Inflatables

... and other deployable surface structures

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Deployable Structures

Fabrication State = Desired Output

Deployment

Inverse Design

Target State = Design Input

Kilian et al. 2017
Guseinov et al. 2017
Skouras et al. 2014
Deployable Structures

Fabrication State

\[ \text{Deployment} \]

Target State

\[ \text{Inverse Design} \]

= Desired Output

= Design Input

Light

\[ \text{Kotikian et al. 2018} \]

Chemical

\[ \text{Wehner et al. 2016} \]

Heat

\[ \text{Mao et al. 2015} \]

Swelling

\[ \text{Tibbits et al. 2014} \]
Deployable Structures

simple
accurate
robust
complex

Fabrication State

Deployment

Target State

Inverse Design

= Desired Output

= Design Input
Previous Work
Overview

Auxetics

Baromorphs

X-Shells
Auxetics

Material

Fundamental - Push Solo
Auxetics

Material

Isotropic Expansion

Fundamental - Push Solo
Auxetics

Material

\[ \lambda : \Omega \rightarrow \mathbb{R}^+ \] be the scaling factor

Initial and target curvature

\[ \Delta u = K - e^{2u} \tilde{K} \]

Yamabe equation

logarithmic scale factor \( u = \log(\lambda) \)

Yamabe equation

\[ \Delta u = K - e^{2u} \tilde{K} \]

Laplace-Beltrami

Initial and target curvature

Conformal Map

- locally: rotation + uniform scale
- let \( \lambda : \Omega \rightarrow \mathbb{R}^+ \) be the scaling factor
**Auxetics**

- **Material**
- **Abstraction**

Yamabe equation

\[ \Delta u = K - e^{2u} \tilde{K} \]

*logarithmic scale factor* \( u = \log(\lambda) \)

Laplace-Beltrami

Initial and target curvature

**Fundamental - Push Solo**
Auxetics

Material
→ Abstraction
→ Optimization
Auxetics

Material

Abstraction

Optimization

Deployment?
Uniform vs. Programmed Auxetics

- Identical triangles
- Varying openings

- Varying triangles
- Full openings

Material maximally expanded everywhere!
Programmed Auxetics

Programmed 2D state

Maximal expansion

Deployed 3D state

Gravity

Inflation
Inflation-deployed Prototype

Design input

Optimized
Gravity-deployed Prototype

Target Surface

Assembly state

Optimized Linkage in 3D

Optimized Linkage in 2D
References

Beyond Developable: Computational Design and Fabrication with Auxetic Materials

Mina Konakovic-Lukovic

Abstract

We present a computational tool for the parametric 3D design and fabrication of auxetic auxetic materials, in which the auxetic structure is attached to a 3D shape. The tool allows for the creation of auxetic auxetic surfaces with a variety of auxetic structures, and the auxetic structure can be customized to fit specific requirements. The tool has been validated through experimental testing, and has been shown to be effective in producing auxetic auxetic materials with high auxetic properties.

Keywords: auxetic materials, computational design, fabrication, auxetic surfaces.

Rapid Deployment of Curved Surfaces via Programmable Auxetics

Mina Konakovic-Lukovic

Abstract

Programmable auxetic auxetic surfaces are deployable surfaces that can be folded into complex shapes and then unfolded to return to their original shape. The tool presented in this paper allows for the design and fabrication of programmable auxetic auxetic surfaces with high auxetic properties. The tool is validated through experimental testing, and has been shown to be effective in producing deployable surfaces with high auxetic properties.

Keywords: deployable surfaces, programmable auxetics, auxetic materials.

Computational Design of Deployable Auxetic Shells

Mina Konakovic-Lukovic

Abstract

We propose an interactive computational design method for deployable auxetic shells. We enable deployable auxetic auxetic shells that can be folded into complex shapes and then unfolded to return to their original shape. The tool presented in this paper allows for the design and fabrication of deployable auxetic auxetic shells with high auxetic properties. The tool is validated through experimental testing, and has been shown to be effective in producing deployable auxetic auxetic shells with high auxetic properties.

