Sim-to-Real for Autonomous Tumor Resection via Minimally-Invasive Robotics

Problem

- ❖ **Autonomous surgical robotics** have the potential for:
  - ➢ Unprecedented **precision and dexterity**
  - ➢ Improved **safety**, thus reducing operative risk
  - ➢ Expanded **access** to high-quality care [1].
- ❖ However, most systems deployed in clinical settings remain fully teleoperated because of **challenges** like **anatomical variability**, tissue deformation, and constrained visual fields [2].

Proposed Solution

- ❖ The present research proposes **autonomous robots** to **remove tumors** from anatomy via the **Sim-to-Real paradigm**
  - ➢ The robot will **learn** the procedure in **simulation**
  - ➢ Simulated anatomy will be obtained from **medical scans**
  - ➢ The robot will train via a **hybrid learning approach**
- ❖ The research offers **adaptability** to tissue deformation, **preoperative validation** of surgical success, and greater **precision** via autonomous robots.

Methods

Step 1 - Recreate Patient Anatomy in Simulation

To recreate patient anatomy in simulation, **medical scans** are segmented via existing machine learning systems to produce 3D models of the healthy and tumor matter. These models are simulated with **soft-body physics**, such that they deform like human tissue.
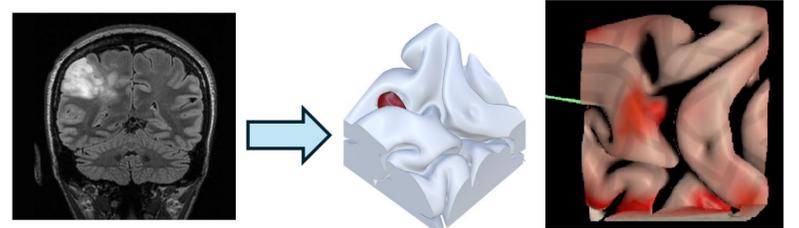

Figure 1: Scan to Simulation. Diagram created by Finalist using PowerPoint, 2025. *Note.* MRI image adapted from [5].

Figure 2: PSM Kinematics. Diagram created by Finalist using PowerPoint, 2025.

Step 2 - Recreate the Surgical Robot in Simulation

A virtual replica of the Patient Side Manipulator (PSM) of the **da Vinci robot** is configured within simulation [3]. The PSM enters the patient through an incision and pivots about it. The simulated robot has an attached instrument that allows **grasping and cutting**.
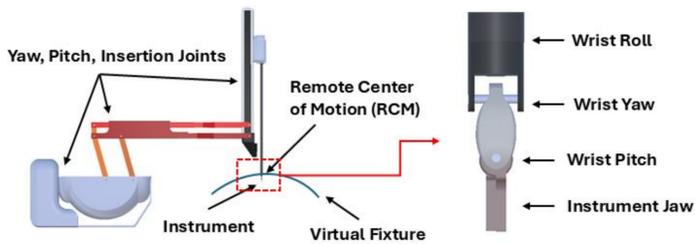
Step 3 - Train a Policy to Control the Surgical Robot

A policy to control the robot autonomously is **trained** via **multistage approach**. First **behavior cloning** is used to mimic an initial trajectory, in this case: a spiral cut to remove the tumor. Then, the policy is fine-tuned with **reinforcement learning** to account for tissue deformation. The policy continuously observes its environment and predicts the next best action that maximizes its reward metrics, including include tool tangency, tool adjacency, tool force applied, and tumor surface area coverage.
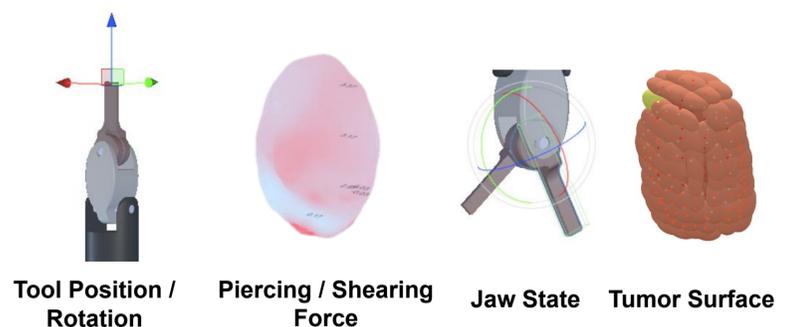

Tool Position / Rotation   **Piercing / Shearing Force**   **Jaw State**   **Tumor Surface**

Figure 3: Policy Observations Space. Diagram created by Finalist using PowerPoint, 2026.

