Three-dimensional Morphological Reconstruction of Millimeter-Scale Soft Continuum Robots based on Dual-Stereo-Vision

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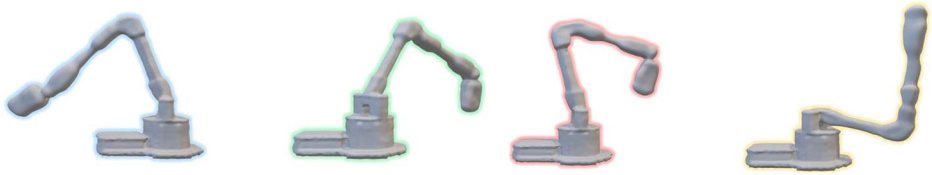
Background – Morphological Reconstruction for Robot's Self Modeling

Why

- **Self Modeling:** The ability for a robot to simulate its physical self
- Essential for **robot motion planning and control –** when the robot has complex morphology (outlook)

Current

- **General setup:** A multi-depth-camera system for morph data collection
- Only for **well-structured large rigid robots** (meter-scale)



Chen et al., **Sci. Robot.** (2022)

Target – Notched Tubular Continuum Robots (NTCR)

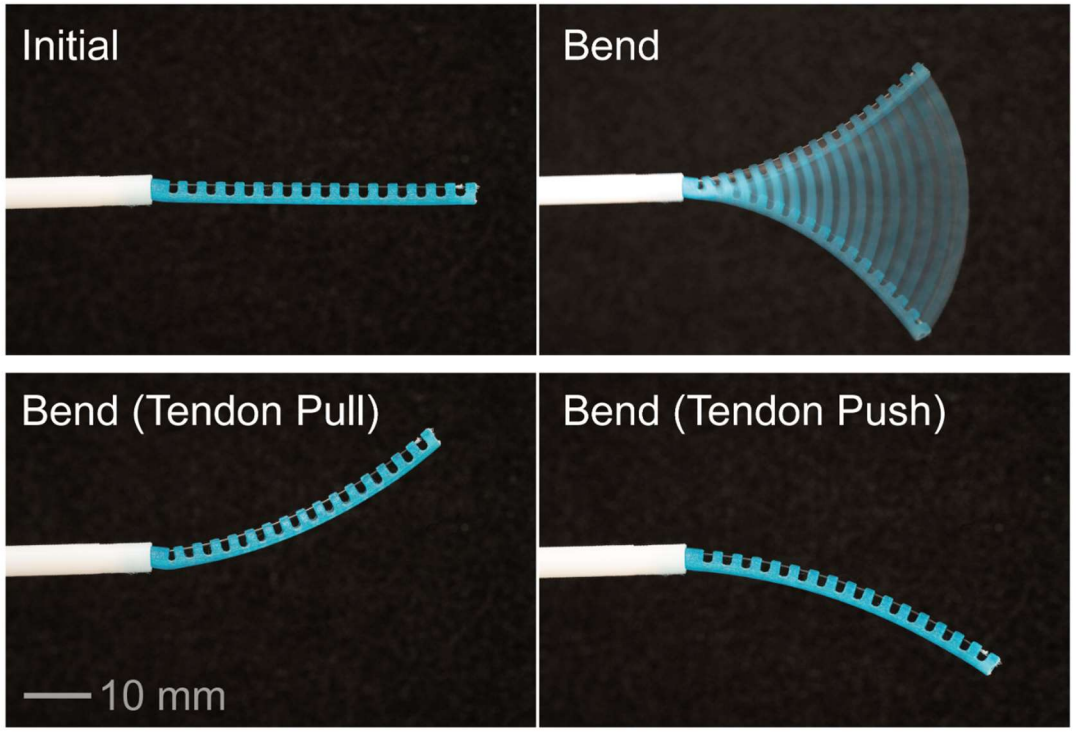
Problems

- Notch's geometric parameters significantly affect the deformation

→ Benefit from self-modeling

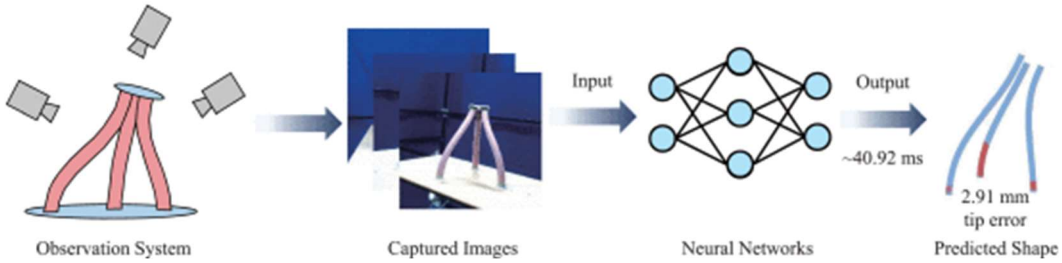
- Challenging to reconstruct small body & notches (length < 1 mm)

→ Need either better camera (hardware) or improved algorithm (software)

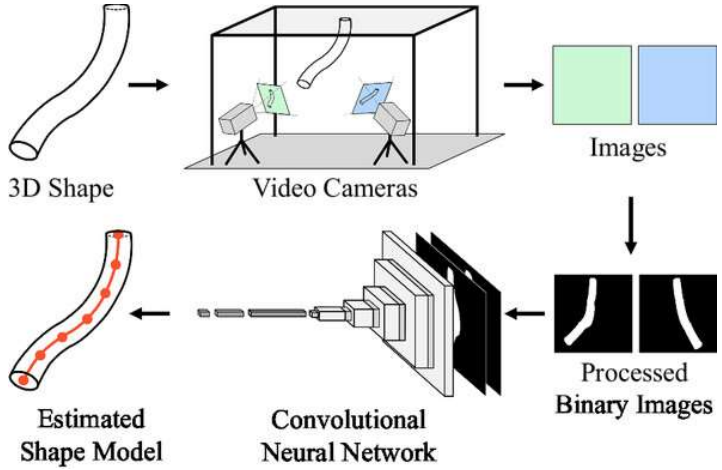


How to reconstruct the soft robot on a millimeter scale?

Existing Solutions



Rong & Gu, **IEEE RA-L** (2024)



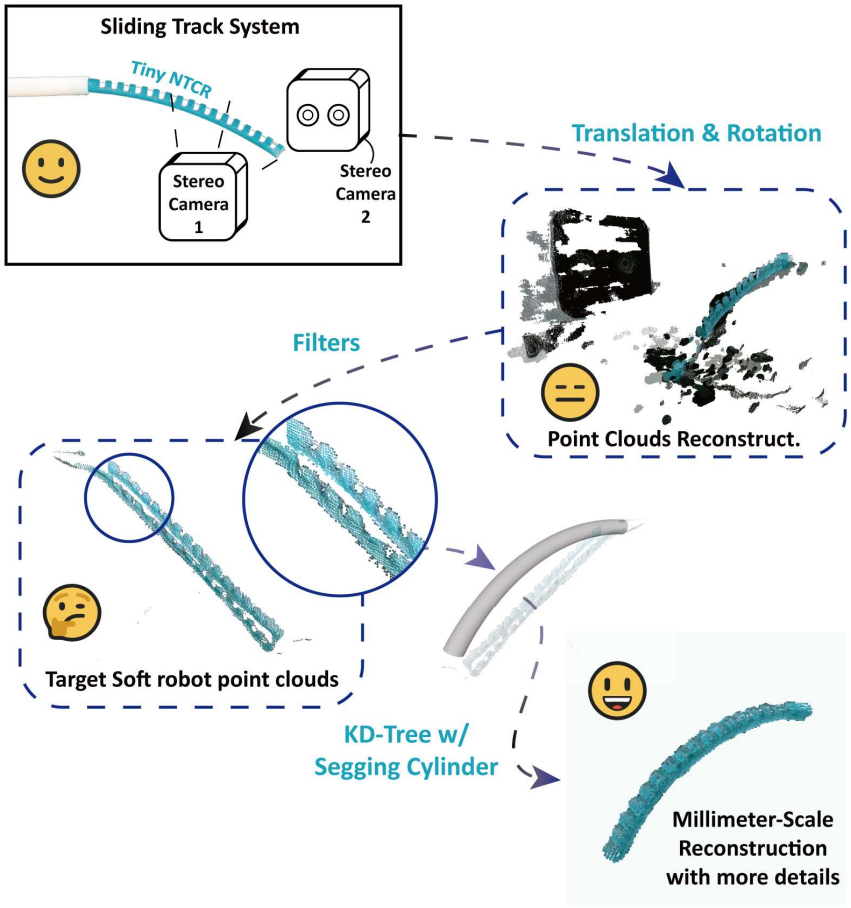
Zheng et al., **Adv Intell Syst** (2024)

