In-Situ Collaborative Robotics in Confined Spaces

Andrew Orekhov[1], Garrison Johnston[1], Colette, Abah[1], David Neiman[2],
Julian Whitman[2], Yizhu Gu[2], Howie Choset[2], Nabil Simaan[1]

[1] ARMA Lab, Dept. of Mech. Engineering, Vanderbilt University, Nashville, TN 37235 – **CMMI #1734461**
[2] Biorobotics Lab, Carnegie Mellon University, Pittsburgh, PA 15213 – **CMMI #1734360**

Motivation

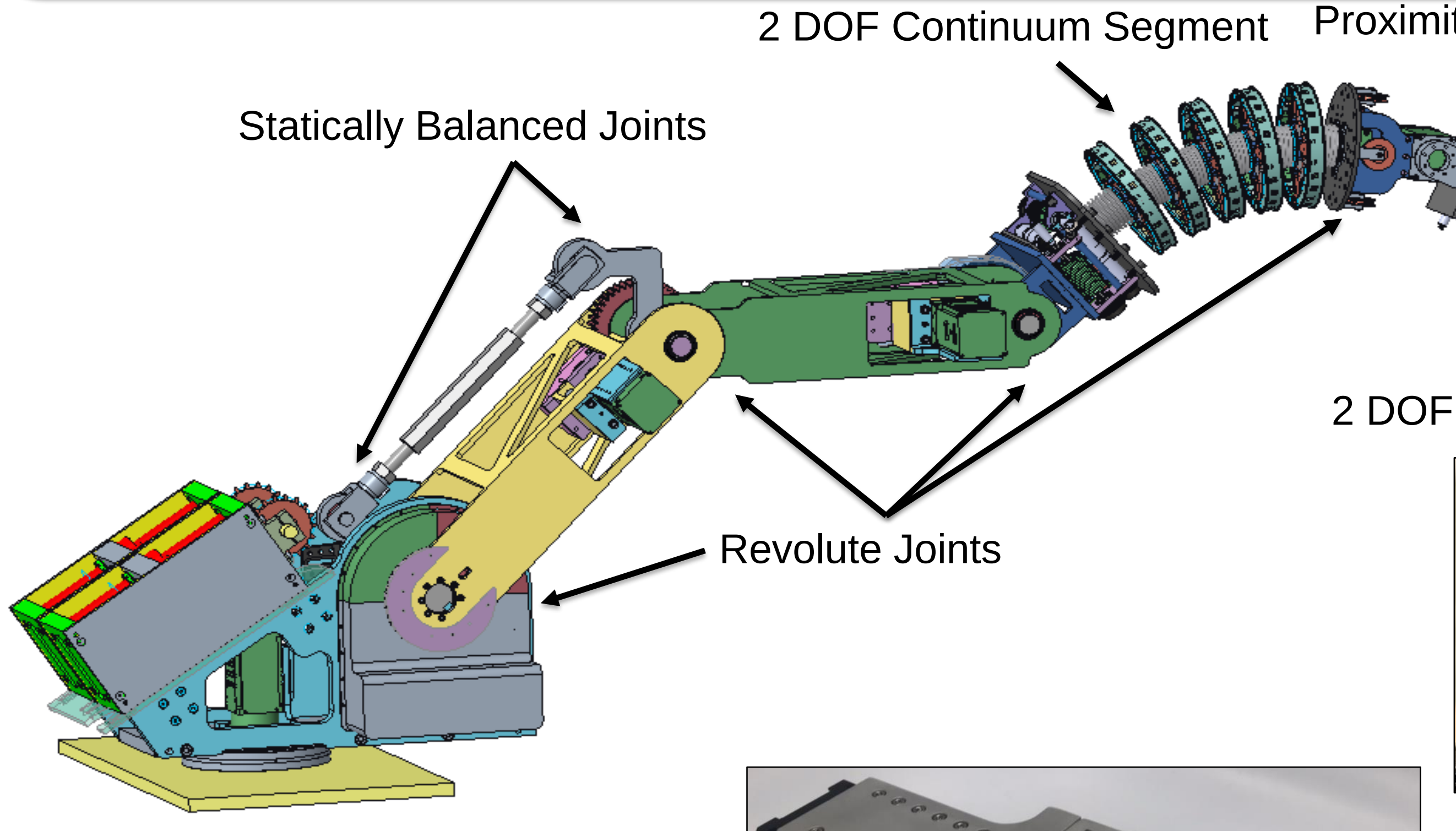
- Industrial workers often have to perform manufacturing or service tasks in tight spaces.
- Cooperative manufacturing in confined spaces demands cooperation modes and levels of dexterity, sensing, and safety that exceed capabilities of existing robotic systems.
- **Goal**: Develop and validate new technologies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

