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Introduction

Needle-based procedures are widely used in cancer diagnosis and treatment, such as biopsy and brachytherapy, where accurate needle placement is critical for targeting tumors while avoiding healthy tissue.

Fiber Bragg Grating (FBG) sensors enable internal strain sensing along the needle, providing the potential to reconstruct its shape during insertion. However, existing methods are limited to estimating the current shape and often fail to generalize from synthetic to real data.

In this work, we propose a synthetic-to-real learning framework to predict future needle shape from partial FBG measurements, enabling more accurate and clinically relevant guidance.

Objectives

- Predict the future 3D shape of a needle during insertion
- Develop a synthetic-to-real learning framework for better real-world performance

Methods

Approach Overview

This work combines physics-based modeling and data-driven learning to predict future needle shape from partial FBG measurements.

Sensing and Modeling

FBG sensors provide internal strain measurements, from which curvature is estimated. The 3D needle shape is reconstructed using a Lie group-based formulation.

Physics-Based Shape Reconstruction

The 3D needle shape is reconstructed by integrating curvature along the arc length using a Lie group-based formulation, providing a physically consistent representation of deformation.

Learning Framework

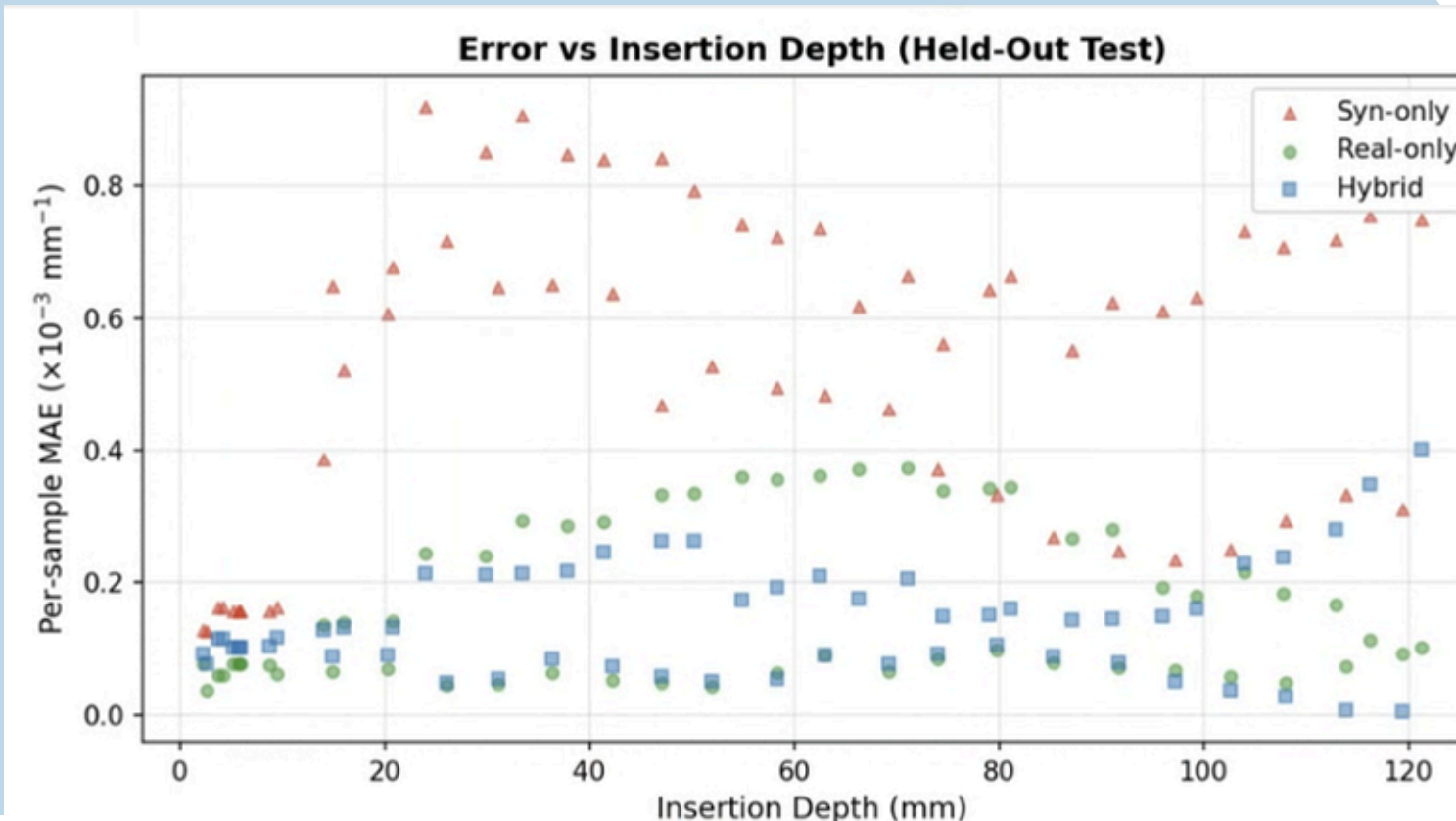
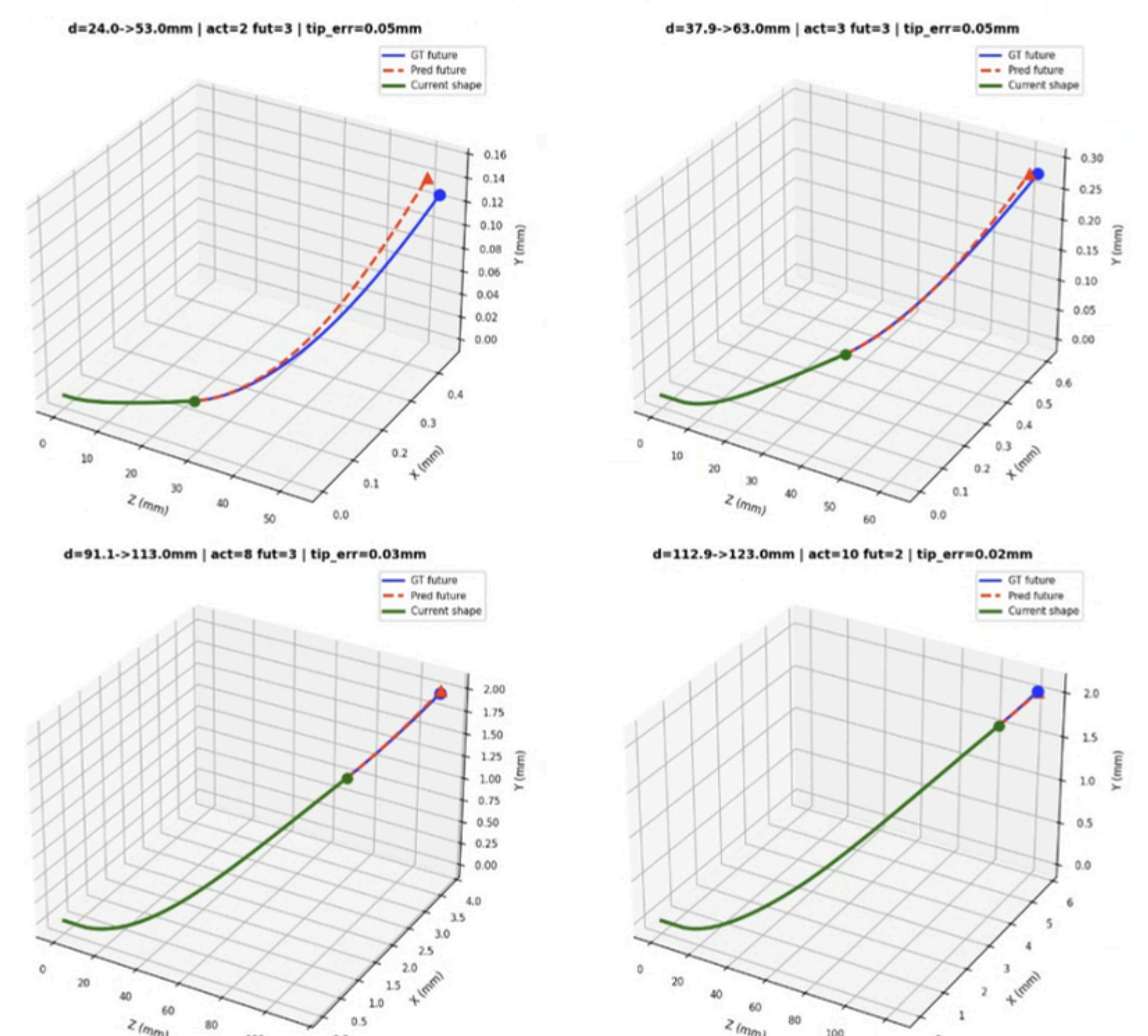
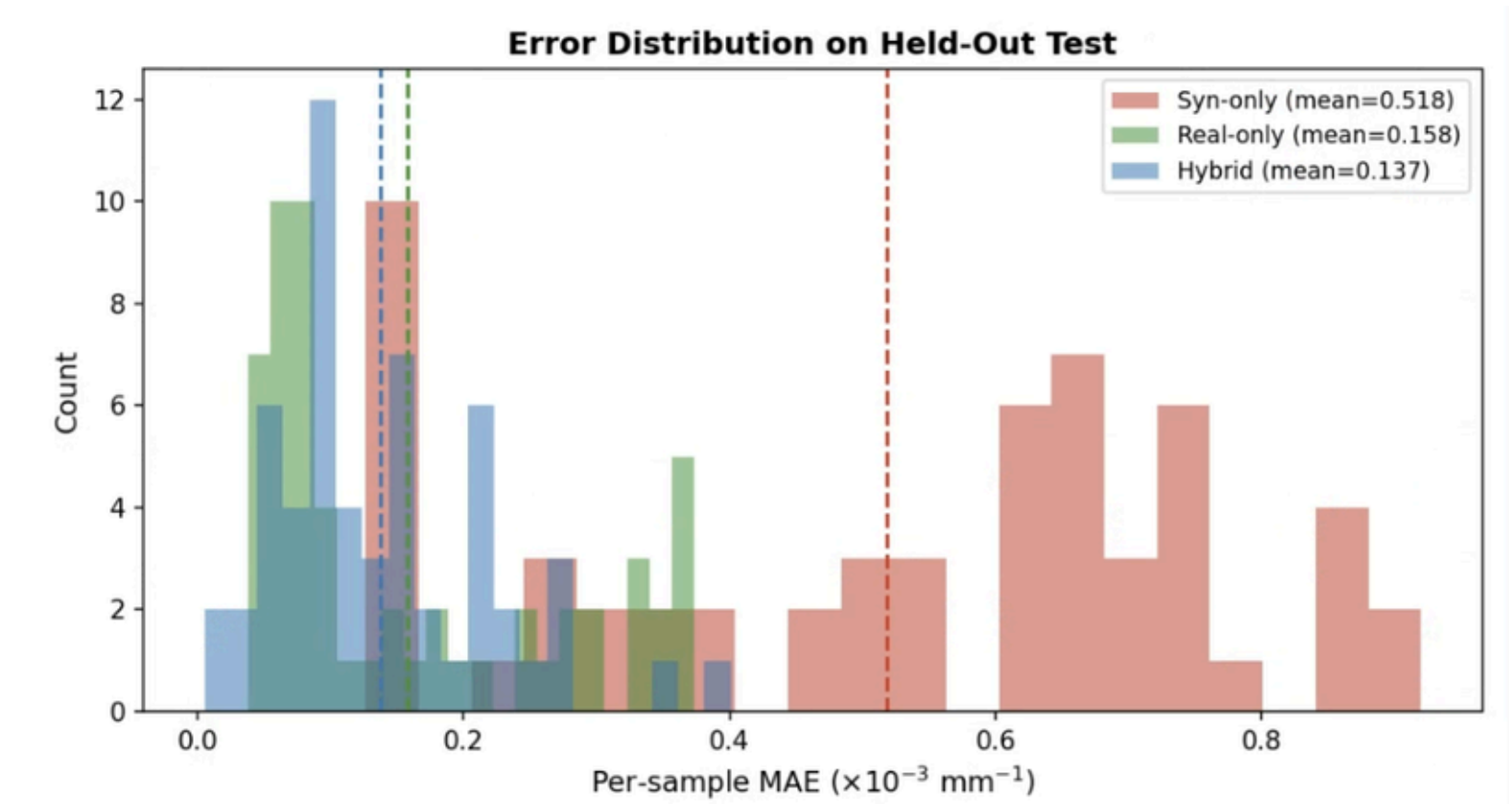
Synthetic data are generated using a physics-based model. A learning model is trained on synthetic data and adapted to real measurements to improve performance.

