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.
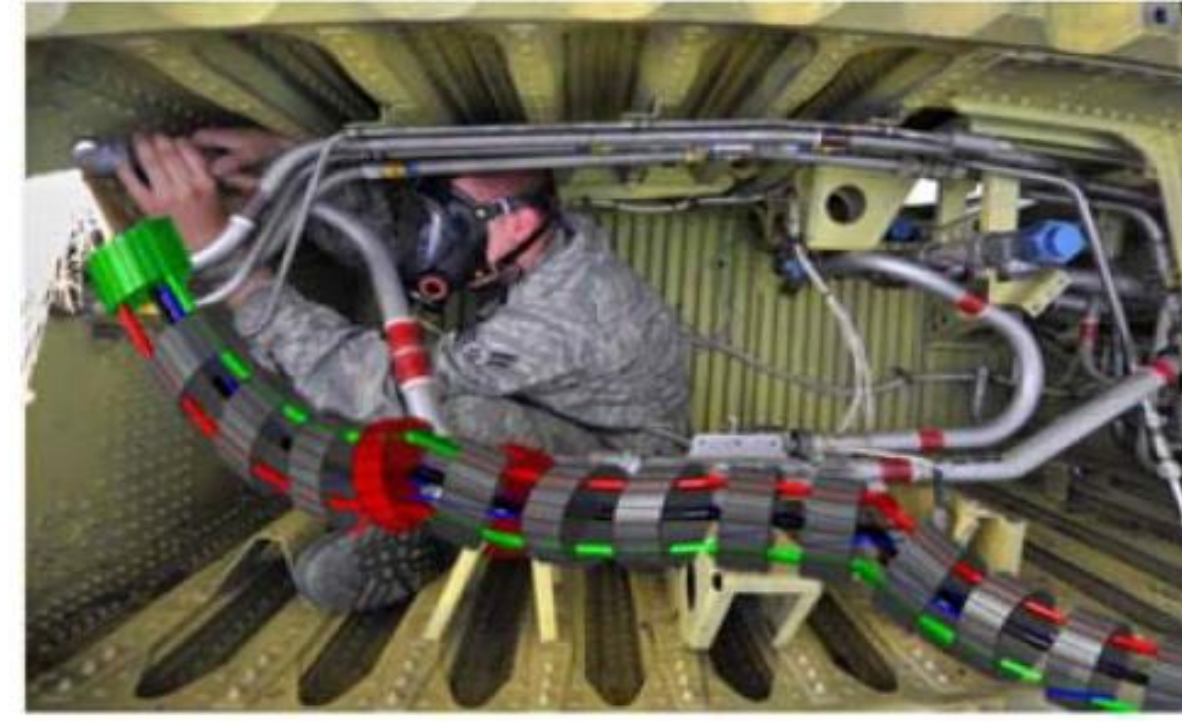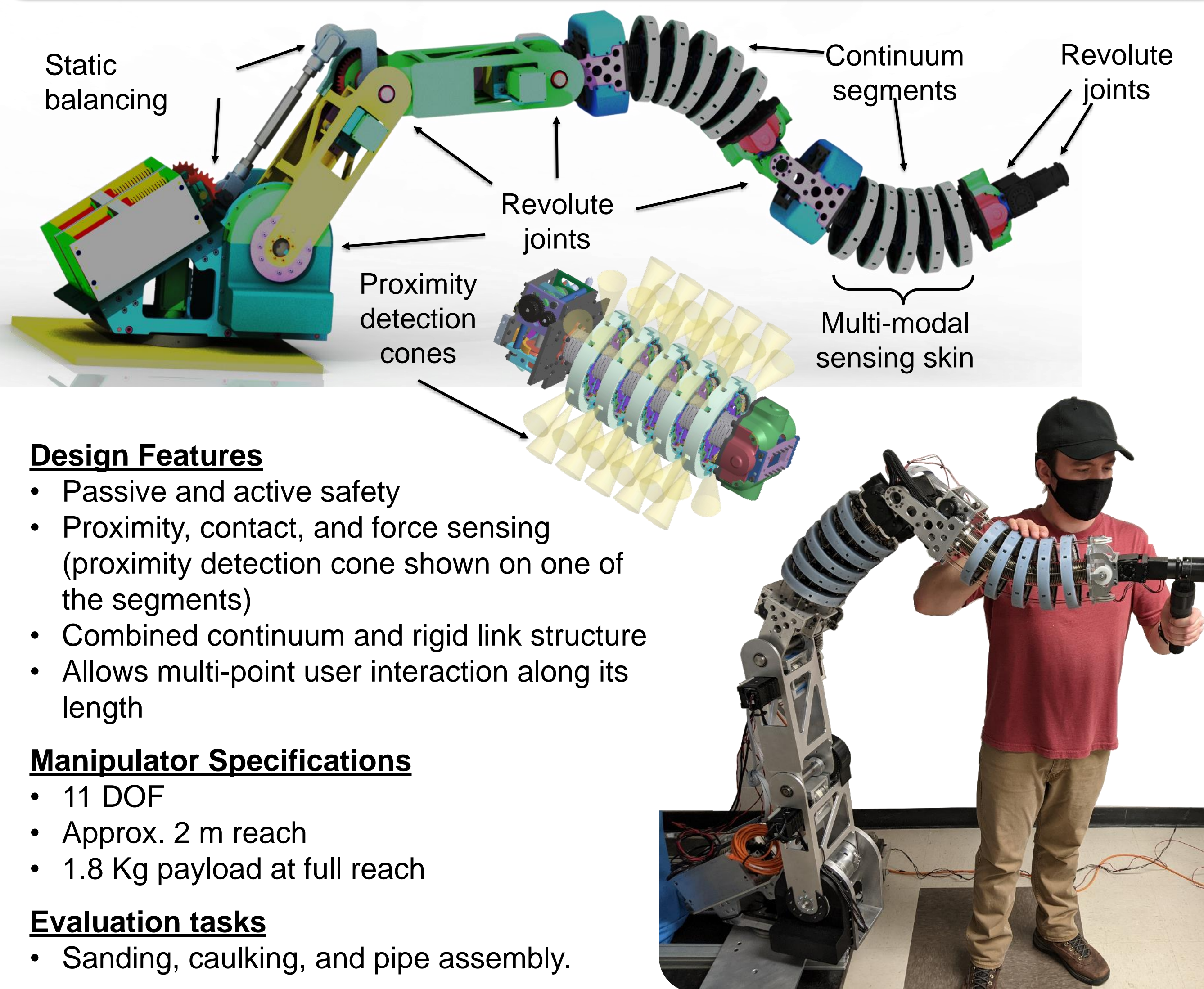

