

# Fabricating 3D Shapes by Shrinking-Thread Embroidery

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We propose a computational method that repurposes embroidery as a tool for 3D fabrication. Given an input mesh, our method computes a freeform stitching pattern, such that an embroidered flat fabric approximates the target geometry. The stitching is done with polyester threads that permanently shrink when heat is applied, thereby generating curvature. Our approach is based on vector field optimization: we jointly optimize a shrinking field over the mesh surface and a corresponding planar parameterization that also allows for seams to arise in order to achieve higher curvatures than through shrinkage alone. Our energy formulation balances fabrication adherence, field smoothness, stitch consistency and validity of stretch values, and is minimized via an alternating algorithm. We demonstrate our method on a variety of target shapes and validate our results through both a digital preview tool and physical fabrication.

CCS Concepts: • **Computing methodologies** → *Mesh models*.

Additional Key Words and Phrases: Fabrication, Deployable structures, Vector field optimization, Parameterization

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## 1 Introduction

Textiles offer a compelling platform for computational fabrication thanks to their flexibility, durability, lightness, wearability and ubiquity in everyday life. Unlike rigid materials, textiles are capable of large deformations, making them suitable for a wide variety of applications ranging from clothing and upholstery to shape-morphing structures and wearable devices. Their inherent softness also opens opportunities in human-centered design, such as personalized fashion, medical wearables and artistic installations. Additionally, textiles are not limited to developable surfaces: due to the presence of void spaces in their micro-structure, they allow for a degree of stretching and shearing, making them more forgiving to work with than paper or sheet metal. Through sewing different parts of fabric together, one can further create curvature and assemble complex 3D shapes.

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Fig. 1. Photo of fabricated 3D shapes achieved through our method of shrinking-thread embroidery.

A particularly interesting mechanism for inducing curvature in flat fabric is thread shrinkage: by embroidering threads that contract when heat is applied, fabric can be locally compressed in a controlled direction, causing it to lift and curve. A big advantage of this is that embroidery add-ons are relatively affordable for home sewing machines and industrial embroidery machines are widespread in textile production, which makes this approach easy to adopt. Additionally, the process is nearly automatic, so unlike traditional sewing and smocking, it can easily be scaled. However, computing the embroidery pattern that produces a desired 3D shape is a nontrivial inverse design problem. We address exactly this issue by offering a computational inverse design pipeline, providing the embroidery pattern for a given target shape. The results can directly be fabricated and produce 3D shapes made from fabric, as depicted in Fig. 1. Compared to other deployable surface approaches, which are often fabricated entirely from plastics or polymers, our embroidery method has a favorable sustainability profile: the base fabric can be natural material such as cotton, with only the active shrinking thread required to be polyester-based.

## 2 Related work

Inverse design and fabrication processes consider a multitude of constraints, with extensive literature available. We survey the works most closely related to our setting.

*Deployable structures.* A wide range of morphable materials have been explored for fabricating structures in a planar state that deploy into 3D shapes, including plastic sheets for inflatable structures [He et al. 2026, 2025; Panetta et al. 2021; Ren et al. 2024a], 3D printing

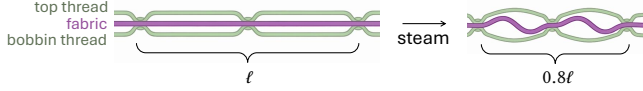


Fig. 2. Shrinking thread illustration: the thread contracts in its length, locally deforming the fabric to wrinkle and effectively shrink as well.

filaments and hydrogels [Aharoni et al. 2018; An et al. 2018; Griniasty et al. 2019; Jourdan et al. 2023; Malomo et al. 2018; Narumi et al. 2023], paper [Choi et al. 2019; Dudte et al. 2016; Ion et al. 2020] and fabric [Jourdan et al. 2022; Pérez et al. 2017; Segall et al. 2024]. The inverse design problem in this setting is naturally framed as surface parameterization, typically solved by minimizing a distortion measure suited to the fabrication process [Hormann et al. 2007]. For isotropic processes using auxetic (meta) materials, conformal parameterizations are a natural choice [Floater 1997; He et al. 2026, 2025; Konaković et al. 2016; Konaković-Luković et al. 2018]; when area preservation also matters, as-isometric-as-possible methods modeling materials as developable surfaces are preferred [Julius et al. 2005; Liu et al. 2008; Malomo et al. 2018; Yamamoto et al. 2026].

*Anisotropic methods and shrinkage-based optimizations.* Some materials exhibit anisotropic deformation behavior, thus anisotropic approaches are often better suited for associated inverse problems. Surfaces fabricated using polymers that shrink along their printing direction require parameterizations that take the directional shrinkage field into account. Aharoni et al. [2018] introduce a method that locally estimates optimal shrinkage directions and globally enforces consistency, akin to ARAP parameterization [Liu et al. 2008]. Depending on the specific application, this method is often used as a starting point and then further refined, keeping the specific physical characteristics in mind. A notable example is Shrink & Morph [Jourdan et al. 2023], where flat-printed polymer sheets are designed to transform into complex 3D shapes upon thermal activation. To do so, sensitivity analysis is done on a proposed simulation energy, and via multi-layer printing the approximation accuracy can be improved, leveraging the bilayer effect. Similarly, the challenge of planning the fused tube paths for inflatables has been addressed by using sensitivity analysis on the simulation energy [Panetta et al. 2021], which has been further enhanced in terms of structural stability [Ren et al. 2024a]. We take a different route and offer a purely geometric optimization of our shrinking thread embroidery design, eluding the need for an expensive and complex simulation in our algorithm. Beyond this methodological difference, the two fabrication processes also differ in the design space they afford. Unlike Panetta et al. [2021], we allow parameterization singularities and cuts to emerge naturally through our PolyVector field, expanding the achievable curvature beyond what shrinkage alone provides. The two processes also differ in their anisotropy: fused tubes enforce a single shrinkage direction everywhere, whereas embroidery permits overlapping stitches and unstitched regions, allowing for more shrinkage patterns. At the same time, shrinkage is more constrained as our thread induces a fixed amount of shrinkage, restricting us to only two possible values for the local deformations, while tube width can be varied continuously to realize a range of singular values (see Fig. 5 in [Panetta et al. 2021]).

