24 OCTOBER 2023

Robotic Software Architecture for In-Space Outfitting Operations

Amy Quartaro

PhD Student, Mechanical Engineering
Virginia Tech

Dr. John Cooper
Aerospace Engineer
NASA Langley Research Center

Dr. Erik Komendera
Assistant Professor, FASER Lab Director
Mechanical Engineering Virginia Tech

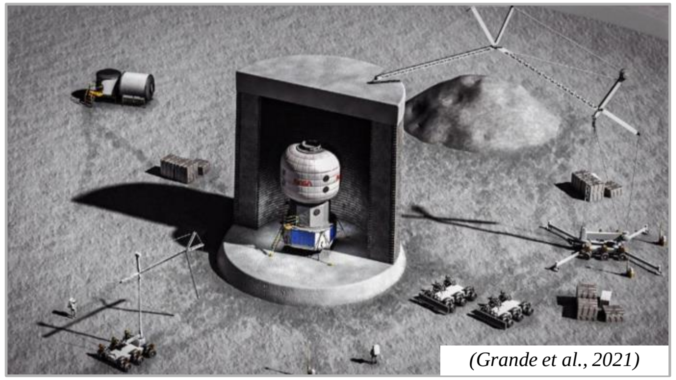
Published by the American Institute of Aeronautics and Astronautics, Inc.

ASCEND

Lunar Construction and Outfitting

- Goal to have a sustained, long-term presence on the lunar surface
- Excavation, Construction, and Outfitting technologies critical to infrastructure
  - *M2M Objectives LI-2: Demonstrate advanced manufacturing and autonomous construction capabilities in support of continuous human lunar presence and a robust lunar economy.*
- A permanent facility will not have a constant crewed presence
  - Robotic capabilities crucial for infrastructure


(NASA, 2023)

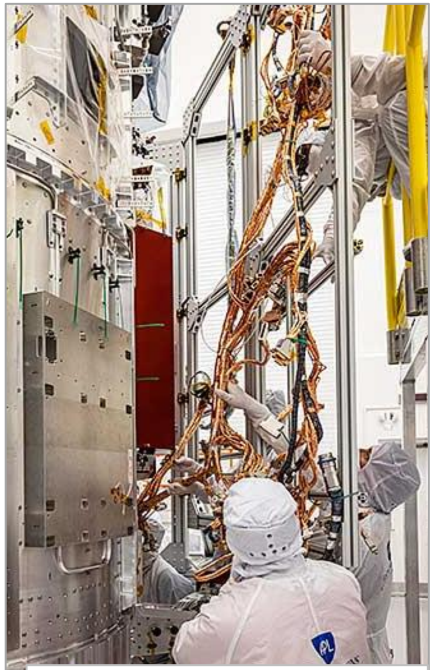

(Grande et al., 2021)

ASCEND

Robotic Outfitting

- This work focuses on performing **outfitting tasks with autonomous systems**
  - *In-situ* installation of subsystems to create a fully functional system
- Outfitting often involves the routing and installation of cables
  - Cables are considered Deformable Linear Objects (DLOs)
- Challenges of autonomous cable routing:
  - System complexity (computational difficulty)
  - Complications of in-space environment
  - Obstacle Density


(NASA, 2023)

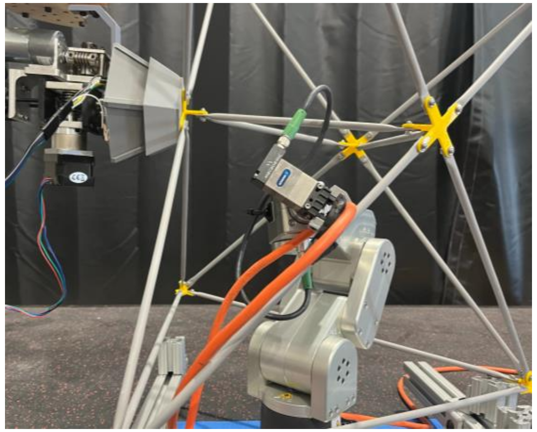

(Johns Hopkins APL/Ed Whitman, 2021)

