NSF CMMI #1734461, #1734360

NRI-2.0: INT: Manufacturing America:

In-Situ Collaborative Robotics in Confined Spaces


Nabil Simaan[1]

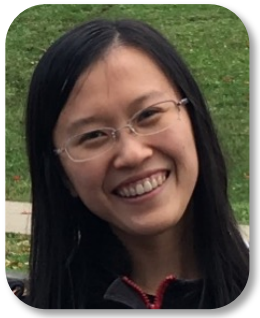

Howie Choset[2]


Andrew Orekhov[1]


Colette Abah[1]


Garrison Johnston[1]


David Neiman[2]


Y. Gu[2]

[1] Vanderbilt University

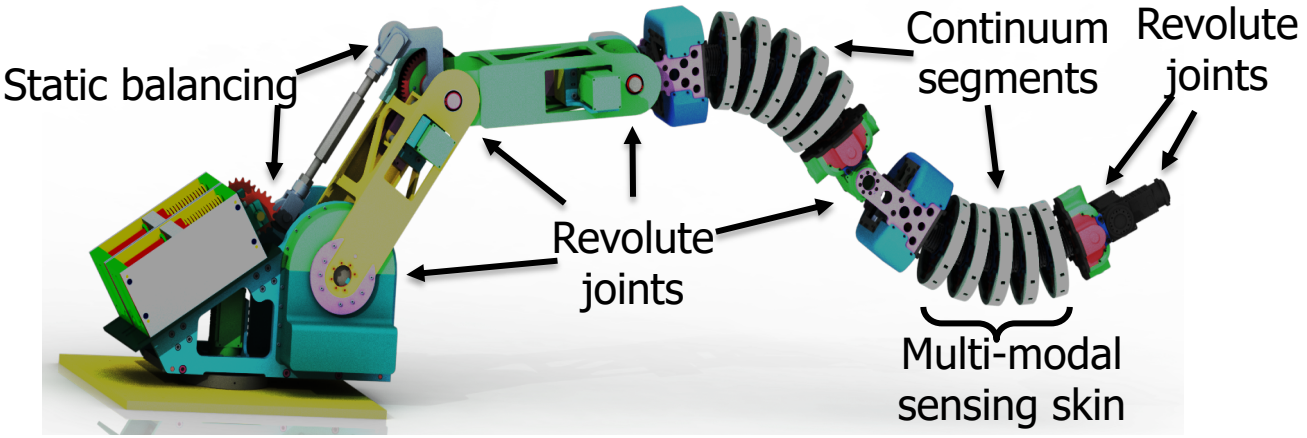
[2] Carnegie Mellon University

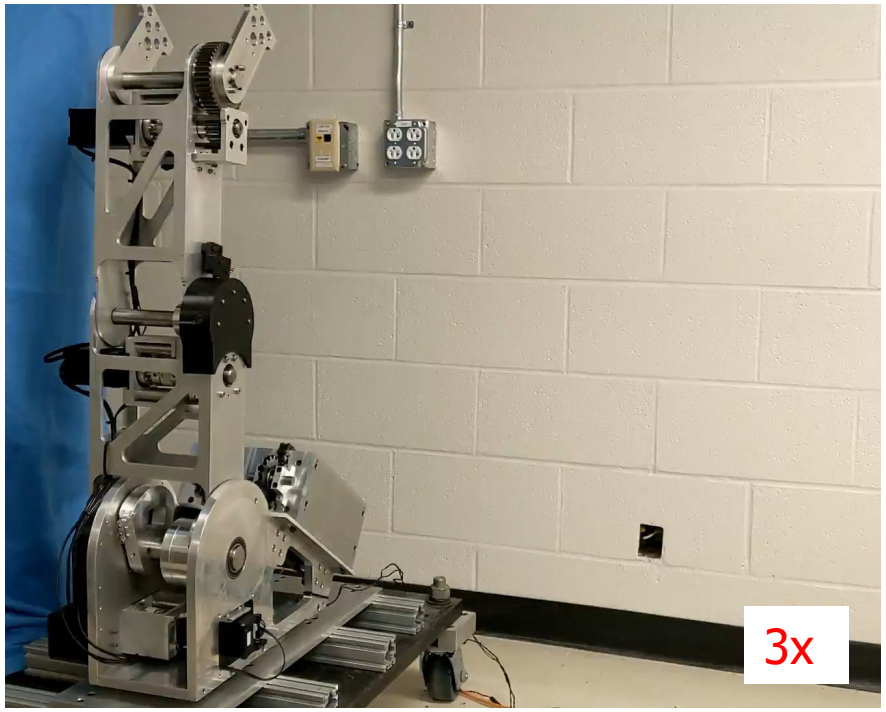
Motivation & Goal:

