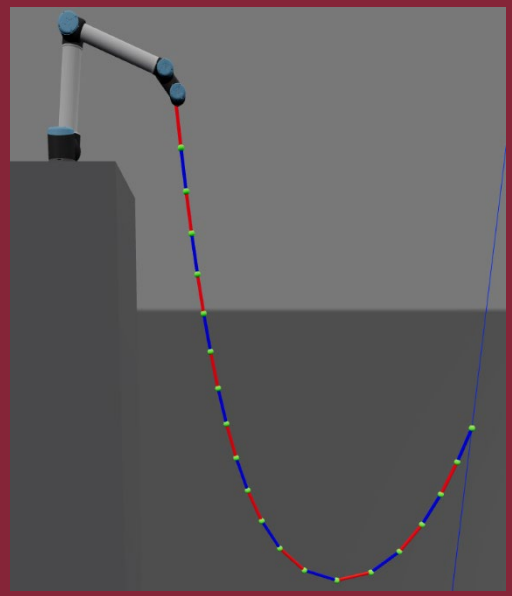
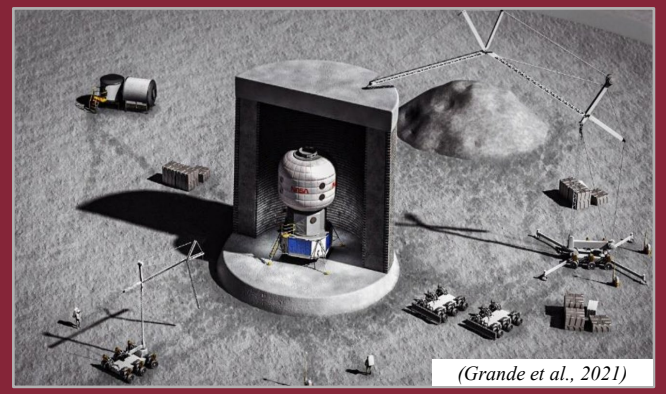
MODELING DEFORMABLE LINEAR OBJECTS FOR AUTONOMOUS ROBOTIC OUTFITTING OF LUNAR SURFACE SYSTEMS

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Amy Quartaro,
NSTGRO Researcher
PhD Candidate, Mechanical Engineering
Virginia Tech

John Cooper, Ph.D., Joshua Moser, Ph.D., Erik Komendera, Ph.D.



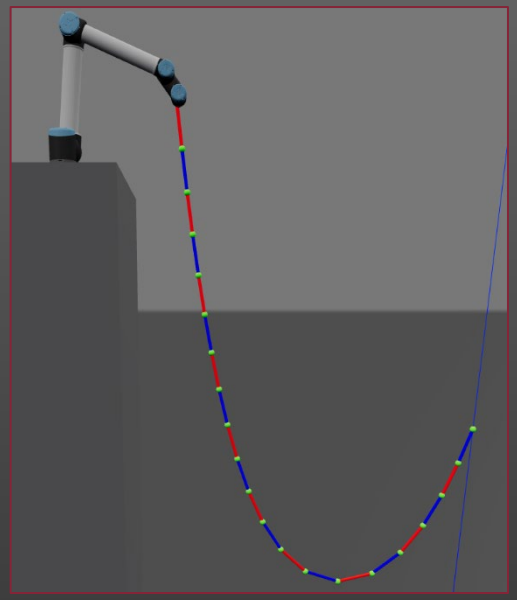


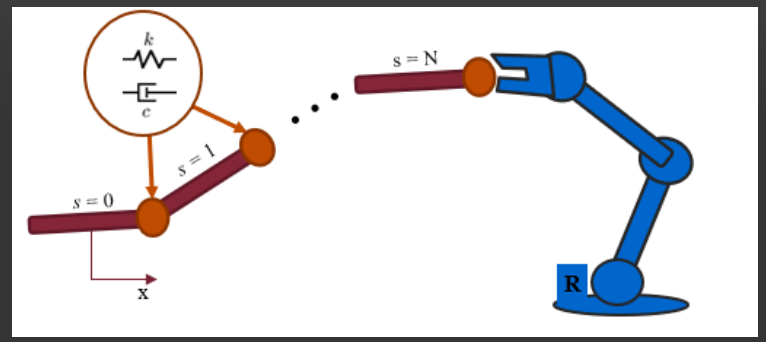
(Grande et al., 2021)

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AGENDA

- Lunar Construction and Outfitting
- Robotic Outfitting
- Deformable Linear Object (DLO) Modeling
  - Multibody Springs
  - Cosserat Rods
- Comparison Results
- Further Work



