KISS Short Course

One Shot to Glory: Designing Adaptive Missions to the Outer Solar System and Beyond

Adaptive Robotics Technologies – Hardware

Caltech
11/03/25

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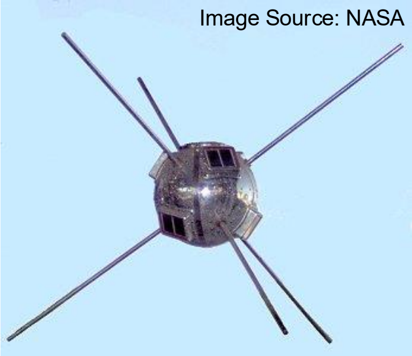
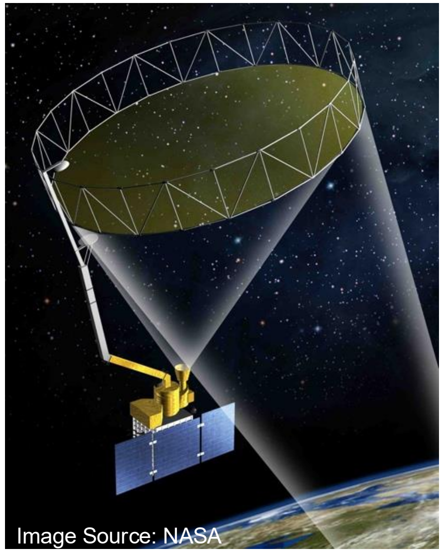
Stanford | Reconfigurable & Active Structures Lab

Adapting Shape in Dynamic Environments

Deployable structures

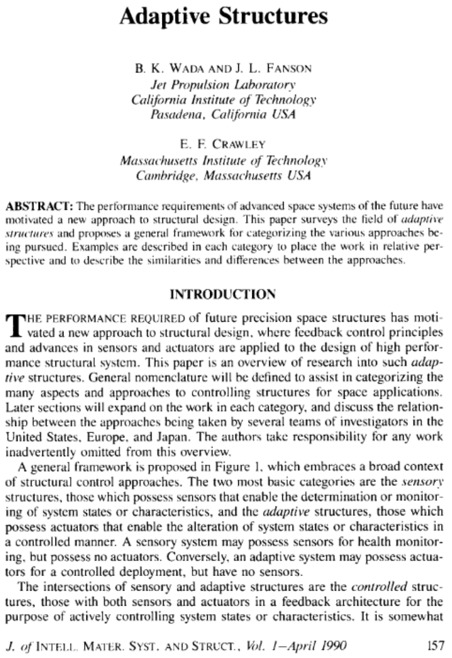


Vanguard 1 (1958)



SMAP (2015)

Adaptive structures



Adaptive Structures

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Cambridge, Massachusetts USA

ABSTRACT: The performance requirements of advanced space systems of the future have motivated a new approach to structural design. This paper surveys the field of *adaptive structures* and proposes a general framework for categorizing the various approaches being pursued. Examples are described in each category to place the work in relative perspective and to describe the similarities and differences between the approaches.

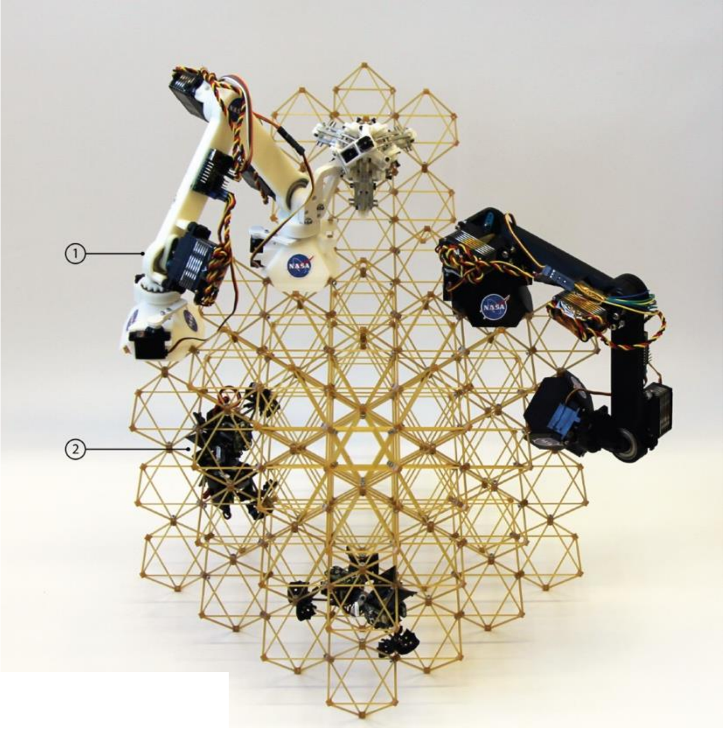
INTRODUCTION

The performance required of future precision space structures has motivated a new approach to structural design, where feedback control principles and advances in sensors and actuators are applied to the design of high performance structural system. This paper is an overview of research into such *adaptive* structures. General nomenclature will be defined to assist in categorizing the many aspects and approaches to controlling structures for space applications. Later sections will expand on the work in each category, and discuss the relationship between the approaches being taken by several teams of investigators in the United States, Europe, and Japan. The authors take responsibility for any work inadvertently omitted from this overview.

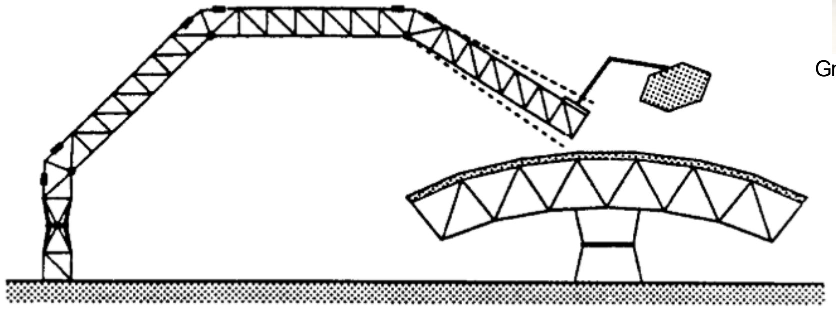
A general framework is proposed in Figure 1, which embraces a broad context of structural control approaches. The two most basic categories are the *sensory* structures, those which possess sensors that enable the determination or monitoring of system states or characteristics, and the *adaptive* structures, those which possess actuators that enable the alteration of system states or characteristics in a controlled manner. A sensory system may possess sensors for health monitoring, but possess no actuators. Conversely, an adaptive system may possess actuators for a controlled deployment, but have no sensors.

