Locomotion of Mobile Tensegrity Robots in Unstructured Environments for Space and Agriculture Applications

Lauren Ervin

FIU ECE Seminar

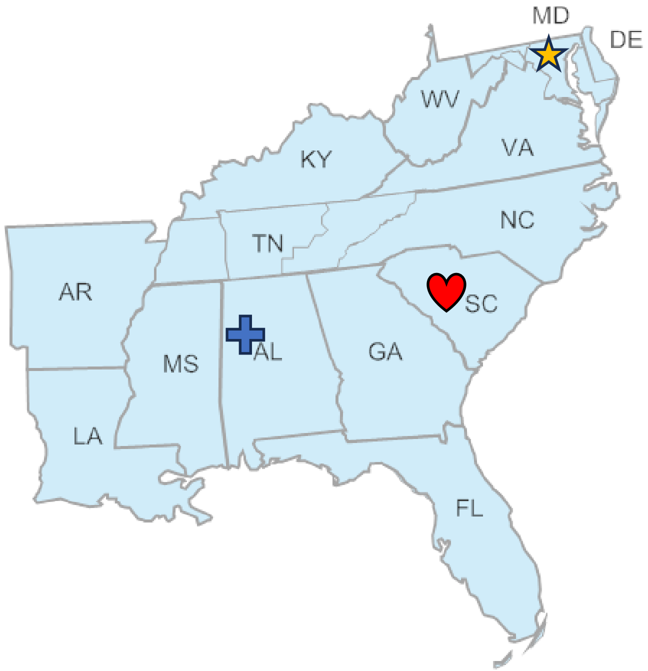
November 15th, 2024

Agile Robotics Lab (www.arl.ua.edu)

College of Engineering

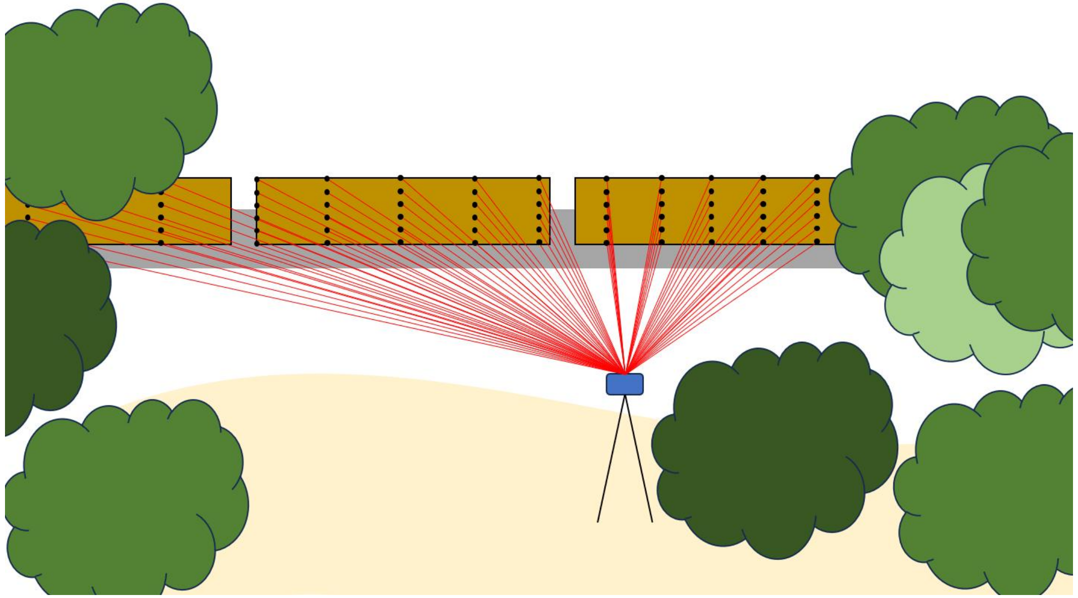
agile robotics lab

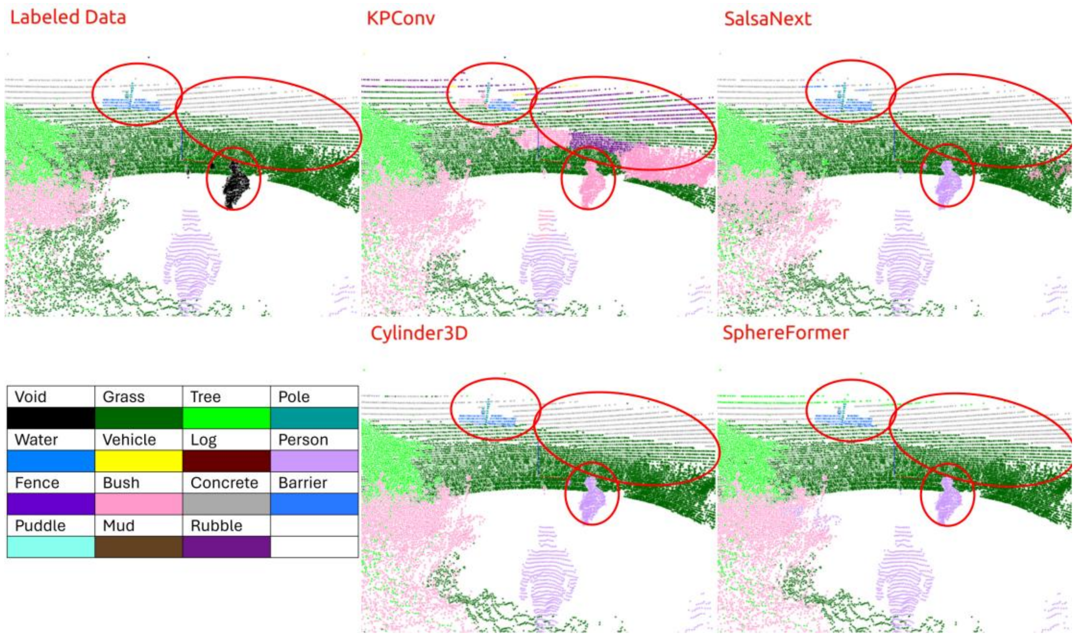
About Me

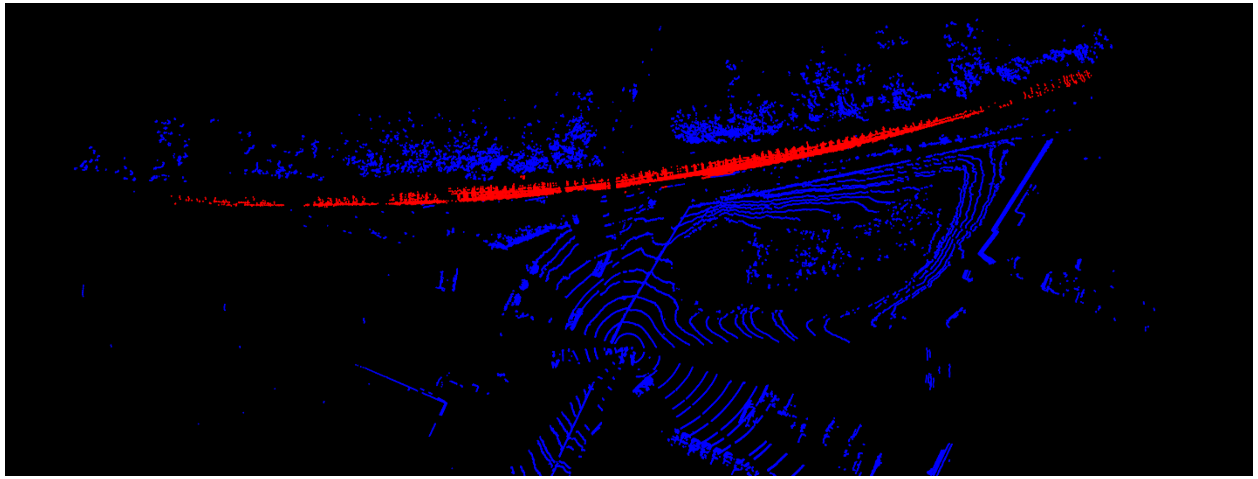


- 1998: Born in Irmo, South Carolina
- 08/2016-05/2020: received Bachelor's in ECE with a Math Minor from UA
  - 4 Co-op rotations with the DoD in Maryland
- 05/2020-*current*: entered Master's program in ECE at UA and began GRA position as computer vision researcher + lab manager of ERSYL
- 05/2021: transitioned to Ph.D. program in EE at UA
- 08/2022-*current*: became robotics researcher in ARL
- 08/2025: expected graduation of Ph.D. in EE at UA

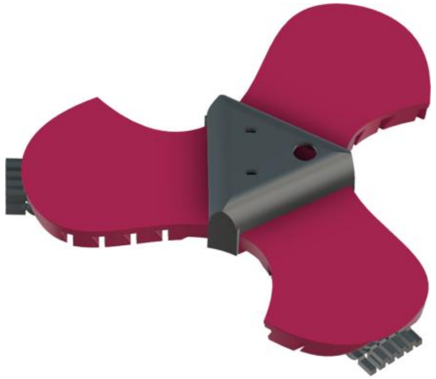
Embedded Robotics and Systems Lab (ERSYL)







Agile Robotics Lab (ARL)