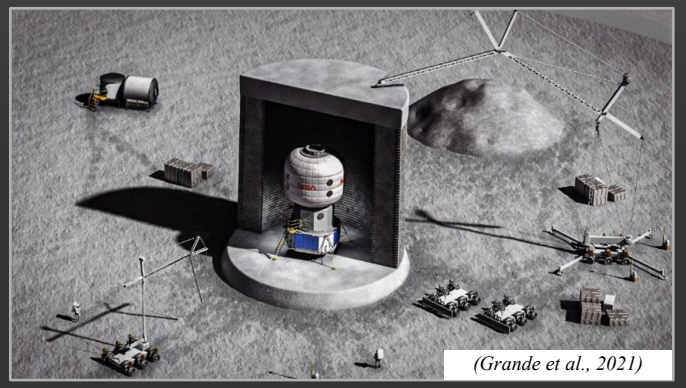


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LUNAR CONSTRUCTION AND OUTFITTING

- 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)

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ROBOTIC OUTFITTING

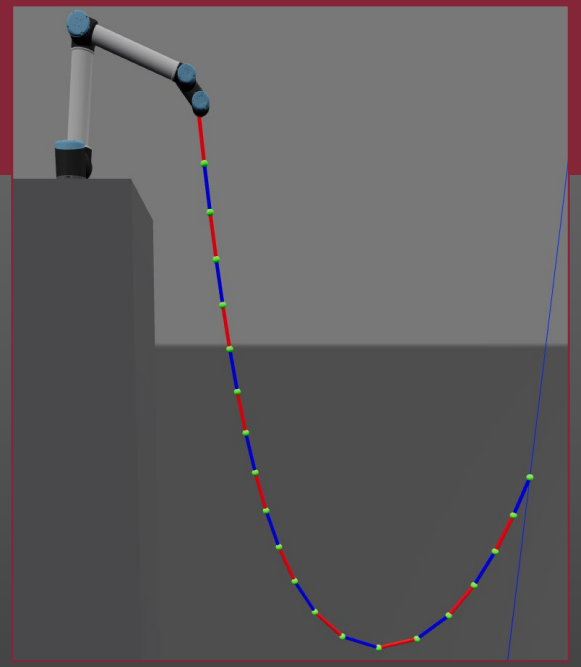
- This work focuses on performing **outfitting tasks with autonomous systems**
  - *In-situ* installation of subsystems to create a fully functional system
- Outfitting often involves the routing and installation of cables
  - Cables are considered Deformable Linear Objects (DLOs)
- Challenges of autonomous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


(NASA, 2023)

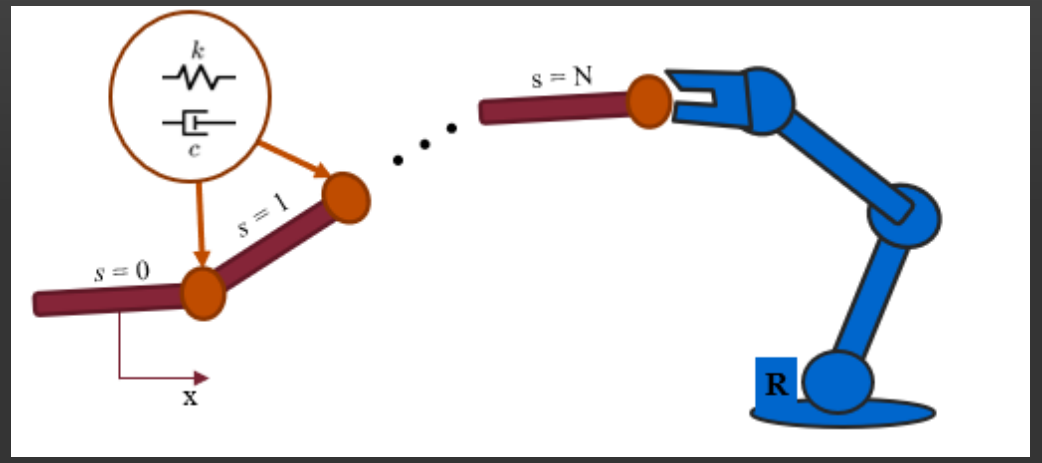

(Johns Hopkins APL/Ed Whitman, 2021)

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MODEL FORMULATION



- Understanding the DLO model is essential
  - Represent cable
  - Start with static implementation to verify model fundamentals
- Discrete Multibody Model
  - Cable broken up into a fixed number of rigid body segments
- Static Configuration
  - Links connected with springs only
  - 2D to simplify derivations
  - Compare with hardware images



