In-Situ Collaborative Robotics in Confined Spaces

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Motivation

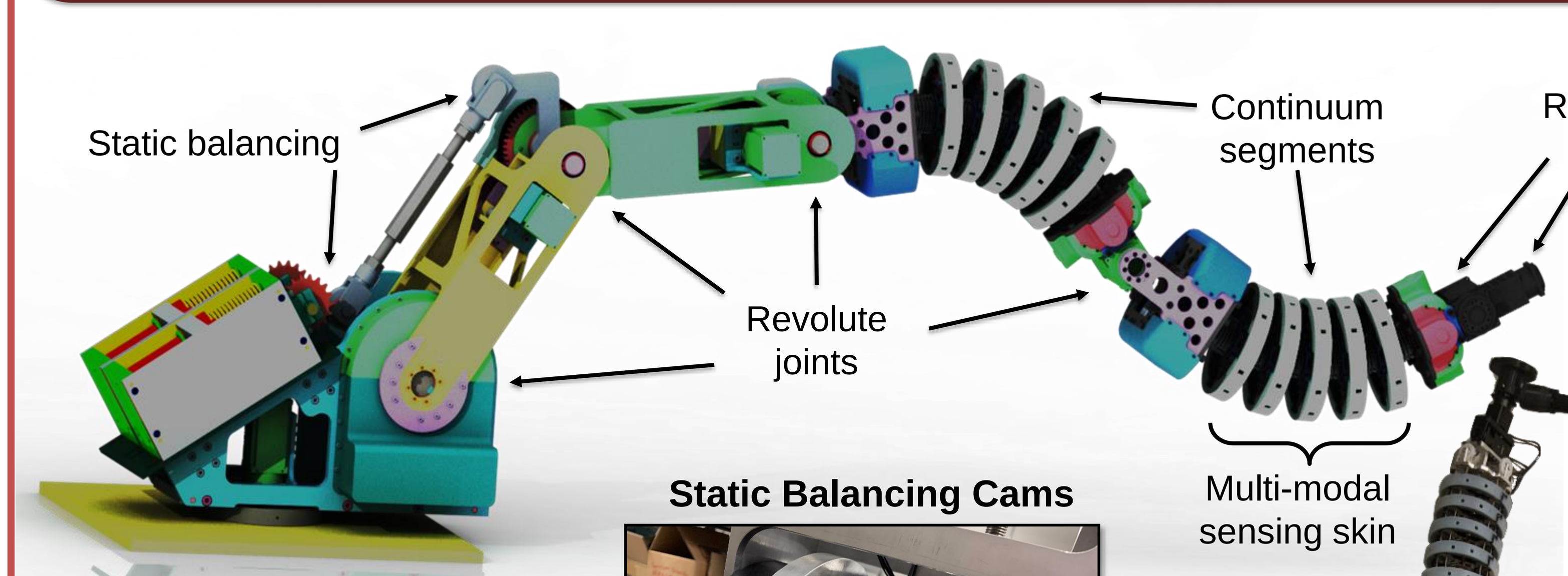
- Industrial workers often perform manufacturing or service tasks in tight spaces.
- Cooperative manufacturing in confined spaces demands cooperation modes and levels of dexterity, sensing, and safety that exceed capabilities of existing robotic systems.
- **Goal**: Develop and validate new technologies including associated control, sensing and planning to enable cooperative manipulation in confined spaces.

Illustrative example of a cooperative robot assisting a human user in a manufacturing operation in a confined space.

Scientific Merit:

- Introduce a new architecture of In-Situ Collaborative Robots (ISCR) in confined spaces.
- Facilitate physical interaction between the user and the robot using the robot's flexibility, contact sensing and localization, and proximity measurements along body.
- Modeling, compliant motion control, and planning with contact for ISCRs.
- Development of an approach for multi-point interaction between the user and the robot.

