Geometric Static Modeling Framework for Piecewise-Continuous Curved-Link Multi Point-of-Contact Tensegrity Robots

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Introduction and Motivation

A <u>tensegrity</u> structure is comprised of rigid struts under compression with prestressed members held in <u>tension</u> to achieve structural <u>integrity</u>. Tensegrity structures are lightweight, packable, impact resistant, and internally stable making them ideal candidates for locomotion in unstructured environments such as search and rescue and space scenarios. A speed comparison of recent tensegrity robots, Fig. 1, shows the increased efficiency in spherical link designs. **The reality gap – movement in a non-lab setting – remains an unsolved problem from the perspective of mobility, controls, and design.**
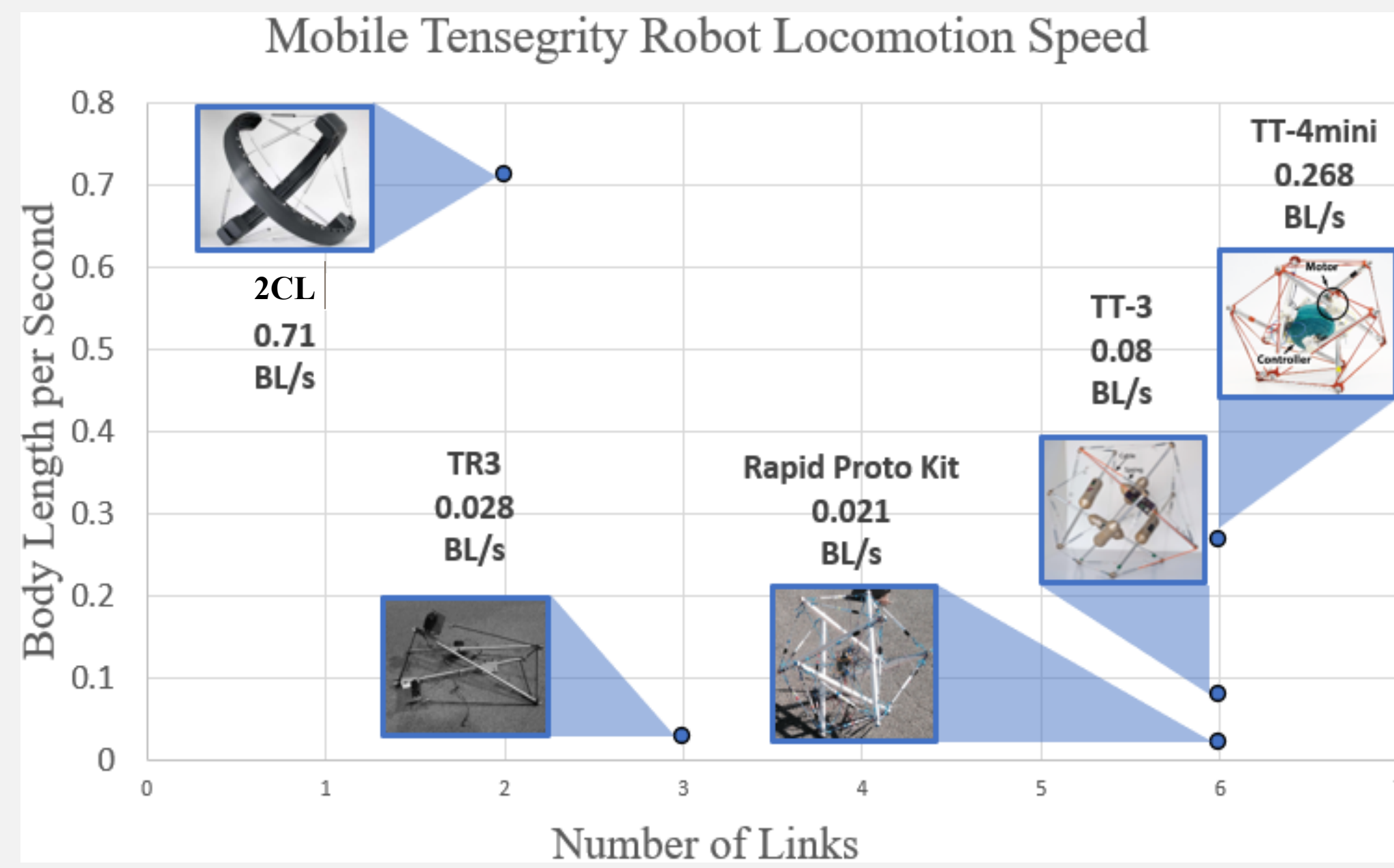

Fig. 1: Tensegrity Robot Locomotion Speed [1-5]

<u>**Contributions:**</u> **The curved-link TeXploR (Tensegrity eXploratory Robot) [6] has**
1. <u>Geometric Framework</u> that statically models the multi point-of-contact system.
2. <u>Adaptability</u> to robots with multiple points of contact/different morphologies.
3. <u>Four-State Hybrid System</u> where each state corresponds to TeXploR instantaneously pivoting about the end of one link while rolling along the other.
4. <u>Input-Output Relationship</u> between internal mass positions and contact points (robot orientation). A tetherless prototype experimentally validates the model.

