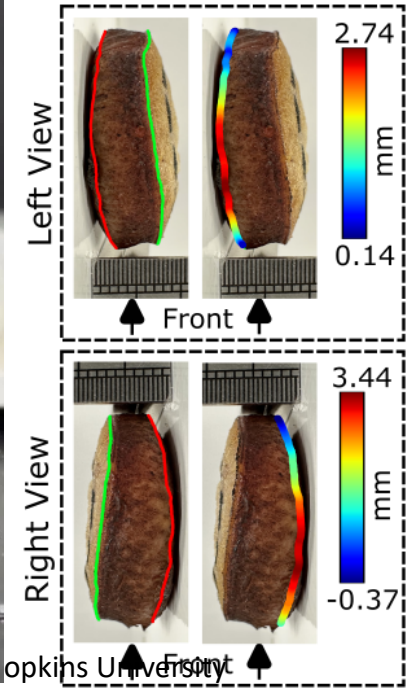


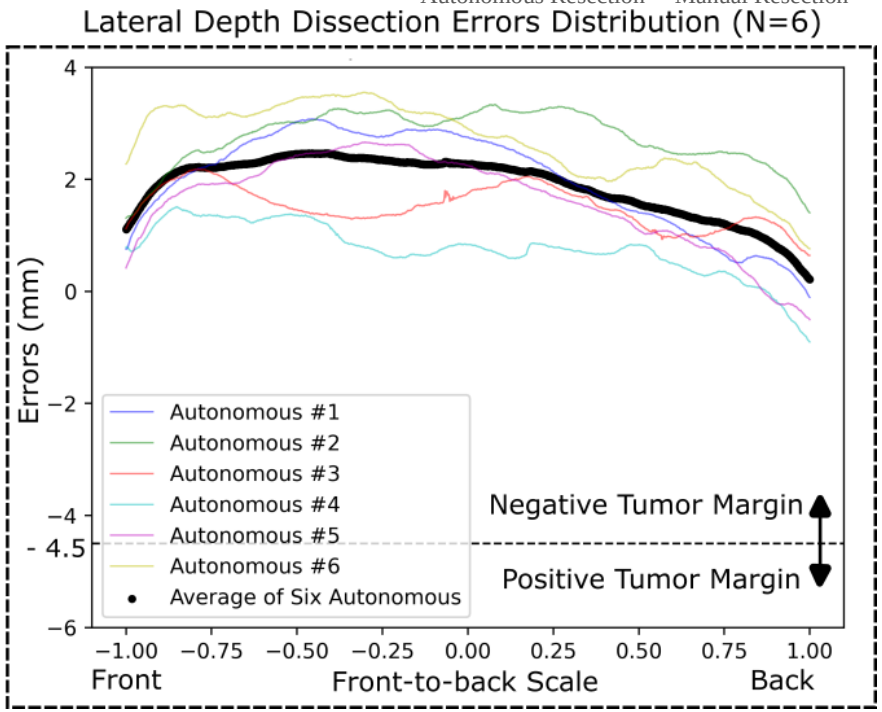
ASTR - Dual-Arm Robotic Midline Partial Glossectomy











Questions?

Why learning?

Model based approach:

- ☒ Requires domain expertise
- ☒ One method, one task
- ☒ Difficult to scale

- ☑ Predictable and more safe

Learning based approach:

- ☑ Only demonstrations required
- ☑ One method, many tasks
- ☑ Improves with more data