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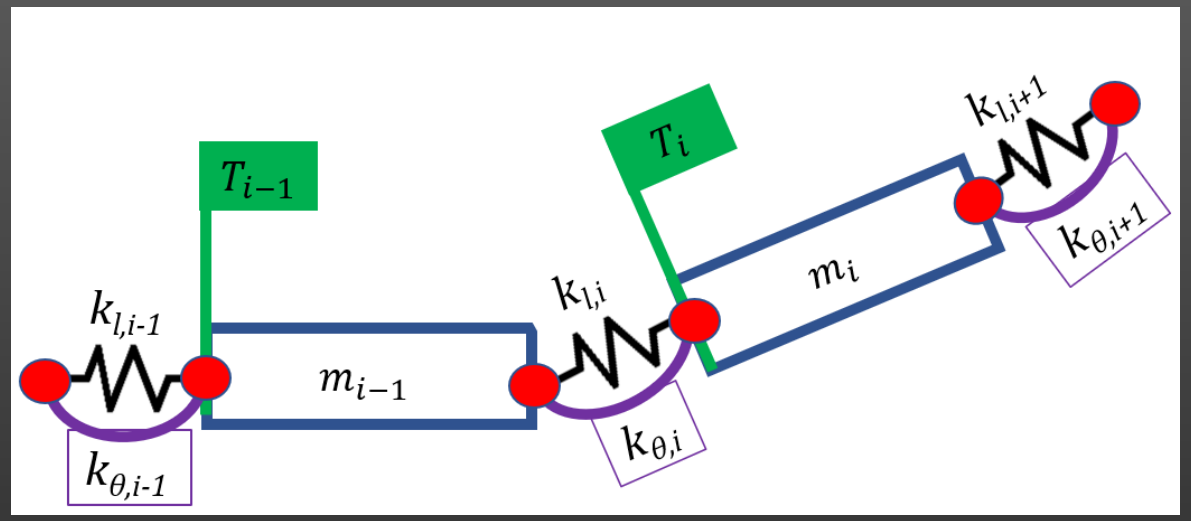
MULTIBODY SPRINGS

- 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

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



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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 $y_i(q)$ for gravity potential
    $$U = m_{link} g\, y_i$$
- Formulate as optimization problem
  - **Cost:** Potential Energy
  - **Variables:** Generalized Coordinates, 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

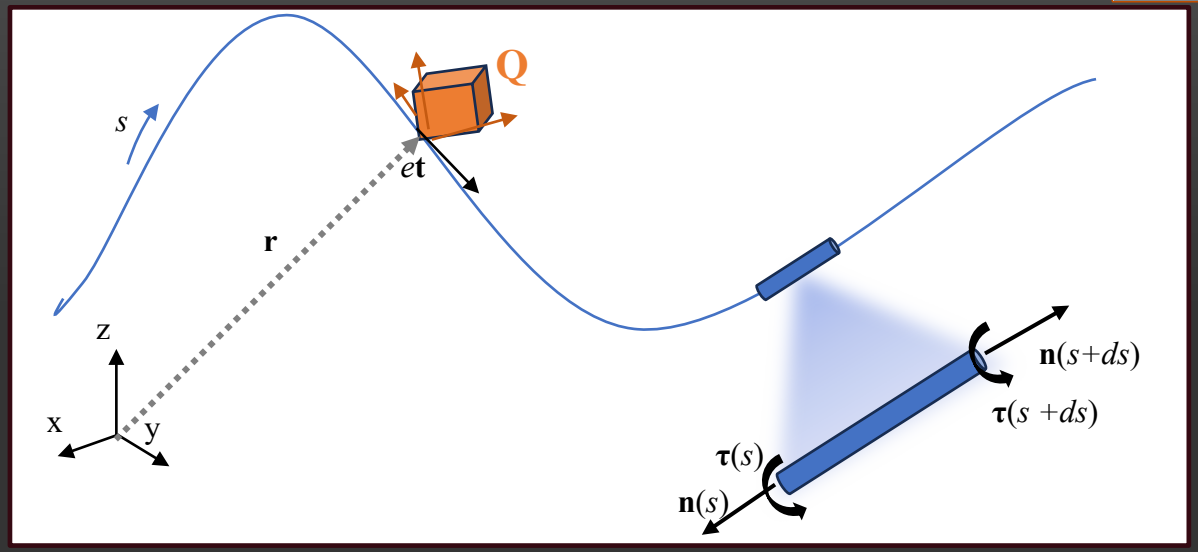
Start position

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COSSERAT ROD

- Rod theory based on piecewise Equations of Motion (EoM)
  - Pyelastica Toolbox [1]

