Modeling, Planning, and Control for Whole-Body Manipulation of Unknown Objects with Large-Scale Soft Robots

Curtis Johnson

Vocabulary

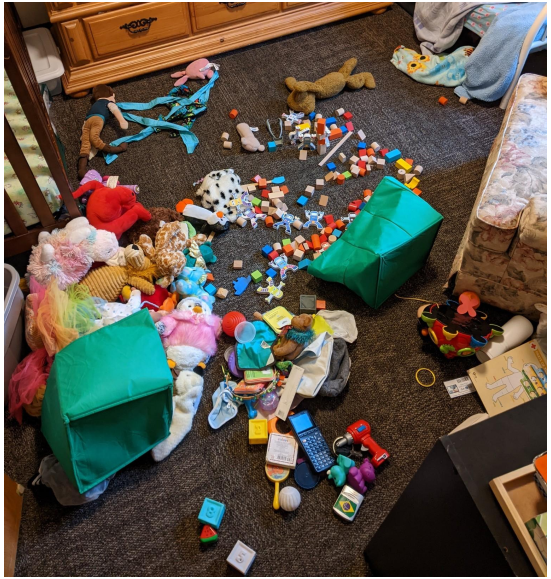
"**Manipulation**": Agent's control of environment through selective contact





Vocabary

“**Open World**”: The idea that the world is inherently unstructured and objects have infinite variability

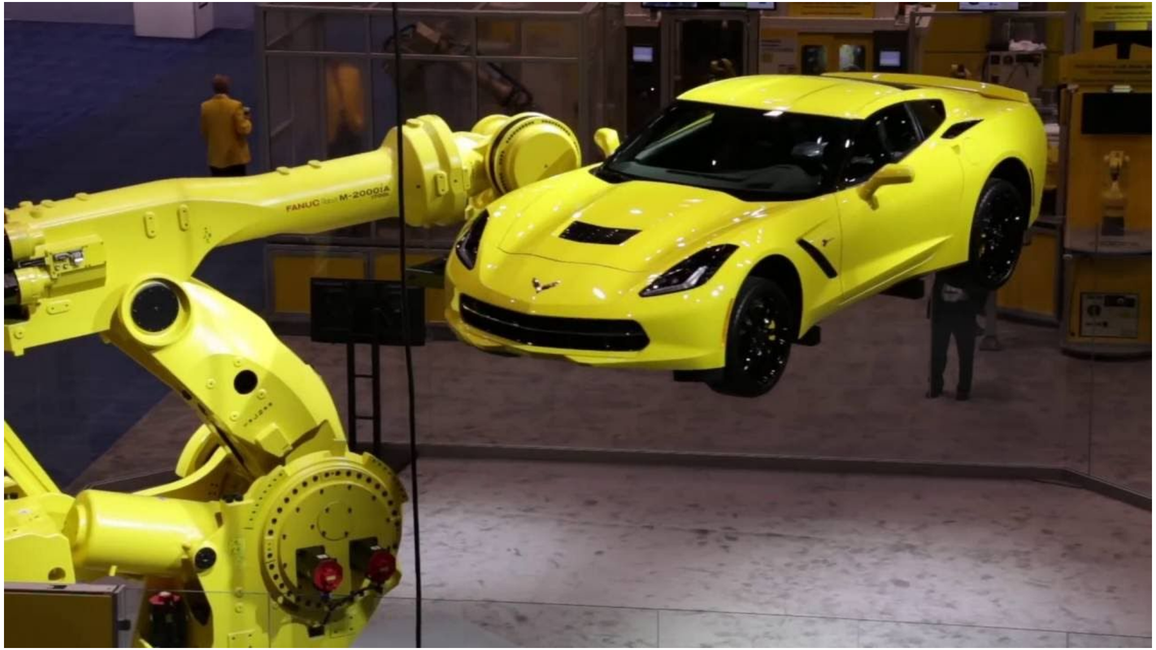


Outline

- Problem Statement
- Background
- Research Objectives
- Proposed Research
- Anticipated Contributions

Problem Statement

- What if we want a robot to manipulate large/heavy objects?

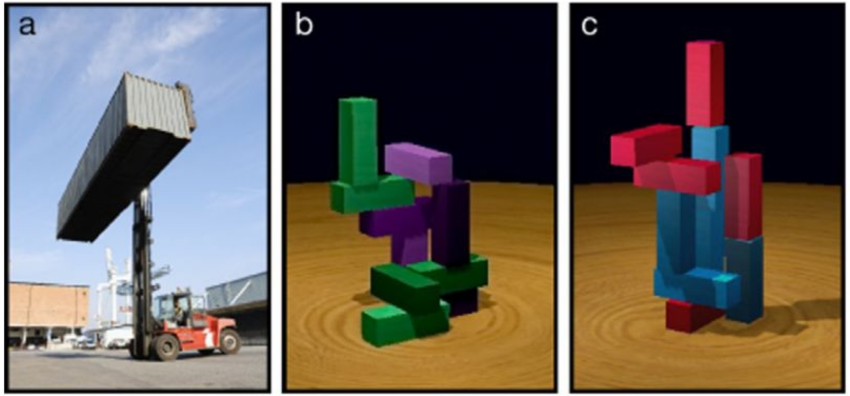


Problem Statement

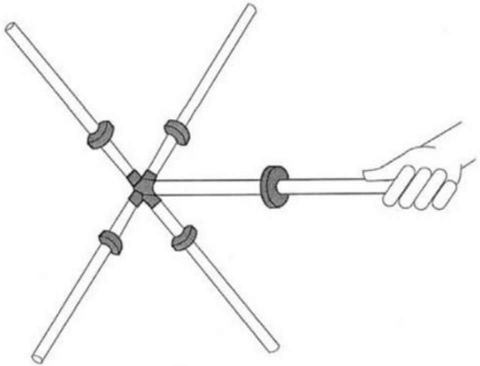
- What if we want a robot to manipulate large/heavy objects?

Problem Statement

- Since the object is large/heavy, how can a robot reason about objects whose physical properties are unknown?



(a)


(b)

Problem Statement

- Some inspiration from nature

Problem Statement

Modeling, Planning, and Control… → Robot reasoning

for Whole-Body Manipulation… → For Large/Heavy Objects

of Unknown Objects… → “Open world”

with Large-Scale Soft Robots → Type of robot

How to do this?