Manipulator Design



Static Balancing Cams

Design Features

- Passive and active safety
- Proximity and contact sensing
- Combined continuum and rigid link structure

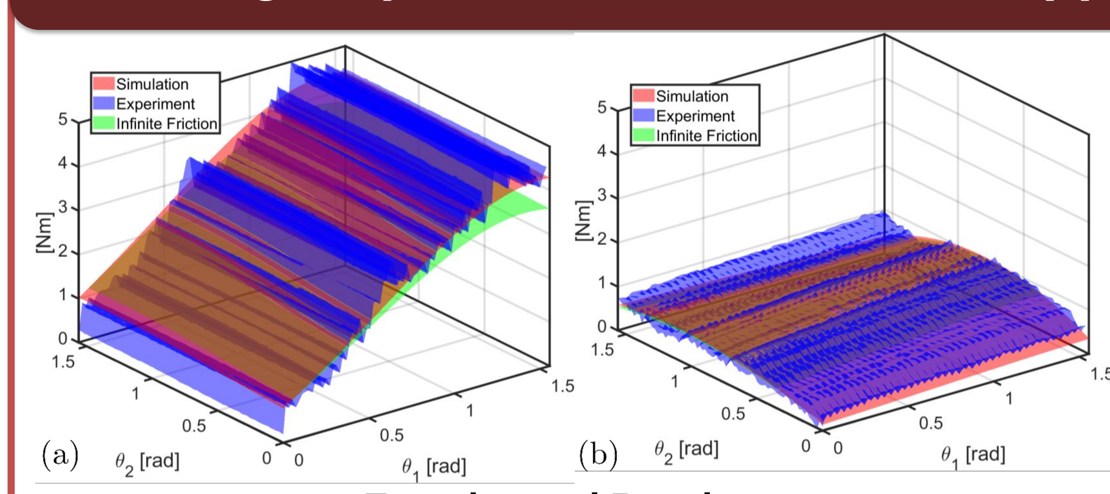
Manipulator Specifications

- 11 DOF
- Approx. 2 m reach
- 1.8 Kg payload at full reach

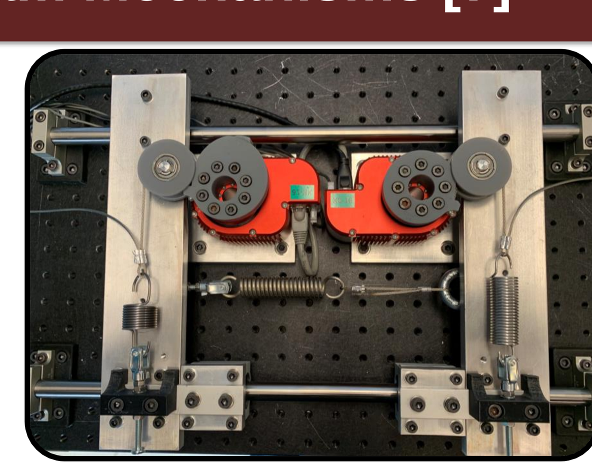
Evaluation tasks

- Sanding, caulking, and pipe assembly.

Design Optimization for Wire-Wrapped Cam Mechanisms [7]