$s \in [0, l] \Rightarrow parametric\ cable\ length$



Local dilation

$$e(\hat{s}, \mathbf{t}) = \frac{ds}{d\hat{s}}$$

Strain

$$\sigma = \mathbf{Q}(e\mathbf{t} - \mathbf{d}_3)$$

load-strain *torque-curvature*

$$\mathbf{n}(s) = \mathbf{S}\sigma(s) \quad \tau(s) = \mathbf{B}\kappa(s)$$

+

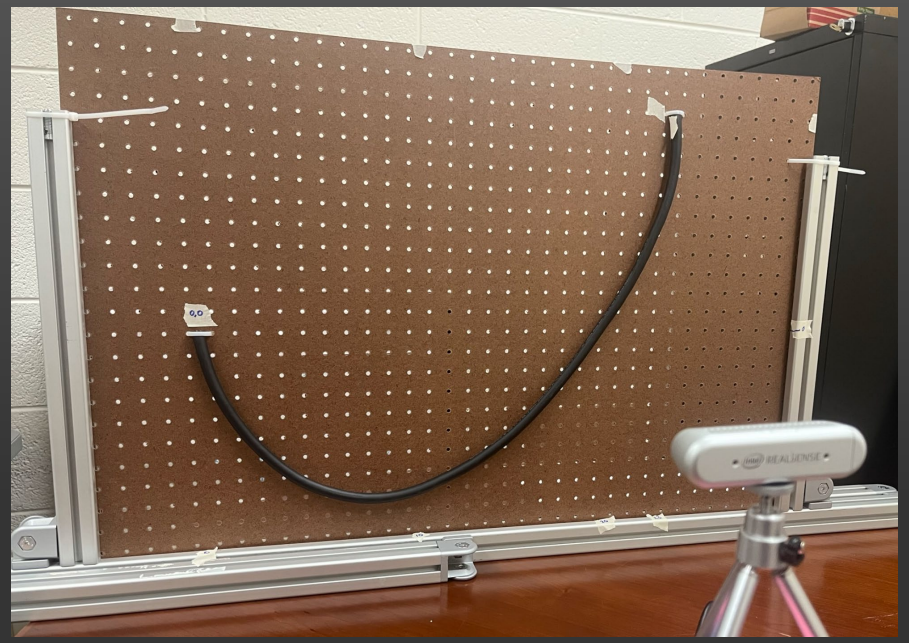
External Forcing

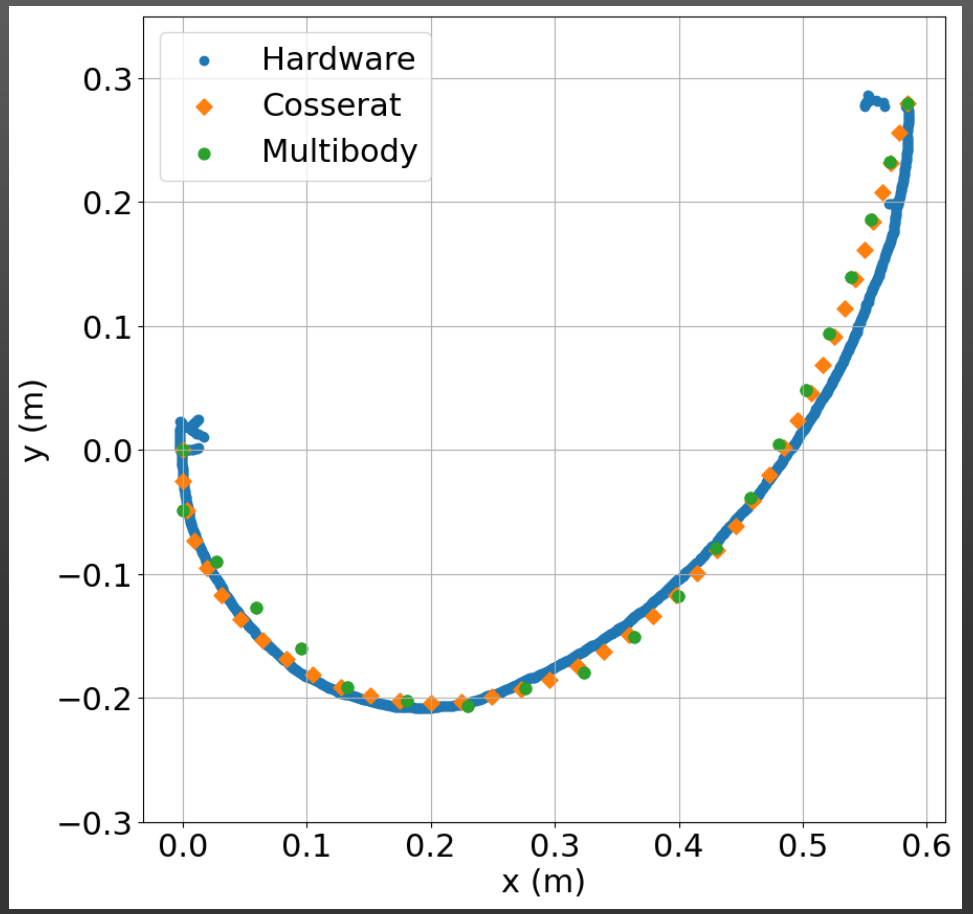
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[1] Tekinalp et. al (2023). "GazzolaLab/PyElastica: v0.3.1 (May).