Outline

- Problem Statement
- Background
- Research Objectives
- Proposed Research
- Anticipated Contributions

Outline

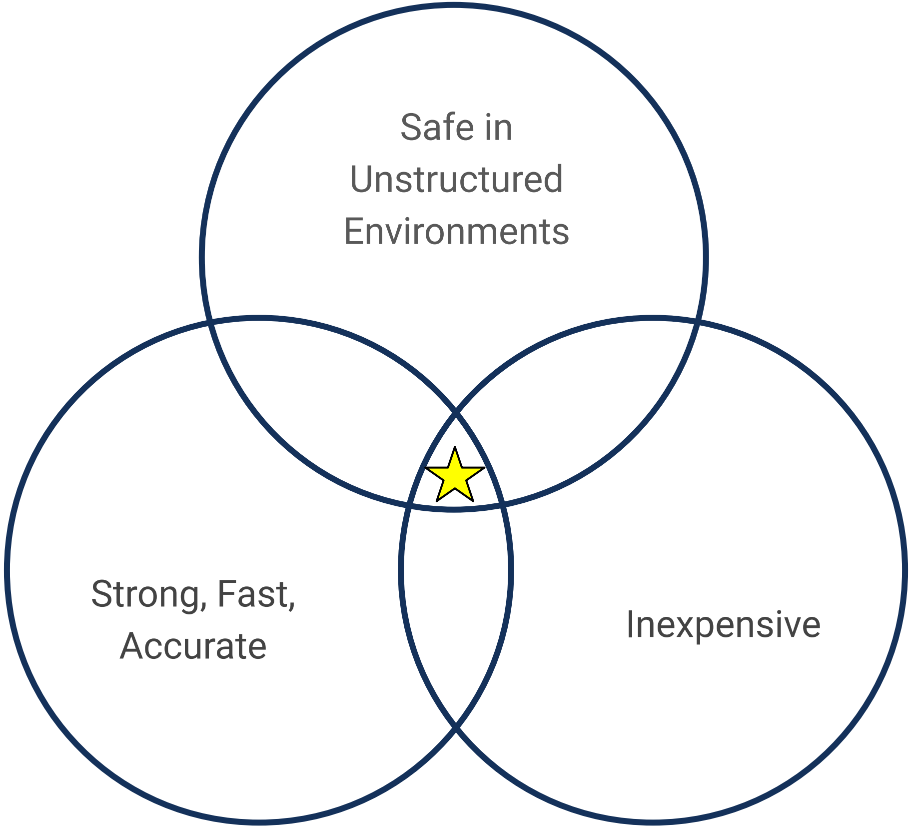
- Problem Statement
- Background
    - Whole Body Manipulation
        - Mechanism Design
        - Perception
        - Modeling and Control with Contact
        - Planning
- Research Objectives
- Proposed Research
- Anticipated Contributions

Whole Body Manipulation

- Main Challenges:
  - Mechanism Design
  - Perception
  - Modeling and Control with Contact
  - Planning

Whole Body Manipulation

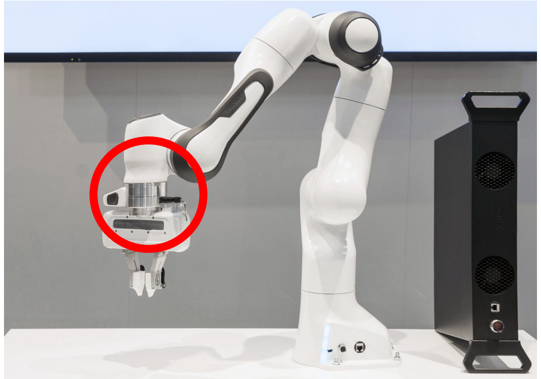
- 2 Approaches to mechanism design:
  - Outfit with soft materials
  - Soften manipulator
- ‘Mechanical Intelligence’
- Potential of Soft Robots



Whole-Body Manipulation

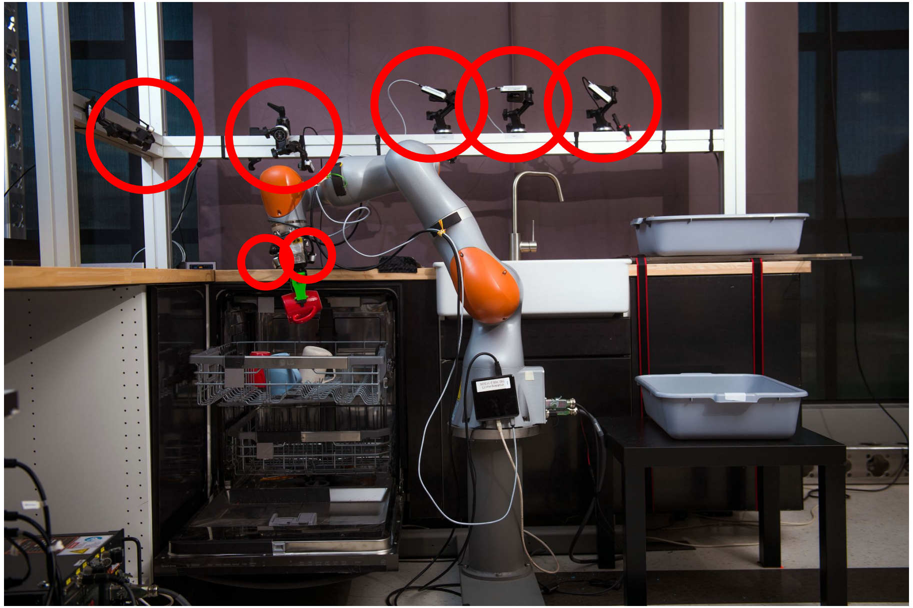
- Perception - Tactile

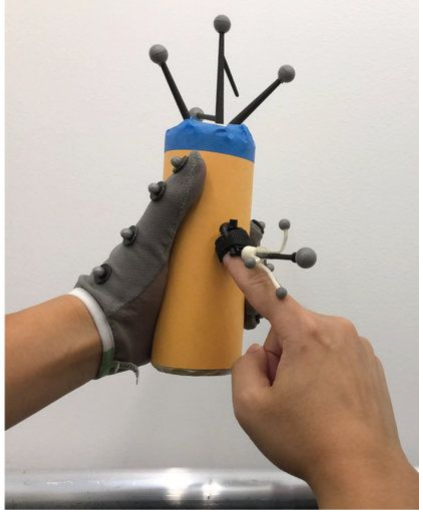
Fig. 2. Shadow Dexterous Hand (left) that has been covered with a tactile skin [51] (middle) in order to provide tactile information at several locations (highlighted green regions on the right rendering).



