Design and Modeling Framework for DexTeR: Dexterous Continuum Tensegrity ManipulatoR

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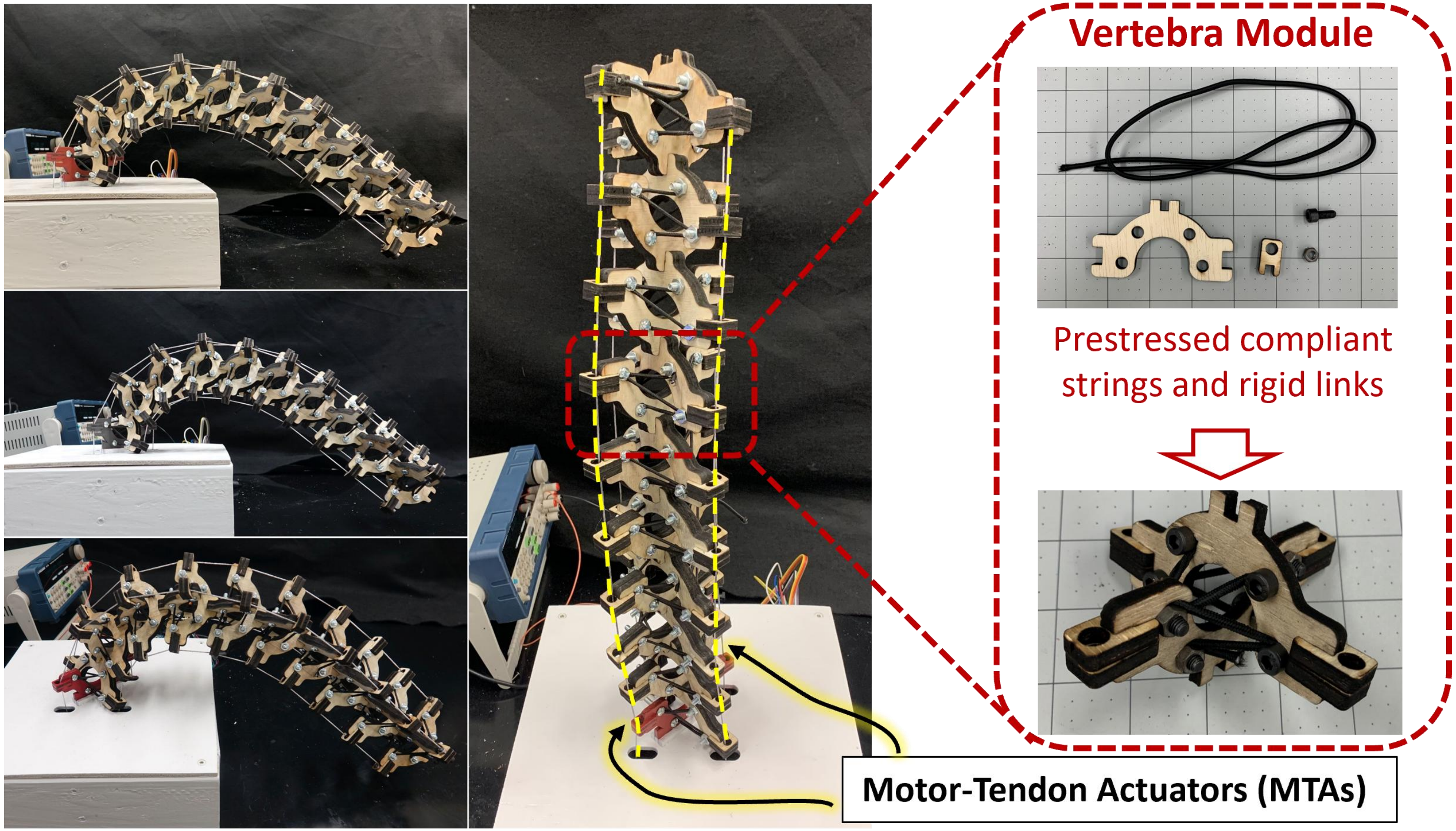
agile robotics lab

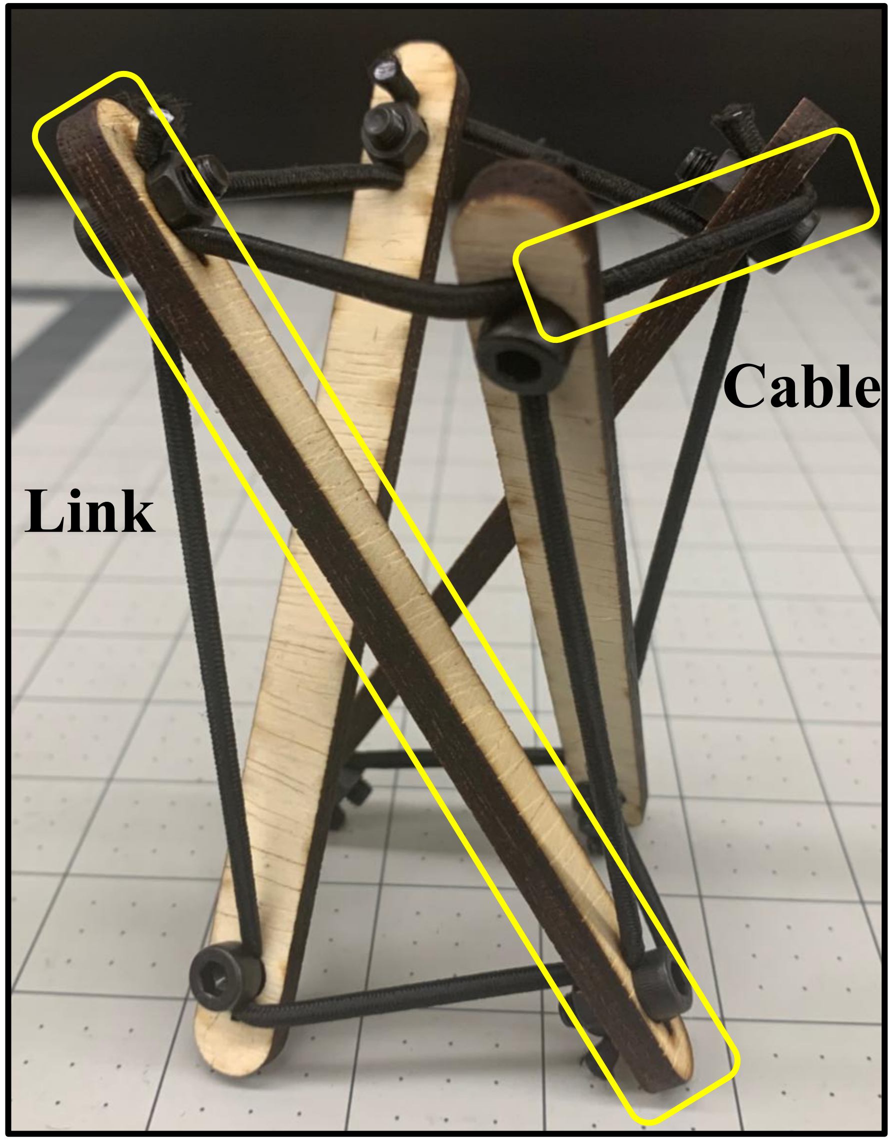
DexTeR

DexTeR: Dextrous continuum Tensegrity ManipulatoR



What is Tensegrity?

