Teleoperation Data Collection for Imitation Learning in Autonomous Robotic Tumor Resection

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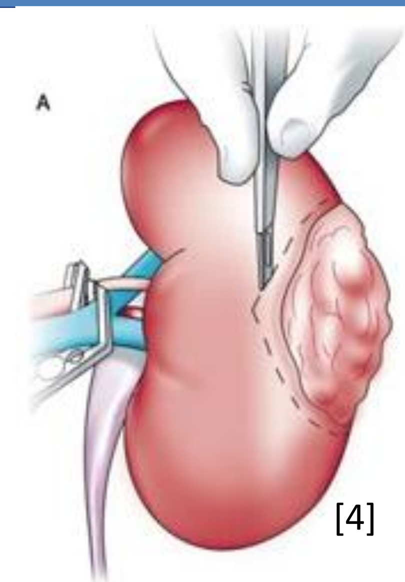
Introduction

Clinical Background

- More than 65,000 patients are diagnosed with kidney and renal pelvis cancers annually [2].
- Tumors in kidneys are often treated through partial nephrectomy - removal of a portion of the kidney - to completely excise unhealthy tissue.
- Traditional manual surgical approaches face inherent limitations in consistency and precision, leading to potential complications.
- Advanced automation in the operating room offers potential to reduce these complications.
- This work contributes to the development of an experimental autonomous surgical robot designed for tumor resection.



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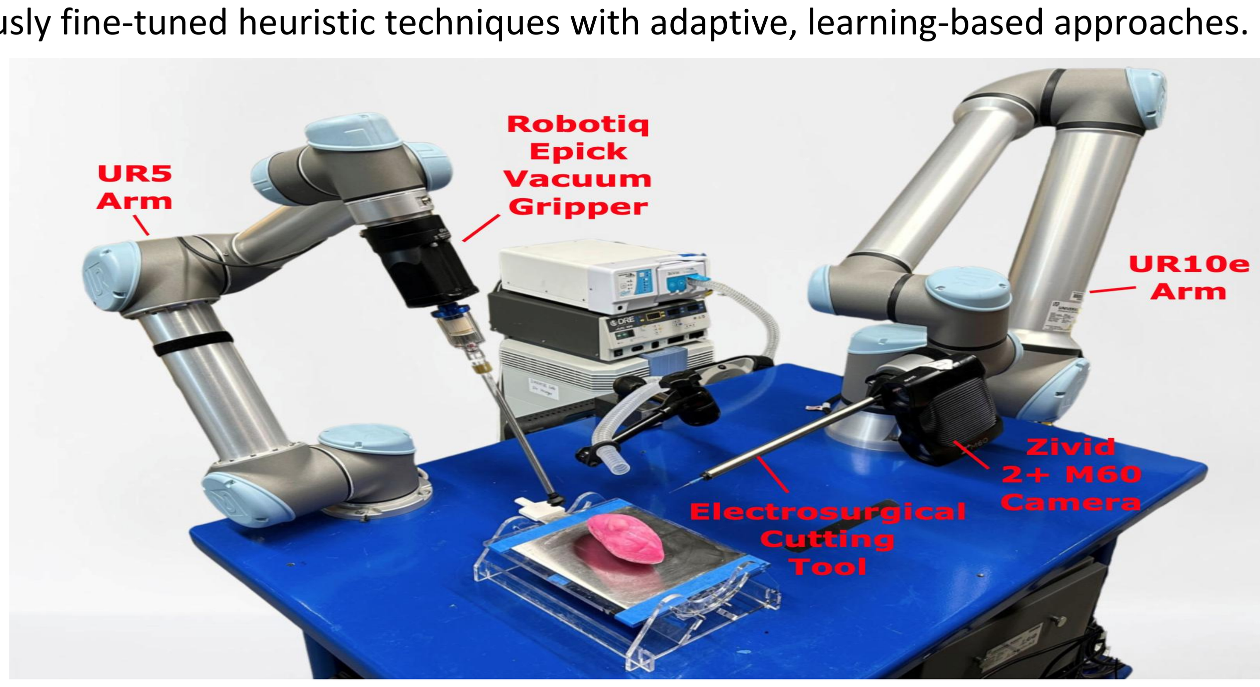
Proposed Robotic Solution

- The Autonomous System for Tumor Resection (ASTR) is a dual-arm robotic platform with UR5 and UR10e robots equipped with vacuum gripper, electrosurgical tools, and 3D vision for autonomous partial nephrectomy [3].
- Previous studies achieved successful imitation learning on da Vinci systems using frameworks like SRT and SRT-H, but ASTR's UR platform lacks an intuitive teleoperation interface, creating a barrier for collecting high-quality training datasets [1].
- **Project Goal: Integrate a Force Dimension haptic device for intuitive UR5 teleoperation, enabling researchers to generate high-quality datasets for imitation learning applications.**
- Ultimate Goal: Apply imitation learning to tissue retraction tasks in partial nephrectomy, replacing previously fine-tuned heuristic techniques with adaptive, learning-based approaches.



