FORMAX

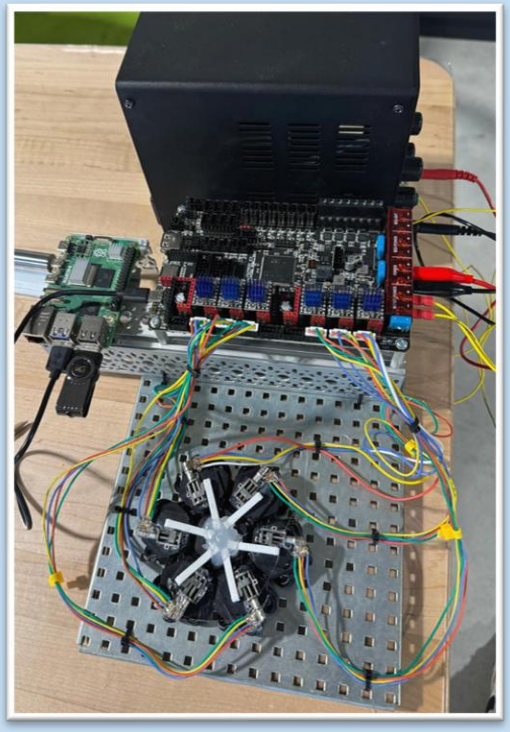
A Shape Shifting Robotic Surface

Ritvik Shah | Dec 2023 - Present



Why Formax

Watching a manta ray at the Georgia Aquarium made me wonder whether I could recreate its motion. I developed a mathematical framework for surface transformations and built an actuated chainmail prototype.



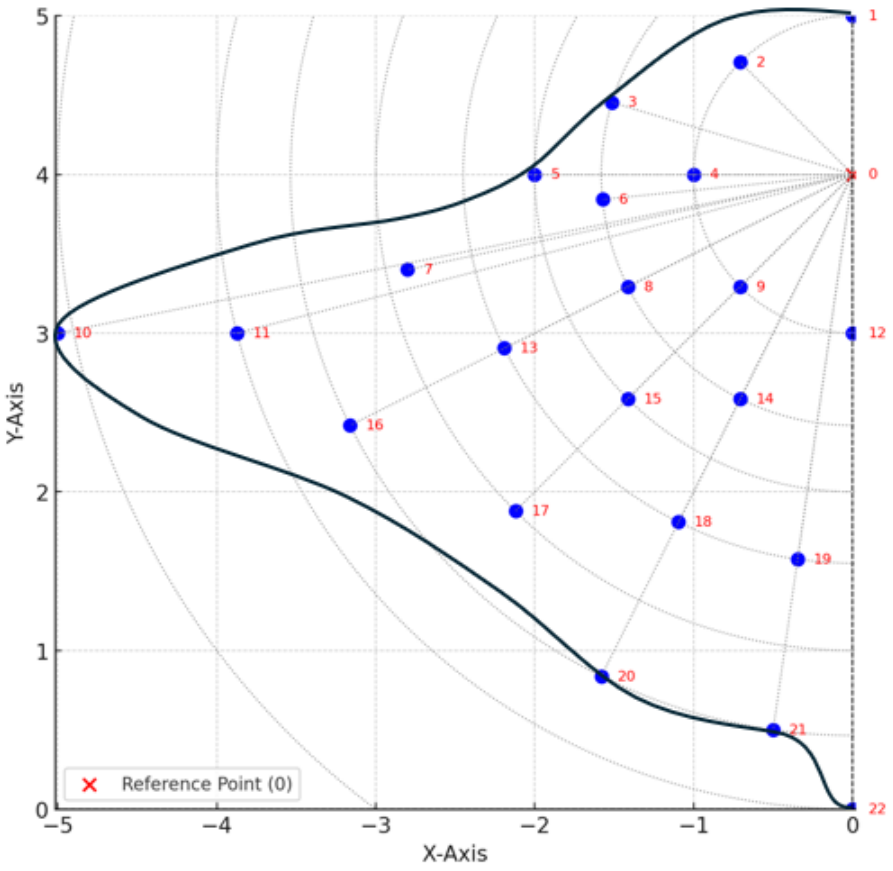
The Working Prototype

I designed and built this prototype with six linear actuators that adjust the angles between neighboring chainmail links. Controlled through a Raspberry Pi running Klipper, the assembly changes shape by coordinating the actuators' movements.

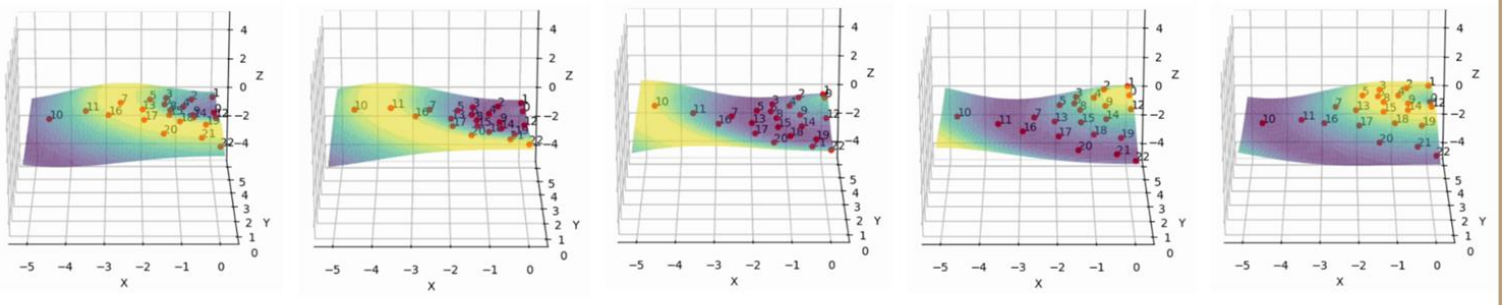
Modeling the Fin's Deformation

I developed a method for mapping points onto 3D surfaces while preserving arc length and angles relative to a reference point.

Point Number	X	Y
0.0	0.0	4.0
1.0	0.0	5.0
2.0	-0.70711	4.70711
3.0	-1.51446	4.45434
4.0	-1.0	4.0
5.0	-2.0	4.0
6.0	-1.57329	3.84267
7.0	-2.8	3.4
8.0	-1.41421	3.29289
9.0	-0.70711	3.29289
10.0	-5.0	3.0
11.0	-3.87298	3.0
12.0	0.0	3.0
13.0	-2.19089	2.90455
14.0	-0.70711	2.58579
15.0	-1.41421	2.58579
16.0	-3.16228	2.41886
17.0	-2.12132	1.87868
18.0	-1.09545	1.80911
19.0	-0.34641	1.57513
20.0	-1.58114	0.83772
21.0	-0.5	0.5
22.0	0.0	0.0



	Frame 10			Frame 20			Frame 30			Frame 40			Frame 50		
Pt	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
0	0.00	4.00	-0.54	0.00	4.00	-0.41	0.00	4.00	0.29	0.00	4.00	0.59	0.00	4.00	0.08
1	0.00	4.87	-0.16	0.00	4.92	-0.60	0.00	4.98	-0.28	0.00	4.97	0.43	0.00	4.89	0.51
2	-0.61	4.61	-0.16	-0.65	4.65	-0.60	-0.69	4.69	-0.28	-0.68	4.68	0.43	-0.63	4.63	0.51
3	-1.33	4.40	0.15	-1.36	4.41	-0.50	-1.44	4.43	-0.50	-1.47	4.44	0.14	-1.40	4.42	0.60
4	-0.87	4.00	-0.16	-0.92	4.00	-0.60	-0.98	4.00	-0.28	-0.97	4.00	0.43	-0.89	4.00	0.51
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
22	0.00	0.34	0.35	0.00	0.30	0.58	0.00	0.27	0.05	0.00	0.30	-0.56	0.00	0.34	-0.36



Modeled configurations at different moments in the motion

The Research Behind Formax

Published method & extended results in topology in
Journal of Geometry and Physics

ELSEVIER

Journal of Geometry and Physics

Volume 213, July 2025, 105472



Topological and numerical approaches to surface transformations

Selcuk Koyuncu [a], Ritvik Shah [b], Cenap Ozel [c]

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https://doi.org/10.1016/j.geomphys.2025.105472

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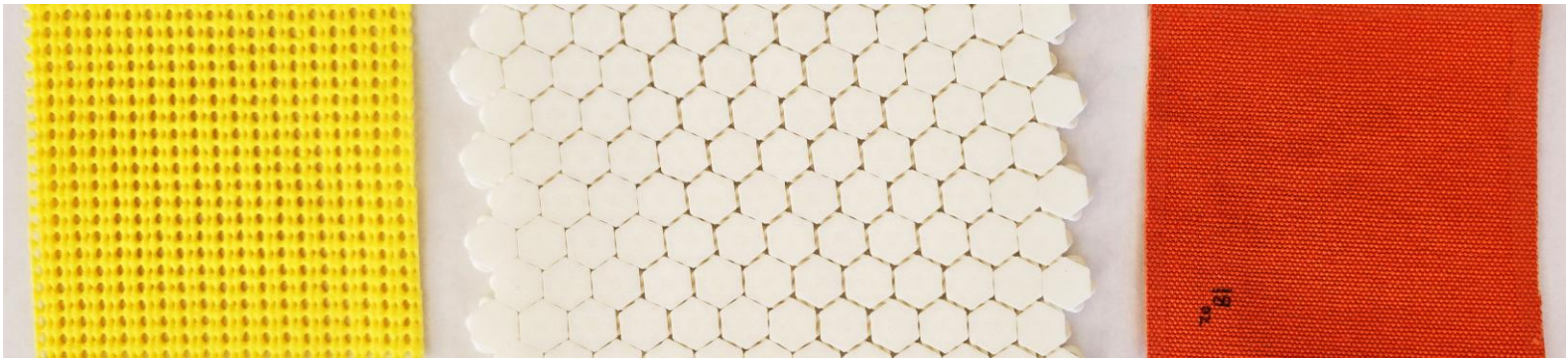
My contribution

I developed a method for mapping points between 3D surfaces while preserving arc lengths and angles. With Dr. Selcuk Koyuncu and Dr. Cenap Özel, I extended the work to topology, proving that topologically distinct surfaces have a strictly positive minimum distortion. We then co-authored the paper. I independently designed and built the robotic prototype.