- ***Tensegrity*** **mechanisms synergistically combine *ten*sion elements (pre-stressed cables) with compression elements (rigid rods) to achieve structural int*egrity*.**
- **Tensegrity occurs naturally in varying sizes (i.e. heavenly bodies acted upon by gravity to micro-scale biological organisms)[1, 2]**



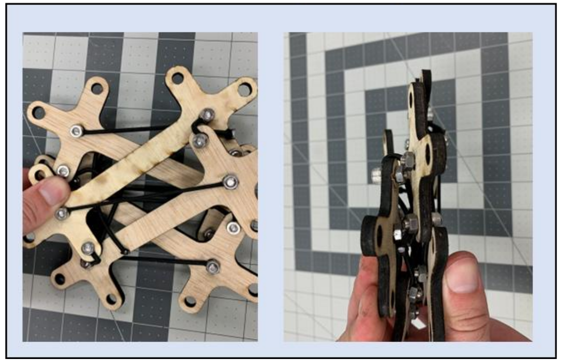
1. *Motro, R., 2003. Tensegrity: structural systems for the future. Elsevier*
2. *Ingber, D. E., 1993. "Cellular Tensegrity: defining new rules of biological design that govern the cytoskeleton". Journal of cell science, 104(3), pp. 613-627*

Motivation

Tensegrity mechanisms are

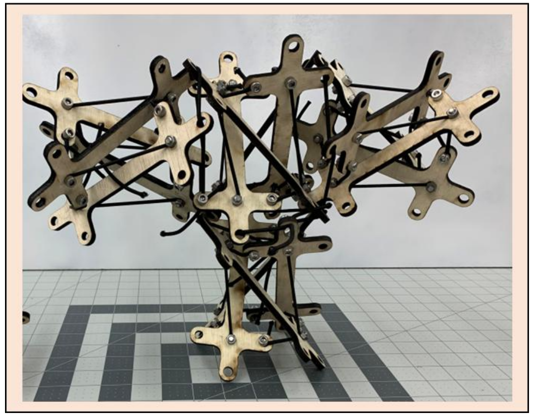
- Packable & portable
- Internally stable (no gravity required for structural stability)
- Modular and reconfigurable
- High strength-to-weight ratio

Packed and collapsed primitive



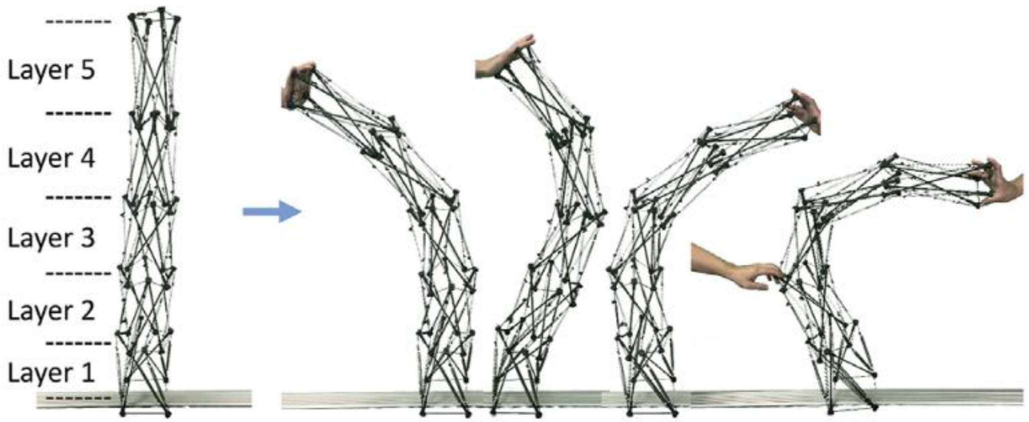
Tensegrity primitive

Modular and reconfigurable

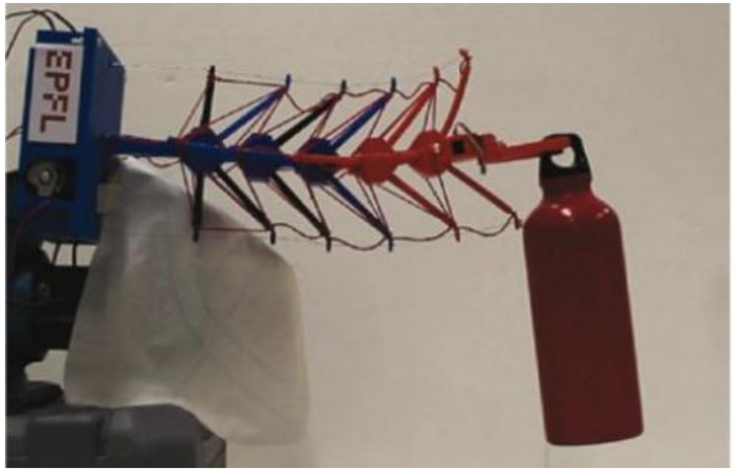


<u>Challenge</u>: They are difficult to fabricate and model given the antagonistic nature of compressive and tension elements.

Tensegrity Continuum Manipulators



[3]



[4]

[5]

[6]

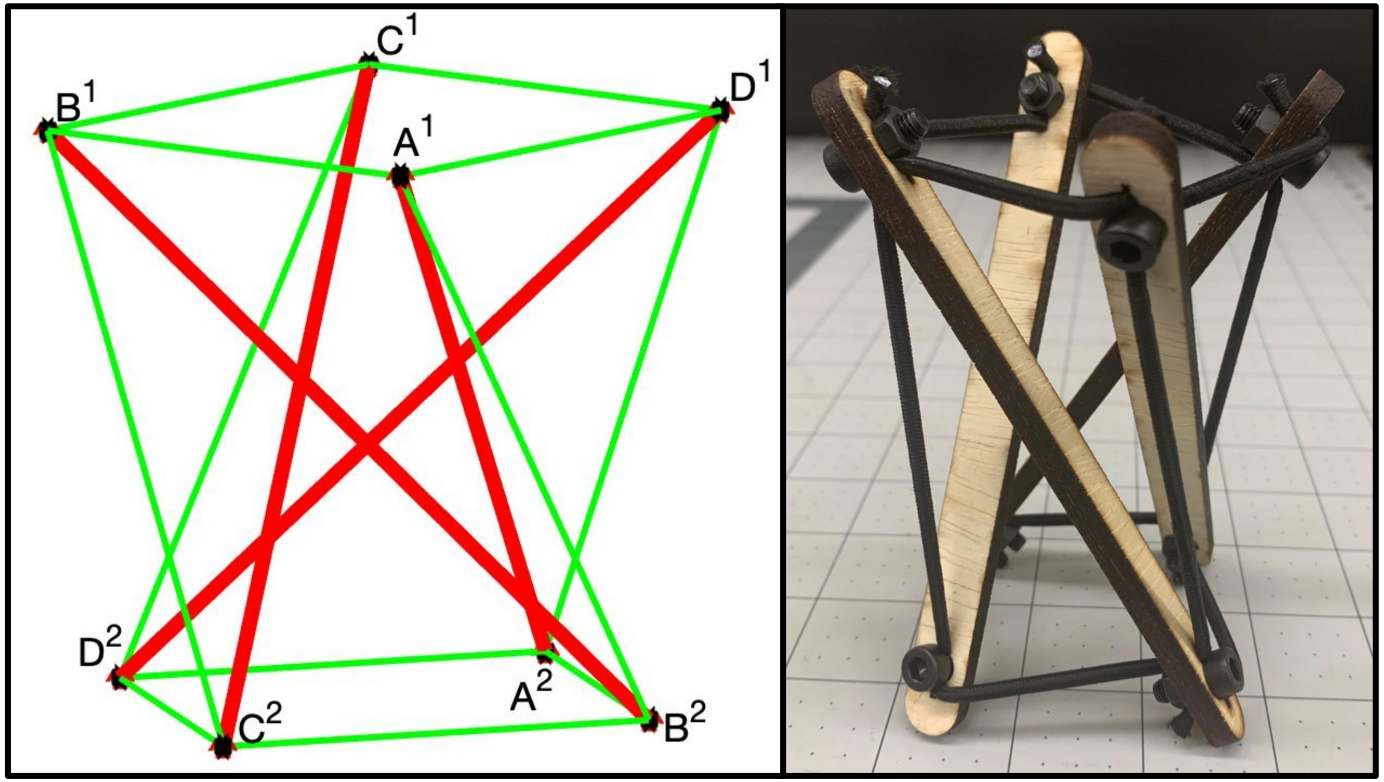
3. Iketmoto, S., Tsukamoto, K., Yoshimitsu,Y., 2021. "Development of a modular tensegrity robot arm capable of continuous bending". Frontiers in Robotics and AI, 8, 11.
4. Zappeti, D., Arandes, R., Ajanic, E., and Floreano, D., 2020. "Variable-stiffness tensegrity spine". p. 075013.
5. Abourachid, A. Böhmer, C., Wenger, P., Chablat, D., Chevellereau, C., Fasquelle, B. and Furet, M., 2019. "Modelling, design and control of a bird neck using tensegrity mechanisms".
6. Ramadoss, V. Sagar, K., Ikbal, M.S., Calles, J. H. L., Siddaraboina, R., and Zoppi, M. 2022. "Hedra: a bio-inspired modular tensegrity robot with polyhedral parallel modules". In 2022 IEEE 5th International Conference on Soft Robotics (Robosoft), pp. 559-564.

