Programming Bistability in Geometrically Perturbed Mechanical Metamaterials

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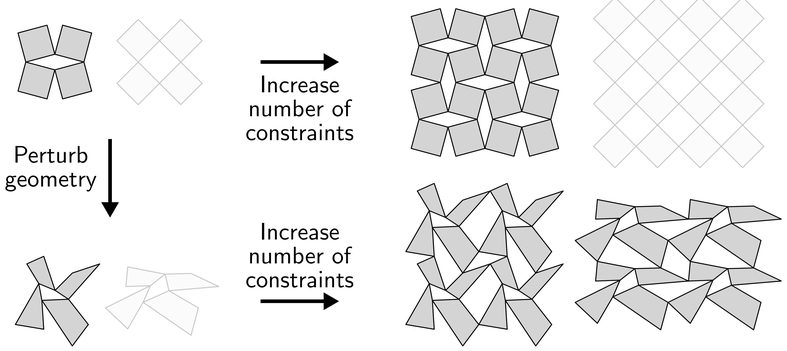
Code is available
Design your own Kirigami!

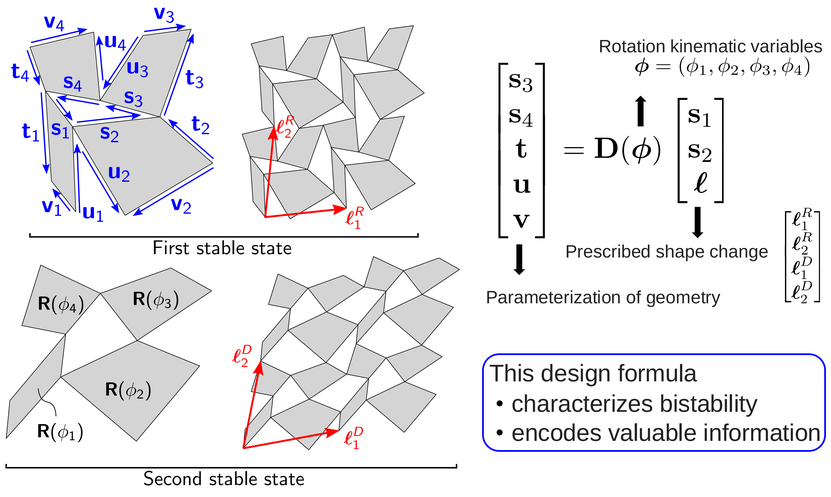
Motivation and Background

- Bistable systems are pervasive in nature and attractive in engineering, enabling aero*space structures*, *soft robots*, *MEMS and medical devices*.
- Most bistable systems stem from known bistable units or arise by chance.
- General design principles remain scarce despite their immense potential.



Methods

Design principle for bistable planar kirigami



Optimization framework for tuning bistability

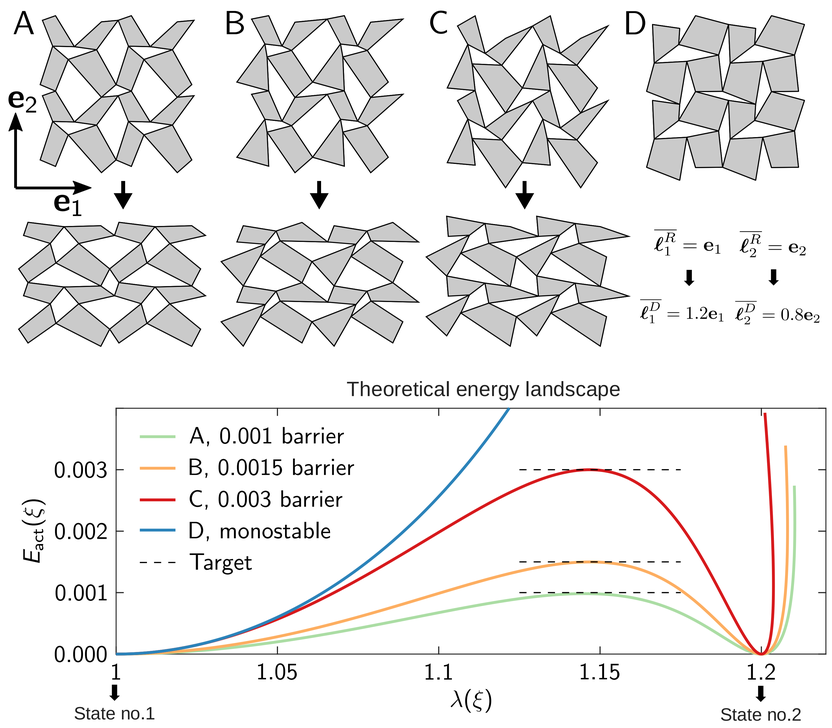
$$\min\left\{f_{\text{obj}}(\mathbf{s}_1,\mathbf{s}_2,\boldsymbol{\phi}) \;\middle|\; \mathbf{g}_{\text{ineq}}(\mathbf{s}_1,\mathbf{s}_2,\boldsymbol{\phi}) \geq \mathbf{0}\right\}$$

$$f_{\text{obj}}(\mathbf{s}_1,\mathbf{s}_2,\boldsymbol{\phi}) = \underbrace{c_b|E_b(\mathbf{s}_1,\mathbf{s}_2,\boldsymbol{\phi}) - E_b^{\text{targ}}|^2}_{\text{target energy barrier}} + \underbrace{\sum_{i=1,2} c_i|k_i(\mathbf{s}_1,\mathbf{s}_2,\boldsymbol{\phi}) - k_i^{\text{targ}}|^2}_{\text{target stiffnesses}}$$