Illustrative example of a cooperative robot assisting a human user in a manufacturing operation in a confined space.

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 · Continuum segments · Revolute joints · Revolute joints · Proximity detection cones · Multi-modal sensing skin

Design Features
- Passive and active safety
- Proximity, contact, and force sensing (proximity detection cone shown on one of the segments)
- Combined continuum and rigid link structure
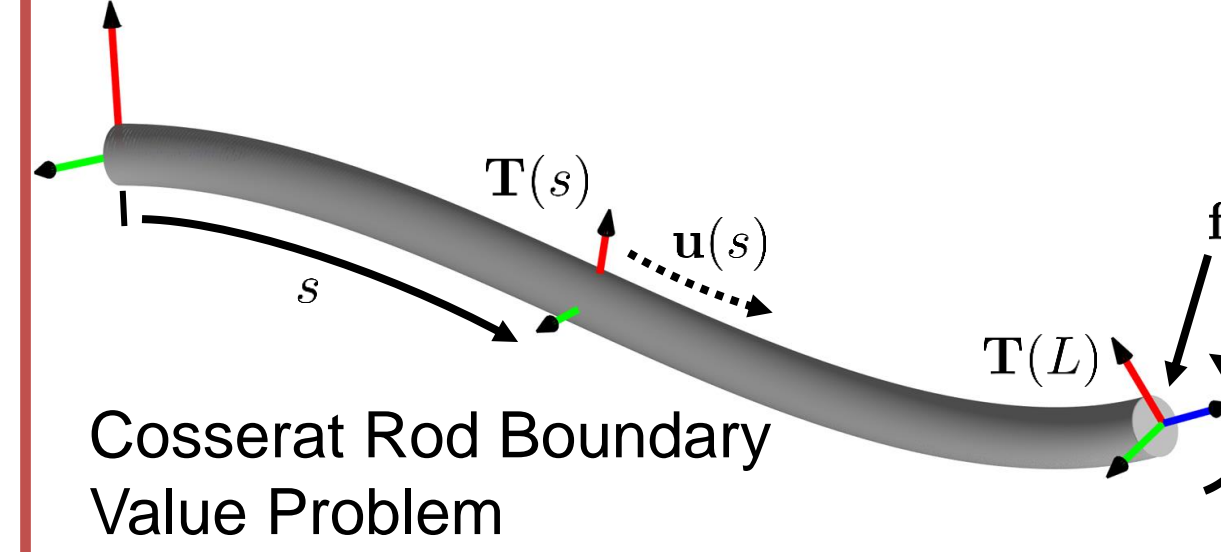- Allows multi-point user interaction along its length

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

Evaluation tasks
- Sanding, caulking, and pipe assembly.

Static Balancing Wrapping-Cam Design Optimization

Design framework for
- Ensuring cam is convex
- Staying within spring limits
- Increasing robustness to parameter uncertainty
- Friction modeling for cam/wire
- Balancing of coupled 2 DoF systems

2 Dof System Design

Wire/cam Friction FBD

Cam Torque Simulations

Sensory Disk Design and Characterization [1]

Silicone Skin · Contact (x8) · Proximity (x8)

Multi-Modal Sensing Unit

Cartesian Robot (3 DOF) · Rotary Stage · Force Sensor

Silicone Skin Force Calibration

Sensory disk arrays calibrated for proximity, contact detection and force sensing.