Contributions

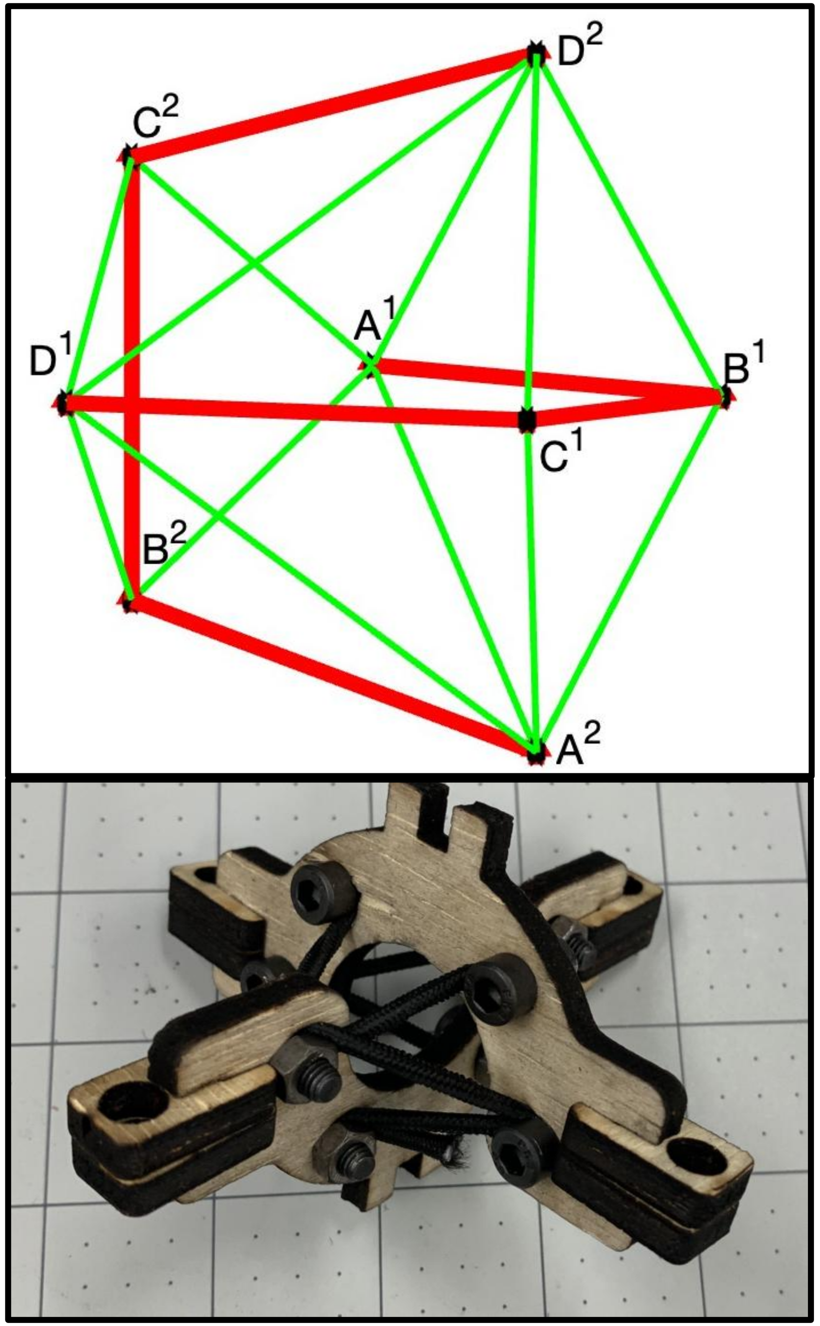
1. ***DexTeR Design:*** **5-fold design methodology for efficient fabrication of modular tensegrity system.**
2. ***Screw theory modeling approach*** **allows for a geometric basis where the number of unknowns is proportional to the number of rigid links. Applicable to complex geometries, and facilitates ease of representation of forces and torques, with spring-tension model of compliant strings.**

Module Design

<u>Module selection:</u> **Each vertebra based of J_{84} Johnson solid (snub disphenoid)**