HARDWARE VALIDATION

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



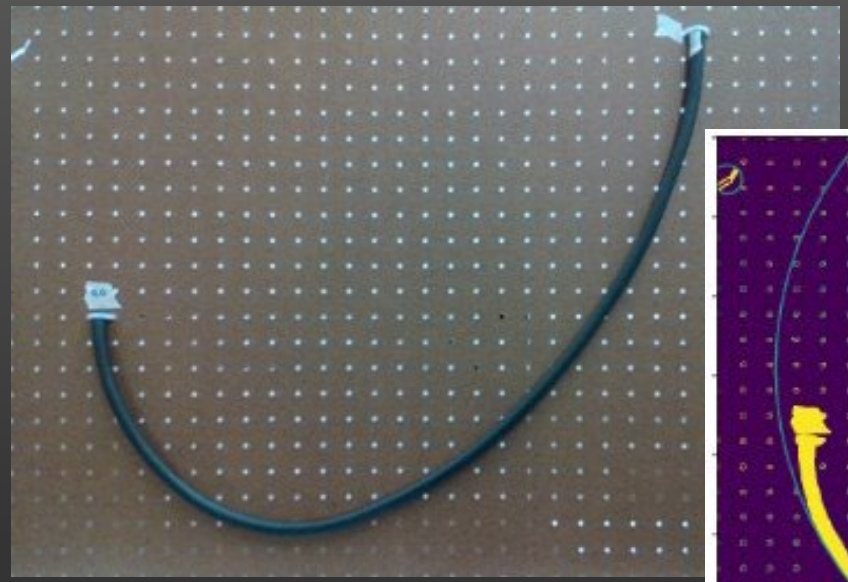


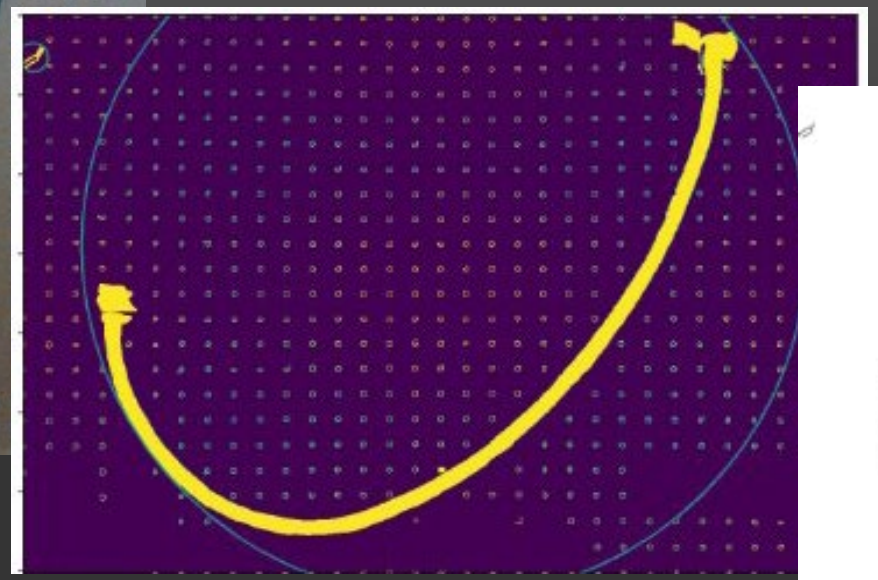
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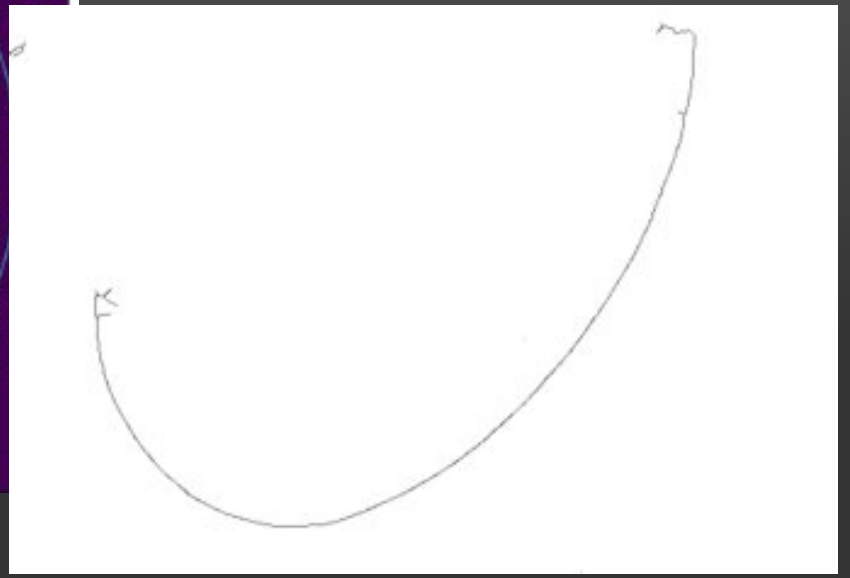
COMPARISON TO HARDWARE