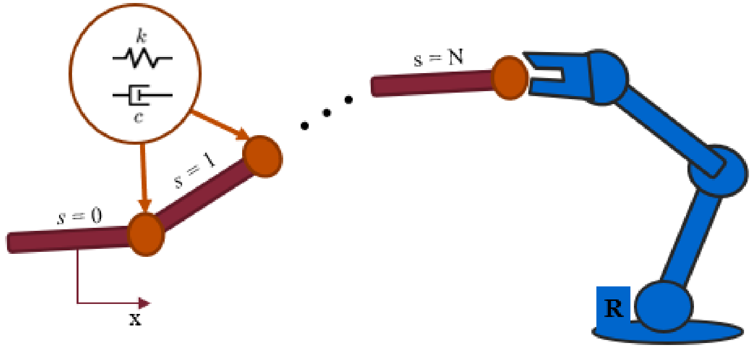
ASCEND

Research Problem Formulation

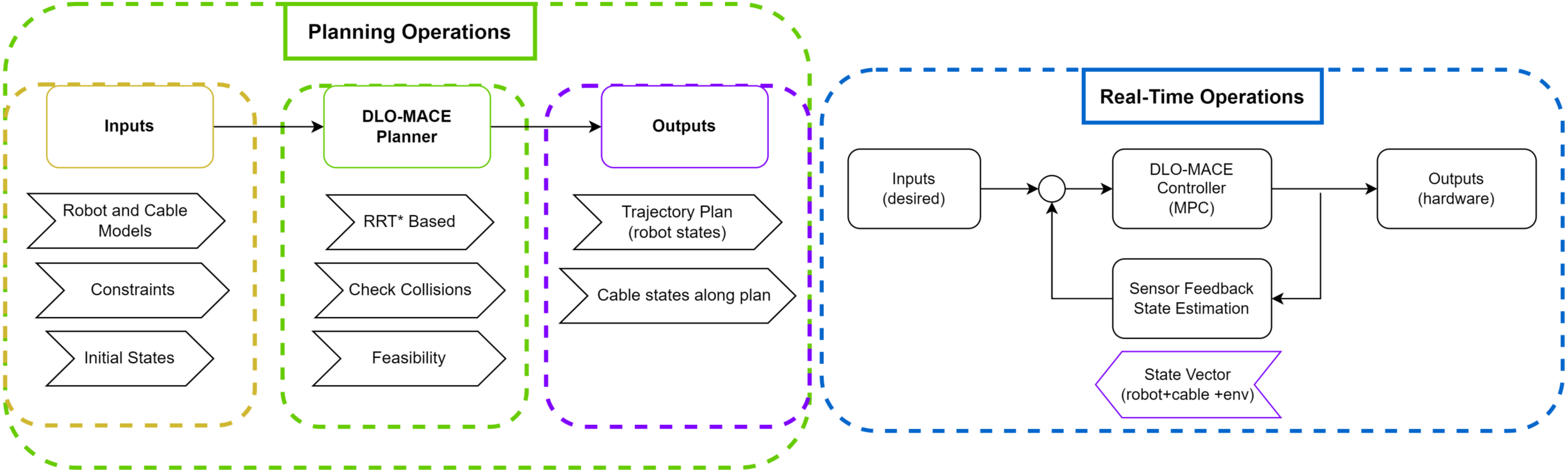
Solution: <u>Architecture</u> to facilitate a <u>computationally viable</u> model for both structural and non-rigid elements in <u>autonomous assembly</u> operations with complex workspaces.

- Leverage state-of-the-art in various robotic disciplines
- DLO Manipulation Architecture for Cluttered Environments (DLO-MACE)