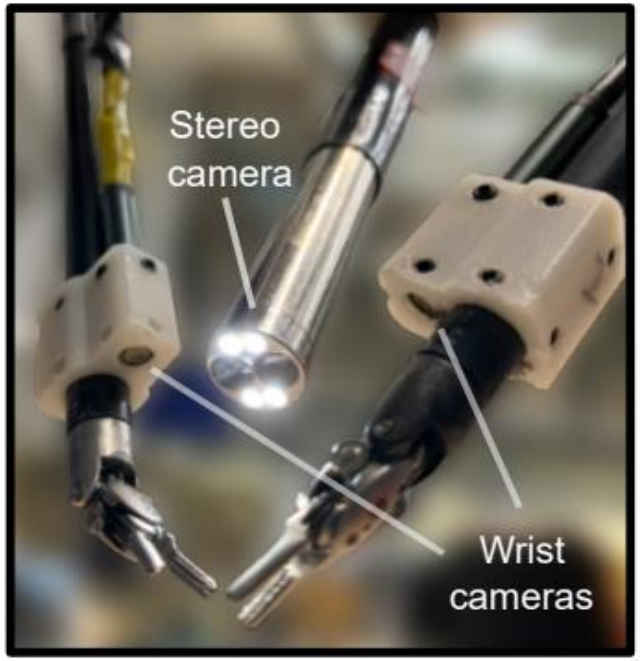
- ☒ black-box model – can be unsafe

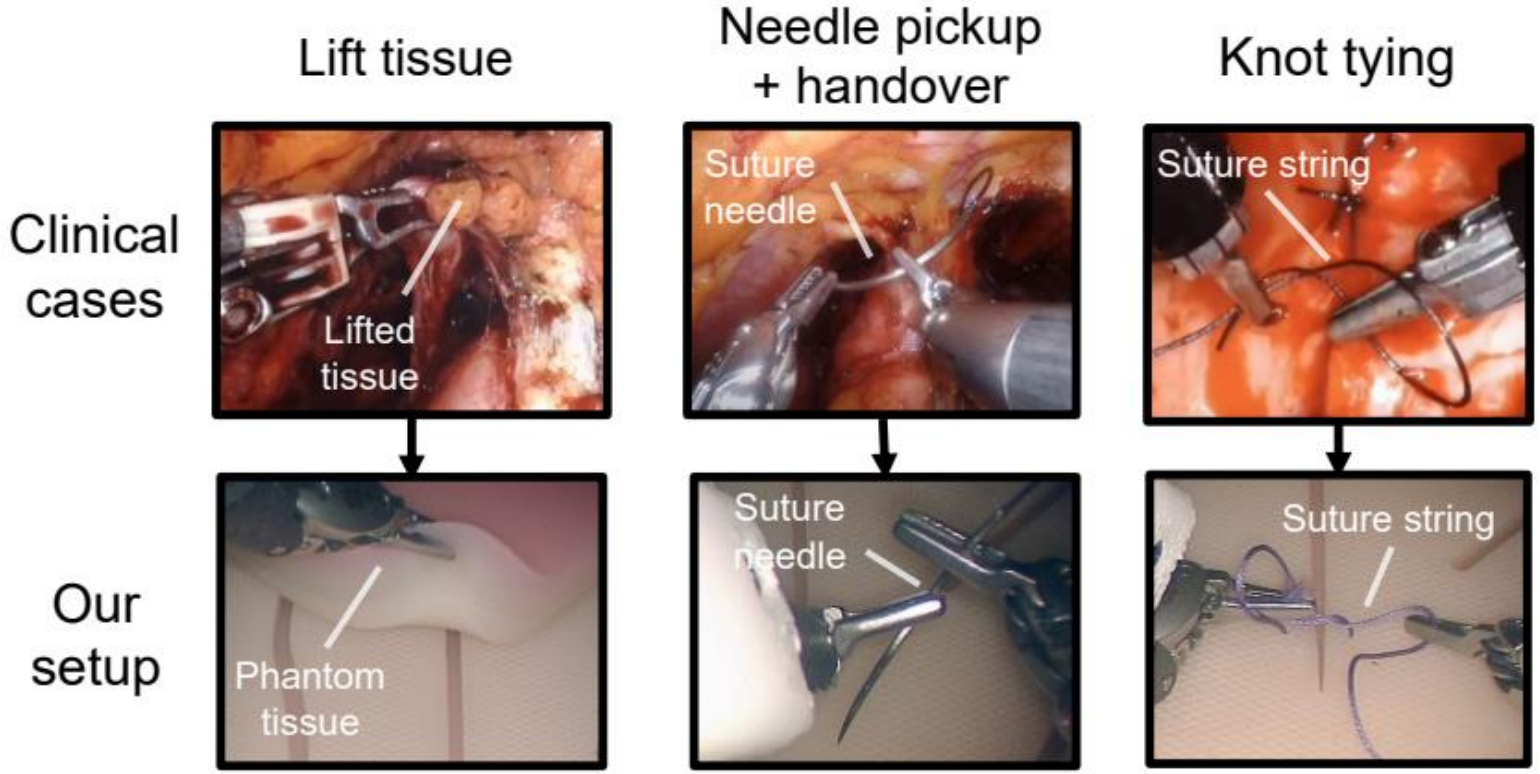
Surgical Diffusion Policy: Learning Autonomous Surgical Subtasks (Ongoing work)