The connection to the hardware

The mathematical framework I developed allows me to represent a target continuous 3D surface as a set of spatial points, which I use to program the prototype to approximate different physical surface configurations.
Code: https://github.com/Ritvik22/Formax

Choice of Flexible Surface



Mesh | NASA Chainmail | Canvas Fabric

Material samples explored during development

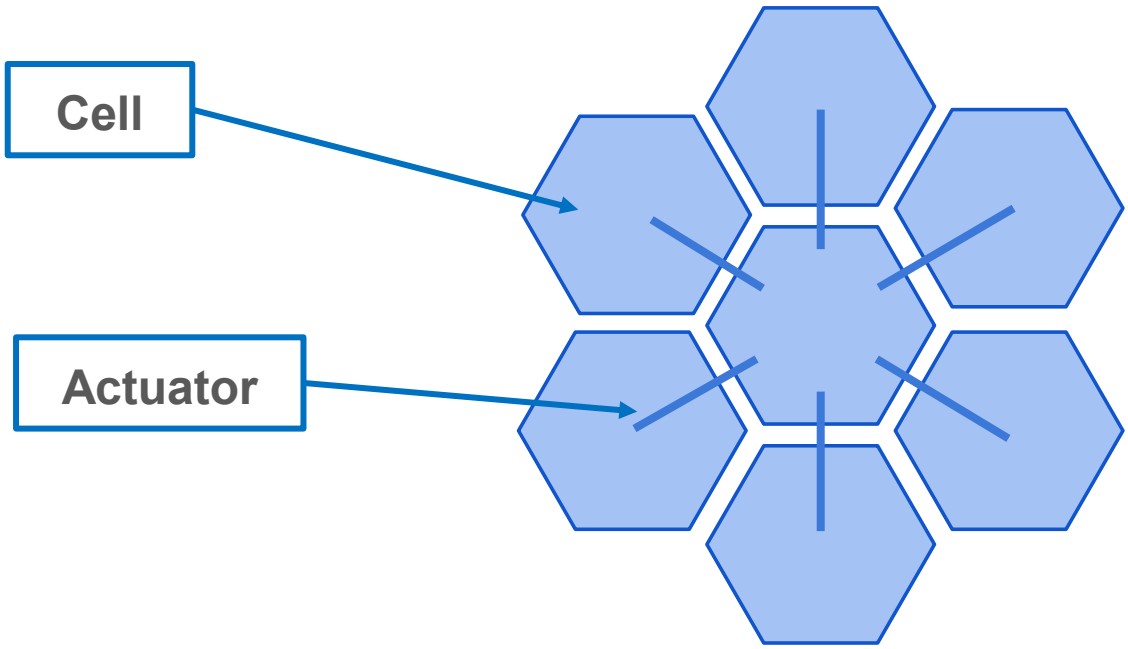
Why not Fabric or Mesh

- Fabric: Too flexible to provide stable surface.
- Mesh: Openings limited mounting area, making it difficult to secure actuators.

Why NASA Chainmail

- Rigid areas to mount actuators.
- Flexible connections between neighboring links.

Concept sketch to actuate angles across the fabric to program the surface to match multiple different shapes.

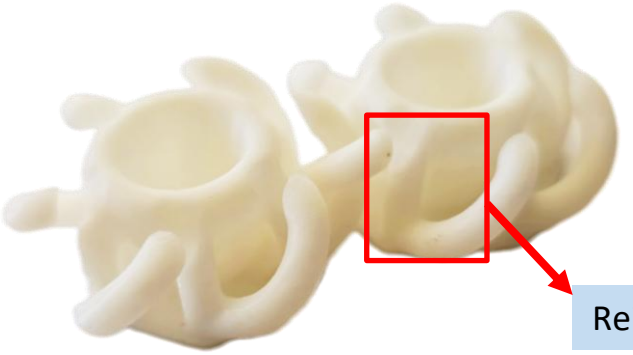


NASA's Chainmail Hex Connector & Stepper Motors



Open design allowed for too much play.

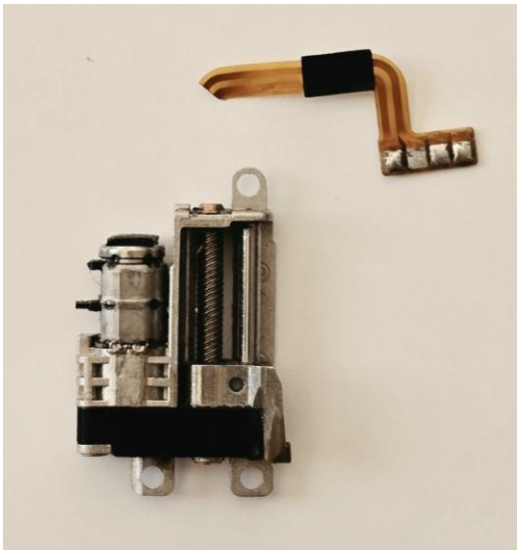
Unsupported Link Design



Reinforcement bars kept links in place while allowing them to change vertical angles.

Reinforced Link Design

Design Attribution: NASA-inspired hexagonal chainmail connectors by Chainmail Weaves, sourced from Printables (CC BY-SA). Used as part of my independently designed and actuated Formax robotic surface.



Fragile wire connections kept breaking

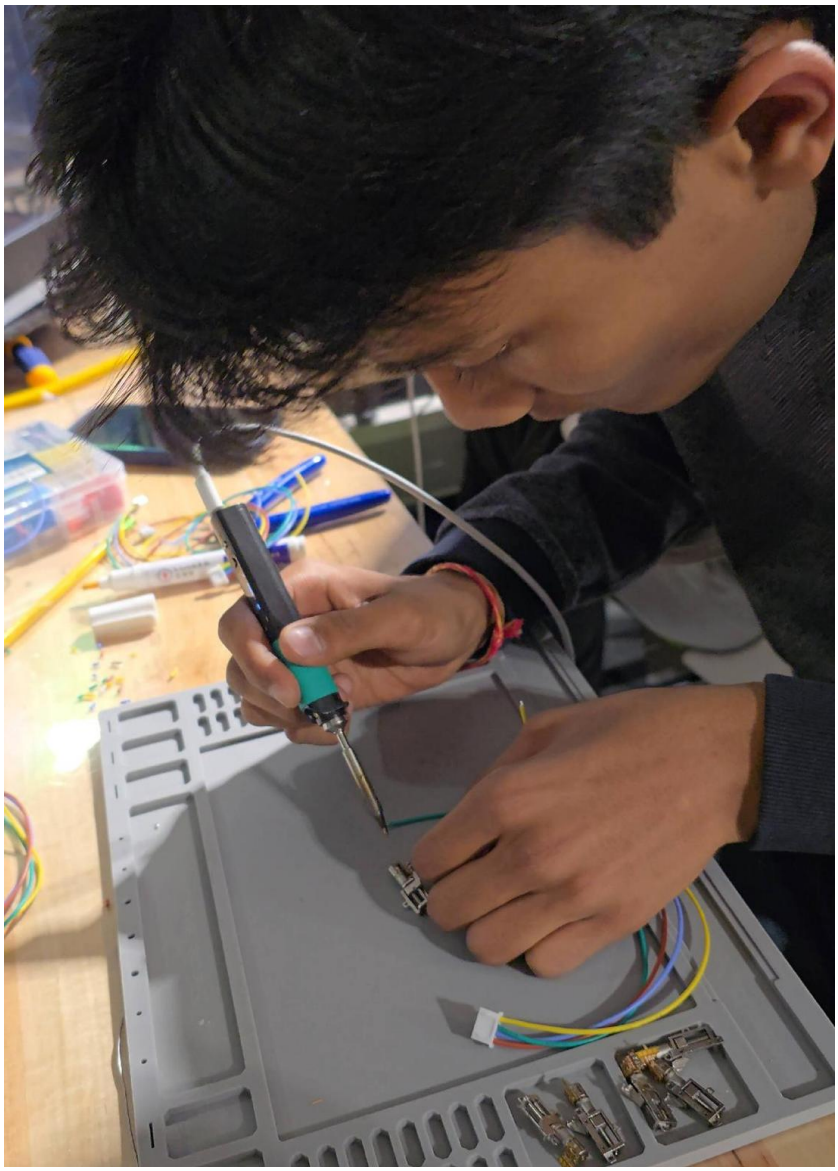
Linear Actuators: LUISAS, Miniature Precision Stepper-Motor Linear Actuators, sourced from Amazon



Wire connections were strong

Miniature Linear Actuators: Cylewet, 5mm Planetary Gearhead Precision Stepper Motors (CYT1125), sourced from Amazon

Wiring and Controlling Actuators



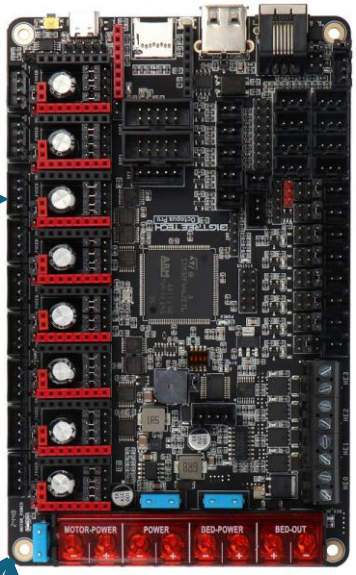
The challenge

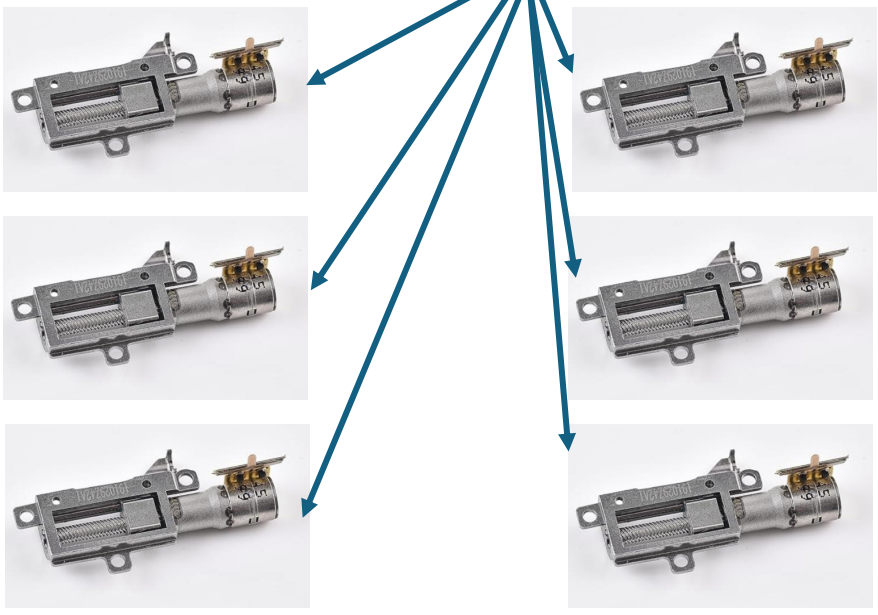
Control multiple stepper motors within one system.