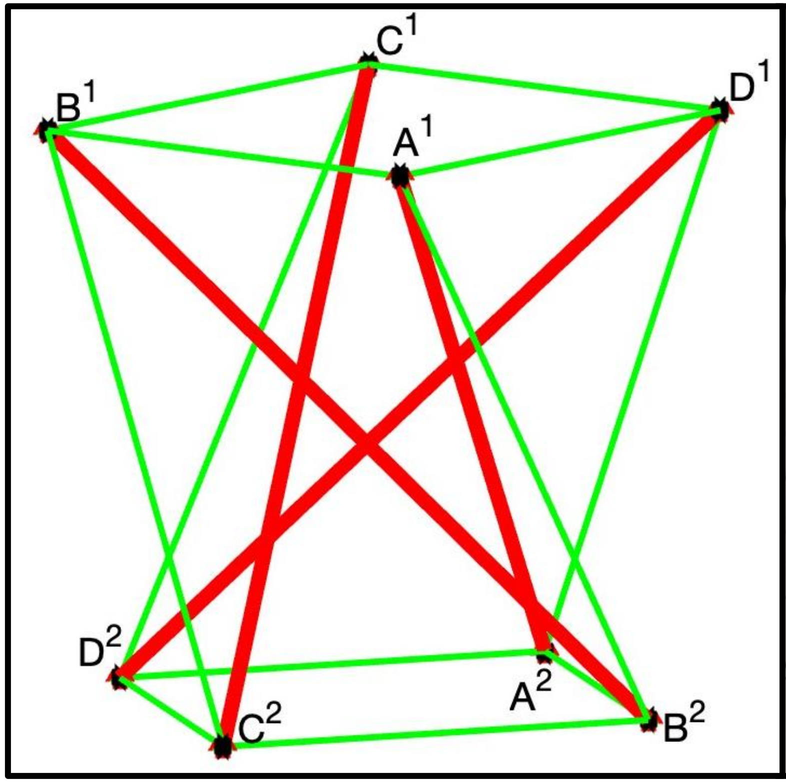
Rectangular Prism



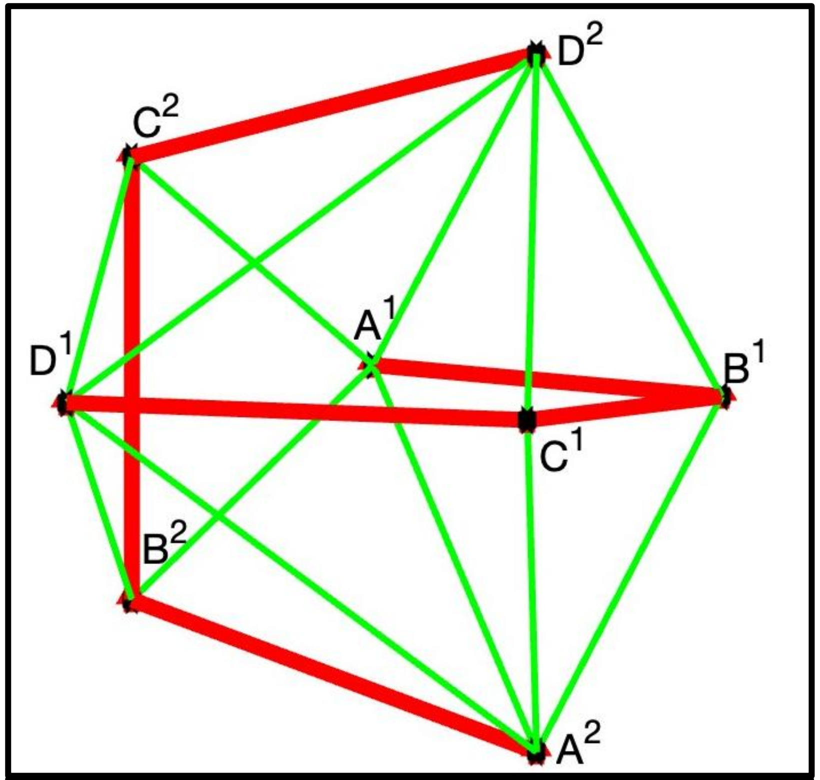
Snub Disphenoid

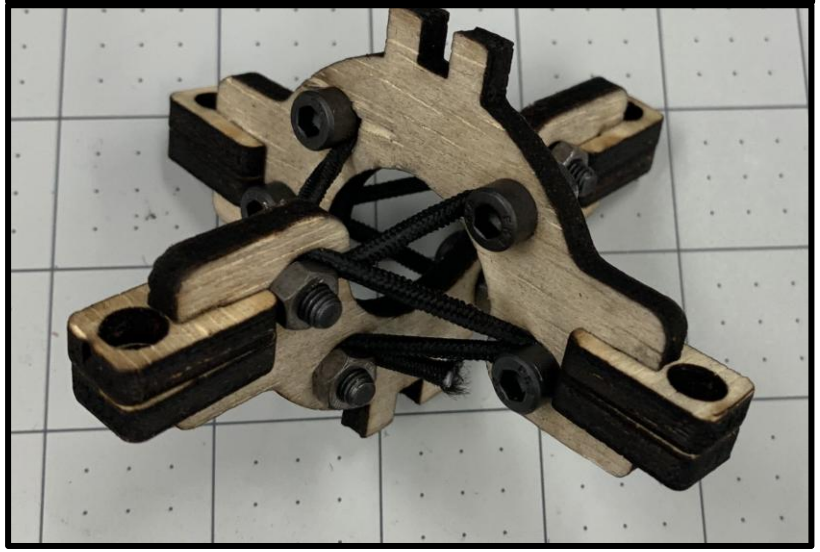
Module Design

Identification of string paths: **Identified using the graph of the snub disphenoid vertices. Euler path traverses all the green edges (strings), resulting in need for only one string!**



Rectangular Prism





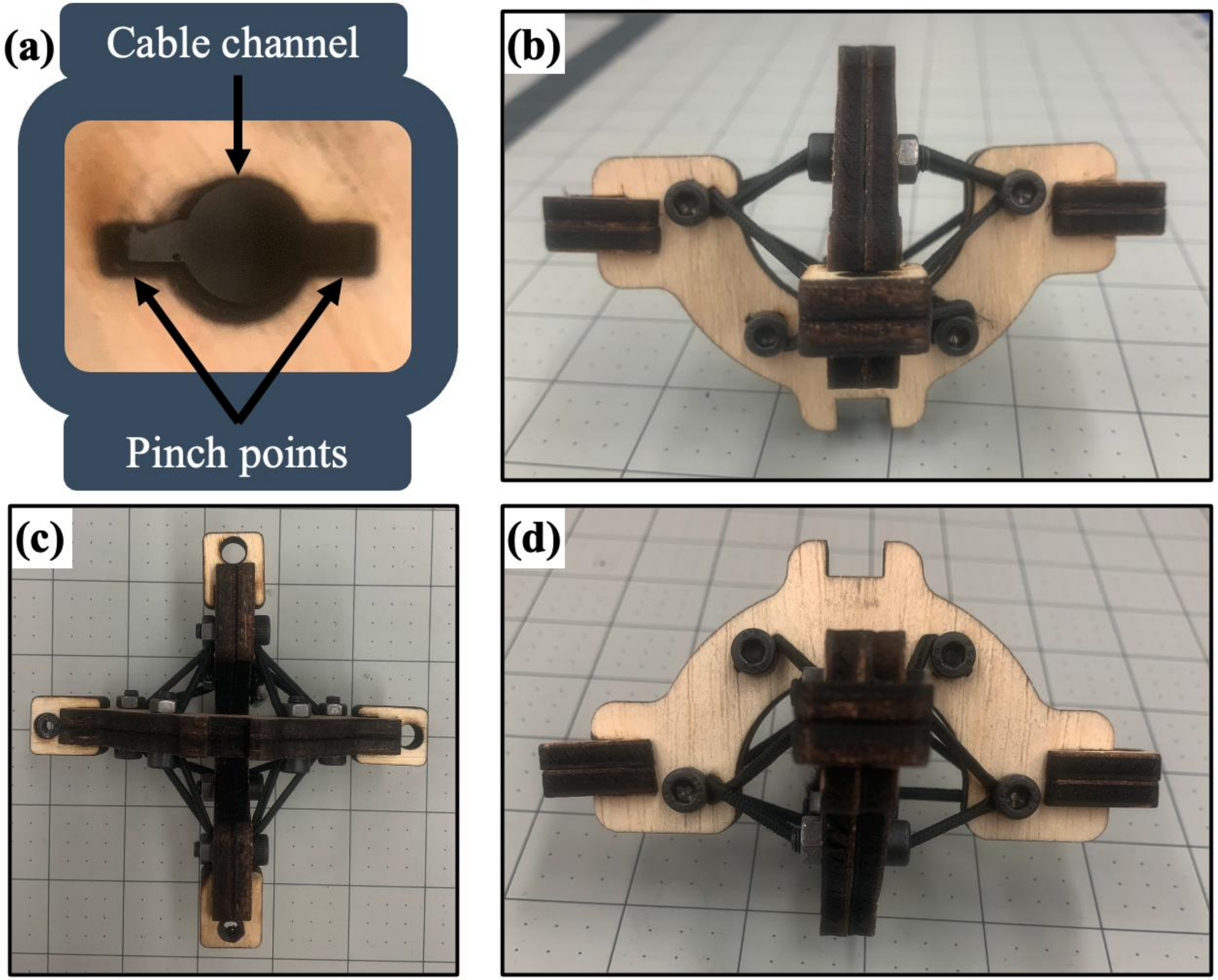
Snub Disphenoid

Module Design

Pre-stressing and structural stability: **Physical tuning of form/shape of the mechanism**

- **Time-consuming process**
- **Need for jigs, pinch points, or other innovative tactics to aid in process**