Hybrid System and Static Modeling

TeXploR poses the following modeling challenges:
1. Discontinuous nature of the curved links requiring state switching.
2. Constantly changing ground contact points.
3. Instantaneous movement of the masses along the links.

TeXploR rolls by shifting an internal mass along each arc, instantaneously changing the robot's CoM.
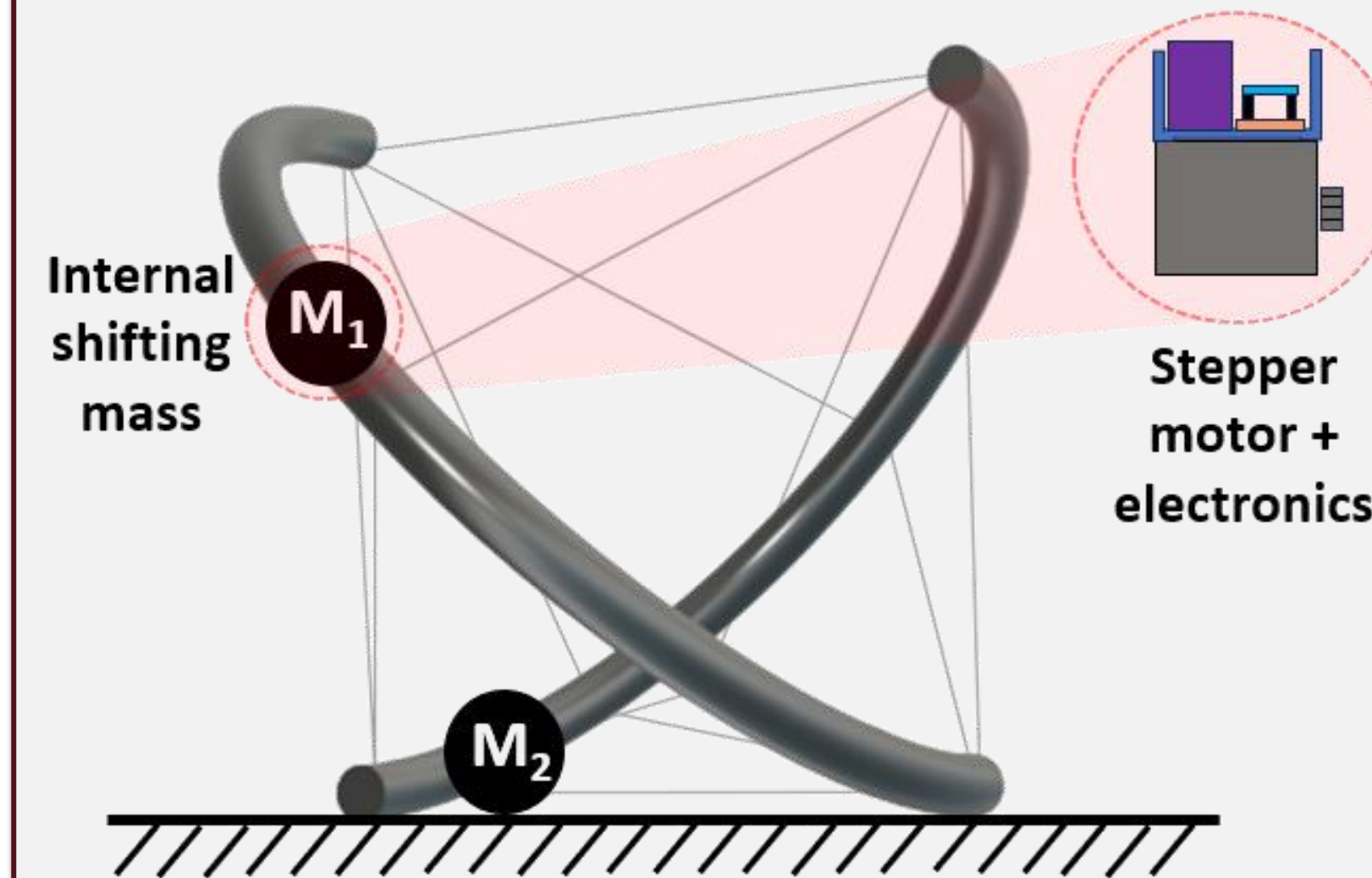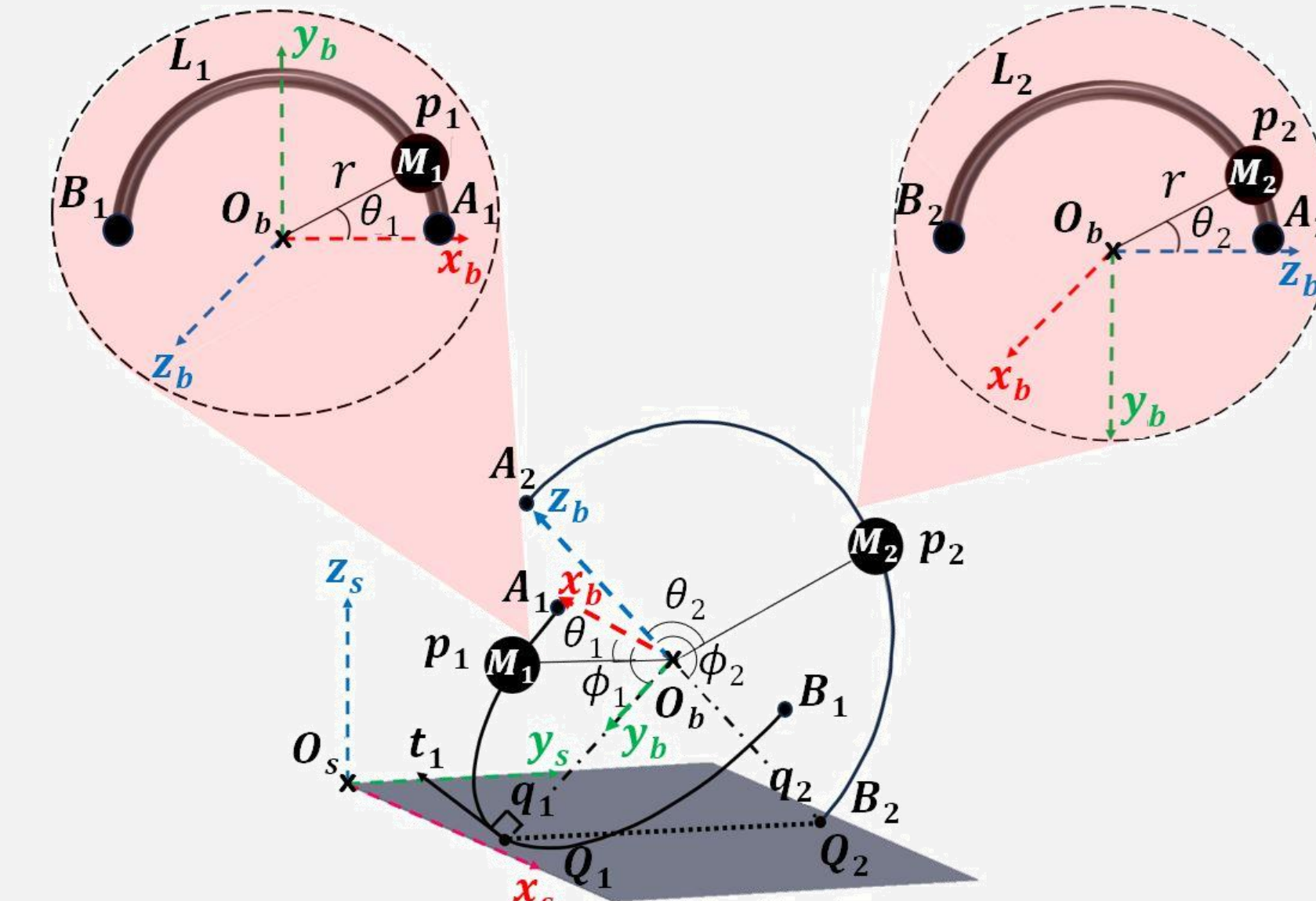