Raspberry Pi
Runs Klipper

Controller board
Drives the motors







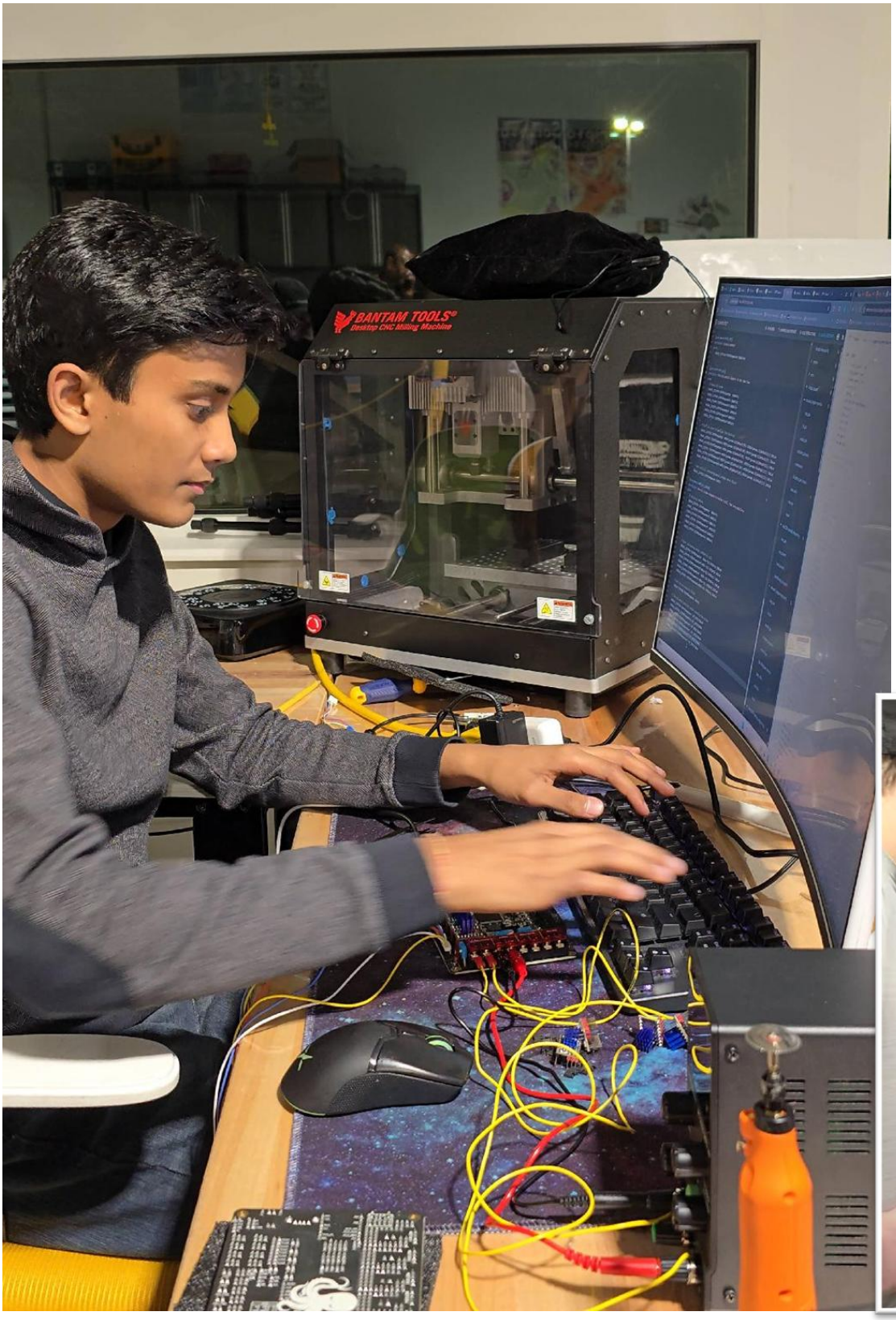
My approach

I soldered the actuator wiring and used Klipper, a 3D-printer firmware, to control the motors.

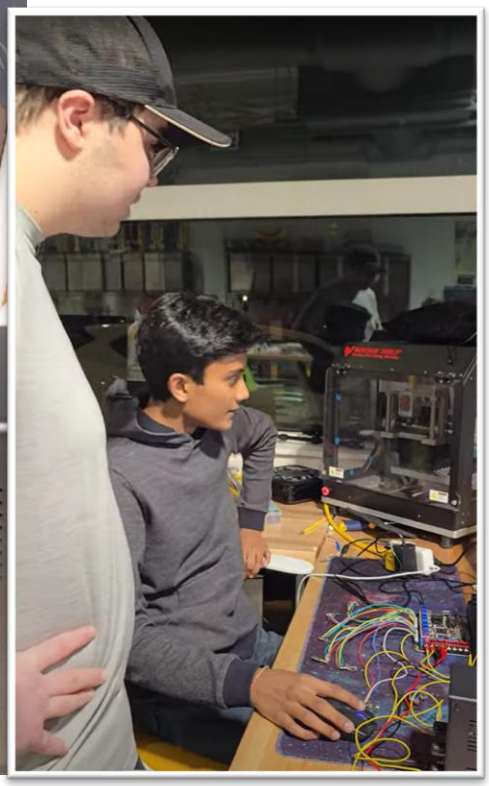
Actuators
Move the links

Programming

I programmed the Klipper configuration and set up the connected actuators for the first robot tests.
The configuration connects the physical motor wiring to the software that commands actuator motion.

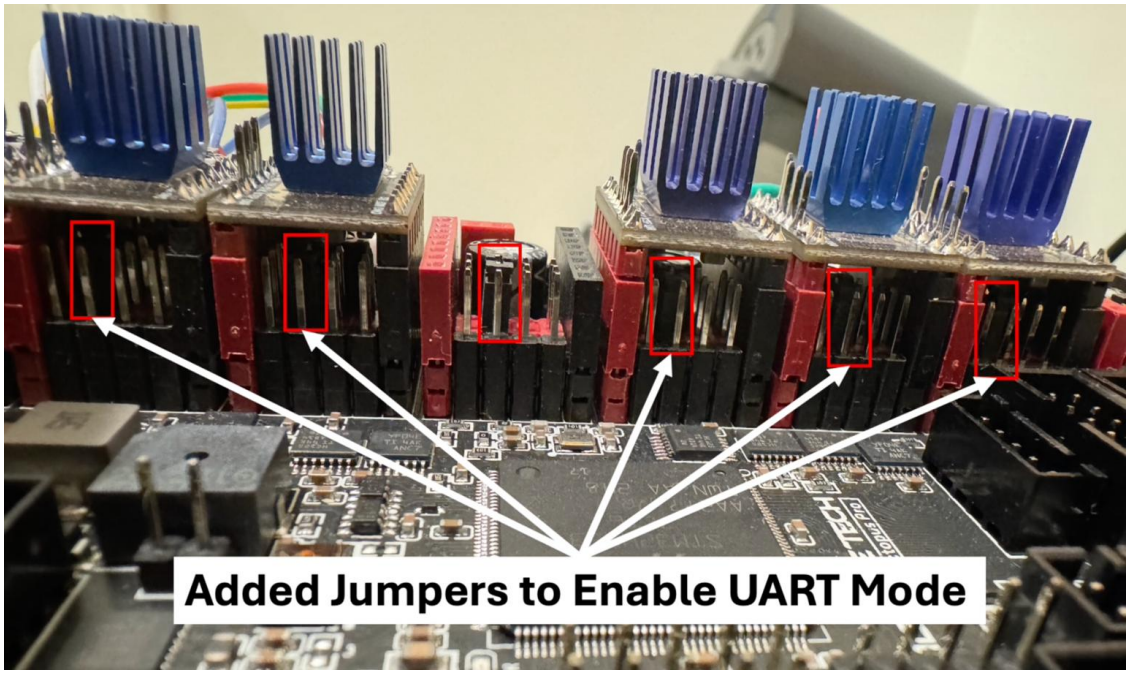


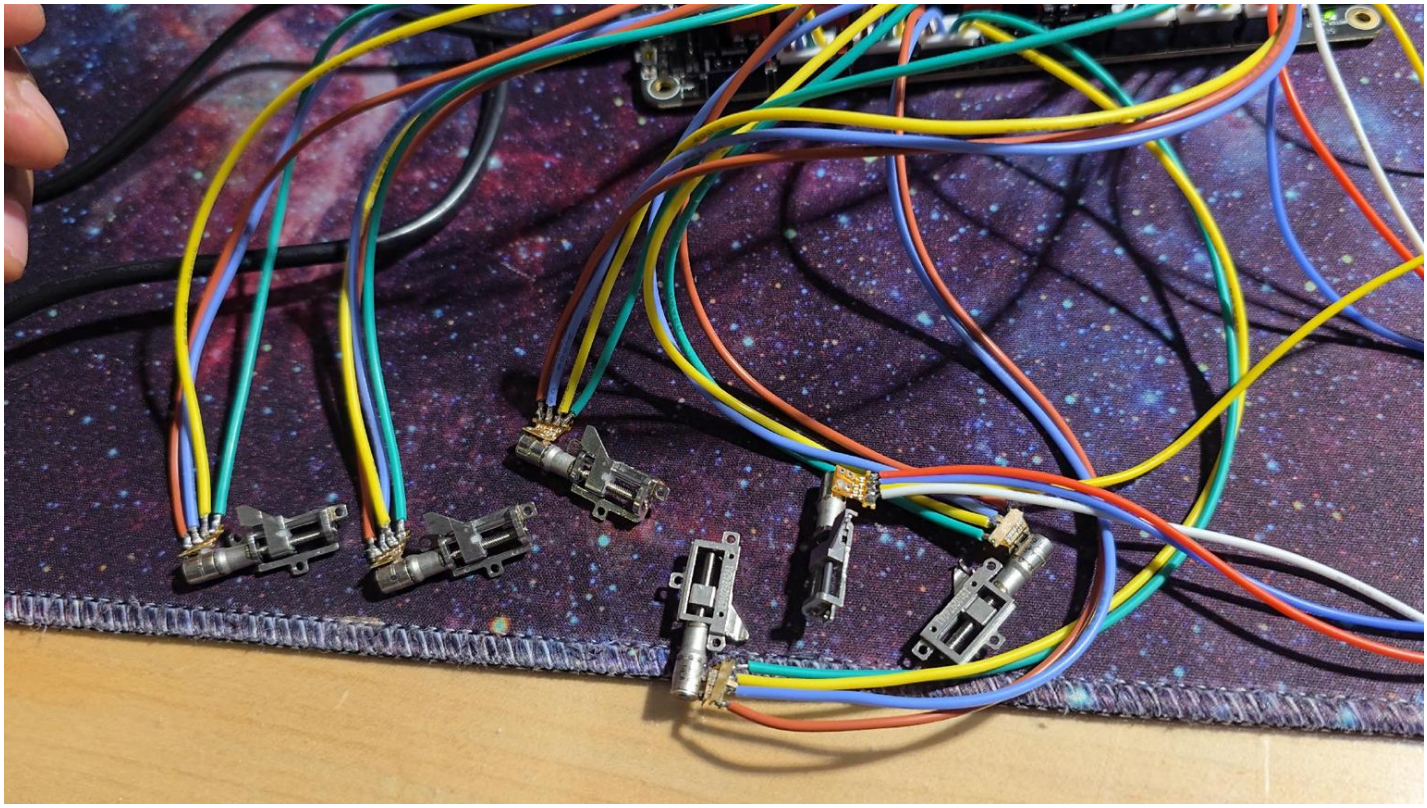
Omer, our school's engineering lab assistant, taught me how to use Klipper



Homing Without Limit Switches

The compact actuators had no built-in end stops.