Results

The system was tested on the **da Vinci Research Kit (dVRK)** operating on **gel phantoms** mimicking simulation anatomy [4]. Running the trained policy in simulation moves the virtual robot and updates the anatomical models. The movements are sent to the dVRK to be performed on the physical anatomy which ideally deforms in the same way.
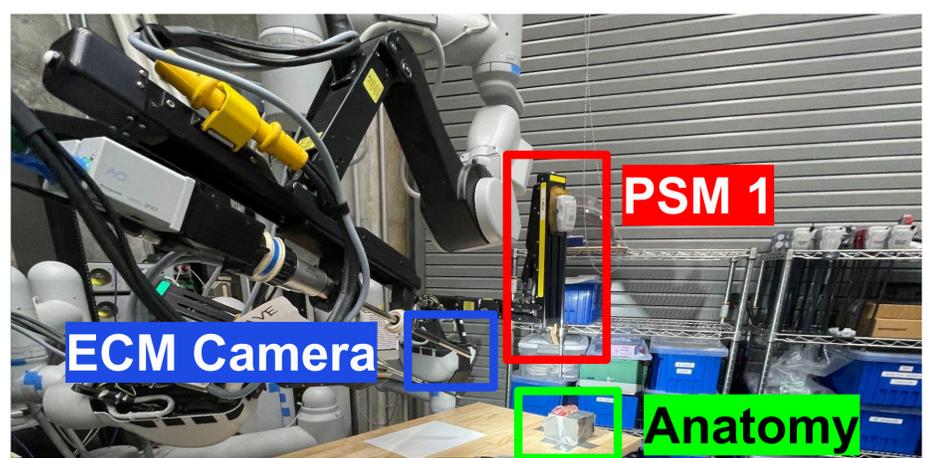

PSM 1
ECM Camera
Anatomy

Figure 4: Hardware Overview. Diagram created by Finalist using PowerPoint, 2025.

Entrance and Initial Cut   **Circumferential Cut**   **Exit and Removal**
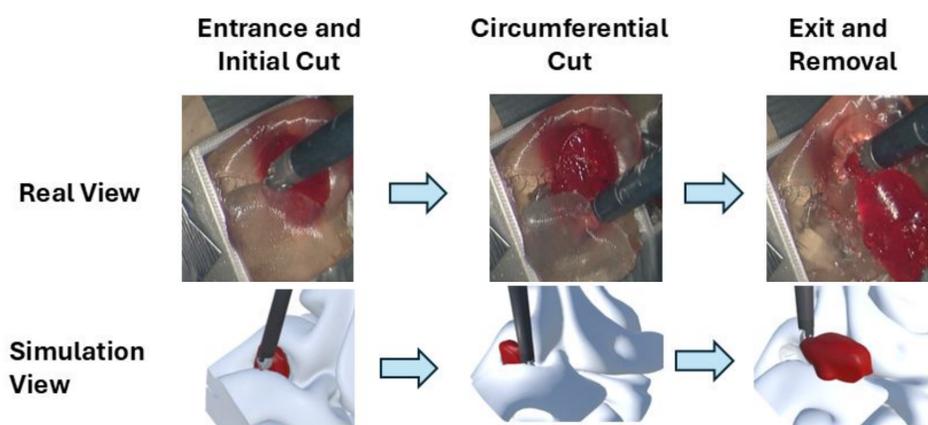
Real View

Simulation View

Figure 5: Sim-to-Real. Diagram made by Finalist using PowerPoint, 2025.

The experiment measures the **extent of resection** to quantify the success of the robot using a **Geometry-based Estimate**. Using the pre/post removal 3D scans of the phantoms, the volume removed is calculated, including the amount of tumor and healthy matter resected.

The present system is tested on **four gel phantoms**. Each phantom is **anatomically different** and generated from a real patient MRI. Geometric estimates yielded a **100% fully successful resection** for **3 out of 4 phantoms tested.**

Pre-Removal   **Ground Truth Volume**

Post-Removal   **Resulting Intersections**

Tumor Volume Removed

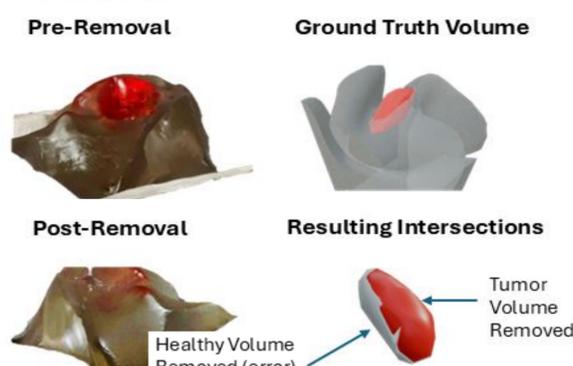Healthy Volume Removed (error)

Figure 6: Geometry-based Resection. Diagram made by Finalist using PowerPoint, 2025.

References

[1] J. Han, J. Davids, H. Ashrafian, A. Darzi, D. S. Elson, and M. Sodergren, "A systematic review of robotic surgery: From supervised paradigms to fully autonomous robotic approaches," *The International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 18, no. 2, p. e2358, 2022.

[2] G. P. Moustris, S. C. Hiridis, K. M. Deliparaschos, and K. M. Konstantinidis, "Evolution of autonomous and semi-autonomous robotic surgical systems: a review of the literature," *The International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 7, no. 4, pp. 375–392, 2011.

[3] L. Qian, A. Deguet, and P. Kazanzides, "dVRK-XR: Mixed Reality Extension for da Vinci Research Kit," in *The Hamlyn Symposium on Medical Robotics*, The Hamlyn Centre, Faculty of Engineering, Imperial College London, 2019.

[4] P. Kazanzides, Z. Chen, A. Deguet, G. S. Fischer, R. H. Taylor, and S. P. DiMaio, "An open-source research kit for the da Vinci® surgical system," in *IEEE Intl. Conf. on Robotics and Auto. (ICRA)*, (Hong Kong, China), pp. 6434–6439, Jun 2014.

[5] UCSF Health. (n.d.). Aggressive surgery increases survival with low-grade brain tumors. https://medconnection.ucsfhealth.org/news/aggressive-surgery-increases-survival-with-low-grade-brain-tumors

Papar, R.