Whole-Body Manipulation

- Perception - Visual





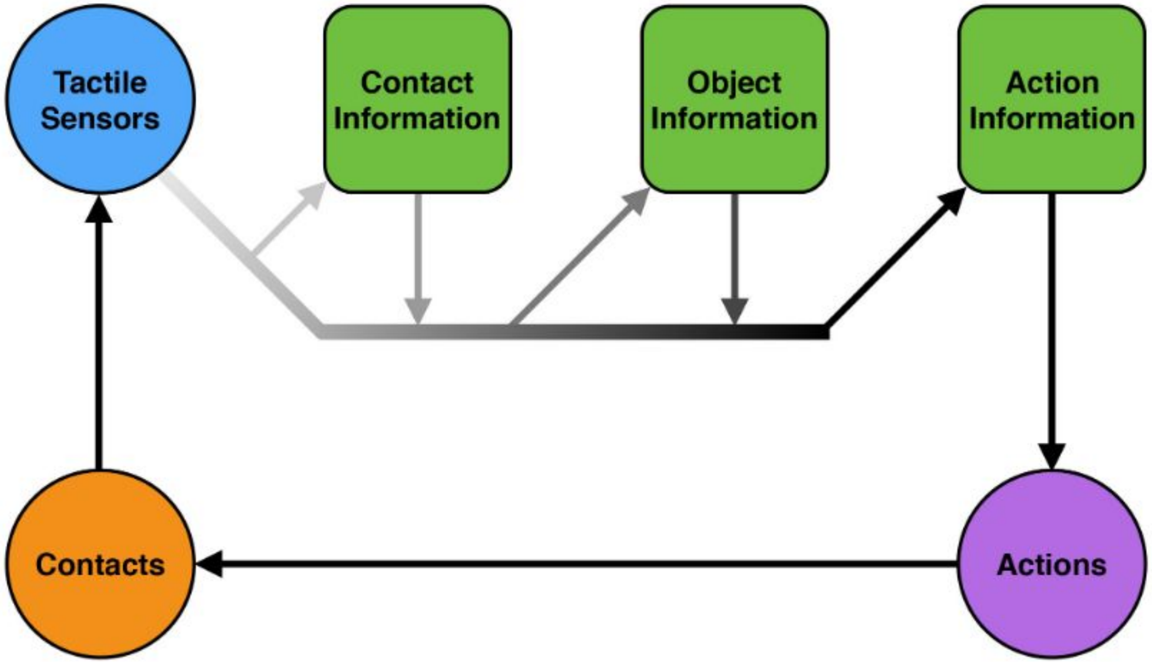
Whole Body Manipulation

- Perception

Contact-Level	Object-Level	Action-Level
• Force/Torque Sensors • Visuo-tactile sensors • Distributed Tactile sensors	• Localization • Shape • Mass/dynamics	• Motion capture • Vision

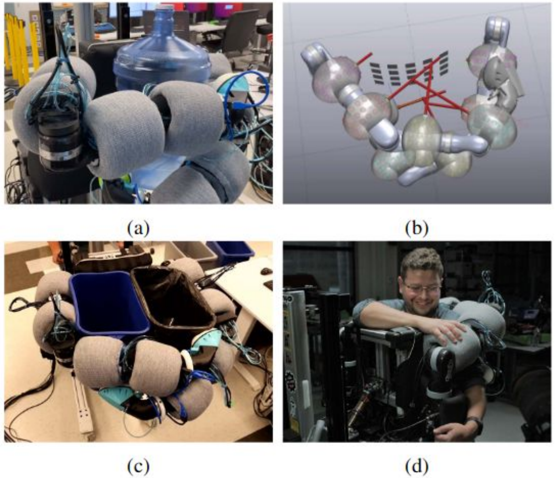
Whole Body Manipulation

- Perception

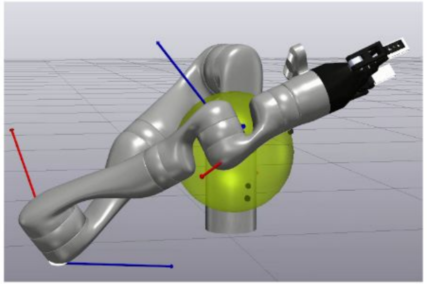


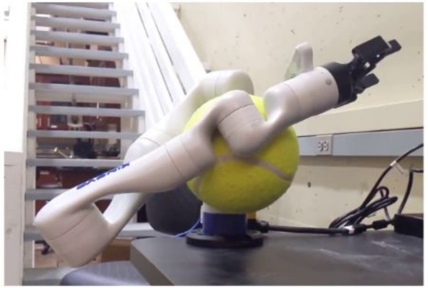
Whole Body Manipulation

- Modeling and Control with Contact



?