Lie Group Methods for Solving Statics of Continuum Robots [2]

Cosserat Rod Boundary Value Problem

$$\mathbf{T}'(s) = \mathbf{T}(s)\mathbf{X}(s)$$
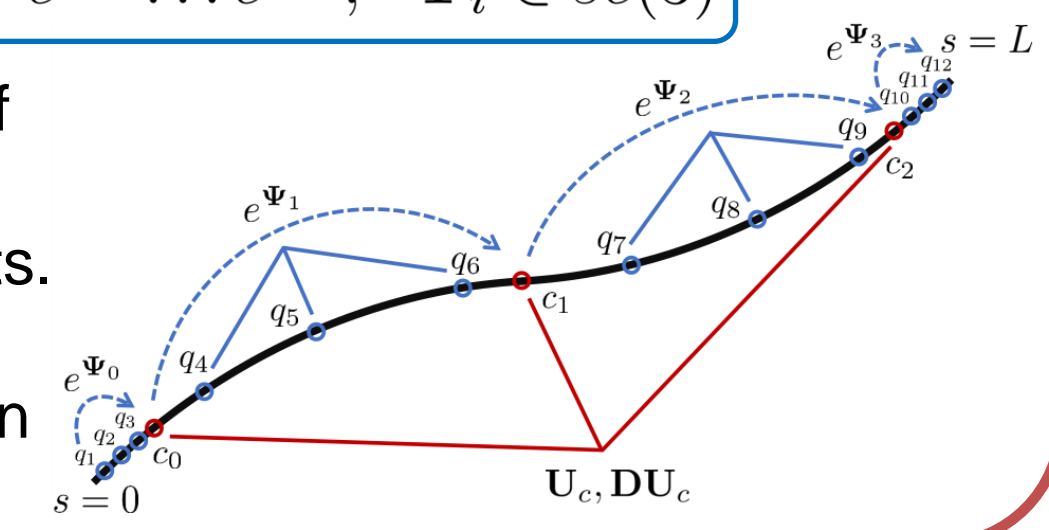$$\mathbf{u}'(s) = -\mathbf{K}^{-1}\left(\hat{\mathbf{u}}(s)\mathbf{K}\mathbf{u}(s) + \hat{\mathbf{e}}_3\mathbf{R}^{\mathrm{T}}(s)\mathbf{f}_e\right)$$

TABLE III: Fourth Order Magnus Tip Error as a Function of Collocation Polynomial Order ($L = 200$ mm)

|	Pos. e_p (%)		Rot. e_r (deg)		
	Avg.	Max.	Avg.	Max.	Speed (Hz)
$n = 2$	2.97	28.0	4.28	36.3	179.6
$n = 4$	0.141	2.15	0.235	3.78	112.1
$n = 6$	0.00573	0.147	0.00889	0.183	71.6
$n = 8$	0.00122	0.0173	0.00453	0.0571	46.3
$n = 10$	5.46e-4	0.00707	0.00448	0.0543	33.1

Orthogonal collocation + Magnus expansion

$$\mathbf{T}(c_k) = e^{\Psi_0}e^{\Psi_1}\ldots e^{\Psi_\kappa}, \quad \Psi_i \in se(3)$$

- The Cosserat rod equations predict the deflected shape of externally loaded continuum robots, but they can be computationally expensive with many kinematic constraints.
- Our approach combines Lie group integration and collocation to efficiently solve the equations and provide an analytic product of exponential formula.
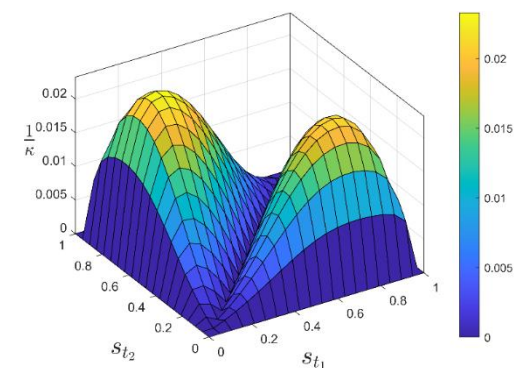
Shape Sensing with General String Encoder Routing [3]

