

Interconnected Actuation Networks for Shape Shifting Robots

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Research Question

How can actuator networks be partitioned into physically meaningful subnetworks to reduce control dimensionality while preserving morphing capability?

Introduction

As actuator count increases, control dimensionality scales proportionally (N actuators $\rightarrow N$ control inputs).

This leads to:

- \uparrow Computational burden
- \uparrow Coordination difficulty
- \uparrow Instability

Most existing approaches treat actuators as independently controlled elements, limiting scalability in large morphing systems.

Architectural restructuring is therefore required to reduce control complexity while preserving mechanical expressivity.

Objective

To develop and experimentally validate a scalable actuation architecture for thermomechanically coupled Shape Memory Alloys (SMA) systems that reduces effective control dimensionality through physically embedded subnetworks while preserving global morphing capability.

Background Design Context

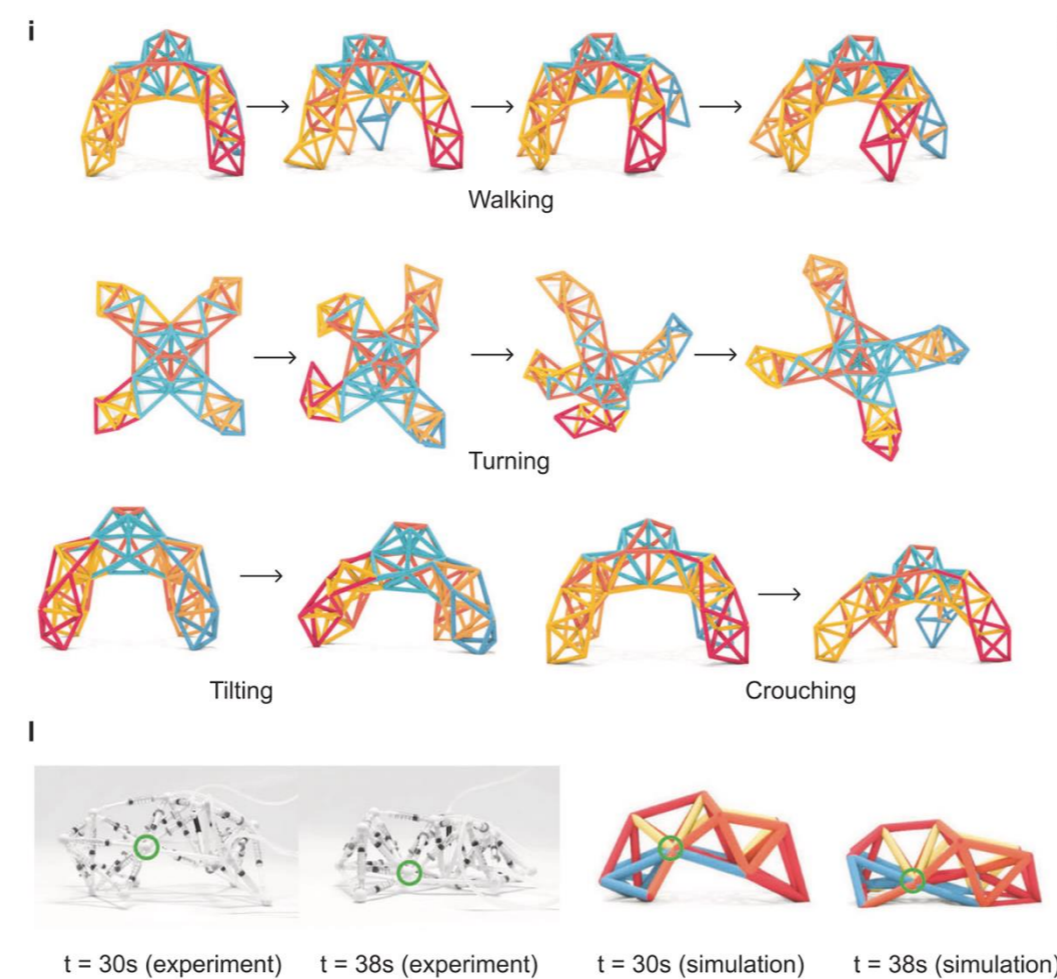


Fig. 2. Demonstration of variable-geometry SMA actuator networks performing locomotion and morphing behaviours, including walking, turning, tilting, and crouching, with experimental and simulation comparisons. Reproduced from Gu et al. [2].

