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]

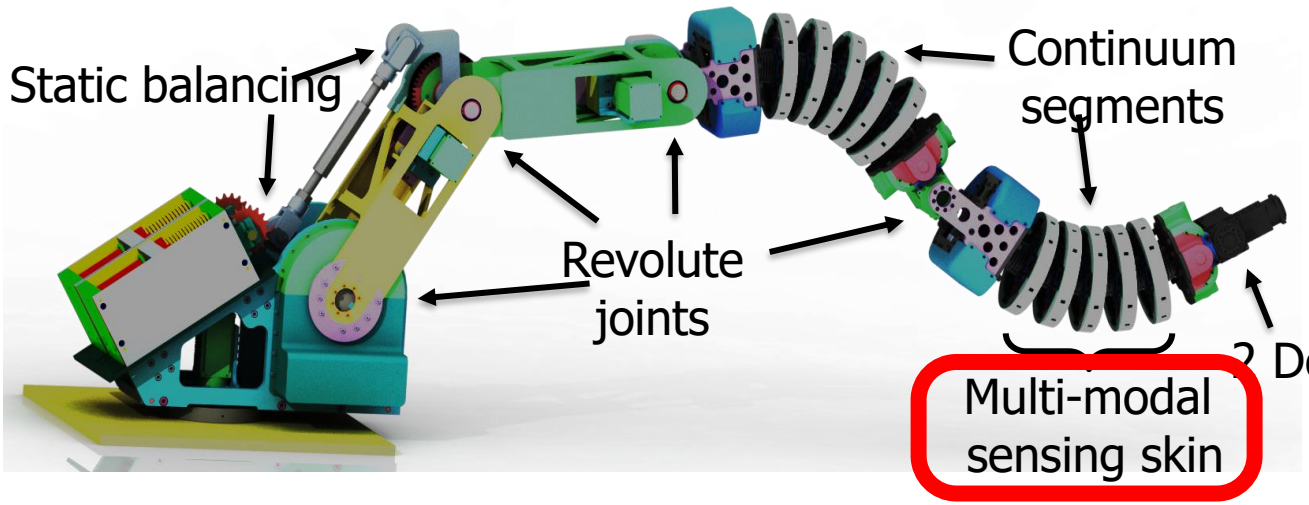
Y. Gu[2]

Ramkumar Natarajan[2]

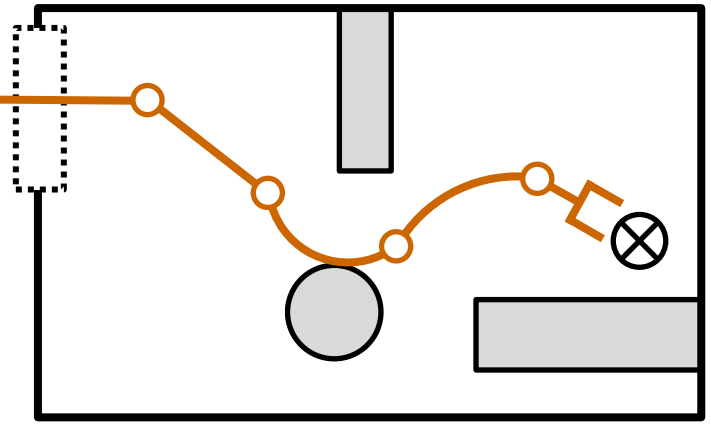
[1] Vanderbilt University

[2] Carnegie Mellon University

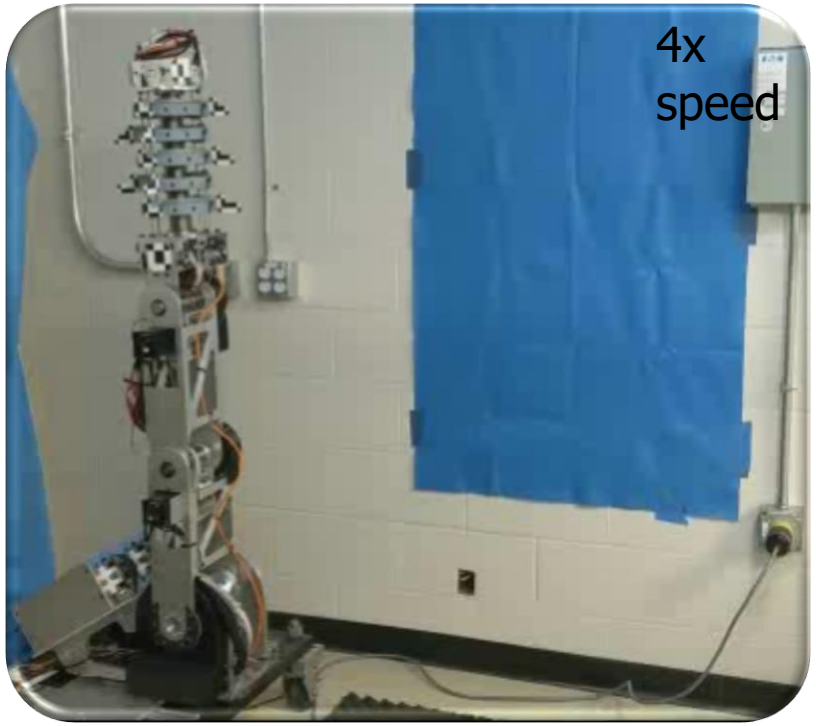
In-situ Collaborative Robots (ISCRs)