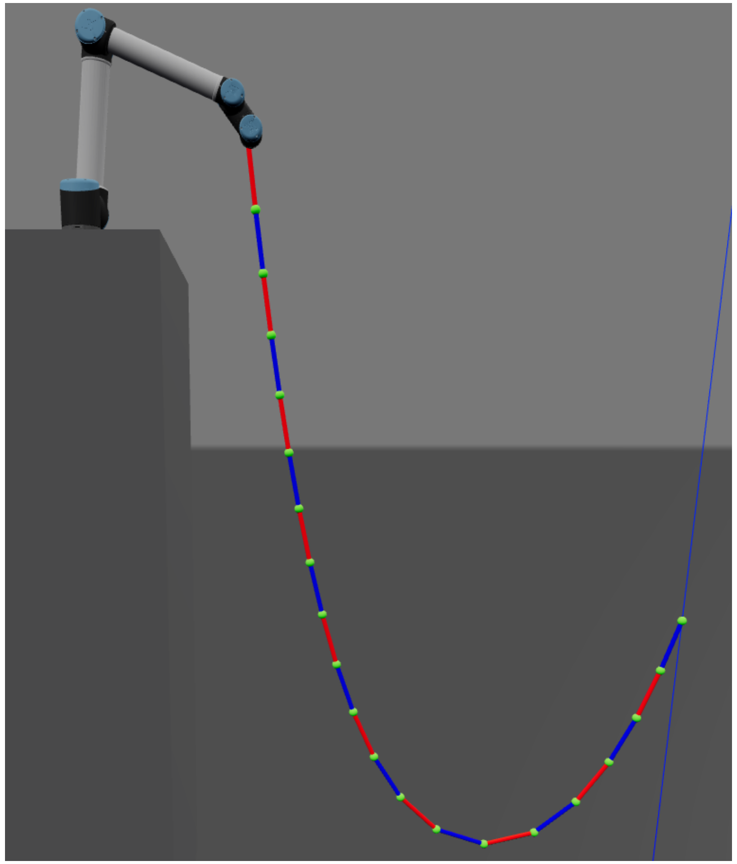
Architecture Overview



ASCEND

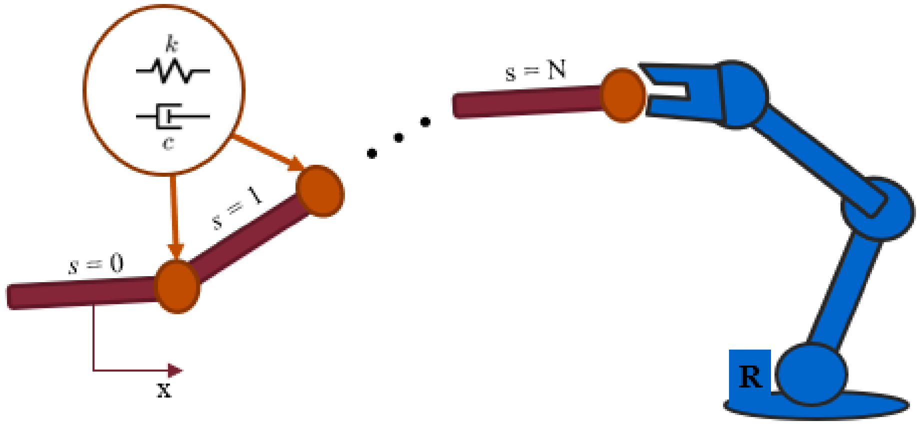
Research Problem Formulation

- DLO-MACE Components
  - **DLO Modeling**
  - Optimization Planning
  - Real-time Control
  - State Estimation
- Understanding the DLO model is essential
  - Represent cable
  - Start with static implementation to verify model fundamentals



Model Formulation

- Modeling Cables as DLOs
  - Multiple formulation approaches: discretized models, continuum models, model-free neural-network
- Discrete Multibody Model
  - Cable broken up into a fixed number of rigid body segments
  - Connect links with springs and dampers
- Static Configuration
  - Only springs
  - 2D to simplify derivations
  - Compare with hardware images



ASCEND

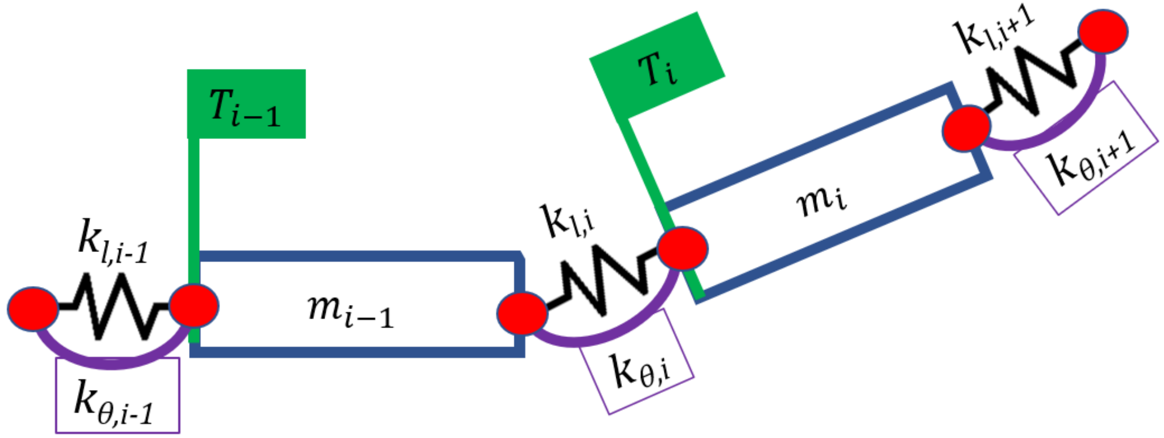
Model Formulation

- n Link Segments
  - Rigid component with mass $m_i = m_{link} = \frac{m_{cable}}{n}$
  - Base and forward nodes
  - Linear and rotational springs
- Generalized Coordinates:
  - Spring deformation

$$\boldsymbol{q} = [\, \theta_1 \; \delta x_1 \; \ldots \theta_{n+1} \; \delta x_{n+1}]$$

- Homogeneous transformation matrices
  - Link orientation and position

$$\boldsymbol{T}_i \in \mathbb{R}^{\boldsymbol{4x4}} = \begin{bmatrix} \boldsymbol{R}_i & \boldsymbol{p}_i \\ \boldsymbol{0} & 1 \end{bmatrix}$$



Minimum Potential Energy

- Static configuration at minimum potential energy
  - At rest, no kinetic energy
- Total potential energy (U) in system
  - Linear and torsional spring potential

$$U = \frac{1}{2} k\, \delta^2$$

  - Calculate height of link $y_i(\boldsymbol{q})$ for gravity potential

$$U = m_{link} g\, y_i$$

- Formulate as optimization problem
  - **Cost:** Potential Energy
  - **Variables:** Generalized Coordinates, $\boldsymbol{q}$
  - **Constraints**: Start and end points of cable

Total Potential Energy

$$U(\mathbf{q}) = \sum_{i=1}^{n} \frac{1}{2} k_r \theta_i^2 + \frac{1}{2} k_l \delta x_i^2 + m_{link} g y_i(\mathbf{q})$$

Optimization Problem

$$\min_{\mathbf{q}} f(\mathbf{q}) = \sum_{i=0}^{n} \frac{1}{2} k_r \theta_i^2 + \frac{1}{2} k_l \delta x_i^2 + m_{link} g y_i(\mathbf{q})$$