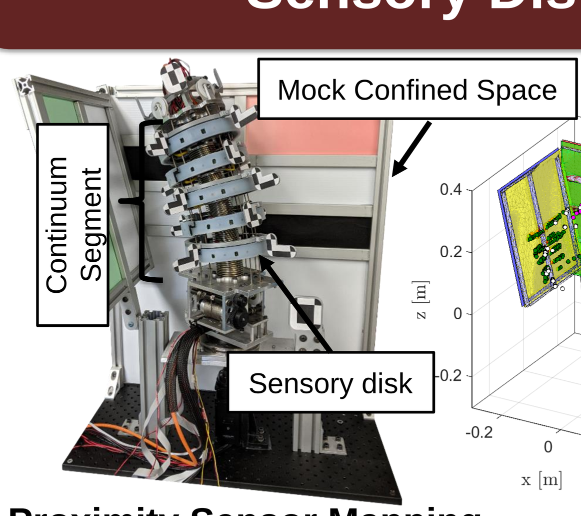
Experimental Results



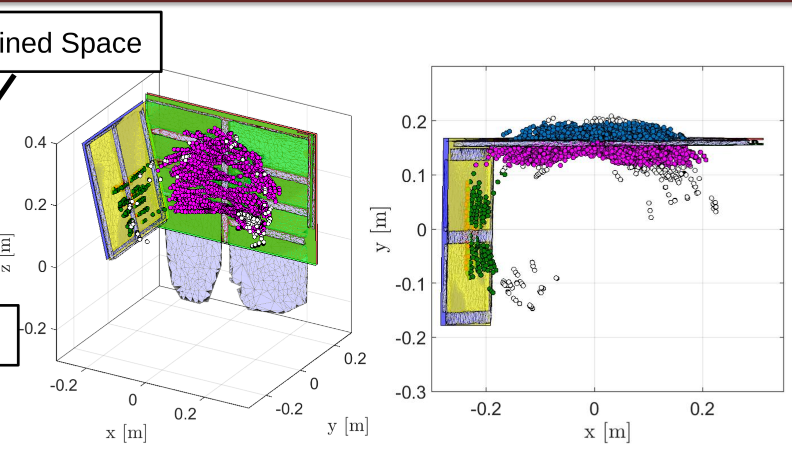
Experimental Setup

- Optimization-based, 2 DOF cam design procedure that minimizes effect of spring parameter uncertainty, ensures the cam stays convex, ensures the spring extension limits are not violated, and includes the effect of wire-cam friction
- Experimental validation shows 353.0 Nmm of RMS error for cam 1 and 166.3 Nmm for cam 2.

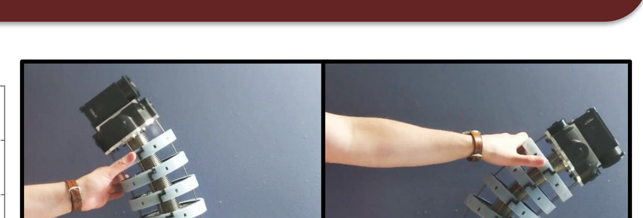
Sensory Disk Mapping and HRI Capabilities [1,2]



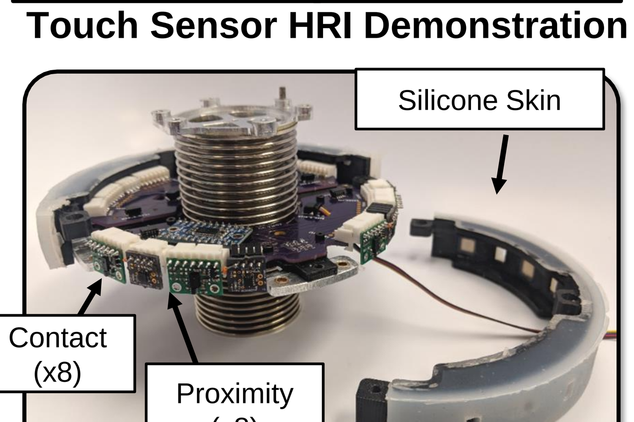
Proximity Sensor Mapping Experimental Setup



Proximity Sensor Mapping Results



Touch Sensor HRI Demonstration

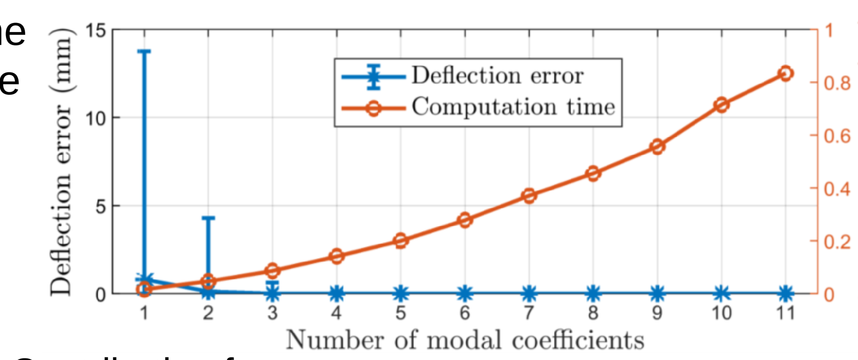


Sensor Disk Design

- Used proximity sensors to map a mock confined space
- 9.83 mm RMSE in mapping
- Used touch and proximity sensors to demonstrate HRI with the continuum segments