- Tri-RGB-D camera system
- Large diameter: 18 mm for a single soft robot
- Simplified to parameterized B-spines
- CNN for training (Images)

- Dual-RGB camera system
- Large diameter: 40 mm for a single soft robot
- Simplified to parameterized Key Points
- CNN for training (Key points)

Shape Reconstruction for large soft robots with simple geometry (cylindrical shape)

Ours



T.-A. Ren et al, **ROBIO** (2024)

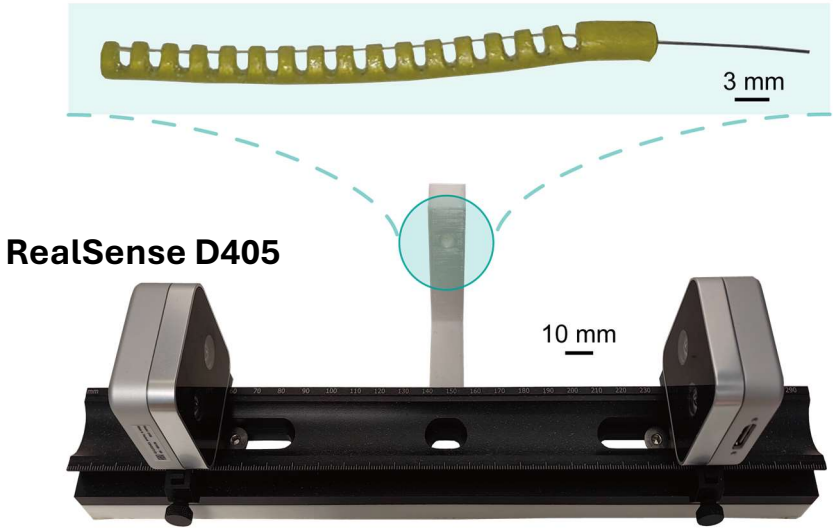
What's new

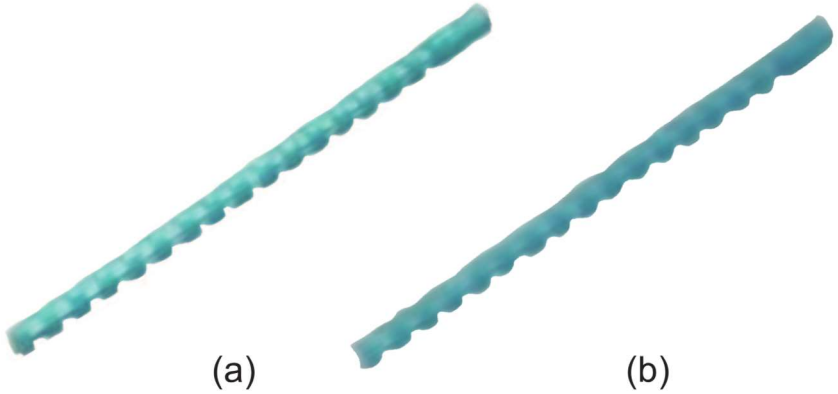
- Dual stereo vision-based 3D morphological reconstruction method for millimeter-scale soft continuum robots
- KD-tree-based point cloud optimization for improved morphological reconstruction