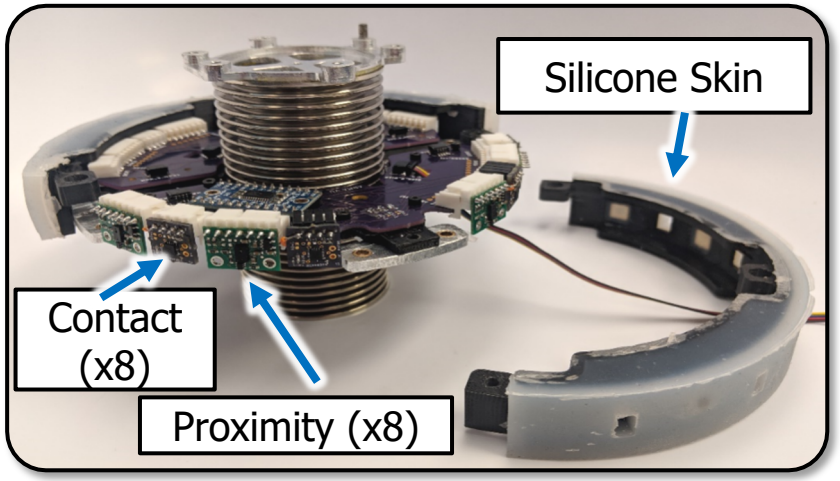
- Enable safe cooperative manipulation in deep confined spaces to reduce work-related musculoskeletal disorders (>600k per year account for 34% of lost workdays)

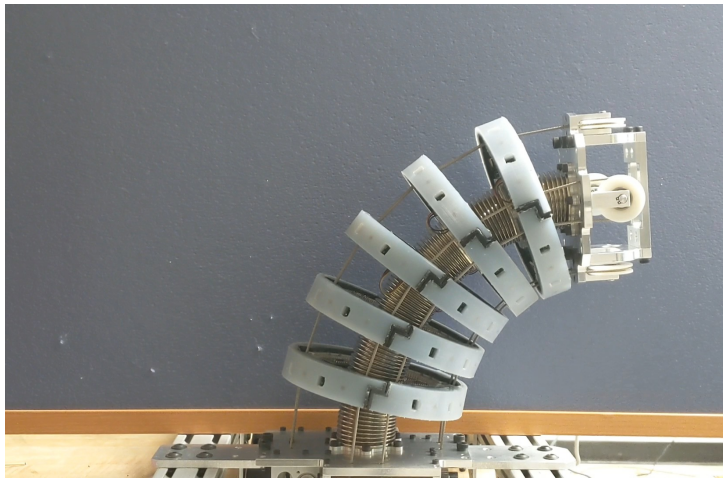
Approach:

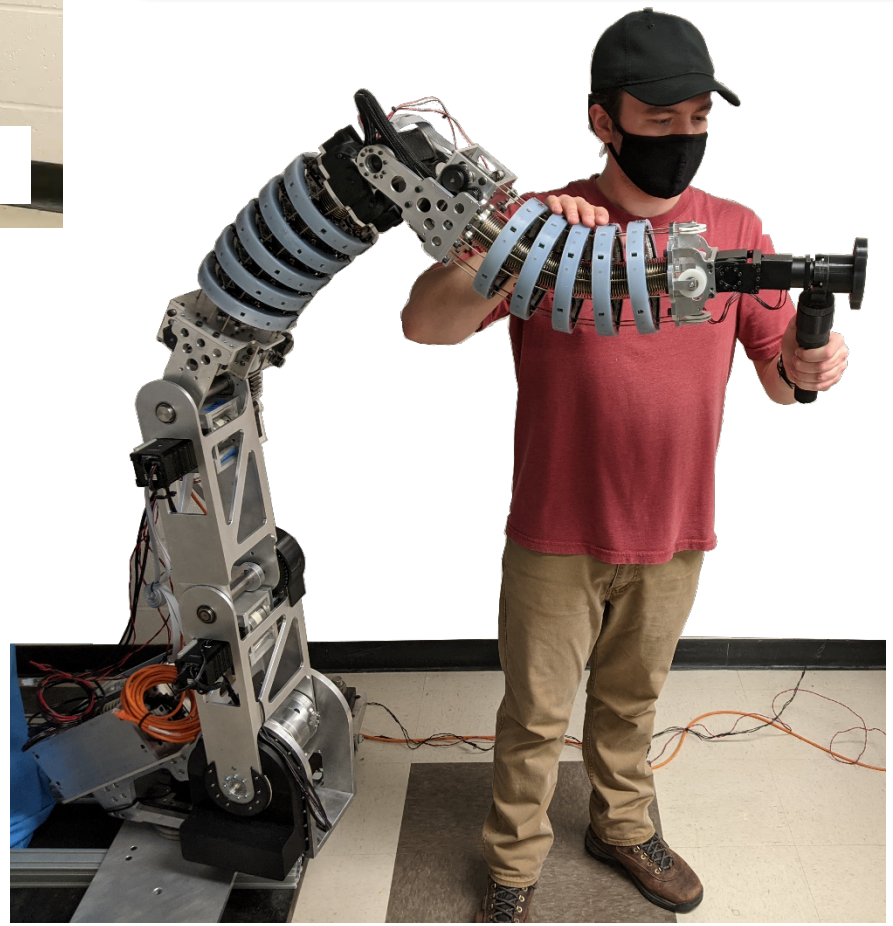
- Reconfigurable serial-continuum robots
- Whole body sensing and interaction
- Planning and control for bracing
- Sensing & environment model update