- Image data from Intel RealSense
- Processed with OpenCV [2]

Process:
1. Canny Edge
2. Morphology Kernel (ellipse) Dilation
3. FindContours
4. thining





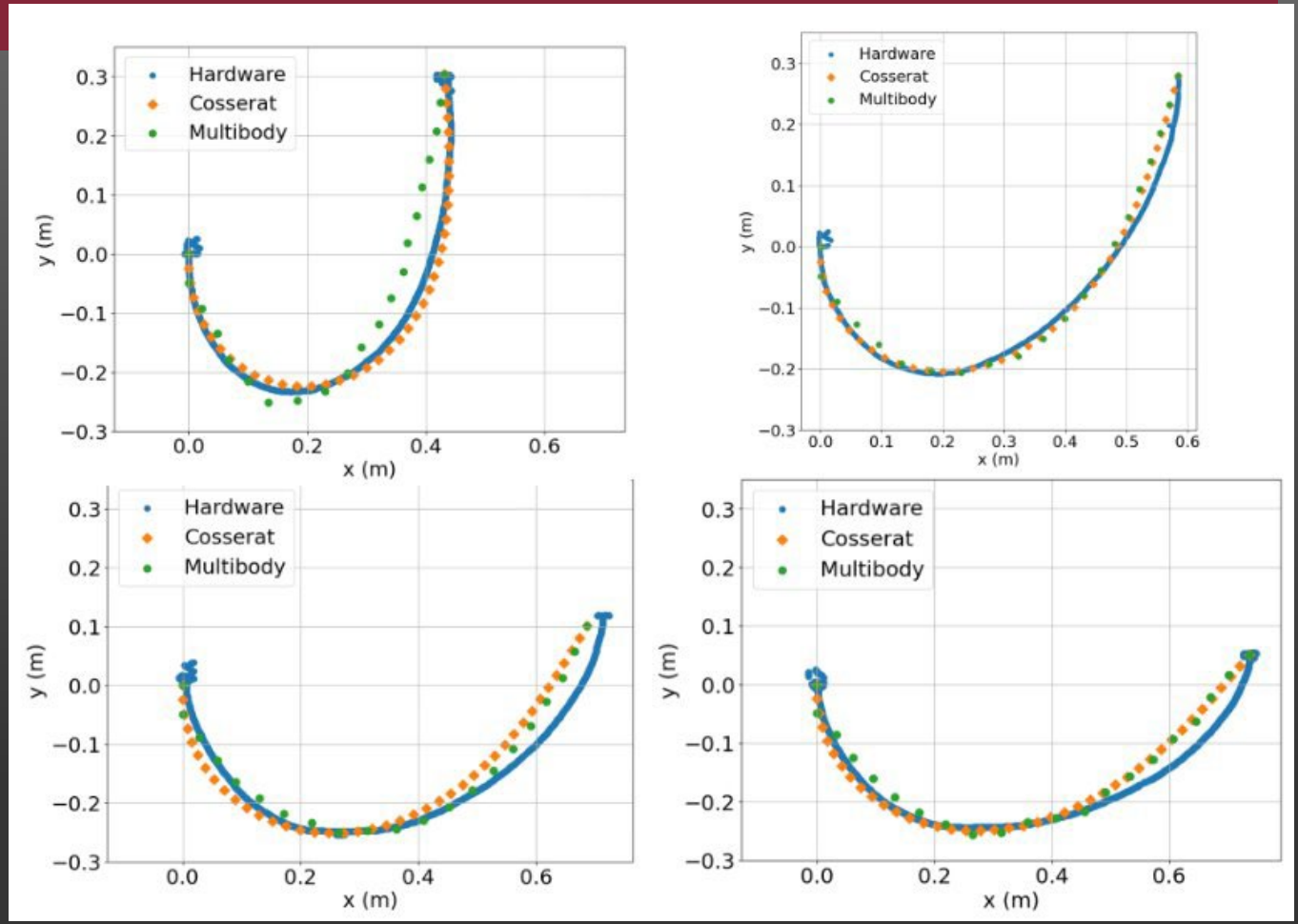


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[2] Bradski, G. (2000). "The OpenCV Library." Dr. Dobb's Journal of Software Tools.

MODEL COMPARISON

- Model Comparison: MSE = 4.213E−05m^2
  - Top-right configuration
- More tuning to be done
  - Constraints on both ends



Compared to Hardware

Simulation Model	Mean Square Error $[m^2]$
Cosserat Rod	6.531E-05
Multibody (n=5)	4.263E-03
Multibody (n=10)	2.010E-04
Multibody (n=20)	1.307E-04
Multibody (n=50)	2.292E-04