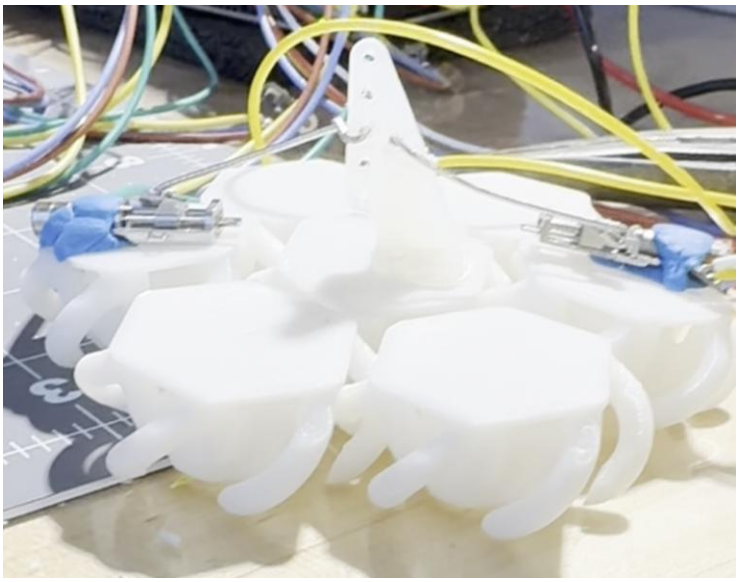


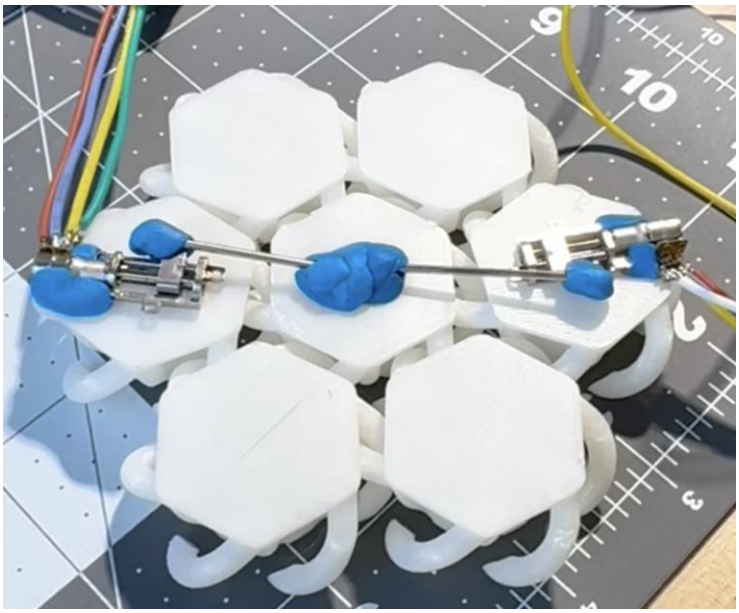


Because these compact linear actuators lacked built-in endstops, I configured stall detection over UART to identify each actuator’s travel limit and establish its home position.

Paper Clips and Putty Prototype

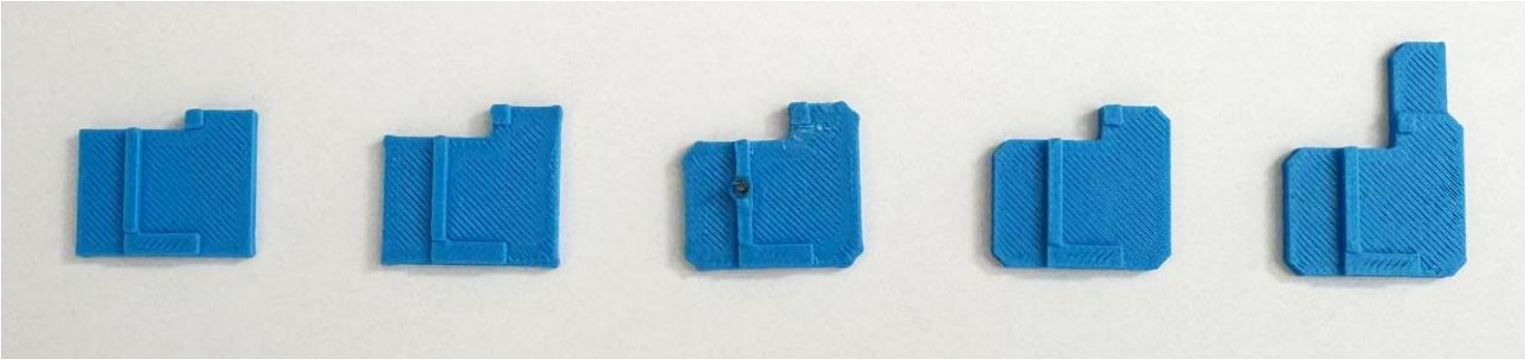


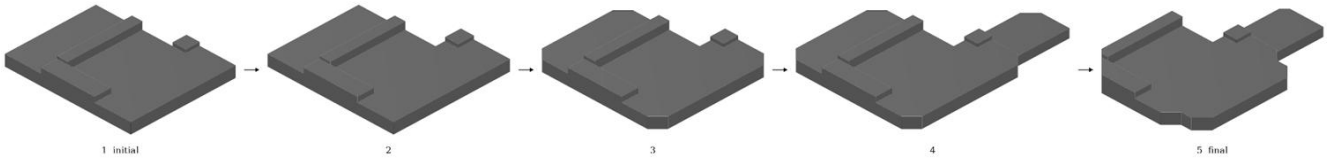




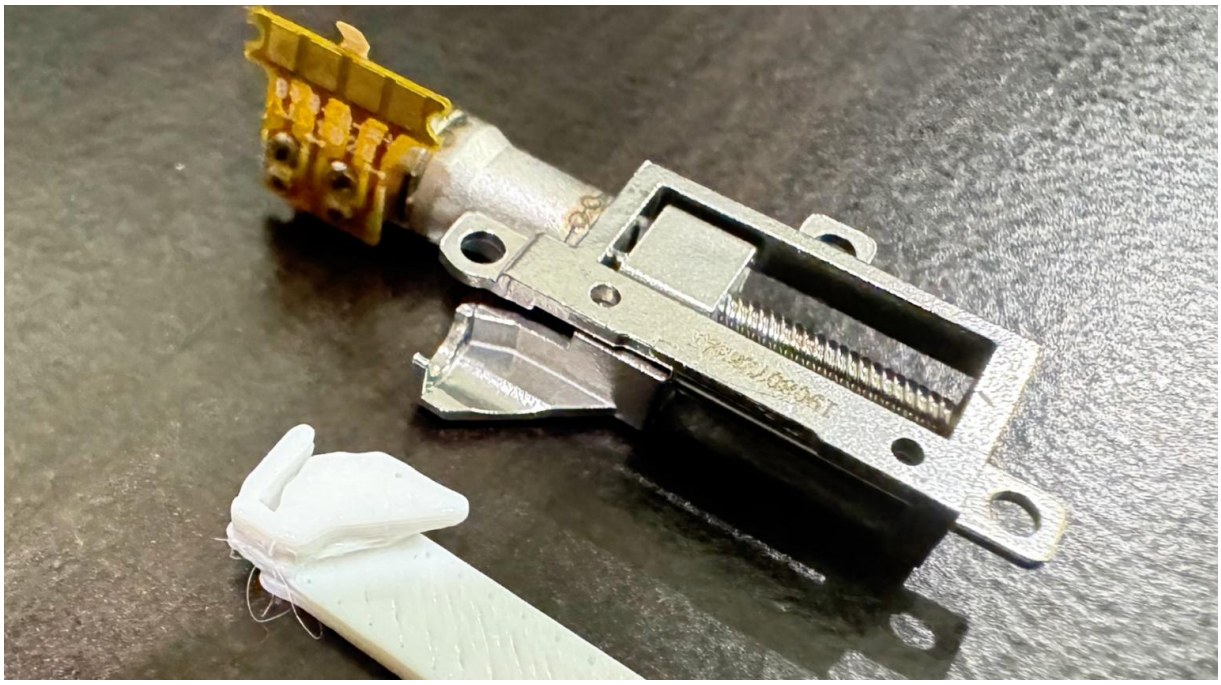
I used paper clips and putty to connect an actuator to the chainmail. These early tests let me observe how linear motion changed the angle between links before designing permanent mounts.

Iterating & Designing the Actuator Mount





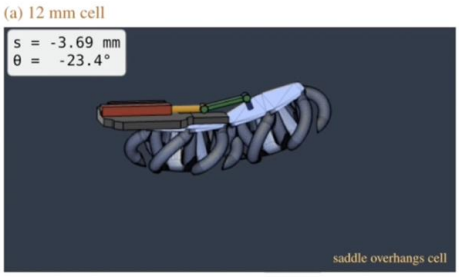
I refined the motor saddle design to optimize adhesion area, the motor pocket, and wire support.



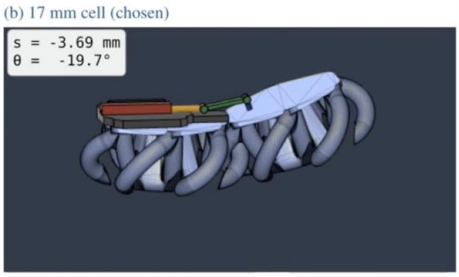
A removable connection

I designed a clip-on link that easily snaps on and off of motors for easy assembly and repair.