Scientific Merit:

- The proposed work introduces a new architecture of In-Situ Collaborative Robots (ISCR) in confined spaces.
- Use the robot's flexibility to facilitate physical interaction between the user and the robot. These capabilities include contact sensing and localization, and proximity measurements along the robot.
- Modeling and planning with contact for such robots.
- A new approach for compliant motion control of ISCRs.
- Development of an approach for multi-point interaction between the user and the robot.

Manipulator Design



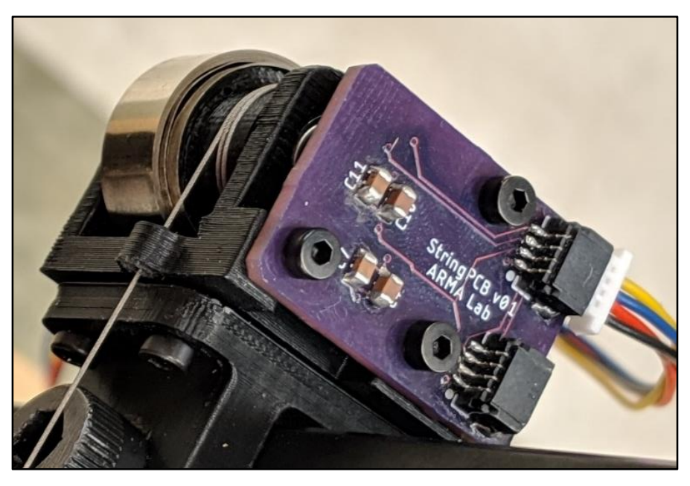
2 DOF Continuum Segment

Proximity and Contact Sensors

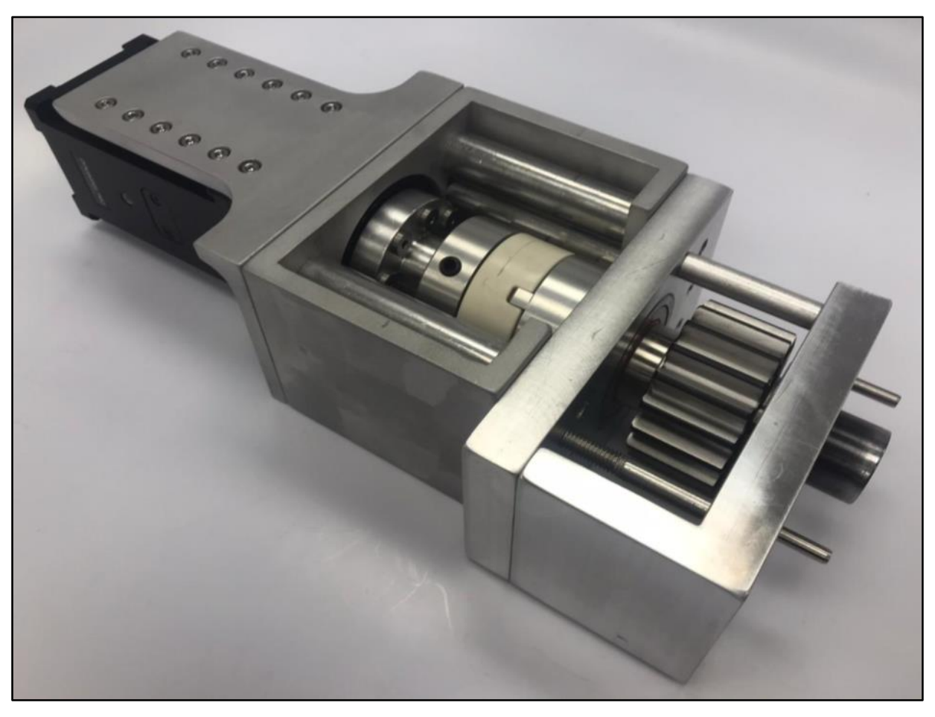
Statically Balanced Joints

2 DOF Continuum Segment

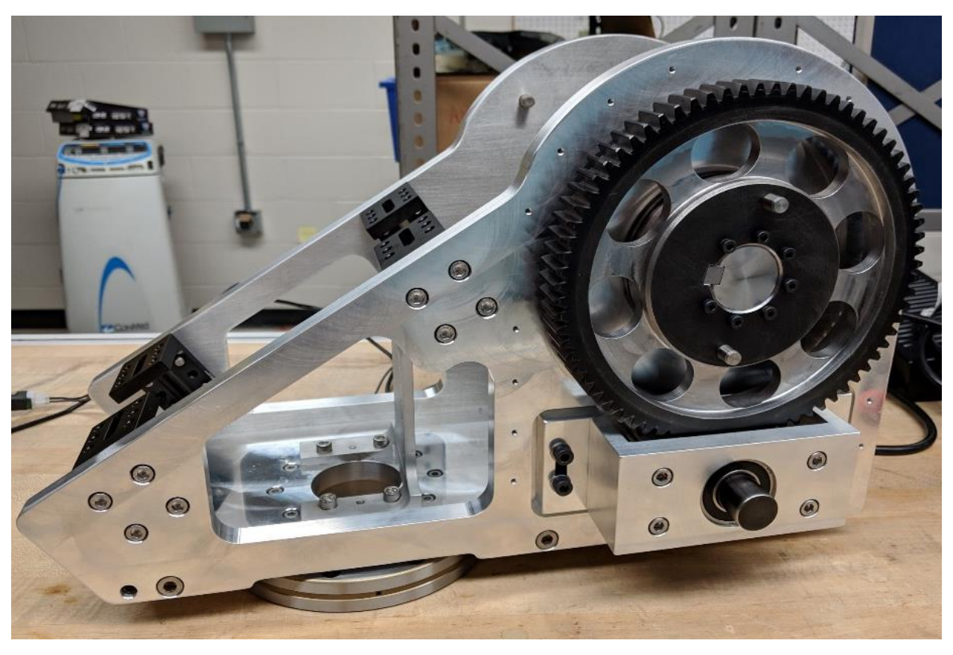
Revolute Joints



String Potentiometer for shape sensing