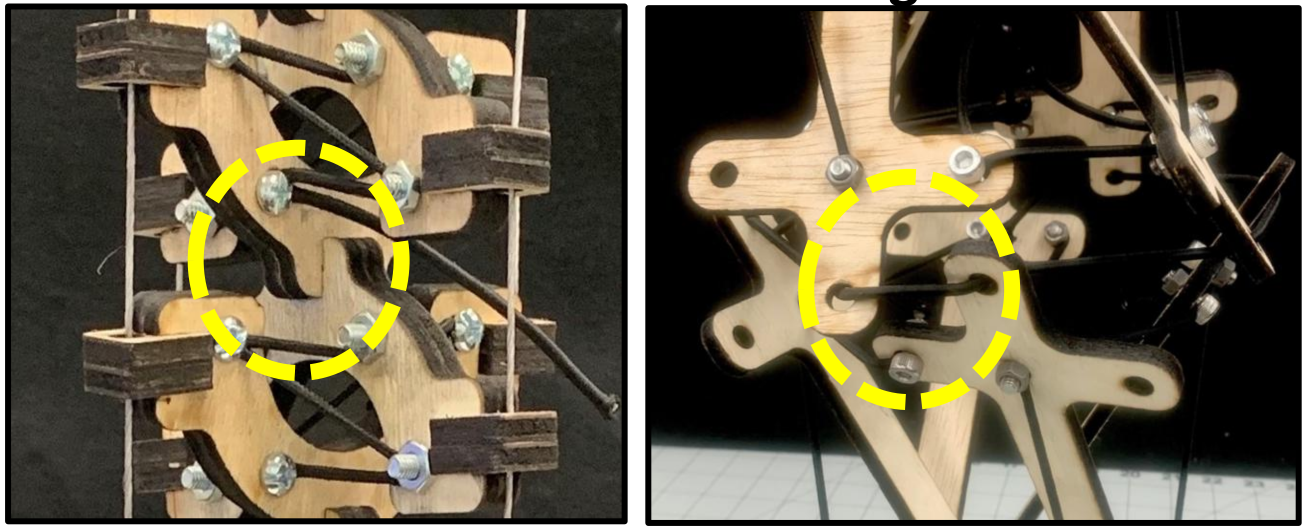
10-15 min to build a single primitive!

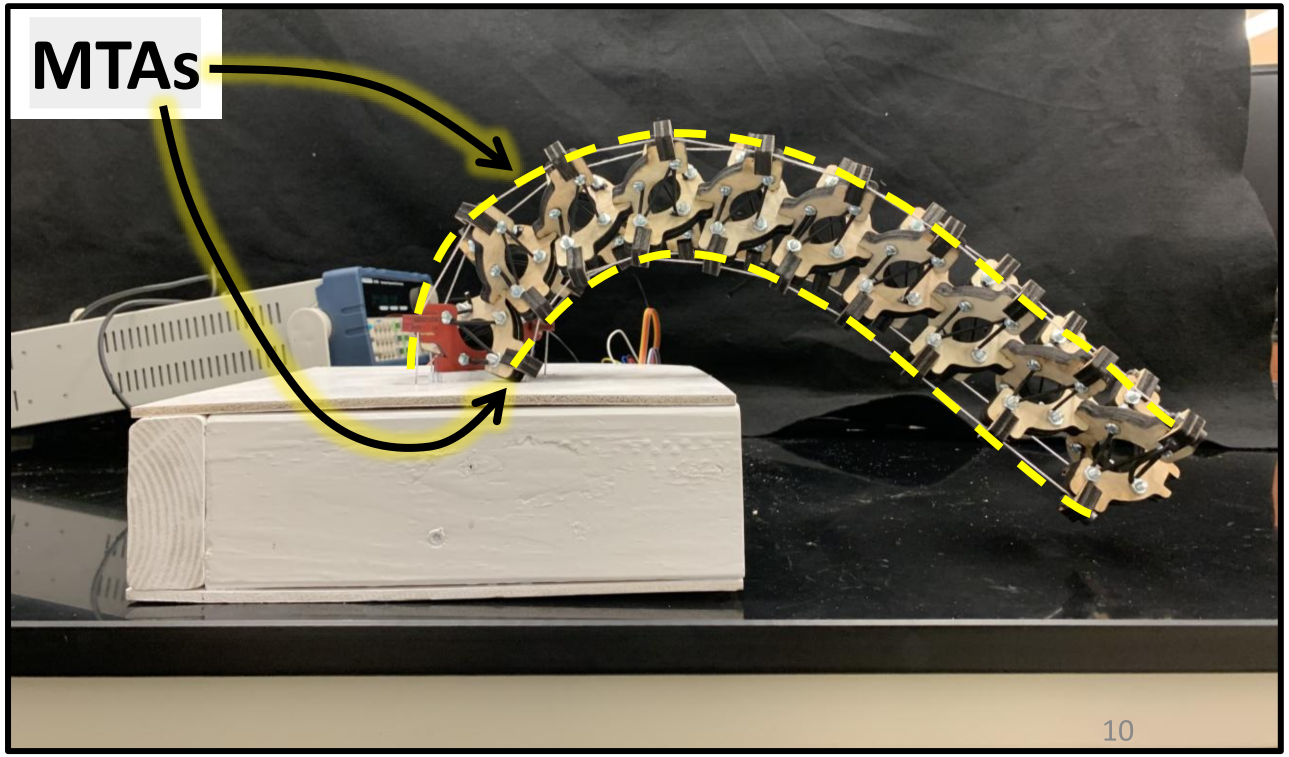


System Design

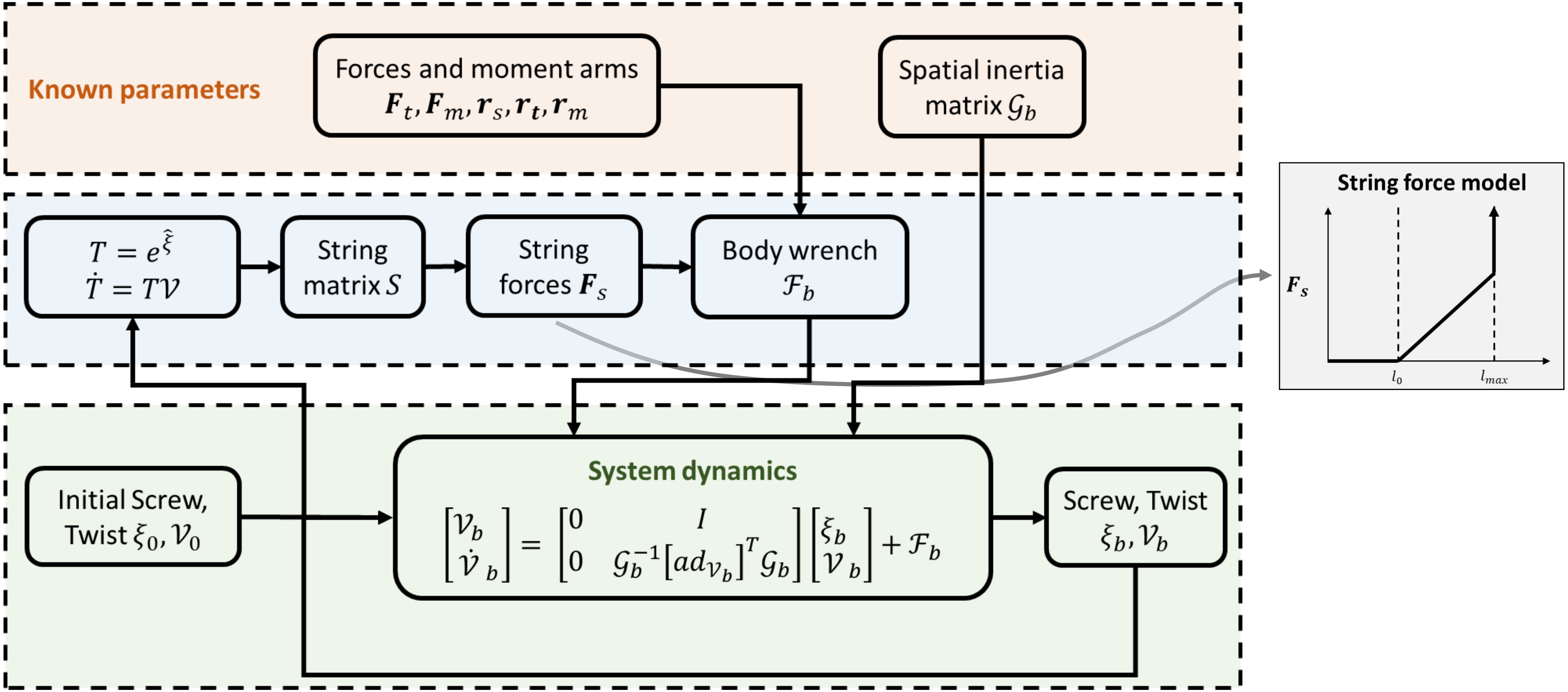
- ***Intermodular docking:*** Two different modes of intermodular docking: vertex-to-vertex or string-to-vertex.
- ***Actuation:*** four Motor-Tendon Actuators (MTAs) are routed along the outside of the manipulator and controlled using four motors at the base.