Continuum Segment Compliance Modeling [9]

- The Lie group formulation we use for modeling the robot kinematics/statics [3] enables computing the continuum segment compliance matrix in closed form from the principle of virtual work.
- Changing the modal function order allows for trade-off between computation time and model accuracy to be made.



Compliance definition:

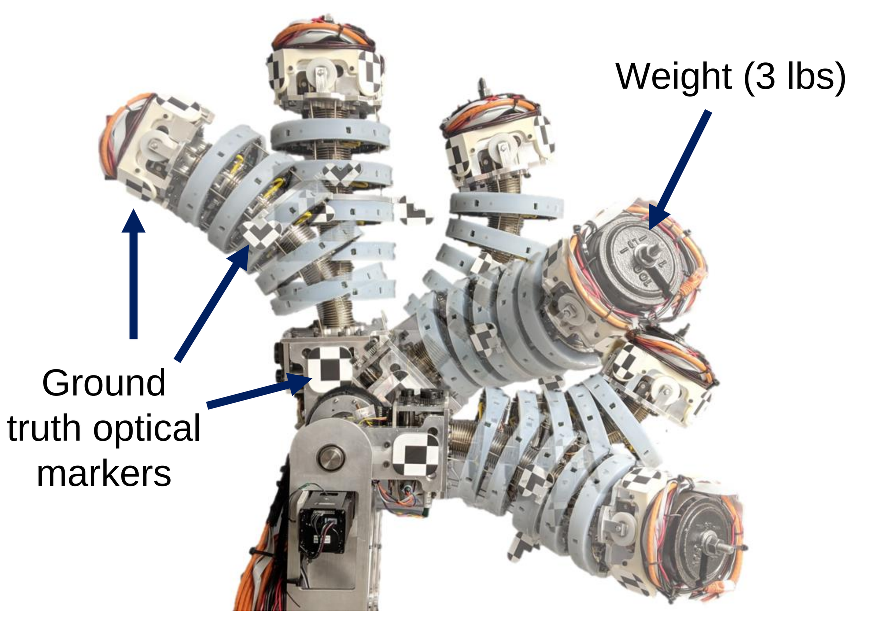
$$\mathbf{C} = \frac{\delta \mathbf{x}}{\delta \mathbf{w}} \in \mathbb{R}^{6\times 6}$$

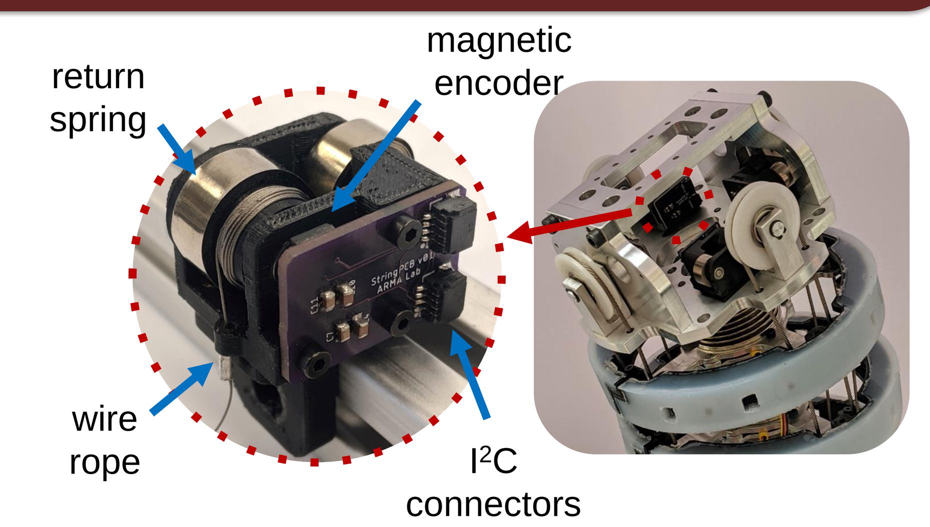
(Change in pose; Change in wrench)

