UNCERTAINTY-AWARE ULTRASOUND-GUIDED ROBOTIC NEEDLE INSERTION

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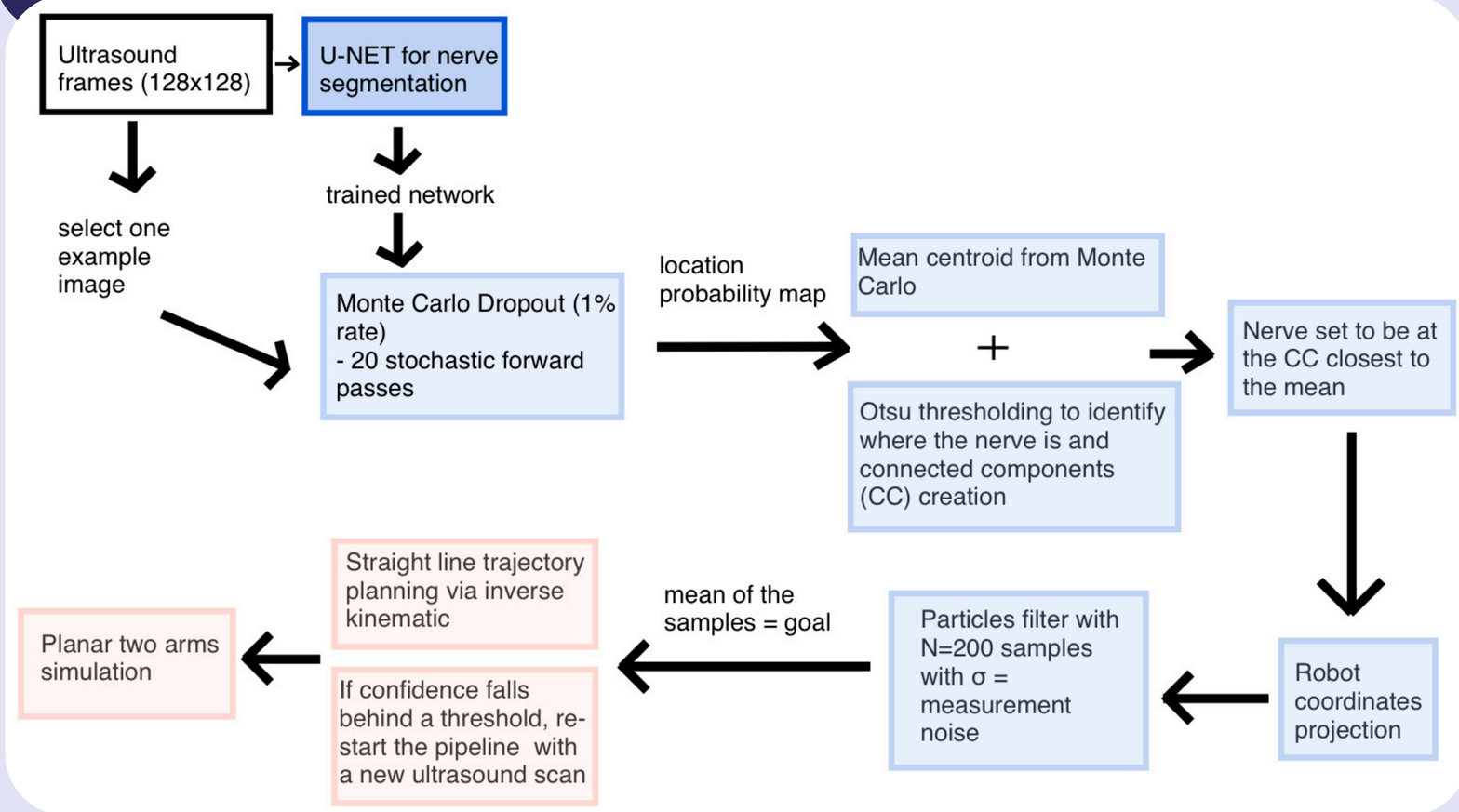
Objectives

Simulate a robotic arm for ultrasound-guided needle insertions that quantifies segmentation uncertainty, enabling the robot to pause and re-scan when confidence is low so it can plan a safer trajectory to reach the nerve, in software.