*Vector field optimization.* When material directions are visible in the final fabrication, or when automatically placed singularities are desirable to expand the design space, vector field optimization becomes a valuable tool; we refer to Vaxman et al. [2016] for a comprehensive treatment and only highlight PolyVector field smoothing here, as it plays a key role in our method. Diamanti et al. [2014] introduce N-PolyVector fields, which generalize N-RoSy fields to allow arbitrary magnitudes and angles between vectors, avoiding integer variables and nonlinear matchings. In fabrication contexts, such fields have been applied to principal curvature aligned quadrilateral remeshing of developable surfaces [Verhoeven et al. 2022], strip-decomposable quad meshes for woven structures [Mitropoulou et al. 2024], Chebyshev parameterizations for nets [Sageman-Furnas et al. 2019] and stitch layout design for smocking [Segall et al. 2024]. In concurrent work, it has been shown that principal stretch directions across a surface can be used to optimize sewing patterns to best approximate a shape in fabric formwork [Sati et al. 2026].

*Shaping textiles through shrinkage.* Shrinkage is employed to induce curvature in various ways in the textile domain. One approach is to pre-stretch fabric and introduce stiff elements on it by embroidering regular thread into dense primitive shapes, such as rectangles [Jiang et al. 2024], depositing plastic ribbons [Jourdan et al. 2022] or networks of thin curves [Pérez et al. 2017] using a 3D printer on the fabric, or similarly printing rigid triangle tiles on stretched latex [Guseinov et al. 2017]. When released, the fabric shrinks back to rest shape except at the stiff elements, creating curvature. Similarly, crochet structures on shrinking film can be used to control the stiffness of the material [Wang et al. 2025], creating curvature. Shrinking thread, as in our work, has also been used, for example in lifting free-standing lace embroidery from the plane [Nabila et al. 2023] or using it to embroider onto laser-scored fabric to automate origami fold formation [Chang et al. 2025].

The works above demonstrate that shrinkage-based actuation can be leveraged to create curvature, and that anisotropic inverse design methods can effectively harness directional deformation fields. However, no existing work gives an algorithm for inverse design considering the specific fabrication constraints shrinking-thread embroidery poses.

### 3 Problem statement

#### 3.1 Objectives

Our goal is to design embroidery patterns that, when stitched and steamed, deform a flat piece of fabric into a prescribed curved surface. The key physical mechanism to allow for this is thread shrinkage. We work with a thread that shrinks to  $z = 0.8$  of its original length, contracting by 20%, after steaming (see Fig. 2). This locally compresses the fabric in the direction of the stitch. By spatially varying the presence and orientation of stitches across the fabric, we can induce a deformation that lifts the flat fabric into a curved surface, as illustrated in Fig. 3. We therefore frame our inverse design problem as a parameterization problem: We are looking for a map from the target 3D surface to the  $uv$  plane (the embroidery pattern) such that the inverse map, which deforms the flat pattern to the surface, is locally consistent with the shrinkage our thread can

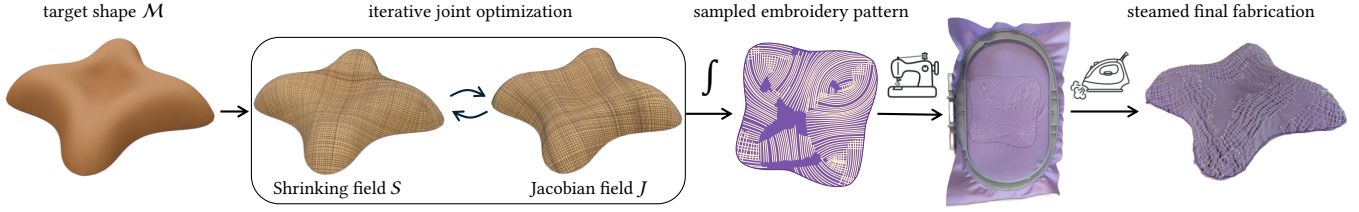


Fig. 3. Pipeline: given the target surface  $M$ , we iteratively optimize the shrinking field  $S$  and the Jacobian field  $J$ , which are used to compute the embroidery pattern by integrating  $J$  to flatten the shape and tracing the stitching curves on  $S$ . This embroidery pattern can be directly fabricated and subsequently steamed, deforming the fabric to approximate the target geometry. We display a photo of our physical fabrication on the right.

produce. Concretely, we seek a parameterization function whose principal shrinkage directions correspond to a shrinkage of either 1 or  $z$  everywhere and can thus be mapped to stitches directly.

Beyond shape approximation, we also want a good embroidery pattern that satisfies some practical fabrication requirements. First, we want stitch lines to be *consistent*: long, uninterrupted curves are strongly preferred over many short disconnected segments. Every interruption requires the embroidery machine to cut the thread, which is the slowest and most error-prone part of the embroidery process, as the needle can lose the thread, and the thread can get entangled. Thus, we want to trade off the number of stitching curves with the approximation quality. Second, we seek stitch directions that are *smooth* across the fabric, as they produce aesthetically pleasing curves, avoid sharp turns that slow down the machine, and help the discretely sampled stitch pattern to faithfully represent the continuous deformation field. Finally, we want cut seams that are sewn together in fabrication to naturally emerge in regions where the shrinkage mechanism alone is not sufficient to achieve the target curvature.