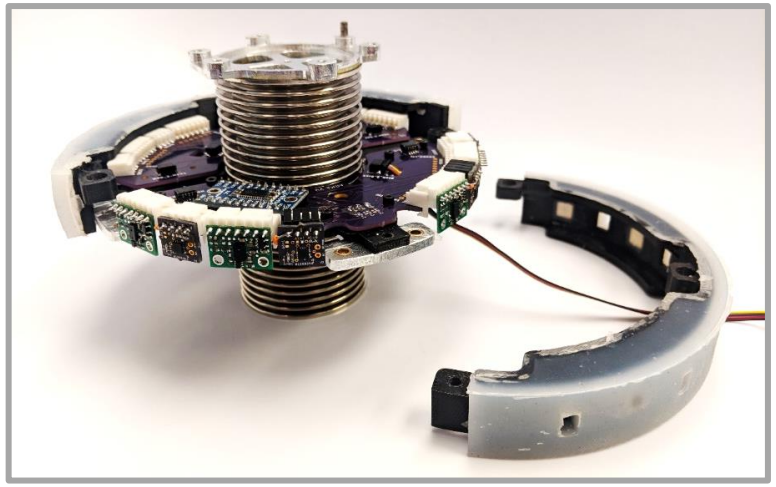
CMU Team: Planning for bracing

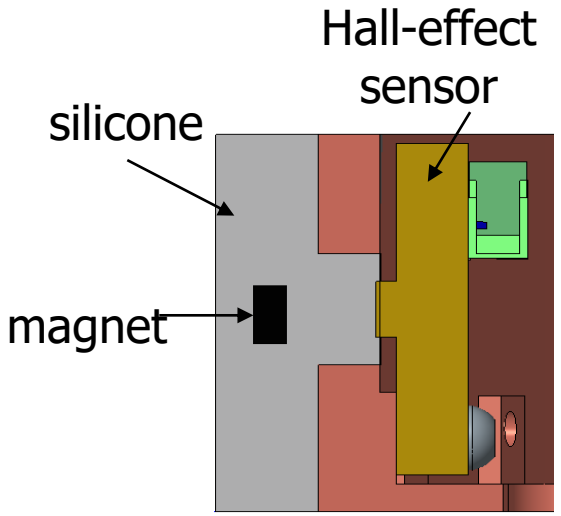


- Dexterity, Reach, and Load Capacity
- Whole-body situational awareness
- Active\Passive Safety