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KEY DIFFICULTIES

- Internal preload of cables
- Sensing limitations
- Update rate of simulation
- Feedback control loop (main problem to solve)

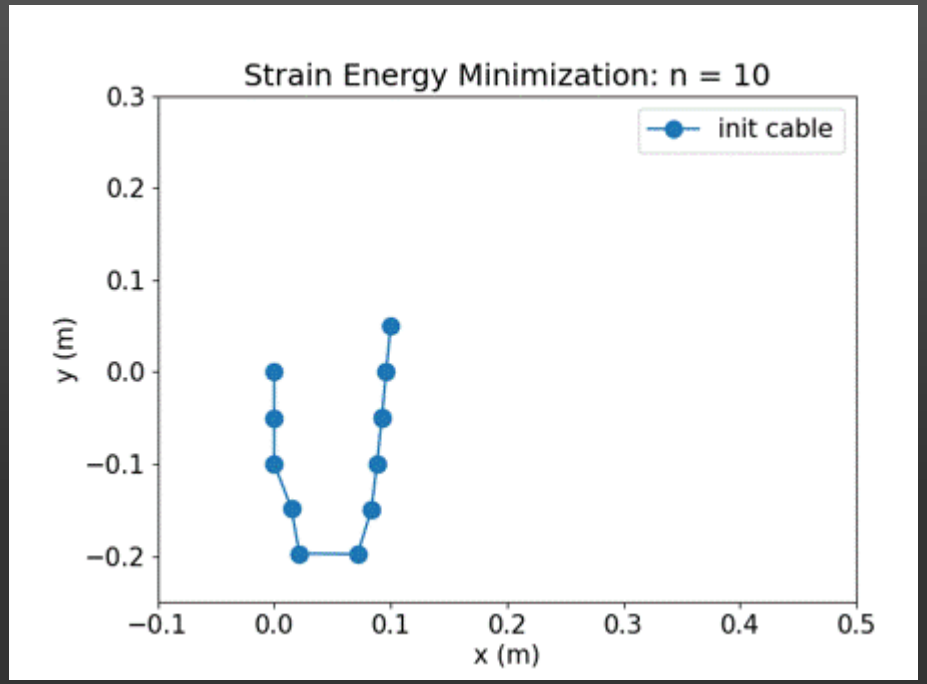
POSSIBLE APPLICATIONS

- Robotic cable laying during *in-situ* assembly (ISRU printing, brick-laying, underground, etc.)
- Maintenance operations
  - Manipulate in/around pre-installed structures
- Both outfitting and payload manipulation is modeling and traversal well understood

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ONGOING EFFORTS

- Integrate method for robust parameter estimation
- Improved data collection procedures