3x


Silicone Skin
Contact (x8)
Proximity (x8)

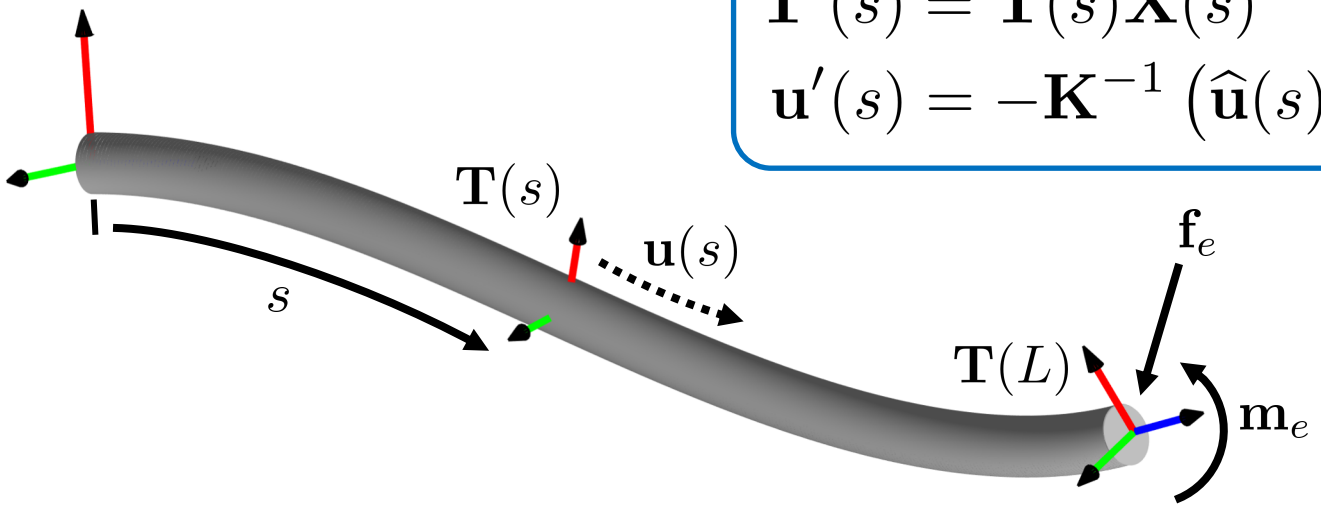




Lie Group Methods for Solving Statics of Continuum Robots

Cosserat Rod Boundary Value Problem

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

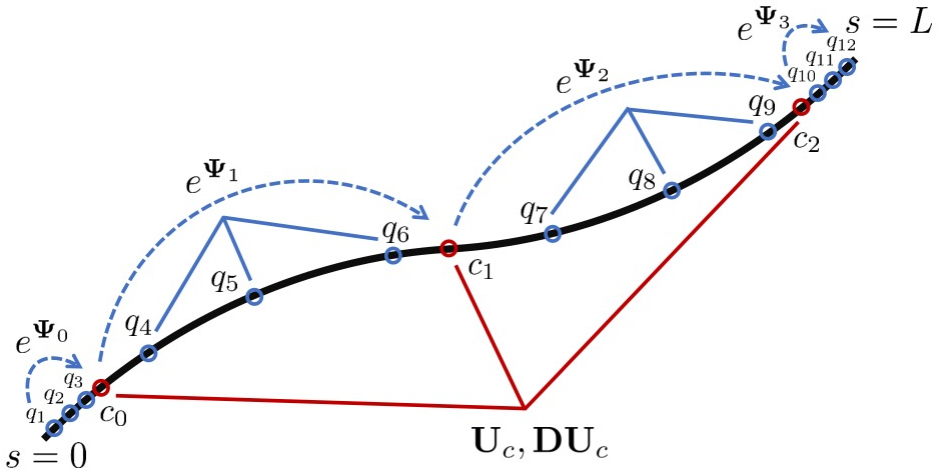


Orthogonal collocation + Magnus expansion

$$\mathbf{T}(c_k) = e^{\mathbf{\Psi}_0} e^{\mathbf{\Psi}_1} \ldots e^{\mathbf{\Psi}_k}, \quad \mathbf{\Psi}_i \in se(3)$$