Design Architecture:

- Embedded SMA actuator networks reducing independent control.
- Integrated bias springs for reversible contraction.
- Actuate with controlled electrical currents using PWM MOSFET drivers.

Experimental Evaluation:

- Displacement is measured using optical tracking
- Performance is evaluated by \rightarrow contraction size, response time, recovery time, and repeatability.

Robot Design

- **Geometry:** Modular hinged tetrahedral truss ($15 \times 15 \times 15$ mm unit cell)
- **Structural elements:** Rigid tubular members with pin and rotational joints
- **Actuator type:** 0.8 mm NiTi SMA wires
- **Routing method:** Axially through selected members
- **Anchoring:** Joint nodes
- **Recovery mechanism:** Passive bias elements providing elastic restoring force during SMA cooling
- **Control structure:** C-networks reducing N inputs to K channels
- **Optimisation layer:** NSGA-II assigns actuator subnetworks under symmetry and connectivity constraints prior to deployment.

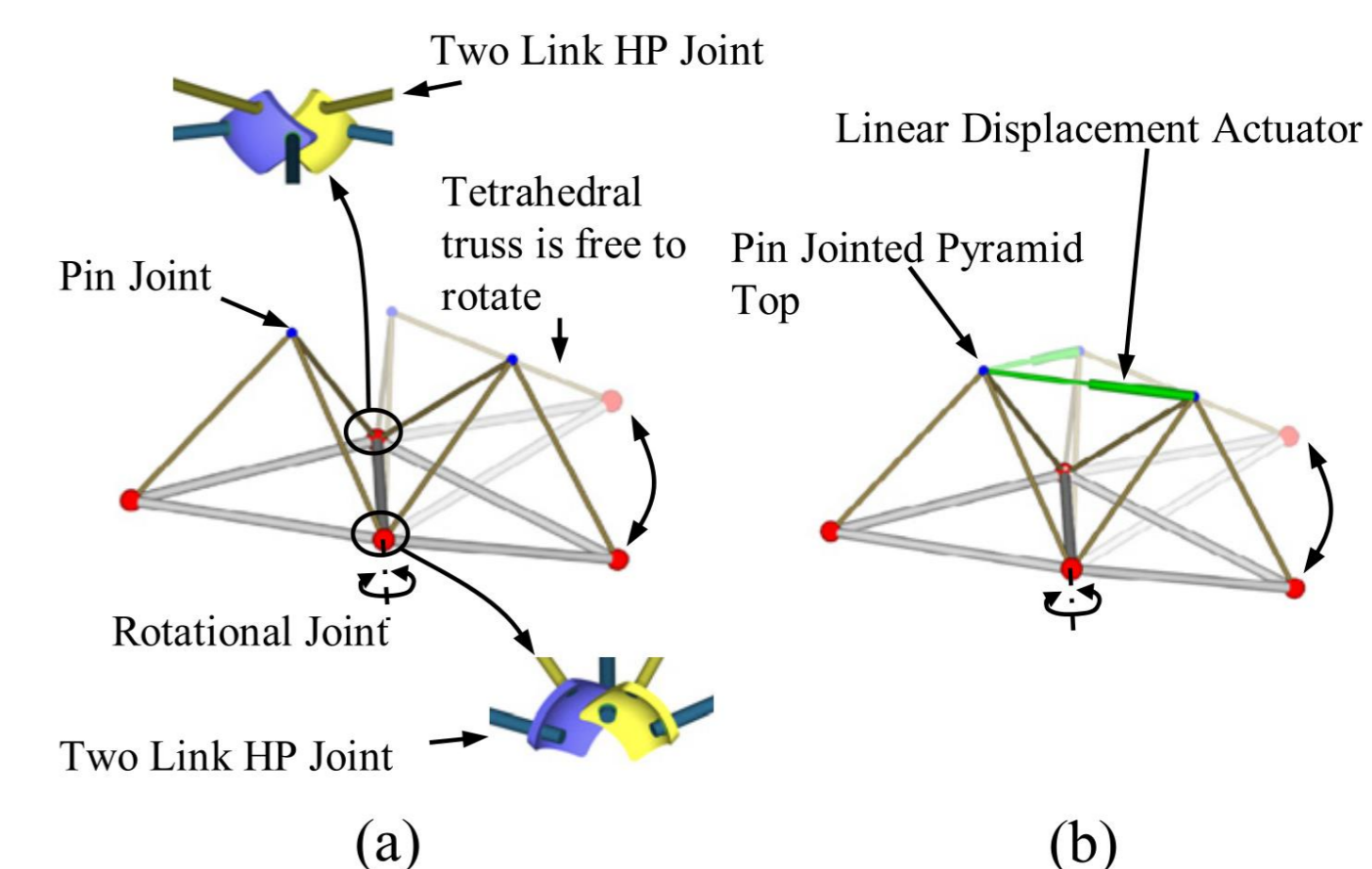


Fig. 4. Hinged tetrahedral truss module illustrating rotational degrees of freedom and integration of a linear displacement actuator within a pin-jointed pyramidal top structure. Reproduced from Sofla et al. [4].w

MVP#1 Experiment (Nitinol - NiTi)

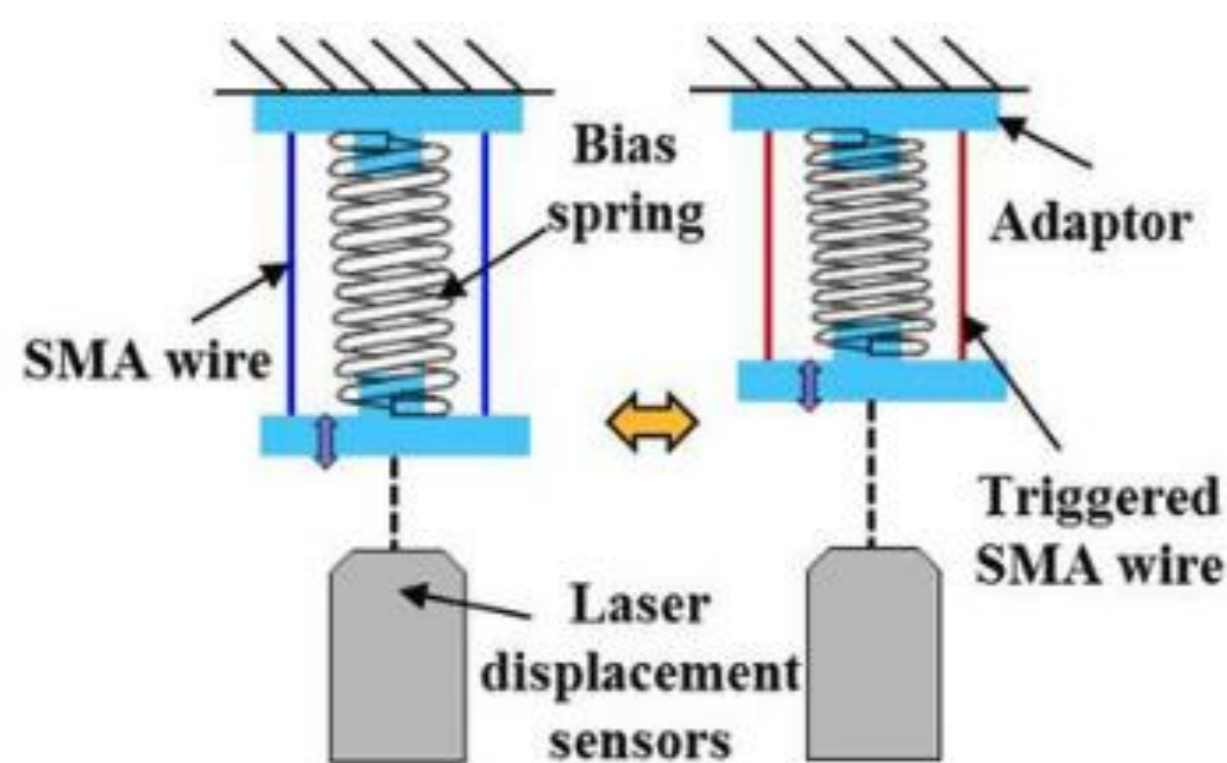


Fig. 1. Experimental setup for characterising SMA wire contraction using a bias spring and laser displacement measurement system. Reproduced from Tsai et al. [1].