Fig. 3: TeXploR Geometric Representation

Fig. 2: Internal Shifting Mechanism

Holonomic Constraints
Shifting mass → angle θ_i and position p_i
Ground contact → angle ϕ_i and position q_i
Arc tangent at q_i → t_i
✓ t_2 undefined → State 1: $\phi_2 = 0°$
  or
  State 2: $\phi_2 = 180°$
✓ t_1 undefined → State 3: $\phi_1 = 0°$
  or
  State 4: $\phi_1 = 180°$
~~t_1, t_2 defined~~ → $\phi_2 = -\phi_1$ or $\phi_2 = \phi_1 + 180°$

Four-State Hybrid System

The use of Lie groups and Screw Theory provides an analytical solution with ease of transforming c.s. This results in a closed form solution dependent on the hybrid system state. One internal mass always acts as the pivot while the other traverses its arc, resulting in a piecewise continuous trajectory with four traversal states.
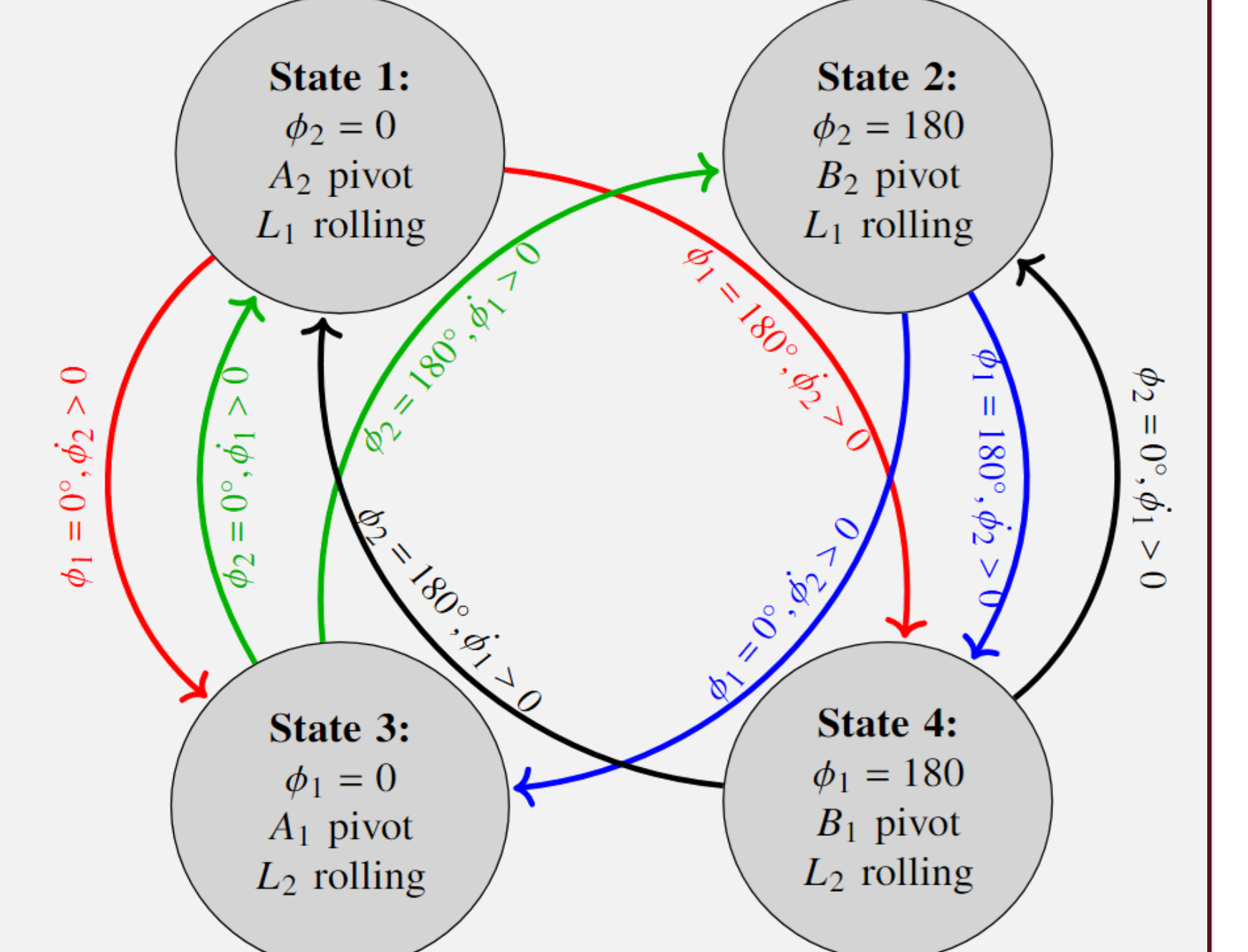