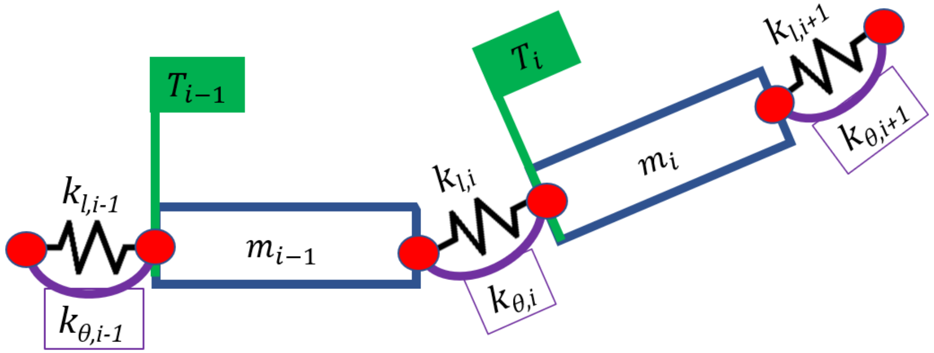
$$\text{subject to } g(\mathbf{q}) = |\mathbf{p}_n - \mathbf{p}_{des}| \leq \mathbf{0}$$

$$h(\mathbf{q}) = \mathbf{p}_0 = \mathbf{0}$$

End position

Start position

Optimization Problem



- Spring deflections between links $(i-1)$ and (i)

$$\boldsymbol{q}_i = [\theta_i \quad \delta x_i]$$

- Current link transformation

$$\boldsymbol{T}_i(\boldsymbol{q}) = \boldsymbol{T}_{i-1}(\boldsymbol{q})\boldsymbol{T}_{link}\boldsymbol{T}_{spr,i}^{link}(\boldsymbol{q}_i)$$

$$\boldsymbol{T}(\boldsymbol{q}_i)_{spr,i}^{link} = \begin{bmatrix} \boldsymbol{R}(\theta_i) & \boldsymbol{R}(\theta_i)\begin{bmatrix}\delta x_i \\ 0\end{bmatrix} \\ \boldsymbol{0} & 1 \end{bmatrix}$$

Transformations to solve cost and constraint eqns.

- Solve for center of mass height

$$y_i(\boldsymbol{q}) = \boldsymbol{e}_2\boldsymbol{T}_i(\boldsymbol{q})\boldsymbol{T}_{COM}(\boldsymbol{q})\boldsymbol{e}_4$$