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



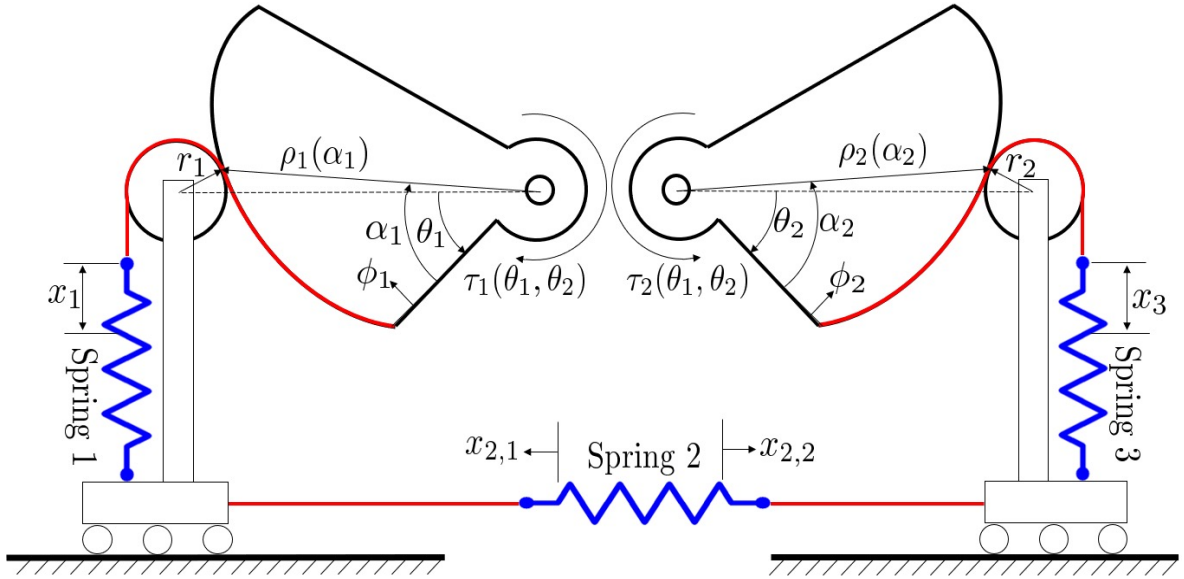
A. L. Orekhov and N. Simaan, "Solving Cosserat Rod Models via Collocation and the Magnus Expansion," IROS 2020, pp. 8653-8660, doi: 10.1109/IROS45743.2020.9340827.