Second Pitch Joint Actuation Unit



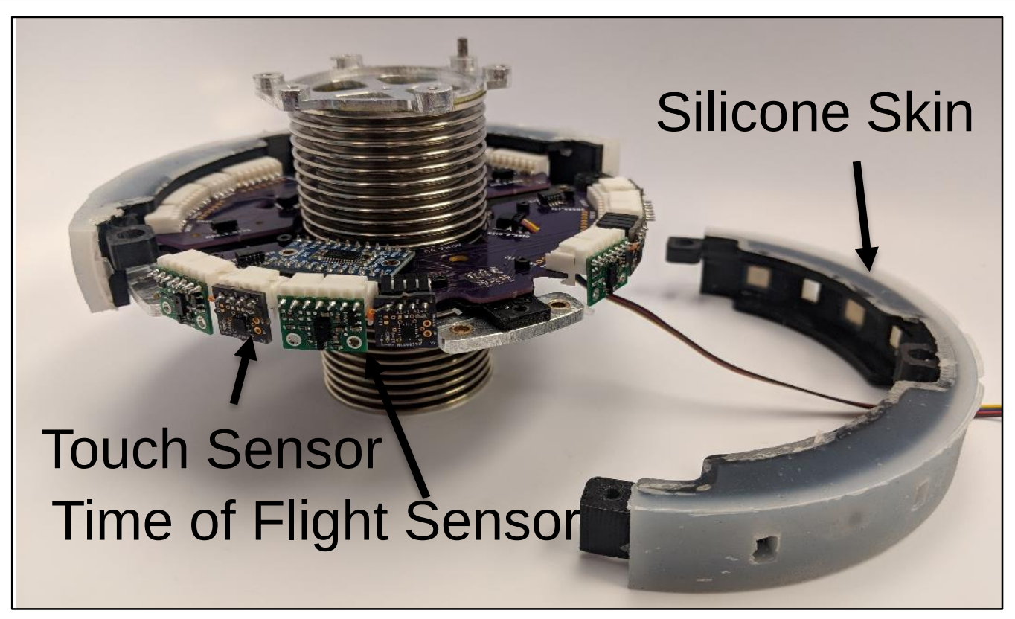
Robot Base

Continuum Segment Base Structure

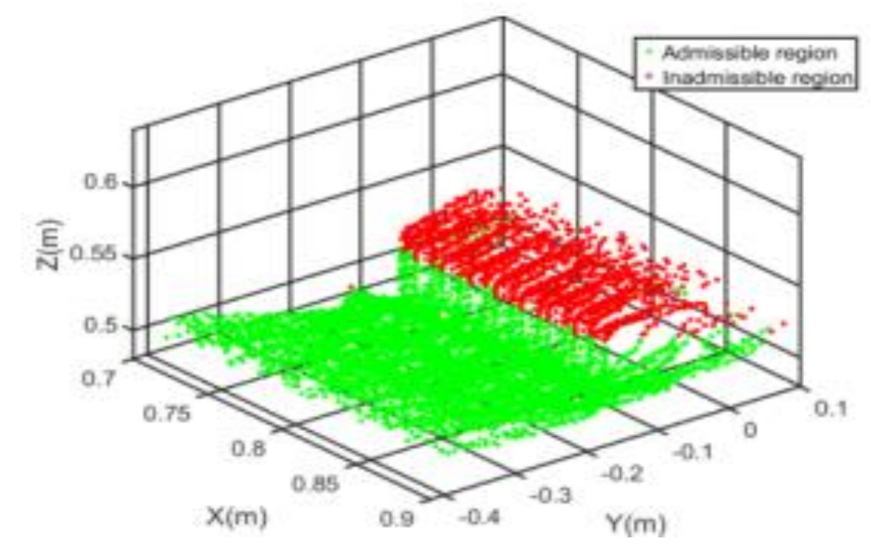
The proposed modular ISCR combines rigid links, revolute actuators, and flexible continuum segments with proximity and contact sensors in each continuum segment disk for environment mapping, controlled bracing against the environment, and improved human safety.