return spring · magnetic encoder · wire rope · I²C connectors

String routing functions
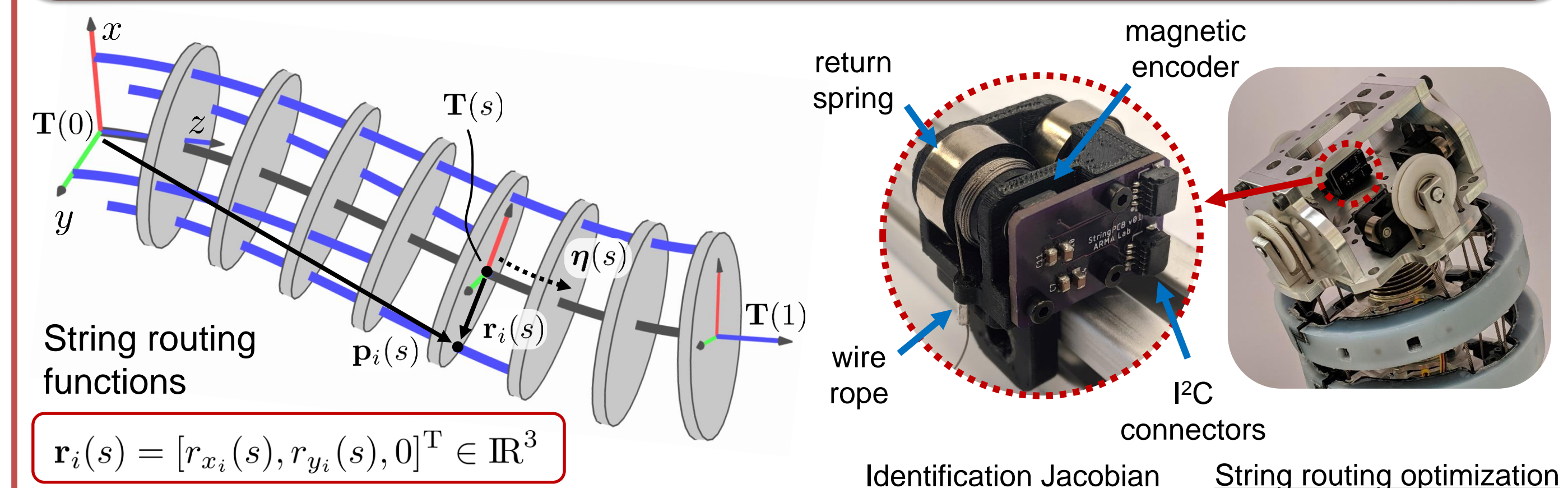
$$\mathbf{r}_i(s) = [r_{x_i}(s), r_{y_i}(s), 0]^{\mathrm{T}} \in \mathbb{R}^3$$

- String encoders are used to provide sensing of the continuum segment shape.
- We present a kinematic model to solve for the segment shape with general string encoder routing and are investigating how to design the strings to improve kinematic conditioning.

Identification Jacobian · String routing optimization

$$\mathrm{d}\boldsymbol{\ell} = \mathbf{J}_{\ell c}\mathrm{d}\mathbf{c}$$
$$\frac{\partial \ell_i}{\partial \mathbf{c}} = \int_0^{s_{t_i}} \left(\mathbf{r}_i \times \left(\frac{{}^b\mathbf{p}_i'}{\|{}^b\mathbf{p}_i'\|}\right)\right)^{\mathrm{T}} \boldsymbol{\Phi}\,\mathrm{d}s$$