https://surgical-robot-transformer.github.io/

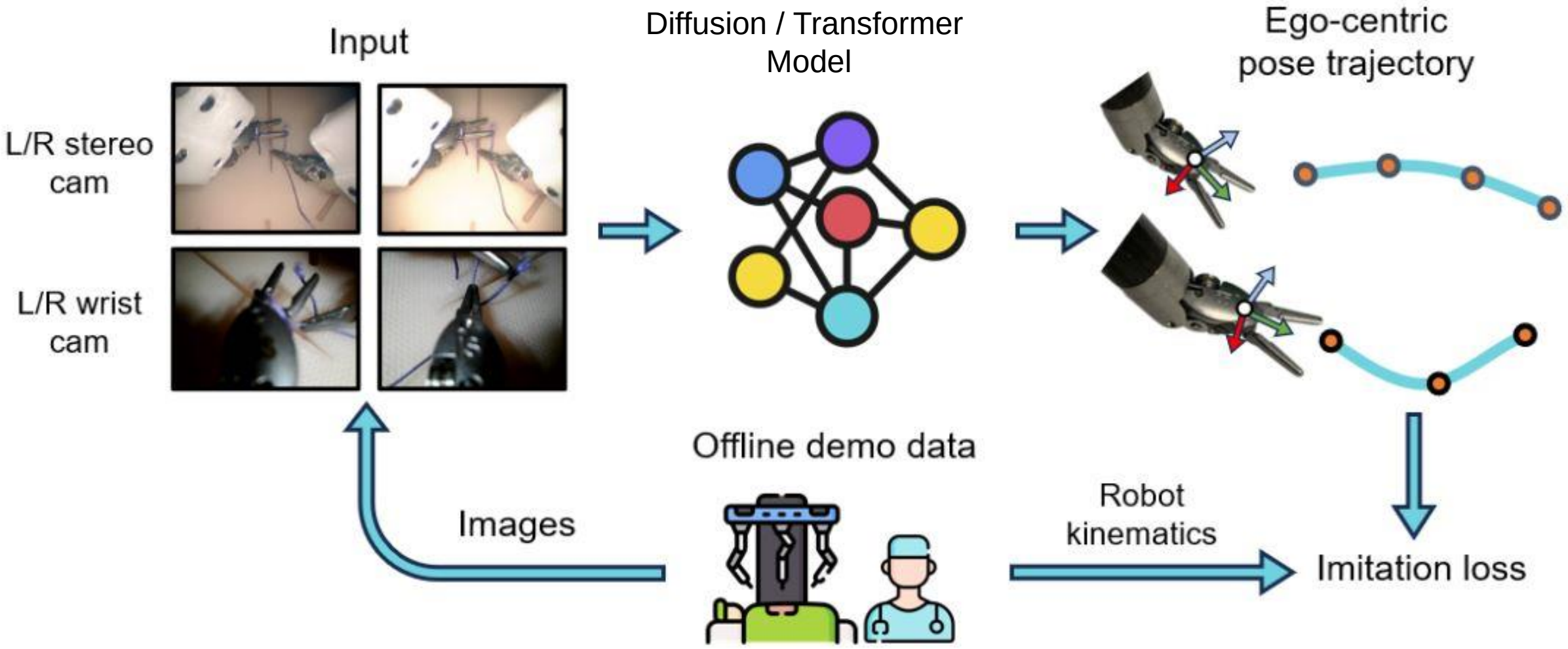
Motivating question: Can we learn difficult surgical manipulation skills using a data driven approach?