$$\mathbf{C} = \widetilde{\mathbf{J}}_{\xi c}\left(\frac{\partial^2 E}{\partial \mathbf{c}^2} - \mathbf{C}_\tau - \mathbf{C}_w - \mathbf{J}_{\ell c}^T \mathbf{K}_\ell \mathbf{J}_{\ell c}\right)^{-1} \widetilde{\mathbf{J}}_{\xi c}$$

(Energy Hessian; Contribution from joint forces; Contribution from external wrench; Joint-level stiffness; Configuration space Jacobian; Task-space Jacobian)

Shape Sensing with General String Encoder Routing [4,5]



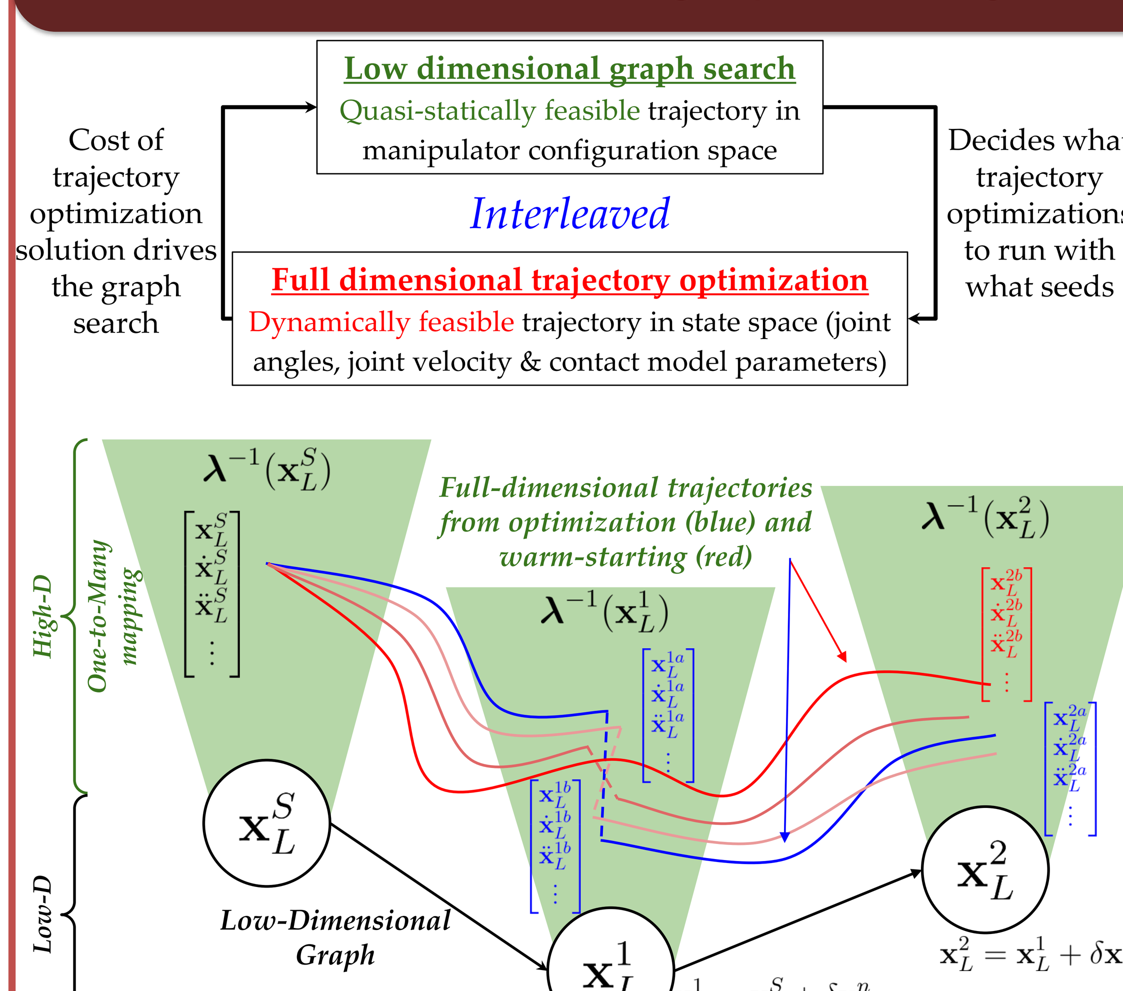


- We present a kinematic model to solve for the deflected continuum segment shape using general string encoder routing and show how optimize string routings to reduce sensing error.
- Experimental validation shows mean and max end disk position error of 2.0% and 4.8% of arc length.

Avg. (Max) Absolute Position (mm) and Orientation Errors (°), specified for the end disk ($s = L$) and the 3rd disk ($s = s_3$)