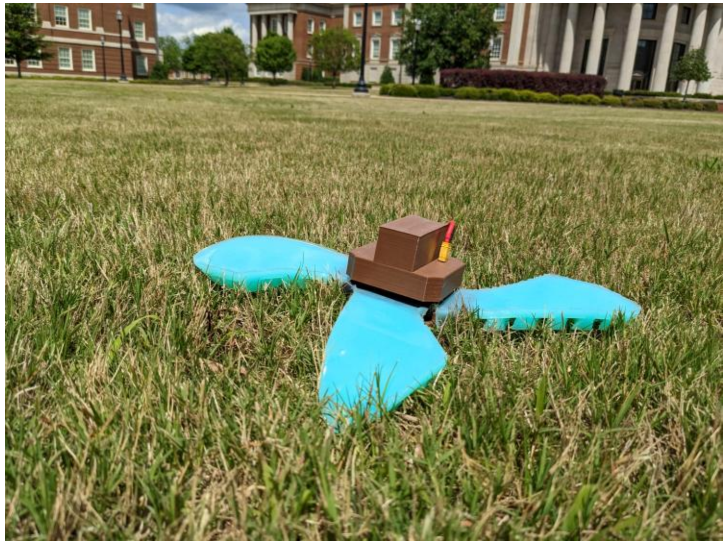


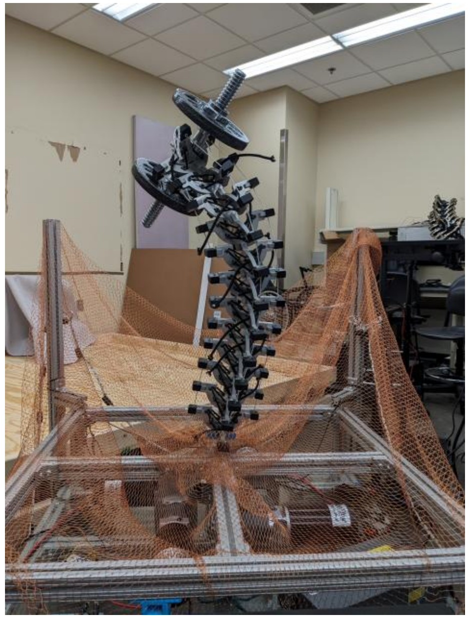
Rolling

Turn left

Turn right

Rolling

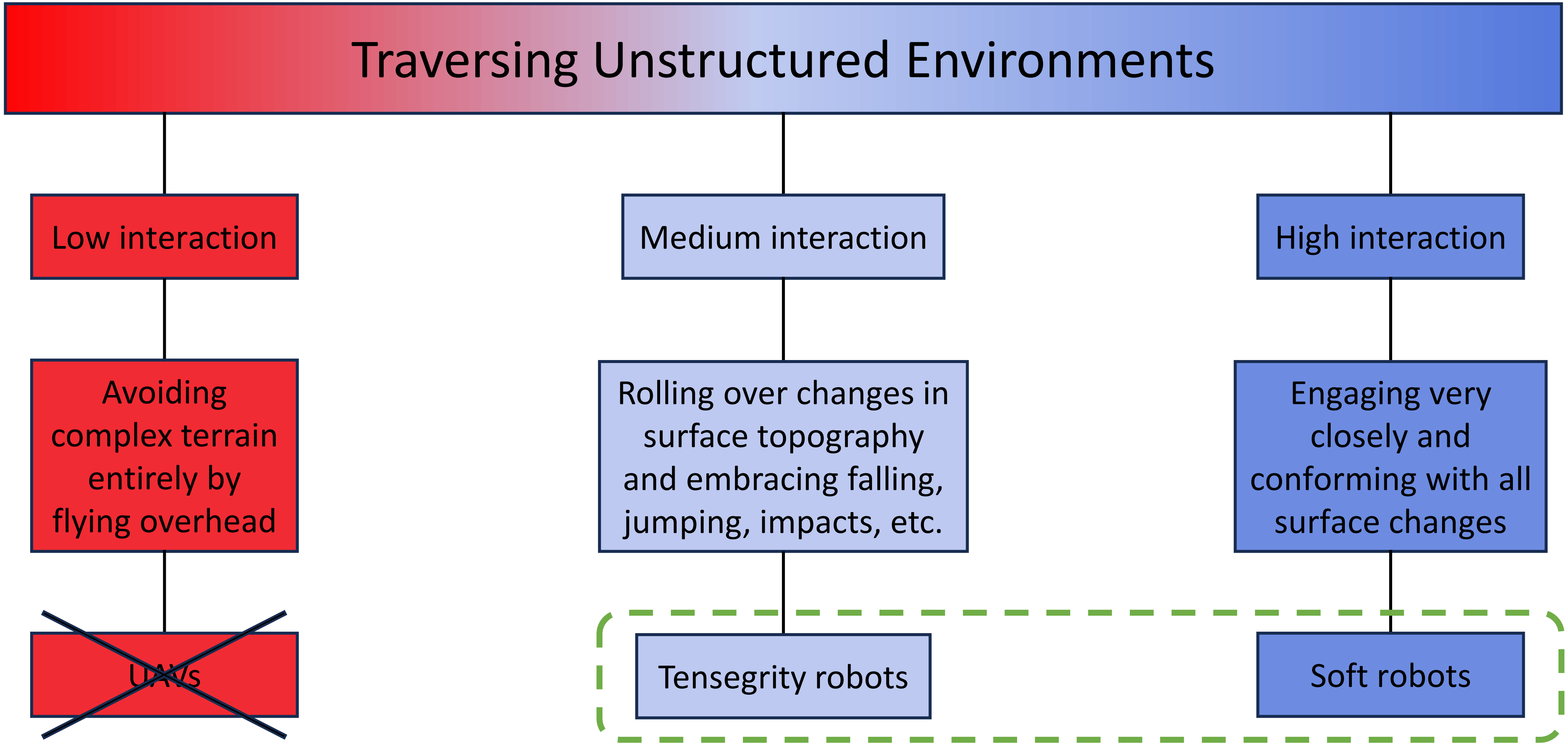




Talk Outline

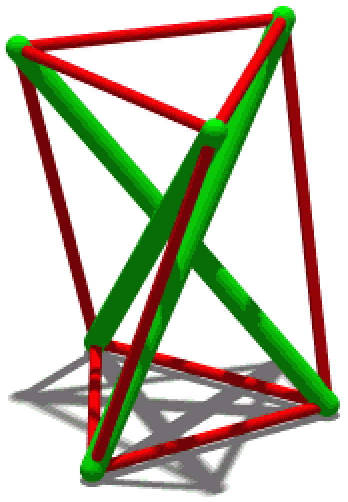
- History of tensegrity
- Motivation and background
- Modeling curved-link, mobile tensegrity robots
- Design of tensegrity continuum manipulator
- Utilizing deep learning for manipulator shape estimation

Research Overview



What is Tensegrity?

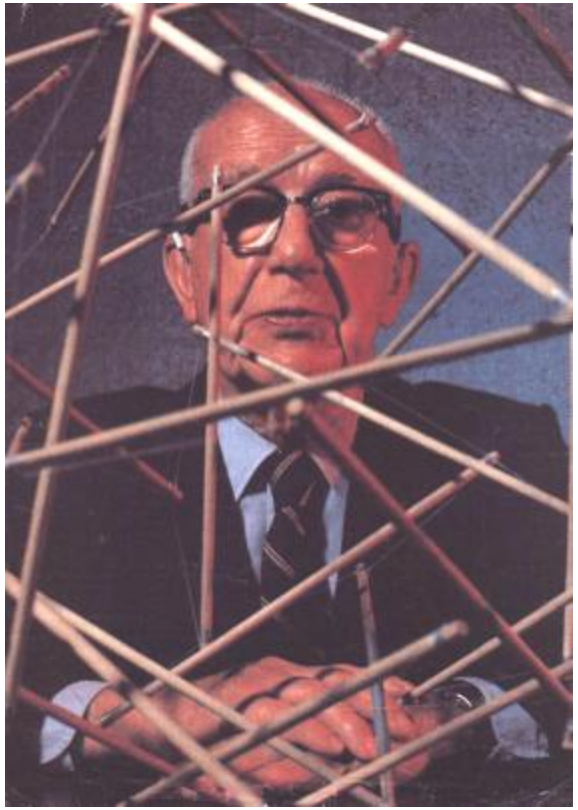
Tensegrity **mechanisms synergistically combine *tens*ion elements (pre-stressed cables) with compression elements (rigid rods) to achieve structural int*egrity*.**



History of Tensegrity

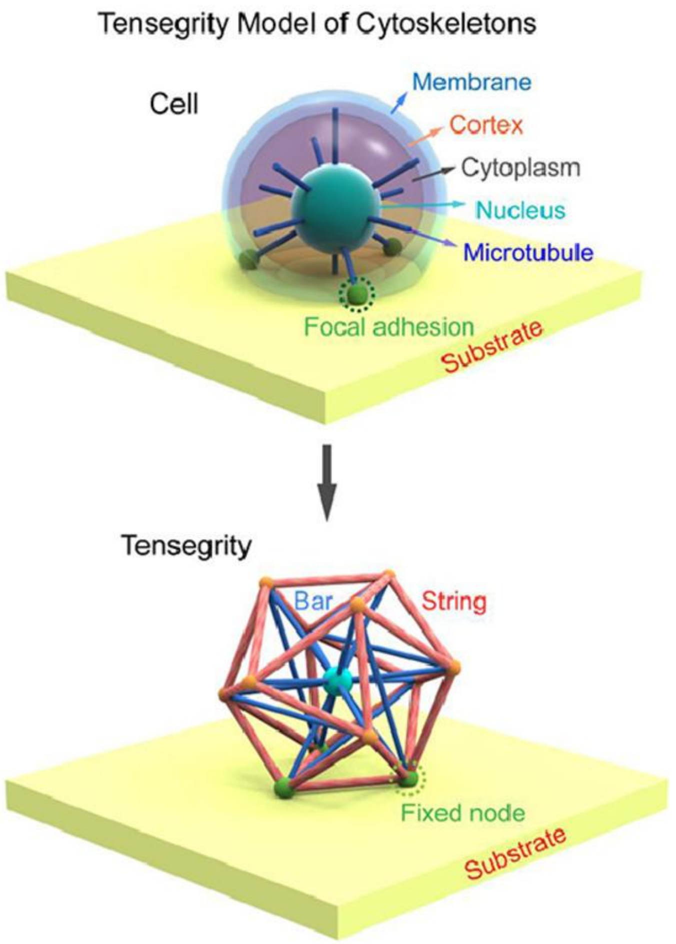
- Invented by Buckminster Fuller in 1950s
- Initially used in architecture and art installations
- Adapted to robotics within the past two decades
- Many pieces of modeling software exist:
  - NTRT
  - TsgFEM
  - MOTES
  - MuJoCo
- None of them can currently handle curved-links

- **Research gap:** lack of curved-link modeling



[1] Buckminster Fuller Institute

Examples of Tensegrity



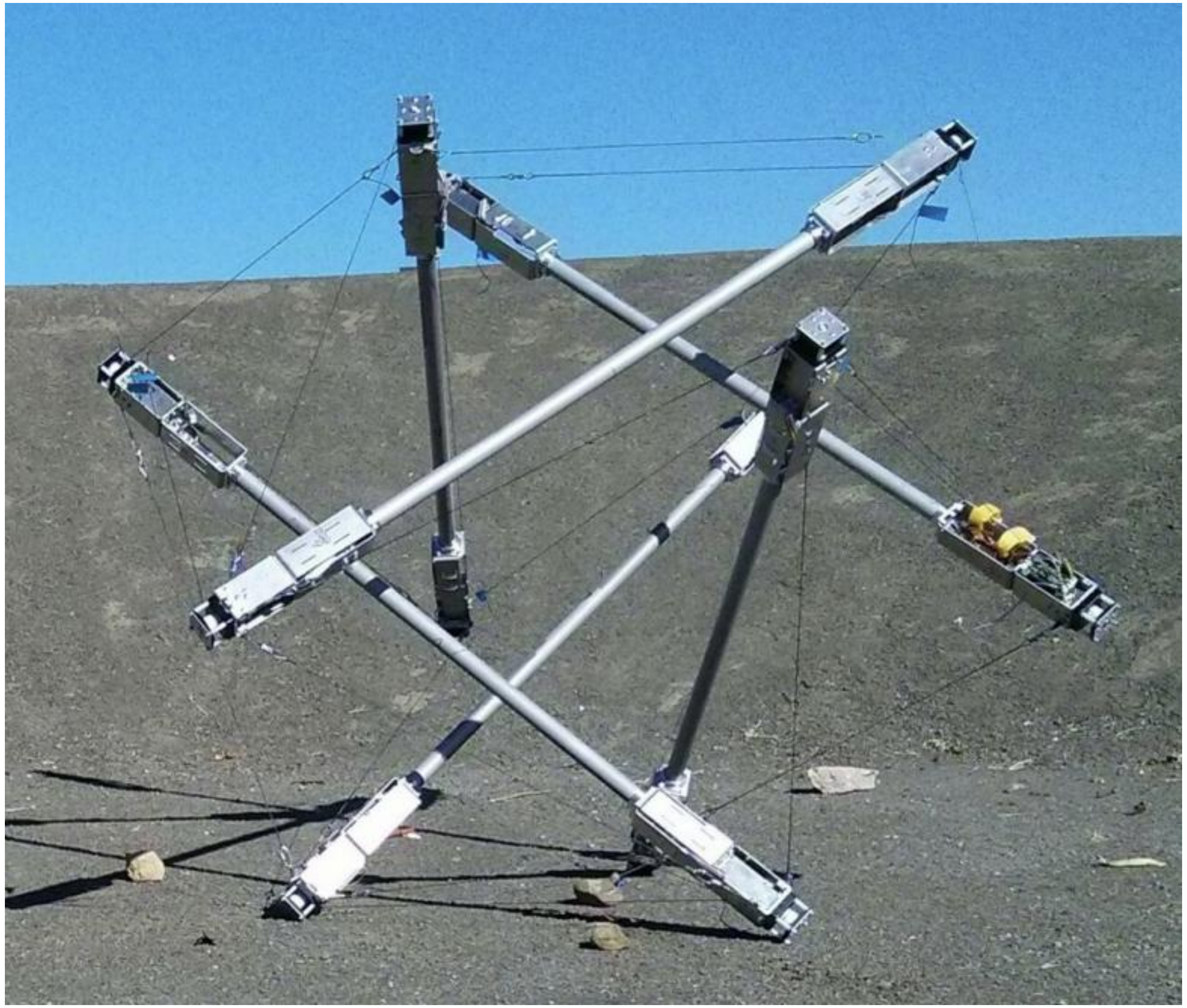
[2] Sun Et al. “Biochemomechanical Tensegrity Model of Cytoskeletons”

[3] Baulderstone, Kurilpa Bridge

[4] Kenneth Snelson, Needle Tower II

Examples of Tensegrity Robots

[5] Agogino Et al. Squishy Robotics



[6] SunSpiral Et al. “Super Ball Bot - Structures for Planetary Landing and Exploration”

Why use Tensegrity?