Da Vinci Research Kit (dVRK)



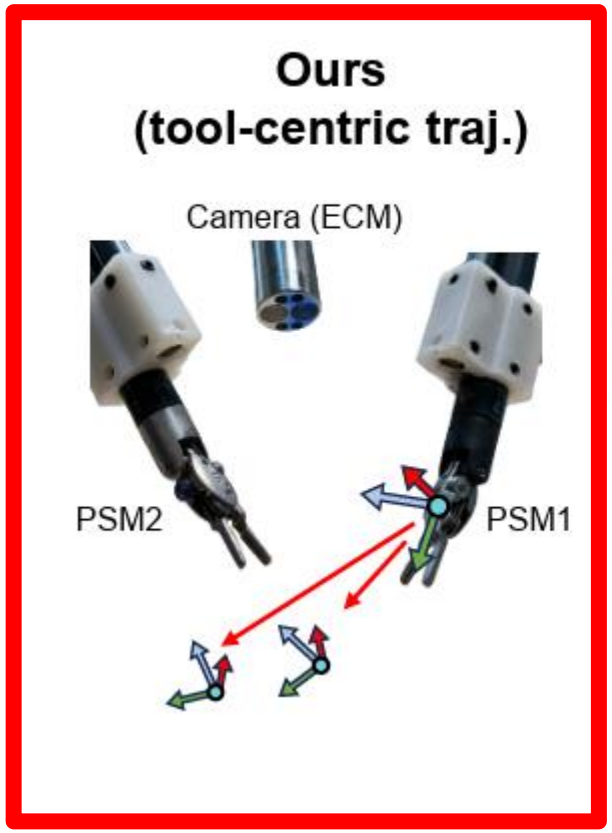


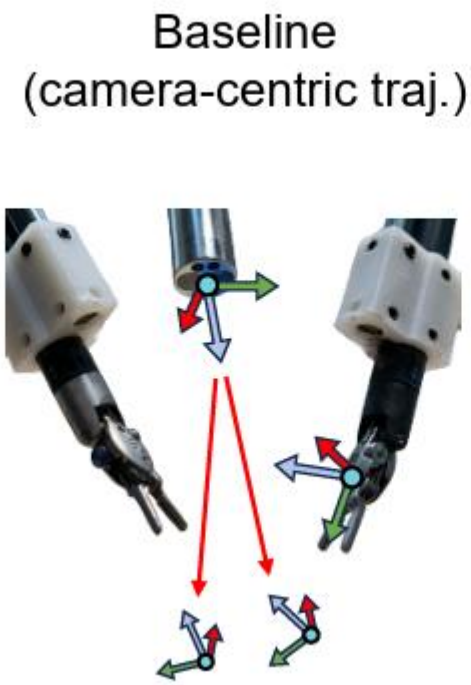
Approach

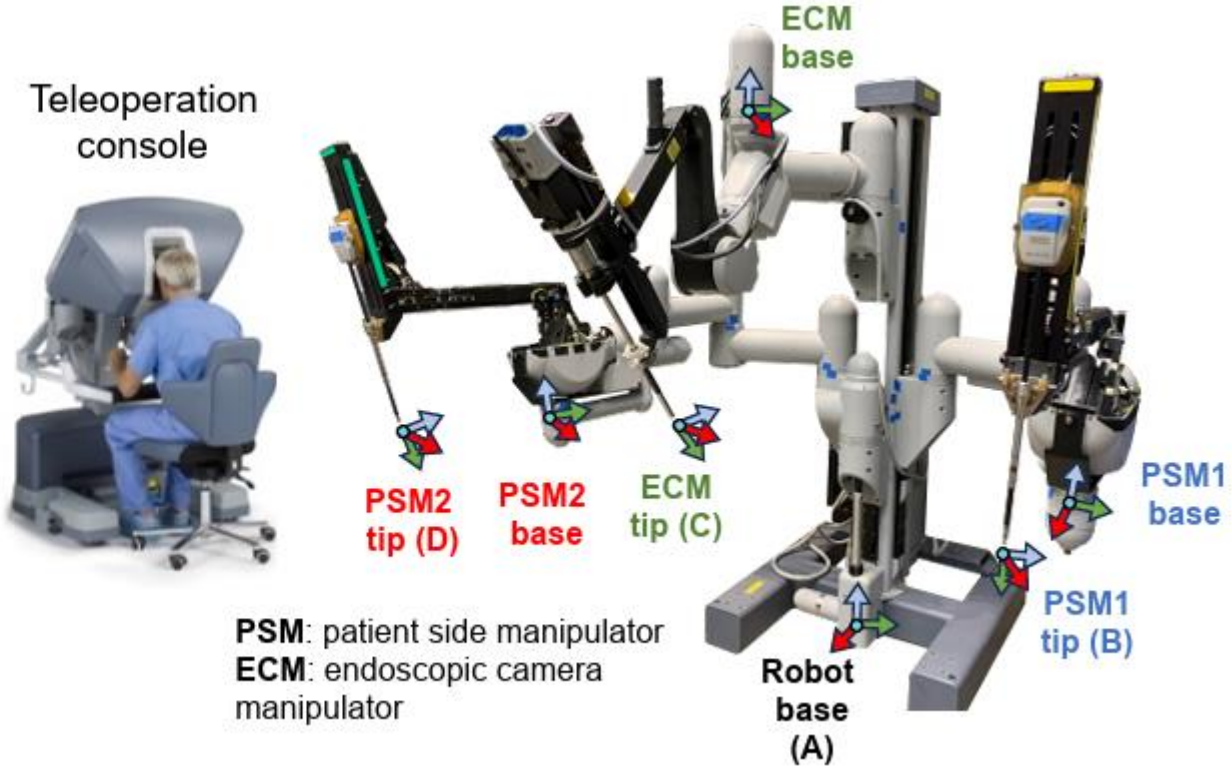