Introduction

- No existing software pipeline integrates segmentation uncertainty into the control loop for robotic needle insertion
- Current research focuses on hardware improvements
- Robotic needle insertions are increasingly being used in hospitals, yet they still make errors which harm patients
- Quantifying uncertainty would allow robots to 'know when they don't know,' and re-scan and re-plan trajectories when they are too unsure

Methods



Results

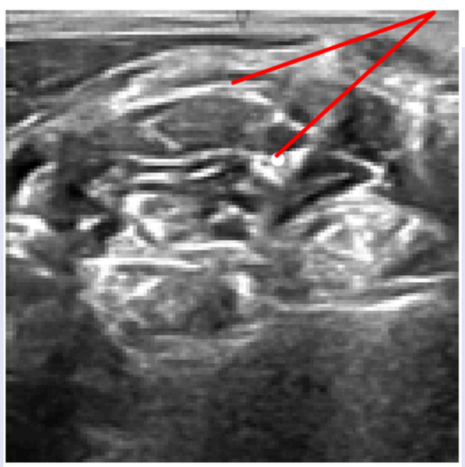
Perception/ Segmentation:

- Training: Dice=0.78, IoU=0.63
- Validation: Dice=0.65, IoU=0.49

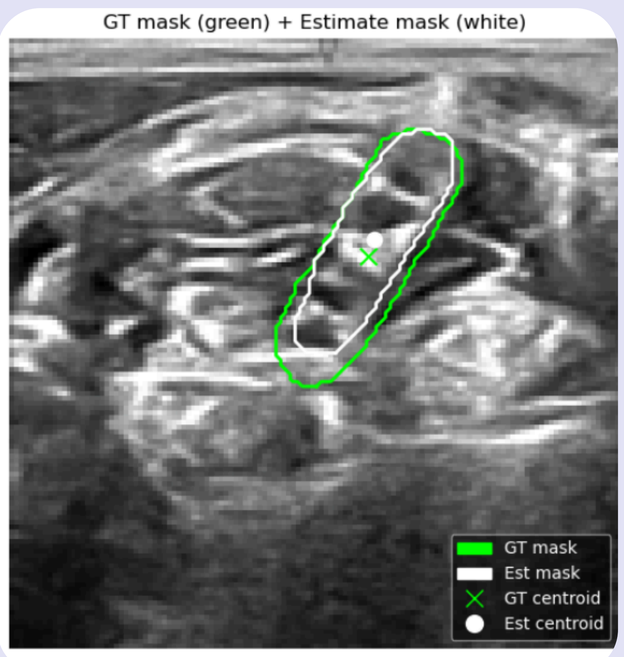
Uncertainty: ECE=0.012, on average the predicted confidence deviates from the true accuracy by only 1.2%

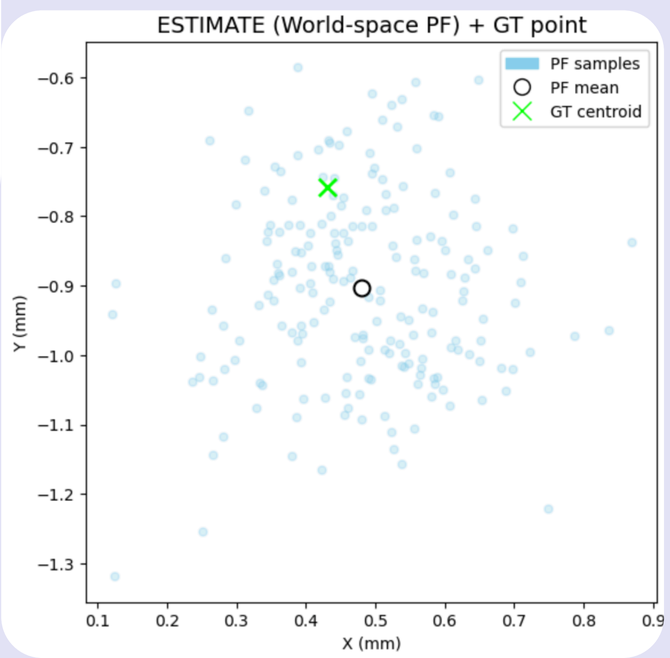
Robot World: The mean Particle Filter centroid leads to a pixel error of 3.7px (139.3 μm)

Pause and re-scan: Given the static dataset, it is hard to simulate. With a "fake" re-scan (same image transformed), we decrease the error to 3.5px



Robotic Arm simulation (when reaching nerve)





Discussion

- Modeling segmentation uncertainty improves simulated insertion safety by catching low-confidence regions before risky needle motions
- Connected-component + particle-filter yield a stable nerve location even when raw masks were noisy.
- The "pause and re-scan" policy further reduces worst-case error
- Key limitations: we only used a single static ultrasound slice per nerve, and our two-link arm is a highly simplified robot model
- Ethical considerations: our dataset's limited anatomical diversity may introduce bias

References and Related Work

- Kaggle Dataset - Ultrasound Nerve Segmentation https://www.kaggle.com/competitions/ultrasound-nerve-segmentation/data?select=test
- M.A.M. de Rooij. "Safe and Efficient Ultrasound-Guided Needle Placement Using Uncertainty-Aware Deep Learning", Master's thesis, Delft University of Technology, 2022