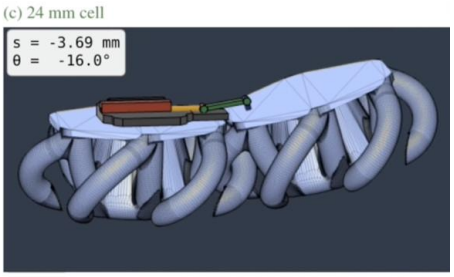
Choosing the Link Size



12 mm

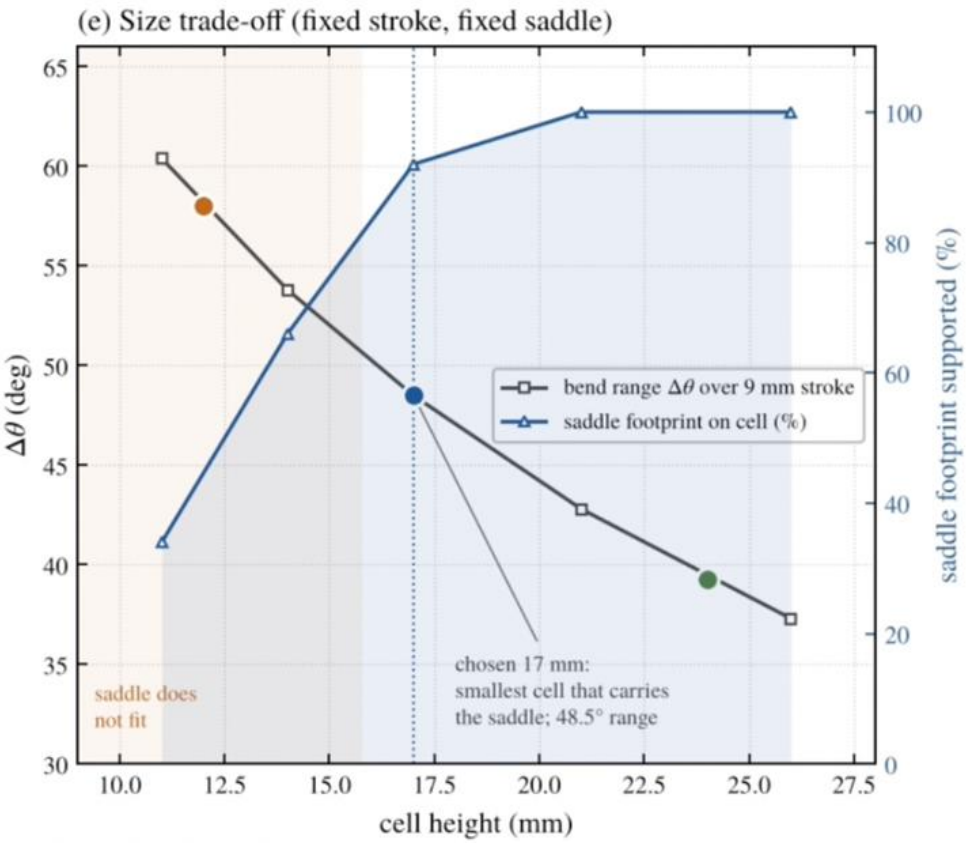


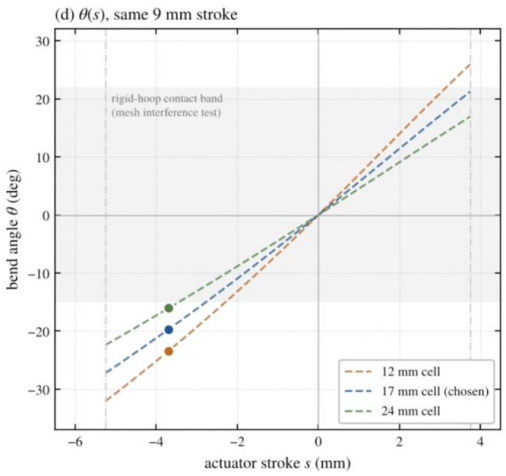
17 mm · selected

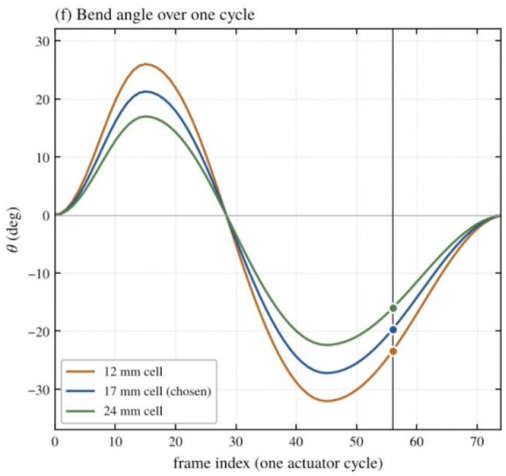


24 mm

Smaller links bend more for the same actuator stroke, but still need enough space for the motor saddle.

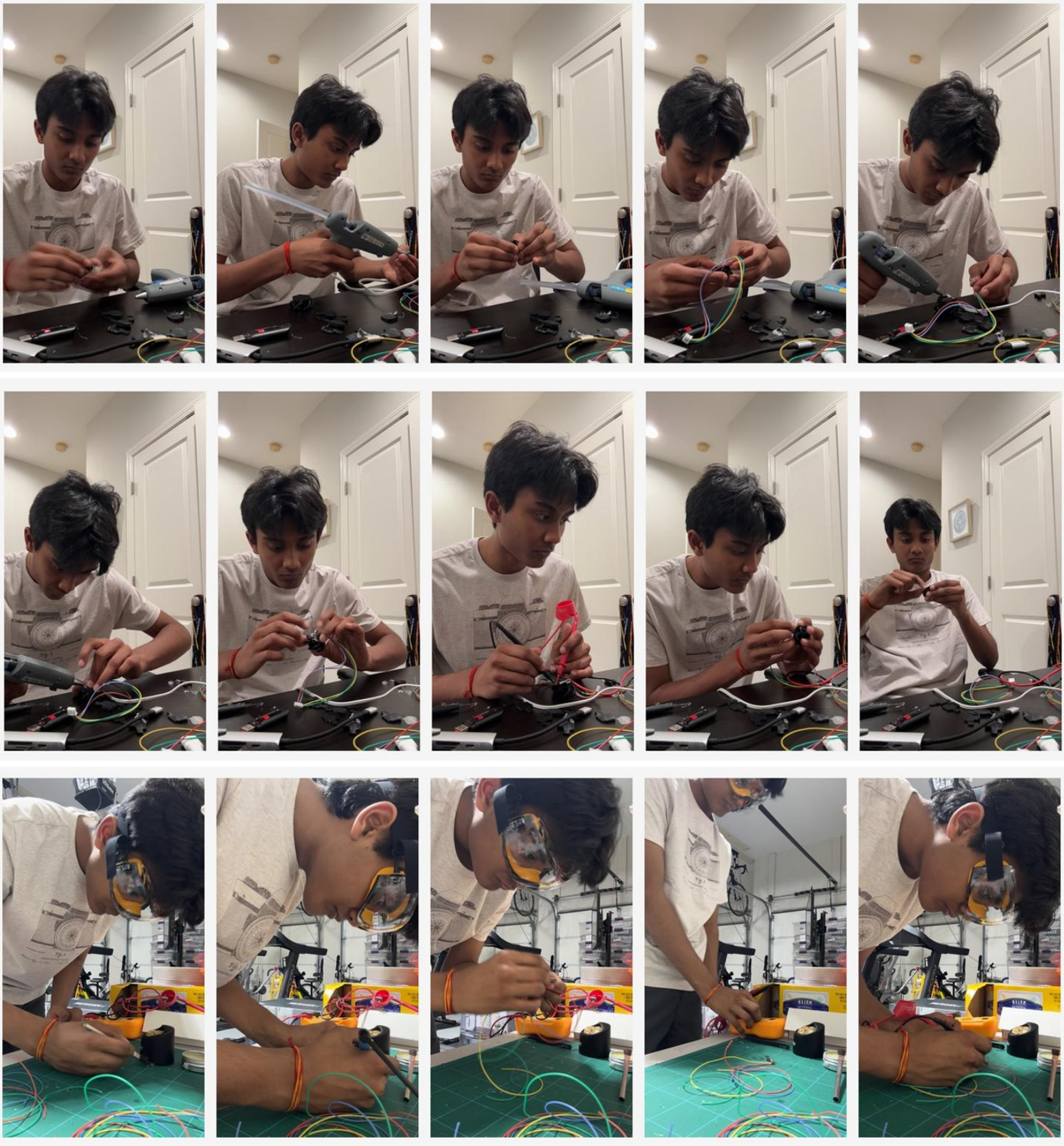






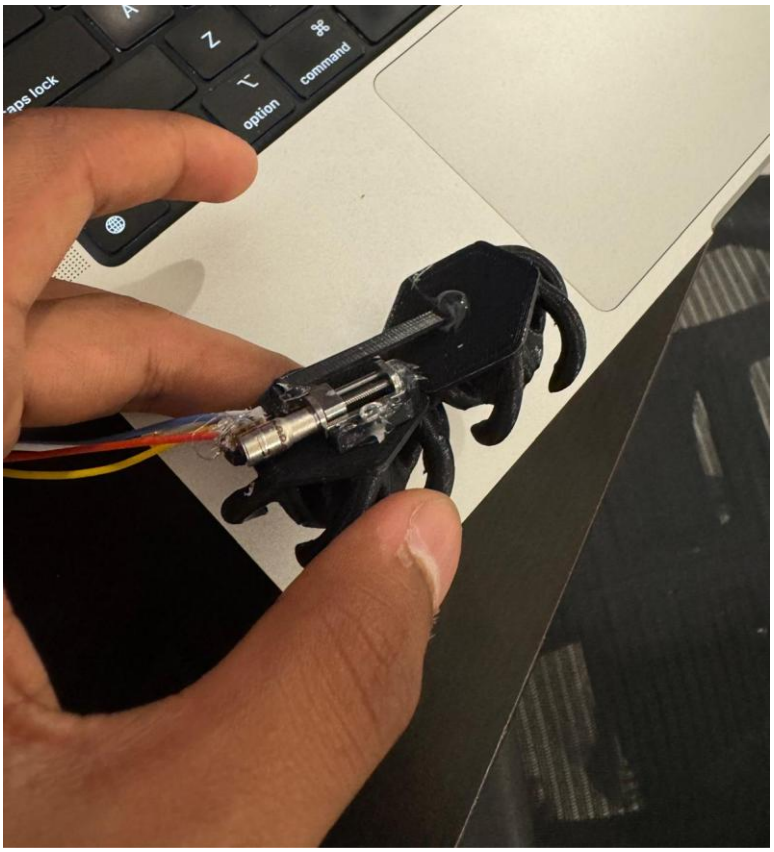
The selected size balances saddle support with bending range.