Choosing the Right Action Representation Matters

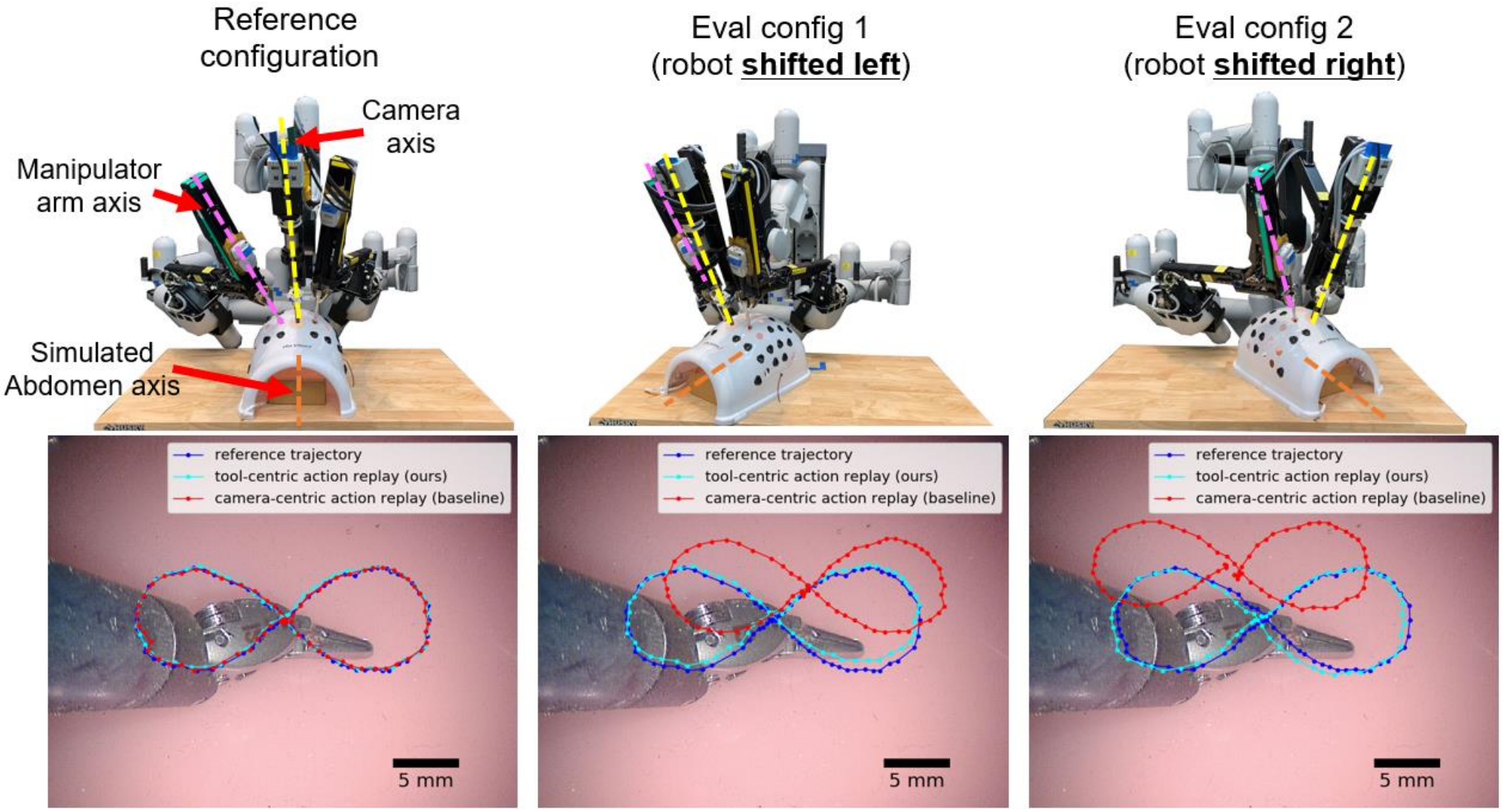
Key idea: use tool-centric actions, which is robust to joint measurement errors