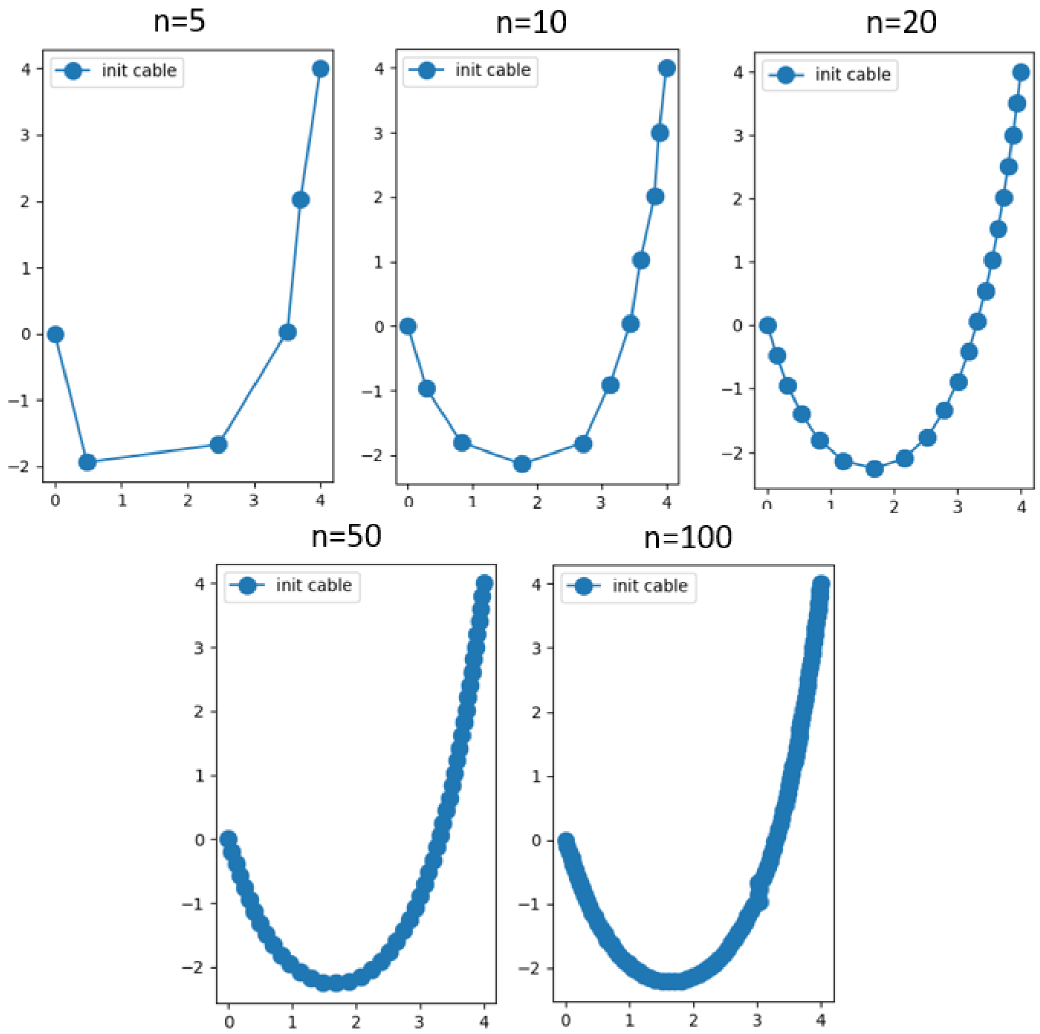
- End position constraint

$$\boldsymbol{p}_n(\boldsymbol{q}) = \boldsymbol{T}_n(\boldsymbol{q})\boldsymbol{T}_{link}\boldsymbol{T}_{spr,n+1}^{link}(\boldsymbol{q}_i)\boldsymbol{e}_4$$

$\boldsymbol{e}_i = [0 \ldots 1 \ldots 0] \in \mathbb{R}$^4
One in i^{th} entry

Minimized State Vector

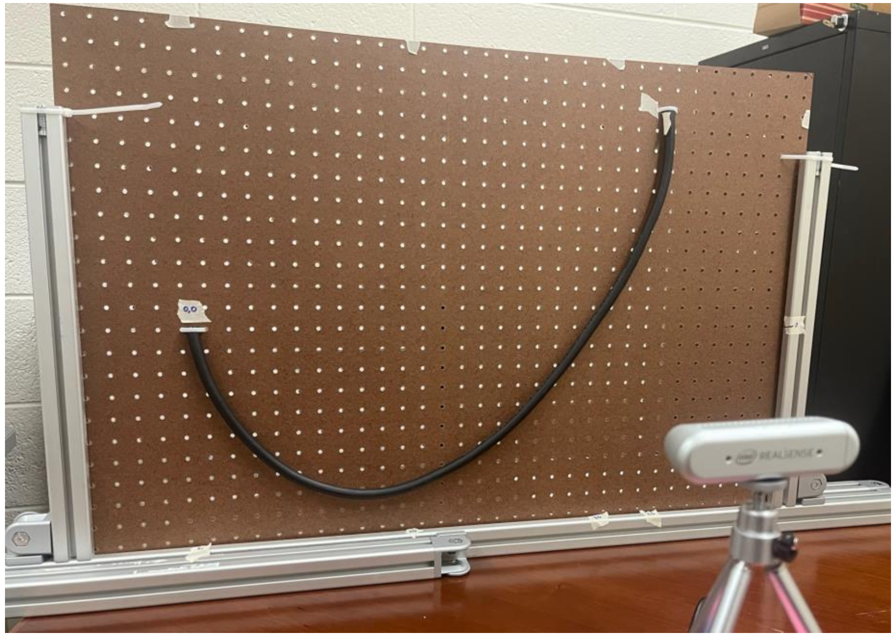
- Parametric model
  - Number of links as design parameter
- Tradeoff between accuracy and size of state space
  - Higher accuracy requires more computational time
  - Future work into generating tradeoff curve
- Leverage scenario goals to determine minimal state vector size
  - How cluttered is environment?
  - How fast does the control loop need to be?