Performance

Reconstruct the notched robot's shape with clear details**, identifying 1.5 mm-width notches**

Setup

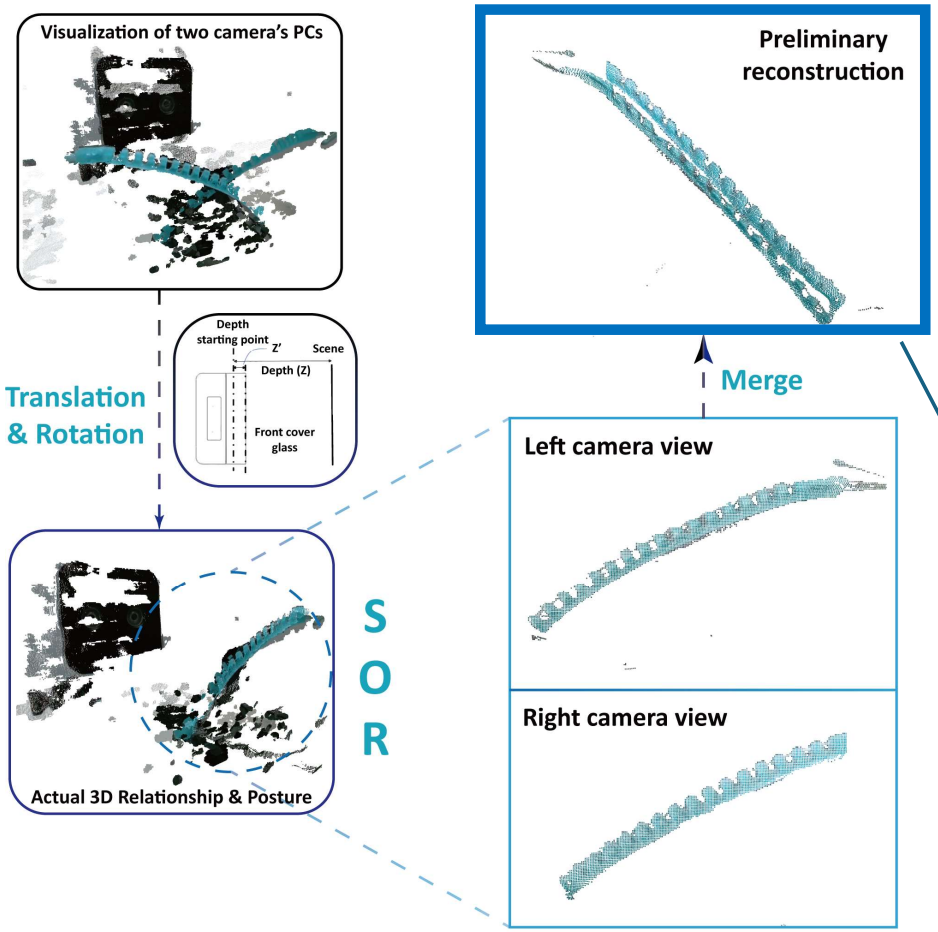




- **Point cloud acquisition platform:** Dual stereo cameras in the opposite direction
- **Camera-Object distance:** 90 mm
- **Target Robot:** 3.5 mm diameter, 50 mm length

Comparison: 3D Point Clouds captured by Intel RealSense **(a) D405** and **(b) D435i**.

Preliminary 3D Reconstruction



Statistical Outlier Removal (SOR) is used to identify and exclude points that significantly deviate from their neighbors