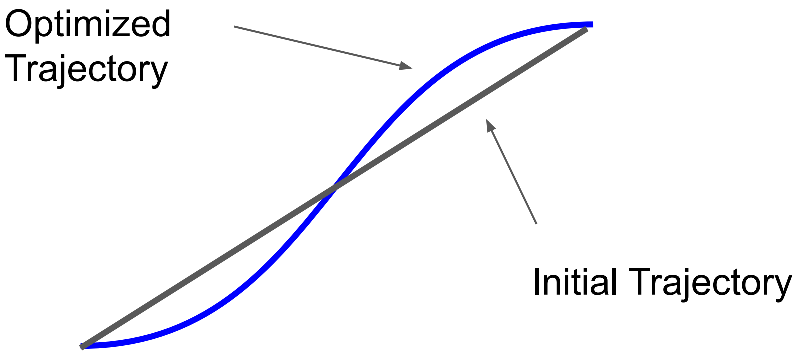
Nothing

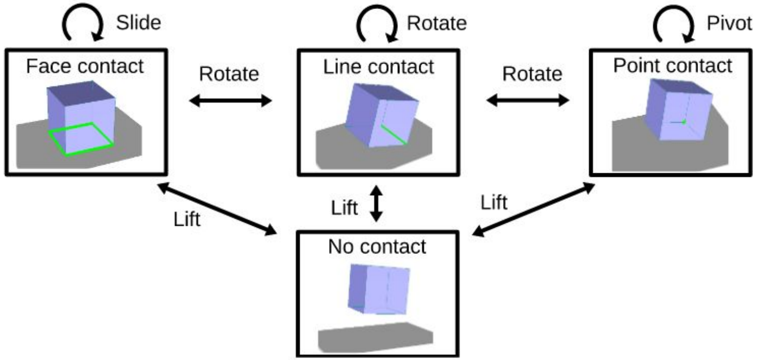
Spectrum of Assumptions made about the World in Whole-Body Manipulation (2022)

Everything

Whole Body Manipulation

- Planning
  - Reinforcement Learning
  - Graph Search
  - Offline Trajectory Generation



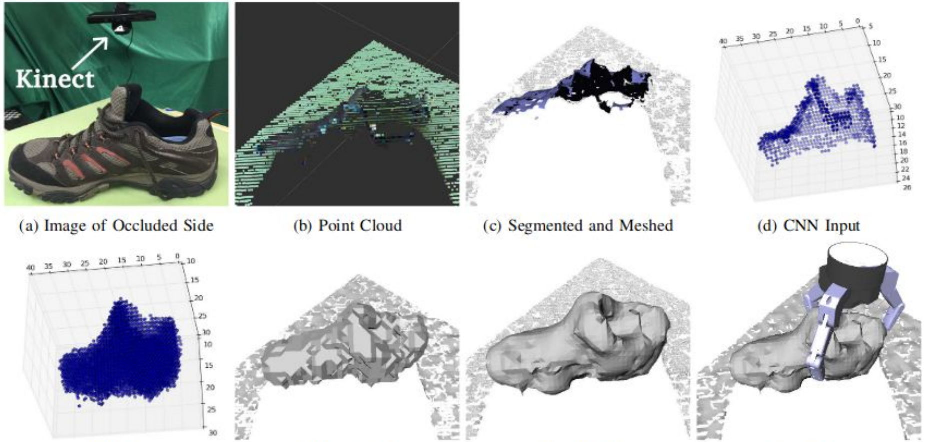


Outline

- Problem Statement
- Background
  - Whole Body Manipulation
  - Object Learning
- Research Objectives
- Proposed Research
- Anticipated Contributions

Object Learning

- Localization
- Shape Estimation
- Physical Parameters Estimation



(a) Image of Occluded Side (b) Point Cloud (c) Segmented and Meshed (d) CNN Input

(e) CNN Output (f) Fast Mesh (g) Detailed Mesh (h) Grasp Planning

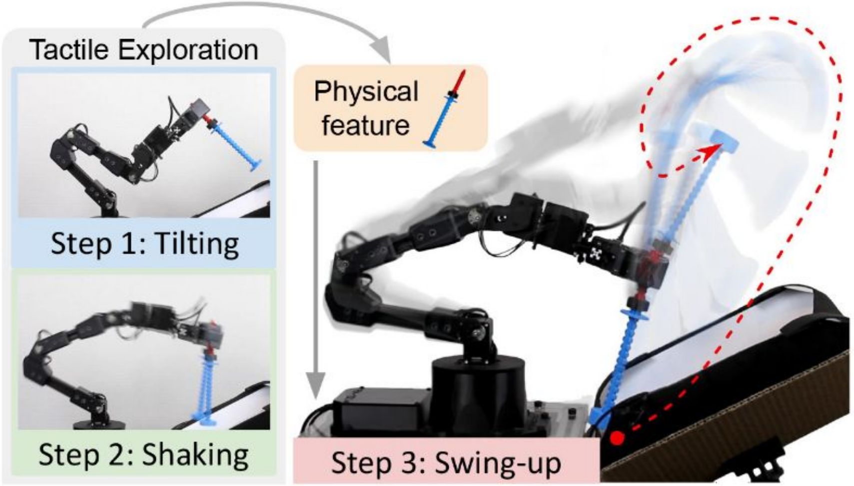


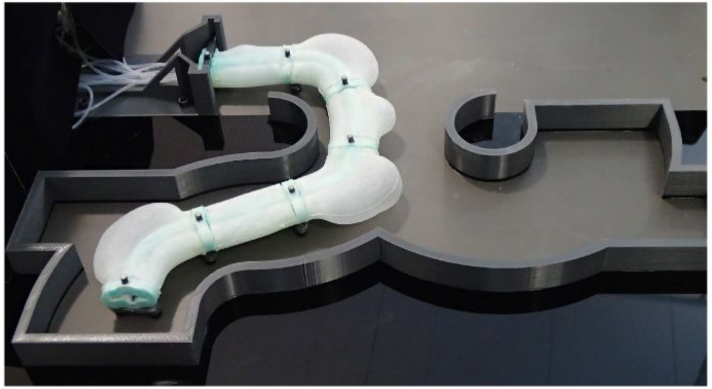
Fig. 1: **SwingBot.** We develop a learning-based in-hand physical feature exploration method with a GelSight tactile sensor, which assists the robot to perform accurate dynamic swing-up manipulation.

Outline

- Problem Statement
- Background
  - Whole Body Manipulation
  - Object Learning
  - Manipulation with Large Scale Soft Robots
- Research Objectives
- Proposed Research
- Anticipated Contributions

Manipulation with Large Scale Soft Robots

- Challenges in scaling up soft robots
- Models and controllers are lacking



Background Summary

- Problem Statement
- Background
  - Whole Body Manipulation
  - Object Learning
  - Manipulation with Large Scale Soft Robots
- Research Objectives
- Proposed Research
- Anticipated Contributions

Outline

- Problem Statement
- Background
- Research Objectives
- Proposed Research
- Anticipated Contributions

Hardware Platform

- Explore/exploit passive mechanical compliance for whole-body manipulation
- Existing sensory feedback
  - Pressure
  - RGBD
  - Tactile
  - Orientation

Research Objectives

1. Develop dynamic models and evaluate a simulation framework of the proposed soft robot torso.
2. Explore the combined use of visual and tactile sensory feedback to learn geometric and inertial properties of large unknown objects.
3. Develop and evaluate algorithms that utilize learned knowledge about a large object in order to manipulate it into a desired configuration.