Tensegrity mechanisms are

- **Packable & portable**
- **Impact resistant**
- **Internally stable (no gravity required for structural stability)**
- **Modular and reconfigurable**
- **High strength-to-weight ratio**

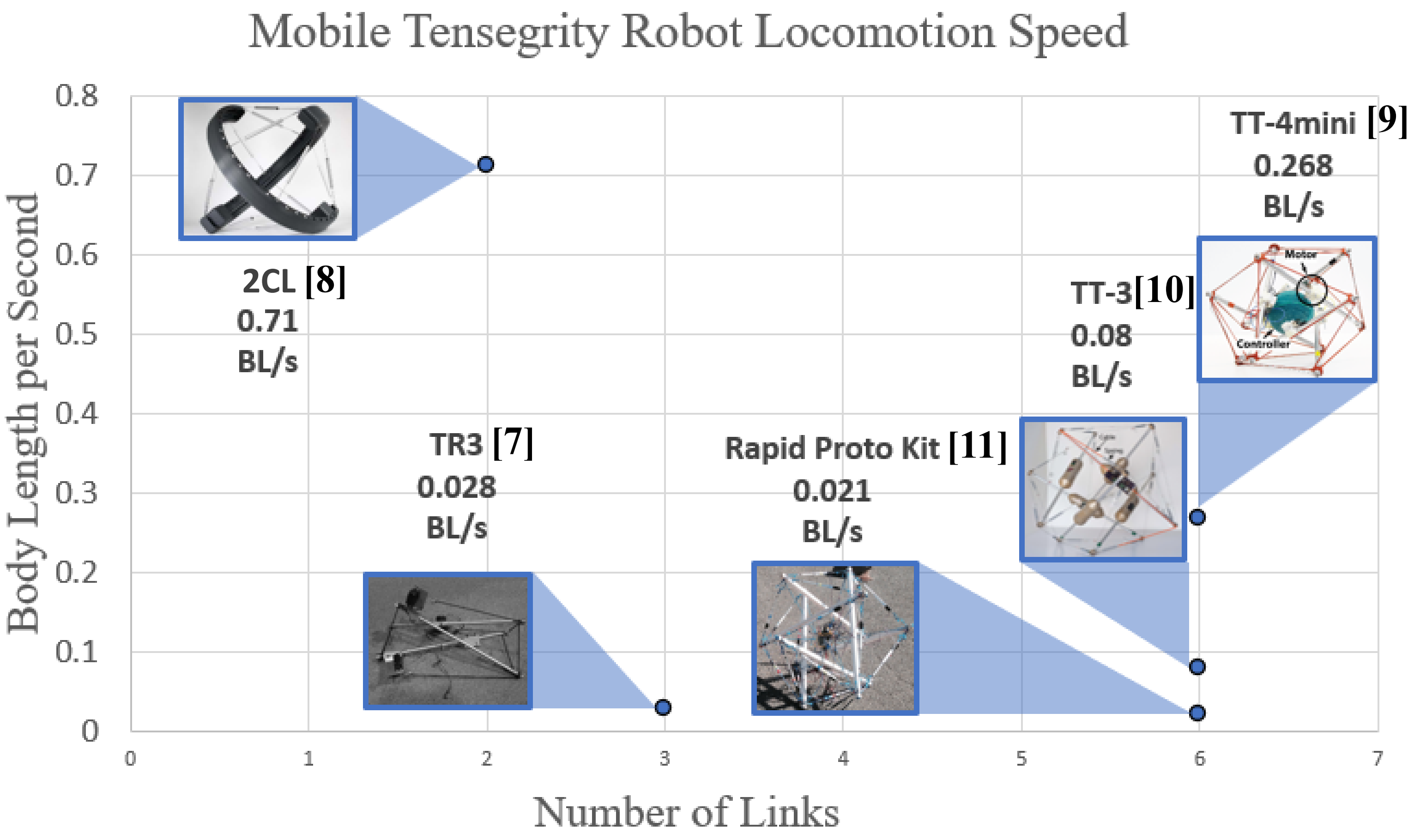
Challenge: They are difficult to model and control given the non-linear, antagonistic nature of compressive and tension elements.

Solution: A geometric modeling framework that is generalizable to different robot morphologies.

Motivation

The two curved-link robot is ~3x faster (normalized to body length/s) than the fastest straight-link counterpart.

Curved-links = efficient rolling = speed!



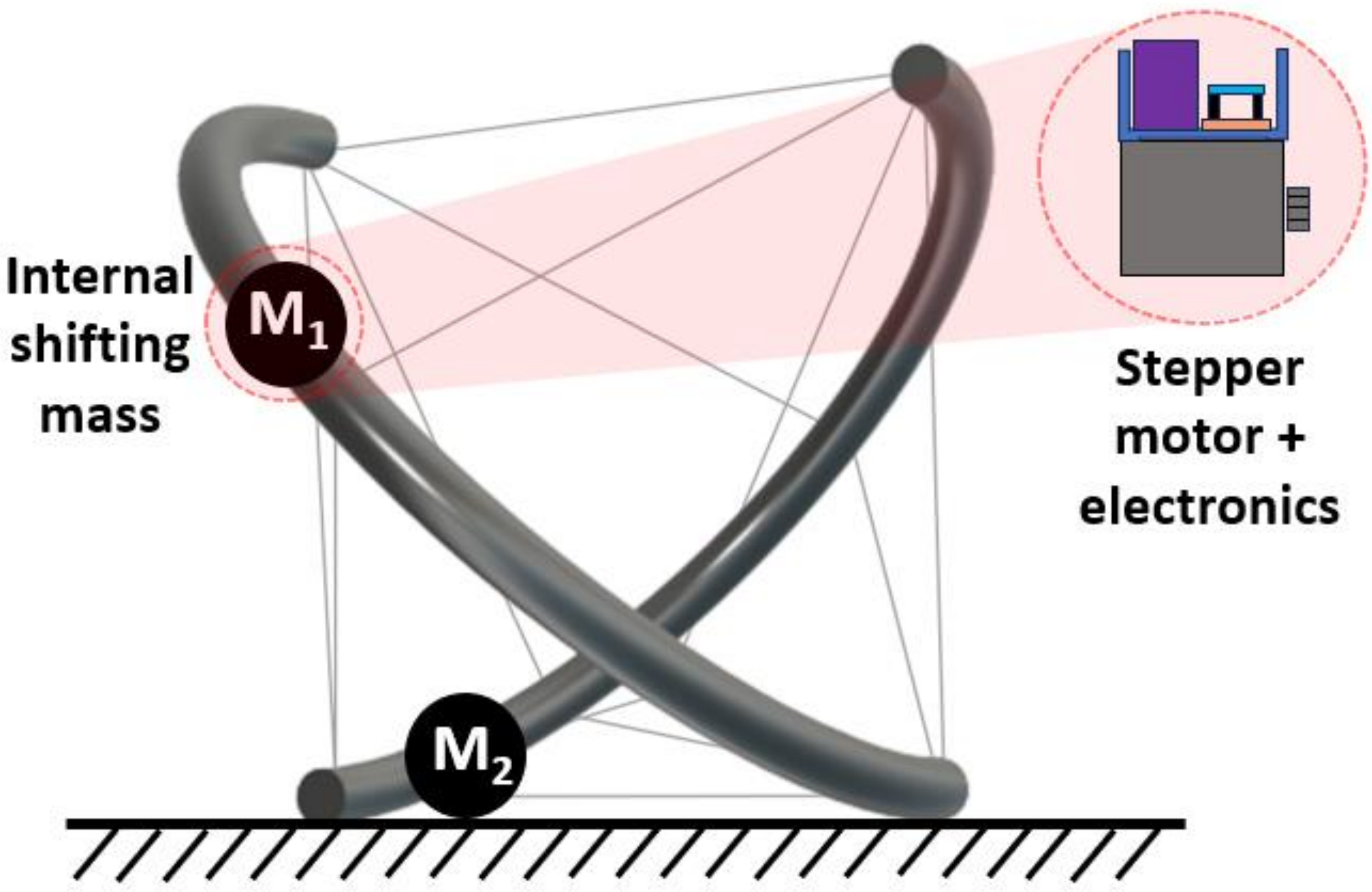
[7] Paul Et al. "Design and Control of Tensegrity Robots for Locomotion"
[8] Kaufhold Et al. "Indoor locomotion experiments of a spherical mobile robot based on a tensegrity structure with curved compressed members"
[9] Chen Et al. "Inclined Surface Locomotion Strategies for Spherical Tensegrity Robots"
[10] Chen Et al. "Soft Spherical Tensegrity Robot Design Using Rod-Centered Actuation and Control"
[11] Kim Et al. "Rapid Prototyping Design and Control of Tensegrity Soft Robot for Locomotion"

Motivation

Discontinuous, curved morphology well suited for unstructured environments

Tensegrity eXploratory Robot (TeXploR) Design

Curved-links with two points of contact



Robot Kinematics

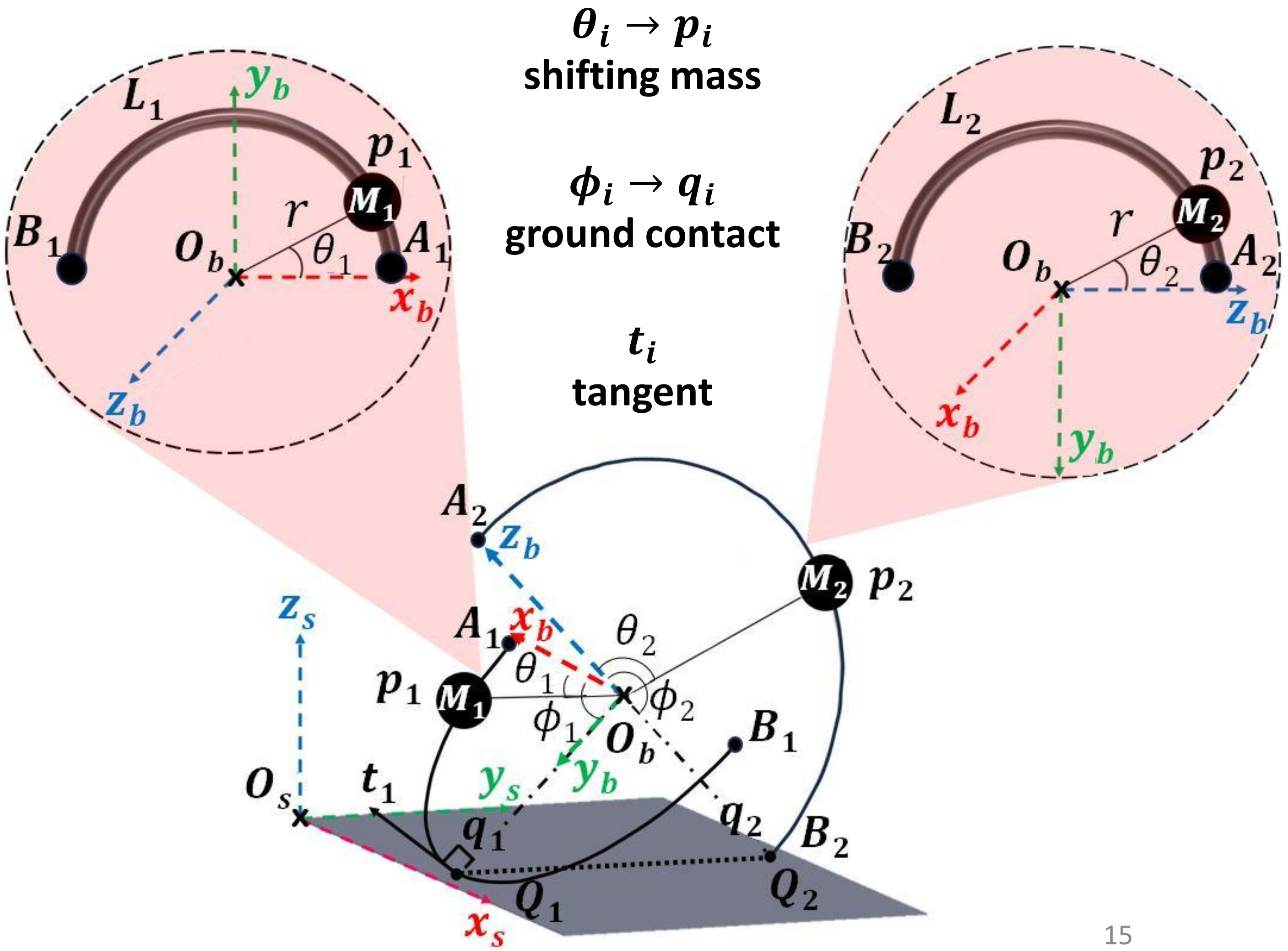
Geometric representation using Lie Groups and Screw Theory