Assembling the Working Prototype



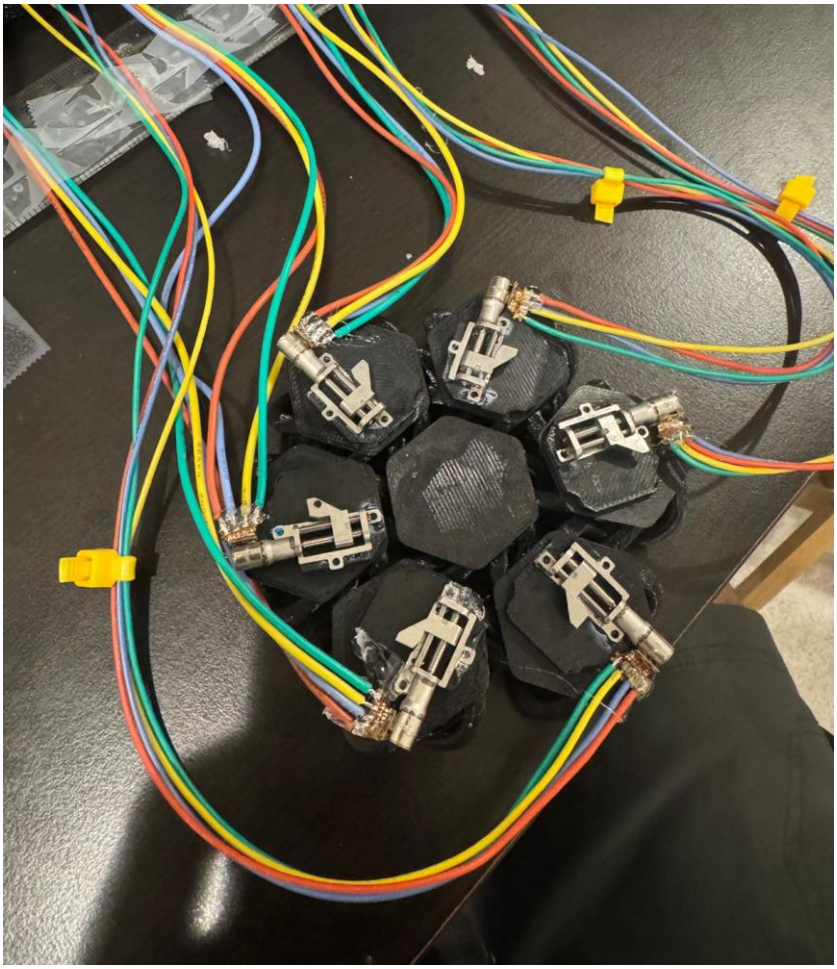
I assembled the printed chainmail links with the actuator mounts, then connected the motors to the control electronics.

How Does One Actuator Bends a Link

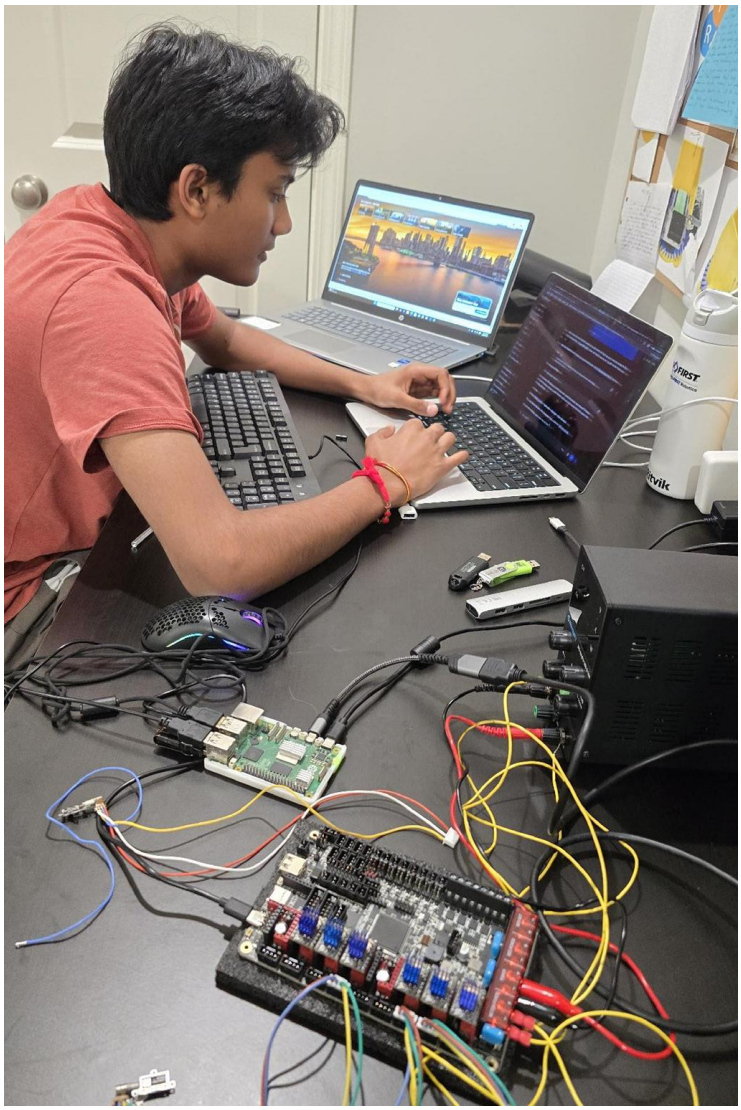


One actuator changes the angle between two neighboring chainmail links.

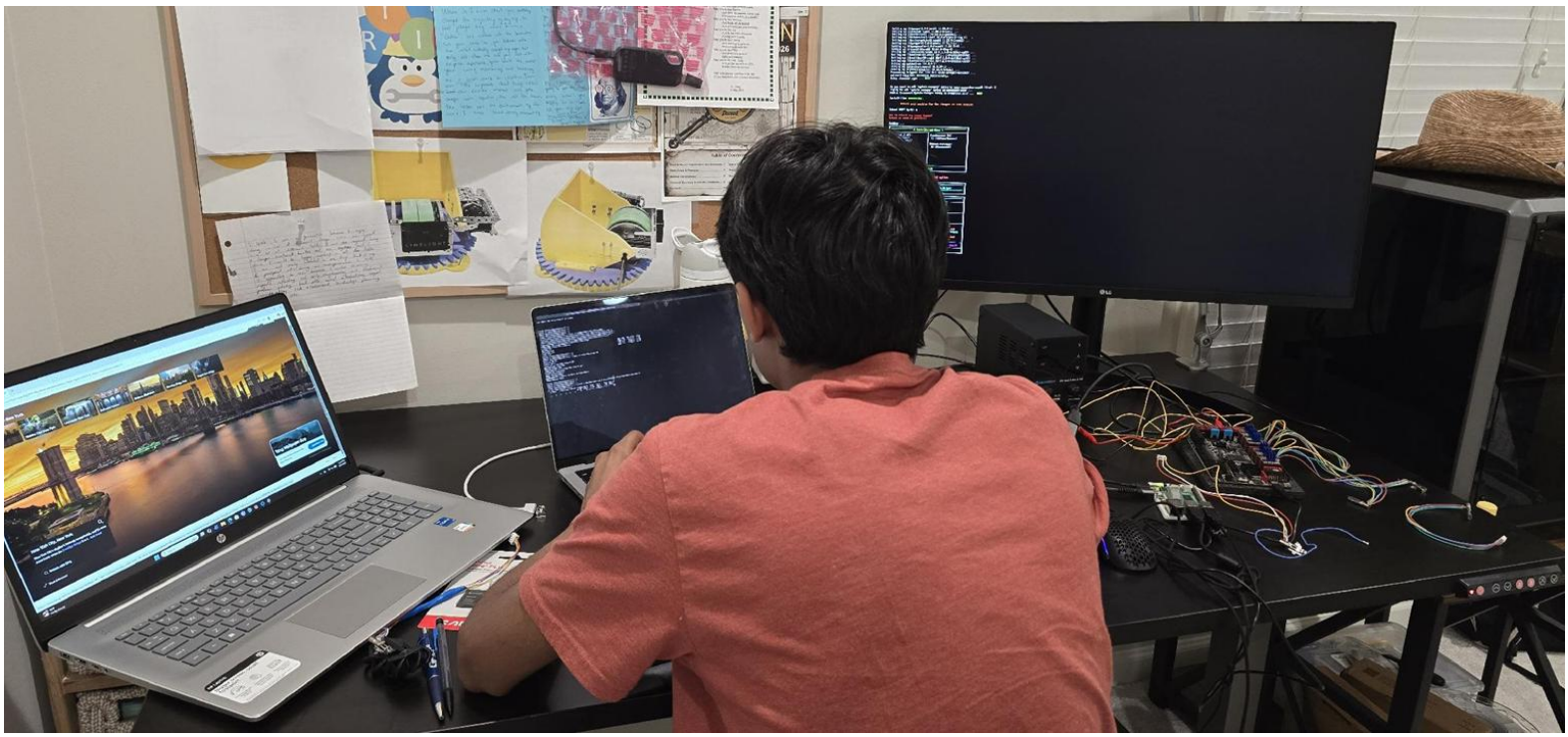
Six actuators around the central link allow for more complex shapes.



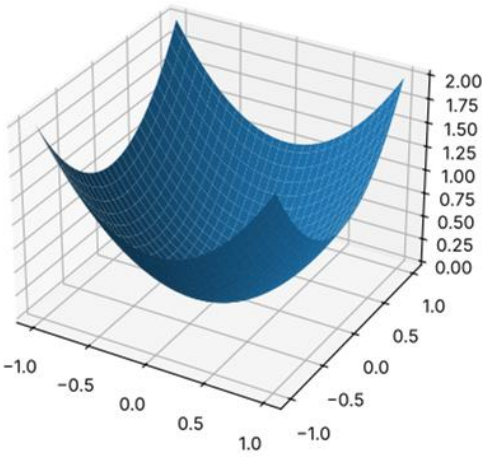
System Configuration

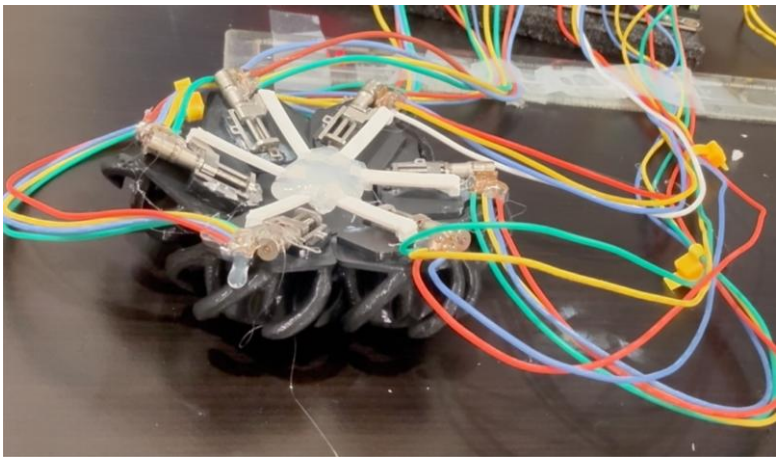


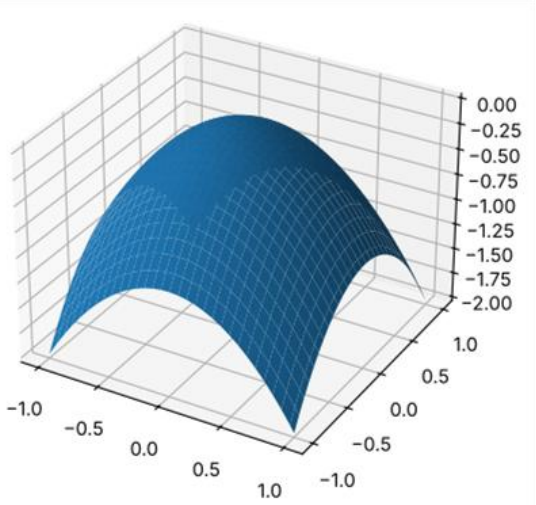
Configured network settings and troubleshot firmware issues