Static Balancing Wrapping-Cam Design Optimization

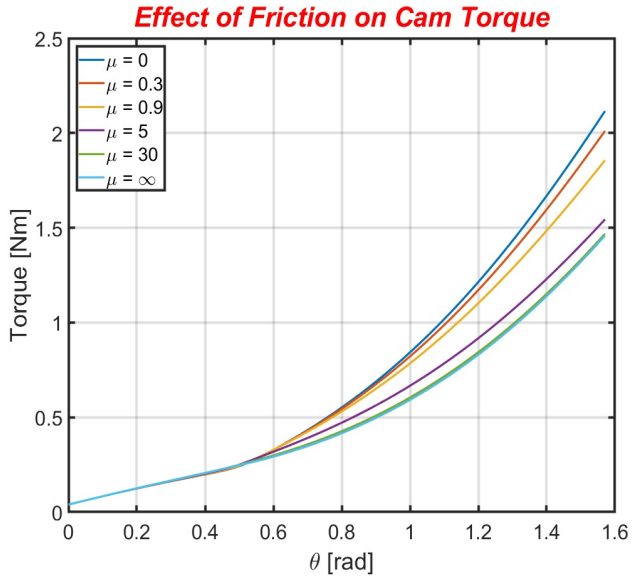
Contribution

Design framework for

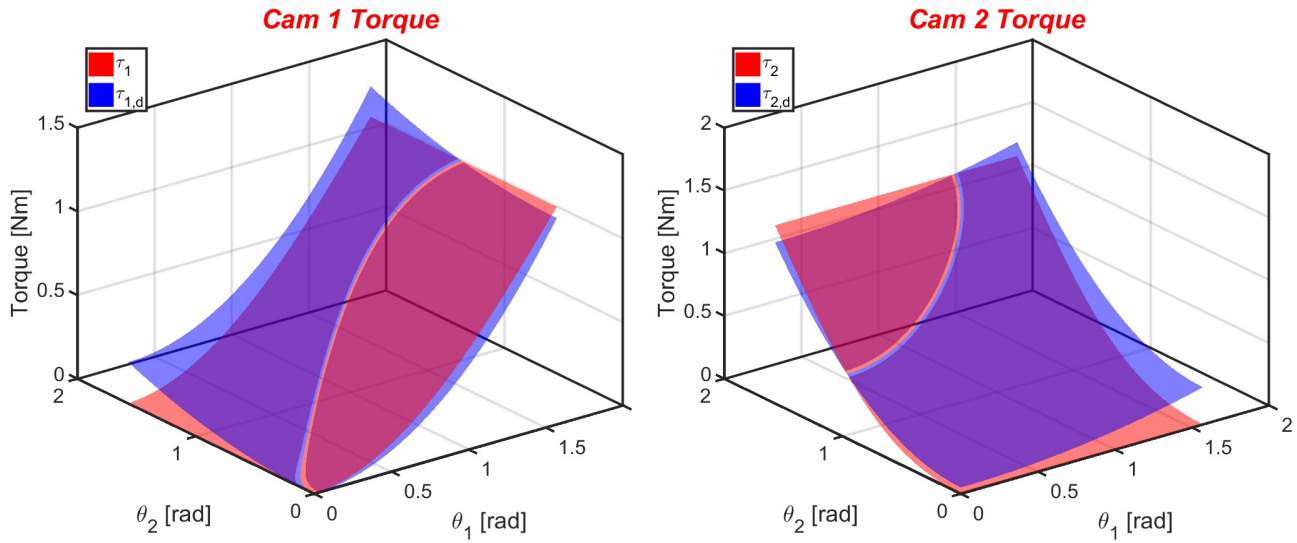
- Ensuring cam is convexity
- Staying within spring limits
- Increasing robustness to parameter uncertainty
- Friction modeling for cam/wire
- Balancing of couples 2DoF systems