Fig. 4: Hybrid State System

Design, Mechatronics, and Fabrication

1. <u>**Mechanical Design:**</u> 3D printed 180° arcs comprise the body. An internal GT2 timing belt enables precise motion.
2. <u>**Electrical Design:**</u> An Arduino Nano33 IoT, A4988 motor driver, custom PCB, and 1,100mAh LiPo battery mounted to a NEMA17 stepper motor comprise the shifting mass per arc.
3. <u>**Tendon Routing:**</u> A single, elastic cable routes through each of the four sets of holes on an arc. Each of the graph's edges are traveled only once, following an Euler path. Individual cable segments can be tightened as necessary to ensure proper tension between the arcs.
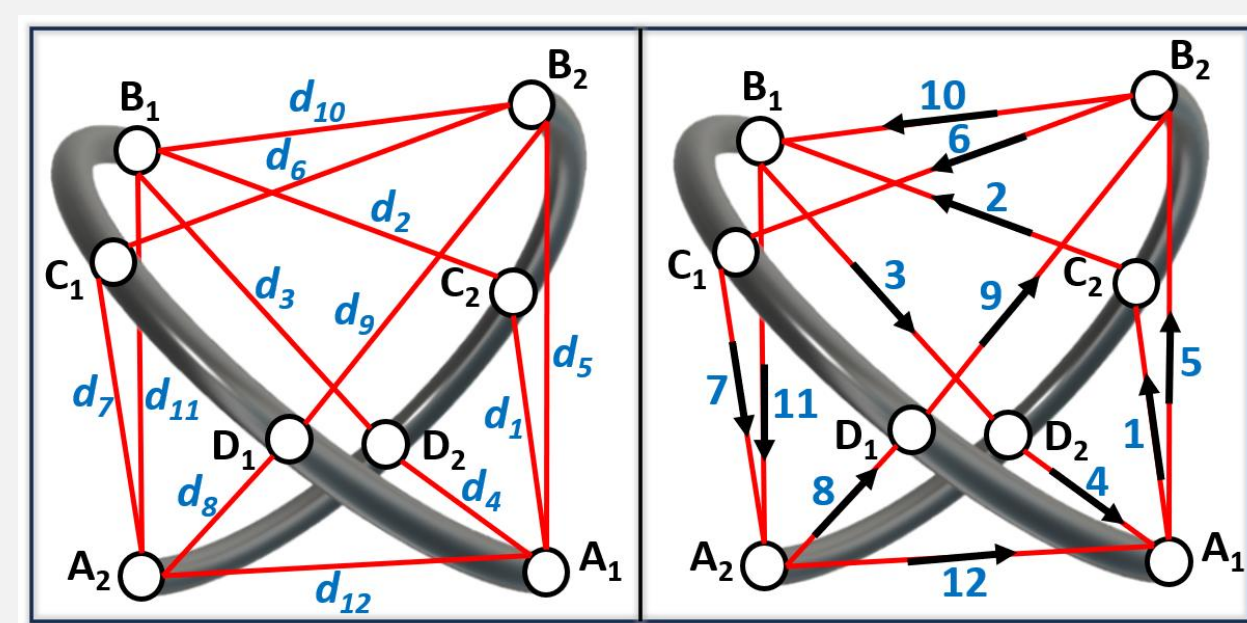
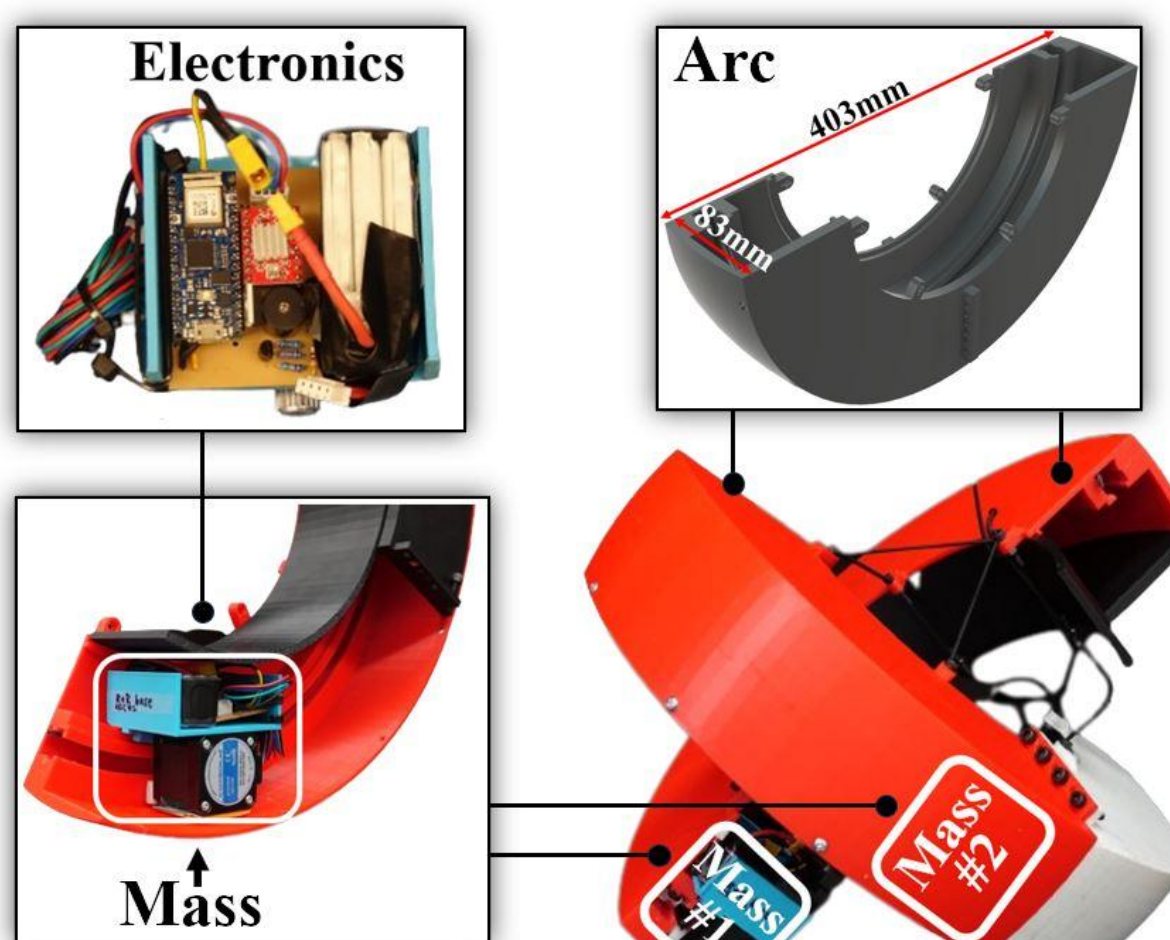
Fig. 5: Cable Routing Assembly