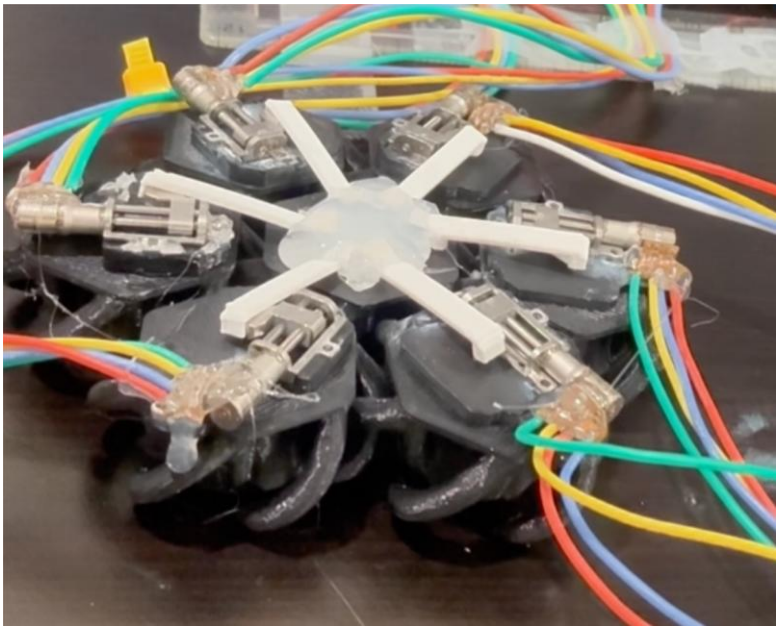


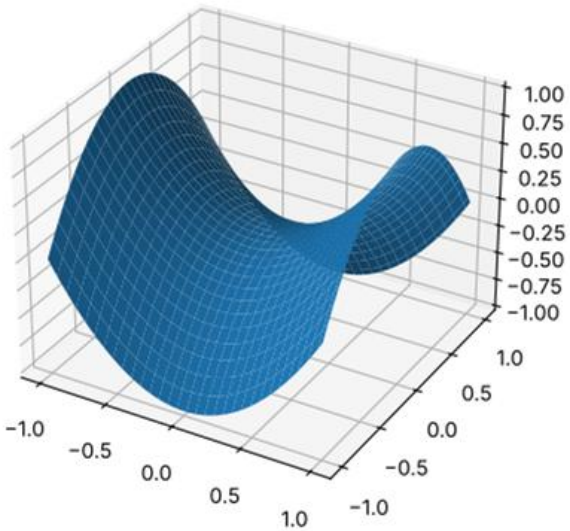
Testing Three Surface Configurations

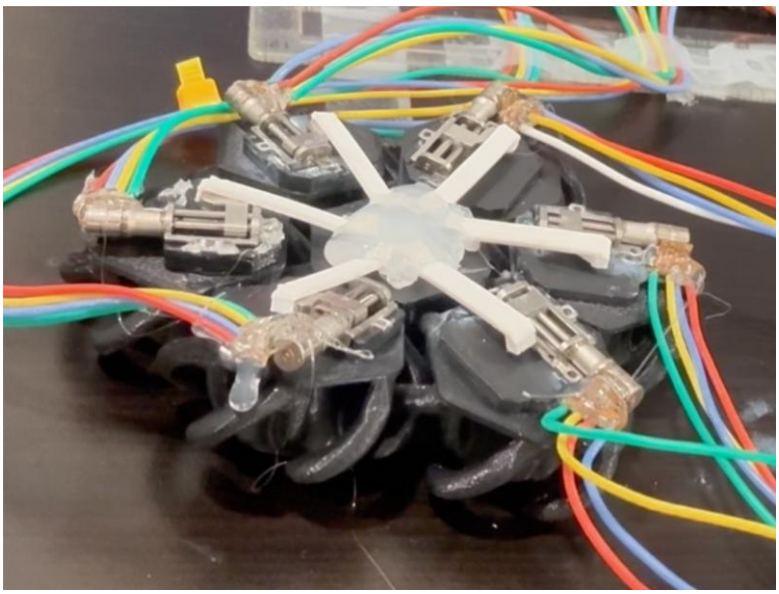






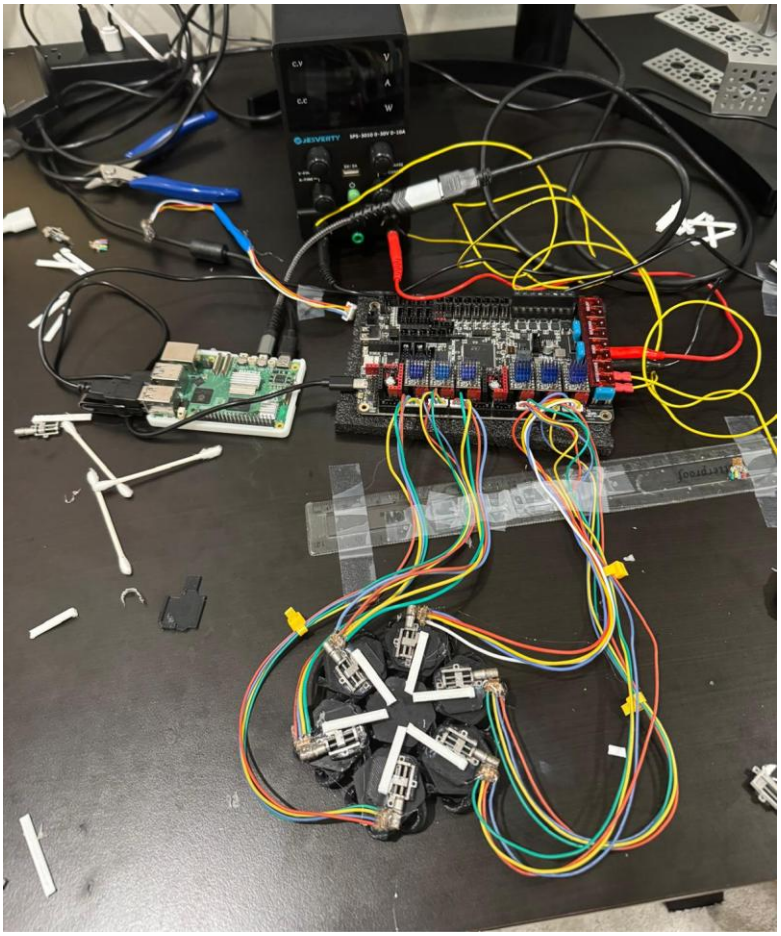


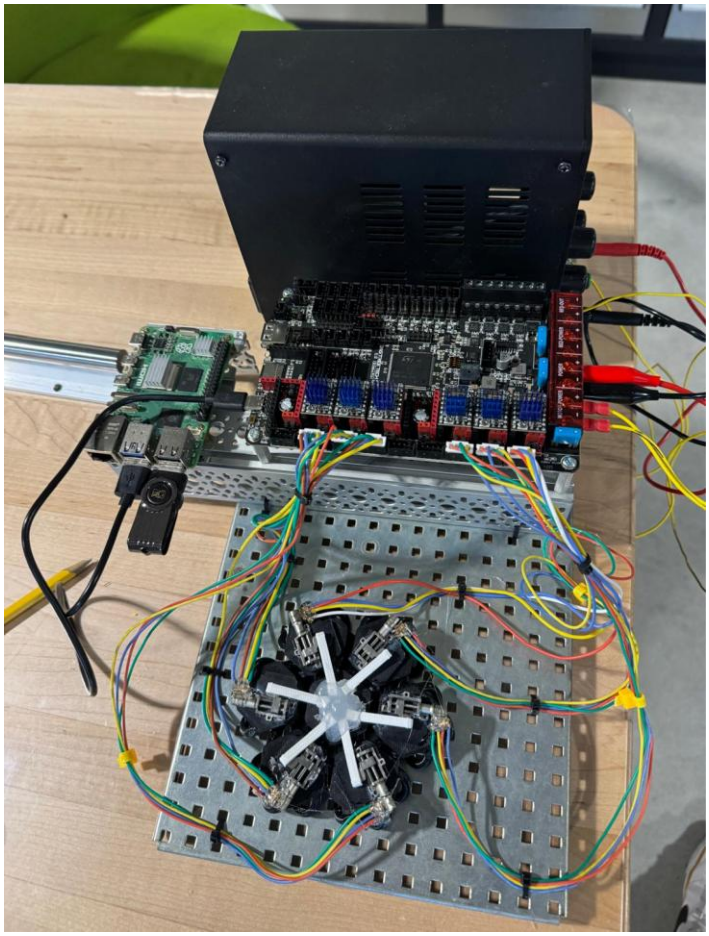


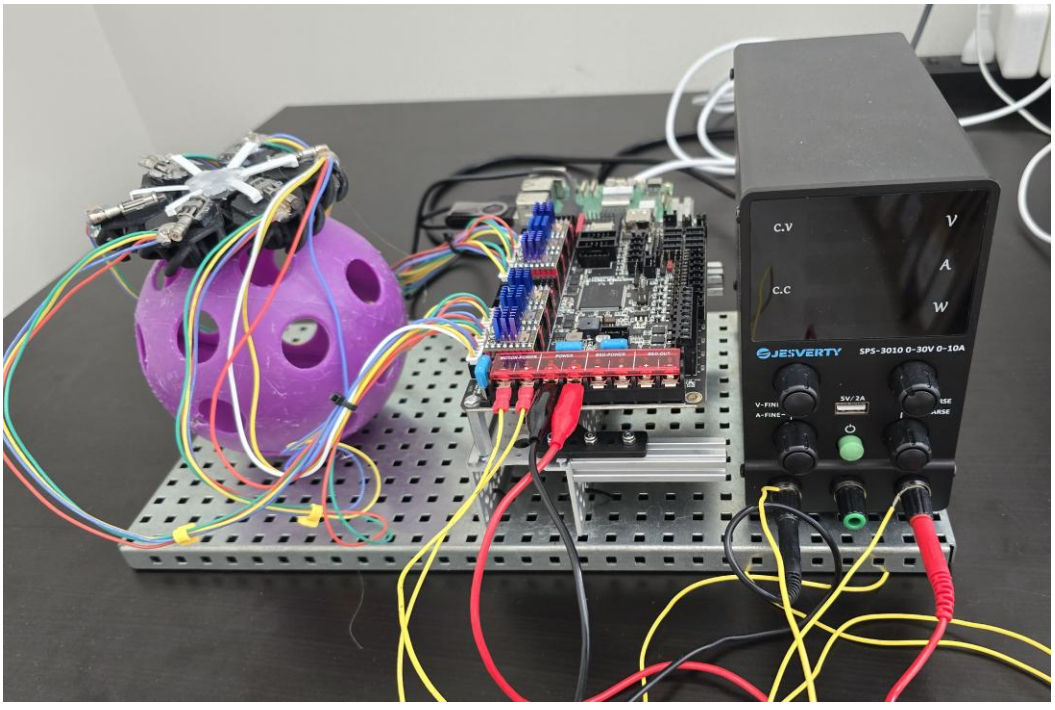


Consolidating the Prototype & Setup

Consolidated the electronics and actuators into a compact, organized assembly for easier transport and maintenance.