Sampling-Based Path Planning with Bracing

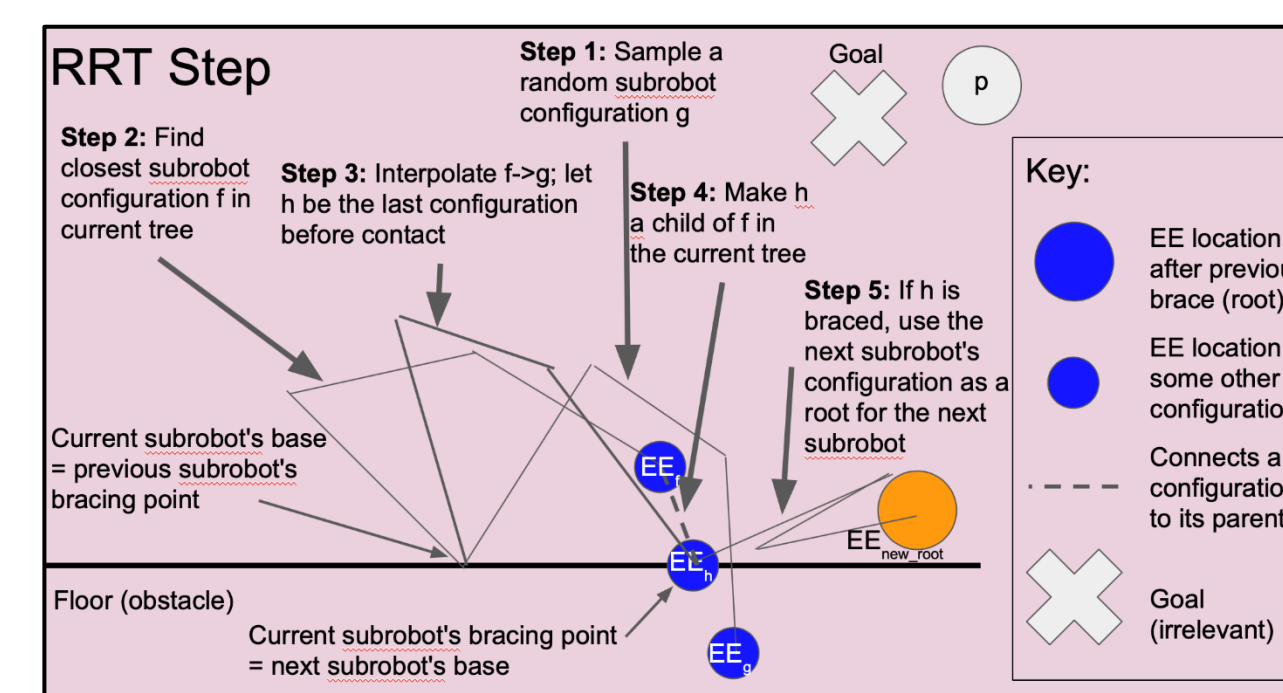**Sample path from our RRT algorithm:**
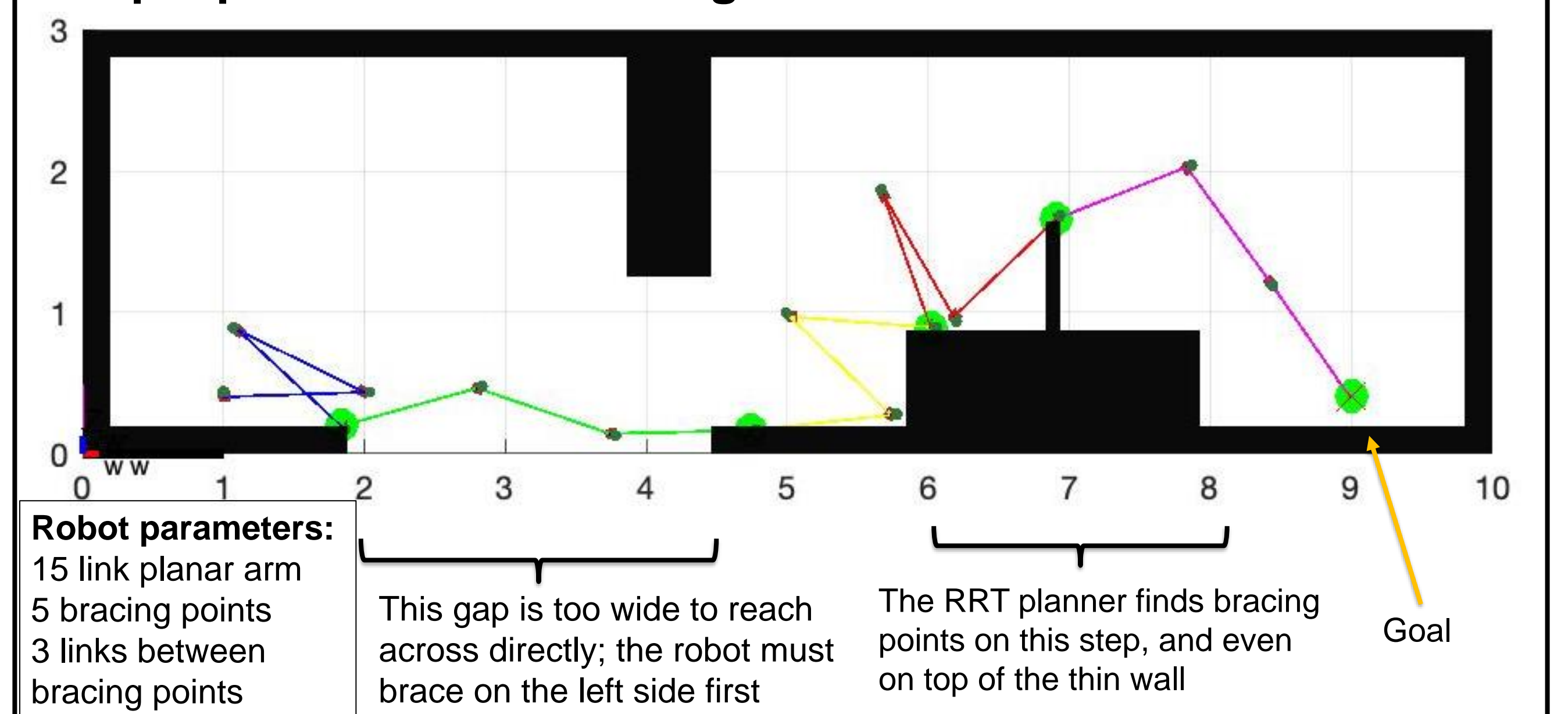
Robot parameters:
15 link planar arm
5 bracing points
3 links between bracing points

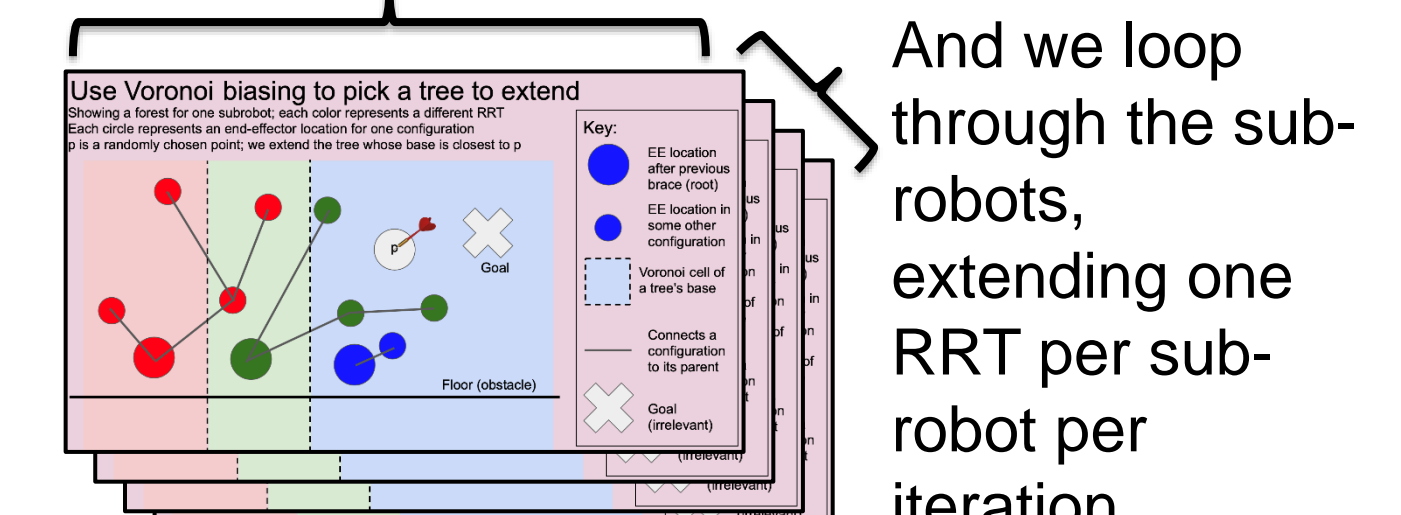This gap is too wide to reach across directly; the robot must brace on the left side first