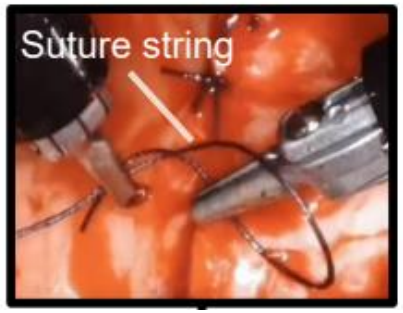


Relative motion is more consistent



Results

Knot tying

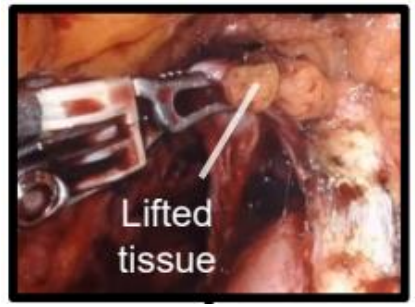


18 / 20 success
(500 demos)

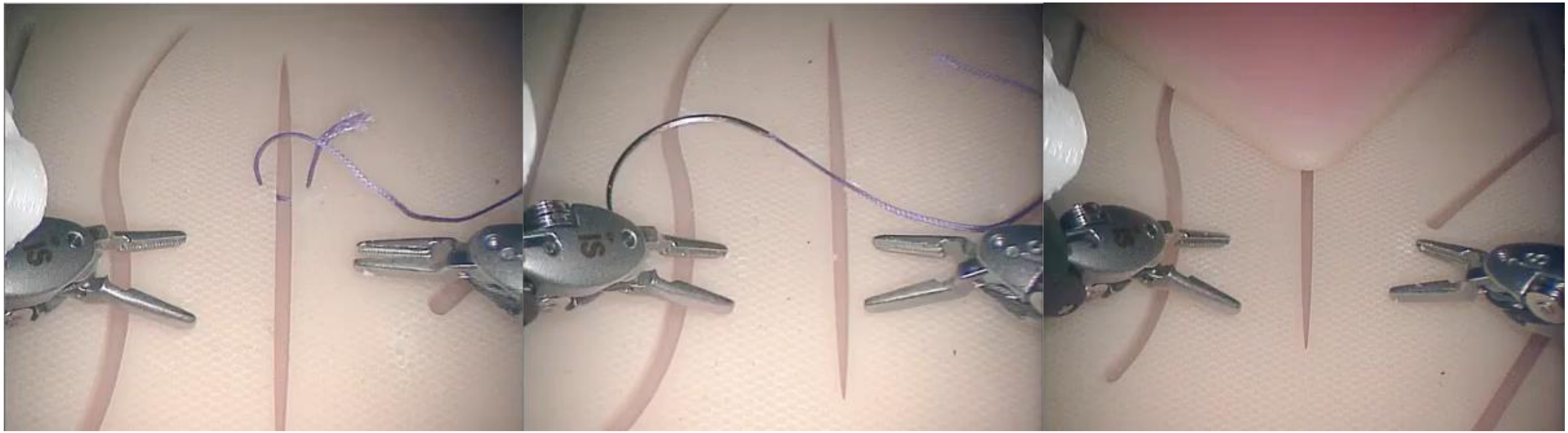
Needle pickup
+ handover

9 / 9 success
(250 demos)

