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 Ultrasound **U-NET** for nerve frames (128x128) segmentation trained network select one Mean centroid from Monte example location image Carlo probability map Monte Carlo Dropout (1% Nerve set to be at rate) the CC closest to - 20 stochastic forward the mean passes Otsu thresholding to identify where the nerve is and connected components (CC) creation Straight line trajectory planning via inverse mean of the Particles filter with kinematic samples = goal Planar two arms N=200 samples simulation Robot with $\sigma =$ If confidence falls coordinates measurement behind a threshold, reprojection noise start the pipeline with a new ultrasound scan

Results

Perception/ Segmentation:

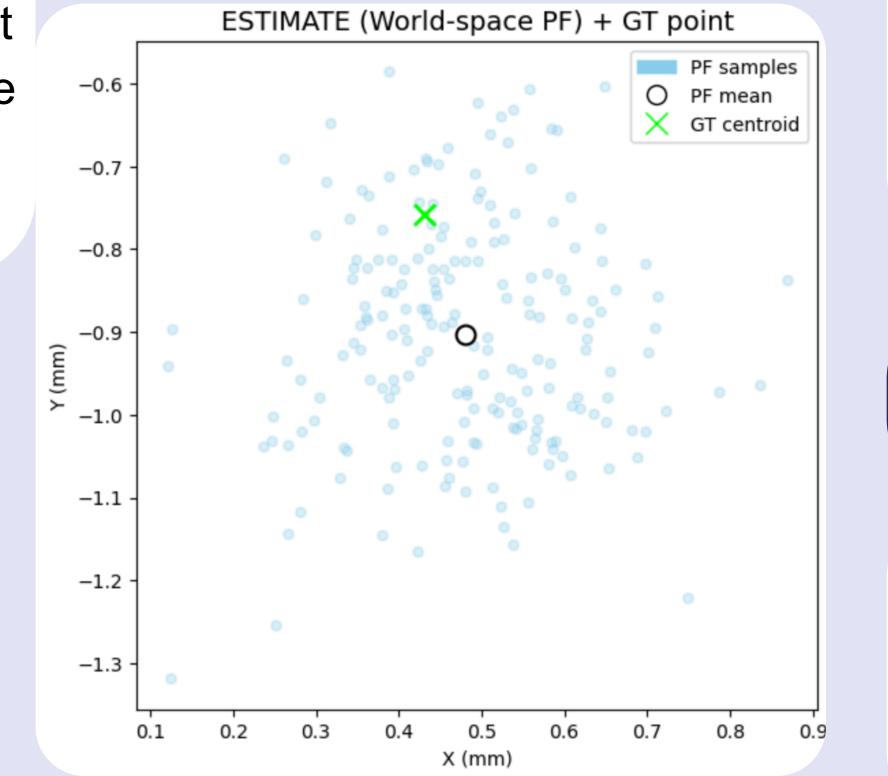
Training: Dice=0.78, IoU=0.63Validation: Dice=0.65, IoU=0.49

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

GT mask (green) + Estimate mask (white) GT mask Est mask GT centroid Est centroid



Discussion

- Modeling segmentation uncertainty improves simulated insertion safety by catching lowconfidence 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

Robotic Arm simulation (when reaching nerve)