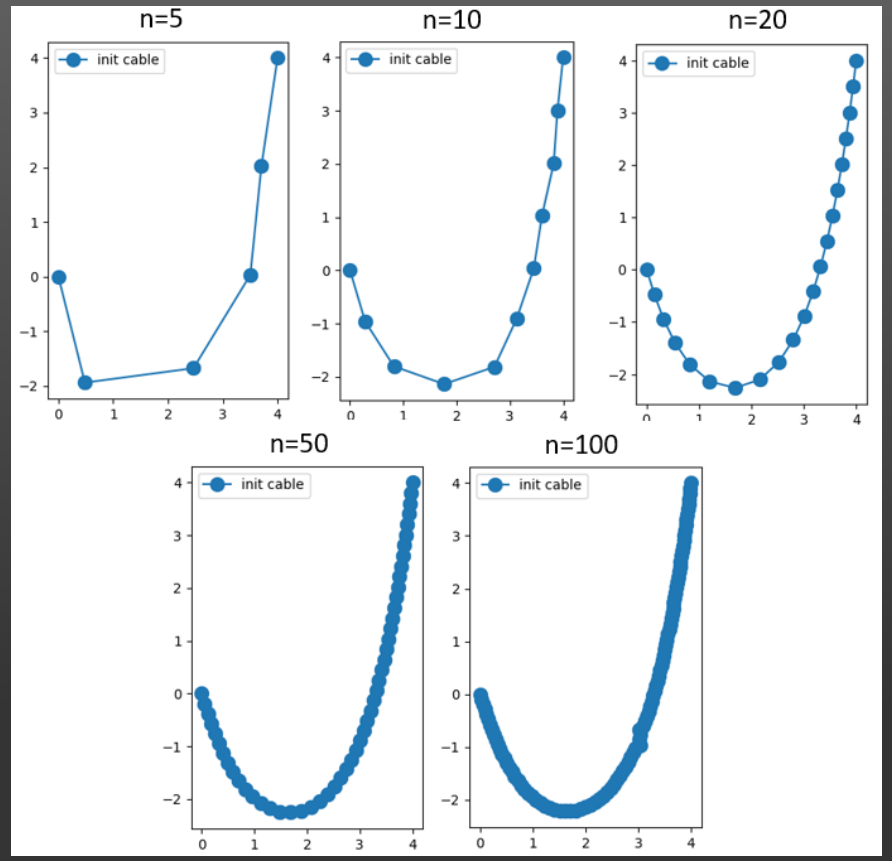
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BACKUP

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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?



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BACKGROUND

CURRENT STATE OF THE ART

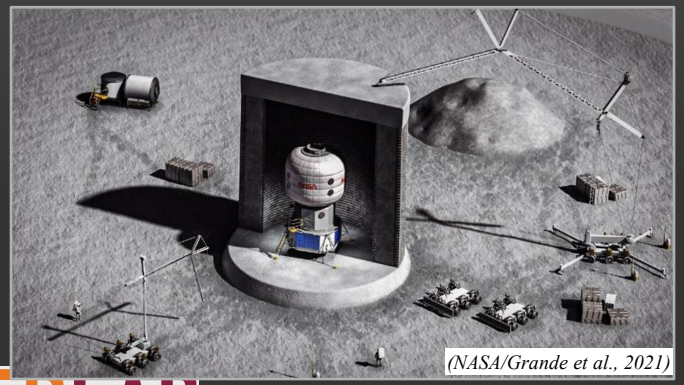
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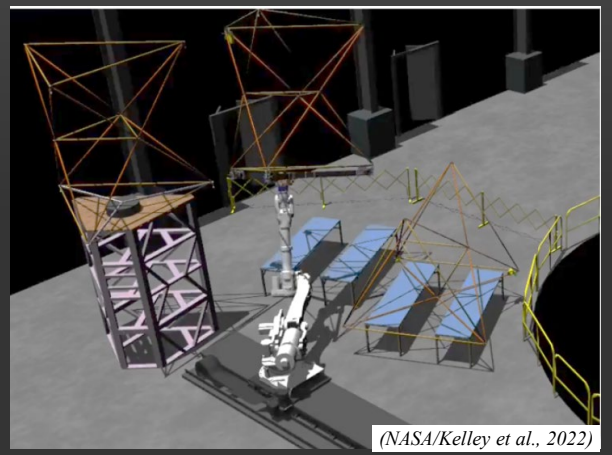
IN-SPACE ASSEMBLY AND CONSTRUCTION

- Architectural need for construction and maintenance
- Assembled trusses
- 3D manufacturing
- Robotic/Autonomous assembly


(NREL/Muthumanickam et al., 2023)


(NASA/Komendera et al., 2017)


(NASA/Grande et al., 2021)


(NASA/Kelley et al., 2022)

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