$$\boldsymbol{p}_i^i = r\begin{bmatrix} c_{\theta_i} \\ s_{\theta_i} \\ 0 \end{bmatrix}, \quad \boldsymbol{q}_i^i = r\begin{bmatrix} c_{\phi_i} \\ s_{\phi_i} \\ 0 \end{bmatrix}$$

$$T_{12} = \begin{bmatrix} R_{12} & \boldsymbol{o}_{12}^1 \\ \boldsymbol{0}_{1\times 3} & 1 \end{bmatrix}, R_{12} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & -1 & 0 \\ 1 & 0 & 0 \end{bmatrix}, \boldsymbol{o}_{12}^1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$R_{12} \in SO(3)$ where
$SO(3) = \{R \in \Re^{3\times 3}: R^T R = I, \det R = +1$

$T_{12} \in SE(3)$ where
$SE(3) = \{T \in \Re^{4\times 4}: A, B \in T \rightarrow AB \in T,$
$A, B, C \in T \rightarrow (AB)C = A(BC),$
$A \in T \rightarrow AI = A, A, A^{-1} \in T \rightarrow AA^{-1} = I$



Form Finding

Identifies cable segment lengths to achieve desired shape

$$P = \begin{bmatrix} \boldsymbol{p}_A & \boldsymbol{p}_B & \boldsymbol{p}_C & \boldsymbol{p}_D \\ 1 & 1 & 1 & 1 \end{bmatrix} = \begin{bmatrix} -r & 0 & 0 & 1 \\ \frac{-r}{2} & \frac{-\sqrt{3}r}{2} & 0 & 1 \\ \frac{r}{2} & \frac{\sqrt{3}r}{2} & 0 & 1 \\ r & 0 & 0 & 1 \end{bmatrix}^T$$

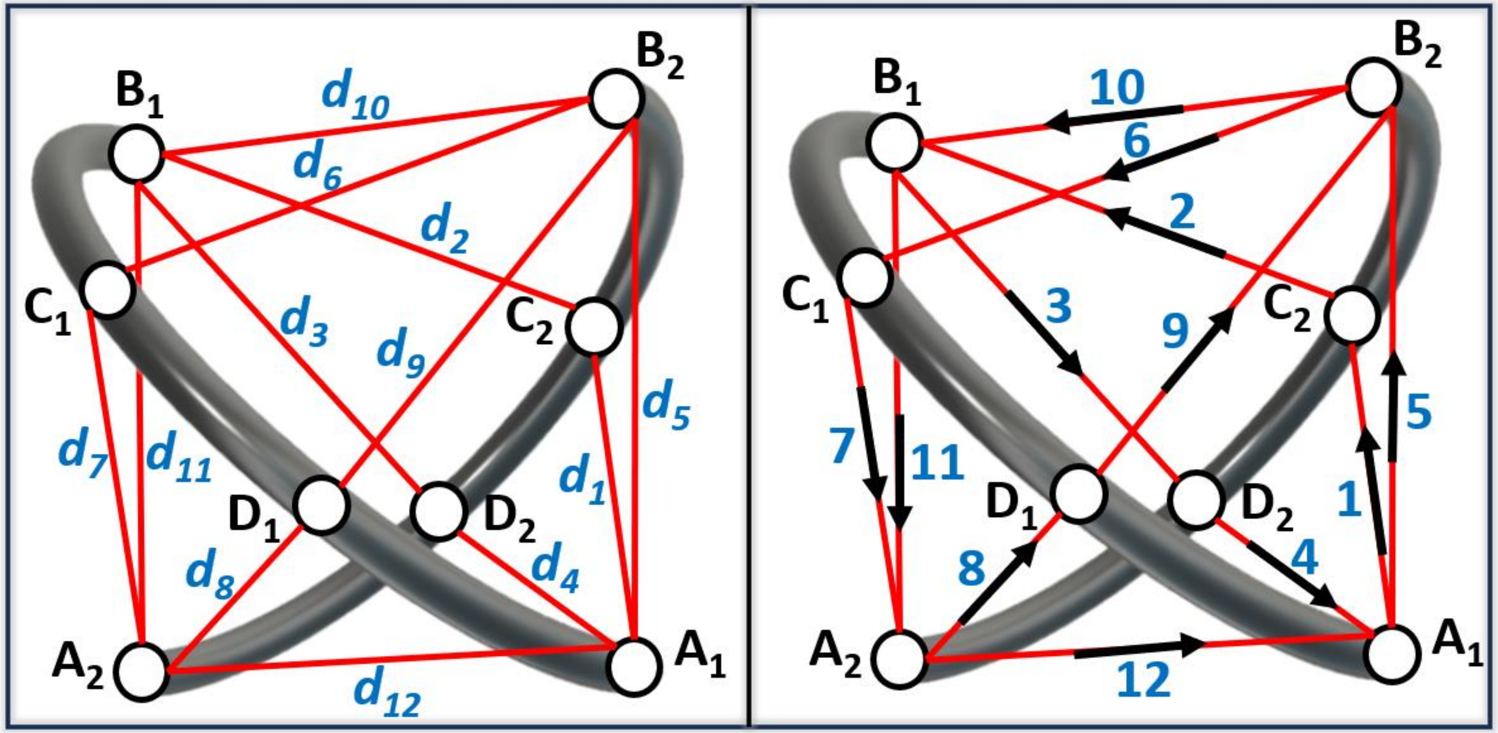
$$C^i[j,k] = \begin{cases} 1, & \text{if cable k contains vertex j on link i} \\ 0, & \text{otherwise} \end{cases}$$

$$D(\xi) = PC^1 - e^{\hat{\xi}} PC^2 = PC^1 - T_{12} PC^2$$

$$D = [\boldsymbol{d}_1, \boldsymbol{d}_2, \cdots, \boldsymbol{d}_{12}], \quad |\boldsymbol{d}_i| = \sqrt{|d_{1,i}|^2 + \cdots + |d_{4,i}|^2}$$

$$\xi_b = \begin{bmatrix} \omega_b \\ v_b \end{bmatrix}, \quad \hat{\xi}_b = \begin{bmatrix} \hat{\omega}_b & v_b \\ 0 & 0 \end{bmatrix}$$

$$\xi^* = \min_{\xi} \sum_{i=1}^{12} \frac{1}{2} k \left(|\boldsymbol{d}_i| - d_{0,i} \right)^2$$



$A_1 \rightarrow C_2 \rightarrow B_1 \rightarrow D_2 \rightarrow A_1 \rightarrow B_2 \rightarrow C_1 \rightarrow A_2 \rightarrow D_1 \rightarrow B_2 \rightarrow B_1 \rightarrow A_2 \rightarrow A_1$

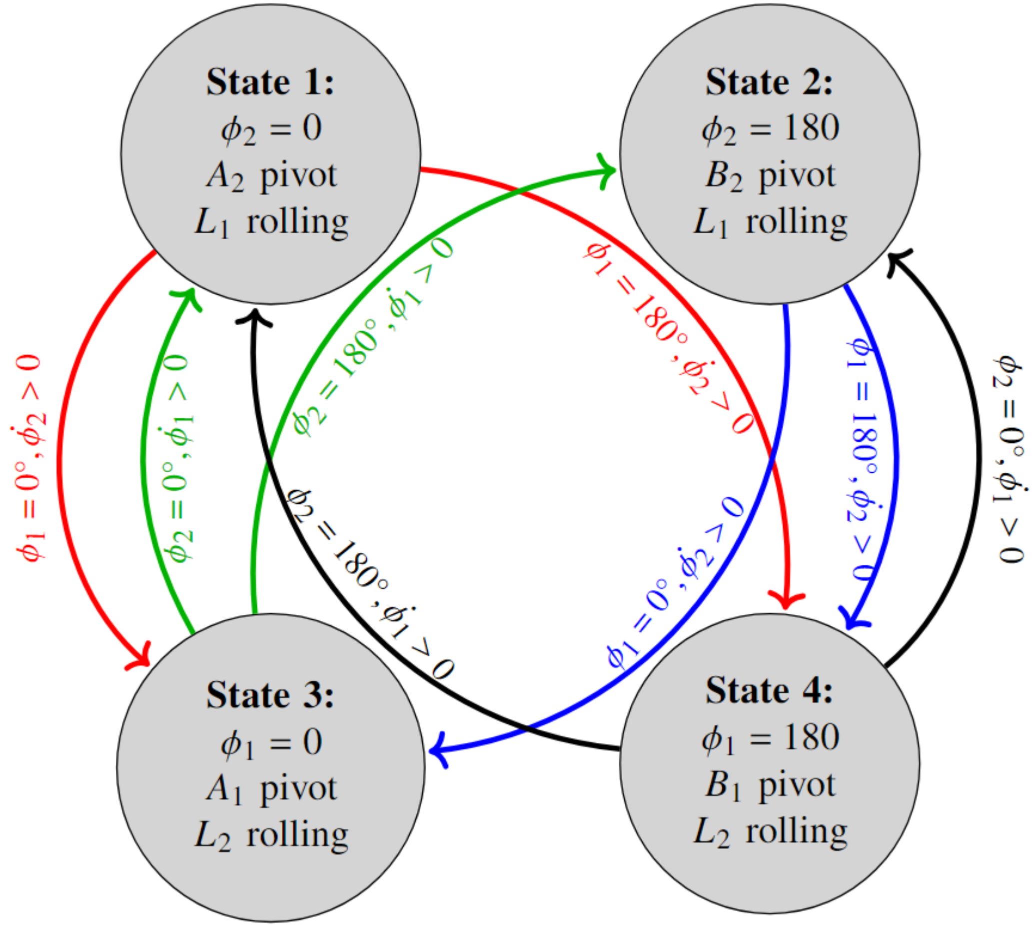
Hybrid State System

Four states of locomotion for rolling sequence from holonomic constraints

Case 1: t_2 undefined → State 1: $\phi_2 = 0$ or State 2: $\phi_2 = 180$

Case 2: t_1 undefined → State 3: $\phi_1 = 0$ or State 4: $\phi_1 = 180$

~~Case 3: t_1, t_2 defined~~ → $\cancel{\phi_2 = -\phi_1}$ or $\cancel{\phi_2 = \phi_1 + 180}$



Geometric Static Modeling Framework

Internal mass inputs → static equilibrium position output

Holonomic constraints

↓

Hybrid system → State 1 ... State 4

$$\mathcal{F} = \begin{bmatrix} \boldsymbol{f} \\ \boldsymbol{m} \end{bmatrix} = \sum_{i=1}^{2} \begin{bmatrix} (M_i + m_i) g \boldsymbol{z}_s + \boldsymbol{F}_{ri} \\ M_i g \hat{\boldsymbol{p}}_i \boldsymbol{z}_s + m_i g \hat{\boldsymbol{r}}_i \boldsymbol{z}_s + \hat{\boldsymbol{q}}_i \boldsymbol{F}_{ri} \end{bmatrix} = 0 \quad \text{s.t.}$$