### 3.2 Notation and geometric representation

We work with a triangle mesh  $M = (\mathcal{V}, \mathcal{E}, \mathcal{F})$  representing the input target surface, where  $\mathcal{V}$  is the set of vertex positions,  $\mathcal{F}$  the set of triangle faces and  $\mathcal{E}$  the set of edges. All vector fields on  $M$  used in the following are sign-symmetric and defined per face, expressed in their local 2D tangent frame unless stated otherwise. We define  $\mathbf{v}_f^i$  to be vector  $i \in [1, N]$  on face  $f$  of an  $N$ -field  $V$ . We also utilize the PolyVector representation [Diamanti et al. 2014] of the fields, in which the  $N$  vectors of face  $f$  are represented by the coefficients  $v_{f,k}$  of a monic complex polynomial  $Z^N + \sum_{k=0}^{N-1} v_{f,k} Z^k$ , whose roots are the vectors in standard Cartesian coordinates  $\{\mathbf{v}_f^i\}_{i=1}^N$ . Because these coefficients and roots are simply different representations of the same underlying field  $V$ , assuming a consistent counter-clockwise ordering, we use them interchangeably and convert freely between the raw Cartesian vectors  $\mathbf{v}_f^i$ , the complex PolyVector coefficients  $v_{f,k}$ , and the matrix representation  $\mathbf{V}_f = [\mathbf{v}_f^1 \cdots \mathbf{v}_f^N]^\top \in \mathbb{R}^{N \times 2}$ , i.e., the vector field in the local frame encoded row-wise.

Our optimization involves several related fields:

- 1) Stitch direction  $O$ : A 4-RoS field tracing the stitch curves, optimized with regard to a smoothness objective (Sec. 4.1). We treat the directions as unit vectors, since only the orientation matters.

- 2) Stretch  $s_f^i$  and combined field  $S$ : Each direction  $i$  of  $O$  may independently carry a stitch, with the local shrinkage encoded by a non-negative scalar  $s_f^i$ , optimized independently of  $O$  via consistency and stretching objectives (Sec. 4.2, Sec. 4.4). For notational convenience, we define the vector field  $S$  to unite the orientation with the stretch value as the magnitude,  $s_f^i = s_f^i \mathbf{o}_f^i$ , as this fully determines the induced deformation.
- 3) Jacobian  $J$ : A frame field of candidate Jacobians of the flattening map, capturing the local deformation from the 3D surface to the 2D embroidery pattern domain.  $J$  is coupled to  $S$  by requiring it to match  $J$ 's principal stretch directions and magnitudes (Sec. 4.3).

Note that during optimization, we work with continuous stretch values as magnitudes, but we would like the magnitude of each vector in  $S$  to ultimately converge to one of two discrete values: 1, indicating no stitch and hence no shrinkage, or  $\frac{1}{z}$ , indicating a stitch that induces its standard shrinkage rate  $z$ . The inverse relationship between magnitude and shrinkage arises because we solve the inverse problem, going from 3D to 2D, where stitches must expand to account for the shrinkage they will later produce.

### 4 Energy formulation

Our goal is to find a parameterization function whose principal shrinkage directions correspond to a shrinkage of either 1 or  $z$  and make for smooth stitching curves with few interruptions. We formulate these objectives into an energy  $E(O, S, J)$  over the stitching directions  $O$  and with their corresponding shrinkage captured in  $S$ , as well as the Jacobian field  $J$  that can be used to compute the final flattening.  $E(O, S, J)$  consists of the following objectives:

$$E(O, S, J) = \underbrace{E_{\text{stretch}}(S) + E_{\text{fab}}(S, J) + E_{\text{sing}}(J)}_{\text{feasibility}} + \underbrace{E_{\text{smooth}}(O) + E_{\text{cons}}(S)}_{\text{ease of fabrication}}. \quad (1)$$

The feasibility terms  $E_{\text{stretch}}$ ,  $E_{\text{fab}}$  steer our parameterization to converge to allowed shrinking values and make sure that the Jacobians are the result of shrinking along the directions imposed by  $S$ . Additionally,  $E_{\text{sing}}$  is used to let singularities emerge in high-curvature regions, which allows expanding the design space by making the achievable curvature higher than through shrinkage alone. The seams emerging through  $E_{\text{sing}}$  help lower the error of the other



feasibility terms. Together, these terms increase the approximation quality and ensure we fit the target geometry. The ease of fabrication objectives help make sure that our embroidery pattern is good and that it is a faithful representation of the continuous vector fields (see Sec. 3.1). The term  $E_{\text{smooth}}$  favors smooth shrinking directions, so the stitching curves traced over  $O$  are more regular to embroider, and  $E_{\text{cons}}$  increases the consistency of lines, penalizing small interruptions. In the following, we describe each energy term in more detail.

#### 4.1 Orientation smoothness

The energy term  $E_{\text{smooth}}(O)$  encourages the smoothness of the stitching directions because, as noted in Sec. 3.1, smoothly varying stitch orientations are essential for high-quality embroidery.

Since  $O$  is a 4-RoS, it can be represented as a power field [Knöppel et al. 2013] with  $o_{f,0} \in \mathbb{C}$  uniquely defining the vectors  $\mathbf{o}_f^i$  as its 4<sup>th</sup> roots,  $\mathbf{o}_{f,0} = (\mathbf{o}_f^i)^4$ ,  $\forall i \in [0, 3]$ . We denote the connection coefficient between the tangent spaces of adjacent faces  $f$  and  $g$  by  $r_{fg} \in \mathbb{C}$  and the harmonic weight  $\omega_e$  (according to [Brandt et al. 2018]). Our smoothness energy is

$$E_{\text{smooth}} = \lambda_{\text{smooth}} \sum_{e=(f,g) \in \mathcal{E}} \omega_e |o_{f,0} r_{fg}^N - o_{g,0}|^2. \quad (2)$$