Vertex-to-vertex String-to-vertex

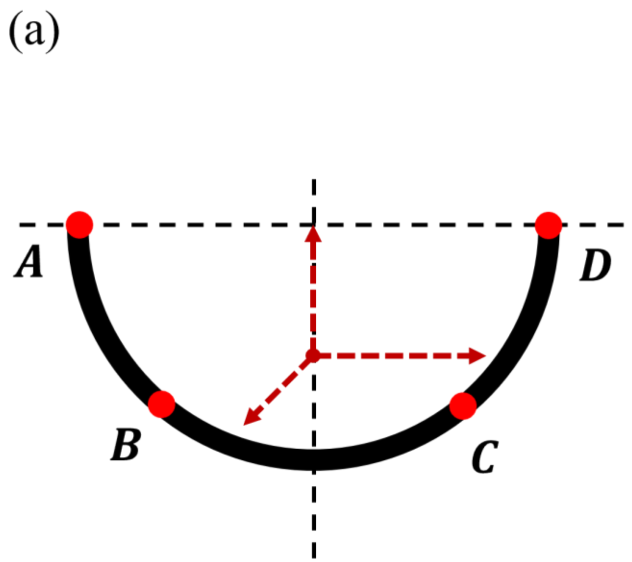


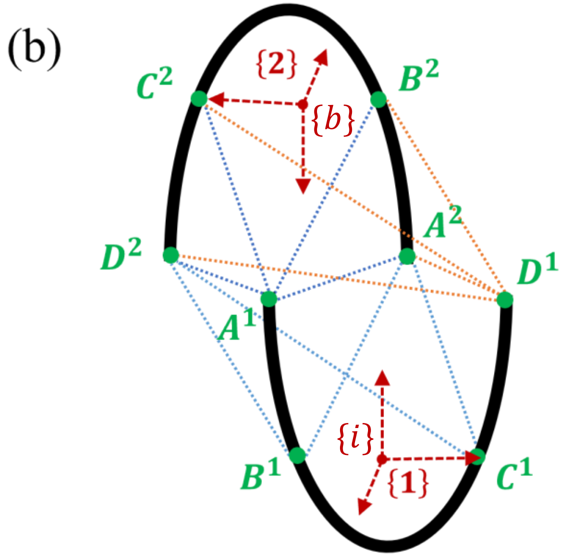


DexTeR Modeling



DexTeR Modeling





String Vectors:

Vertices of sub-vertebra: $P = [\boldsymbol{p}_a, \boldsymbol{p}_b, \boldsymbol{p}_c, \boldsymbol{p}_d, \cdots] \in \mathbb{R}^{4\times N_n}$

Connectivity matrix: $C_i[j,k] = \begin{cases} 1, & \text{if string k contains vertex j} \\ 0, & \text{otherwise} \end{cases}$

Transformation matrix: $T_{12} = \exp(\hat{\xi}) = \exp(\widehat{\mathcal{V}t})$

String vector calculation:

$$S_1 = PC_1 - T_{12}PC_2$$

$$S_2 = PC_2 - T_{12}^{-1}PC_1 = -T_{12}^{-1}S_1$$

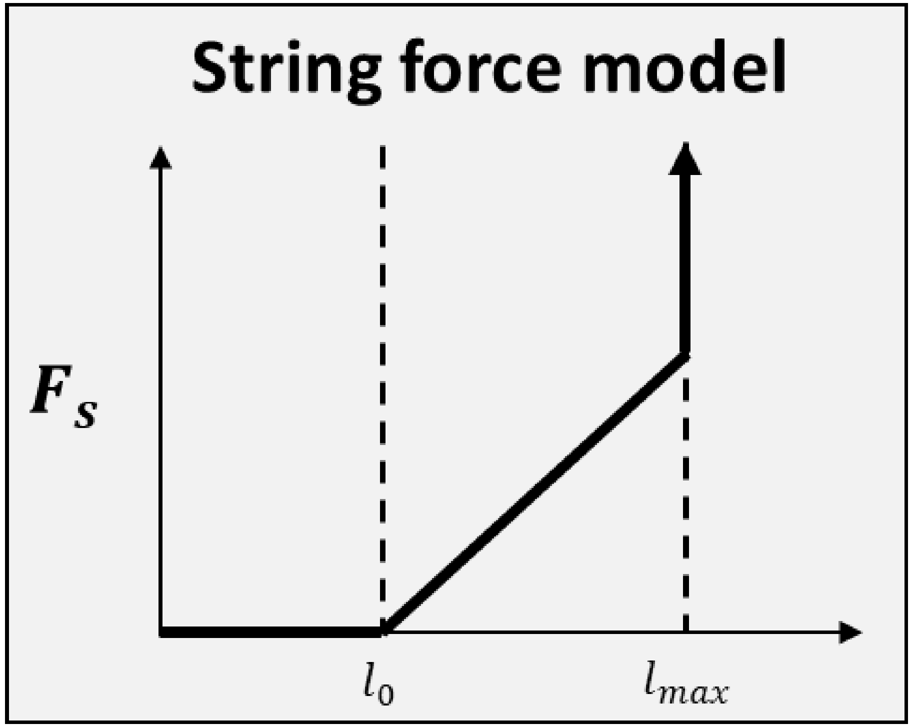
Length of each string: $\boldsymbol{s}_j = \mathrm{col}_j(S), \quad l_j = |\boldsymbol{s}_j|$

DexTeR Modeling

<u>*String Force Model:*</u> **Three force regions of the string:**

- **Slack: force is zero**
- **Spring: force is found using Hooke's Law**
- **Pure tension: string is fully stretched and acts as an inelastic cable**

Note: Operating in region well below failure



$$f_{s,j} = \begin{cases} 0 & , \quad l_j < l_0 \\ k_j(l_j - l_0)/l_j & , \quad l_0 < l_j < l_{max} \\ k_j(l_{max,j} - l_0 + l_{t,j})/l_j, & \quad l_j = l_{max} \end{cases}$$

$$\text{where} \quad l_j = |\boldsymbol{s}_j|, \quad \boldsymbol{s}_j = \mathrm{col}_j(S)$$

DexTeR Modeling

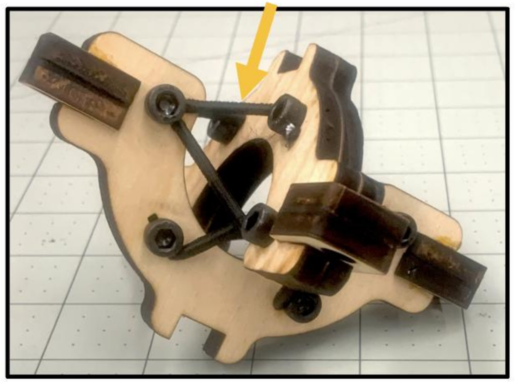
Single vertebra dynamics:

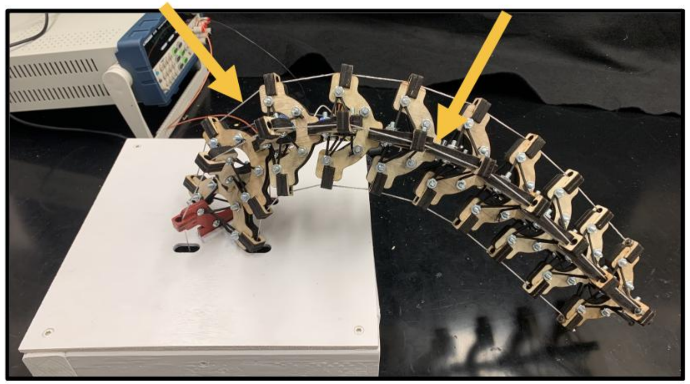
$$\mathcal{V}_b = [\omega_b^T, v_b^T]^T$$

$$\begin{bmatrix} m_b \\ f_b \end{bmatrix} = \begin{bmatrix} I_b & 0 \\ 0 & m\mathbf{1} \end{bmatrix} \begin{bmatrix} \dot{\omega}_b \\ \dot{v}_b \end{bmatrix} + \begin{bmatrix} \hat{\omega}_b & 0 \\ 0 & \hat{\omega}_b \end{bmatrix} \begin{bmatrix} I_b & 0 \\ 0 & m\mathbf{1} \end{bmatrix} \begin{bmatrix} \omega_b \\ v_b \end{bmatrix}$$

$$\mathcal{F}_b = \mathcal{G}_b \dot{\mathcal{V}}_b - (ad_{\mathcal{V}_b})^T \mathcal{G}_b \mathcal{V}_b$$

$$\boxed{\begin{bmatrix} \mathcal{V}_b \\ \dot{\mathcal{V}}_b \end{bmatrix} = \begin{bmatrix} 0 & I \\ 0 & G_b^{-1} (ad_{\mathcal{V}_b})^T G_b \end{bmatrix} \begin{bmatrix} \xi_b \\ \mathcal{V}_b \end{bmatrix} + \begin{bmatrix} 0 \\ G_b^{-1} \mathcal{F}_b \end{bmatrix}}$$



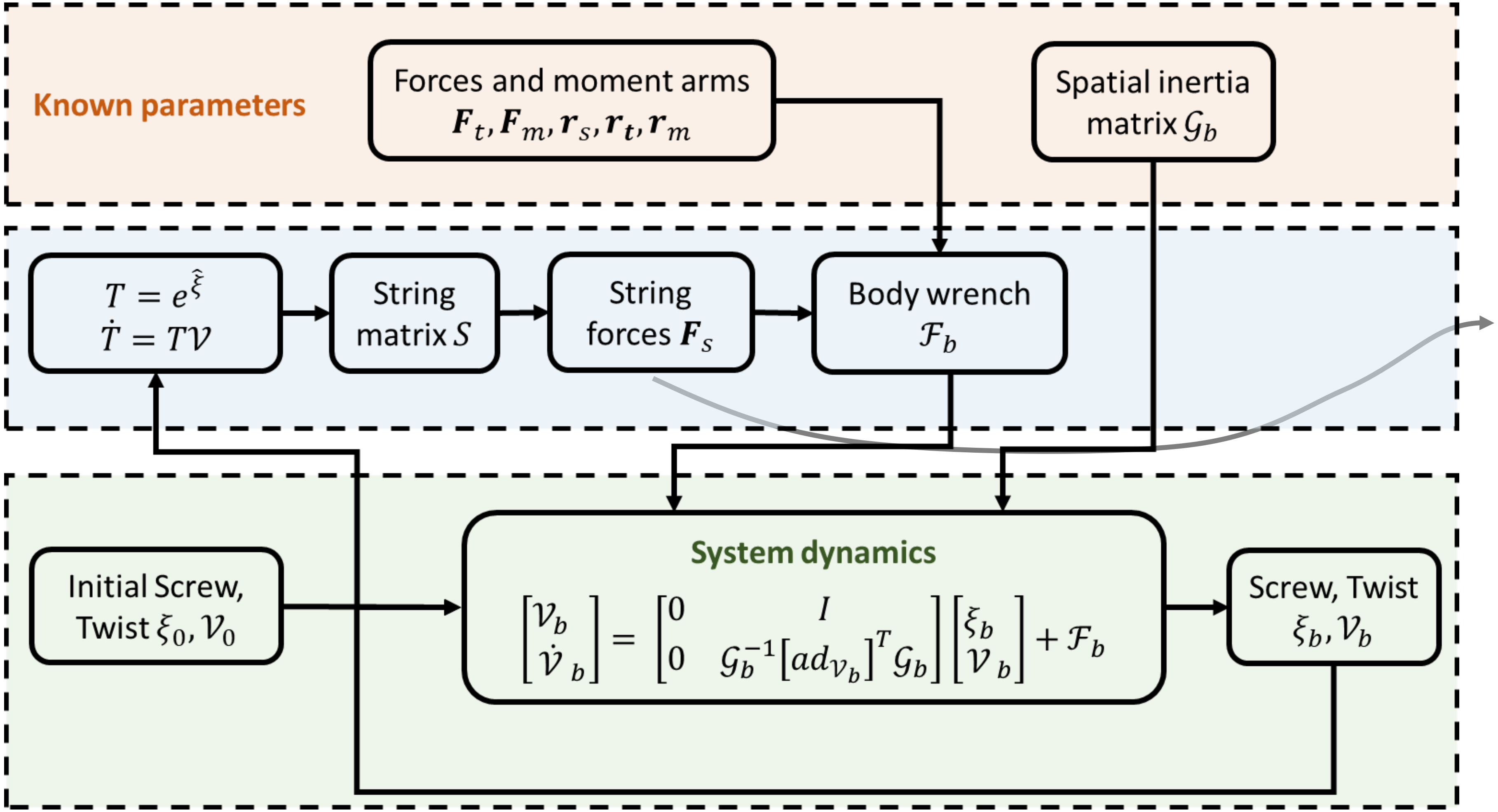


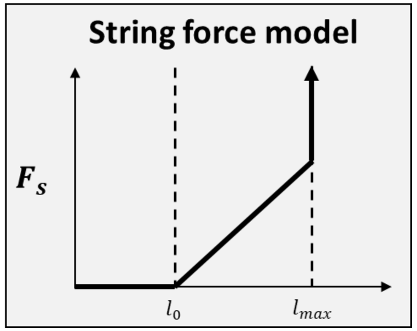
$$\mathcal{F}_b = \mathcal{F}_s + \mathcal{F}_t + \mathcal{F}_m \qquad \text{s.t.}$$

$$\mathcal{F}_t = \begin{bmatrix} \sum_k F_{t_k} \\ \sum_k \boldsymbol{r}_{t,k} \times F_{t_k} \end{bmatrix}, \quad \mathcal{F}_m = \begin{bmatrix} F_m \\ \boldsymbol{r}_m \times F_m \end{bmatrix}$$

$$\mathcal{F}_s = \begin{bmatrix} \sum_{j=1}^{N_c} f_{s,j} \boldsymbol{s}_j \\ \sum_{j=1}^{N_c} \boldsymbol{r}_j \times (f_{s,j} \boldsymbol{s}_j) \end{bmatrix}, \quad \boldsymbol{r}_j = \mathrm{col}_j(PC)$$