Sensory Disk Design

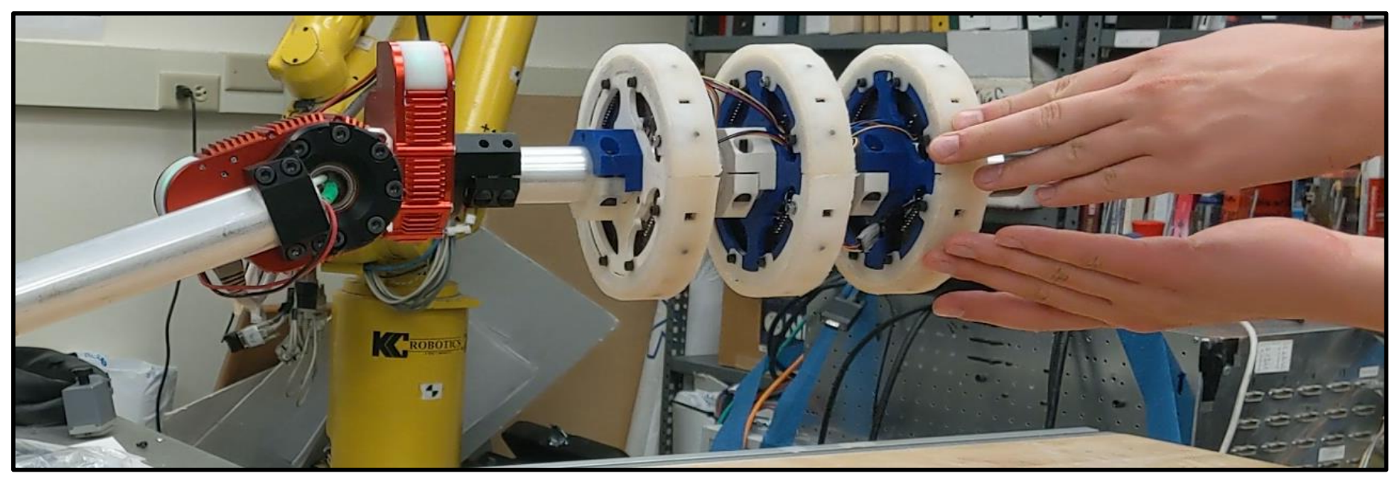
Continuum segment spacer disks are lined with proximity and contact sensors. These sensors will enable environment mapping, controlled bracing against the environment, and improved human safety [1][2].



Sensory Disk Assembly



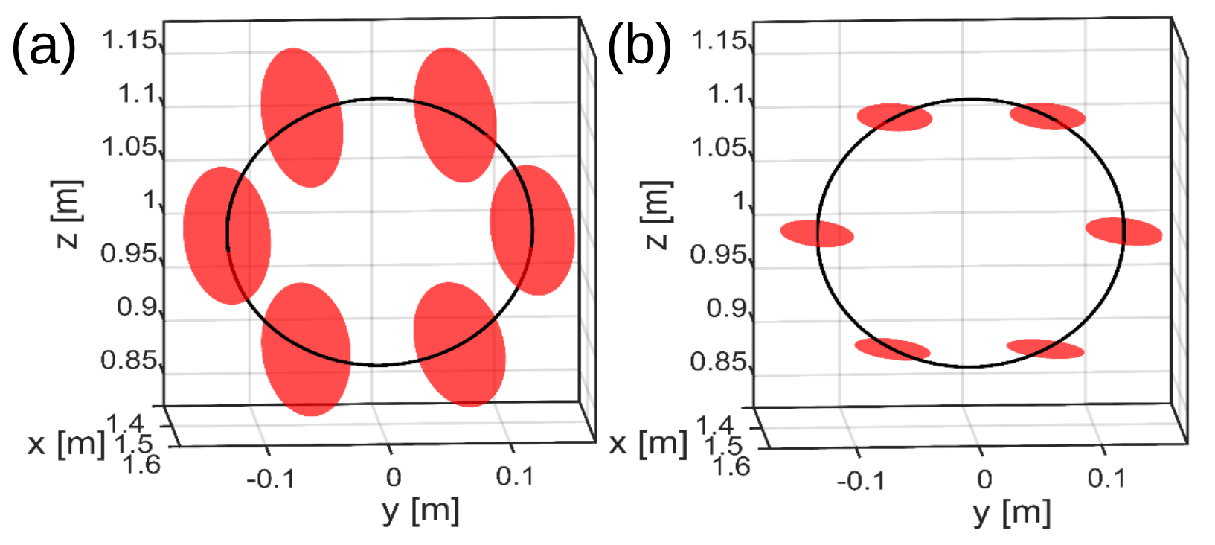
Result of Feature Mapping Experiment [1]