Outline

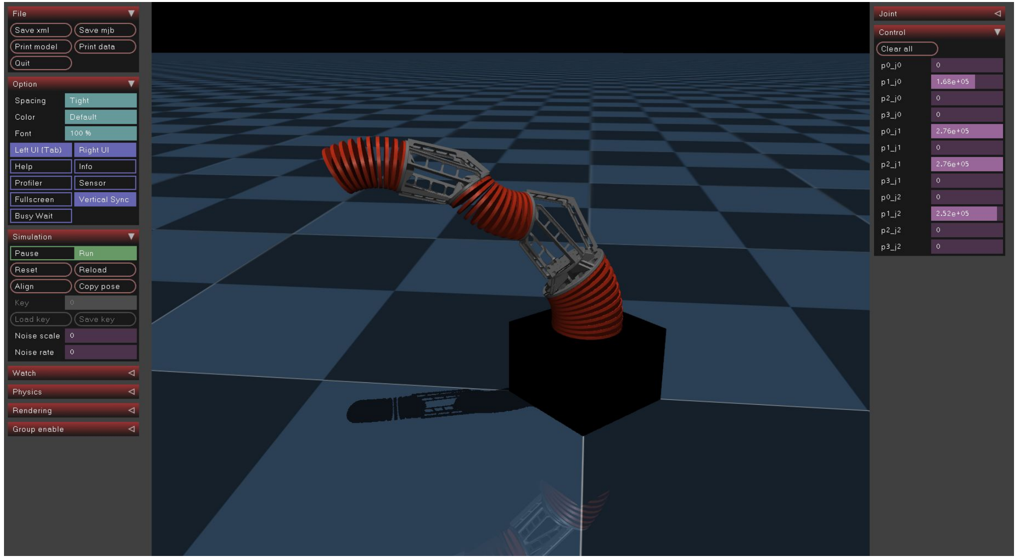
- Problem Statement
- Background
- Research Objectives
- Proposed Research
- Anticipated Contributions

Outline

- Problem Statement
- Background
- Research Objectives
- Proposed Research
  - Dynamic Modeling and Simulation of Soft Robots
- Anticipated Contributions

Dynamic Modeling and Simulation of Soft Robots

- Finalize adaptation of well-supported rigid body simulator
- Represent continuum joints with discrete disks in MuJoCo.
- Compatible models
- Almost complete

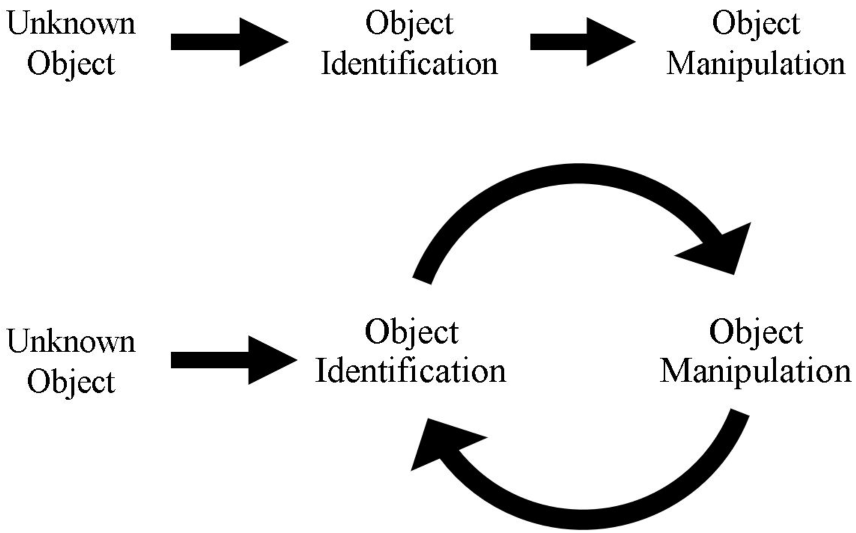


Outline

- Problem Statement
- Background
- Research Objectives
- Proposed Research
  - Dynamic Modeling and Simulation of Soft Robots
  - Learning about Unknown Objects
- Anticipated Contributions

Learning about Unknown Objects

- Must the object be entirely known before manipulating it?
- Use ideas from Simultaneous Localization and Mapping (SLAM) for mobile robots.