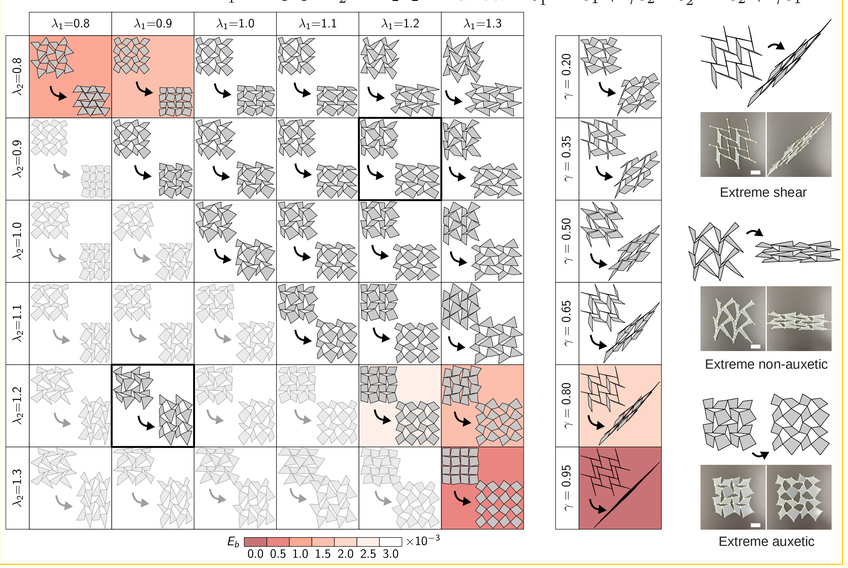
The design can be optimized to achieve any general objectives.

Results: Homogeneous Shape Change

Square-to-rectangle transformation examples

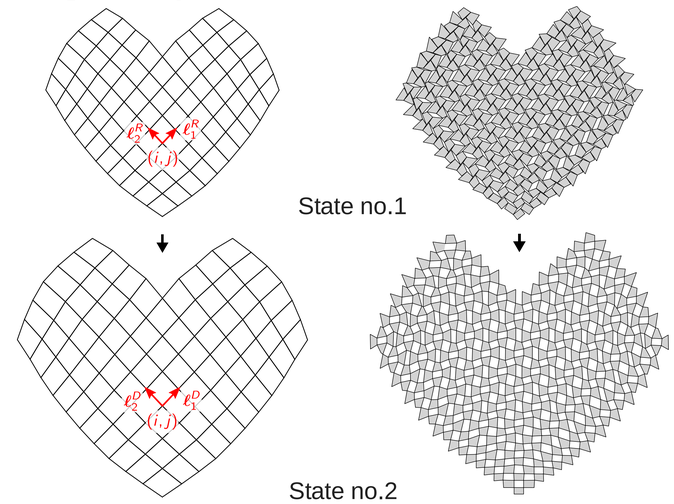


Design explorations of various shape change



Results: Heterogeneous Shape Change

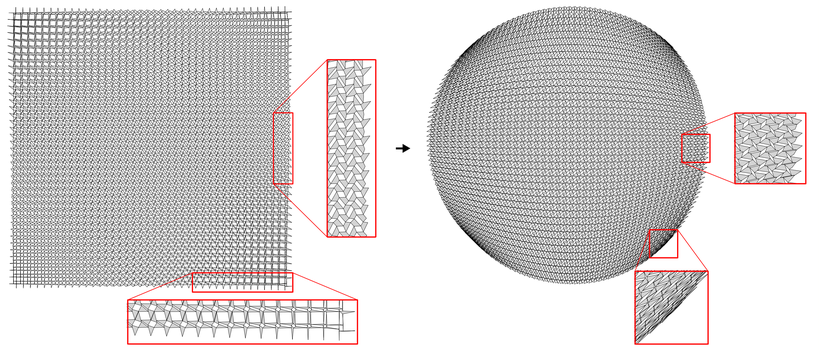
"Beating-heart" pattern



A **general** and **fast** framework that extends beyond periodic structures:

- ✓ Needs only regular and bijective quad meshes
- ✓ Produces designs within 3 minutes on a standard laptop

Square-to-Disk pattern



Conclusions

- *Geometric perturbations* are a key ingredient in designing metamaterials.
- A *versatile* design framework for designing bistable metamaterials:
  - Periodic patterns with tailored shape change and elastic properties
  - Nonperiodic designs with two arbitrarily shaped stable states
- **This general approach to engineer bistability greatly broadens the bistable systems and structures.**

Peng, Y., Niloy, I., Kam, M., Celli, P., & Plucinsky, P. (2024). Programming bistability in geometrically perturbed mechanical metamaterials. *Physical Review Applied*, *22*(1), 014073.