Keywords: deployable auxetic shells, interactive computational design, auxetic materials.
Overview

Auxetics

X-Shells

Baromorphs

Inflatables

Initialization
Conformal Metric

Deployment
Geometric

Optimization
Geometric
X-Shells

- Easy-to-fabricate flat configuration
- Easy deployment via 1 DoF actuation
Design Specification

Graph with vertex positions

Elastic rod linkage
Deployment Simulation

Equilibrium optimization based on discrete elastic rod model

- Deployment via torque actuation at joints
Design Optimization

Manually crafted layouts tend to have high stresses

• Changing one design variable leads to large global effects
• Extremely challenging to manually adjust beams to reduce stress/tune shape
Design Optimization

Goal: Find planar rest configuration such that deployment achieves desired target shape with low stresses
Design Optimization

Design Parameter Optimization

- Nonlinear Optimization for Deployed Equilibrium
- Nonlinear Optimization for Flat Equilibrium
- Step Calculation

3D deployed state

2D assembly state

2x Speed
Optimization Results

Initial State

Optimized Design

5x reduction in deployed state energy
7x reduction in assembly state energy
Physical Prototypes

90 Joints
GRP Beams
Simulation vs Prototype
X-Shell Pavilion
X-Shell Pavilion
Overview

Auxetics

X-Shells

Baromorphs

Initialization
- Conformal Metric
- Forward Exploration

Deployment
- Geometric
- Equilibrium Simulation

Optimization
- Geometric
- Inverse Physics
Overview

Auxetics | X-Shells | Baromorphs

Initialization | Conformal Metric | Forward Exploration

Deployment | Geometric | Equilibrium Simulation

Optimization | Geometric | Inverse Physics
how we got interested in shape changing and geometry

observation of a physical phenomenon

Sharon et al
Fracture plasticity

distortion of metric

complex 3D shape
Morphogenesis: a simple coding for very complex shapes.

Growth more active on edges

Longer at edges
distortion of metric

complex 3D shape

how many wrinkles? why a cascade?

Can we control the metric in experiments?

Can we design a material where we can control in-plane « growth »?
swelling gels

Kim Science 2012

liquid crystal elastomers

Aharoni PNAS 2007
Baromorph

PolyVinylSiloxane elastomer

3D printed mold
Top view
Side view
Concentric channels

1 cm
Shape-changing structures

PolyVinylsiloxane elastomer

Concentric channels

3D printed mold

Top view

Side view

non-isotropic growth
Sheets description

Anisotropic deformation

Orthogonal growth
Parallel growth

Extension vs. Pressure graph
Minimal model for rings

Relative channel height

$$\Psi = \frac{h}{h + 2e}$$

In plane channel density

$$\Phi = \frac{d}{d + d_w}$$

\begin{align*}
\sigma_{x}^{(1)} &= \frac{p \Psi}{1 - \Psi} \\
\sigma_{z}^{(1)} &\approx 0 \\
\sigma_{x}^{(2)} &= -\frac{p}{\Phi} \\
\sigma_{z}^{(2)} &= \frac{p}{1 - \Phi} \\
\sigma_{\text{mean}} &= p \frac{\Phi \Psi}{1 - \Phi \Psi}
\end{align*}

Average strain in the baromorph

+ Hooke’s Law
Target deformation

Relative channel height $\Psi = 0.69$, fixed:

In plane channel density $\Phi = 1/2$, fixed:

Increasing $\phi$:

Increasing $\psi$:

Solid lines: simple model without any fitting parameter
Concentric pattern

\[ \varepsilon_r \gg \varepsilon_\theta \]
Concentric pattern

\[ (1+\varepsilon_r)L \]
Predicting conical angle

\[ U_{cl} = \frac{1}{2} \int \int \sigma : (\epsilon - \epsilon^t) dS \]

\[ U_{bend} = \frac{1}{2} \int \int D(\kappa_1^2 + 2\nu\kappa_1\kappa_2 + \kappa_2^2) dS \]

Geometrical limit

Weakly non linear model

\[ \epsilon_\theta \sim 0 \]

\[ \cos \alpha = \frac{1}{1 + \epsilon_r} \]
exhibition 130 years of the Eiffel Tower
what pattern for a given 3D shape? (inverse problem)

a simple explicit solution:

tuning orientation and intensity of expansion
Dynamical actuation

a family of soft equilibrium shapes
Overview

Auxetics | X-Shells | Baromorphs
---|---|---
Initialization | Conformal Metric | Forward Exploration | Projection
Deployment | Geometric | Equilibrium Simulation | Geometric
Optimization | Geometric | Inverse Physics | ?
simple-to-fabricate materials can deploy to complex 3D surfaces. Material design needs to incorporate accurate simulation of deployment. Forward and inverse design requires robust optimization algorithms. Geometry & Physics are key!