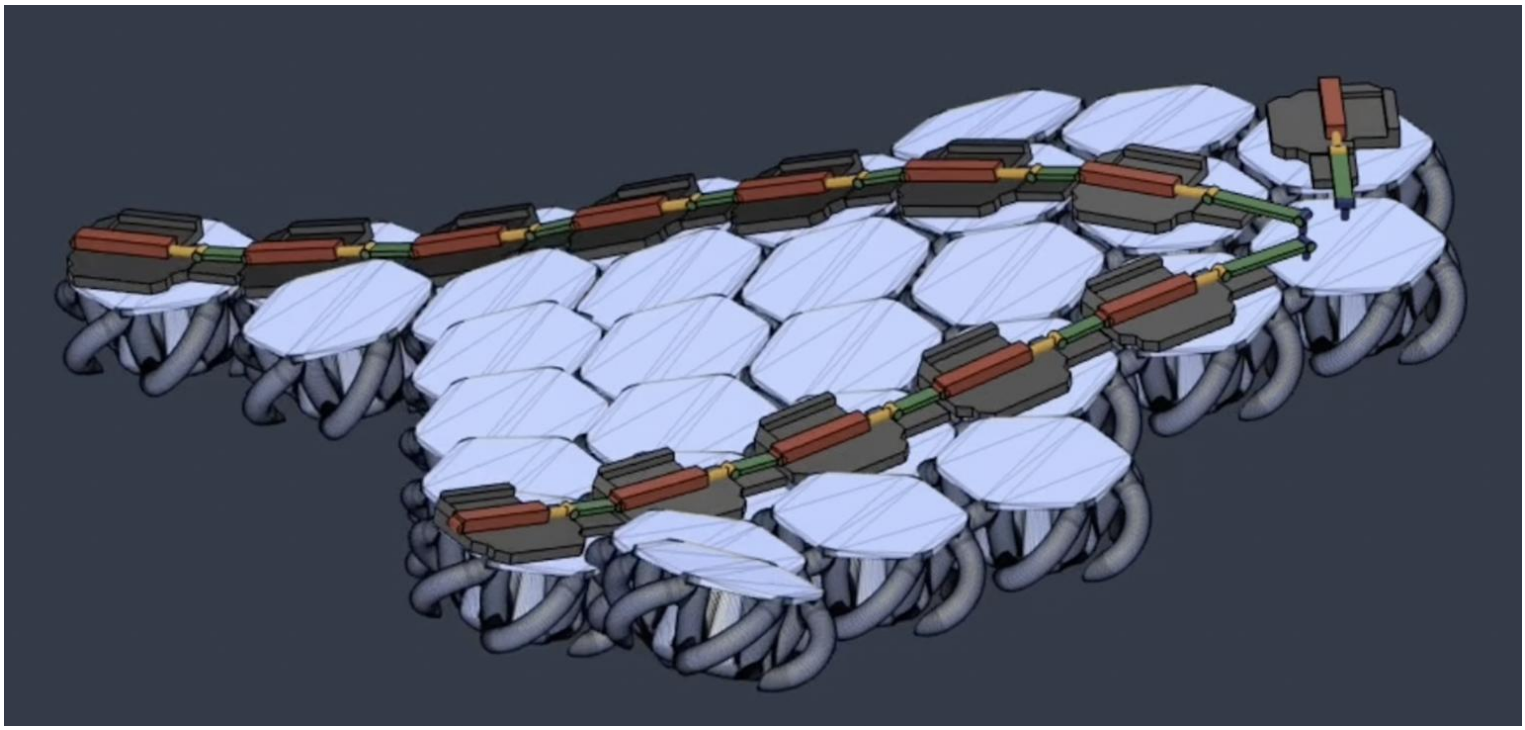






Mounted a ball and tested Formax's ability to conform to its shape.

Work in Progress | What's Next



CAD rendering of an expanded Formax design with additional chainmail links and actuators for more complex 3D surface deformation.

Future Work

I want to explore alternative actuation methods and smaller hexagonal links to achieve smoother, more complex deformations.

Outreach & Impact – 400 Copies Distributed

While teaching robotics to children from underprivileged backgrounds in India, I noticed how their questions reflected a desire to help the people they loved.

Inspired by their curiosity and my own experiences learning from nature, I wrote the illustrated book *Manta Math* to help children discover how nature can inspire engineering.

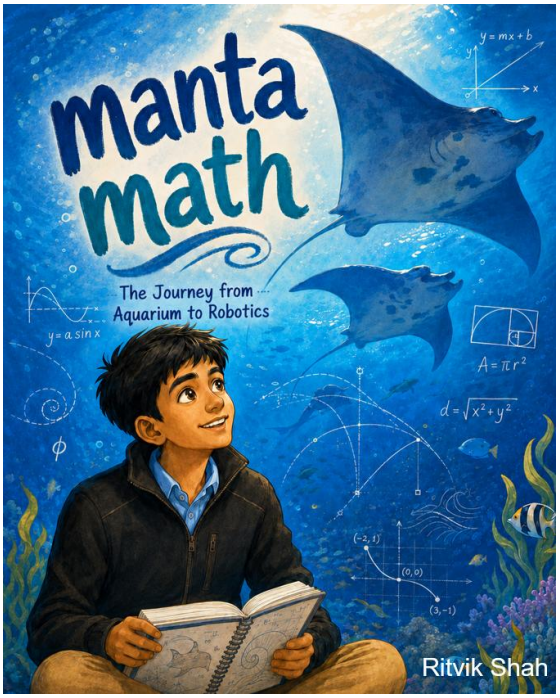














Formax Timeline

Dec 2023

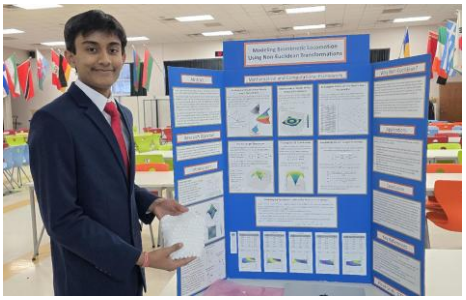
Inspired at the Georgia Aquarium by the motion of a manta ray's fins. My curiosity led me to begin researching whether that motion could be described mathematically and recreated in a robot.





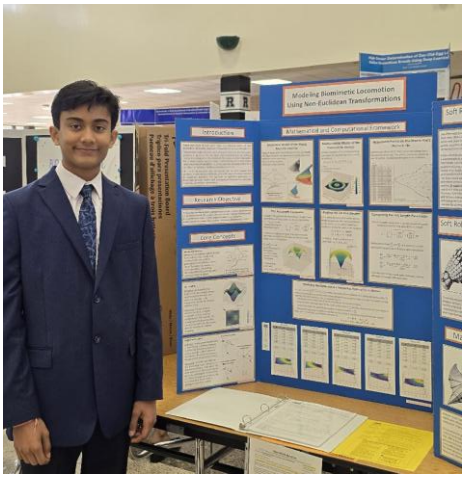
Dec 2024

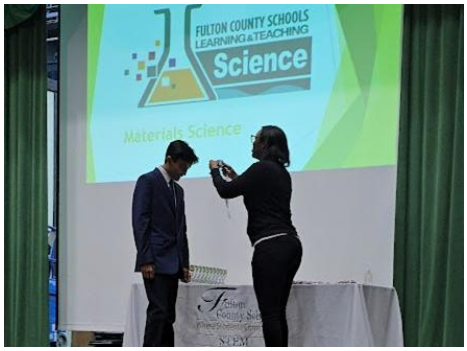
Presented my mathematical framework for mapping deforming 3D surfaces at the school science fair. Won and advanced to the regional level.



Feb 2025

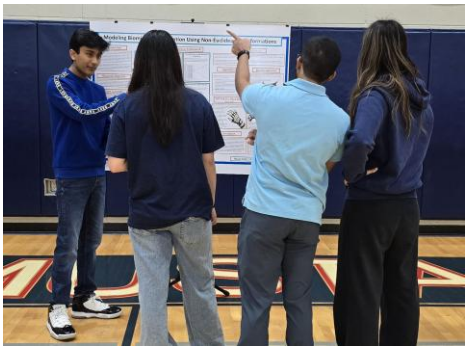
Won First Place in Mathematics at the Fulton County Science and Engineering Fair for my research on surface transformations.





April 2025

Presented my findings at the Spark Symposium, explaining how geometry can model the motion of a manta ray fin.



July 2025

Co-authored a research paper, published in the *Journal of Geometry and Physics* (Vol. 213): "Topological and Numerical Approaches to Surface Transformations."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Topological and numerical approaches to surface transformations

Selcuk Koyuncu ª ✉, Ritvik Shah ᵇ ✉, Cenap Ozel ª ✉ Show more

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Abstract

Transforming a set of points between surfaces in three-dimensional space while preserving certain relative geometric constraints such as arc-lengths and angles from a reference point is a nontrivial task, especially in applications like swarm robotics. Although local differential and numerical methods can approximate these transformations, global properties often obstruct perfectly preserving all desired metrics. In this paper, we introduce a topological and geometric framework for understanding such transformations. We introduce a notion of "distortion" that quantifies how closely a transformation preserves prescribed arc-lengths and angular relationships originating from a point and show that if two surfaces differ topologically, there is a positive lower bound on the minimal distortion achievable by any continuous transformation. In the last section, we explore two numerical approaches and include several numerical examples.

July 2026

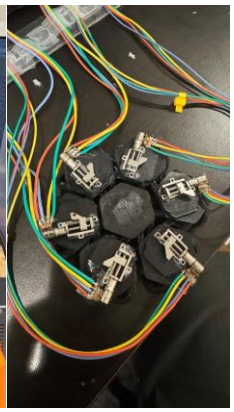
Presented Formax at the NCSS Student Conference, sharing how published mathematics became the foundation for a shape-shifting robot.



July - Sep 2026

Built the first working Formax prototype: a hexagonal chainmail lattice driven by six linear actuators and a Raspberry Pi running Klipper, able to reshape itself on command.





Oct 2026

Wrote and published *Manta Math*, a children's storybook tracing the journey from aquarium to robotics, with 400 copies distributed.

