In-Situ Collaborative Robotics in Confined Spaces

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Motivation

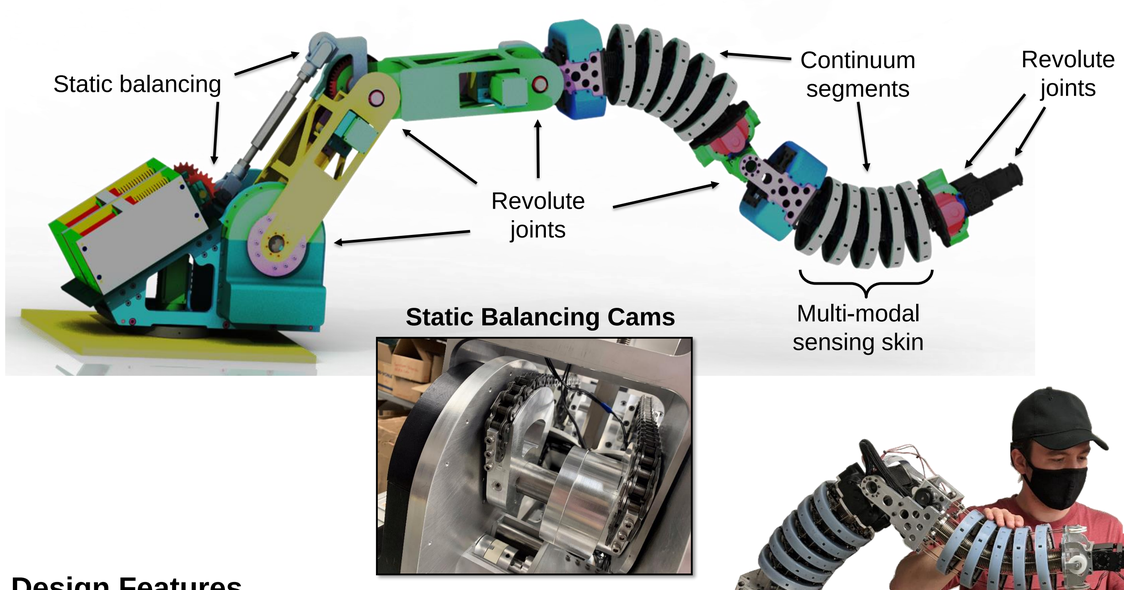
- Industrial workers often perform manufacturing or service tasks in tight spaces.
- Cooperative manufacturing in confined spaces demands cooperation modes and levels of dexterity, sensing, and safety that exceed capabilities of existing robotic systems.
- **Goal**: Develop and validate new technologies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



Design Features

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

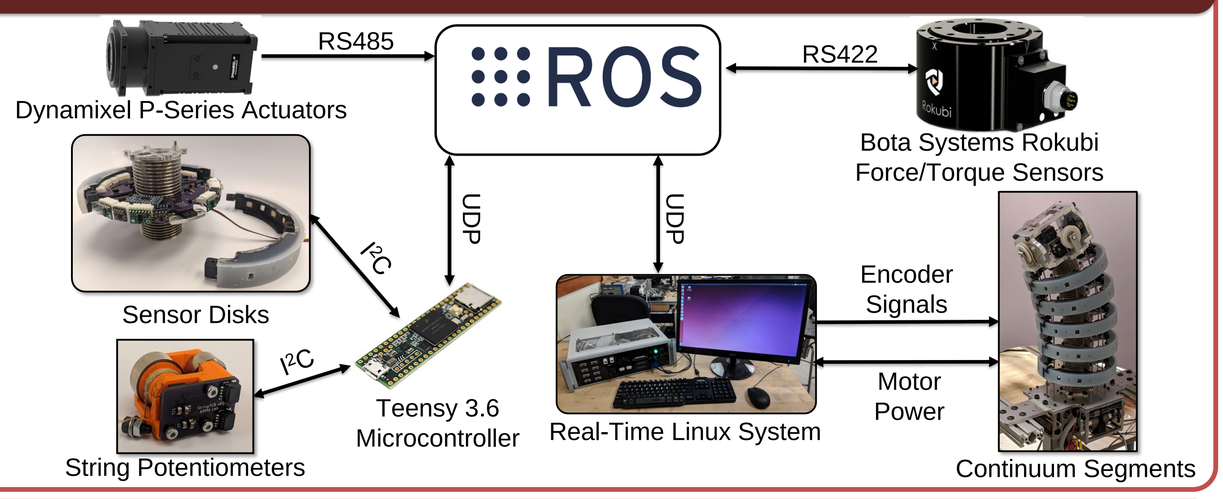
Manipulator Specifications

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

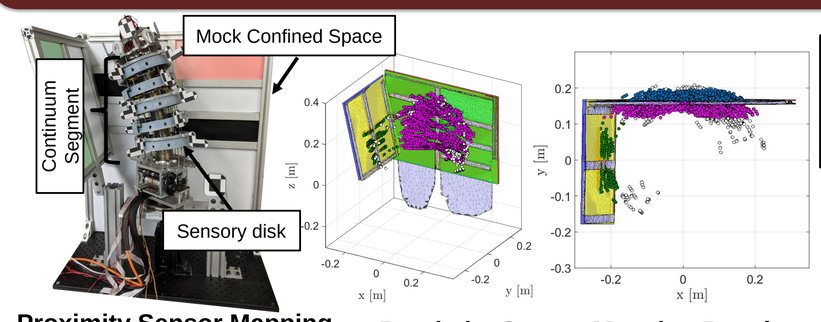
Evaluation tasks

- Sanding, caulking, and pipe assembly.