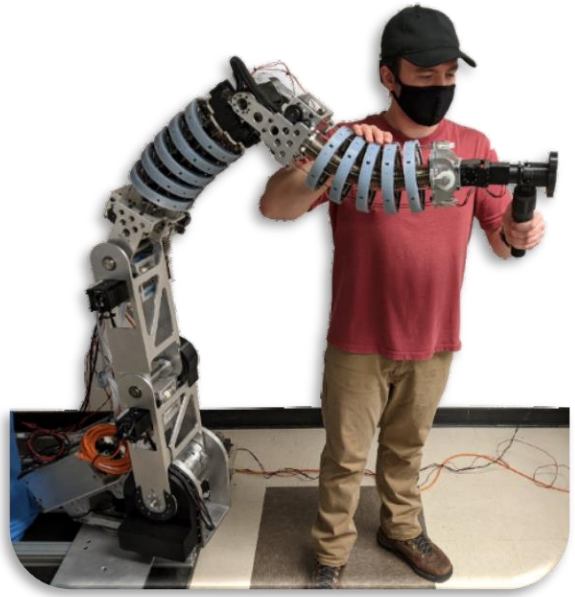


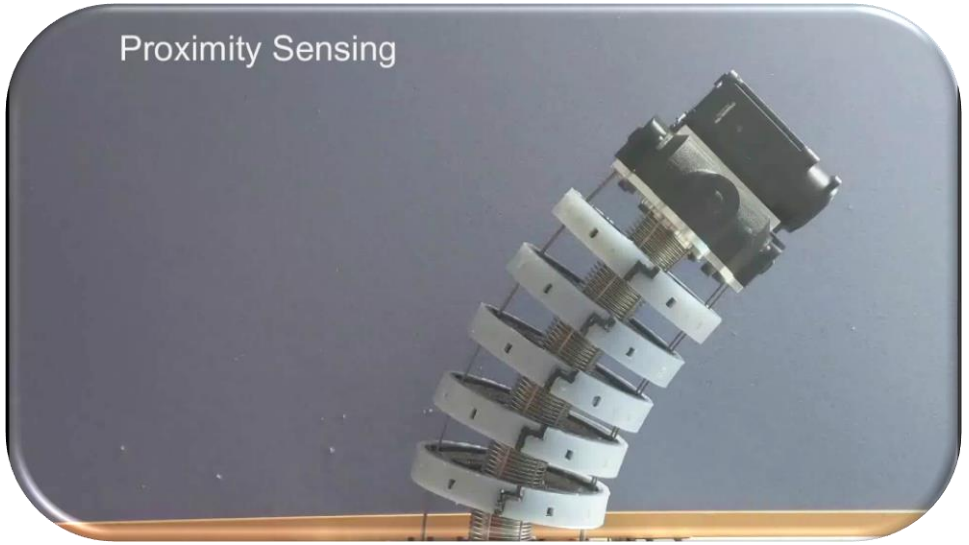
Multi-Modal Sensing & Control

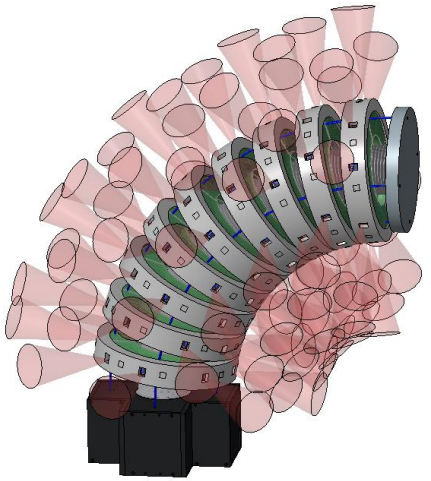




- Proximity sensing
- Contact detection
- Force sensing
- Mapping



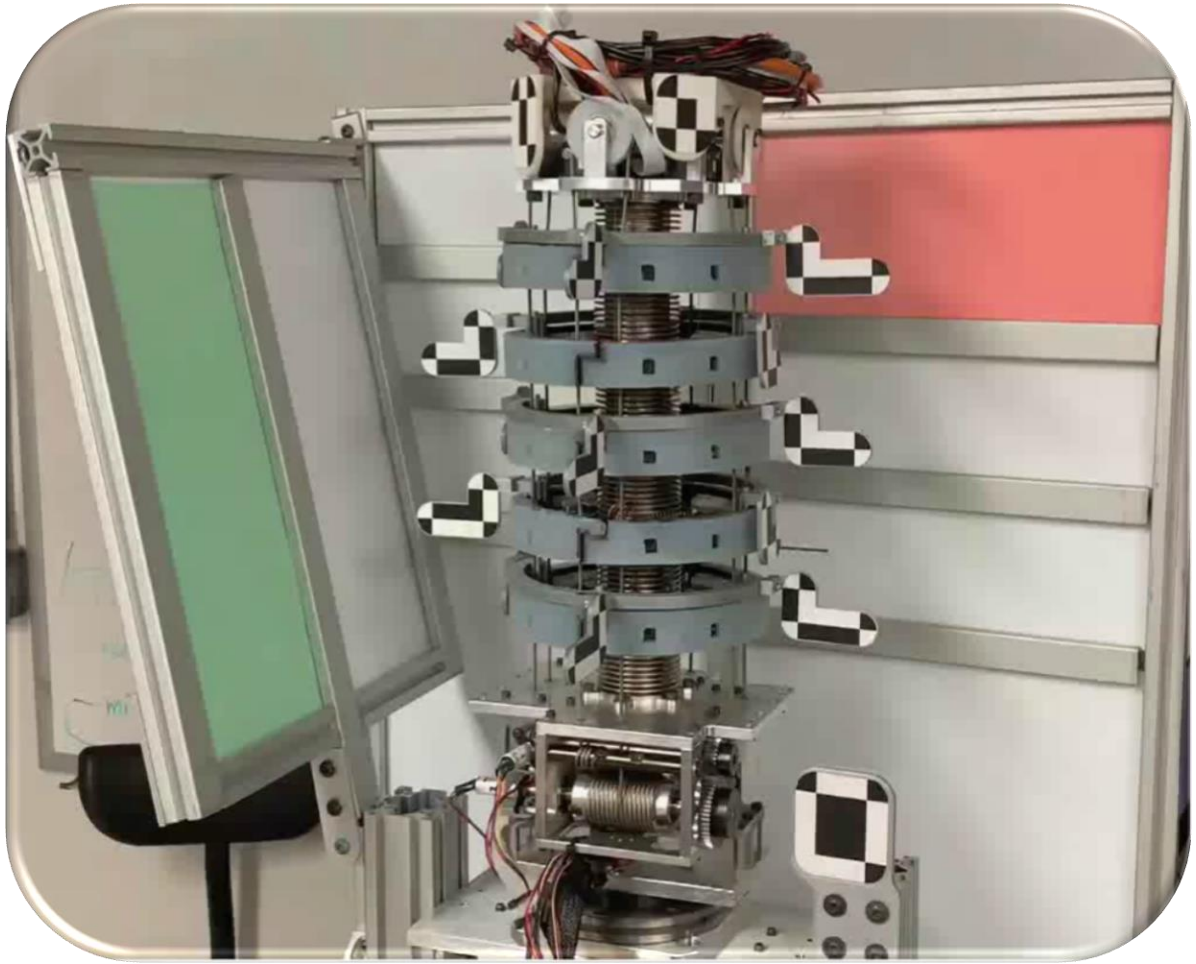


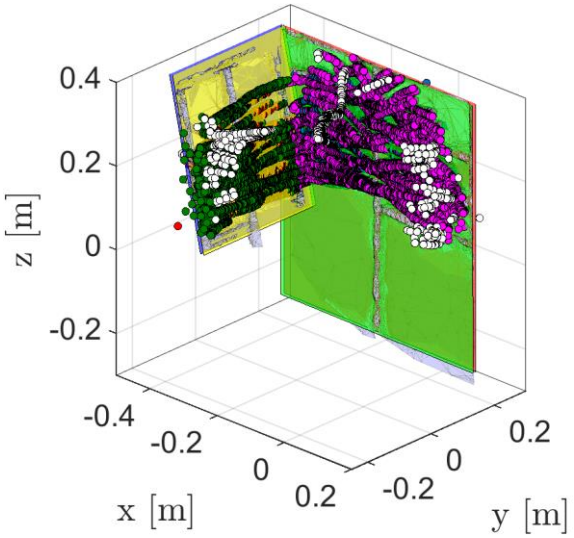