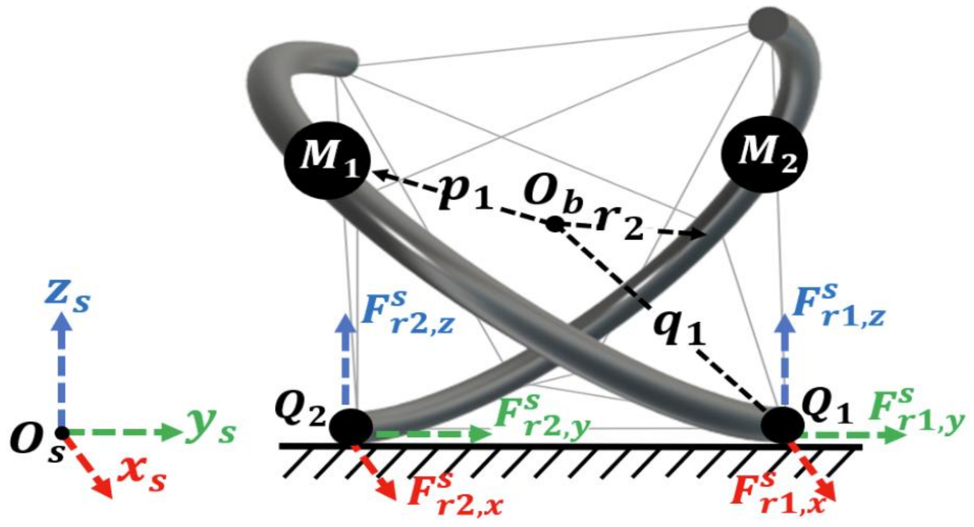
$$\boldsymbol{f}^s = \begin{bmatrix} F^s_{r1,x} - F^s_{r2,x} \\ F^s_{r1,y} - F^s_{r2,y} \\ (M_1 + M_2 + m_1 + m_2) g - (F^s_{r1,z} + F^s_{r2,z}) \end{bmatrix}$$

$$\boldsymbol{m}^b = \begin{array}{l} \sum_{i=1}^{2} \left(M_i g \hat{\boldsymbol{p}}_i^b + m_i g \hat{\boldsymbol{r}}_i^b - F^s_{ri,z} \hat{\boldsymbol{q}}_i^b \right) \boldsymbol{z}_s^b \\ + \left(F^s_{r1,x} \hat{\boldsymbol{q}}_1^b - F^s_{r2,x} \hat{\boldsymbol{q}}_2^b \right) \boldsymbol{x}_s^b + \left(F^s_{r1,y} \hat{\boldsymbol{q}}_1^b - F^s_{r2,y} \hat{\boldsymbol{q}}_2^b \right) \boldsymbol{y}_s^b \end{array}$$

$$\boldsymbol{z}_s^b = -\frac{1}{\sqrt{2}} [c_{\phi_1}, s_{\phi_1}, 1]^T, \quad \boxed{\tan\phi_1 = \frac{s_{\theta_1} - s_{\theta_2}}{c_{\theta_1}}}$$

$$F_{r1,z} = Mg\left[-1 + \frac{c_{\phi_1+\theta_2}}{2} - c_{\theta_2} + c_{\phi_1-\theta_1} - \frac{c_{\phi_1-\theta_2}}{2}\right] - mg$$

$$F_{r2,z} = Mg\left[-1 - \frac{c_{\phi_1+\theta_2}}{2} + c_{\theta_2} - c_{\phi_1-\theta_1} + \frac{c_{\phi_1-\theta_2}}{2}\right] - mg$$