	End Disk Routing	Third Disk Routing	Constant Curvature
$\bar{p}_e(L)$, max $(p_e(L))$	5.9 (14.4)	6.0 (13.8)	56.2 (104.9)
$\bar{p}_e(s_3)$, max $(p_e(s_3))$	3.8 (10.2)	3.3 (9.2)	31.8 (58.6)
$\bar{\theta}_e(L)$, max $(\theta_e(L))$	1.5 (8.6)	1.5 (3.9)	3.6 (14.4)
$\bar{\theta}_e(s_3)$, max $(\theta_e(s_3))$	2.0 (6.0)	1.6 (4.2)	15.4 (28.1)

Planning by Bracing using INSAT [8]



Full dimensional trajectory optimization

Cost to reach low-D node from graph search — *Minimize torque and momentum*

$$\min_{\mathbf{u}[.],\mathbf{k},\mathbf{b},\boldsymbol{\mu}} \left\|\mathbf{x}_L[N] - \mathbf{x}_L^G\right\| + \sum_{i=0}^{N-1}\left(\|\mathbf{u}[i]\| + \|\dot{\mathbf{x}}[i]\|\right) + \sum_{n=1}^{N_\Gamma}\|\mathbf{k}\| + \|\mathbf{b}\| + \|\boldsymbol{\mu}\|$$

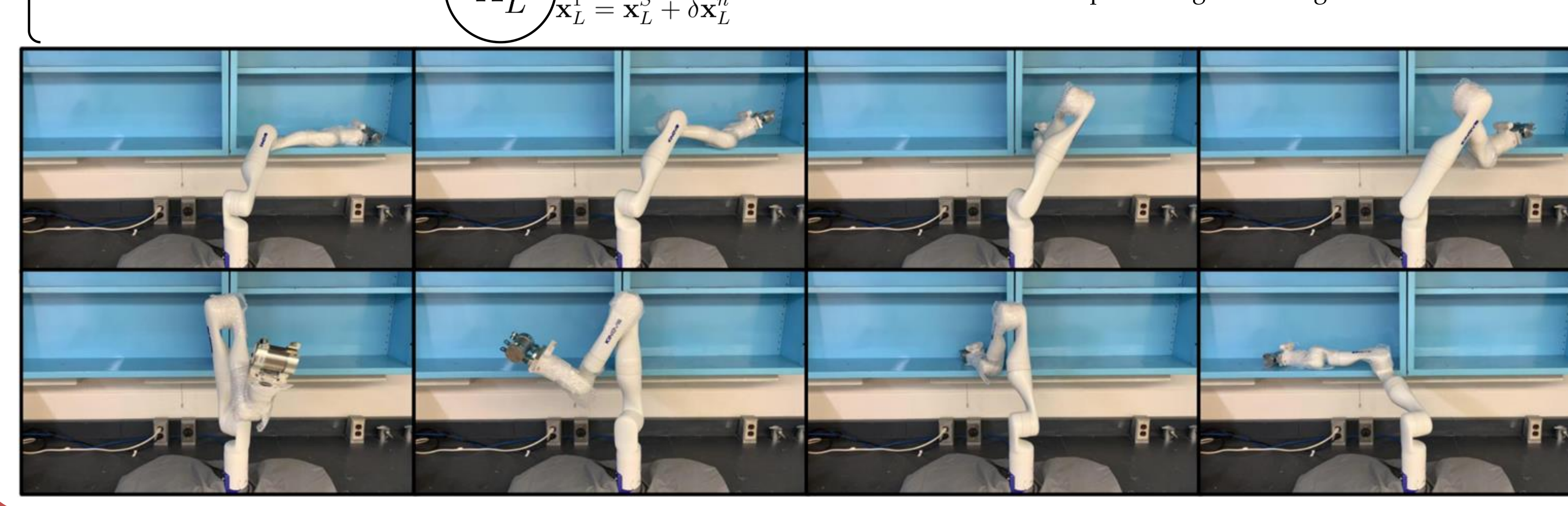
$$\text{s.t.} \quad \mathbf{x}[0] = \mathbf{x}^0;\ \mathbf{x}[i+1] = \mathbf{f}(\mathbf{x}_i, \mathbf{u}_i)$$