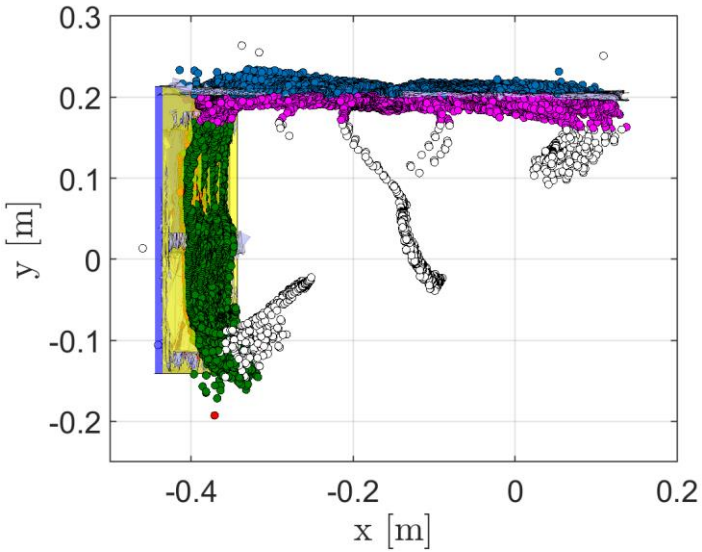
C. Abah, A. L. Orekhov, G. L. H. Johnston and N. Simaan, "A Multi-Modal Sensor Array for Human–Robot Interaction and Confined Spaces Exploration Using Continuum Robots," in *IEEE Sensors Journal*, vol. 22, no. 4, pp. 3585-3594, 15 Feb.15, 2022, doi: 10.1109/JSEN.2021.3140002.