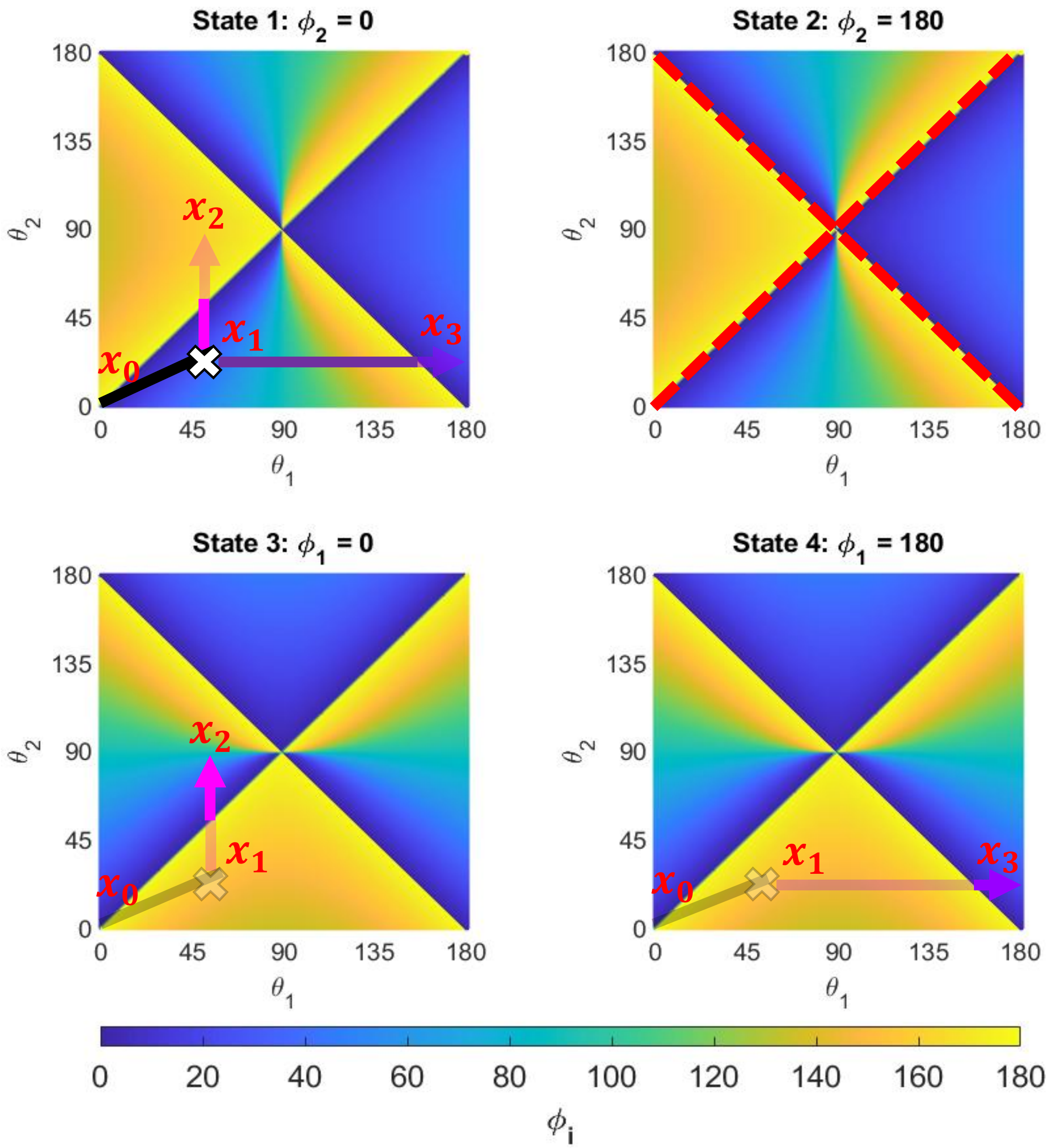
Generalizable to Variable Morphologies

Shape morphing

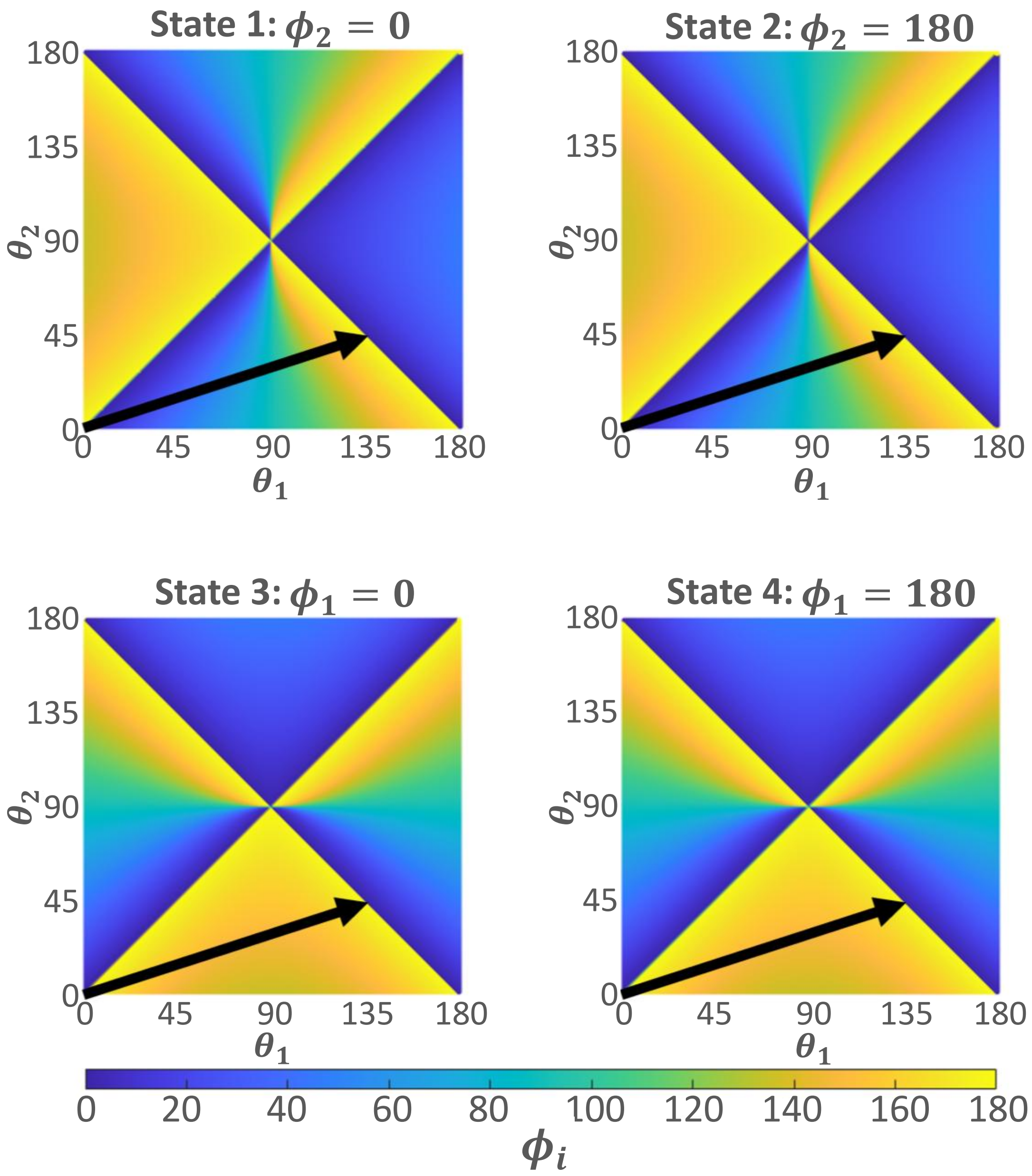
Number of curved links

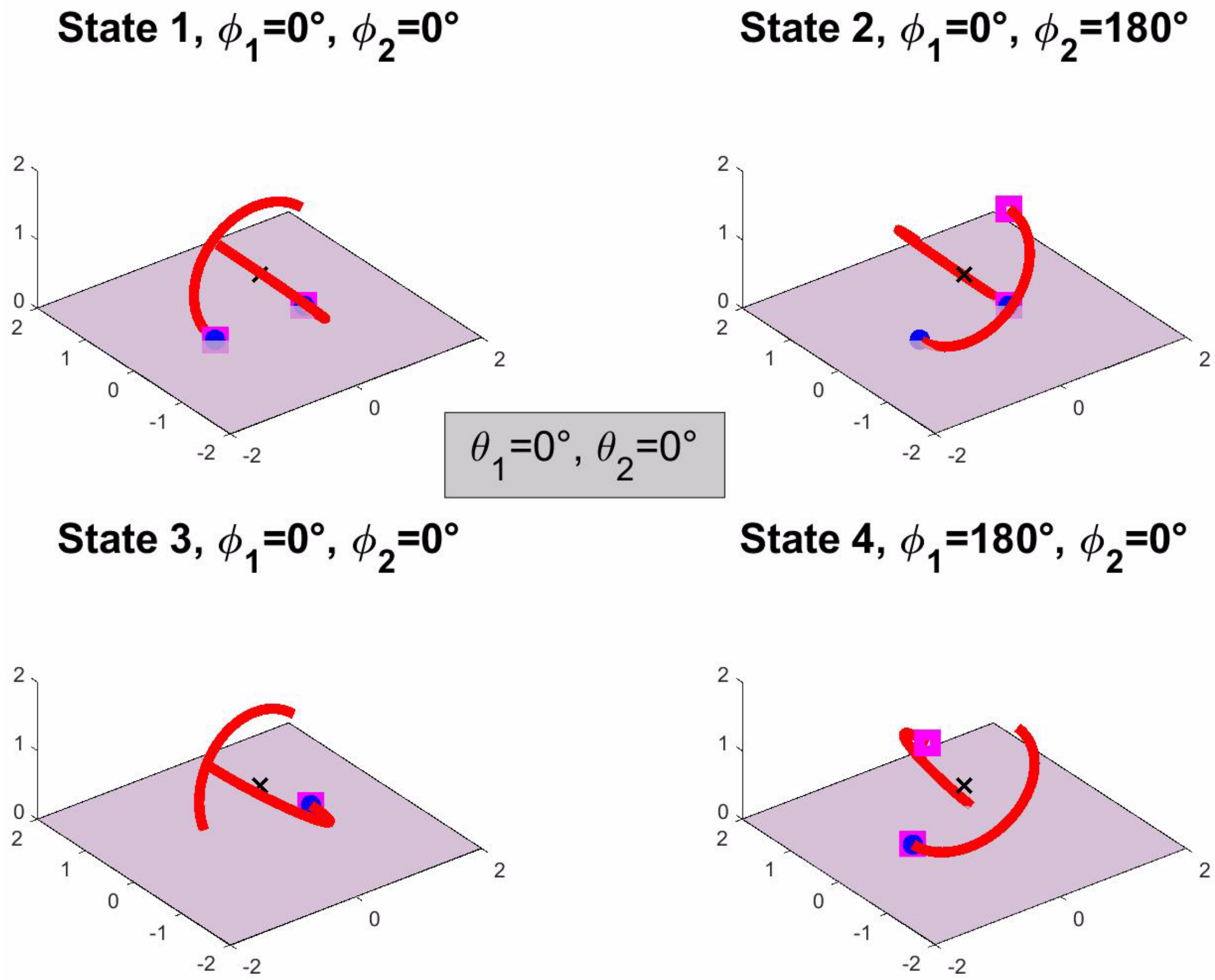
Curved link length

Quasi-Static Simulations



Quasi-Static Simulations

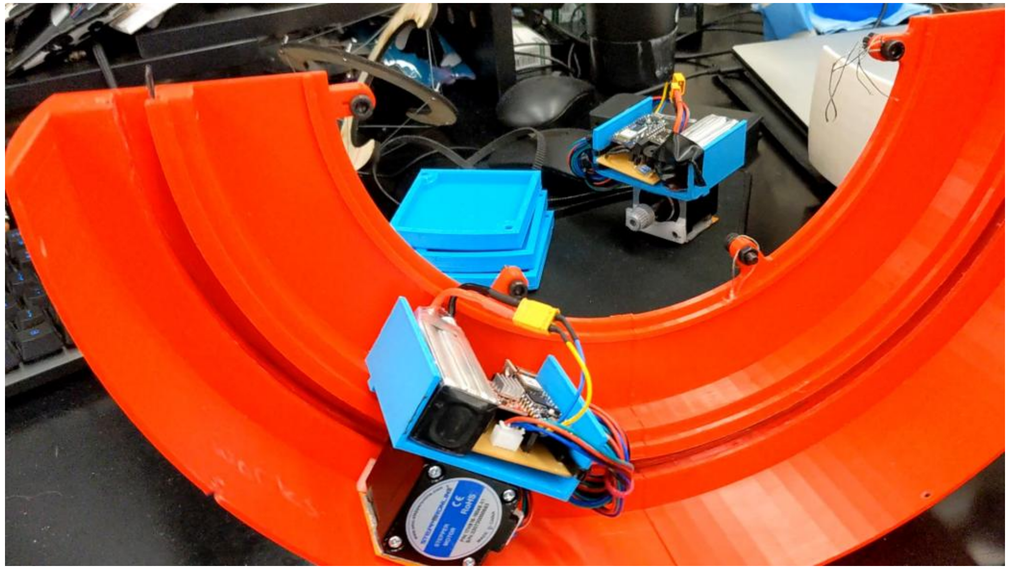


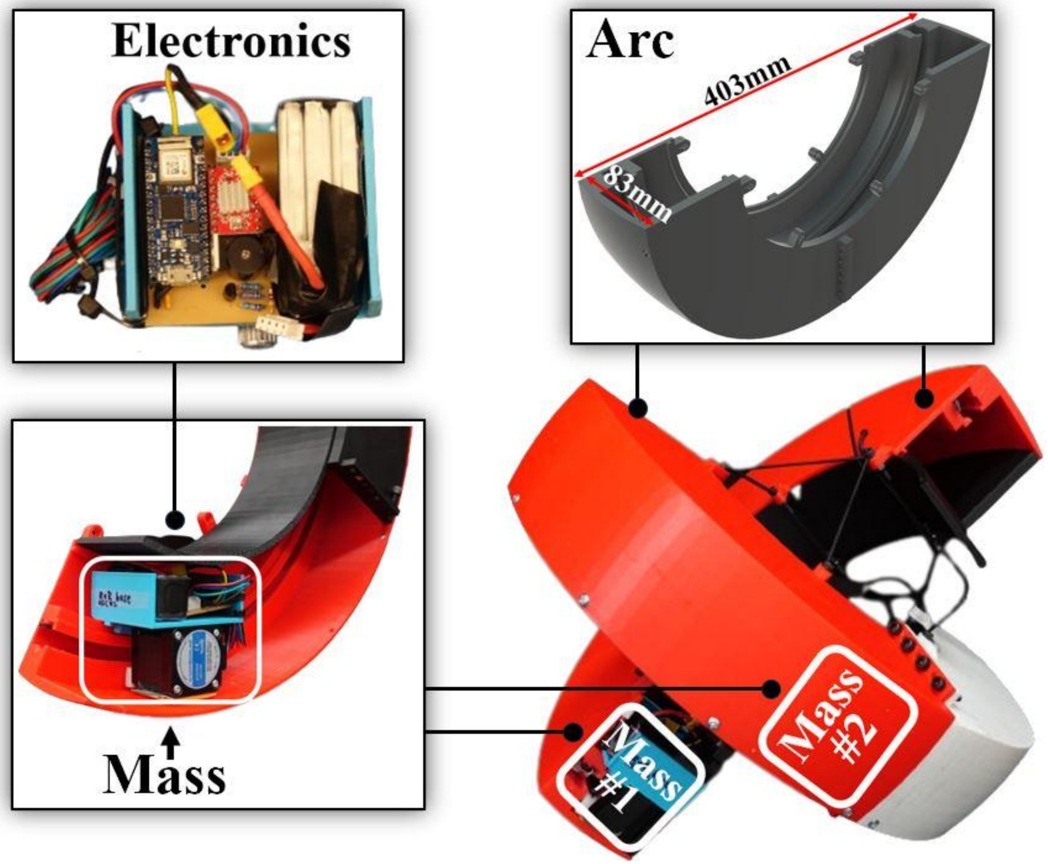


TeXploR Prototype Mechatronics

All electronics mounted internally and shift along arc

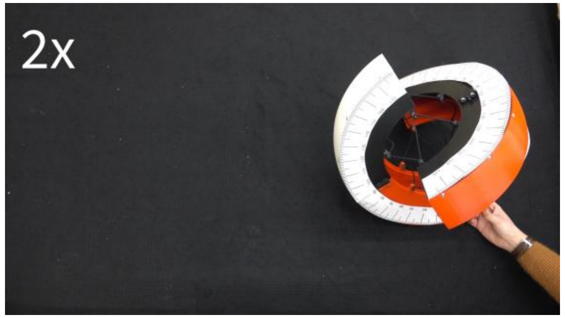
Internal Mass Shifting





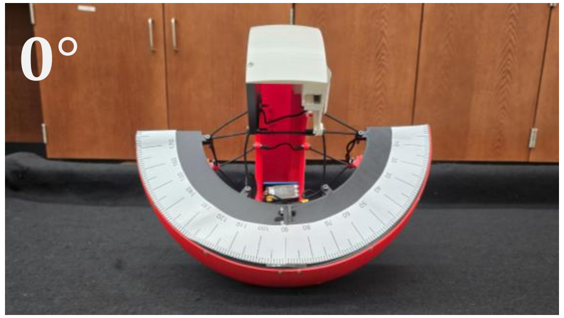
Experimental Validation

State 3, $\theta_1 = 135°, \theta_2 = 135°$

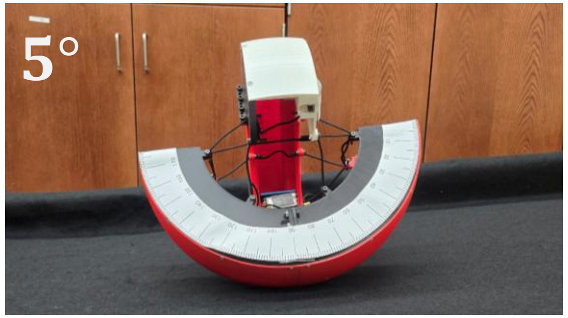


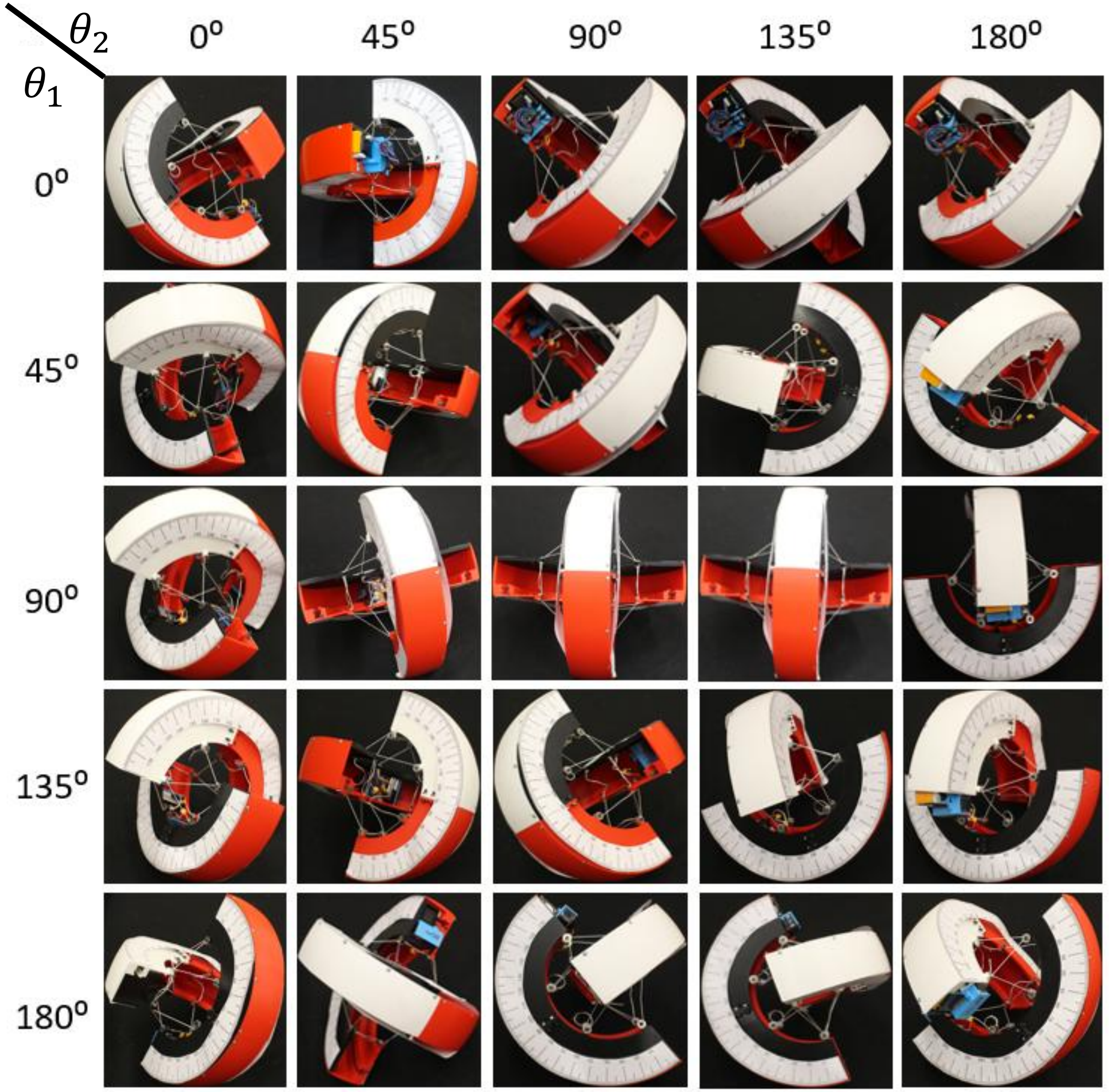
State 4, $\theta_1 = 45°, \theta_2 = 135°$