The intersections of sensory and adaptive structures are the *controlled* structures, those with both sensors and actuators in a feedback architecture for the purpose of actively controlling system states or characteristics. It is somewhat

J. of Intell. Mater. Syst. and Struct., Vol. 1—April 1990 157



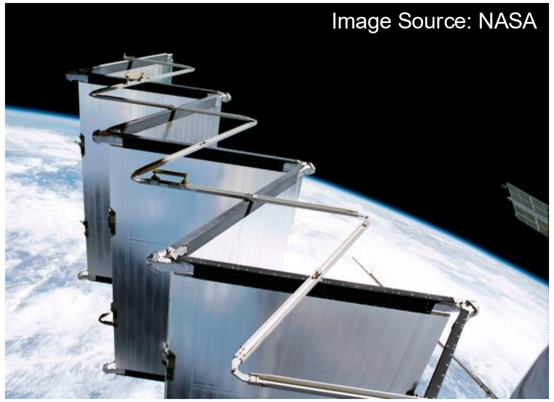
Gregg et al., Science Robotics 9(86), eadi2746, 2024

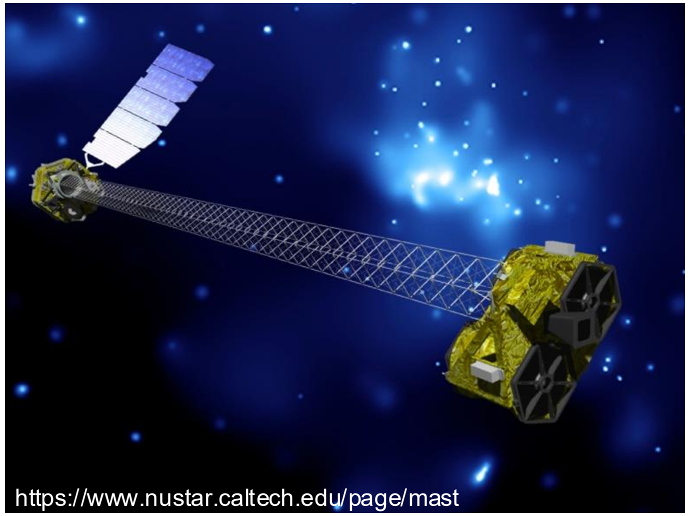


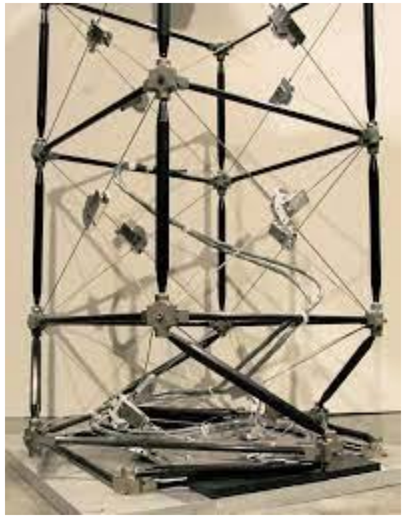
Wada et al., Journal of Intelligent Materials Systems and Structures 1, 1990

Shape adaptation technologies

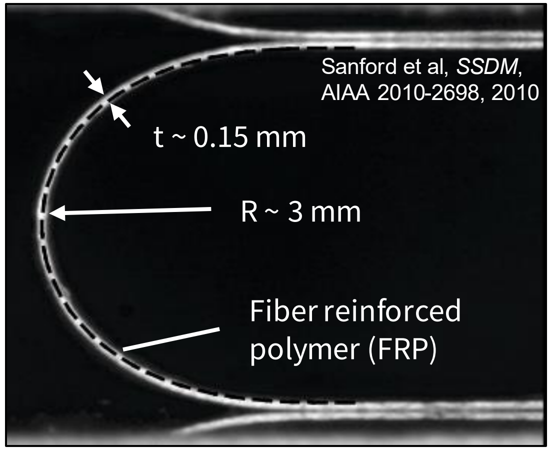
Articulated structures



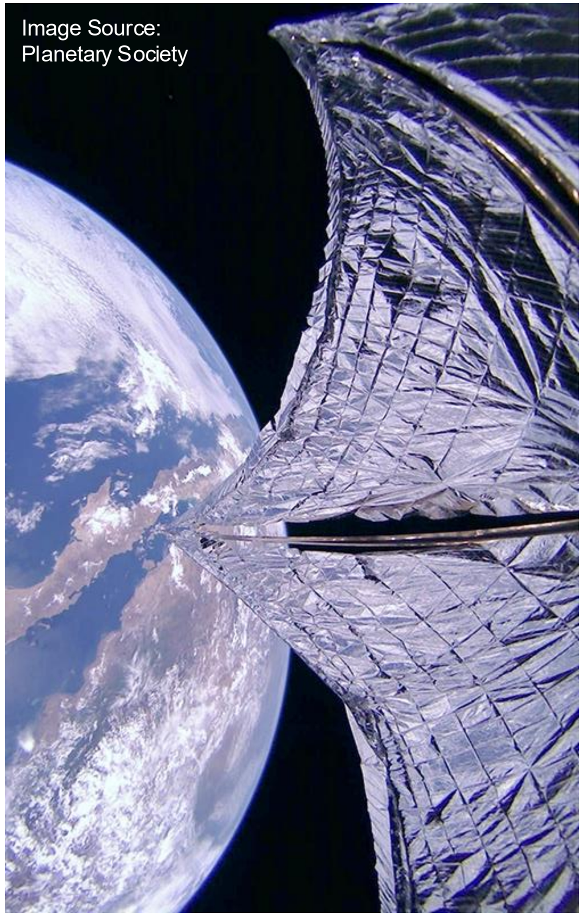




High strain composites



Tensioned-membranes



High precision
High stiffness

Low mass
Efficient stowage

Smart Material Actuators

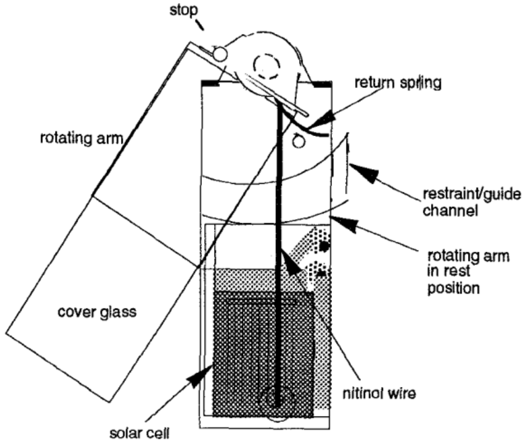
Shape memory alloys (SMAs)

https://www.youtube.com/watch?v=QZVv-OTibc4

Hold Down and Release Mechanisms

https://ebad.com/products/tini-frangibolt/

Mars Pathfinder: Materials Adherence Experiment

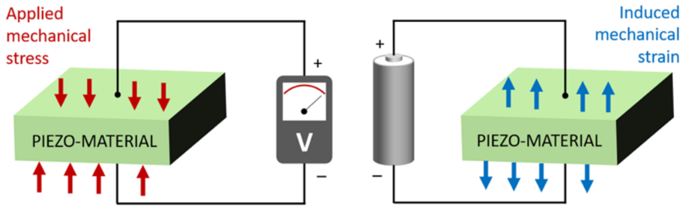


Landis and Jacobs, IEEE Photovoltaic Specialists Conference, 1997.

SMA wheels

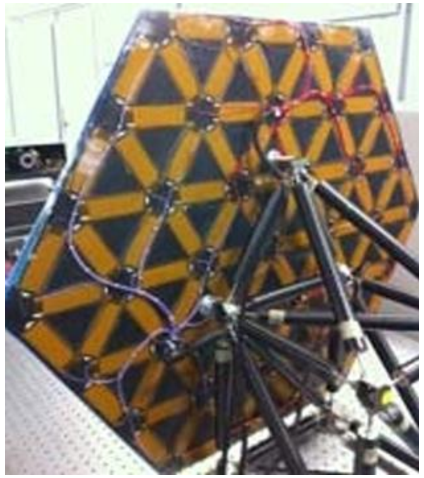
https://www.nasa.gov/centers-and-facilities/glenn/nasa-sets-sights-on-mars-terrain-with-revolutionary-tire-tech/

Piezoelectric materials



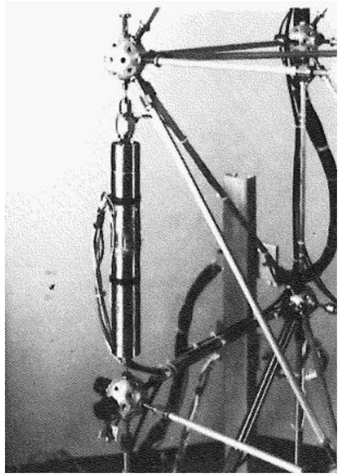
https://www.sintef.no/en/expert-list/sintef-industry/materials-and-nanotechnology/piezoelectric-materials-for-sensors-actuators-and-ultrasound-transducers/

Active figure correction in mirrors



Bradford et al., 54th SSDM Conference, AIAA 2013-1525, 2013.