Lift tissue



10 / 10 success
(200 demos)



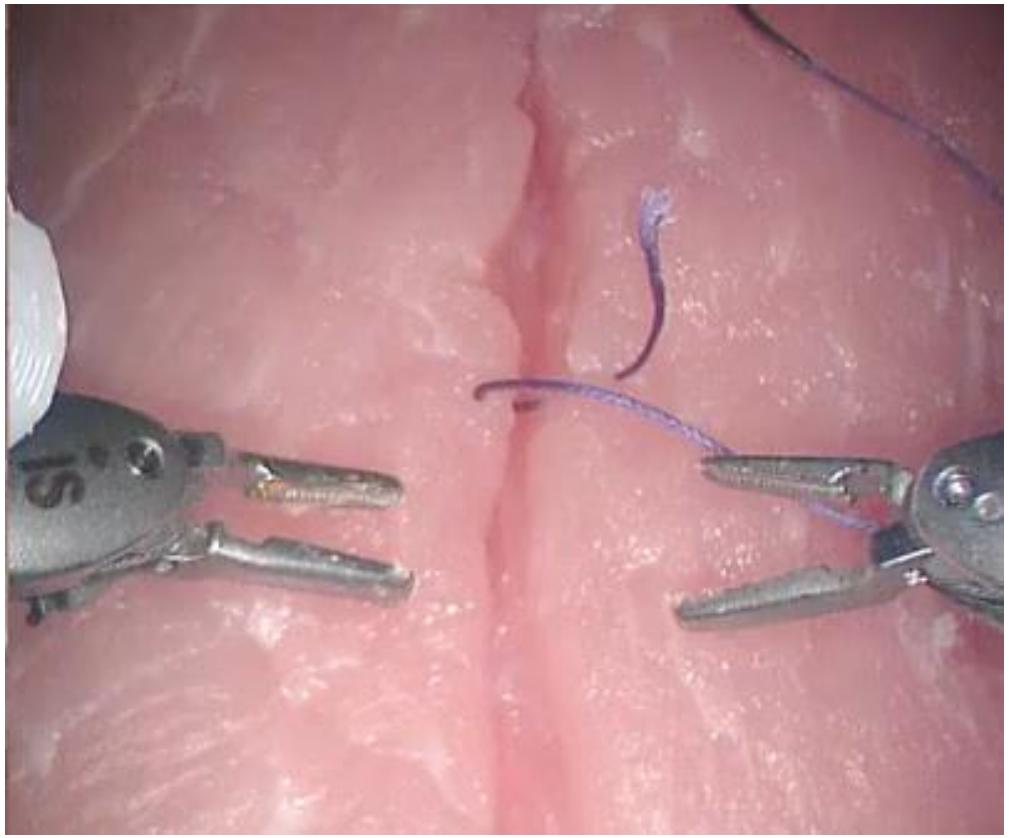
(12x speed)

Robustness test on animal tissues

Note: our model was never trained on animal tissues

Chicken leg

Pork loin



(6x speed)

Conclusion

- Task specific (often model based) autonomous robotic surgery has been demonstrated and could be translated to first in human testing.
- Large potential in learning based robotic solutions for solving procedure level and general surgical tasks.
- Learning based solutions require a large community effort including academic, industry, and funding agencies.