$\phi_1 = 90°, \phi_2 = 0°$, $0°$ **incline**



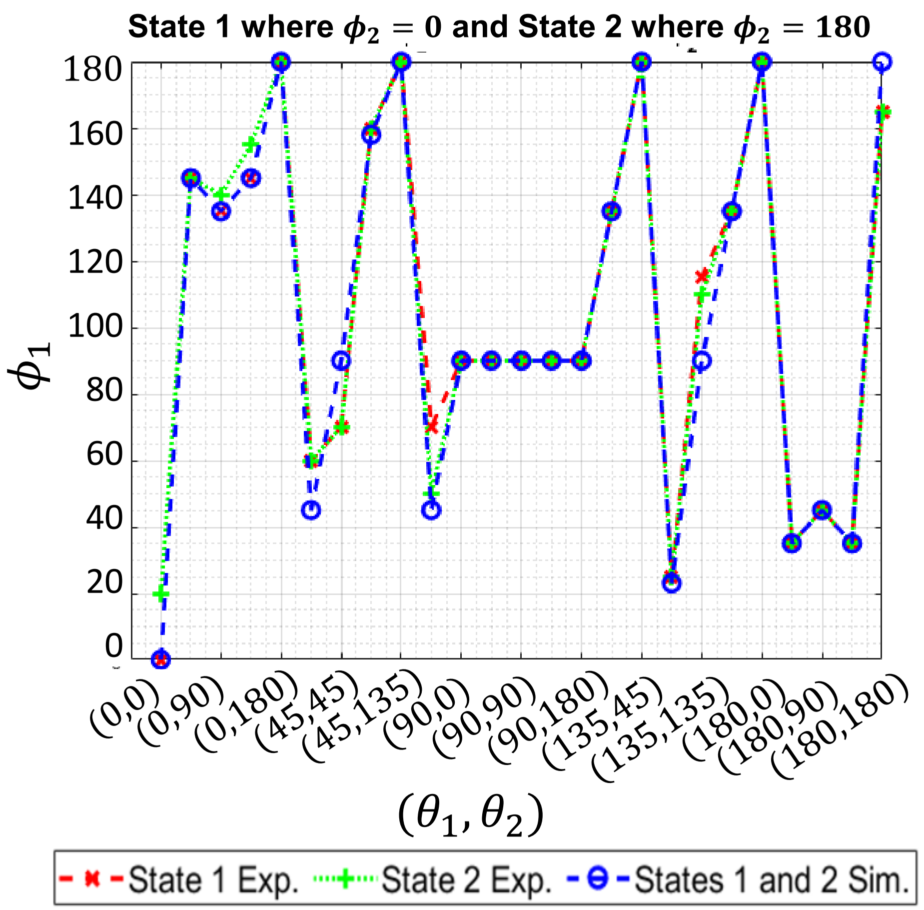
$\phi_1 = 90°, \phi_2 = 0°$, $5°$ **incline**

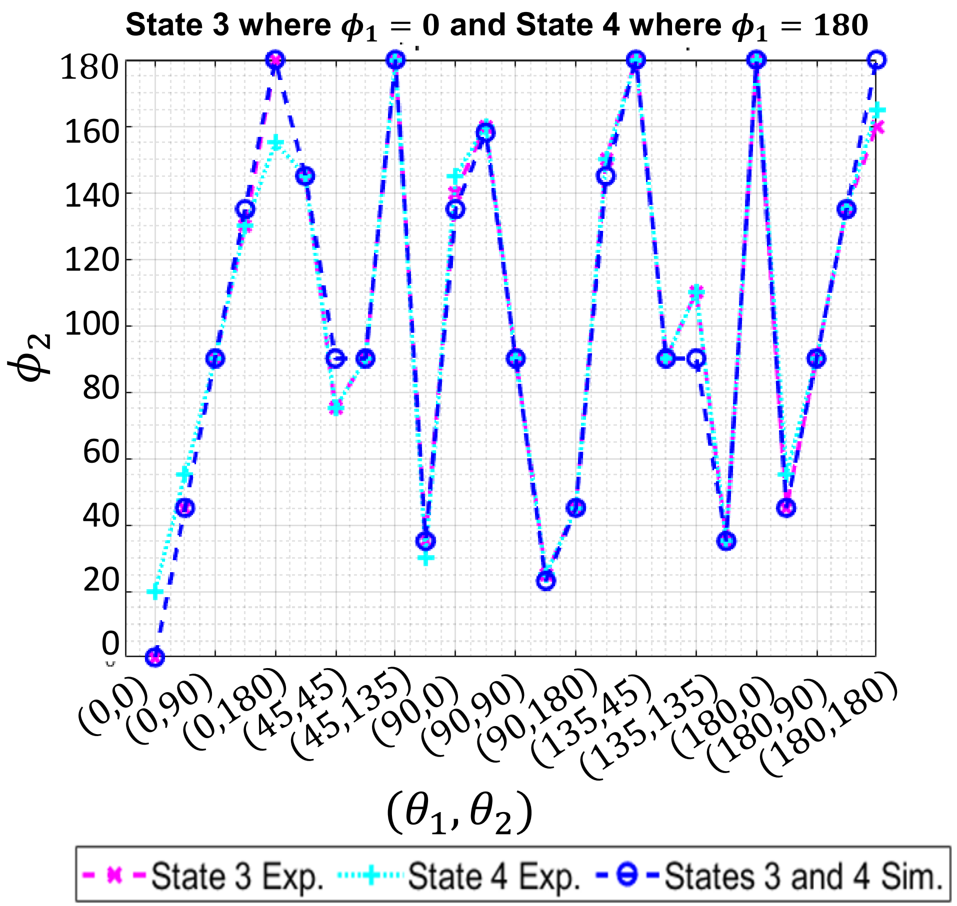




Simulated vs. Experimental Results

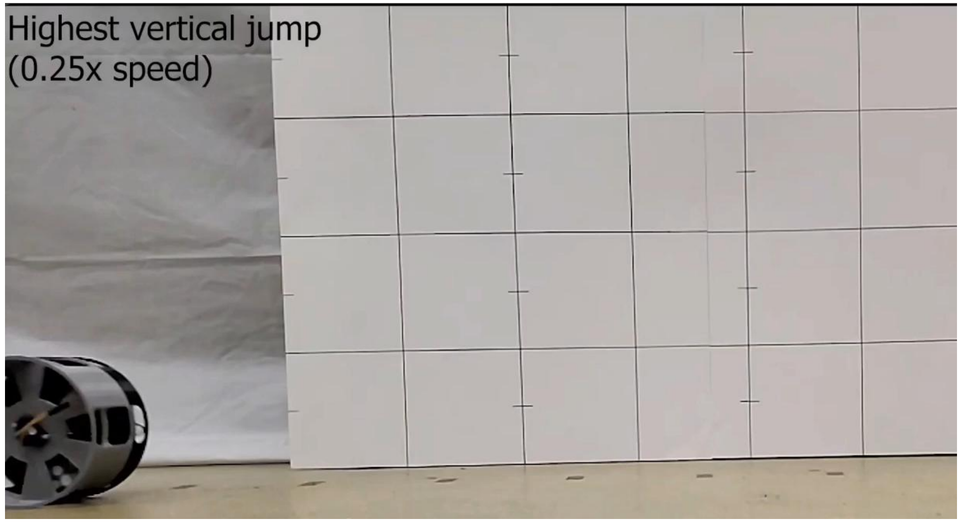
$MAE\ 4.36°$





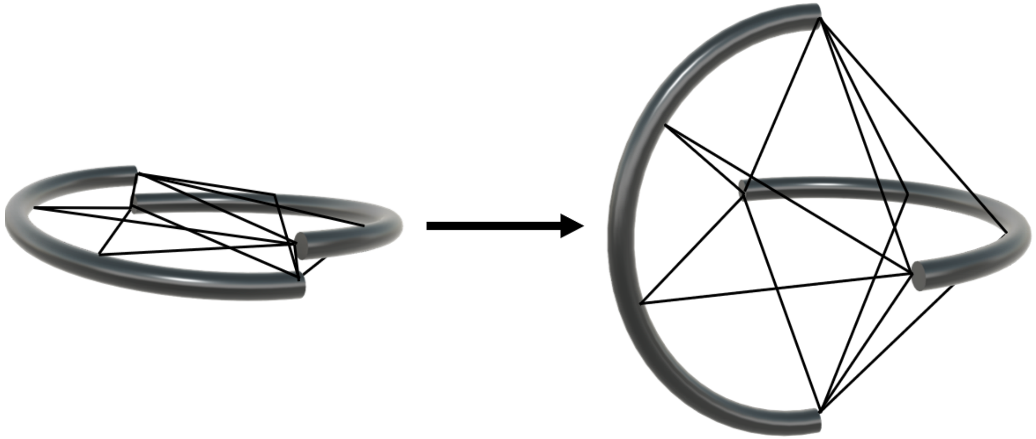
Future Work

Controlling Complex Sequences Such as Jumping/Slipping



[12] Buzhardt Et al. "A Pendulum-Driven Legless Rolling Jumping Robot"