Prediction Task

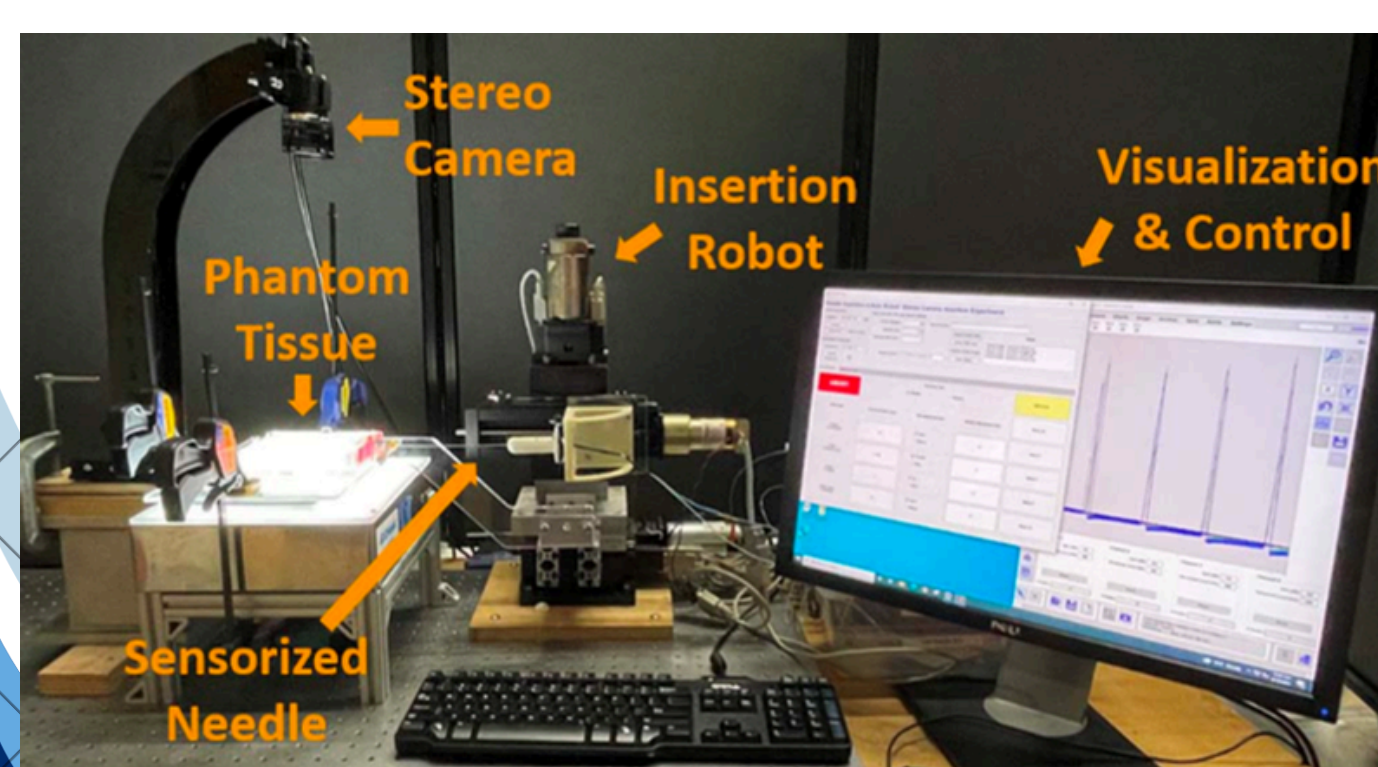
The model predicts needle shape at future insertion depths from partial observations.