$$\delta_{Threshold} = \mu + \alpha\sigma$$

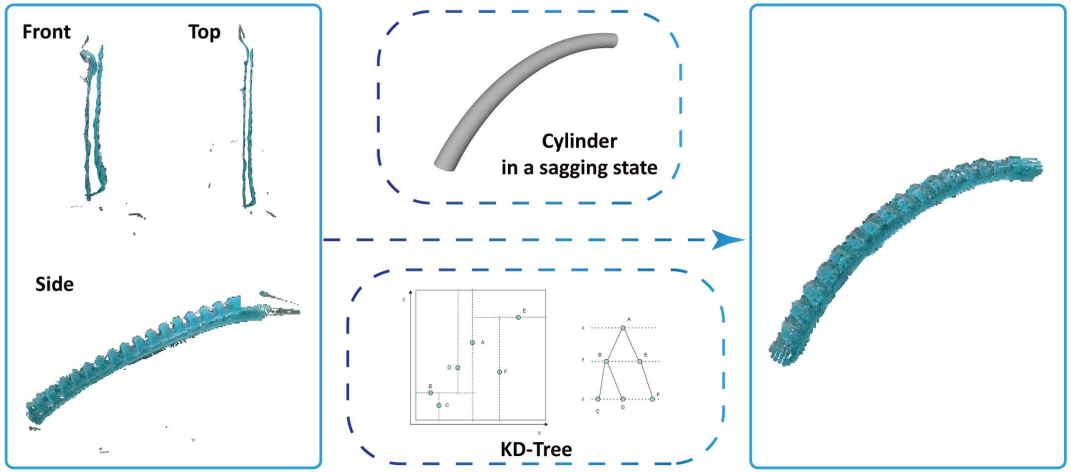
μ: the mean distance (easily tuned within the setup)

σ: the standard deviation of distances

- Showing the robot in detail, including its curvature and notches
- Fail to represent the **cylindrical appearance** of the tiny robot

Needs further optimization

Optimization with K-Dimensional Tree



Optimization workflow

1. For raw 3D point cloud (PC):
    1. Extract geometric backbone
    2. Generate a corresponding cylinder with a pre-defined diameter
2. Align the PC to the cylinder surface with the **KD tree** and **iterative closest point (ICP)** algorithms

Optimization with KD-Tree

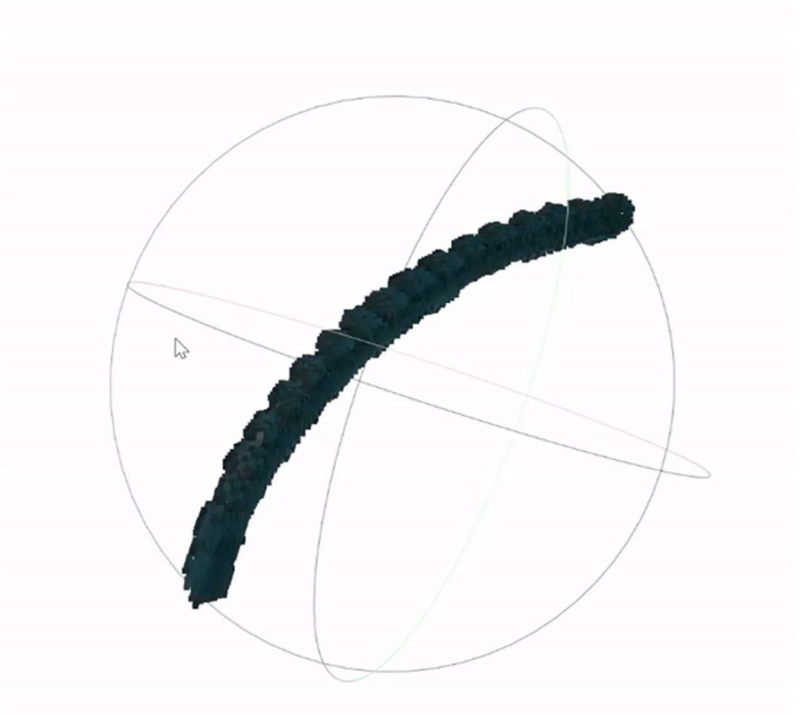
Point Cloud Alignment with ideal cylinder

Iterative closest point (**ICP**) :

- Align the target point cloud to the reference point cloud
- It iteratively solves for the transformation matrix *T* as

$$T = \arg \min_{T} \sum_{i} \|p_i - (Rq_i + t)\|^2$$

p_i *: Points in the target point cloud*
q_i *: Corresponding points in the reference point cloud*