The RRT planner finds bracing points on this step, and even on top of the thin wall

Goal

To find a path, we partition the robot into "sub-robots" (colored set of links above) that can cantilever their own weight plus the weight of all distal sub-robots folded up at their tip

We explore the configuration space of each sub-robot using a modified RRT algorithm. Each time a sub-robot finds a bracing point, it creates the root of a new RRT for the next sub-robot.
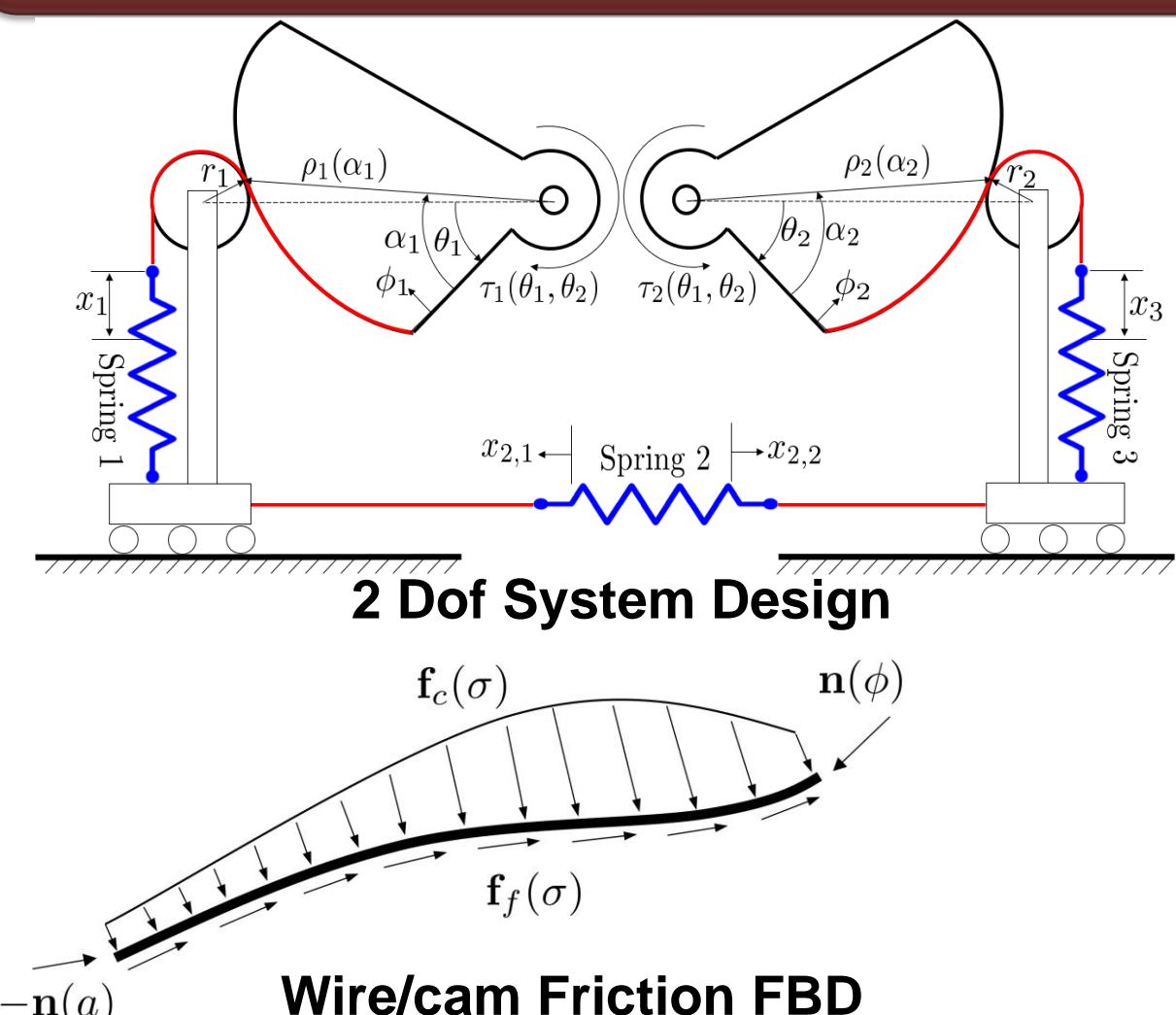