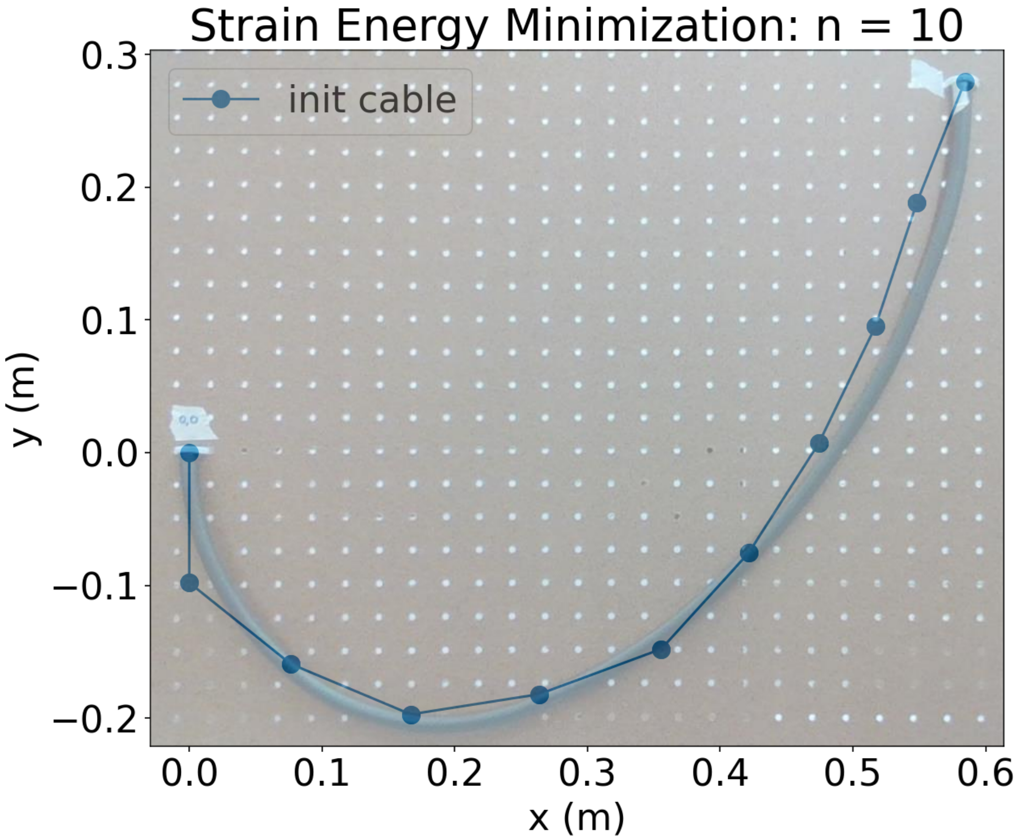


ASCEND

Hardware Validation

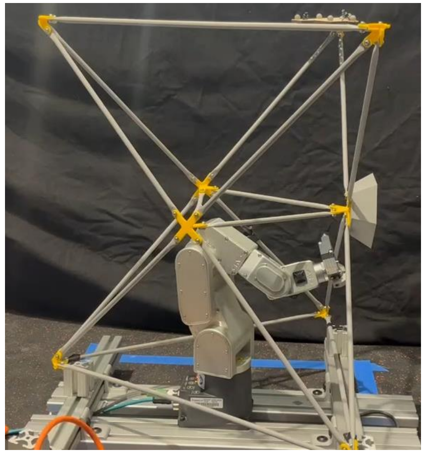
- Two-dimensional evaluation of real cable
- System ID to identify cable stiffness

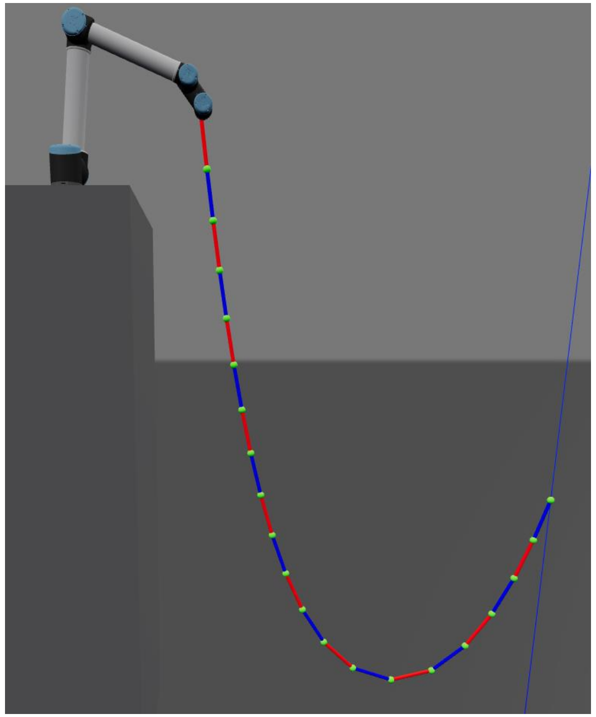




Ongoing Work

- Further evaluate static case with hardware
  - Optimize system ID procedure
- Integrate quasi-static motion with trajectory planner
  - RRT* or similar
- Integrate Dynamics
- Tradeoff between accuracy and degree of discretization
  - Compare with high fidelity Cosserat rod model
- Integrate with robotic system to automate outfitting





Questions?

ASCEND™

References

In order of appearance

- NASA, “MOON TO MARS OBJECTIVES,” , Sep. 2022. URL https://www.nasa.gov/sites/default/files/atoms/files/m2m-objectives-exec-summary.pdf.
- Melanie L. Grande, Robert W. Moses, Patrick A. Cosgrove, Robert P. Mueller, Tracie J. Prater and Alexander J. Blanchard. "Protecting Crew and Surface Systems with a Long-Duration Lunar Safe Haven," AIAA 2021-4070. *ASCEND 2021*. November 2021.
- NASA, “ISS National Laboratory,” , Mar. 2023. URL https://www.nasa.gov/mission_pages/station/research/nlab/index.html, accessed 22 March 2023.
- NASA, “Europa Clipper Propulsion Module,” Online, Aug. 2021. URL https://europa.nasa.gov/resources/207/europa-clipper-propulsion-module/?category=images, accessed 14 September 2023


ASCEND™
ascend.events

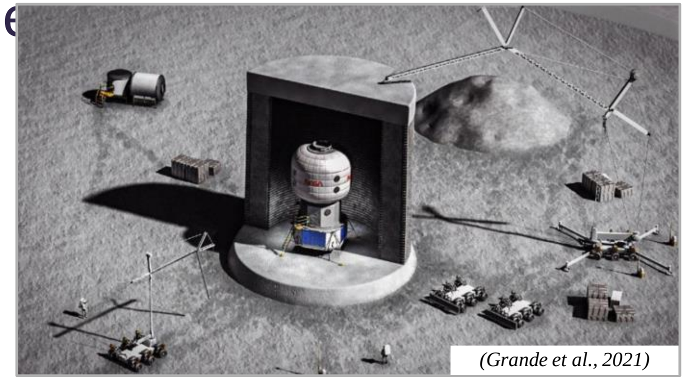
BACKUP

ASCEND

Robotic Construction and Outfitting


(NASA, 2023)