Iterative Refinement Results

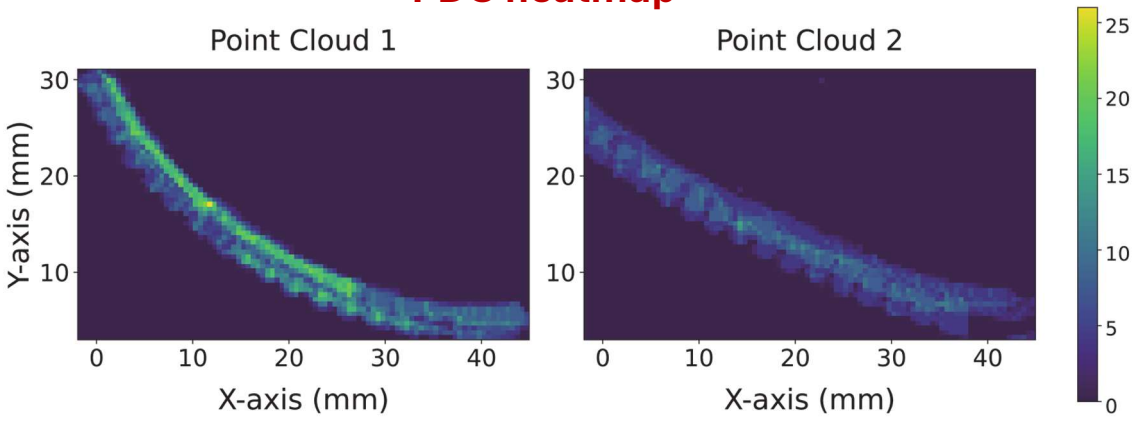
Results

Metrics: Point Density Consistency **(PDC):**

$$\lambda_{PDC} = \frac{\sigma_{PDC}}{\mu_{PDC}}$$

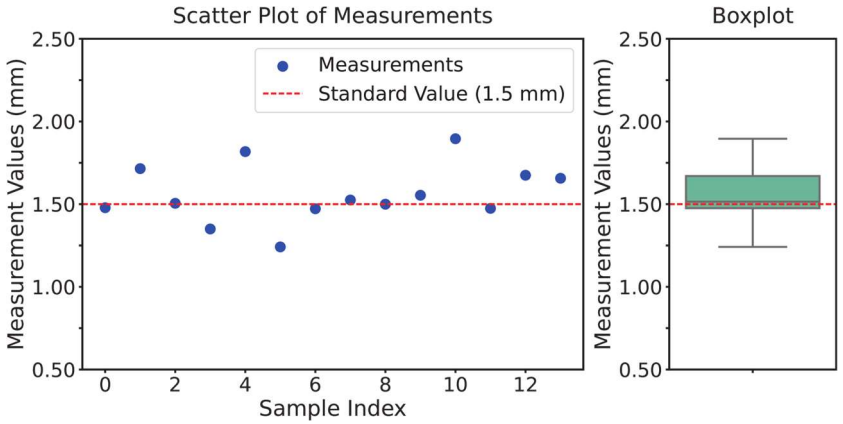
σ_{PDC}: standard deviation of point counts per voxel
μ_{PDC}: mean of point counts per voxel

PDC heatmap



With optimization
(Gen-backbone + KD-tree + ICP)

Without optimization
Sparse Point Cloud



Measurement results on the visible notches' width

Successfully reconstructed mm-scale continuum robot morphology with clear details:

- **14 out of 16** notches
- Notches with a width of **1.5 mm**
- Point Density Consistency Analysis:

Point Clouds	μ_{PDC}	σ_{PDC}	λ_{PDC}
Point Clouds 1 (Optimized)	1.5489	3.9636	2.5590
Point Clouds 2 (Non-optimized)	0.9582	2.2759	2.3752

Conclusion

- Proposed a **dual stereo vision** method for 3D reconstruction of millimeter-scale **NTCRs**.
- Achieved **high-resolution**, **cost-effective**, and **precise** results.

Future work

- **Real-time reconstruction** for dynamic soft robot
- **Self-modeling** for soft robots