Evaluation of Environment Mapping

Speed 9x







Mapping RMSE:
9.73 mm

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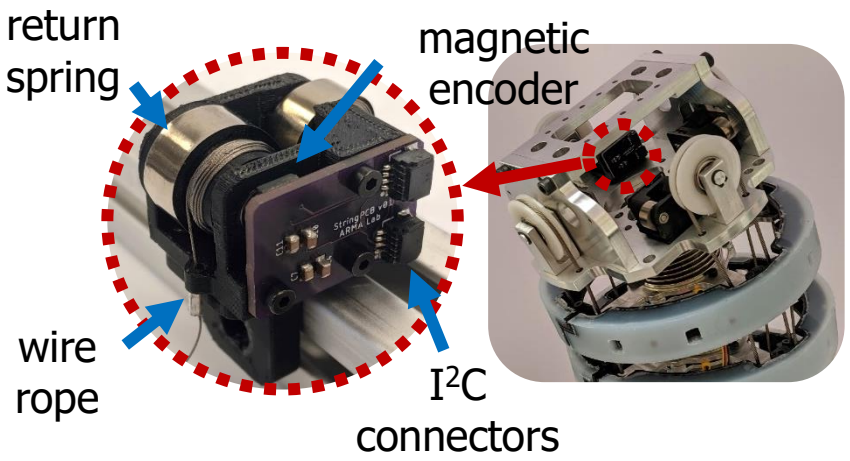
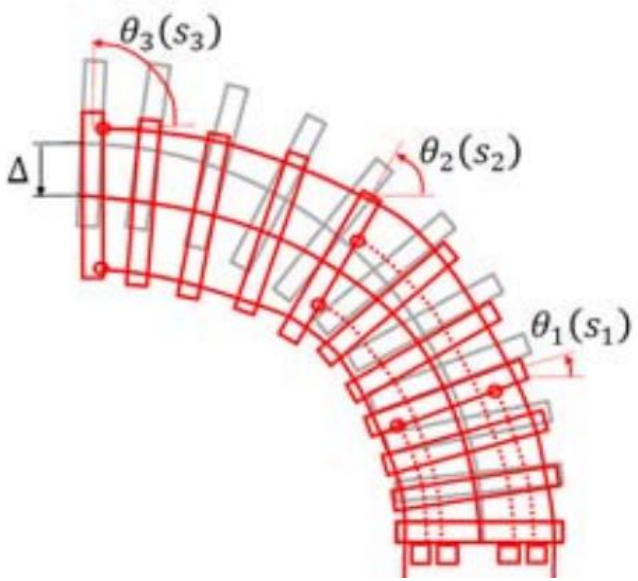
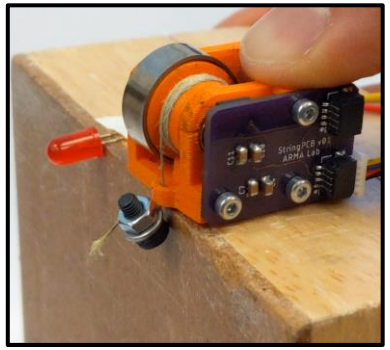
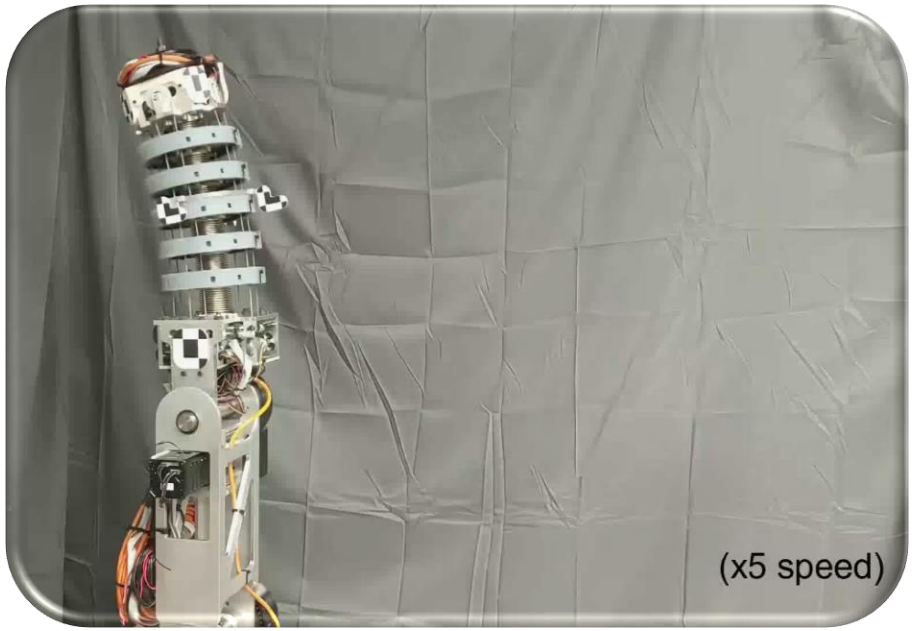
Shape Sensing with General String Encoder Routing









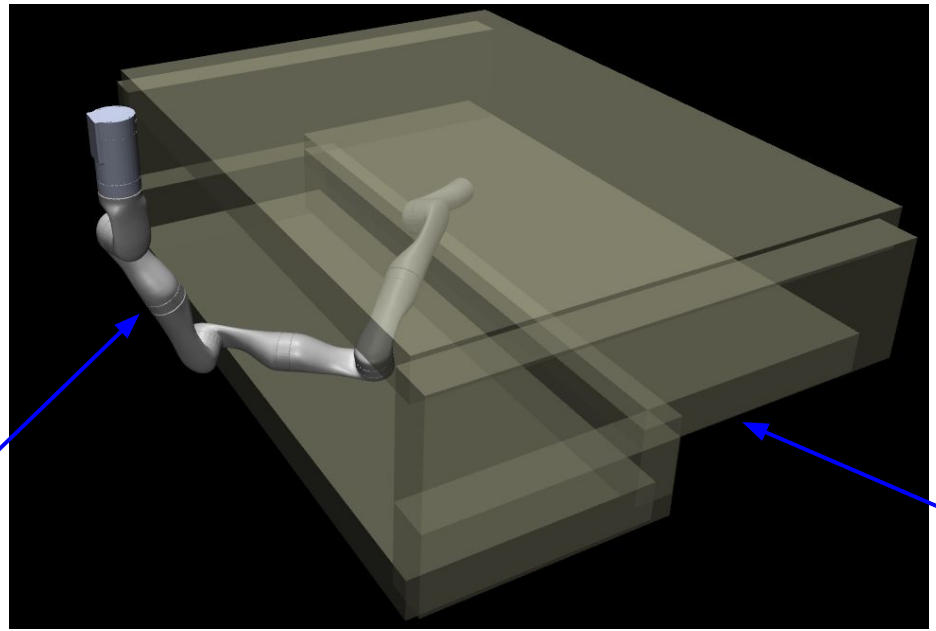
(with 3 lb load)

- Max position error <5% of total length
- 80% reduction in position error vs without shape sensing
- 40% reduction in angle error vs without shape sensing

Orekhov, L, Ahronovich, E. Z., Simaan, N., "Lie Group Formulation and Sensitivity Analysis for Shape Sensing of Variable Curvature Continuum Robots with General String Encoder Routing", In revision, IEEE TRO, 2022

Manipulation Planning through Bracing

INterleaved Search And Trajectory Optimization (INSAT)*



Torque limited manipulator arm

Confined space with a step extrusion

* Natarajan, R., Choset, H., & Likhachev, M. (2021). Interleaving graph search and trajectory optimization for aggressive quadrotor flight. *IEEE Robotics and Automation Letters*, *6*(3), 5357-5364.

