Totimorphic Lattices as a Robotic Platform for Space Exploration

Ariadna reference number: 26-9400
(Standard study)

Project Summary

Objective

To produce an actuatable physical prototype of a totimorphic lattice and assess its suitability as a reconfigurable structural platform for space applications. Building on ESA's ACT developed computational framework for continuously reprogramming totimorphic structures via differentiable optimisation, this study aims to validate theoretical predictions through controlled laboratory experiments.

Target university partner competences

Mechatronics and robotics, fabrication and manufacturing, structural testing

ACT provided competences

Differentiable physics, inverse design, optimisation

Keywords

Totimorphic lattices, reconfigurable structures, differentiable simulation, inverse design

Study Objective

This study will develop and characterise a physical totimorphic lattice prototype capable of continuous geometric reconfiguration. The prototype will serve as a testbed for evaluating programmable mechanical properties predicted by ESA's ACT developed differentiable framework. The long-term vision is to establish totimorphic lattices as a practical backbone for deployable and reconfigurable space systems, mirrors, habitats, antennas, bridging the gap between theoretical potential and engineering feasibility.

Specifically, the study will:

- Produce a small-scale physical totimorphic lattice, exploring actuation concepts such as joint-mounted motors, tuneable springs, friction-lock or magnetorheological detents, and stabilisation strategies inspired by recent zero-stiffness unit-cell demonstrations [1].
- Quantify deviation between simulated and measured behaviour of the lattice under controlled stimuli (compression tests, shape morphing trajectories).
- Demonstrate the ability to reconfigure after damage, recovering at least one mechanical property (e.g. Young's modulus or Poisson ratio) through reconfiguration, validating the self-healing capabilities currently investigated in simulation.

Background and Study Motivation

Natural lattice architectures, bone, plant stems, radiolarians, exhibit extreme mechanical performance through geometry alone [2–3]. Engineered metamaterials [4–5] have followed this insight by manipulating unit-cell geometry to achieve tailored behaviours. Recent advances in inverse-designed disordered lattices [6–13] and deployable, programmable structures for space habitats and large infrastructure [14–17] underscore the growing relevance of geometric design for space systems. Moreover, active and stimuli-responsive metamaterials enable reprogrammable mechanical behaviour, with magneto-mechanical architectures demonstrating tuneable stiffness and shape change through lightweight magnetic actuation [18–19]. Differentiable design tools now optimise such compliant systems end-to-end [20], while responsive materials architected in space and time further highlight the move toward dynamic, programmable substrates [21–22].

Totimorphic lattices represent a recently introduced class of reconfigurable structures whose unique property is neutral stability across a continuous family of shapes [1]. A totimorphic unit cell, consisting of a beam, lever, and two zero-length springs, implements a mechanical analogue of Thales's theorem, enabling continuous geometric changes while maintaining structural validity. ESA's ACT recent computational framework [23] introduced a differentiable parametrisation of totimorphic lattices that guarantees compliance with geometric constraints throughout reconfiguration (see Fig. 1). This enables inverse design of mechanical properties via gradient descent.

Using this framework it was demonstrated in simulation:

- Tuneable Poisson's,
- Tuneable Young's modulus,
- Adaptive structural properties.

Moreover, current investigations focus on how the morphing abilities of such lattice can be used to obtain self-healing behaviour: in the case of a lesion, the remaining cells of the lattice can be reorganized so to achieve similar properties to the ones of the original structure, thus compensating for the damage-induced changes (see Fig. 2).

However, the lack of a physical actuatable prototype remains a critical limitation. Existing implementations [1] have demonstrated passive reconfigurability but lack actuation, stiffness control, or freeze/release mechanisms. The development of such a platform is characterized by several key engineering challenges: joint friction, neutral-stability loss, actuation strategies just to name few.