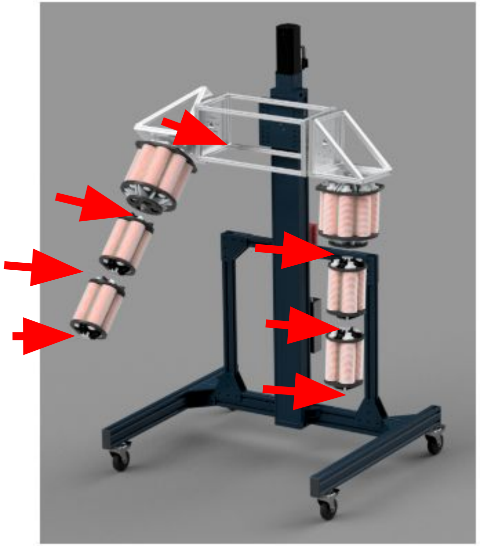


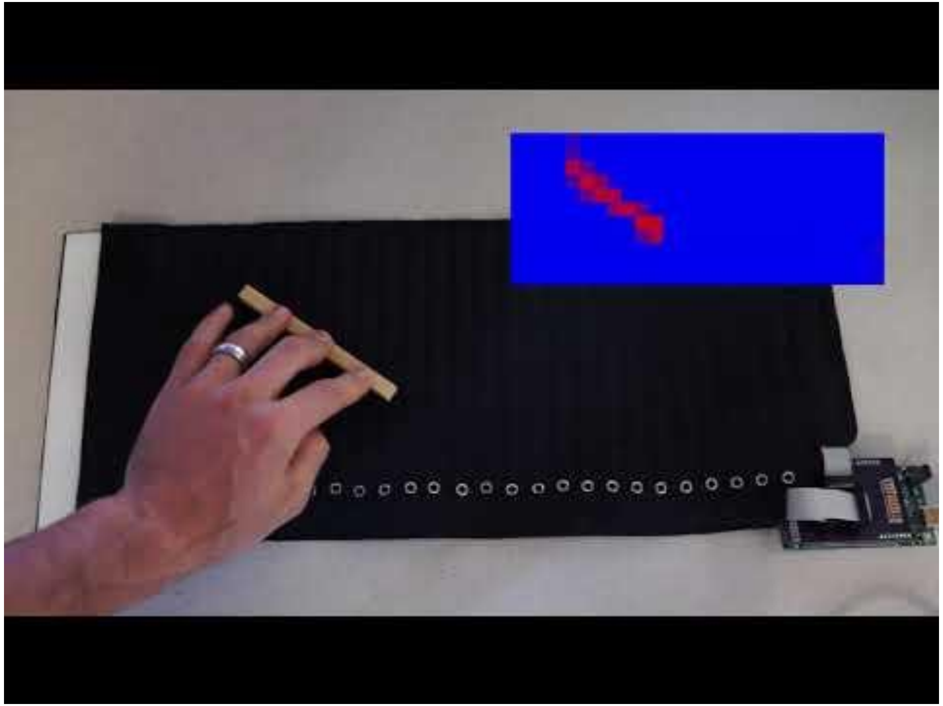
Learning about Unknown Objects

- Visual Feedback
  - ‘Shape Completion’ via Convolutional Neural Networks
  - Provides a prior for tactile estimation

Learning about Unknown Objects

- Tactile Feedback
  - Exploratory motions to refine vision prior





Outline

- Problem Statement
- Background
- Research Objectives
- Proposed Research
  - Dynamic Modeling and Simulation of Soft Robots
  - Learning about Unknown Objects
  - Control and Planning for Whole-Arm Manipulation
- Anticipated Contributions

Control and Planning for Whole-Arm Manipulation

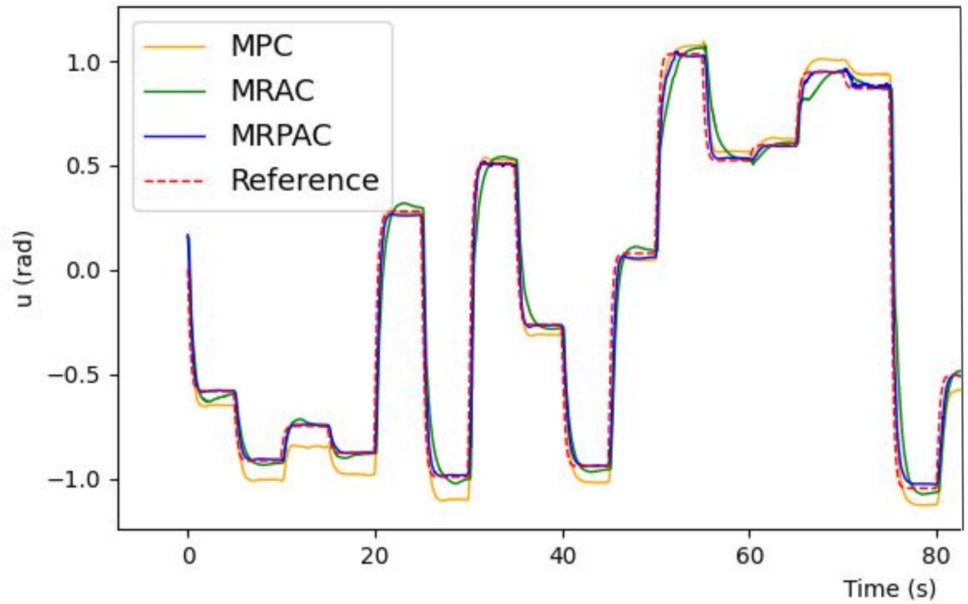
- Two main control challenges:
  - Soft robot and object dynamics are uncertain
  - Hybrid system with unknown contact sequences
- Proposed Solution
  - Adaptive Control + Contact-Implicit Optimization

Manipulation with Large Scale Soft Robots

- Model Reference Predictive Adaptive Control (MRPAC) = MPC + MRAC

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{w} + \tau_{\text{disturbance}}$$

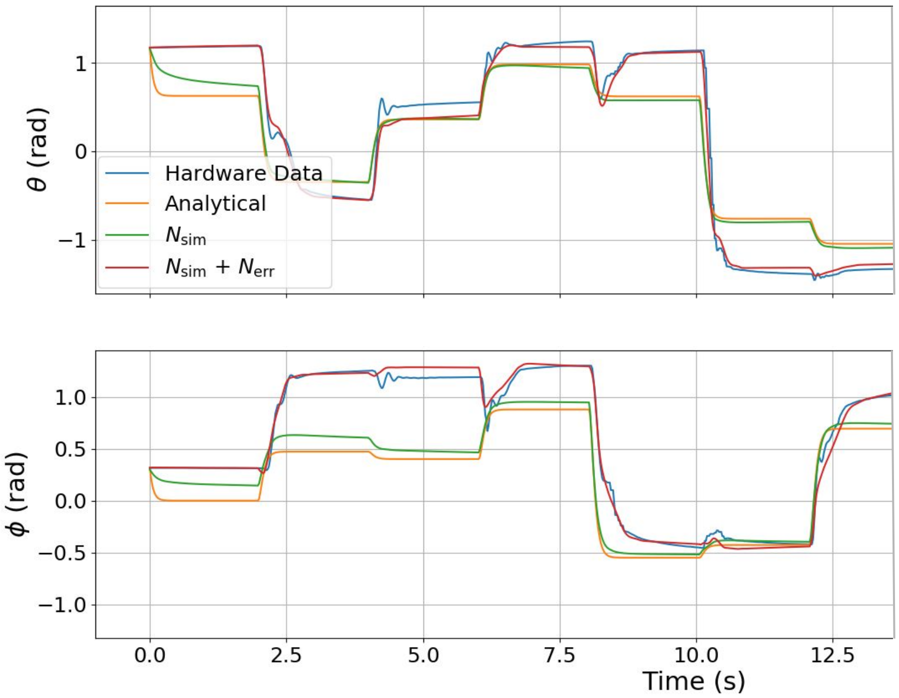
$$\tau_{\text{disturbance}} = -Y(q, \dot{q}, \dot{q}_{\text{ref}}, \ddot{q}_{\text{ref}})\hat{a}$$



P. Hyatt, C. C. Johnson, and M. D. Killpack, “Model Reference Predictive Adaptive Control for Large-Scale Soft Robots,” Front. Robot. AI, vol. 7, 2020, doi: 10/ghrvxs.