Aims

The aim of the experiment is to:

- Characterise the fundamental thermo-mechanical results of a single NiTi actuator under controlled electrical stimulation.
- Create a baseline for contraction, response time, and repeatability metrics for scaling into an interconnected subnetwork of actuators.

Hypothesis

1. Increasing temperature above austenite phase using electrical currents induces transformation and contraction.
2. The recovery time of a NiTi wire post-actuation will be longer than its contraction time, limiting achievable actuation frequency.

Sub-Network Method (NSGA-II)

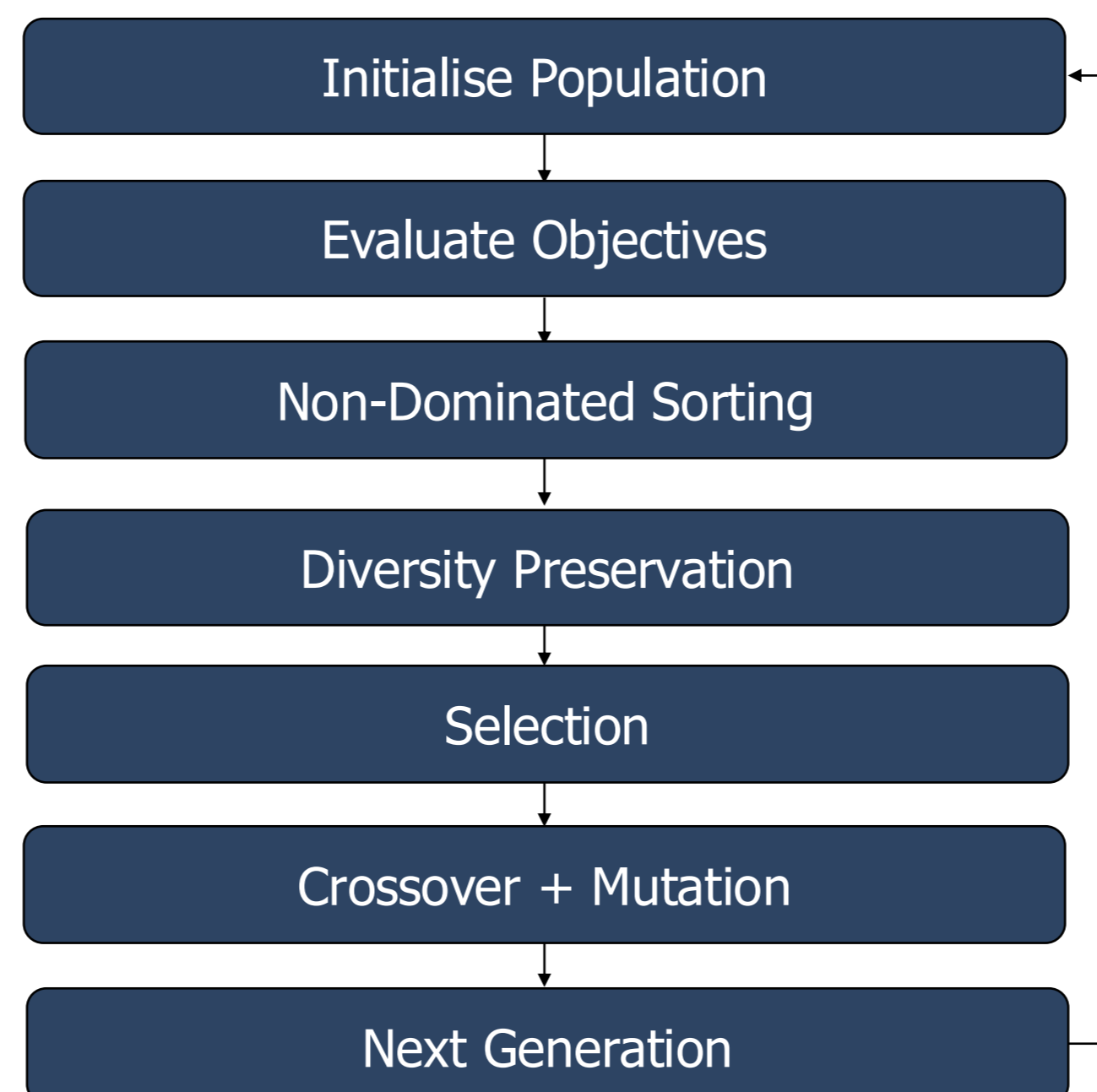
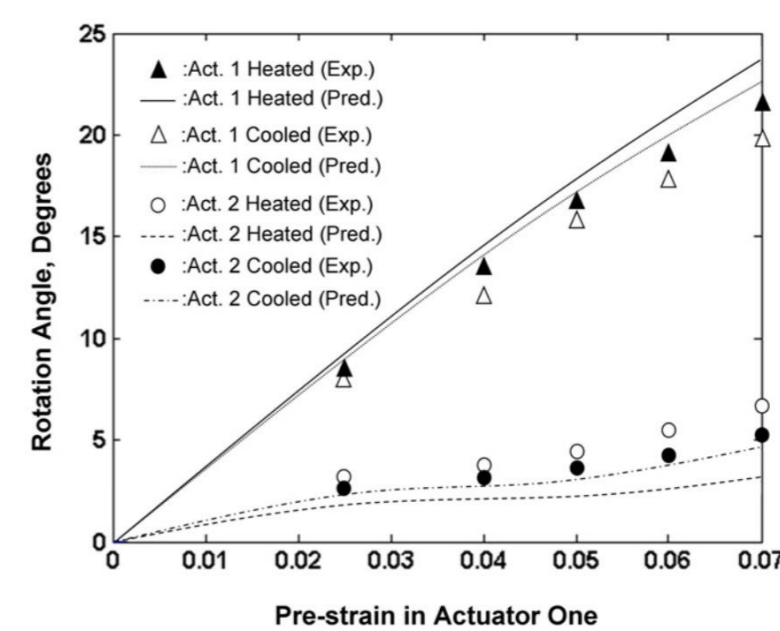