Results

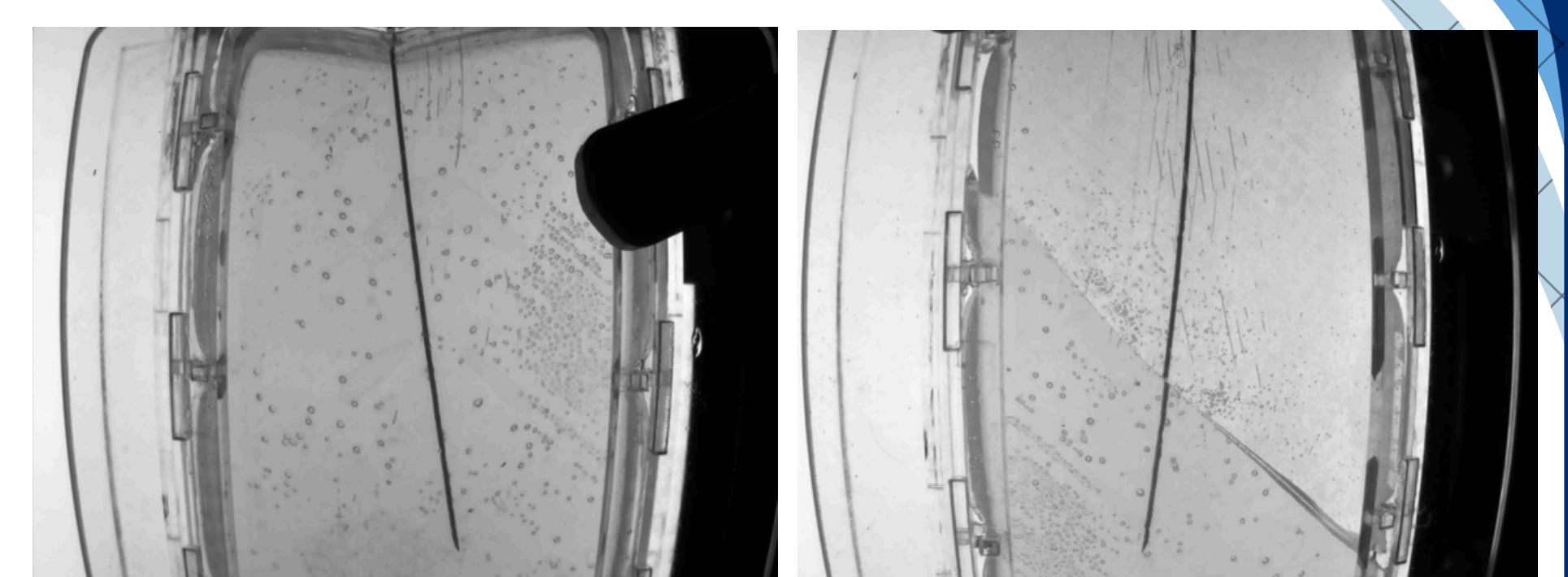
- A Lie-group-based generator is used to produce synthetic curvature data under controlled insertion conditions.
- The proposed hybrid framework (Lie-group-based generator + data-driven model) for single layer phantom achieves:
 - Hybrid reduces curvature error by **73.6%** vs. syn-only baseline
 - Hybrid reduces curvature error by **13.3%** vs. real-only model
- Hybrid learning improves accuracy while maintaining stable performance across insertion depths
- Predicted trajectories closely align with ground truth across different insertion scenarios