Offline Neural Network Compensation

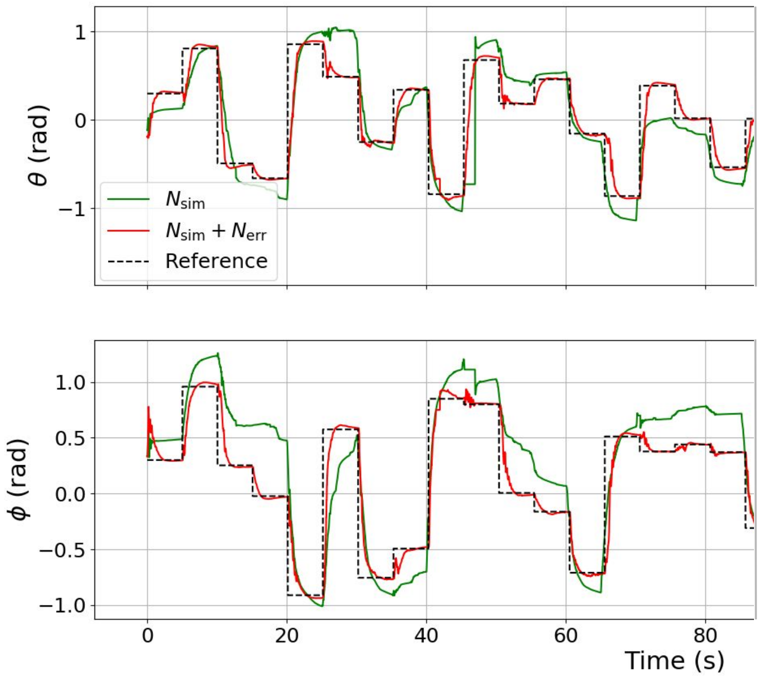
- Neural Networks can compensate for dynamic modeling errors.



C. C. Johnson, T. Quackenbush, T. Sorensen, D. Wingate, and M. D. Killpack, “Using First Principles for Deep Learning and Model-Based Control of Soft Robots,” Front. Robot. AI, vol. 8, 2021, doi: 10/gkc4db.

Offline Neural Network Compensation

- A more accurate model helps significantly with model-based control.
- Some learning/adaptive mechanism seems promising.



C. C. Johnson, T. Quackenbush, T. Sorensen, D. Wingate, and M. D. Killpack, “Using First Principles for Deep Learning and Model-Based Control of Soft Robots,” Front. Robot. AI, vol. 8, 2021, doi: 10/gkc4db.

Contact-Implicit Trajectory Optimization

- Two general methods for dealing with hybrid systems
  - Multi-Phase methods (requires sequence of contact phases before hand)
  - Contact-Implicit (or Invariant) methods:

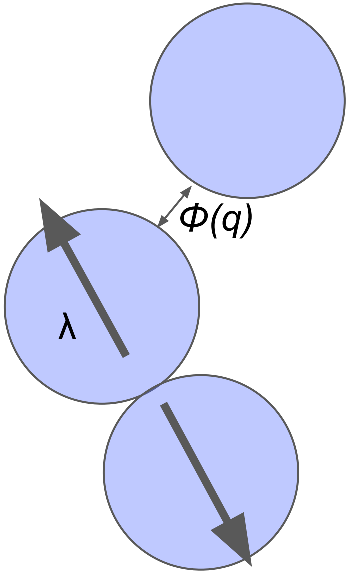
$$\text{find } \ddot{q}, \lambda$$
$$\text{subject to } H(q)\ddot{q} + C(q, \dot{q}) + G(q) = B(q)u + J(q)^{\mathrm{T}}\lambda$$

$$\phi(q) \geq 0$$ ← Non-penetration constraint

$$\lambda \geq 0$$ ← Normal forces

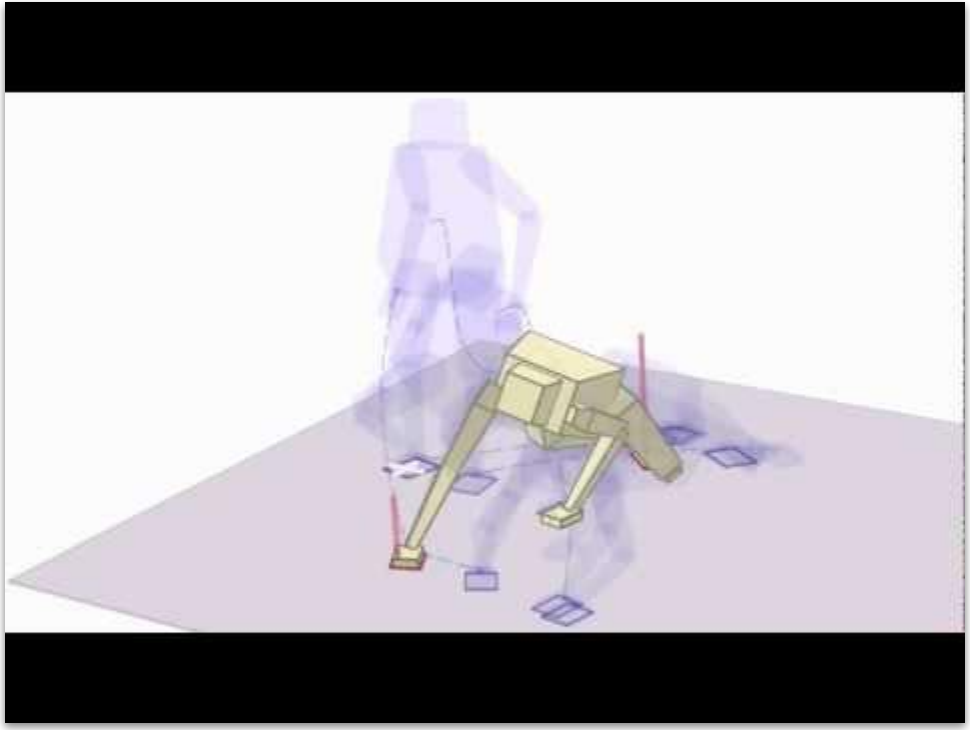
$$\phi(q)^{\mathrm{T}}\lambda = 0.$$ ← Complementarity constraint

$$\underset{\{h, x_0, \ldots, x_N, u_1, \ldots, u_N, \lambda_1, \ldots, \lambda_N\}}{\text{minimize}} \; g_f(x_N) + h \sum_{k=1}^{N-1} g(x_{k-1}, u_k)$$