Manipulation Planning through Bracing

INterleaved Search And Trajectory Optimization (INSAT)*

Low dimensional graph search

i.e. non-convex subset of the state space

Kinostatically feasible trajectory in manipulator configuration space

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Manipulation Planning through Bracing

INterleaved Search And Trajectory Optimization (INSAT)*

Low dimensional graph search

i.e. non-convex subset of the state space

Kinostatically feasible trajectory in manipulator configuration space

High dimensional trajectory optimization

i.e. dynamics (derivative) variables

Dynamically feasible trajectory in state space (joint angles, joint velocity & contact model parameters)

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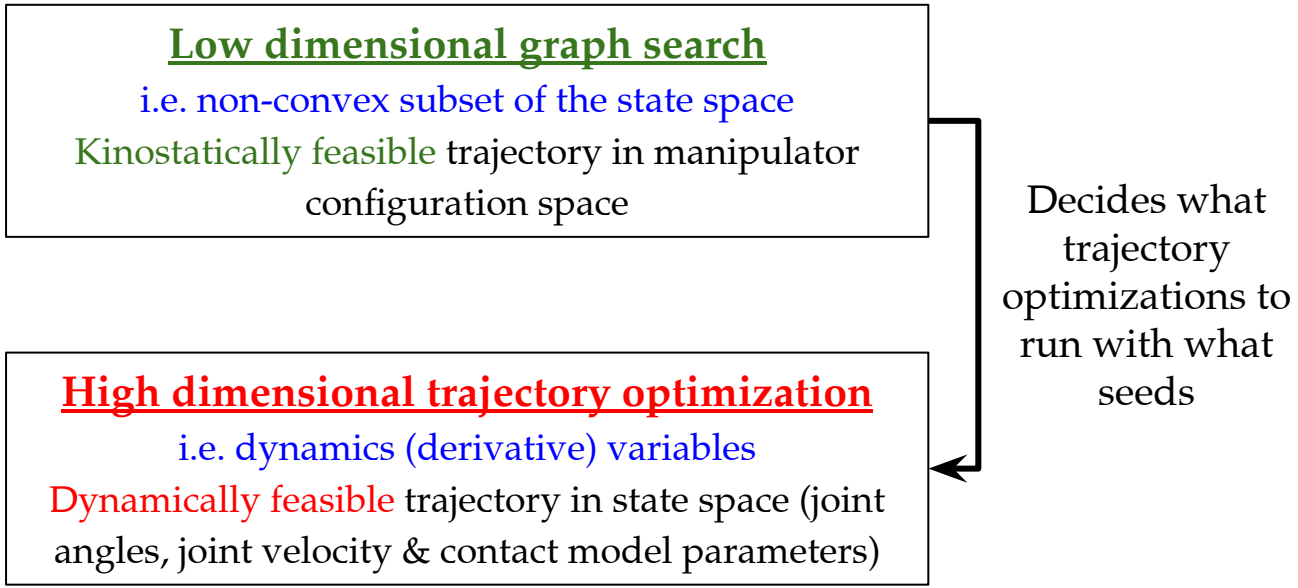

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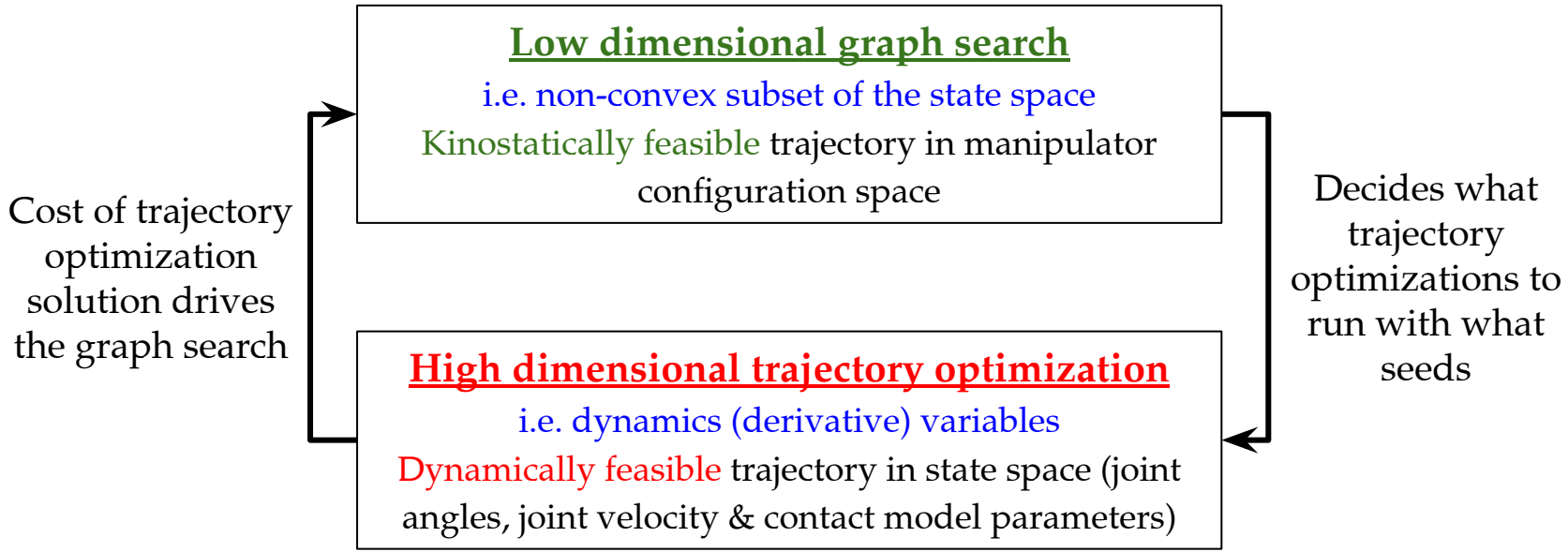

