iTPMS: Interactive Inverse Design of Spatially Varying TPMS Metamaterial Fields

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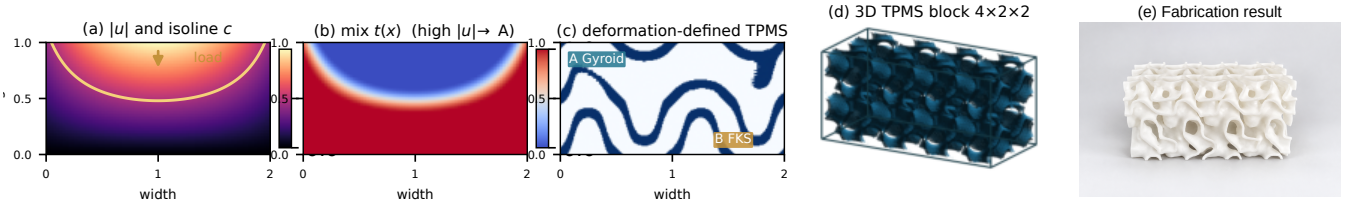


Figure 1: Deformation-defined TPMS interface: (a) displacement and isoline, (b) mix field, (c) Gyroid/Fischer–Koch S slice, (d) tiled block, and (e) our fabricated TPMS specimen.

Abstract

Spatial material design requires control over deformation and local structure. iTPMS maps sparse displacement targets to triply periodic minimal surface (TPMS) fields through differentiable mechanics and response-aware regularization. Examples include deformation-aligned interfaces, inverse reconstruction, interpolation, and a Gyroid–Schwarz P pillow. For the pillow, prescribed head and neck families enforce morphology contrast while density and transition mixtures are jointly optimized using periodic unit-cell elasticity. The resulting connected three-dimensional mesh combines distinct pore patterns with continuous transitions between the prescribed regional families. Its displacement response is evaluated with a homogenized two-dimensional model.

CCS Concepts

• **Computing methodologies** → **Shape modeling**; • **Human-centered computing** → *Interactive systems and tools*; • **Applied computing** → *Computer-aided design.*

Keywords

computational fabrication, mechanical metamaterials, inverse design, TPMS, iTPMS

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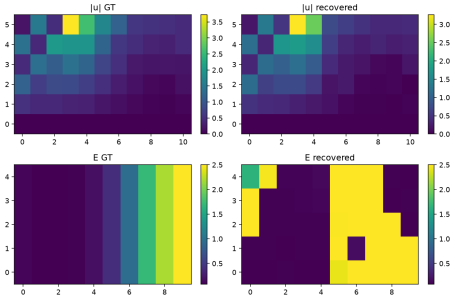


Figure 2: Inverse reconstruction: target/recovered displacement (top) and modulus proxy (bottom). Sparse motion does not uniquely determine E.

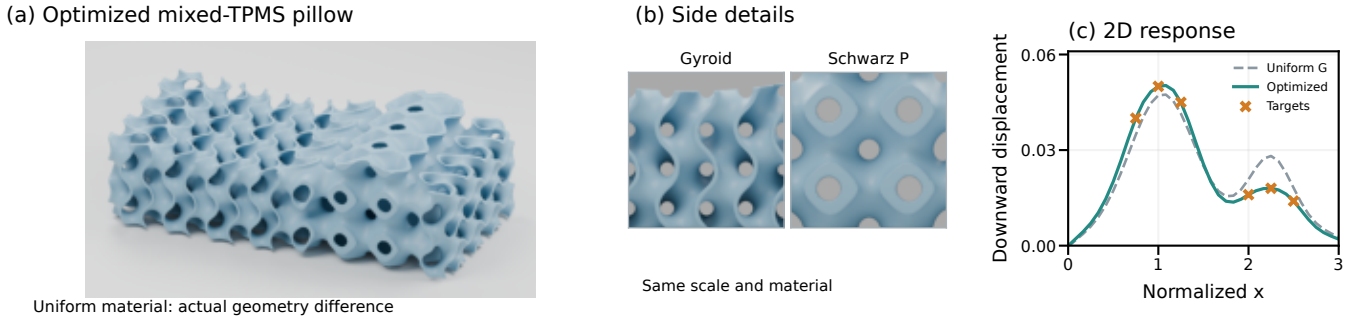


Figure 4: Computed mixed-TPMS pillow: (a) orthographic mesh with uniform material; (b) equal-scale Gyroid head and Schwarz P neck details; (c) homogenized 2D response. Geometry differs in both pore morphology and sheet thickness.