Vibration control in truss structures



Fanson et al., 30th SSDM Conference, 1989.

Applications: Robotic Arms

Motor driven rigid links

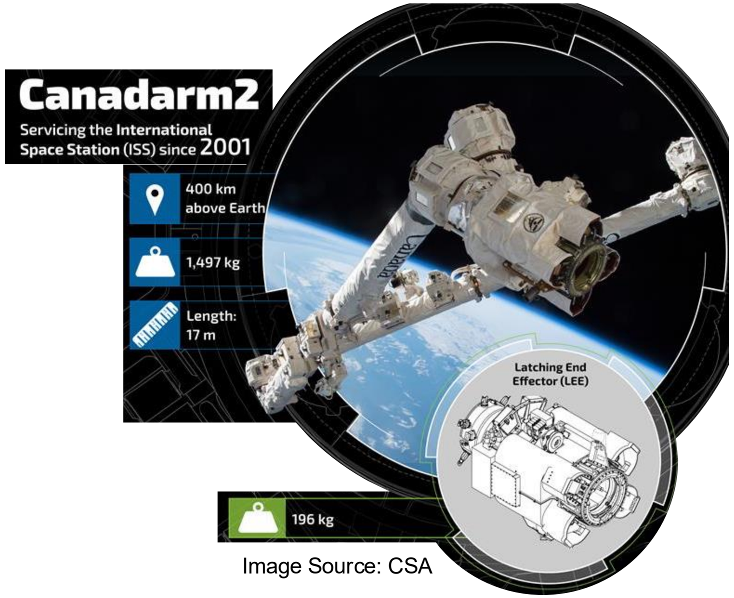


Image Source: CSA

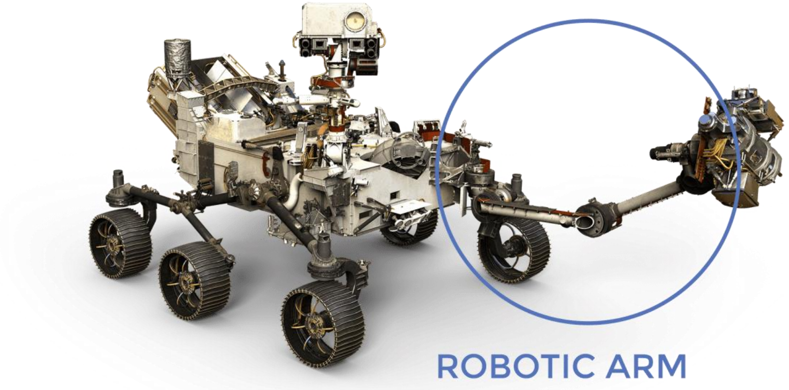
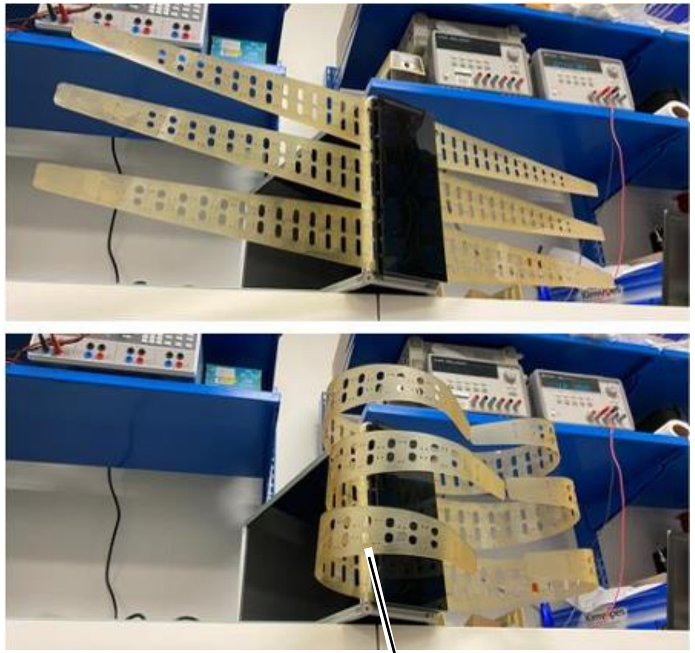


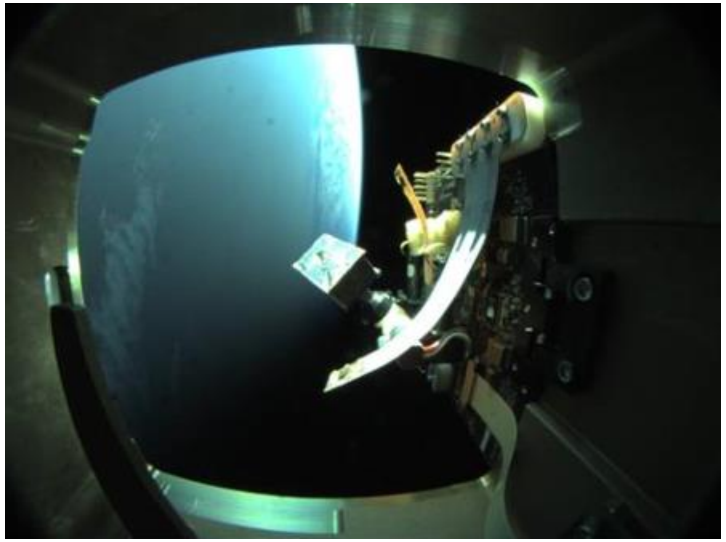
Image Source: NASA

Flexible robotic arms



Polymer membrane with SMA lacing

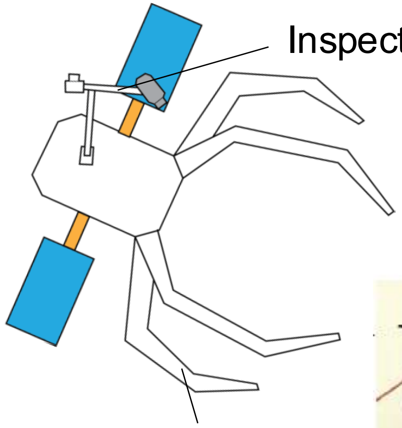
On orbit test of technology in 2023



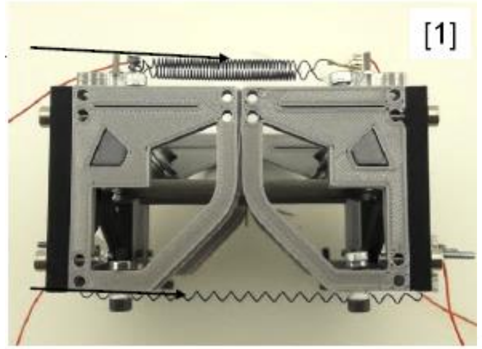
Fuller and Sheerin, 38th Small Satellite Conference, 2024.