2 DoF Wrapping Cam Design

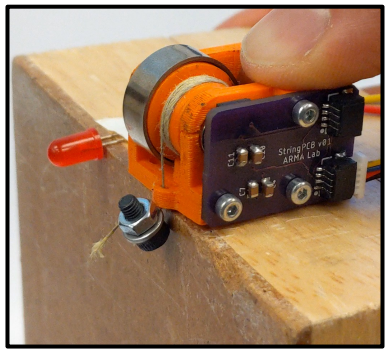


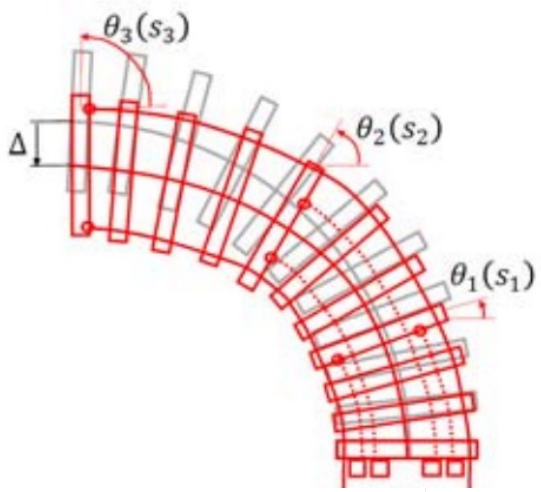
Effect of Friction on a One-Dof Cam

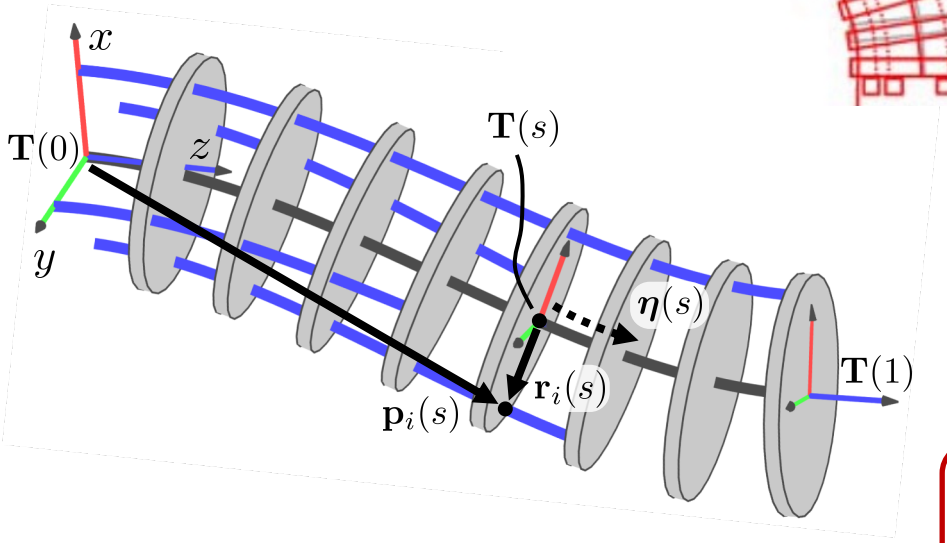


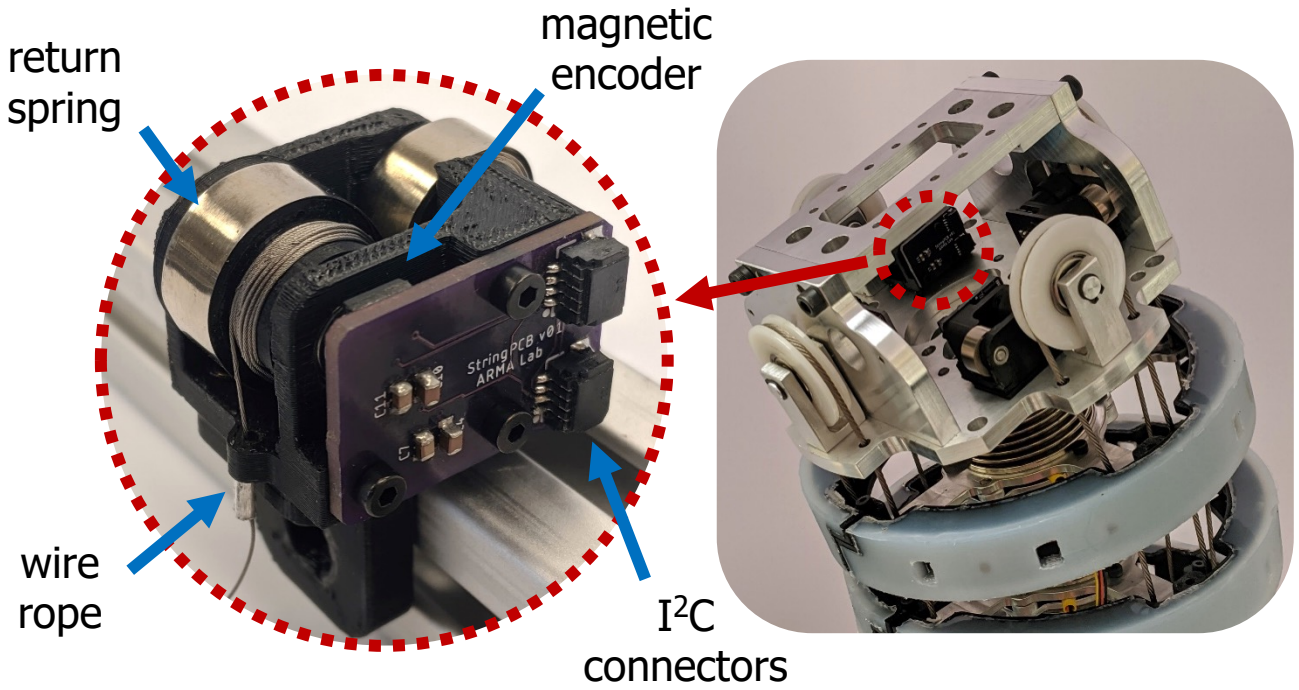
Simulation Progress: Desired vs Actual Cam Torque

Shape Sensing with General String Encoder Routing









String routing functions

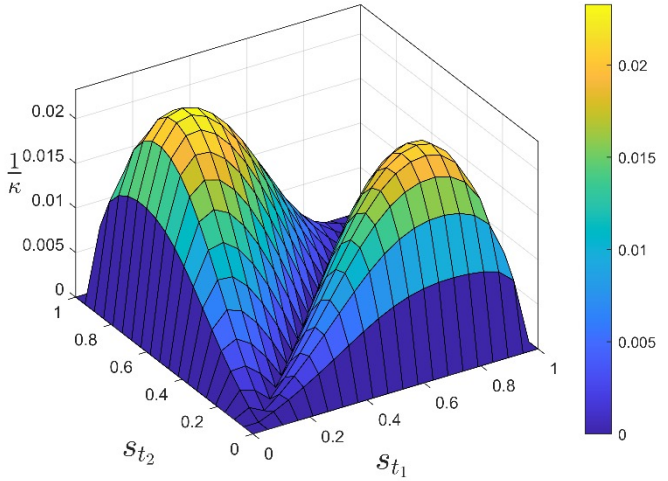
$$\mathbf{r}_i(s) = [r_{x_i}(s), r_{y_i}(s), 0]^{\mathrm{T}} \in \mathbb{R}^3$$