#### 4.2 Consistency

The energy term  $E_{\text{cons}}$  promotes a spatially consistent magnitude of  $S$  along its tracing direction by discouraging abrupt changes in the direction of the stitching curve between nearby faces. Since the magnitude of a vector in  $S$  defines whether a stitch is present in a given direction, minimizing this consistency energy term ensures the generation of fewer stitching lines in the final embroidery pattern. Let  $\mathcal{C}$  be the set of ordered vector pairs within a user-defined radius  $r_c$  of their respective face barycenters  $\mathbf{b}_f$ , where each pair is formed by choosing the vector that best matches the orientation of the other:

$$\mathcal{C} = \{(\mathbf{s}_f^i, \mathbf{s}_g^j) \mid \|\mathbf{b}_f - \mathbf{b}_g\| \leq r_c, j^* = \arg\max_{1 \leq j \leq 4} (\mathbf{o}_f^i)^T (\mathbf{o}_g^j)\}.$$

We represent the vectors  $\mathbf{s}_f^i$  in global 3D coordinates to provide a unified reference frame. This approach simplifies the computation for non-adjacent faces within the radius  $r_c$ , avoiding the need for complex parallel transport between distant tangent spaces. Moreover, we design the weight  $w_{fg}^{ij}$  between the vectors  $\mathbf{s}_f^i$  and  $\mathbf{s}_g^j$  to favor consistency along the flow of the field. This approach avoids penalizing magnitude changes orthogonally to the tracing direction, accounting for the fact that such transitions correspond to distinct stitching lines where continuity is not required. Therefore, we define  $w_{fg}^{ij}$  as a product of the Euclidean distance and directional alignment:

$$w_{fg}^{ij} = \left(1 - \frac{\|\mathbf{b}_g - \mathbf{b}_f\|}{r_c}\right) \left(\frac{\mathbf{b}_g - \mathbf{b}_f}{\|\mathbf{b}_g - \mathbf{b}_f\|} \cdot \mathbf{o}_f^i\right)^4. \quad (3)$$

Alignment is computed in global 3D coordinates by comparing  $\mathbf{o}_f^i$  with the direction between the face barycenters. See Fig. 4 for an example of how this weight is distributed over the mesh.

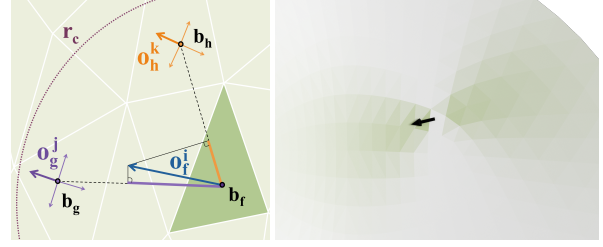


Fig. 4. Visualization of consistency weights: the illustration (left) shows the different variables influencing  $w_{fg}^{ij}$ , with the dot product quantifying the directional alignment being visualized as a projection onto the line between  $\mathbf{b}_f$  and  $\mathbf{b}_g$ . Note that faces that lie in the direction of the vector  $\mathbf{o}_f^i$  result in a larger dot product than faces that don't, as can be seen by the projection of face  $g$  being longer than the one of face  $h$ . The example weight distribution (right) shows a deeper green to indicate a higher weight, while white indicates no influence.

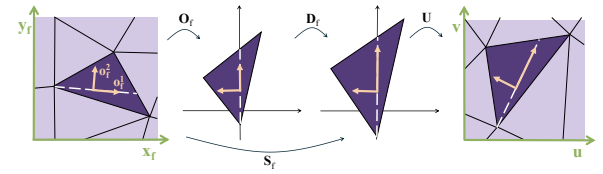


Fig. 5. Relationship between shrinkage vector and Jacobian: The Jacobian  $J_f$  maps from 3D in local frame coordinates to the 2D pattern space; its right singular vectors encode the principal stretch directions and should thus be constrained to align with the stitch direction  $\mathbf{O}_f$ . The singular values  $D_f$  encode the corresponding stretch magnitudes, thus we want them to correspond to the magnitudes of the shrinking field vectors  $\mathbf{s}_f^i$ . The left singular vectors  $U$ , which relate the local 3D tangent frame to the 2D embedding, remain a free variable and are thus fitted for the full Jacobian  $J_f = U D_f U^T = U S_f$ .

Given these definitions, the consistency energy is formulated as follows:

$$E_{\text{cons}} = \lambda_{\text{cons}} \sum_{(\mathbf{s}_f^i, \mathbf{s}_g^j) \in \mathcal{C}} w_{fg}^{ij} (\|\mathbf{s}_f^i\| - \|\mathbf{s}_g^j\|)^2. \quad (4)$$

This ensures that the magnitude is consistent with its neighbors specifically in the direction of the stitch.

#### 4.3 Fabrication adherence

The fabrication term enforces that the local deformation encoded by  $J$  is the result of shrinking the stitches determined by  $S$ . This means that  $S$  needs to correspond to the principal stretch values and directions of  $J$ . This relationship is visualized and further explained in Fig. 5.

To adhere to the constraints induced by  $S$ , we define the fabrication energy as:

$$E_{\text{fab}} = \lambda_{\text{fab}} \sum_{f \in \mathcal{F}} A_f \min_{U \in SO(2)} \|J_f - U S_f\|_F^2. \quad (5)$$



#### 4.4 Validity of stretch values

The term  $E_{\text{stretch}}$  regularizes the magnitude of  $S$  toward a binary state: either matching the prescribed thread shrinkage  $z$  or exhibiting no shrinkage at all. Specifically, we define the following energy:

$$E_{\text{stretch}} = \lambda_{\text{stretch}} |\mathcal{F}| \sum_{s_f^i \in S} A_f \min_{l \in \{1, 1/z\}} \left( l - \|s_f^i\| \right)^2. \quad (6)$$

Note that since the parameterization maps the surface to the plane, we constrain the magnitude of  $S$  along stitching lines to  $1/z$ . This ensures that the inverse mapping, from the flat fabric to the 3D surface, correctly accounts for thread shrinkage after steaming. The area-weighted stretch error is scaled by the number of faces  $|\mathcal{F}|$  to ensure that it is not overpowered by per-face errors such as  $E_{\text{cons}}$  in the evaluation for high-resolution meshes.