Imitation Learning Pipeline

- **Multi-modal data** collection through **Force Dimension haptic teleoperation** of a UR5 surgical robot.
- **Temporal sequence modeling** incorporates previous states to learn sequential dependencies and motion patterns in surgical tasks.
- Multi-modal fusion combines **2D RGB images**, **3D point clouds**, **robot pose**, and **vacuum pressure** through specialized encoders (CNN/ViT, PointNet++, MLP).
- Outputs **relative displacement**, **task completion flags**, and **suction flags** for vacuum grasping applications.
- **Real-time deployment** enables autonomous surgical robot control through trained policy inference with continuous feedback operation.

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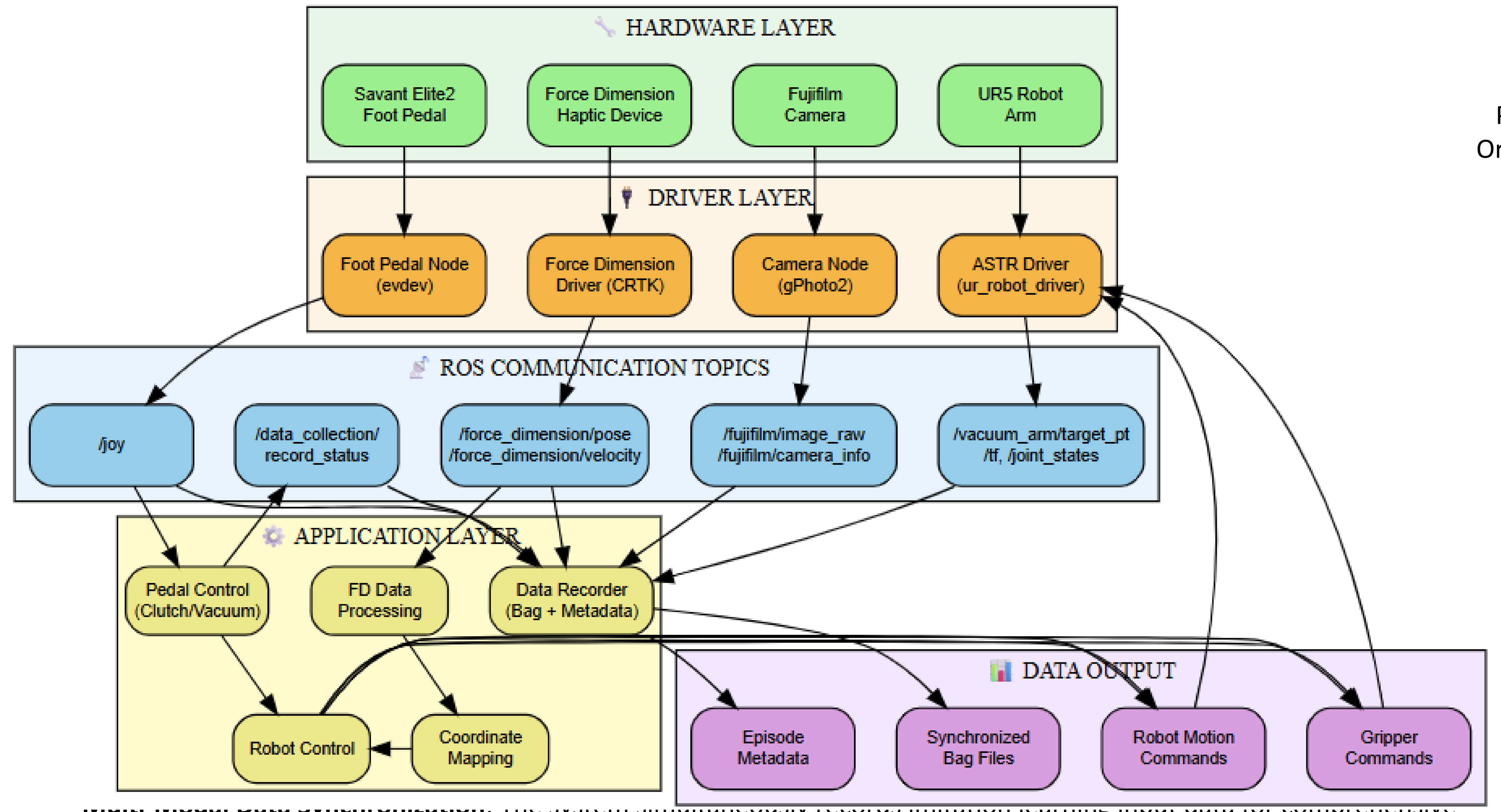
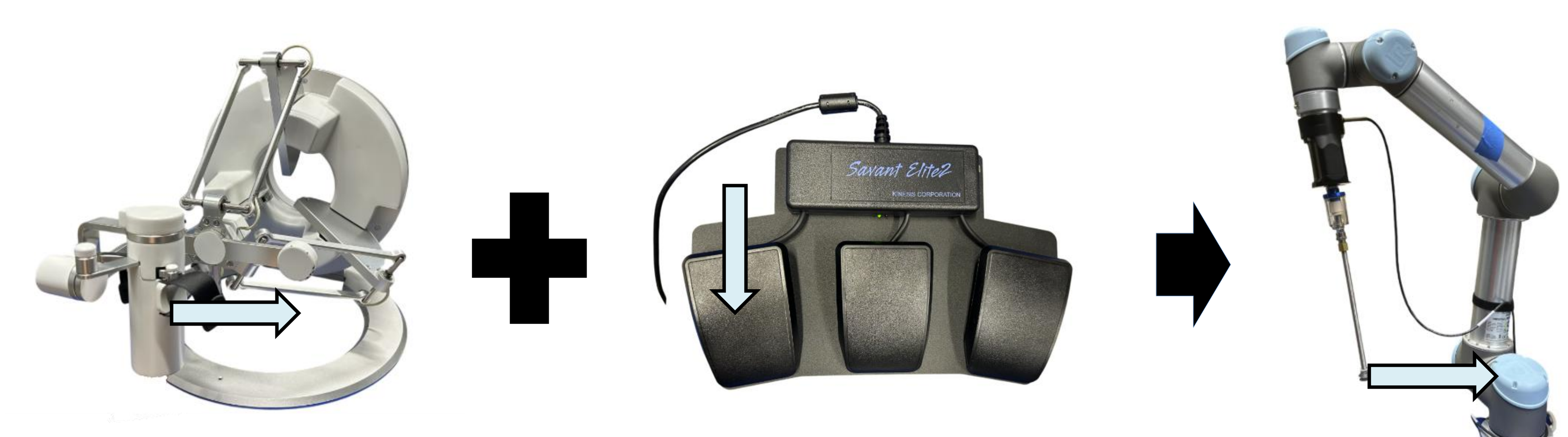
Data Collection Pipeline