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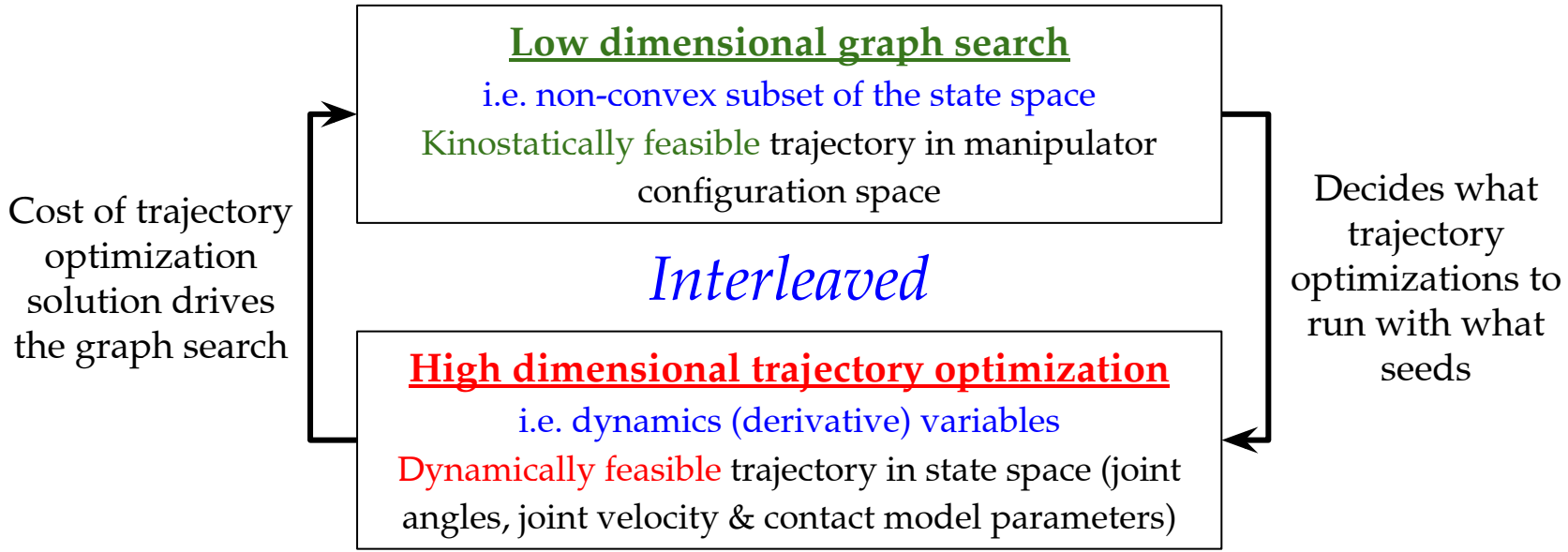