#### 4.5 Jacobian smoothness

To regularize the parameterization and manage singularities (which correspond to physical seams), we include a Dirichlet energy on the Jacobian field  $J$ . For easier computation, we use the PolyVector representation [Diamanti et al. 2014] with complex coefficients  $j_{f,i}$  for each face  $f$ , refer to the original paper for more details. As in Sec. 4.1, we refer to the connection coefficient between the tangent spaces of  $f$  and  $g$  as  $r_{fg} \in \mathbb{C}$  and set  $\omega_e$  to be the harmonic connection weight. The smoothness of  $J$  is then:

$$E_{\text{sing}} = \sum_{i=0}^{N-1} \sum_{e=(f,g) \in \mathcal{E}} \omega_e |j_{f,i} r_{fg}^{N-i} - j_{g,i}|^2. \quad (7)$$

This term promotes a more meaningful distribution of singularities, merging redundant singularities in low-curvature regions and introducing new ones in high-curvature regions. Through this, it improves the seam and approximation quality of the final embroidery pattern.

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#### Algorithm 1 Inverse design for shrinking thread embroidery

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|                                                                                        |              |
|----------------------------------------------------------------------------------------|--------------|
| <b>initialization:</b> ARAP                                                            | ▶ Sec. 5     |
| <b>while</b> $\ S - S_{\text{prev}}\  < 0.001\ S\ $ and $\text{iters} < 200$ <b>do</b> |              |
| $O \leftarrow$ smooth orientation                                                      | ▶ Sec. 5.1.1 |
| $S \leftarrow$ update magnitude                                                        | ▶ Sec. 5.1.2 |
| $U \leftarrow$ fit to $J$                                                              | ▶ Sec. 5.2.1 |
| <b>for</b> $i = 1, 2, \dots, k$ <b>do</b>                                              |              |
| $J \leftarrow$ smooth Jacobians                                                        | ▶ Sec. 5.2.2 |
| $U \leftarrow$ fit to $J$                                                              | ▶ Sec. 5.2.1 |
| <b>end for</b>                                                                         |              |
| $J \leftarrow$ integration                                                             | ▶ Sec. 5.3   |
| <b>end while</b>                                                                       |              |
| trace streamlines and sample curves                                                    | ▶ Sec. 6     |

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### 5 Optimization algorithm

Since our energy  $E$  in Eq. (1) involves many variables and nonconvex terms, it is difficult to minimize directly with off-the-shelf algorithms. Instead, we propose an iterative optimization scheme where each step aims to update a optimization variable in terms of as many

energy terms as possible. We initialize the flattening via as-rigid-as-possible parameterization [Liu et al. 2008]. For non-disk topology meshes, it can also be beneficial to initialize via a smooth cross field that is integrated in order to have higher quality initialization with better singularities. The parameterization can be used to initialize the Jacobians  $J$ .

#### 5.1 Updating $S$

We update  $S$  in two steps, as we have the orientation  $O$  and magnitudes  $\|s_f^i\|$  as independent optimization variables. Because both are involved in  $E_{\text{fab}}$ , we need to know the optimal  $S$  in order to minimize  $E_{\text{fab}}$  while keeping  $J$  fixed. The solution to this can be extracted through the SVD of  $J_f = \mathbf{U}\mathbf{D}\mathbf{R}^T$ , so the optimal  $S$  corresponds to the principal stretching directions and magnitudes  $\mathbf{S}_f = \mathbf{D}\mathbf{R}^T$ . This result is used in the two subsequent steps, where we account for  $E_{\text{smooth}}$  and  $E_{\text{cons}}$  as well.

**5.1.1 Orientation.** We refine  $O$  to minimize  $E_{\text{fab}}$  (Eq. (5)) as well as the smoothness term  $E_{\text{smooth}}$  (Eq. (2)). For this, we treat  $U$  as free rather than fixed, since  $E_{\text{fab}}$  is itself defined via a minimization over  $\mathbf{U} \in \text{SO}(2)$  and thus allows  $U$  to compensate for some rotation. This can be seen for a triangle with fully isotropic shrinkage  $\|s_f^1\| = \|s_f^2\|$ , where the energy  $\min_{\mathbf{U} \in \text{SO}(2)} \|\mathbf{J}_f - \mathbf{U}\mathbf{S}_f\|_F^2$  is constant for all  $\mathbf{O}_f$ , since  $\mathbf{U}$  will make up for any rotation. In the anisotropic case, the rotation matrix  $\mathbf{U}$  cannot fully compensate for changes in  $\mathbf{O}_f$ . In general, the increase in the fabrication term  $E_{\text{fab}}$  by deviating from the direction of principal stretch depends on the anisotropy of the singular values, and it is smaller the more isotropic they are. We can reformulate the problem of minimizing  $E_{\text{fab}} + E_{\text{smooth}}$  in terms of  $O$  into a standard soft-alignment smoothing framework (for details refer to the Directional [Vaxman et al. 2026a] tutorial on smoothing [Vaxman et al. 2026b]), aligning toward the optimal orientation for  $E_{\text{fab}}$  (corresponding to  $R$ ) with a weight

$$w_{\text{align}} = \frac{\lambda_{\text{fab}}}{2} \cdot \frac{(s_1^2 - s_2^2)^2}{s_1^2 + s_2^2}$$

approximating the anisotropy-dependent  $E_{\text{fab}}$  increase for face  $f$ , where  $s_i$  is the  $i$ -th singular value in  $D$ .

**5.1.2 Magnitude optimization.** Using the updated orientation  $O$ , we optimize over the shrinkage magnitudes while keeping the other optimization variables  $O, J$  fixed, which means we optimize  $E_{\text{cons}}$  (4) +  $E_{\text{fab}}$  (5). This reduces to a simple update of each magnitude toward a weighted average between the  $E_{\text{fab}}$  target magnitude (from  $D$ ) and the magnitudes of surrounding faces, increasing consistency. After this update towards the new continuous value, we project the magnitude of each vector  $s_f^i$  to the closer value of 1 or  $1/z$  in order to minimize  $E_{\text{stretch}}$  (6).