- **Multi-Modal Data Synchronization**: The system simultaneously records imitation learning input data for comprehensive capture and easy use.
- **Intuitive Haptic Teleoperation**: Smooth control of the UR5 robot through the Force Dimension allows for natural and precise surgical manipulation demonstrations.
- **Episode-Based Recording Management**: Foot pedal controls enable hands-free start/stop of data recording sessions, allowing operators to focus on surgical tasks while capturing discrete demonstration episodes.
- **Real-Time Quality Assurance**: The system provides live feedback on data collection status, sensor synchronization, and recording quality to ensure high-fidelity datasets suitable for robust imitation learning model training.



Devices Used:
- The **Force Dimension** haptic device provides 6DOF teleoperation control with force feedback for intuitive human demonstration.
- A **UR5 robot** equipped with vacuum gripper serves as both the teleoperated platform and autonomous deployment system.
- The **Fujifilm camera** captures high-resolution 2D RGB images of the surgical workspace for vision-based learning.
- The **Savant Elite2 foot pedal** provides hands-free control for clutch engagement, vacuum activation, and data recording operations.
- A **ROS2-based recording system** ensures synchronized data collection across all sensor modalities for consistent training datasets.

Conclusion & Future Work

This project successfully established a teleoperation system that intuitively integrates a Force Dimension haptic device with a Universal Robot arm, enabling precise and responsive real-time manipulation. This work provides a strong foundation for advanced human-robot collaboration in tasks requiring fine motor control and remote operation.

Future work will focus on:
- **Enhanced Control Framework:** Implementation of PID controller architecture for smoother teleoperation control.
- **Data Collection for Imitation Learning:** Collect vacuum grasper data using the force dimension for training.
- **Imitation Learning Model Architecture Evaluation:** Determine the best features for vacuum grasping performance.
- **Dual-Arm Teleoperation Expansion:** Integration of a second Force Dimension device to enable control of both robotic arms for comprehensive surgical procedure data collection.

Results

Vacuum Retraction Performance

Kidney Phantom Orientations

Vacuum Grasper Initial Positions

- The experiment consisted of four orientations of the kidney phantom and three variations in the initial position of the vacuum grasper for a total of 12 trials.
- **Objective: Teleoperate the vacuum grasper to successfully latch onto and retract the tumor.**
- Purpose: Evaluate performance and usability of force dimension teleoperation for its intended use of tissue retraction in tumor resection tasks

Kidney Phantom Orientation	Vacuum Grasper Initial Position: 1	2	3	Success Rate (%)
1	✓	✓	✓	100
2	✓	✗	✓	66.7
3	✓	✓	✗	66.7
4	✓	✓	✓	100
Success Rate (%)	100	75	75	83.3

- Teleoperation performance decreased when kidney phantoms were oriented with tumors positioned farther from the vacuum grasper's initial starting position, indicating distance-dependent manipulation challenges.
- System limitations were observed in clutching mechanics and vacuum movement smoothness, resulting in less precise control during extended reach maneuvers.