Active Shape Morphing



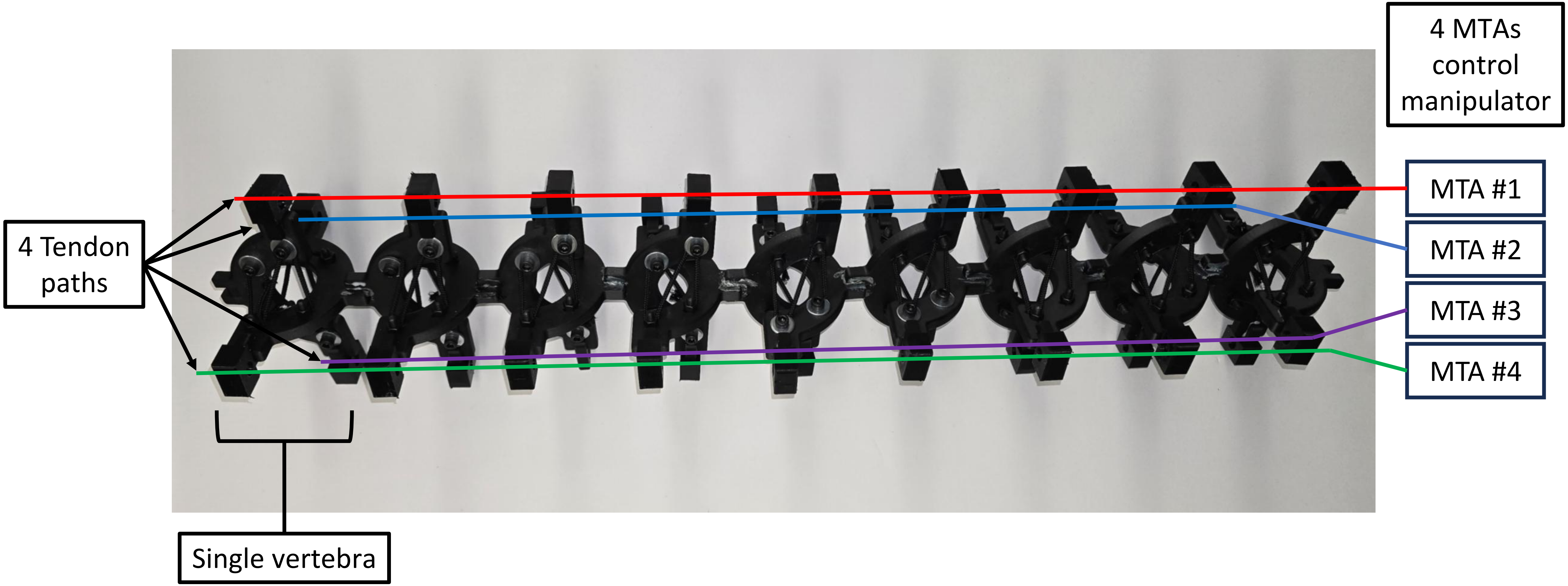
Motivation

Tensegrity continuum manipulator is lighter with wider range of motion

[13] https://www.countrynews.com.au/horticulture/apples-in-reach-of-robotic-eve/

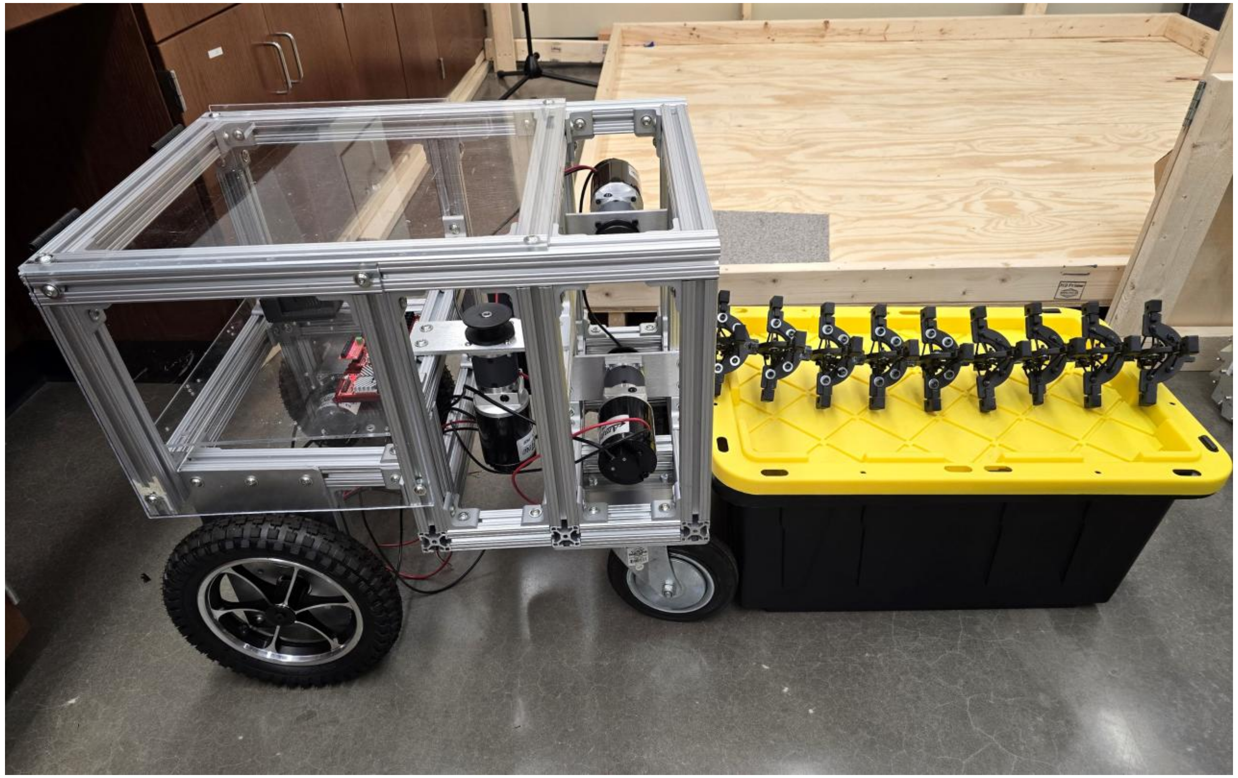
Tensegrity Continuum Manipulator

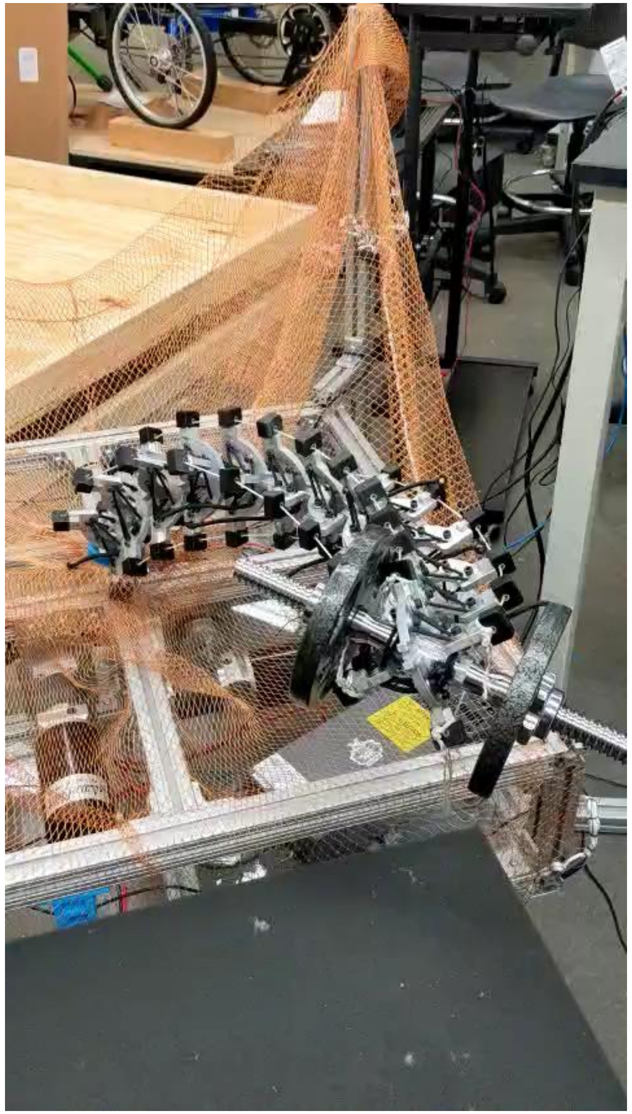
Reduction in control space + high strength-to-weight ratio



AgBot Prototype

Ruggedized platform for agriculture field testing



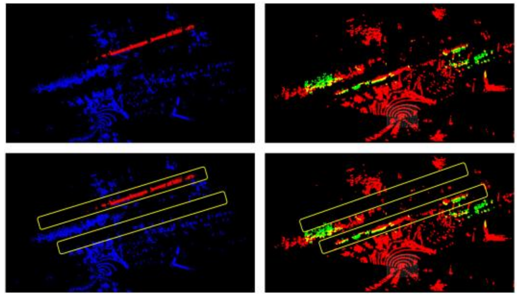


Future Work

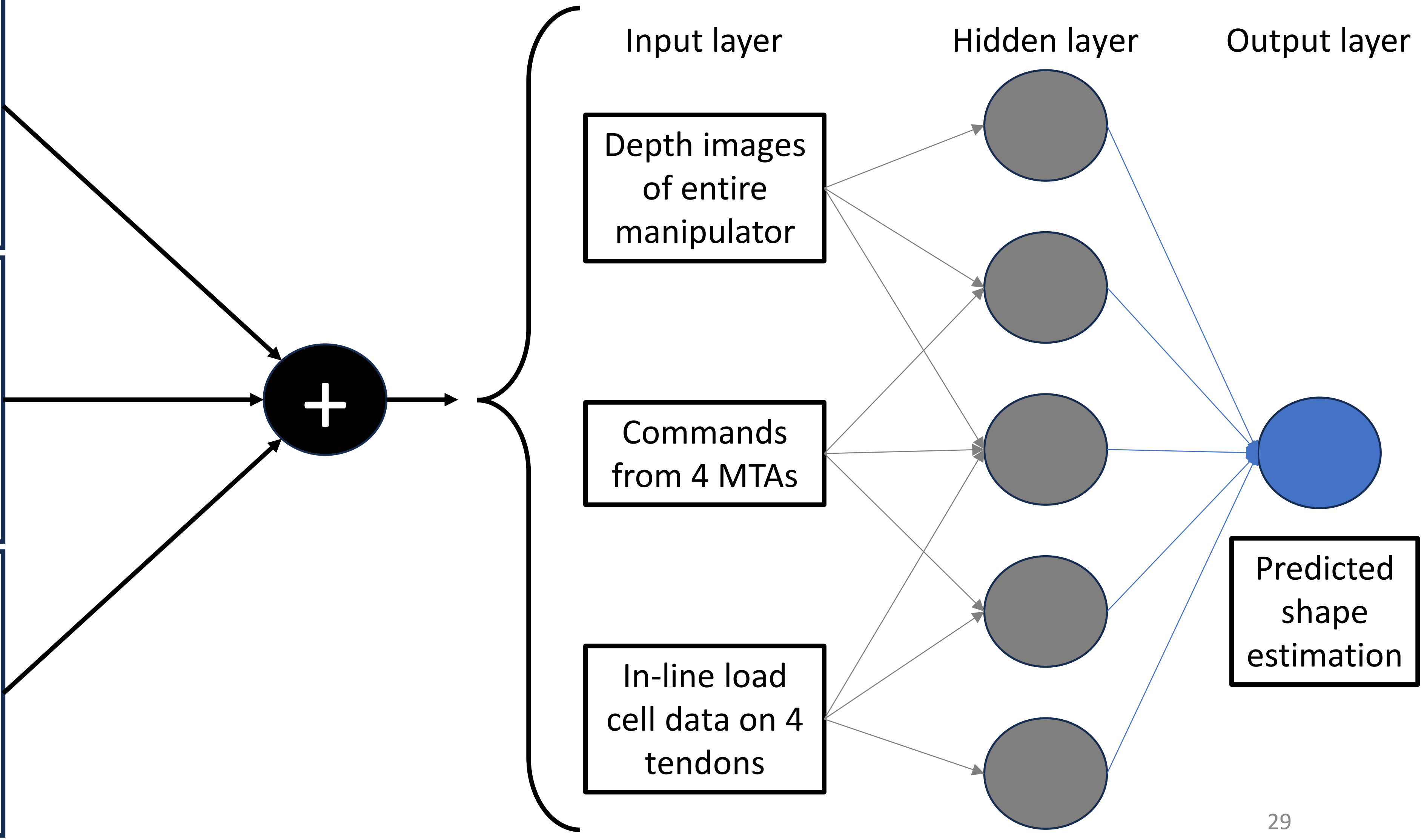
Multimodal input → shape estimation output

Custom dataset crafting

Semantic segmentation



Tensegrity modeling



UA-ECEGSA
Electrical and Computer Engineering Graduate Student Association

Questions?