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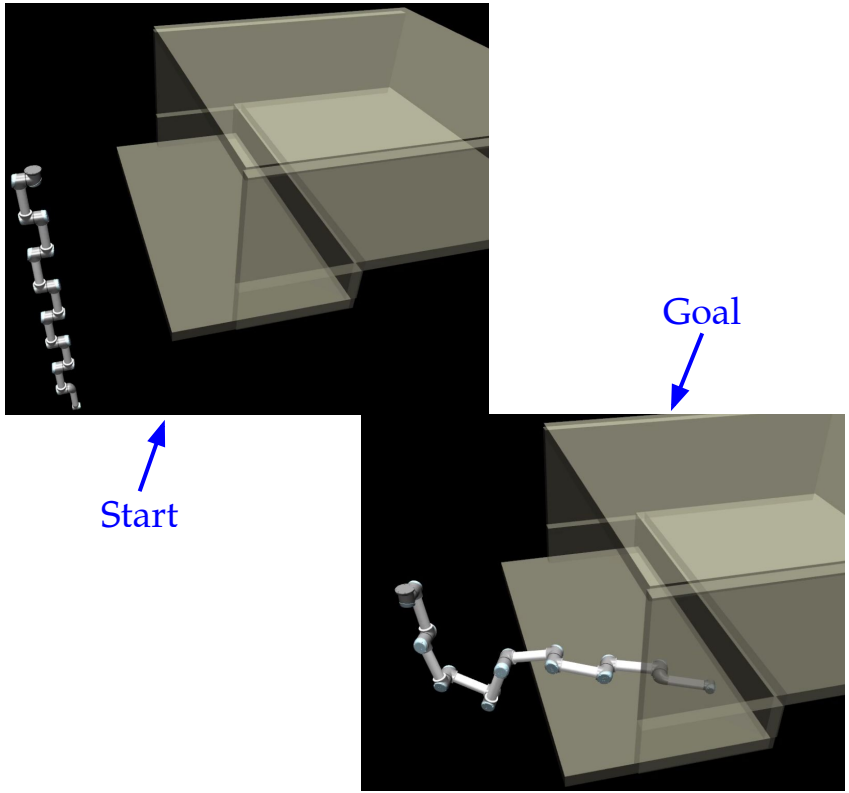
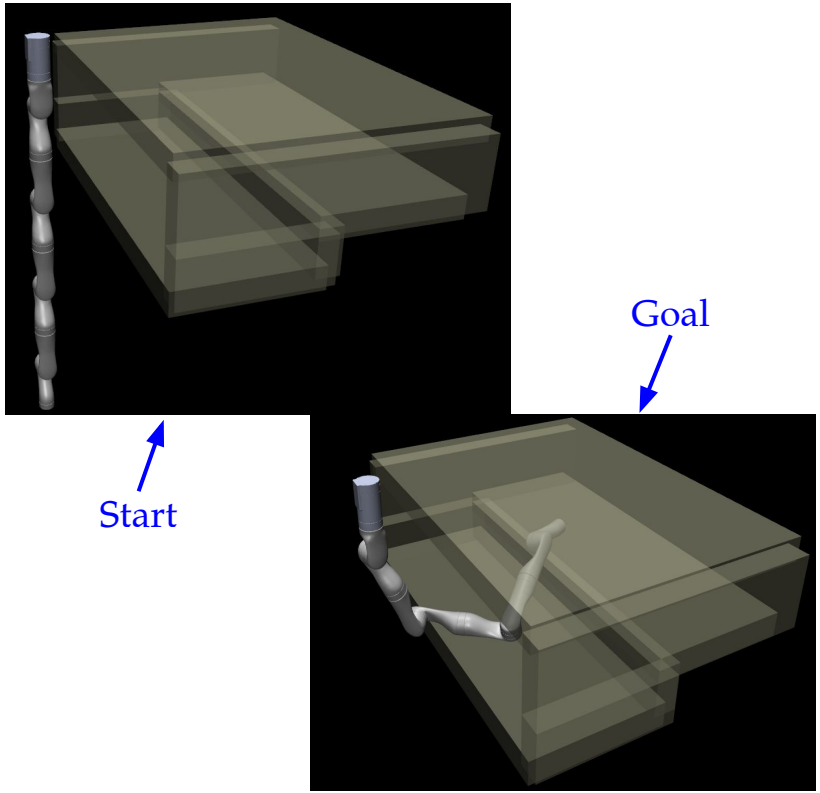
Long redundant manipulator reaches confined space by bracing

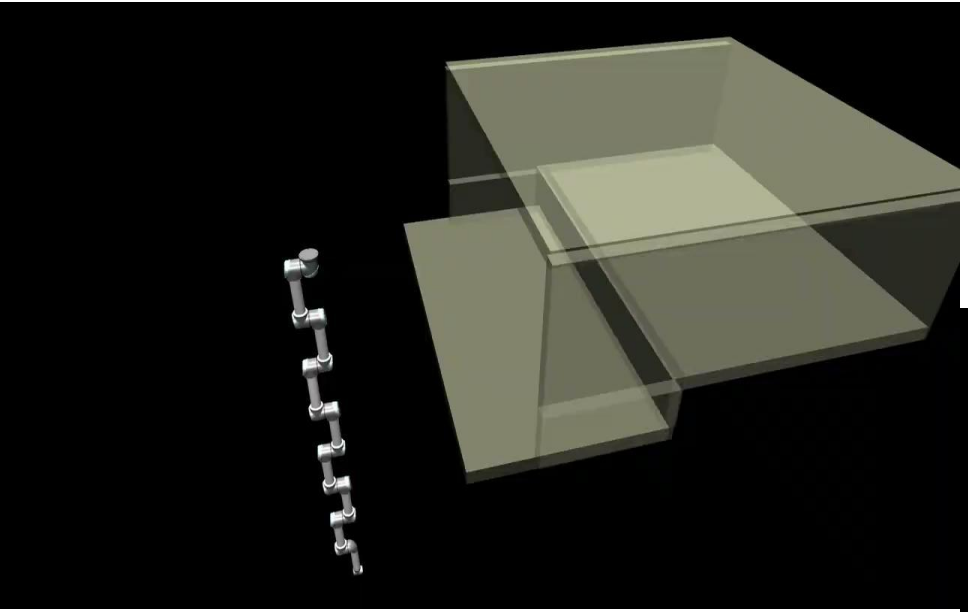
9 link UR arm



8 link Kinova arm



Long redundant manipulator reaches confined space by bracing



Swings and tucks to minimize torque

Swings and slides to reach the goal