Software Architecture

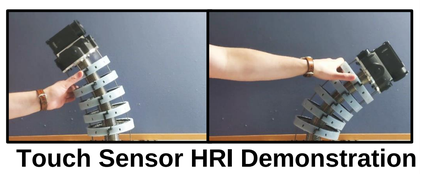


Sensory Disk Mapping and HRI Capabilities [1,2]

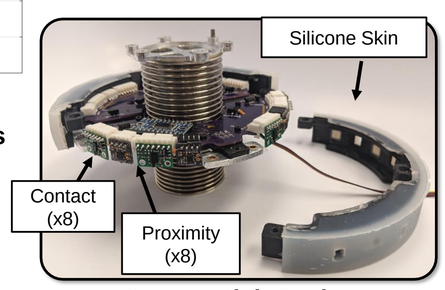


Proximity Sensor Mapping Experimental Setup

Proximity Sensor Mapping Results



Touch Sensor HRI Demonstration

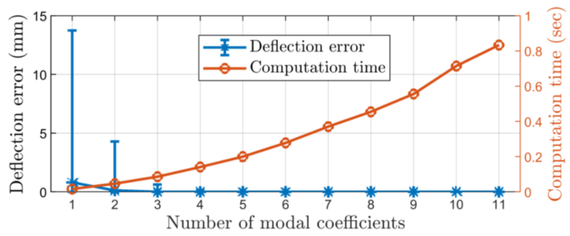


Sensor Disk Design

- 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

- 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:

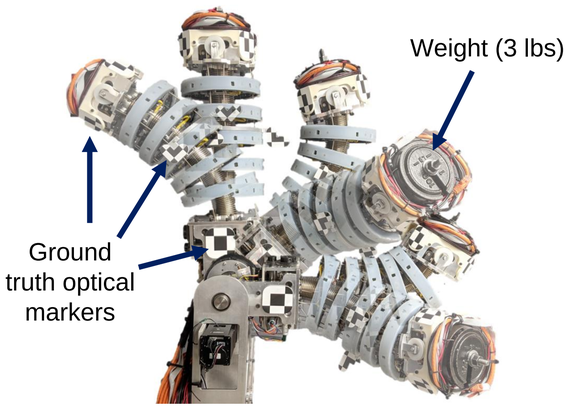
$$\mathbf{C} = \frac{\delta \mathbf{x}}{\delta \mathbf{w}} \in \mathbb{R}^{6\times 6}$$

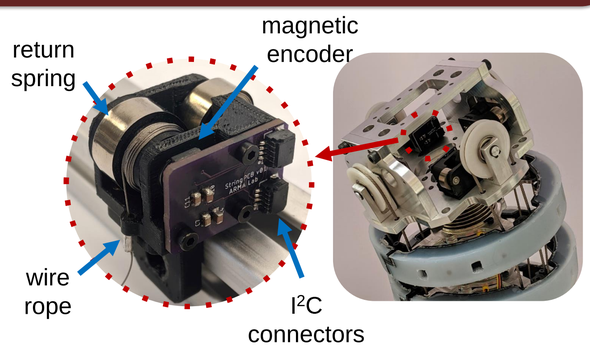
Change in pose; Change in wrench

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

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

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





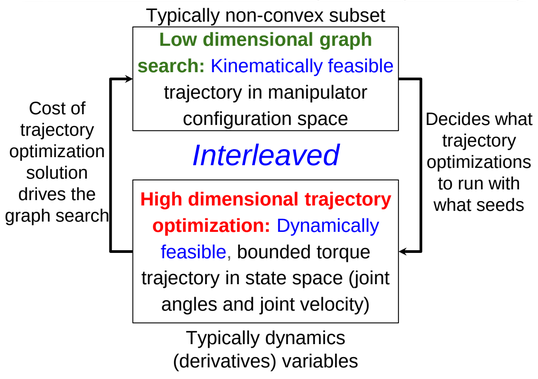
- We present a kinematic model to solve for the deflected continuum segment shape using general string encoder routing and show how optimize string routings to reduce sensing error.
- Experimental validation shows mean and max end disk position error of 2.0% and 4.8% of arc length.

