

Shape-Guided Diffusion Model for Inverse Kinematics of Concentric Tube Robots

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July 13 2026



Concentric Tube Robot

CTRs are **nested, precurved elastic tubes** whose relative rotation and translation produce curvilinear shapes for **minimally invasive surgery (MIS)**.

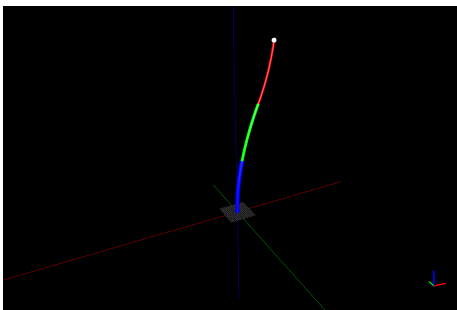


Figure: simulation

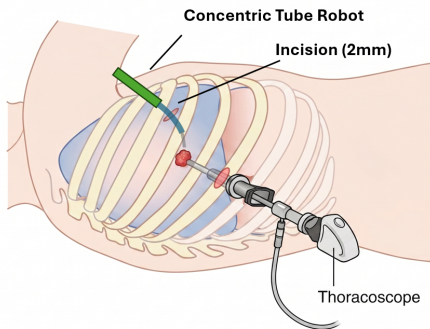


Figure: VATS Surgery



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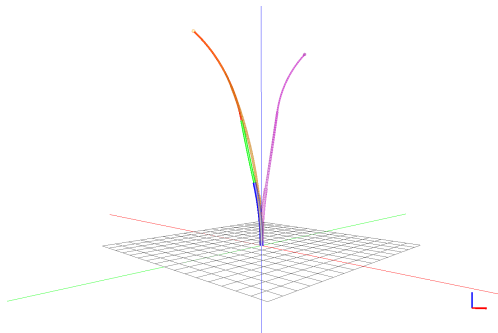
Why L_2 Regression Fails

Inverse Kinematics (IK)

Find the all valid configurations given the target pose:

$$\mathbf{q} = \text{IK}(\mathbf{x}) \quad (1)$$

Same target pose $\mathbf{x}$ admits multiple valid configurations $\mathbf{q}$; L_2 regression collapses them to an invalid average.



- left two CTRs with different configurations reach the same target pose
- The averaged configuration (purple) reaches to a totally different pose.

Shape Guided Diffusion Model for CTR IK

Generative models are not merely preferable but **necessary**: they approximate the full solution distribution rather than collapsing to point-wise averages.

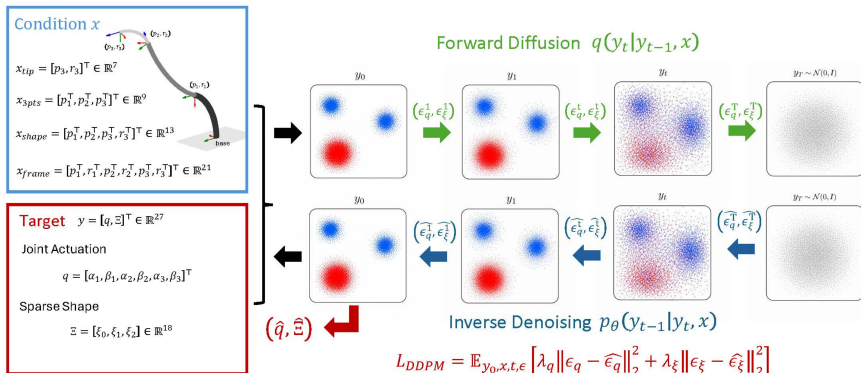


Figure: Diffusion model with shape guidance for IK distribution learning

Primary Results

We tested proposed idea on *CRL-Dataset-CTR-Pose* benchmark [1] which was collected in a physical three-tube CTRs.

Method	Tip Pos. ↓ (mm)	Tip Ori. ↓ (°)	α Err. ↓ (°)	β Err. ↓ (mm)
SE(3)-DDPM Frames	0.083 ± 0.141	0.218 ± 0.285	4.435 ± 4.005	0.771 ± 0.613
SE(3)-DDPM Shape	0.108 ± 0.094	0.291 ± 0.217	6.498 ± 7.324	0.742 ± 0.411
SE(3)-DDPM 3Pts	0.113 ± 0.078	0.976 ± 1.598	6.591 ± 7.003	0.670 ± 0.344
SE(3)-DDPM Tip	0.213 ± 0.132	0.311 ± 0.228	28.943 ± 22.459	2.920 ± 1.984
IK-MSE	16.425 ± 6.150	27.912 ± 15.800	57.364 ± 16.586	28.916 ± 14.838
IK-Cycle	10.109 ± 6.595	17.927 ± 12.493	58.729 ± 23.147	32.205 ± 17.596
DDPM-Tip	0.267 ± 0.142	0.877 ± 1.263	26.668 ± 21.714	3.132 ± 2.001
DDPM-3Pts	0.224 ± 0.130	1.029 ± 1.630	7.277 ± 6.922	0.588 ± 0.275
DDPM-Shape	0.247 ± 0.168	0.885 ± 1.185	6.954 ± 7.032	0.579 ± 0.249





R. M. Grassmann, R. Z. Chen, N. Liang, and J. Burgner-Kahrs, “A dataset and benchmark for learning the kinematics of concentric tube continuum robots,” in *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2022, pp. 9550–9557.