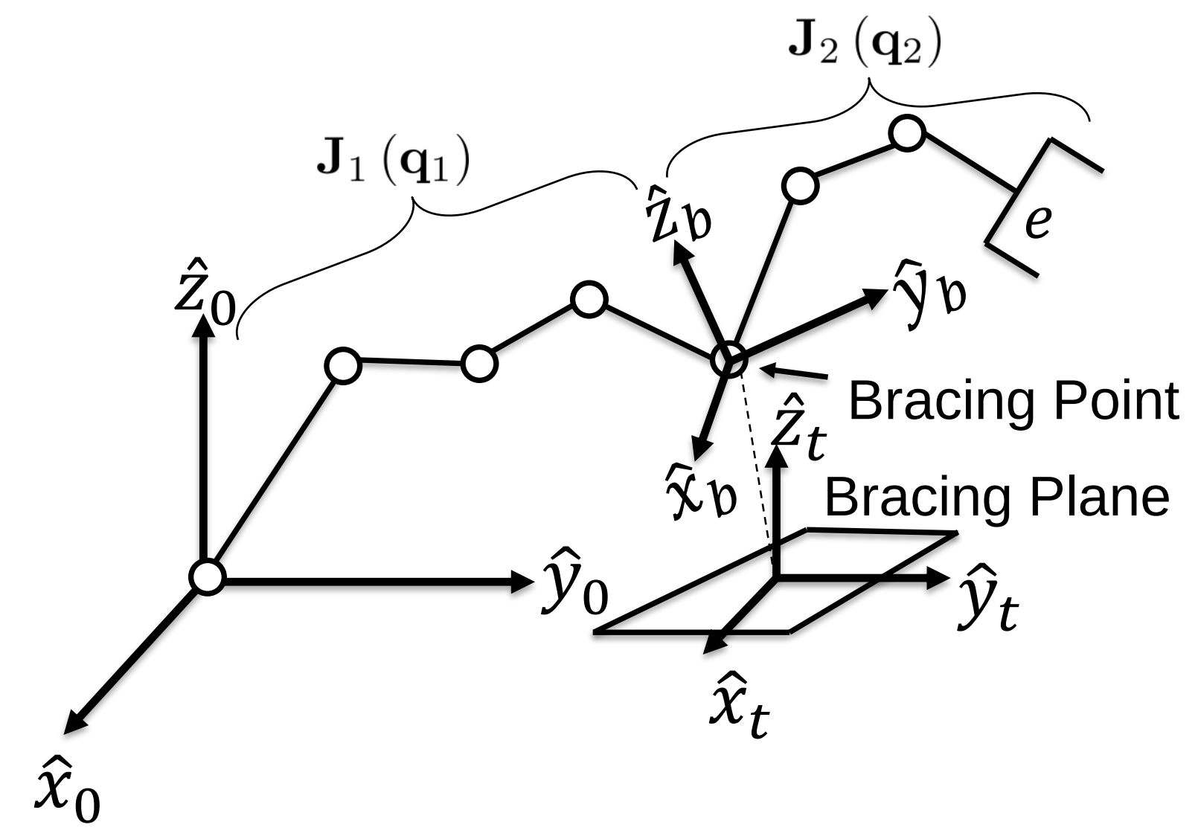
Example of Using Sensory Disk for pHRI [2]

Bracing and Redundancy Resolution

ISCRs have a fundamental design tradeoff between safety and payload/reach. One solution is to design ISCRs to be underpowered relative to the task and brace against the environment [3].