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

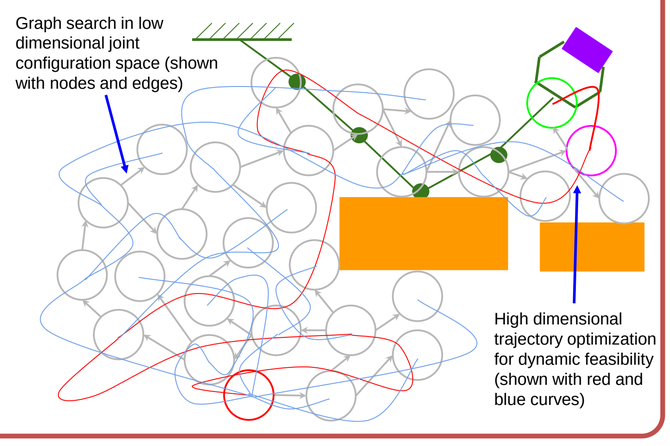
	End Disk Routing	Third Disk Routing	Constant Curvature
$\bar{p}_e(L)$, max $(p_e(L))$	5.9 (14.4)	6.0 (13.8)	56.2 (104.9)
$\bar{p}_e(s_3)$, max $(p_e(s_3))$	3.8 (10.2)	3.3 (9.2)	31.8 (58.6)
$\bar{\theta}_e(L)$, max $(\theta_e(L))$	1.5 (8.6)	1.5 (3.9)	3.6 (14.4)
$\bar{\theta}_e(s_3)$, max $(\theta_e(s_3))$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

Torque-Limited Manipulation Planning through Bracing

Interleaving Graph Search and Trajectory Optimization for planning through bracing



Graphical illustration of our algorithm for a planar manipulator lifting a payload by bracing



Variable Smooth Contact Model

Tunable contact model i.e. from relaxed (virtual force even when not in contact) to tight (contact force only when in contact).

$$\gamma(\mathbf{x}) = k e^{(-\alpha\phi(\mathbf{x}))}$$

Contact force; Tunable parameters

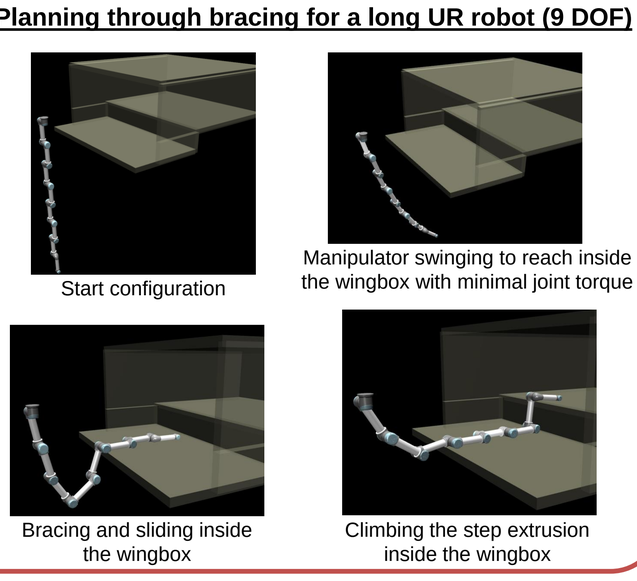
Contact Implicit Trajectory Optimization

Simultaneous optimization of trajectory to reach the goal and parameters of the contact model. We use SCvx (Successive Convexification) to solve the optimization.

$$\begin{aligned} \min_{\boldsymbol{\tau},k,\alpha} \quad & k^2 - \alpha^2 + \|\mathbf{x}(T) - \mathbf{x}_{\text{goal}}\|^2 \\ & + \int_0^T \|\boldsymbol{\tau}(t)\|^2 dt \\ \text{s.t.} \quad & \dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \boldsymbol{\tau}) \\ & \mathbf{x}(0) = \mathbf{x}_0, \mathbf{x}(T) \in \mathbf{x}_{\text{goal}} \\ & |\dot{\mathbf{x}}(t)| \le \dot{\mathbf{x}}_{\text{lim}} \\ & |\boldsymbol{\tau}(t)| \le \boldsymbol{\tau}_{\text{lim}}, \boldsymbol{\tau} \in \mathbf{U} \end{aligned}$$

Manipulator dynamics; State contains joint angles and velocities; Joint torques

Planning through bracing for a long UR robot (9 DOF)



Start configuration; Manipulator swinging to reach inside the wingbox with minimal joint torque; Bracing and sliding inside the wingbox; Climbing the step extrusion inside the wingbox

Publications

[1] C. Abah, A. L. Orekhov, G. L. H. Johnston, P. Yin, H. Choset, and N. Simaan, "A Multi-modal Sensor Array for Safe Human-Robot Interaction and Mapping," *2019 IEEE International Conference on Robotics and Automation (ICRA)*, May 2019.
[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*. (under review)
[6] G. L. H. Johnston, A. L. Orekhov, & N. Simaan. Kinematic Modeling and Compliance Modulation of Redundant Manipulators Under Bracing Constraints. *2020 IEEE International Conference on Robotics and Automation (ICRA)*, 4709–4716.