Identification Jacobian

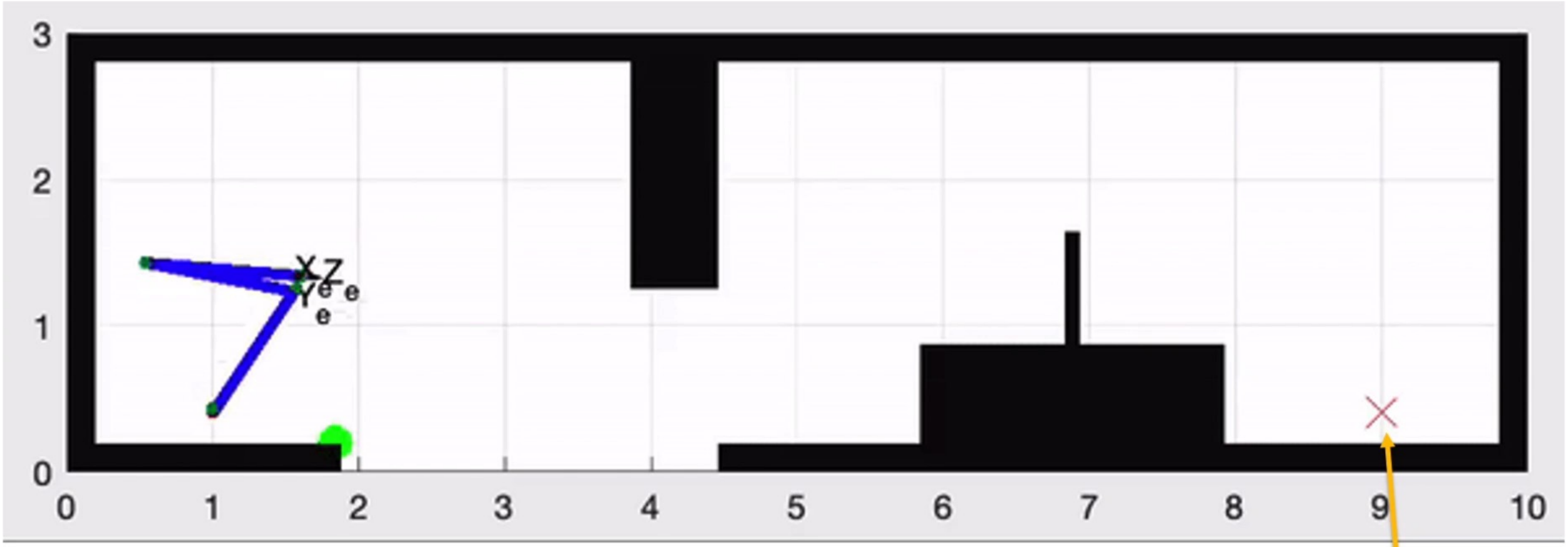
$$\mathrm{d}\boldsymbol{\ell} = \mathbf{J}_{\ell c}\mathrm{d}\mathbf{c}$$