1 Introduction

Microstructures control elasticity [Panetta et al. 2015; Schumacher et al. 2015]; foams [Martínez et al. 2016], two-scale optimization [Zhu et al. 2017], and extremal families [Chen et al. 2018] expand their range. Following displacement-driven design [Skouras et al. 2013] and learned TPMS responses [Perroni-Scharf et al. 2025], we optimize a spatial mixture $w(x)$ for target motion:

$$w^\star = \arg\min_w \sum_k \|S(E(w), f_k, b) - u_k^\star\|^2 + \lambda \mathcal{R}_{\text{mech}}(w).$$

Related work addresses graph toolpaths [Huang et al. 2024], multi-axis printing [Qu et al. 2026], and sparse-view alignment for adaptive wireframe printing [Wang et al. 2026]. We optimize material structure for target deformation.

2 Method

Representation and inverse solve. Weights $w(x) \in \Delta^7$ mix eight TPMS primitives: $F(x) = \sum_i w_i(x) f_i(\phi(x))$. An experimental stress ensemble supplies stiffness proxy $E(w)$. Differentiable, small-strain plane-stress FEM predicts u under prescribed forces and supports. Adam fits sparse $u^\star$ with mechanical pullback regularization $G(w) \approx J_p^\top W J_p$.

Transitions and interaction. A discrete geodesic penalizes neighboring mixture changes under G. In interface mode, a smoothstep around a quantile of $|u|$ defines a blend field; extrusion creates a curved boundary. Users edit targets, loads, supports, and interfaces, then export meshes.

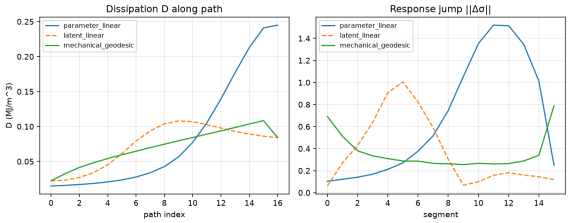


Figure 3: Three interpolation paths. Mechanical geodesics reduce response jumps over most of the path.

3 Results

Figures 2–3 show reconstruction and interpolation.

Computed TPMS pillow. Gyroid head and Schwarz P neck anchors impose morphology contrast; column densities ρ and transition mixtures m are optimized. We homogenize 30 periodic 18^3 voxel cells (five mixtures, six densities; solid $E = 3$, $\nu = 0.3$) and interpolate their plane-stress tensors. On a fixed-base 36×12 mesh, head/neck loads total 0.018/0.006; downward targets are (.040, .050, .045) and (.016, .018, .014), all dimensionless. Adjoint L-BFGS-B fits these targets with penalty $0.002\langle(\Delta\rho)^2 + (\Delta m)^2\rangle$. Model-relative error is 0.0022% (16.6% uniform Gyroid); a 72×24 re-solve changes motion by 0.23%.

Volume-fraction thresholds and envelope clipping (spacing 1/120, period 0.375) yield a closed, connected 2.27M-triangle mesh (Figure 4). Three 24^3 cell checks change stiffness by 3.0–4.8%. This case uses voxel-cell estimates; whole-pillow 3D contact mechanics is not evaluated.

4 Conclusion

iTPMS formulates spatial material design in terms of prescribed deformation. The reconstruction example recovers motion from sparse targets, while its non-unique modulus field highlights the need for structural constraints. Mechanical geodesics reduce response jumps over most of the interpolation path. In the pillow case, regional family anchors and joint density–mixture optimization connect distinct pore morphologies through a continuous field and yield a closed, connected mesh.

These results link displacement objectives to explicit geometry. Future work will quantify homogenization error and calibrate printed material response. Validation will combine three-dimensional contact simulations with specimen compression tests, including large-deformation response.

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