Compliance Ellipsoids Comparing (a) Freespace Motion to (b) Bracing [3]



Example Serial Robot Broken Into a Pre-bracing Region and a Post-bracing Region

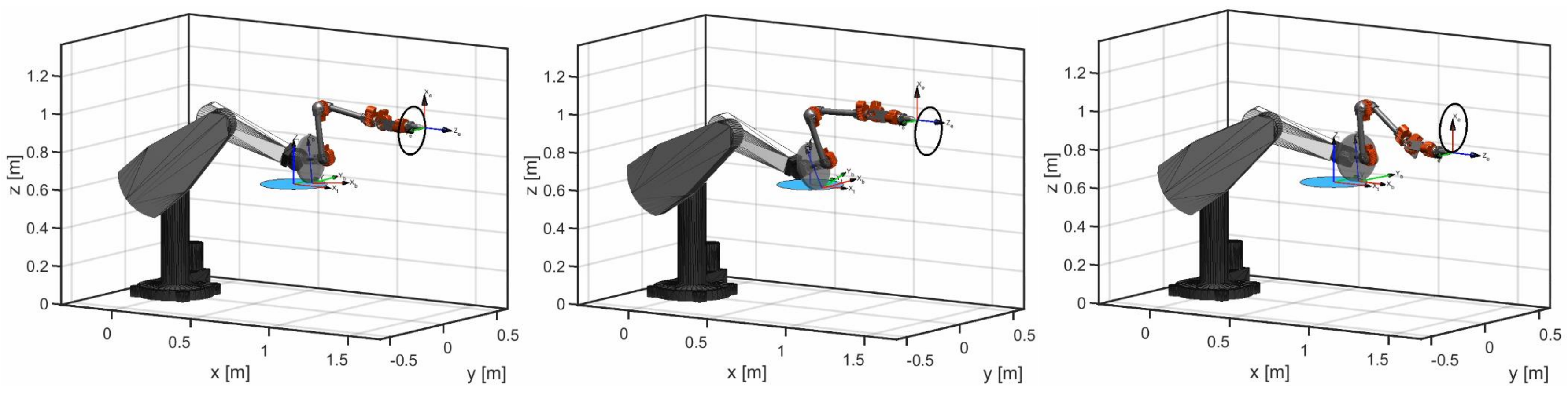
$$\begin{bmatrix} \dot{\tilde{\mathbf{b}}} \\ \dot{\mathbf{q}}_2 \end{bmatrix} = (\mathbf{A}^{+})\,\Delta^0\mathbf{x}_e + (\mathbf{I} - \mathbf{A}^{+}\mathbf{A})\,\alpha\nabla g$$

$$g = \alpha_1 k + \alpha_2 C_i + \alpha_3 \theta_z + \alpha_4 d$$

$$\Delta^0\mathbf{x}_e = \underbrace{\begin{bmatrix} \mathbf{S}_1\mathbf{H} & \mathbf{S}_2\mathbf{J}_2 \end{bmatrix}}_{\mathbf{A}} \begin{bmatrix} \dot{\tilde{\mathbf{b}}} \\ \dot{\mathbf{q}}_2 \end{bmatrix}$$

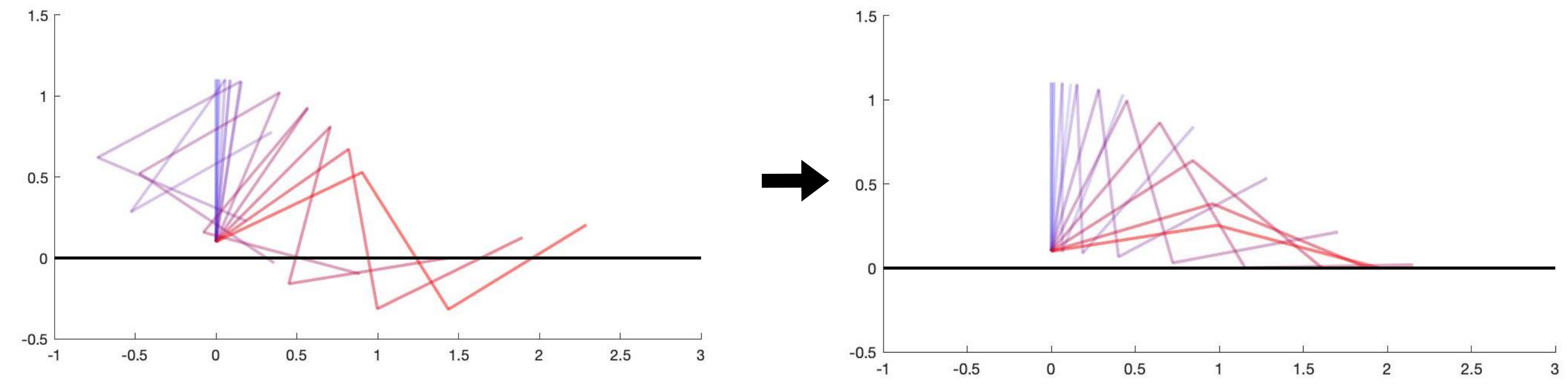
$$\dot{\mathbf{q}}_1 = \left(\mathbf{J}_1^{-1}\right)\mathbf{H}\dot{\tilde{\mathbf{b}}}$$