Fig. 6: TeXploR Fabrication

Static Simulations and Experimental Validation

Simulations vs. Experimental Results

For all four states, static equilibrium positions (outputs) based off internal mass positions (inputs) are simulated in increments of 0.001°. Experimental validation with the tetherless prototype was performed in increments of 45°. **Across all tests, only a small discrepancy of $4.36°$ MAE exists, proving the efficacy of the model.**
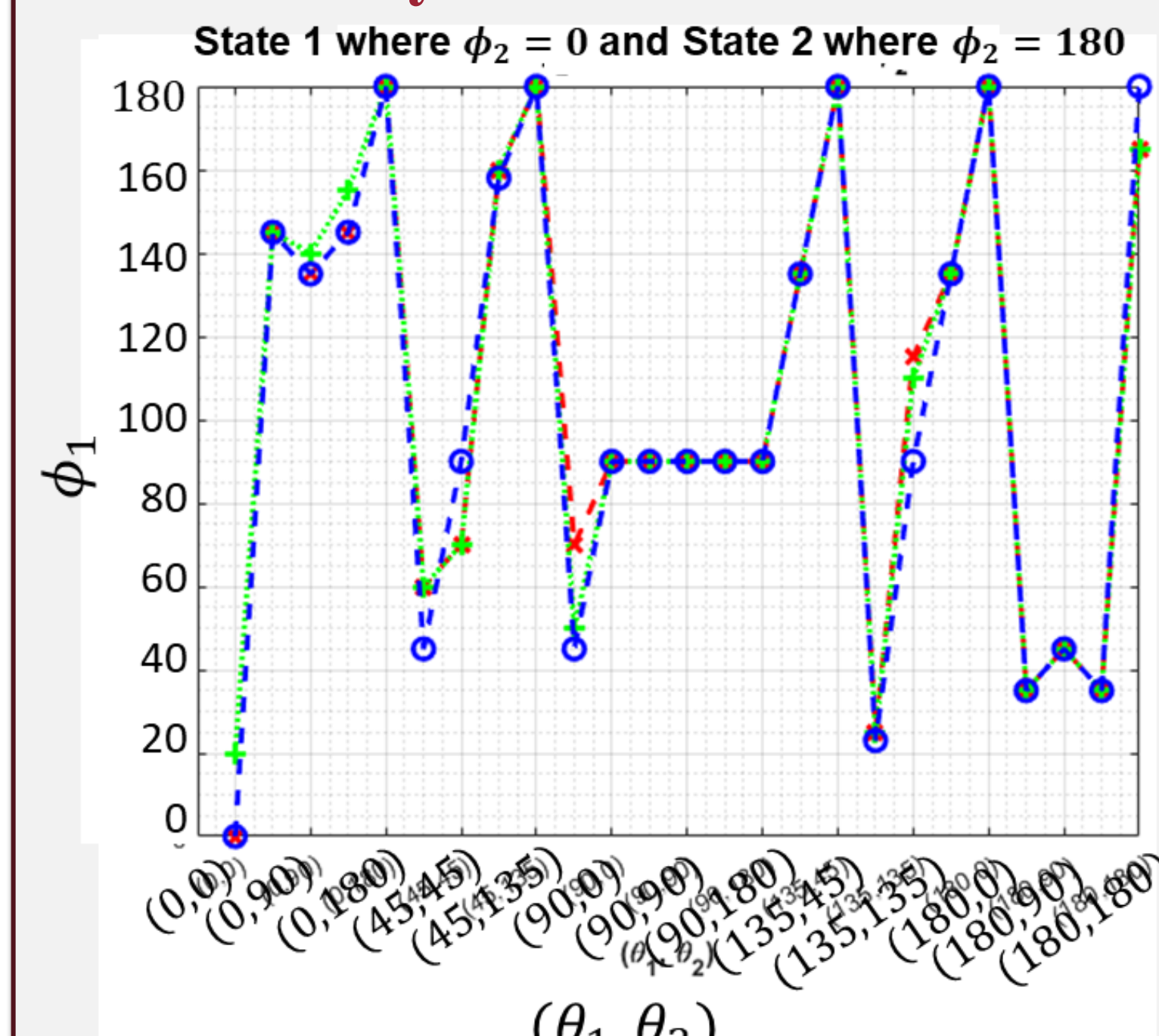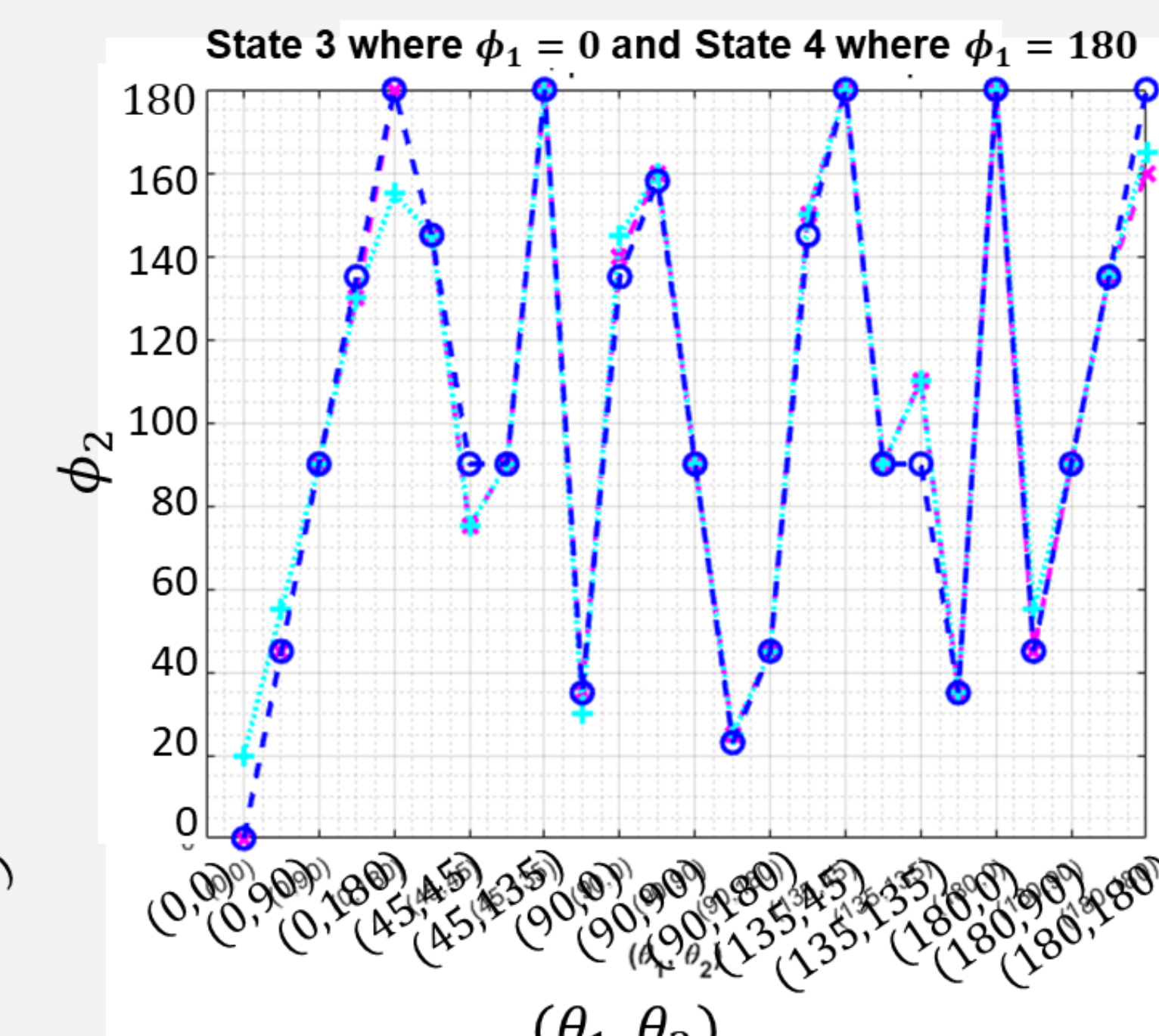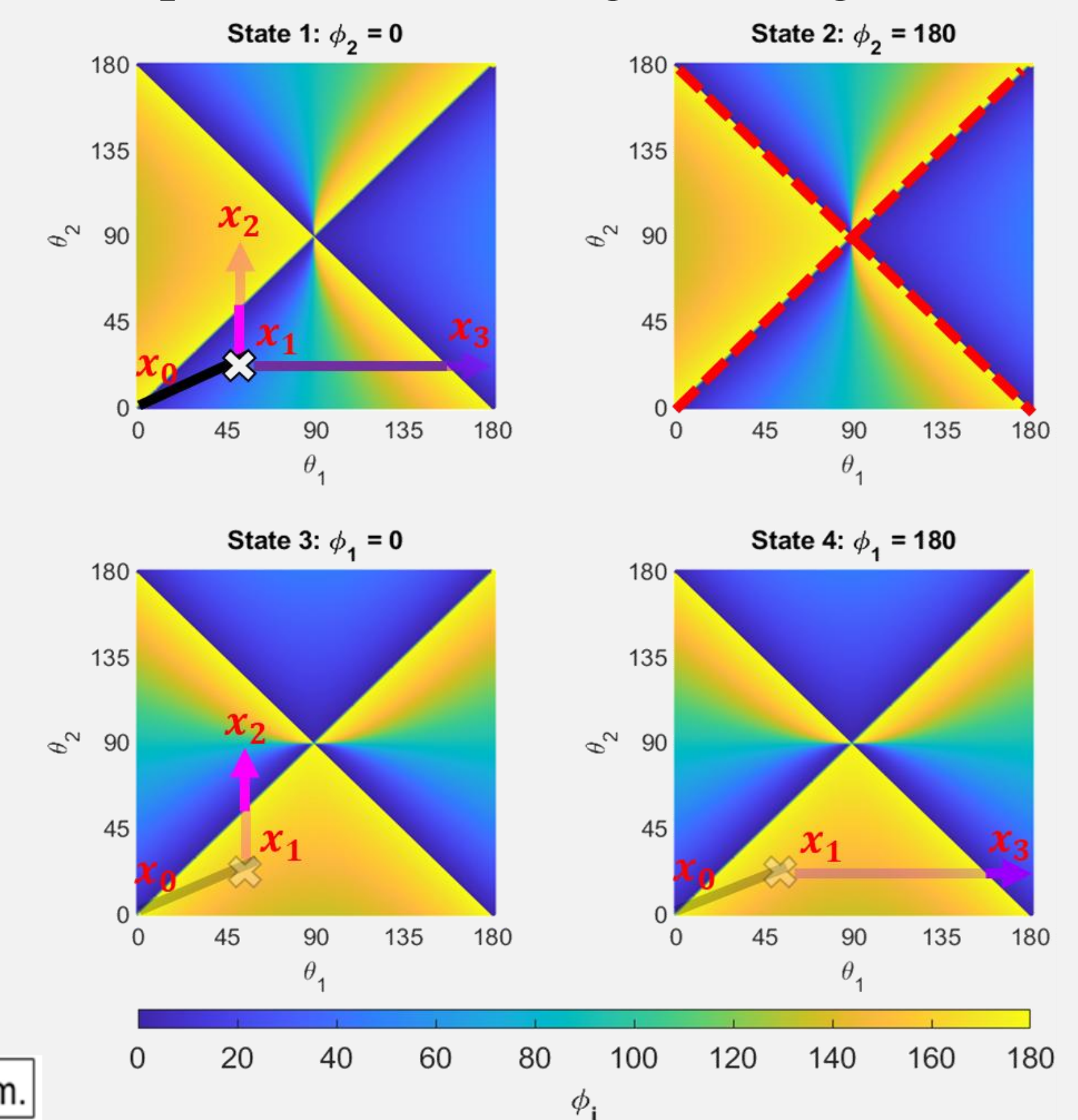