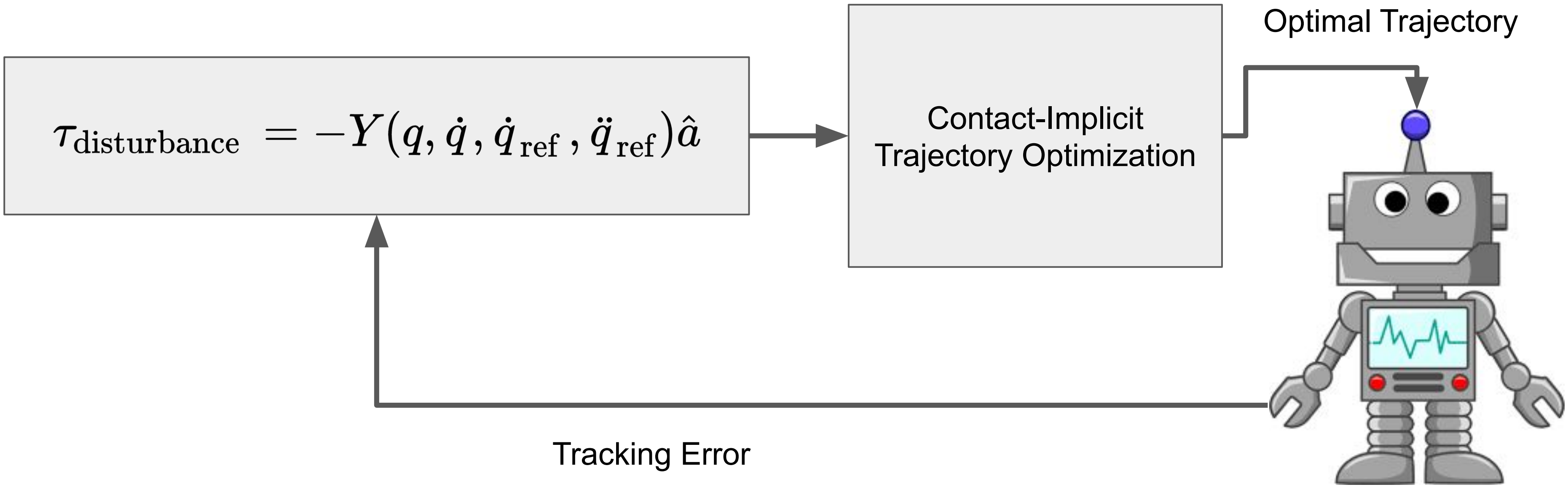


Contact-Implicit Trajectory Optimization

- Has been used to optimize contact-rich trajectories.
  - Example of biped standing



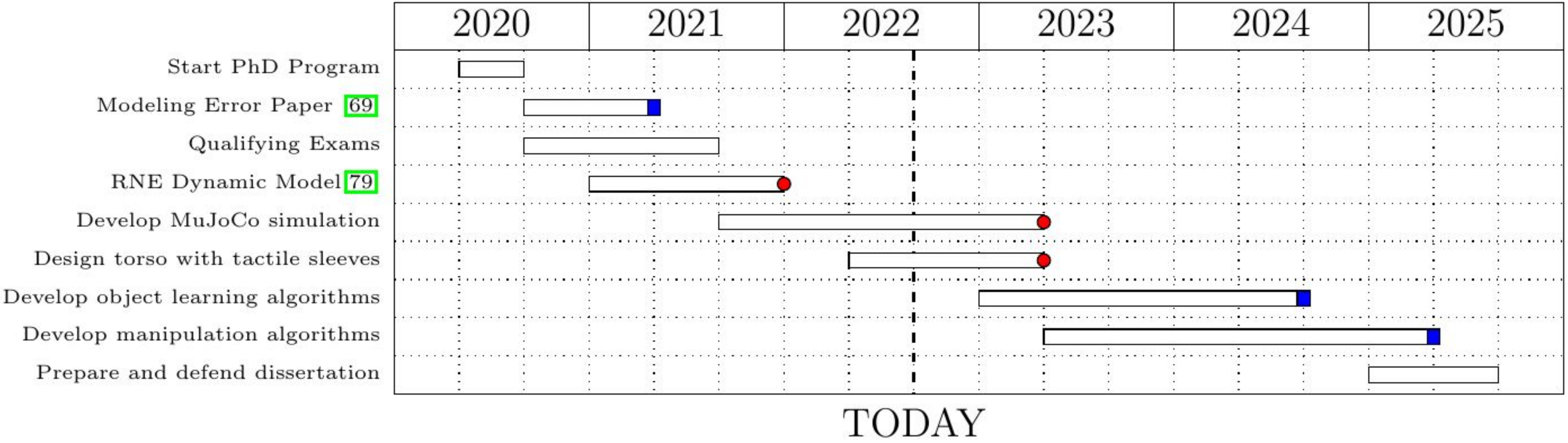
Adaptive Control + Contact-Implicit Optimization



Outline

- Problem Statement
- Background
- Research Objectives
- Proposed Research
- Anticipated Contributions

Anticipated Contributions



Summary of Research Questions Addressed

1. How to model and simulate a large-scale soft robot for contact-rich manipulation.
2. How to use visual and tactile feedback to learn about an object.
3. How to manipulate an unknown object.

Summary

- This research will enable robots to
  - Be more capable, especially in open-world manipulation
  - Be less expensive
  - Have larger workspace