This redundancy resolution strategy utilizes gradient projection to minimize the compliance in a desired direction C_i, the Frobenius norm condition number k, the angle θ_z between the bracing plane normal and the bracing point z axis, and the distance from the bracing plane center d. In these equations, $\Delta^0\mathbf{x}_e$ is the end-effector twist, $\mathbf{H}$ is the bracing constraint matrix, and $\dot{\tilde{\boldsymbol{b}}}$ is the velocity of the bracing point in the allowable directions. Also, $\mathbf{S}_1$ and $\mathbf{S}_2$ are twist transformations.



Film Strip Showing Example of Redundancy Resolution Strategy [3]

Trajectory Optimization with Constraint-Aware ILQR



Optimizing a trajectory for a 3-link arm to reach out to the right, subject to a torque limit on the first joint and a constraint that no joint can drop below a floor (black line).
Left side: Initial input (generated by a poorly-tuned, constraint-unaware PID controller)
Right side: Arm braces on the floor to reach the goal and satisfy constraints

- **Goal:** Plan a path to a goal that satisfies torque limits and avoids collisions
  - Torque limits may require bracing on the environment
  - Intelligent consideration of hard constraints is required
- **Changes from conventional ILQR:**
  - For a fixed combination of constraints, we can compute Lagrange multipliers and the optimal control policy to exactly satisfy ("activate") those constraints
  - Different active constraint sets have different dynamics (e.g.: less torque required when in contact with the floor)
  - Backward step requires an estimate of active constraints to compute optimal control and cost-to-go
  - Forward rollout computes optimal control for each active constraint set and selects the cheapest allowed control

Criterion for a control action $\delta \mathbf{u}_n$ to be locally optimal subject to constraints:

$$\boxed{0 = \left(\mathbf{g}_n^T + \delta\mathbf{x}_n^T\mathbf{G}_n^T\right) + \delta\mathbf{u}_n^T\mathbf{H}_n^T + \lambda\mathbf{C}_u^T}$$

The black terms give the partial derivative of the cost-to-go from applying δun, from standard ILQR. The orange term is new in the Lagrange multiplier formulation. C_u is the matrix of partial derivatives of the active constraints with respect to δun, and λ is the vector of Lagrange multipliers.

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." *IEEE International Conference on Robotics and Automation (ICRA)*. May 2019.

[2] A. L. Orekhov, G.L.H. Johnston, C. Abah, H. Choset, and N. Simaan, "Towards Collaborative Robots with Sensory Awareness: Preliminary Results Using Multi-Modal Sensing," in *ICRA 2019 workshop "Physical human-robot interaction: a design focus,"* May 2019

[3] G.L.H. Johnston, A.L. Orekhov, and N. Simaan. "Kinematic Modeling and Compliance Modulation of Redundant Manipulators Under Bracing Constraints." 2020 *IEEE International Conference on Robotics and Automation.* [Accepted Jan. 2020].