- Goal to have a sustained, long-term presence on the lunar
- Excavation, Construction, and Outfitting technologies criti infrastructure
  - *M2M Objectives LI-2: Demonstrate advanced manufacturing and autono construction capabilities in support of continuous human lunar presence robust lunar economy.*
- A permanent facility will not have a constant crewed presence
  - Robotic capabilities crucial for infrastructure


(Grande et al., 2021)

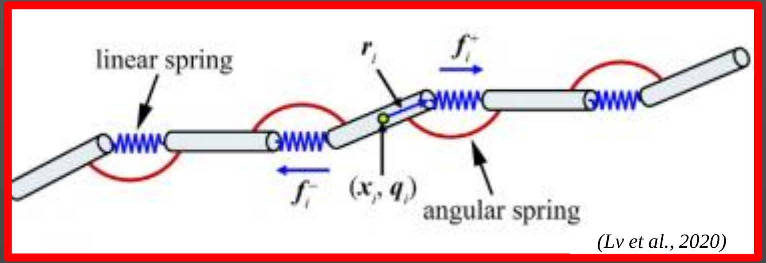
- This work focuses on performing **outfitting tasks with autonomous systems**
  - *In-situ* installation of subsystems to create a fully functional system
  - Applications for lunar surface work, in-space assembly, and terrestrial construction

ARCHITECTURE OVERVIEW

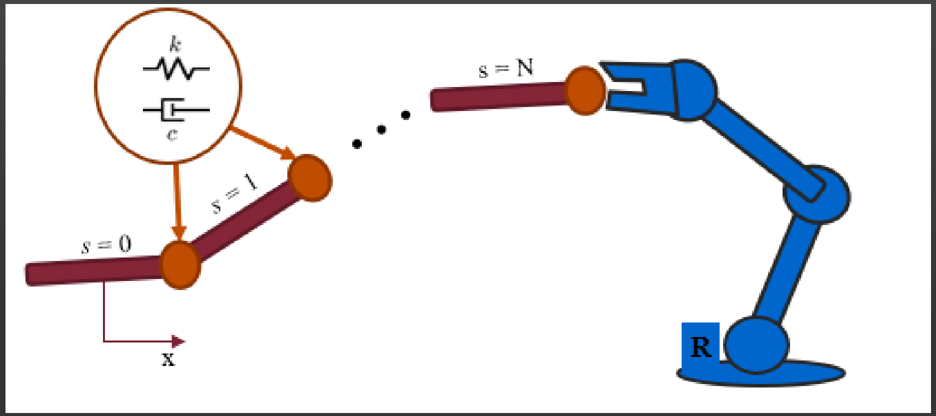
- **Model Formulation**
  - Cable/Robot **Kinematics**
  - Cable/Robot **Dynamics**
  - Environment Complexity
- **Offline Planning**
  - Optimized Trajectory Generation
  - Cable/Robot constraints
- **Real-Time Execution**
  - Control Model (replan ability)
  - State Estimation
  - Minimized State Vector

MODEL FORMULATION
CABLES

- Cables are considered Deformable Linear Objects (DLOs)
  - Multiple formulation approaches: discretized models, continuum models, model-free neural-network

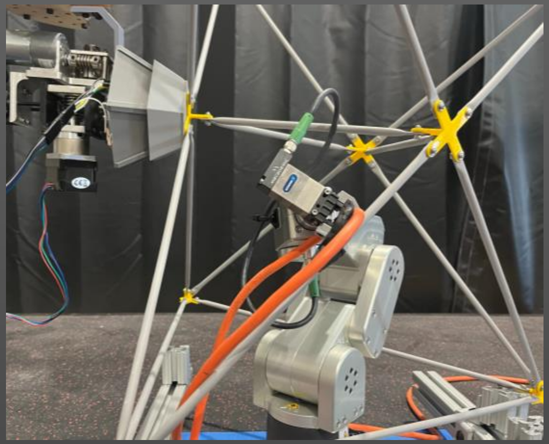


- Discrete Multibody Dynamics Model
  - Cable broken up into a fixed number of components
  - Connect links with springs and dampers



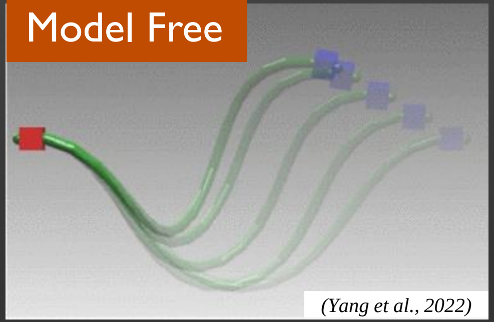
MODEL FORMULATION
ROBOTICS

- Utilize joint information to define robot based on joint position
  - Screw Theory Kinematic Formulation
- Transformation Matrices to represent spatial points of interest
  - Map position/velocities between joint space and task space



- Feasibility Experiments
  - Demonstrate serial robot arm for cable manipulation