#### 5.2 Jacobian refinement

With the updated  $O, S$ , we can now optimize over the other parameters  $U, J$  in  $E_{\text{fab}}$  and  $E_{\text{sing}}$ . This is done by alternating the two steps of rotation fitting and Jacobian smoothing for  $k$  iterations in order to improve on the singularity quality through  $J$  while not straying too far from the fabrication constraints imposed by  $S$ .

**5.2.1 Rotation fitting.** Keeping  $S_f$  and  $J_f$  fixed, we determine the rotation  $U$  that minimizes  $E_{fab}$  Eq. (5) for each face  $f$ . This can be done by solving the classic Procrustes problem:  $U = XZ^T$  with  $J_f S_f^T = XYZ^T$  being the SVD decomposition.

**5.2.2 Jacobian smoothing.** We can now keep  $U, S$  fixed and minimize  $E_{sing}$  (7) while adhering to  $E_{fab}$  (5). This can be done through soft-alignment PolyVector smoothing of  $J$  again, this time by adhering isotropically to the optimal  $J$  for  $E_{fab}$  with a smoothing weight of  $\lambda_{sing}$  and alignment weights of 1. Alternating this with rotation fitting gives the optimization more freedom in choosing the orientation of the final flat pattern, yielding nicer singularities at no distortion cost. We use  $k = 10$  iterations in our experiments.

### 5.3 Vector field integration

Following the iterative optimization of  $J_f$  and  $US_f$  optimization, we compute a field-based parameterization by treating  $US_f$  as target gradients for scalar coordinate functions on the mesh and solving the corresponding Poisson equation, yielding the flat shape of the embroidery pattern. We then take the gradients of the parameterization as  $J$ . This is akin to making  $J$  an integrable field. Despite this integration error, the total energy measured on the field after integration converged in all our experiments, and the resulting fabrication error was sufficiently small to reproduce the target shapes.

## 6 Pattern sampling and fabrication

Once the fields have converged, we extract the embroidery pattern by first densely tracing streamlines following the orientation field  $O$  on the 3D target mesh  $\mathcal{M}$ , using a standard streamline tracer [Gillespie 2025]. We then mask out segments corresponding to non-shrinking vectors - i.e. vectors for which  $(\|s_f^i\| - 1)^2 < (\|s_f^i\| - 1/z)^2$  holds - and apply two small corrections in order to increase consistency (note that the lines are never perfectly consistent otherwise, even with a good consistency energy achieved, due to discretization artifacts): short gaps between masked segments smaller than  $2r_c$  are re-activated to avoid unnecessary jumps, and isolated active segments shorter than  $2r_c$  are masked out. We also detect and split loops, where a streamline segment comes close to a much earlier part of the same line. From the resulting line collection, we sample greedily from longest to shortest: a line is kept if it has non-redundant segments, after which all segments of other lines within distance  $r_s$  and similar direction are marked redundant. Here,  $r_s$  is a user-defined sampling density; we set it to 2 mm for our fabrications. This yields a pattern with lines roughly  $r_s$  apart. An example of the filtering and sampling effects is shown in Fig. 6. Finally, the lines are mapped to the 2D  $uv$ -space and saved as SVG polylines, which are converted to an embroidery file via Inkstitch [Ink 2024; The Inkscape Project 2024] with about 5 mm stitch size and lock stitches at each endpoint of a curve.

## 7 Results

The compute time for a single mesh is typically slightly below one minute, with 23-78 iterations until convergence for the fabrication mesh examples, with face counts of 1008-6590. The code is run on an Intel Core i9-13900KF CPU and is not optimized for runtime,

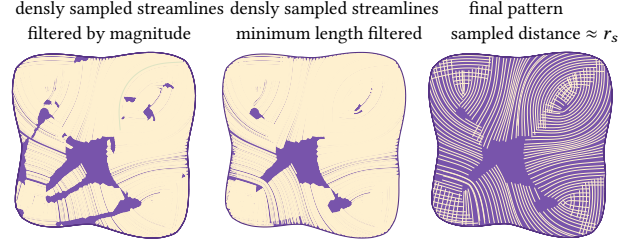


Fig. 6. Pattern sampling process: First, streamlines are densely traced following  $O$  and subsequently filtered by the magnitude of  $s_f^i$  of the corresponding vector (left), then this filtering is adjusted by masking out lines or line interruptions  $< 2r_c$  (middle) and the final pattern samples these lines at a distance of around  $r_s$  (right).

so there is significant room for improvement. The implementation of the method can be found under <https://github.com/oehria/3d-embroidery>.

### 7.1 Virtual preview tool

Since the fabrication can be a timely and costly process, we propose a visualization tool to preview the expected result and estimate the fit to the target surface. The output of our algorithm is a set of 2D stitching edges  $\mathcal{E}_{stitch}$  connecting sampled vertices in the set  $\mathcal{V}_{stitch} \in \mathbb{R}^{n \times 2}$ . We first compute a Delaunay triangulation of  $\mathcal{V}_{stitch}$ , constrained to the parameterization boundary and with a low maximum triangle area constraint, to generate a high-resolution mesh corresponding to the input fabric before the shrinking process. To mimic the draping process and guide the deformation, we initialize by computing an as-rigid-as-possible (ARAP [Sorkine and Alexa 2007]) deformation of the mesh, where the vertices in  $\mathcal{V}_{stitch}$  are fixed to their corresponding positions on the target surface, which are computed by lifting the 2D vertices via the parameterization. We then remove the positional constraints and replace them with a set of shrinking constraints, simulating the shrinking process of the threads. Specifically, we continue the ARAP deformation with an additional energy term that captures the shrinking process:

$$E_{shrink} = w_s \sum_{(i,j) \in \mathcal{E}_{stitch}} \min_{R \in SO(3)} \left\| \mathbf{e}'_{ij} - z R \mathbf{e}_{ij} \right\|_2^2, \quad (8)$$