We randomly select the RRT to expand based on the size of its base location's Voronoi cell.
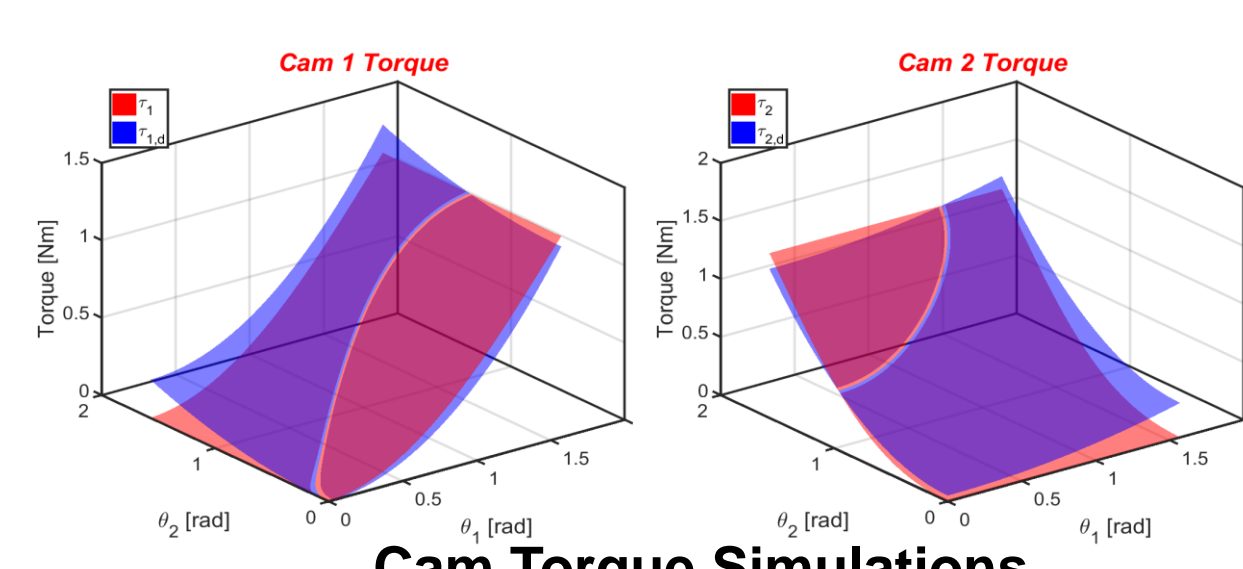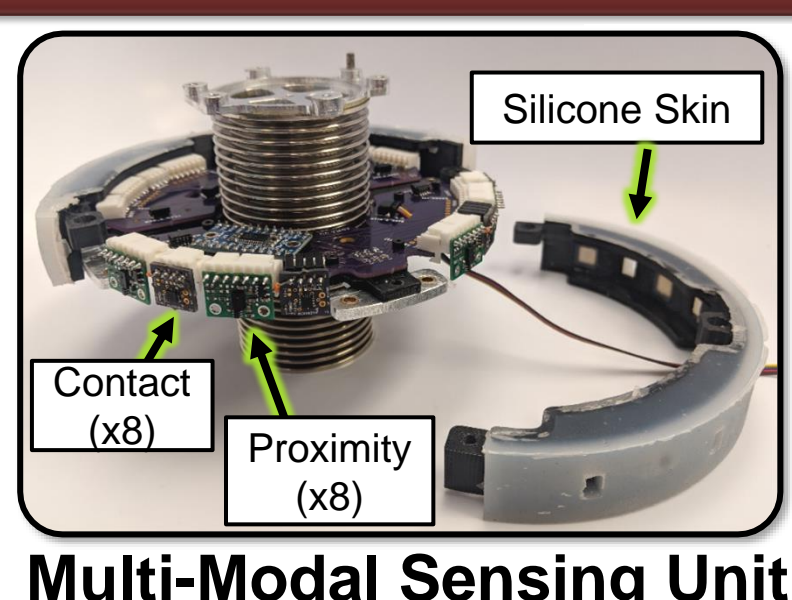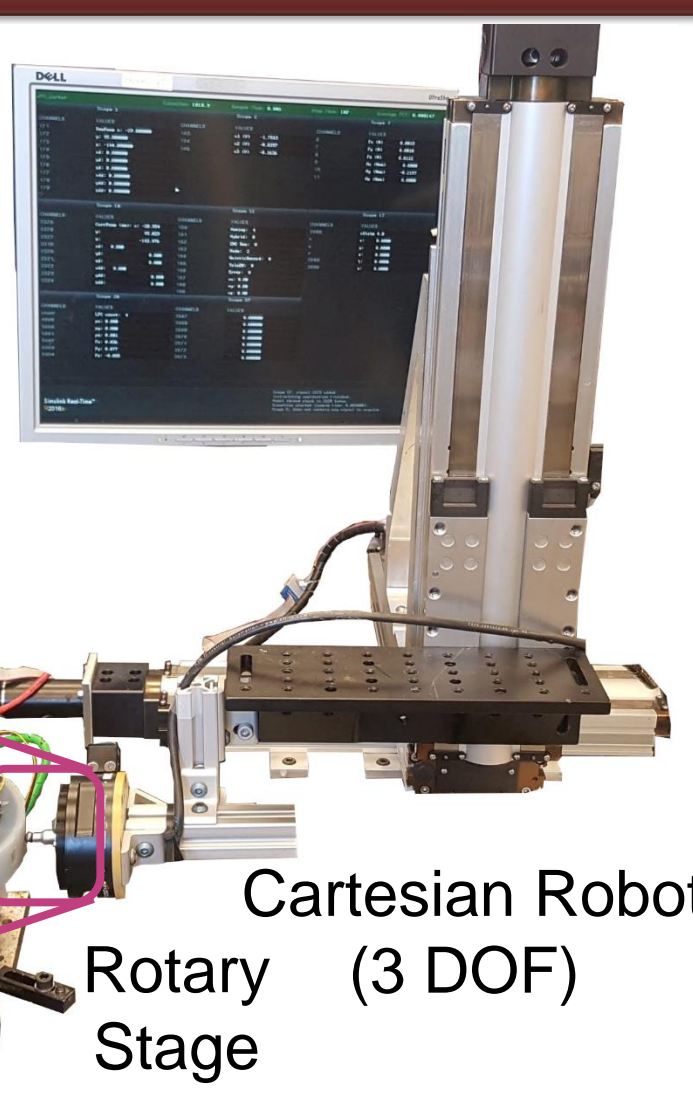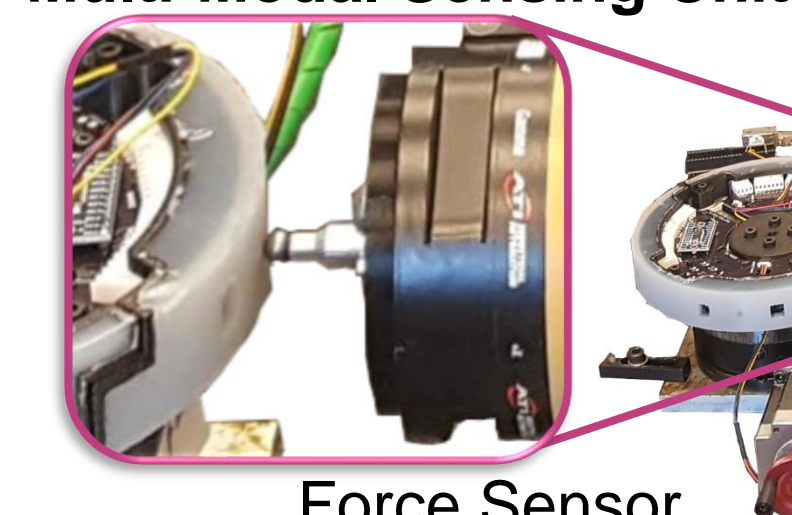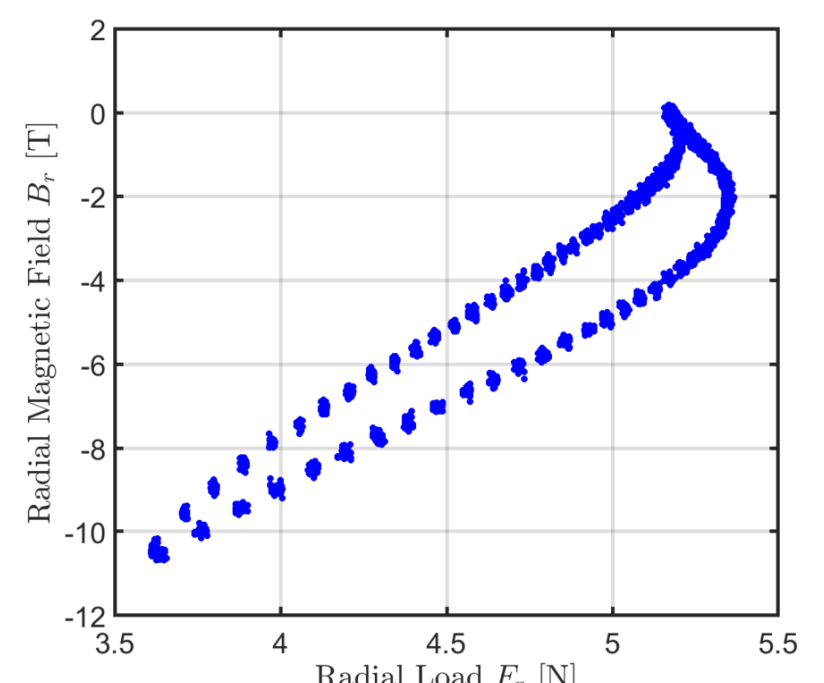
And we loop through the sub-robots, extending one RRT per sub-robot per iteration

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] A. L. Orekhov and N. Simaan, "Solving Cosserat Rod Models via Collocation and the Magnus Expansion," IROS 2020, pp. 8653-8660.

[3] 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.