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

String routing optimization



Planning for Bracing



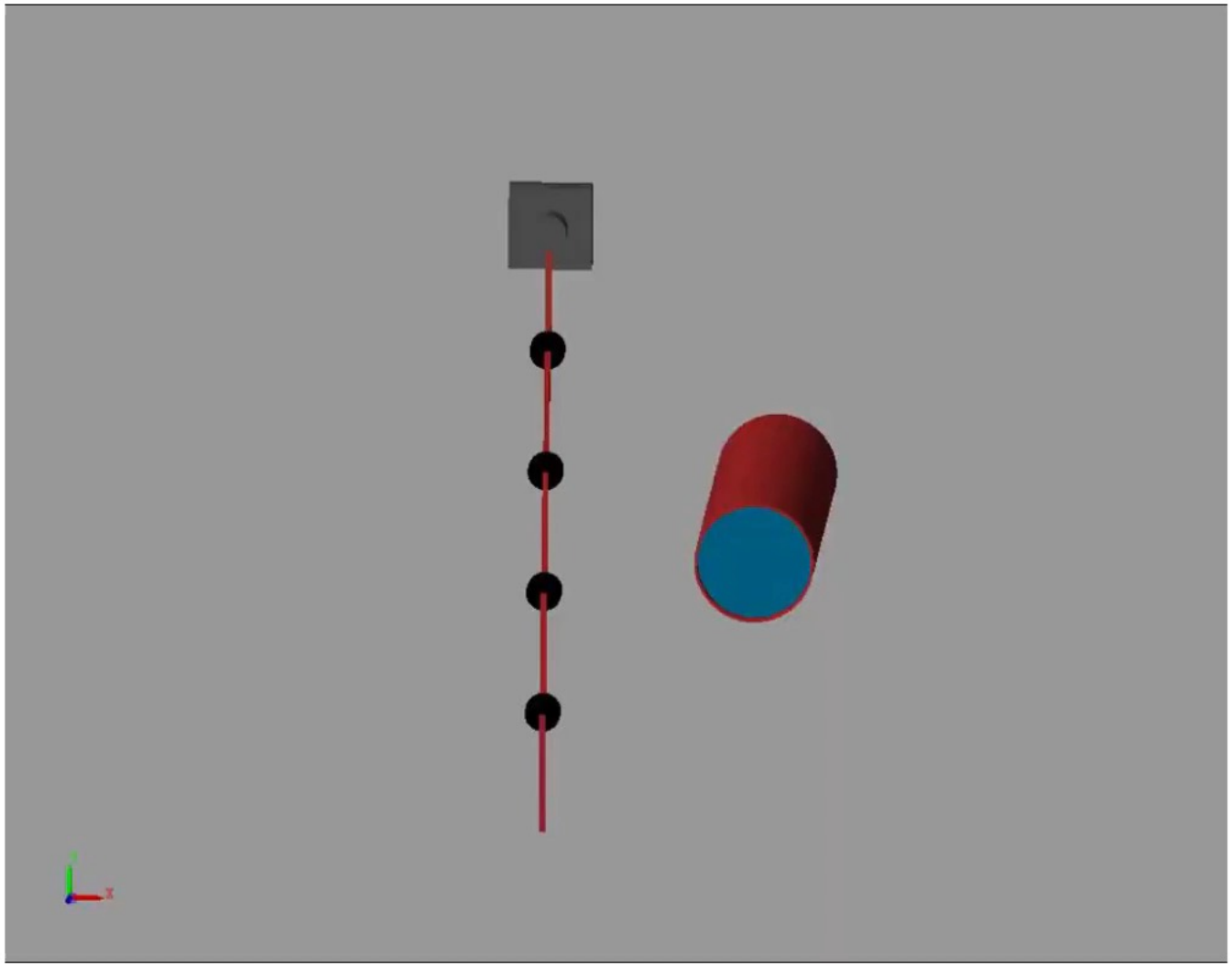
Robot parameters:
15 link planar arm
5 subrobots
3 links per subrobot

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

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

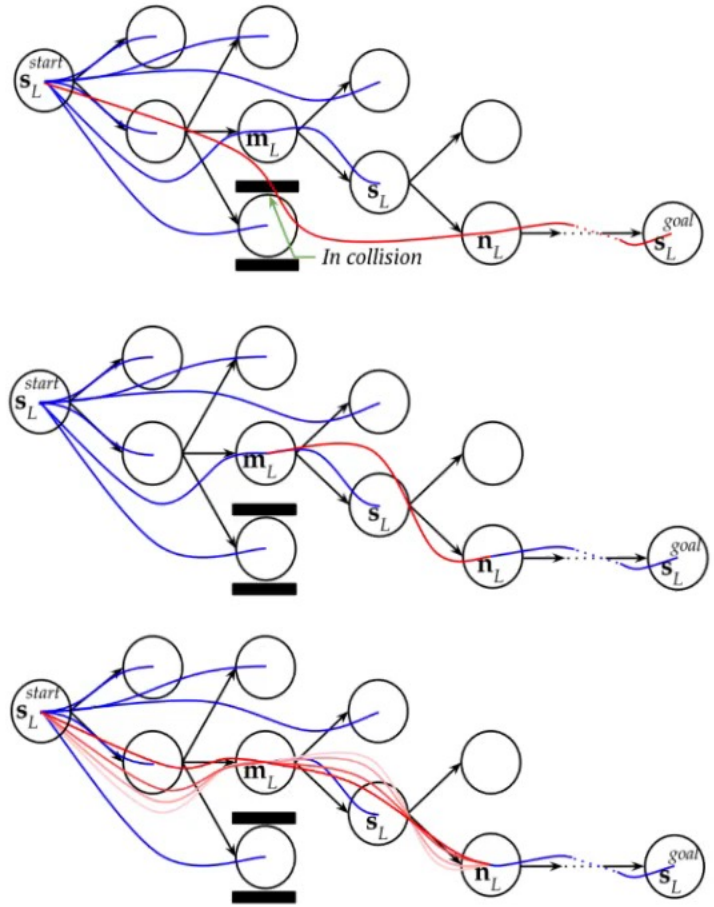
Goal

Planning for Bracing using INSAT algorithm*



- 5 link arm with torque constraints and 1 obstacle
- INSAT finds where to brace on the obstacle to offset torque limits

INSAT Algorithm



Graph search (joint configuration)

Trajectory optimization (joint angles and velocities)

* Ramkumar Natarajan, Howie Choset and Maxim Likhachev, ***"Interleaving Graph Search and Trajectory Optimization for Aggressive Quadrotor Flight,"***
IEEE Robotics and Automation Letters (RA-L), 2021