Functionalities enabled by shape change:
- Reach and manipulation
- Debris capture
- On-orbit servicing

Robotic Arm for Spacecraft Inspection



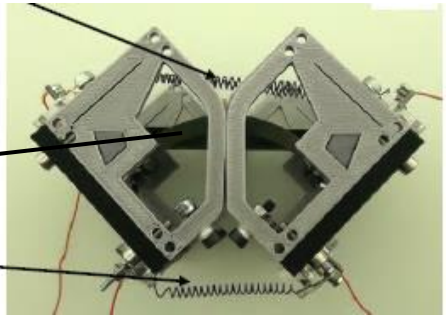
Stable State 1



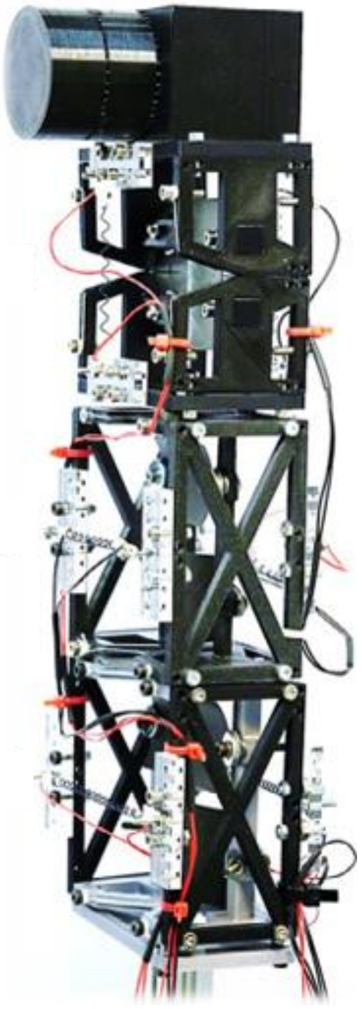
Actuator SMA

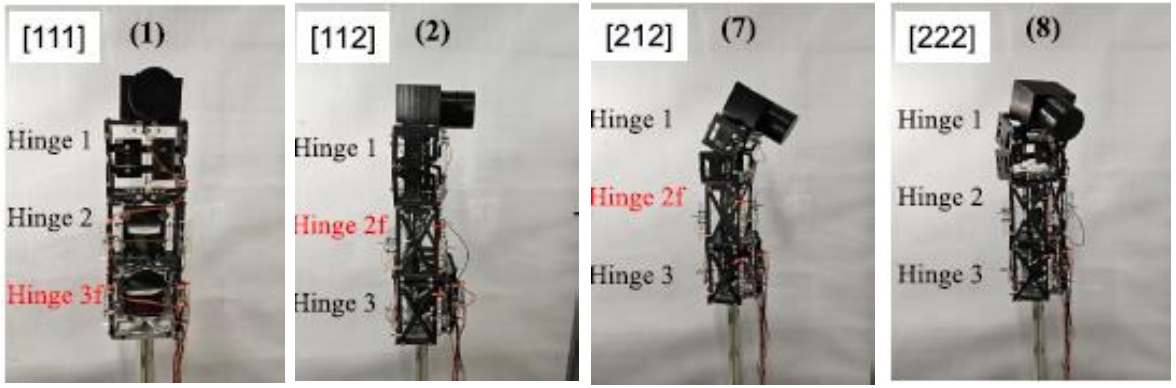
Stable State 2

Bistable composite tape springs



Antagonist SMA





Metric	Hinge 1	Hinge 2	Hinge 3
Actuation Angle [deg]	40	75	114
Fundamental frequency [Hz]	77.7	38.4	25.5
Energy Barrier [mJ]	32	168	260

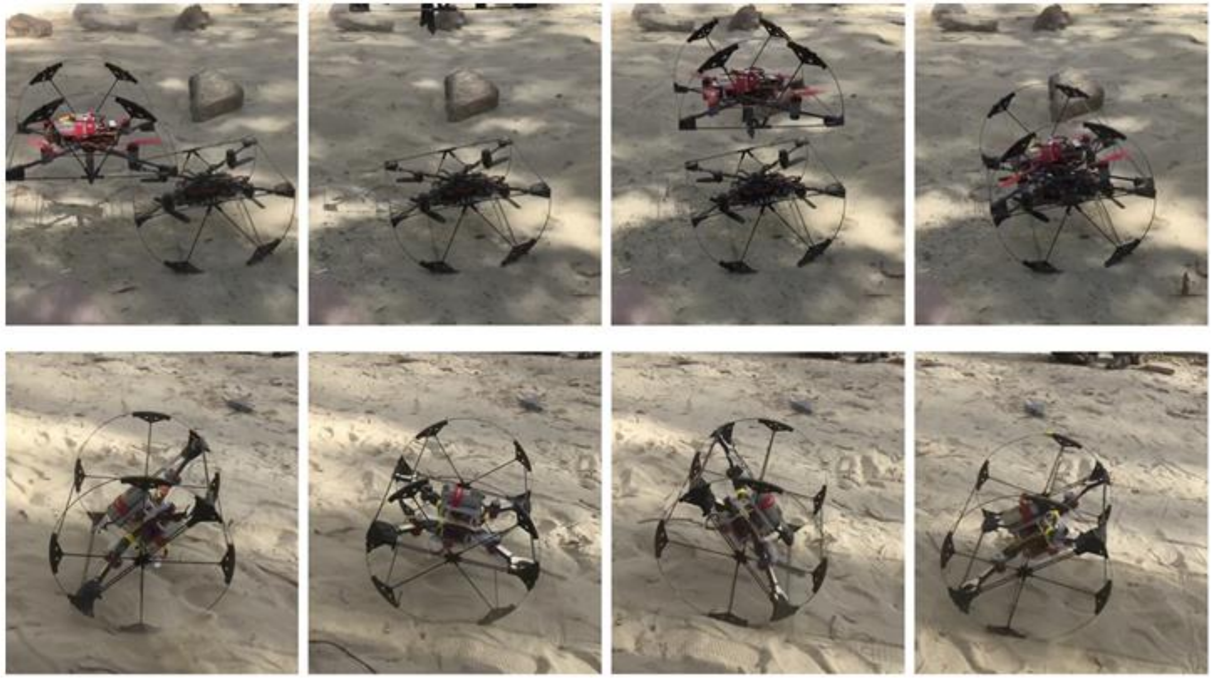
Vogel et al. Materials & Design 244, 113154, 2024

Applications: Multi-modal Robotic Locomotion

Exobiology Extant Life Surveyor (EELS)

https://www.jpl.nasa.gov/robotics-at-jpl/eels/

Shapeshifter Concept



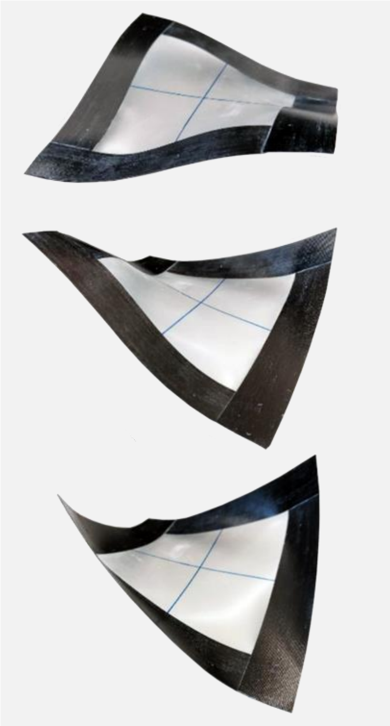
Agha-Mohammadi et al., NIAC Phase I Final Report, 2019.