The IMERSE Lab - https://imerse.lcsr.jhu.edu/

IMERSE

Anuruddha Bhattacharjee, PhD

Postdoctoral Fellow

Medical Robotics, Magnetic Manipulation

Michael Kam, MS

PhD Candidate

Medical Robotics

Jiawei Ge, MS

PhD Candidate

Surgical Robotics

Seda Aslan, MS

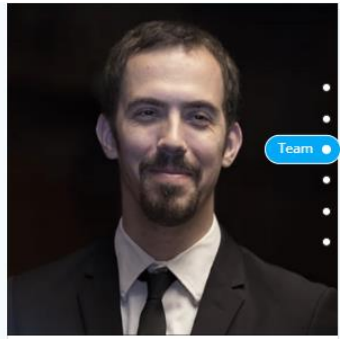
PhD Candidate

Computational Fluid Dynamics

Lydia Zoghbi, MS

PhD Candidate

Surgical Robotics Machine Learning



Justin Opfermann, MS

PhD Candidate

Robotics

Ji Woong Kim, PhD

Postdoctoral Fellow

Robot Learning, Manipulation

Idris Sunmola, BS

CS PhD Student

AI in Surgical Robotics

Noah Barnes, BS

PhD Student

Surgical Robotics

Jesse Haworth, BS

PhD Student

Surgical Robotics

Mariana Smith, BEng

PhD Student

Surgical Robotics

Samuel Schmidgall, BS

PhD Candidate

Machine Learning Surgical Robotics

Xinhao Chen, BEng

Team

MS Student

Magnetic Actuation System

Deepak Raina, PhD

Postdoctoral Fellow

Medical Robotics and Imaging, Deep Learning

Acknowledgements

- IMERSE Lab
  - Justin Opfermann, MS
  - Michael Kam, MS
  - Jiawei Ge, MS
  - Lidia Al-Zogbi, MS
  - Seda Aslan, MS
  - Noah Barnes, BS
  - Idris Sunmola, BS
  - Anuruddha Bhattacharjee , PhD
  - Samuel Schmidgall, BS
  - Ji Woong (Brian) Kim, PhD
  - Deepak Reina, PhD
  - Hamed Saeidi, PhD
  - Xiaolong Liu, PhD
  - Onder Erin, PhD
  - Byeol Kim, MS
- Collaborators
  - Simon Leonard, PhD
  - Jin Kang, PhD
  - Michael Hsieh, MD
  - Chelsea Finn, PhD
  - Alan Kuntz, PhD
  - Mathias Unberath, PhD
  - Kevin Cleary, PhD
  - Richard Cha, PhD
  - Hanh Le, PhD
  - Junichi Tokuda, PhD
  - Russ Taylor, PhD
  - Peter Kazanzides, PhD
  - Iulian Iordachita, PhD
  - Desiree Pantalone, MD
  - Yancy Diaz-Mercado, PhD
  - Irving Weinberg, MD
  - Lamar Lair, PhD
  - Suraj Raval
  - Tony Zhao
  - Ryan Sochol, PhD
  - Mark Fuge, PhD
  - Dheeraj Gandhi, MD
  - Thorsten Fleiter, MD
  - Laura Olivieri, MD
  - Yue-Hin Loke, MD
  - Narutoshi Hibino, MD
  - Martin J. Schnermann, PhD
  - Charles Berul, MD
  - Pranava Sinha, MD
  - Peter Kim, MD
  - Azad Shademan, PhD
  - Ankur Kapoor, PhD
  - Vivek Singh, PhD
  - Weinberg Medical Physics
  - Design Research Group

Funding

- NSF/FRR 2144348 CAREER: Advancing autonomy for soft tissue robotic surgery and interventions
- NIH/NIBIB R01 EB020610/R56EB033807 Next Generation of Surgical Imaging and Robotics for Supervised-Autonomous Soft Tissue Surgery
- NIH/NIBIB R21EB024707 Development and Pre-Clinical Evaluation of a Robotic System for Supervised Autonomous Tumor Surgery
- Intuitive Surgical Technology Research Grant
- ARPA-H 75N91023C00048 Advanced imaging aided autonomous robotic cholecystectomy
- ARPA-H AY1AX000023 Supervised Autonomous Robotic Renal Tumor Surgery

LABORATORY FOR Computational Sensing + Robotics
THE JOHNS HOPKINS UNIVERSITY

JOHNS HOPKINS
MALONE CENTER for ENGINEERING in HEALTHCARE

Thank You and Questions?

axel@jhu.edu