where  $\mathbf{e}_{ij} = (\mathbf{v}_i - \mathbf{v}_j)$ ,  $\mathbf{v}_i, \mathbf{v}_j \in \mathcal{V}_{stitch}$  is the stitching edge before shrinking,  $\mathbf{e}'_{ij}$  is the edge after shrinking,  $z$  is the shrinking factor (set to 0.8), and  $w_s$  is a weighting factor (set to 10). We follow the local-global optimization strategy, where in the local step we compute the term  $z R_{ij} \mathbf{e}_{ij}$  (by simply scaling  $\mathbf{e}'_{ij}$  by  $z|\mathbf{e}_{ij}|/|\mathbf{e}'_{ij}|$ ), and in the global step we solve a sparse linear system to update the vertex positions. We repeat the local-global optimization until the shrinkage energy converges, i.e. all the stitching edges are shrunk to  $0.8 \pm 0.01$  of their original length. We visualize the results of the deformation in Fig. 7 and compare them with real-world fabrications of the same designs. To capture the intricate details of the physical fabrication, we generate a high-resolution mesh with approximately 80K vertices. The generation of the virtual preview takes around 6-7 seconds on a Mac M1 architecture.

To evaluate the approximation quality of our patterns, we compute the approximation error as the distance of the computed preview to the target surface, and display the results in Fig. 12. Additionally, we also show the stretch distribution of an optimized model in Fig. 12, where it can be seen that the values are mostly around the desired singular values 1 and  $1/z$ . We visualize how the embroidery pattern evolves throughout the optimization in Fig. 10, where it initially only reproduces the rough shape, but later captures more details of the surface, such as the bear’s nose, and introduces more meaningful singularities when needed.

## 7.2 Fabrication

Our fabrications are embroidered with the *Bernina B 790 Plus* sewing machine, using the *Madeira* smocking thread on regular woven cotton fabric. Fig. 7 shows a collection of fabrications draped on their 3D-printed target models, together with renderings of the target shape in order to showcase the approximation quality. The result of the digital preview is provided as well for comparison. Since the shrinkage rate depends on the thread tension on the sewing machine, fabric properties and stitch length, we recommend a calibration step before the actual fabrication: stitch and steam a 10 cm test line and measure the resulting length to determine the exact shrinkage factor  $z$  for the final setup. Fig. 9 shows our fabrications without draping on the target meshes, demonstrating that they can assume their target shape without support. We applied starch spray to the fabrications while draped; with that, they easily hold their shape, but at the same time, the flexibility of the fabric is maintained, so the fabrications can still be easily bent and deformed.

Compared to Canadian smocking [Ren et al. 2024b; Segall et al. 2024], our approach offers significant improvements in fabrication efficiency and reduction of material waste. While smocking remains a fully manual, labor-intensive process that takes between 2 and 10 hours to complete, the embroidery in our method is fully automated and takes only around 30-45 minutes. Furthermore, our shrinking thread technique utilizes fabric more efficiently, requiring only  $\sim 1.2\times$  the fabric area relative to the area of the target surface, while traditional Canadian smocking typically requires a factor of  $\sim 3.3$  due to its large pleats.

## 7.3 Ablations and parameter choices

The parameter  $\lambda_{\text{fab}}$  is set to 1 in order to fix the scale of the energy. For  $E_{\text{stretch}}$ , note that as we project the stretch values onto the two allowed ones (see Sec. 5.1.2),  $\lambda_{\text{stretch}}$  can be seen as an arbitrarily large value. For the evaluation in Fig. 13 we set  $\lambda_{\text{stretch}} = 1$ , so it dominates the total energy. These are the essential terms that directly tie the optimization to the physical process. For all of the other terms, we provide ablations on their benefit. The smoothness weight  $\lambda_{\text{smooth}}$  controls the trade-off between alignment to the Jacobian shrinkage directions and smoothness of the resulting vector field and stitching curves. As shown in Fig. 11, setting this parameter too low or leaving away the smoothness objective yields highly irregular curves, while too large a value causes directions to form an orthogonal grid, degrading feature alignment and approximation quality. However, extreme values are required to produce either of these failure modes. We use  $\lambda_{\text{smooth}} = 1$  across all examples.

The consistency term  $E_{\text{cons}}$  is controlled by two parameters: the consistency radius  $r_c$  and weight  $\lambda_{\text{cons}}$ , whose influence is shown in Fig. 14. Both parameters improve stitching line consistency when increased, resulting in fewer but longer lines, but tend to also increase stitch count. Since large  $r_c$  values push results toward isometric shrinkage, we recommend keeping this radius small; too few interruptions limit the optimization too much. We use  $r_c = 5$  mm across all examples. The weight  $\lambda_{\text{cons}}$  affords more flexibility, but we chose  $\lambda_{\text{cons}} = 0.3$  across all tested models.

The singularity weight  $\lambda_{\text{sing}}$  controls the introduction of singularities in high-curvature regions. Too small a value suppresses singularities where they are needed, resulting in poor curvature approximation and a higher overall average stretch error, as illustrated in Fig. 15. Conversely, too large a value introduces unnecessary singularities in regions where shrinkage alone suffices, as seen for *lilium*. For the gummy bear, initialized with many singularities, we further illustrate that  $E_{\text{sing}}$  can also merge redundant singularities as well as place them in more meaningful regions, as it manages to decrease both seam complexity as well as lowering the error significantly when being introduced. We typically find  $\lambda_{\text{sing}} = 10$  to be a good tradeoff and use this for our fabrications, except for the bear mesh, where we increased to 20 in order to get the seam.

Fig. 13 shows the convergence behavior of our optimization. While individual terms may go up and down during the optimization process in order to trade off different objectives, our method converges to a stable configuration after a while.