Inflatable shape changing trusses

Usevitch et al. *Science Robotics 5*, eaaz0492, 2020.

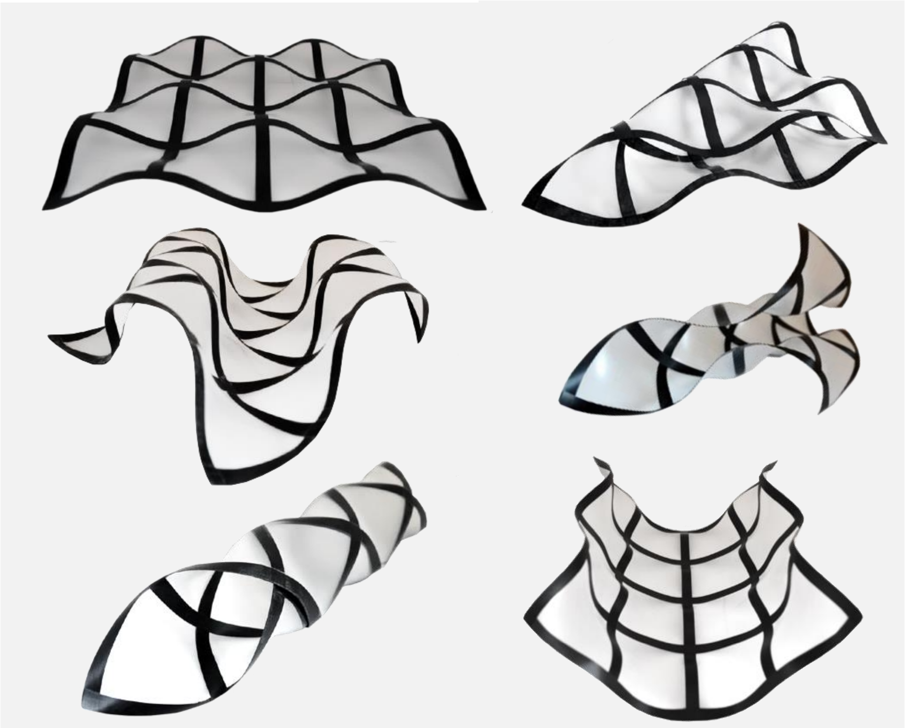
Multi-stable Metamaterials for Robotic Locomotion

Unit cell

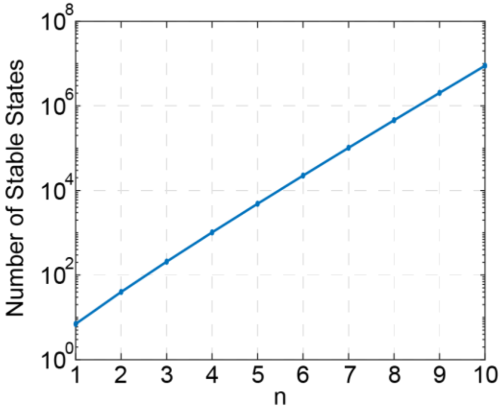


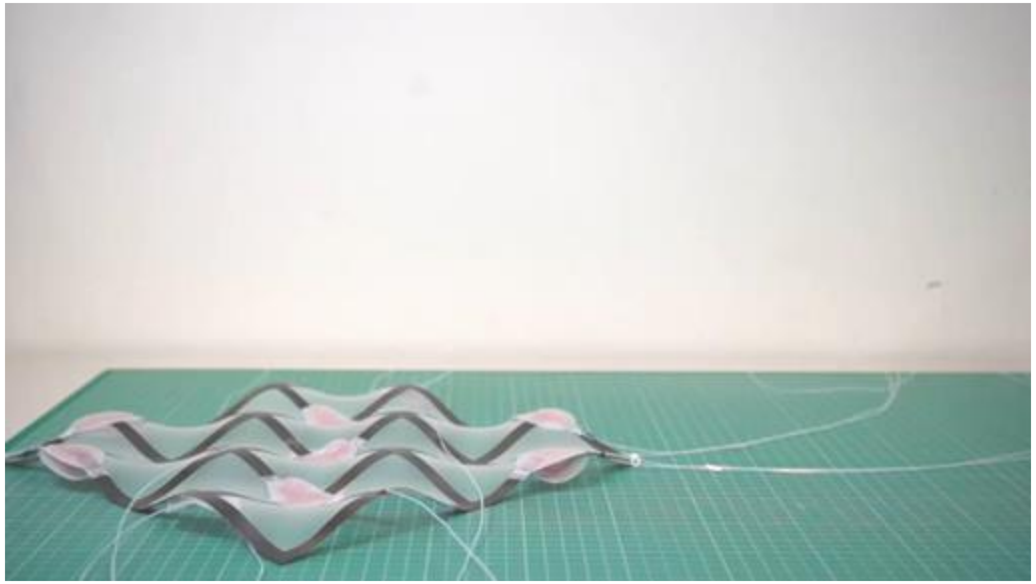
Periodic extensions

Many more stable states



Number of stable states for $n \times n$ surface:





Risso et al., Advanced Science 9(26), 2022

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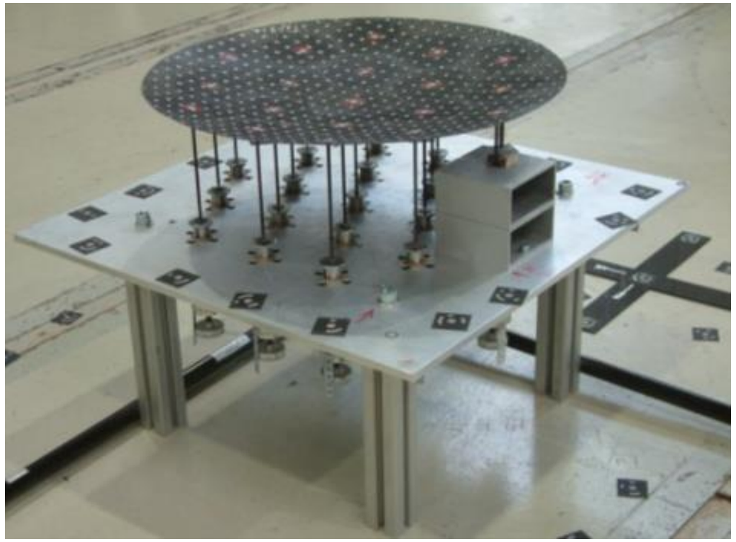
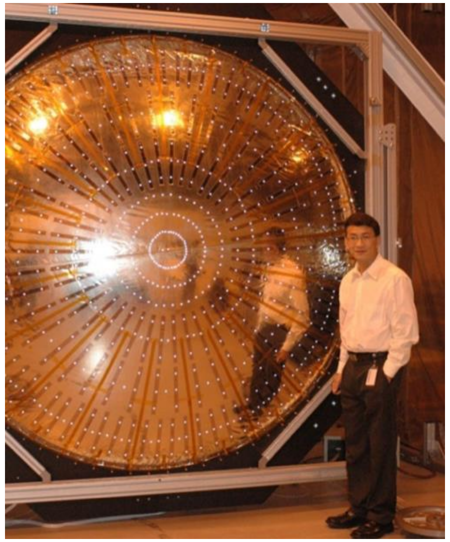
ETH zürich