$$|\dot{\mathbf{x}}(t)| \le \dot{\mathbf{x}}_{\lim};\ |\ddot{\mathbf{x}}(t)| \le \ddot{\mathbf{x}}_{\lim};\ |\mathbf{u}(t)| \le \mathbf{u}_{\lim}$$

Contact-model parameters of tunable soft contact model used in Contact Implicit Trajectory Optimization. Details in [8]

Joint ID	1	2	3	4	5	6	7	Total
Free-space	1.93	33.25	10.14	14.06	0.97	6.29	0.2	66.86
Bracing	4.65	23.96	6.67	11.8	1.28	5.67	0.59	54.62
Difference	-2.72	9.32	3.46	2.26	-0.31	0.63	-0.4	12.24

Experimental RMS torques [Nm] during (i) the braced trajectory shown below and (ii) the same trajectory running in free-space (i.e. without the cabinets) producing net savings of 12.24Nm.



Publications

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[2] C. Abah, A. L. Orekhov, G. L. H. Johnston, N. Simaan, "A Multi-Modal Sensor Array for Human-Robot Interaction and Confined Spaces Exploration Using Continuum Robots" in *IEEE Sensors Journal*, vol. 22, no. 4, pp. 3585-3594, Feb. 15, 2022.
[3] A. L. Orekhov and N. Simaan, "Solving Cosserat Rod Models via Collocation and the Magnus Expansion," *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 8653-8660.
[4] A. L. Orekhov, J. Seo, and N. Simaan, "Kinematics and Shape Sensing of a Collaborative Continuum Robot," in *IROS 2020 workshop on "Application-Oriented Modelling and Control of Soft Robots,"* Nov. 2020.
[5] A. L. Orekhov, E. Ahronovich, N. Simaan, "Lie Group Formulation and Sensitivity Analysis for Shape Sensing of Variable Curvature Continuum Robots with General String Encoder Routing", *IEEE Transactions on Robotics*.
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[7] G. L. H Johnston, A. L. Orekhov, N. Simaan, "Design Considerations and Robustness to Parameter Uncertainty in Wire-Wrapped Cam Mechanisms." ASME. *J. Mechanisms Robotics*. March 2023; 16(2): 021001
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[9] A. L. Orekhov, G. L. H. Johnston, N. Simaan, "Task and Configuration Space Compliance of Continuum Robots via Lie Group and Modal Shape Formulations" *2023 IEEE/RSJ International Conference on Intelligent Robots and Systems.* (Under review)
[10] G. Del Guidice, G. L. H. Johnston, N. Simaan, "Design Considerations for 3RRR Parallel Robots with Lightweight Approximate Static-balancing." *ASME 2023 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC-CIE)*. (Under Review)