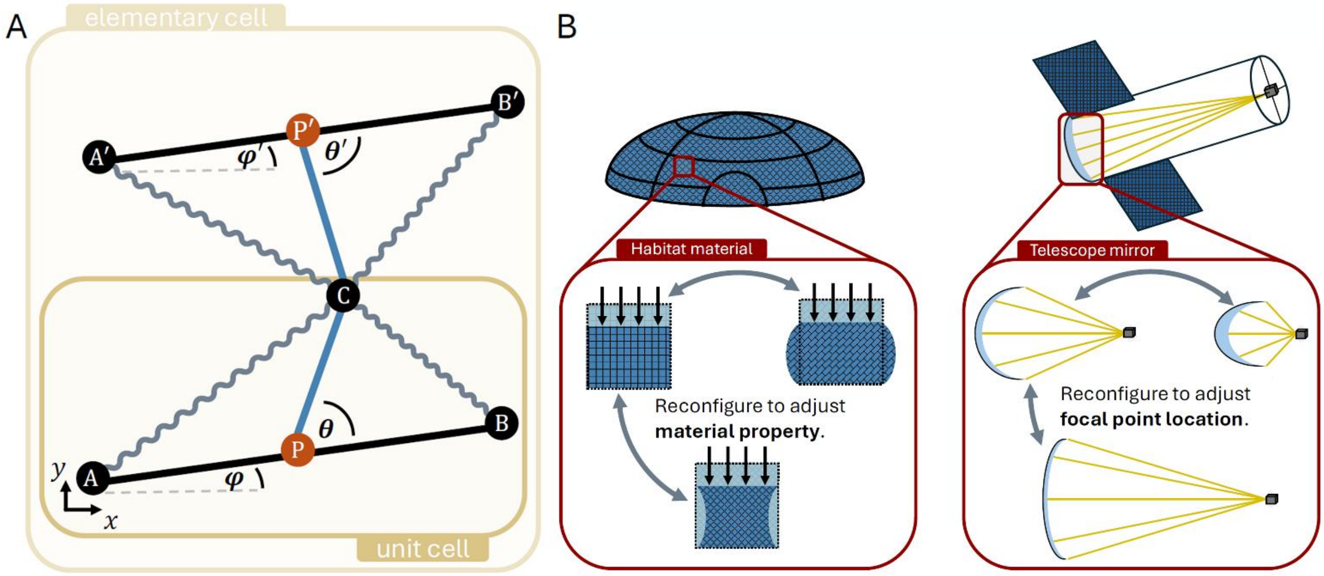

Figure 1: Illustration of totimorphic lattices and potential applications. (A) Totimorphic unit cell and elementary cell used for the tile. (B) Potential space applications of such a technology: reconfigurable habitats and telescope mirrors.

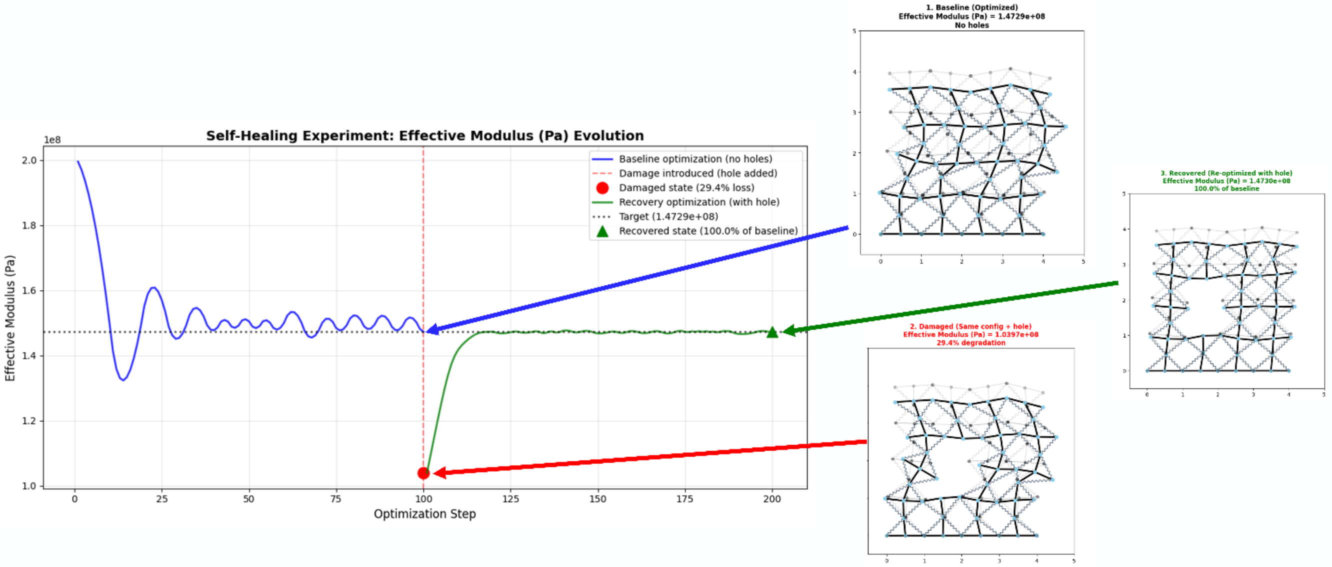

Figure 2: Example of reconfiguration-enabled recovery of mechanical properties of the lattice. A desired Young's modulus is achieved through optimization of the structure. Then, a damage is simulated by removing two elementary cells, resulting in different mechanical properties. However, by allowing further optimization of the remaining parameters, on top of the new DoFs, the lattice can recover the desired property.

To assess the practical viability of totimorphic structures for space applications, tests on a real prototype seem necessary. Only then one can quantify friction, manufacturing tolerances, joint imperfections, and other real-world effects that simulations currently neglect.

Proposed Methodology

To ensure a rigorous and transparent benchmarking process, the project is forseen to include three discrete phases, each to be implemented and quantitatively characterised in isolation, with clearly defined milestones:

1. Passive Prototype
    - Develop a 2D totimorphic lattice prototype with at least 10x10 unit cells (and a foreseen size of 30x30 cm^2) using lightweight materials.
    - Evaluate design options ranging from monolithic prints to hybrid assemblies with mechanical joints.
    - Implement locking mechanisms (friction lock, magnetorheological clutch, mechanical detents) to emulate neutral-stability conditions.
2. Active Prototype
    - Integrate actuation
    - Execute controlled shape changes guided by simulated trajectories from our differentiable model.
    - Compare simulated vs. physical trajectories, identifying systematic biases.
3. Mechanical Characterisation
    - Perform compression tests using a test rig.
    - Measure effective stiffness and Poisson's ratio across configurations, both to confirm simulation data and to investigate self-healing abilities.
    - Validate mechanical inverse-design predictions both from lattices with and without internal voids.

ACT Contribution

To support this joint research the ACT researchers will:

- Provide full simulation pipeline, including the totimorphic model, inverse-design optimisation, online reconfiguration, and integration scripts.
- Supply theoretical feasible trajectories and target configurations for testing programmable mechanical behaviours.
- Analyse experimental data, quantify simulation to reality gaps, and refine the differentiable model accordingly.
- Co-develop strategies to mitigate real-world imperfections (friction modelling, actuator abstractions, joint compliance).ss
- Evaluate prototype performance against space-mission requirements (deployability, robustness, actuation cost, resilience).

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