Applications: Morphing Antennas

Precise surface control using actuator arrays





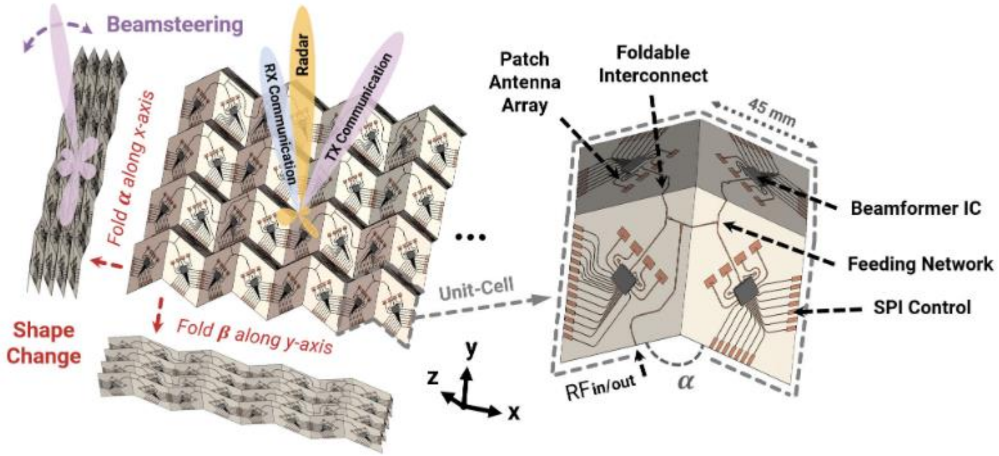
Datashvili et al., ESA antenna workshop, 2010.

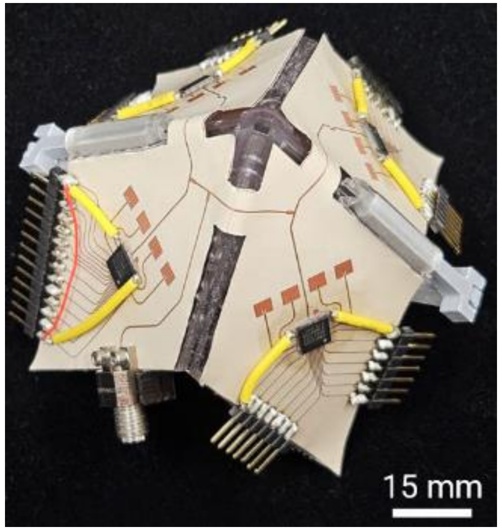
Fang et al., 12th AIAA Gossamer Systems Forum, 2011.

Functionalities enabled by shape change:

- Mass reduction using less precise active structures
- Correction for environmental disturbances
- Adaptive ground coverage
- Adaptive RF performance (e.g., operating frequency, polarization, radiation pattern)

Large shape reconfiguration



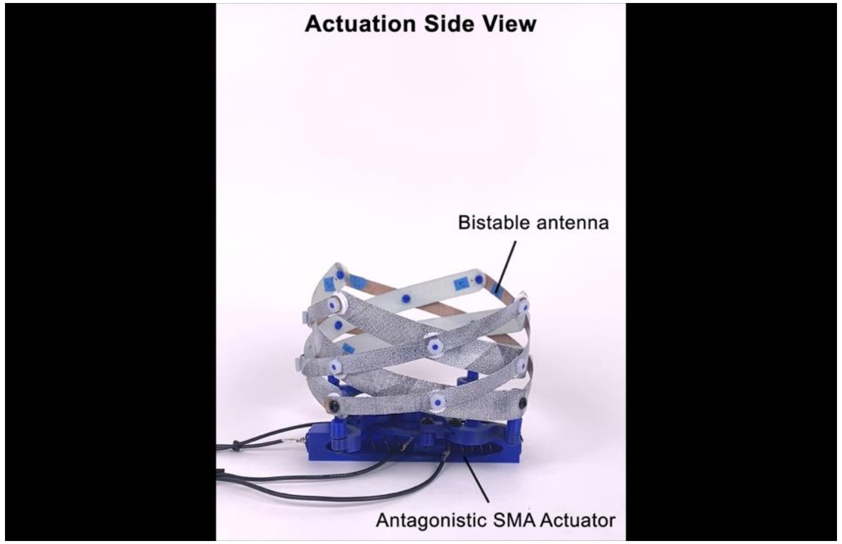


Al Jamal et al., IEEE Transactions on Microwave Theory and Techniques 73(1), 2025

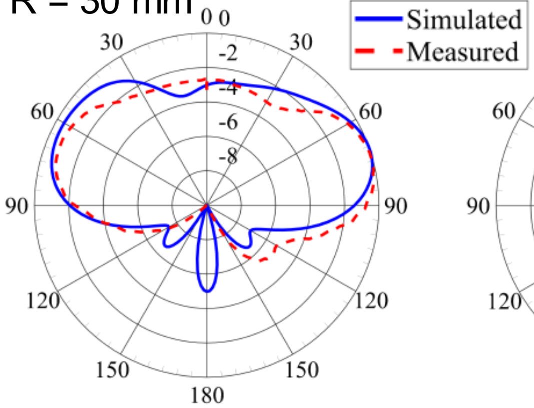
Electronic only:
±41 deg steering

Mechanical + electronic:
full 360 deg steering
polarization reconfiguration

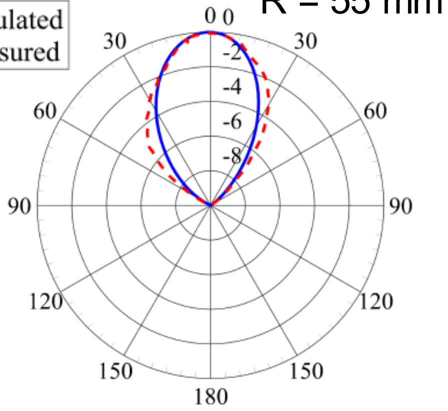
Compliant Mechanisms for Morphing Antennas