Model Free



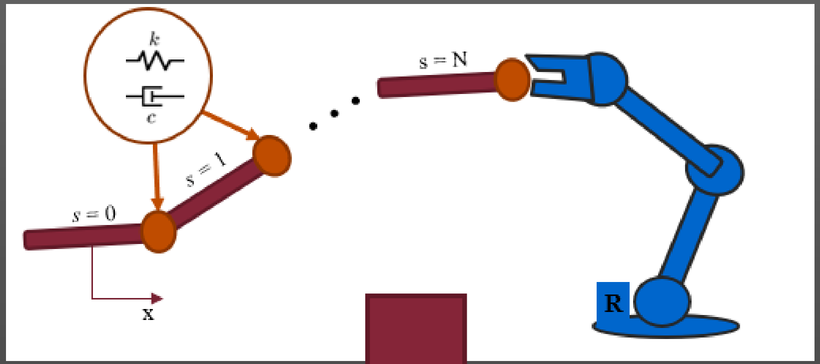
(Yang et al., 2022)

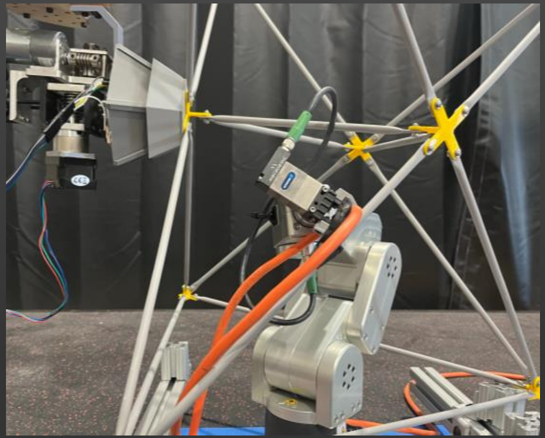
MODEL FORMULATION
ENVIRONMENT COMPLEXITY

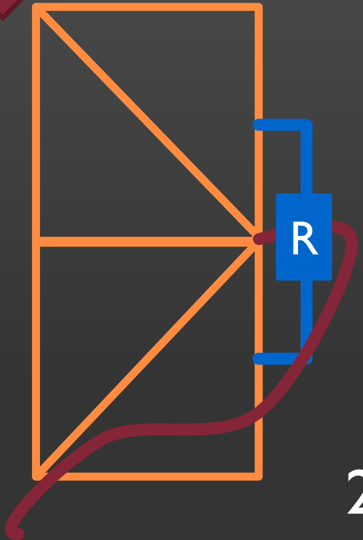
- Cable and Robot models rely on an understanding of the full environment
- Complex applications make it difficult to access individual components
- Slowly introduce complexity into architecture

COMPLEXITY

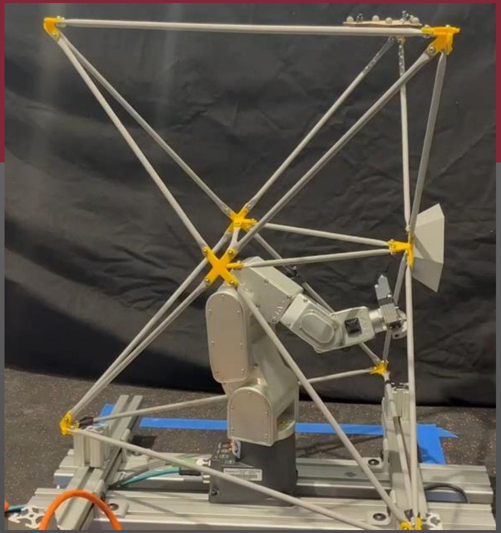
- 2D - Drag cable, no obstacles
- 2D - Drag cable, obstacles in path
- 3D Anchored cable, path w/ obstacles
- 3D cluttered structure, space env.



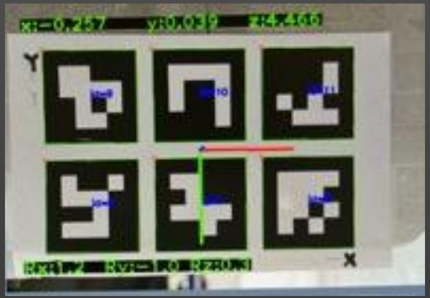




ROBOTICS



- **ROBOTICS**
  - Utilize available hardware (URs) and open-source tools (ROS/Python RTB)
- **TRAJECTORY**
  - Optimal planner (such as RRT*, RRT#) with similar constraints to minimization problem
  - Introduce route intermediate point constraints
- **CONTROL**
  - Model Predictive Control for path following
  - Utilize the dynamics of the system to a certain time horizon to inform the control input to the system
- **STATE ESTIMATION**
  - Non-linear Filtering for SLAM (EKF, UKF, etc.)
  - Model reduction techniques to be evaluated to reduce computational requirements



OFFLINE PLANNING

- Utilize knowledge of the system to generate optimal trajectory
  - Known: Static environment (obstacles), cable model, robot kinematics
  - Cost function: Weighted combination of cable and robot motion
- Rapidly exploring Random Trees (RRT)
  - Graph based path planner to explore known space
  - RRT* - optimal variation, allowing RRT graph to redo edges when lower cost path found
- Constraints
  - Collisions between objects
  - Avoid too much bending in cable
  - Known start, end, and waypoint positions cable must pass through