State Jumping

Switching states can occur anywhere along the border lines for gaits more complicated than straight rolling.

Future Works

- Active shape morphing visualized in Fig. 7
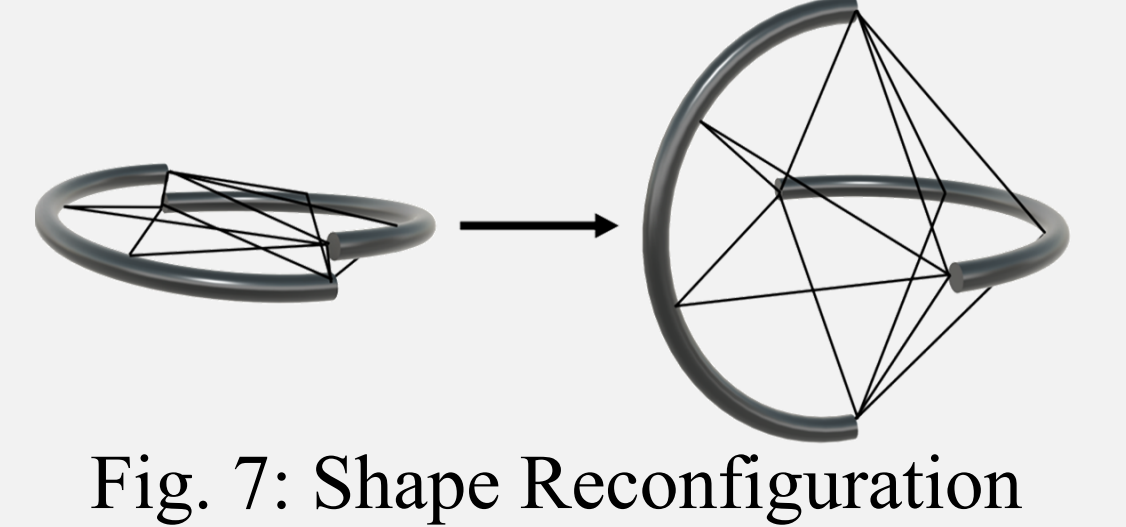- Complex movements - jumping and slipping
- Dynamic modeling

Fig. 7: Shape Reconfiguration

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