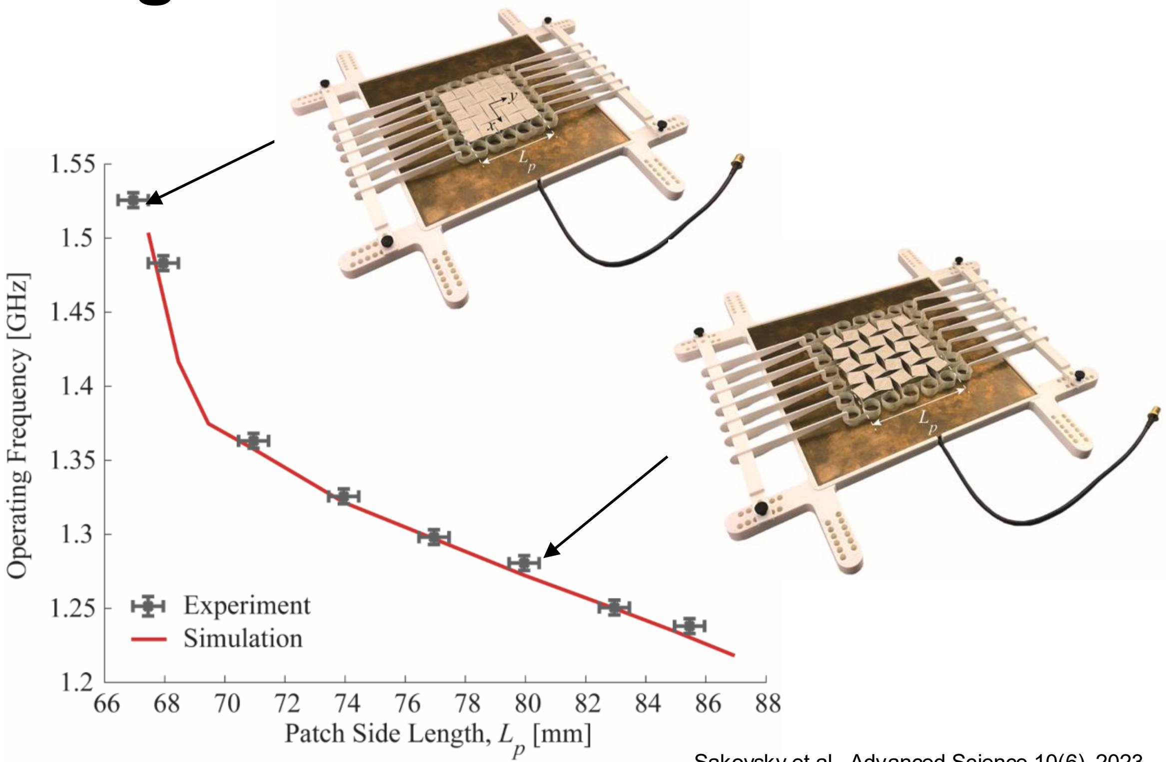
R = 30 mm



R = 55 mm



Bichara et al. Nature Communications 14(1), 8511, 2023.
Schmidt and Sakovsky, *AIAA Journal*, 2025.



Sakovsky et al., Advanced Science 10(6), 2023

Metric	Value	State-of-the-art
Mass	20.4 g	~50 g for CubeSat patch with similar operating frequency
Frequency change	19%	15 – 30%

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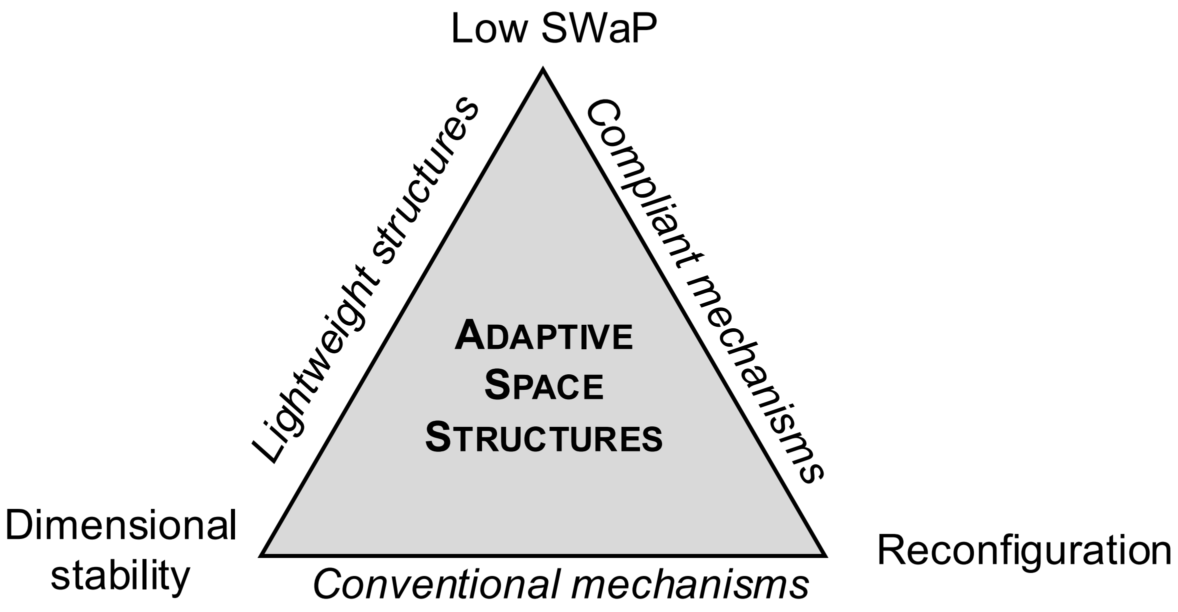
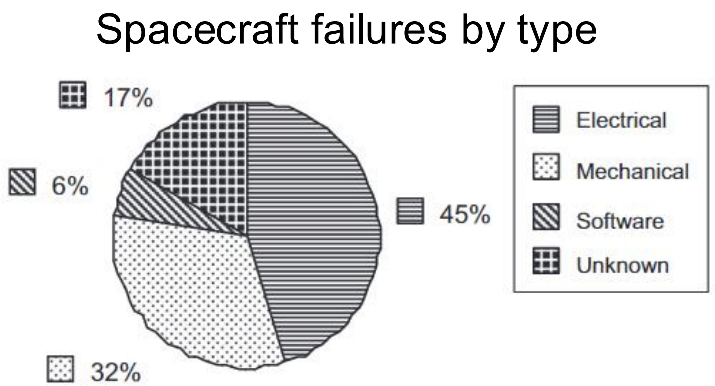
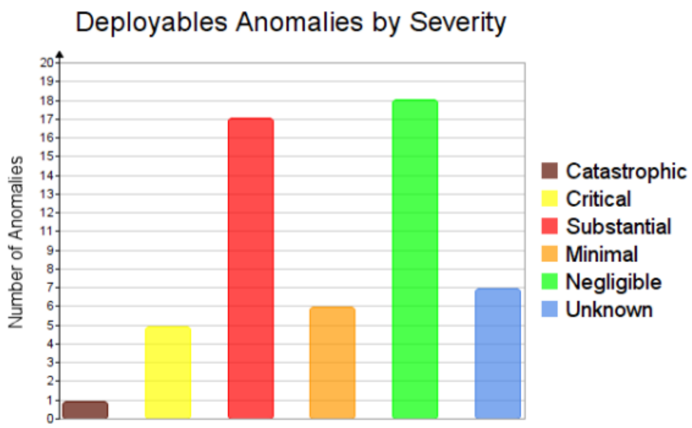
Tradeoffs!

- Tradeoffs between dimensional stability, deformability, and low size, weight, and power (SWaP)
- Space structures must also operate in harsh space environments
- Adaptation adds complexity - mechanical systems still seen as high risk
  - What are appropriate V&V procedures?
  - How to make adaptive structures resilient to failure?
  - Increased flight testing and metrology