Fig. 3. Overview of the Non-dominated Sorting Genetic Algorithm (NSGA-II) optimisation pipeline used to generate and refine actuator subnetworks under structural constraints, adapted from [3].

NSGA-II Algorithms

- Multi-objective evolutionary search for valid actuator subnetworks.
- Handles large, discrete design space under structural constraints.
- Uses Pareto ranking for balancing morphing performance, control dimensionality, and physical feasibility.
- Encode each design as:
 - C-network assignment
 - Contraction levels
 - Activation timings

Quantitative Performance



Rotation angle scales with pre-strain, matching predictions. Amplification factor ($\approx 3.2\times$) enables $>10^\circ$ actuation from modest NiTi strain recovery ($<7\%$).

Fig. 4. Hinged tetrahedral truss module illustrating rotational degrees of freedom and integration of a linear displacement actuator within a pin-jointed pyramidal top structure. Reproduced from Sofla et al. [4].

Conclusion

Physically coupled SMA subnetworks reduce control dimensionality while preserving morphing capability. Optimised actuator grouping enables scalable, low-dimensional control of shape-shifting robotics.

Applications

- Terrain-adaptive robotic mobility
- Assistive and therapeutic morphing platforms
- Safe and adaptive construction and inspection systems

References

- [1] C.-H. Tsai, X. Wu, D.-H. Kuan, S. Zimmermann, R. Zengerle, and P. Koltay, "Digital hydraulic drive for microfluidics and miniaturized cell culture devices based on shape memory alloy actuators," *Journal of Micromechanics and Microengineering*, vol. 28, no. 8, 084001, 2018.
- [2] J. Gu et al., "Optimization and control of actuator networks in variable geometry truss systems using genetic algorithms," *Nature Communications*, vol. 16, p. 8432, 2025, doi: 10.1038/s41467-025-63373-7.
- [3] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," *IEEE Transactions on Evolutionary Computation*, vol. 6, no. 2, pp. 182–197, Apr. 2002.
- [4] H. A. Sofla, D. M. Elzey, and H. N. G. Wadley, "Shape morphing hinged truss structures," *Smart Materials and Structures*, vol. 18, no. 6, 065012, 2009, doi: 10.1088/0964-1726/18/6/065012.