DexTeR Modeling



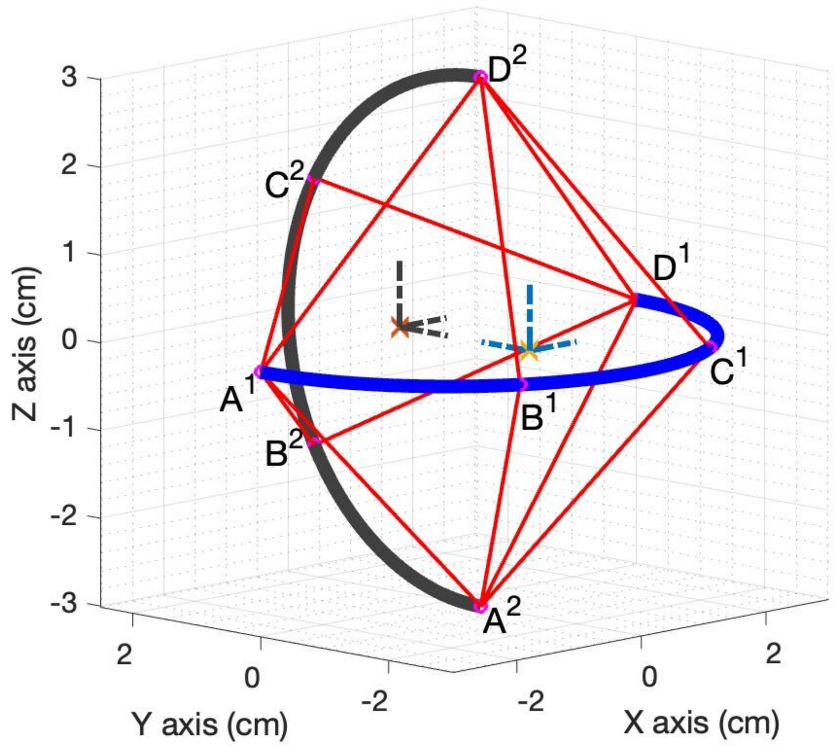


DexTeR Modeling

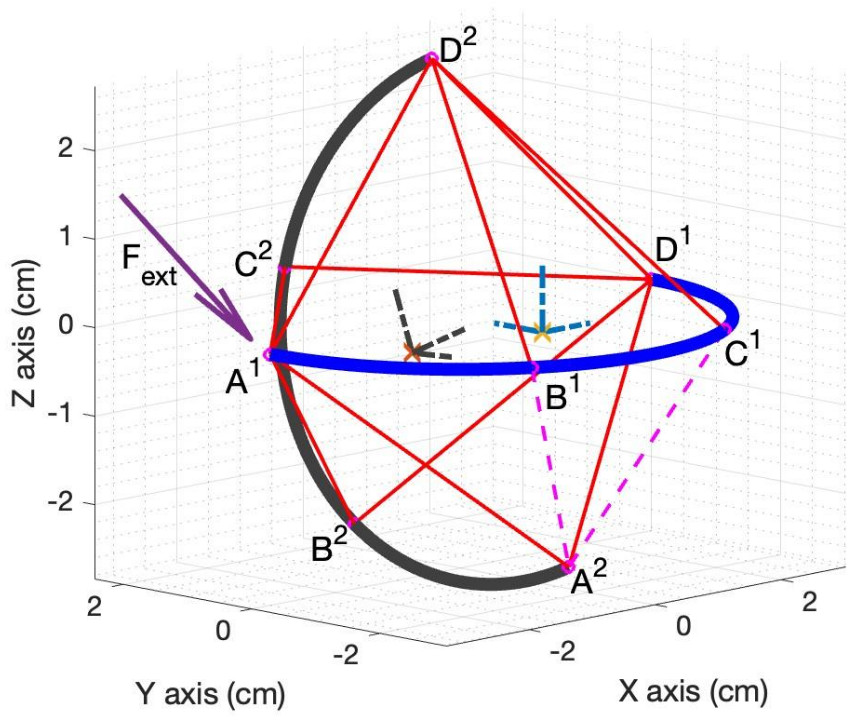
	Node-Based (Traditional)	**Lie Group/Screw Theory** (Proposed)
Unknowns (β links)	$3 \times 4\beta = 12\beta$	$6 \times \beta = 6\beta$
Complex morphologies (e.g., multiple connections)	Performance unknown	Works very well
Force and torque representation	Global coordinate system (tough to change to local)	Local or global coordinate system (ease of representation)
Nonlinear constraints	Length constraints	None
Cable tensile force	Tension	Spring + Tension

Simulation Results

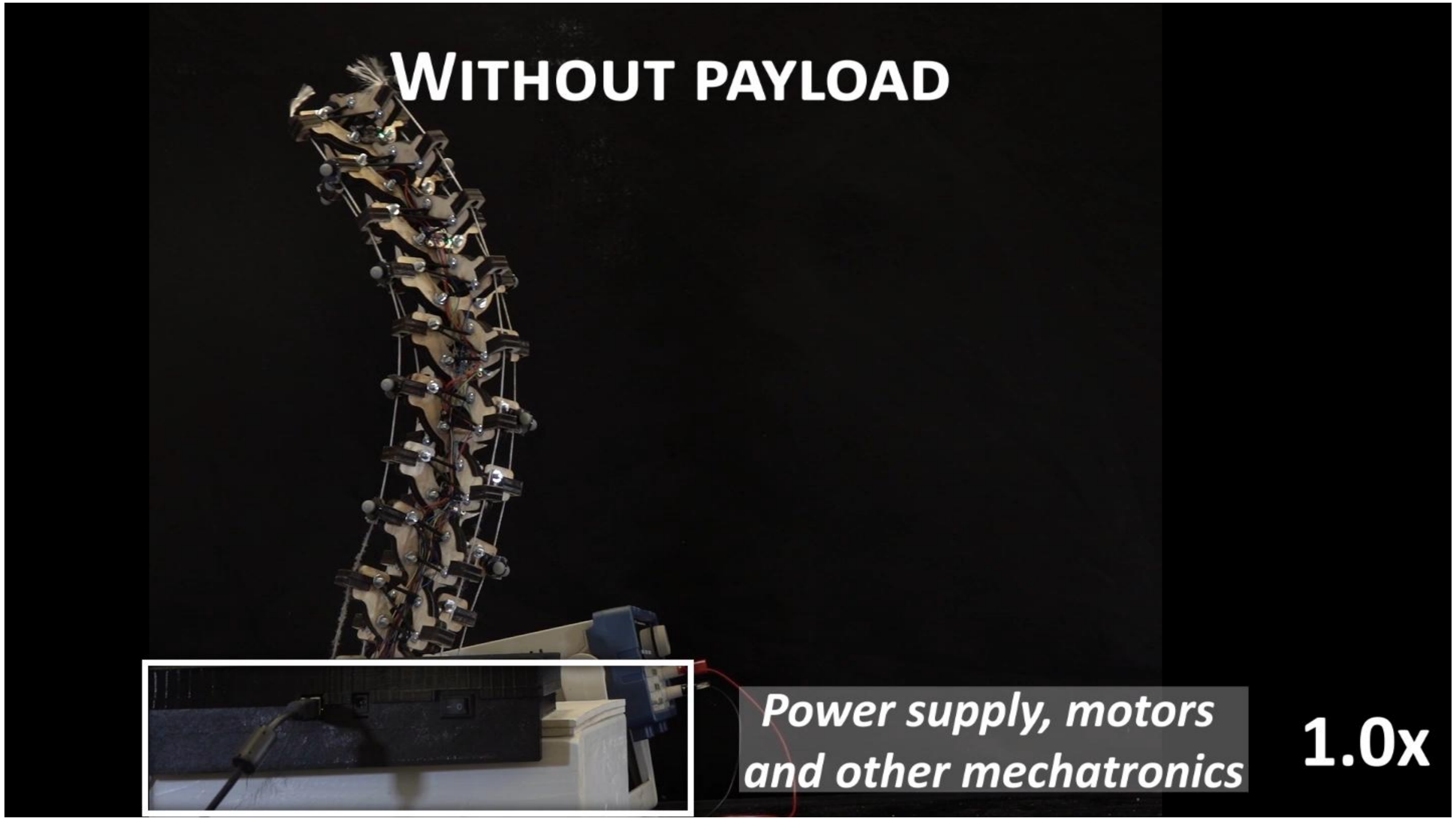
Static with no external forces



Static with single external force



DexTeR Prototype



Future Works

- **Build stronger mobile DexTeR**
- **Extend modeling methodology to multiple modules as an iterative approach to model the complete manipulator**
- **Simulation of DexTeR and its physical open-loop control for validation**
- **Further examine proposed framework with traditional node-based approach**

Questions?

ROLL TIDE!