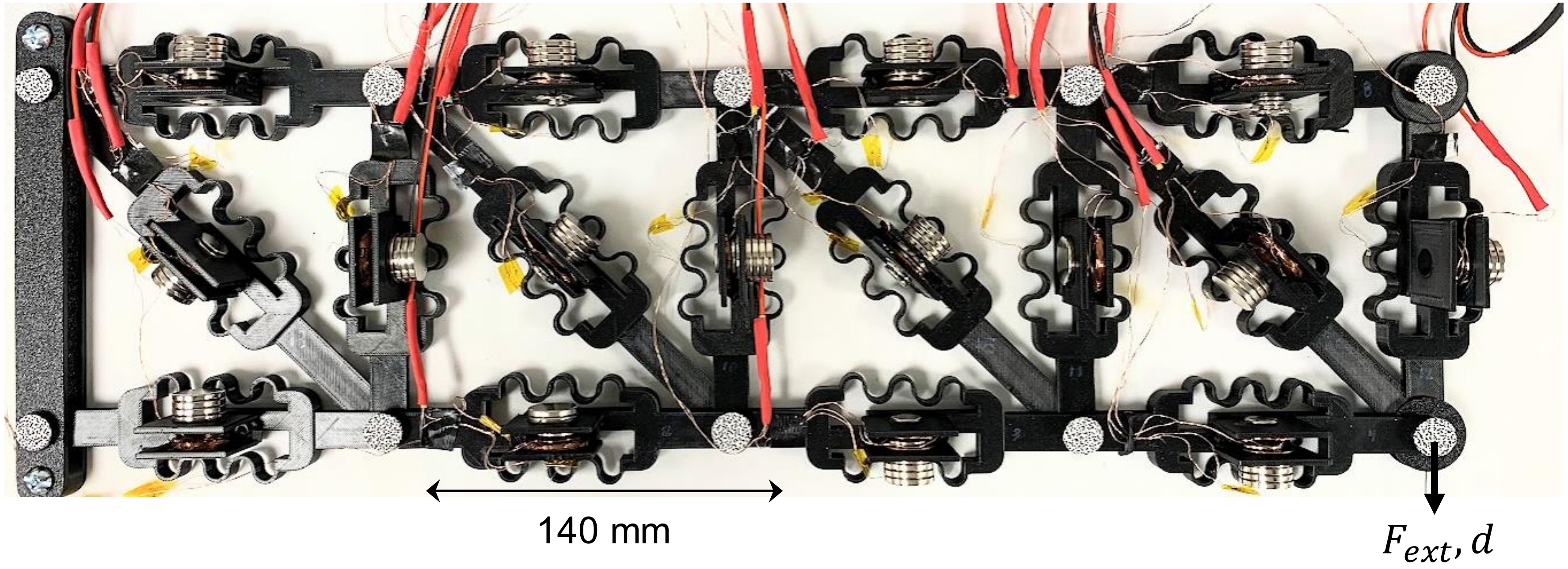
Tafazoli, Acta Astronautica 64, 195 – 205, 2009.

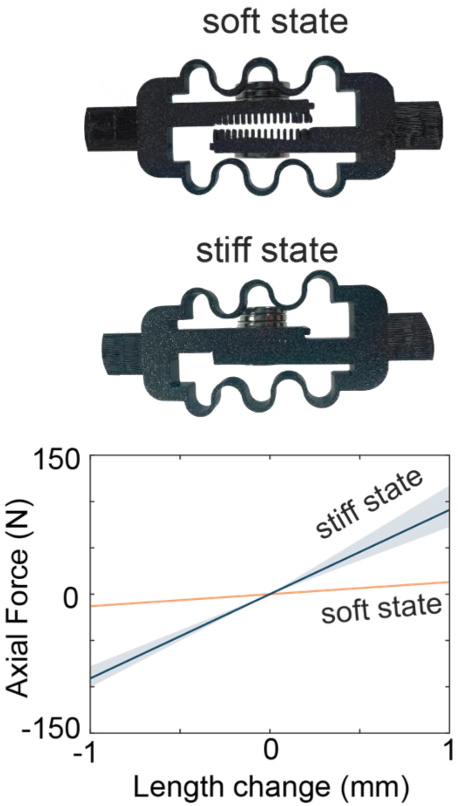


Rivera and Stewart, 19th European Space Mechanisms and Tribology Symposiums, 2021.

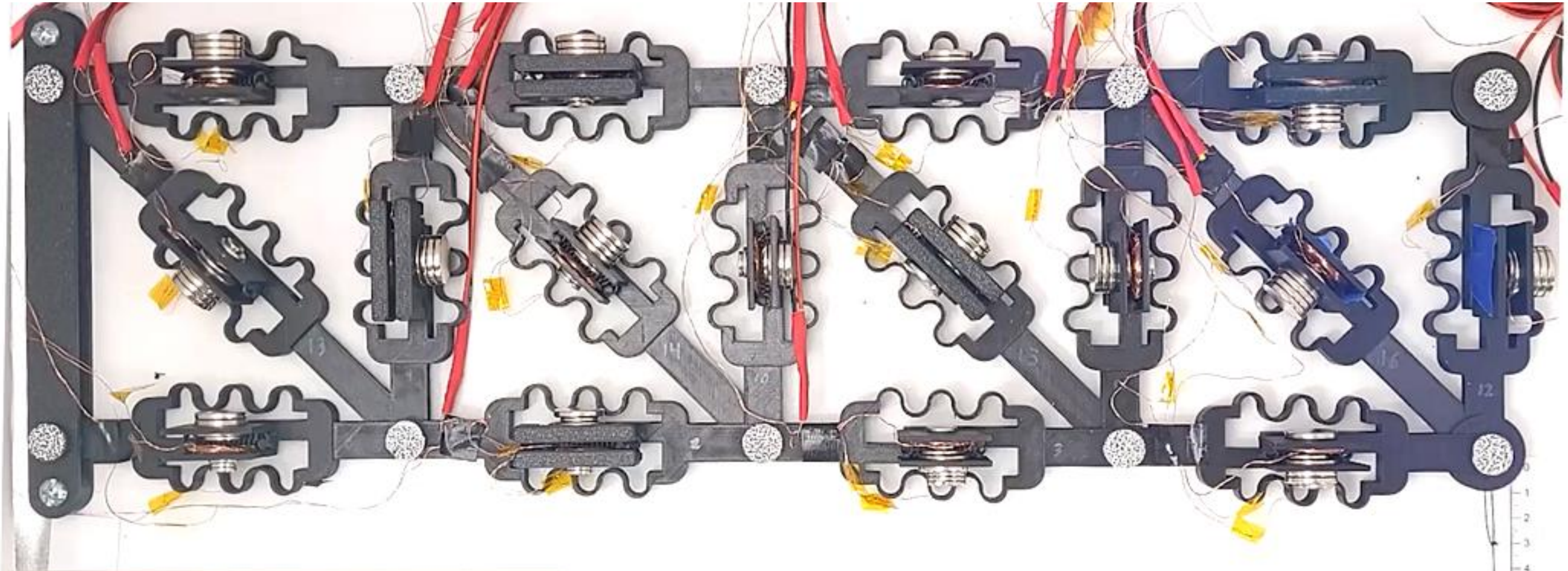
Decision making in unknown environments

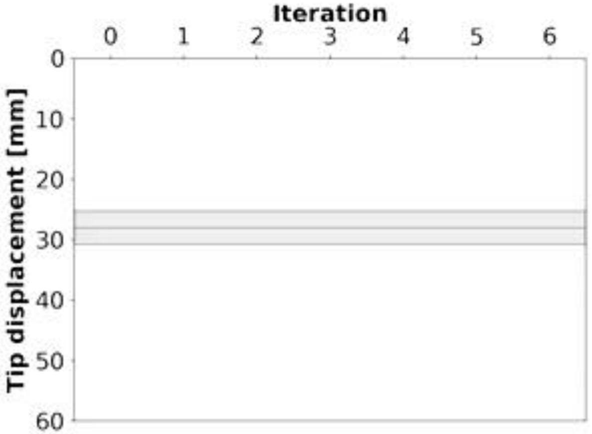
- How should we design an adaptive structure for unknown environments?
- Adaptive metamaterials with many degrees of freedom provide broad adaptation
- We propose bio-inspired learning approaches where structures iterative adapt properties based on interactions with the environment





Chen et al., arXiv:2510.06442, 2025.





Chen et al., arXiv:2510.06442, 2025.

Key Takeaways

- Structural geometry a powerful tool to adapt functionality – a lot of progress made in demonstrating adaptive hardware but little flight testing
- Hardware adaptation can achieve performance not possible through software alone – e.g., multi-modal locomotion, antenna performance adaptation
- Remaining challenges:
    - Identifying ‘pull’ for adaptive structures technology
    - Mitigating risk
    - Operation in highly unknown environments

Questions?

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