Experimental Setup



Experimental Setup

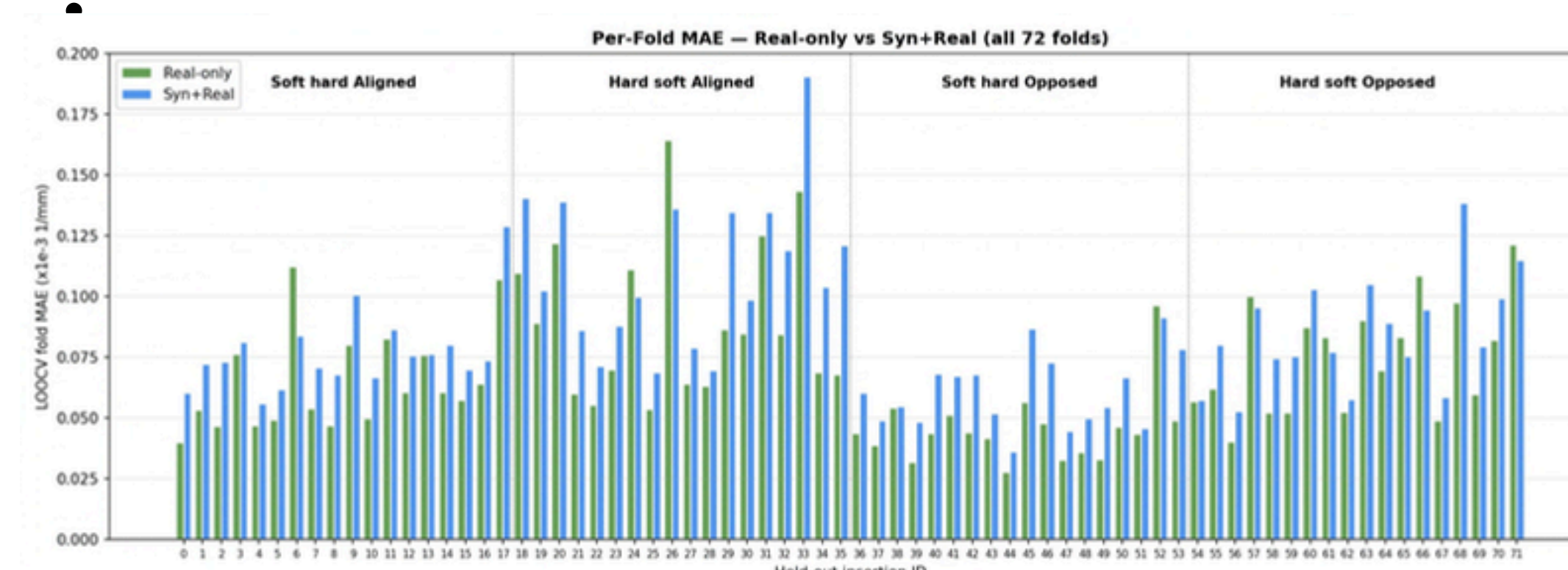


Insertion of Single Layer Phantom

Insertion of Double Layer Phantom

Future Plan

- Improve synthetic data fidelity for complex multi-layer insertion scenarios
- Investigate hybrid performance under different data regimes (e.g., sufficient real data vs. limited data)
- Explore advanced ML models (e.g., temporal models) to improve prediction accuracy
- Evaluate model generalization across different needles and datasets



Conclusion

- We develop a hybrid framework for predicting needle shape from FBG s
- The approach improves prediction accuracy under controlled conditions
- Results highlight the importance of data availability and scenario complexity in hybrid learning
- This work moves toward translating indirect sensing data into actionable, real-time guidance for needle-based cancer interventions