## 8 Discussion

We presented a computational method for fabricating 3D shapes through embroidery with shrinking thread, a nearly fully automatic and accessible technique. Through our proposed iterative optimization scheme we can jointly optimize the flattening of the target shape and the needed stitching curves. Our approach accounts for the anisotropic shrinkage behavior of the thread and handles high-curvature regions through the controlled introduction of singularities. Our results demonstrate that the fabricated pieces closely approximate their target shapes while retaining the natural flexibility of fabric.

We hope this work opens new directions in computational fabrication, bridging the gap between digital shape design and accessible, textile-based manufacturing.

*Limitations and future work.* While our method produces faithful approximations of the tested target shapes, several limitations remain. First, the level of fine-grained surface detail that can be reproduced is inherently limited, as the shape emerges from locally compressed fabric, which introduces wrinkles rather than fully smooth or sharp geometric features. Second, our optimization provides no guarantee of convergence to a global minimum, and it is possible that the needed singularities do not arise in order to get a close approximation to the input. However, across all tested shapes, the approximation quality was consistently good, suggesting that this is not a big issue in practice for simple shapes. For non-disk topology meshes with many features of high curvature, the initialization singularity placement could be refined for better results. Further, for easier joining of seams, one could optimize the shape of



the seams to e.g. turn them into smooth geodesic curves. Third, the integration step does not guarantee an injective mapping, meaning that the resulting embroidery pattern may exhibit overlaps that are physically infeasible (see Fig. 8). In such cases, the pattern must be manually split into non-overlapping parts to restore fabricability. Finally, the workflow is not yet fully automated: seam lines must still be sewn together. For simple seams this requires little effort, but for more complex cases one could draw on [Jiang et al. 2026], which joins seams on a single panel by embroidering thread on the seams that can subsequently be used to pull them together. This automates the traditional sewing step, at the cost of excess thread. A natural direction for future work is the addition of bending control to fully fix the extrinsic configuration of the fabricated piece. This could be achieved, for example, by sewing in flexible wires that can be bent into the desired pose, or by coating the finished shape with a rigid material. That said, we view the inherent flexibility of fabric as a distinct advantage over stiffer fabrication media such as polymers: it makes the results wearable and allows them to be wrapped around curved surfaces, a property that would be lost if the fabrication were made fully rigid.

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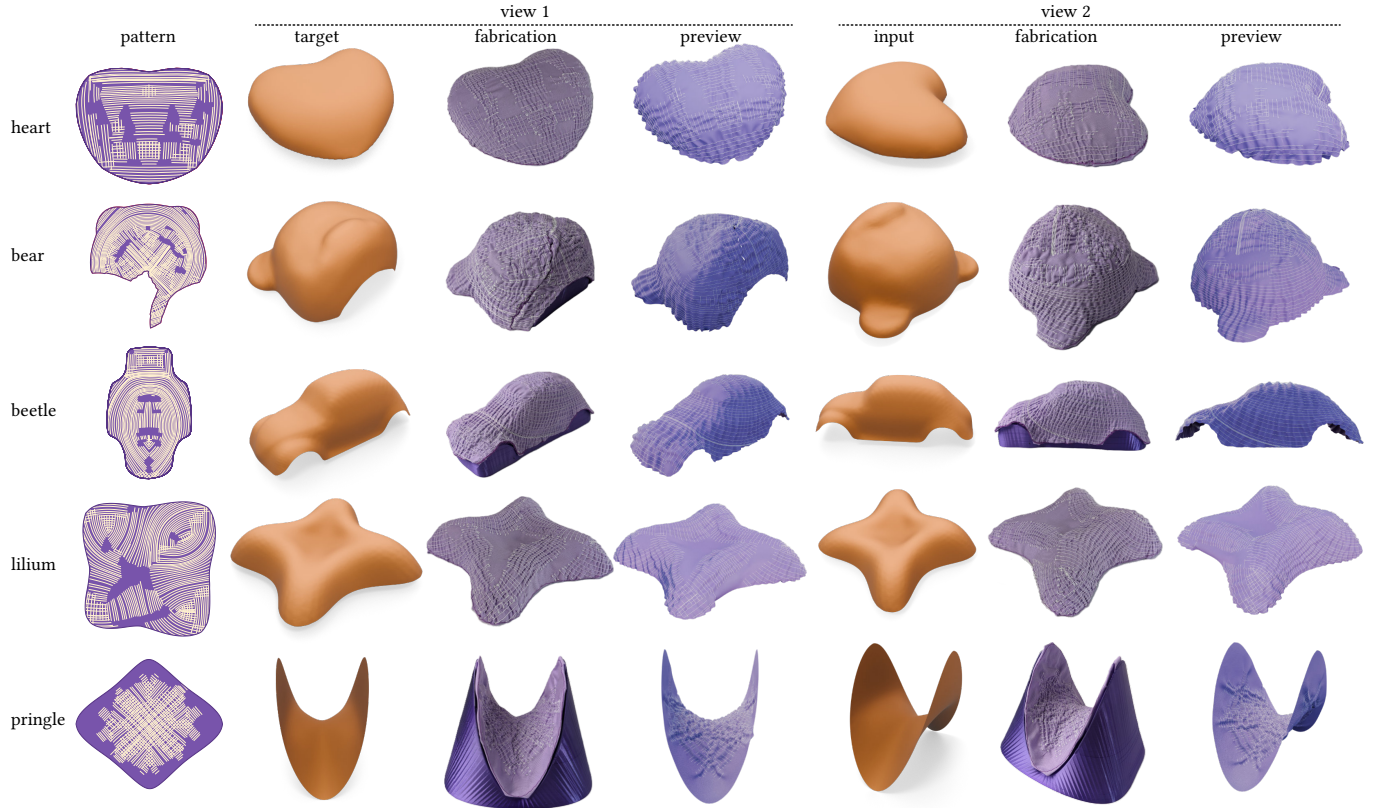


Fig. 7. Example fabrications: we show the pattern and the results from two views, each displaying the input mesh, the physically fabricated result and the digital preview. The model bear is edited from *DS\_Design\_1774304* on printables under CC BY-SA.

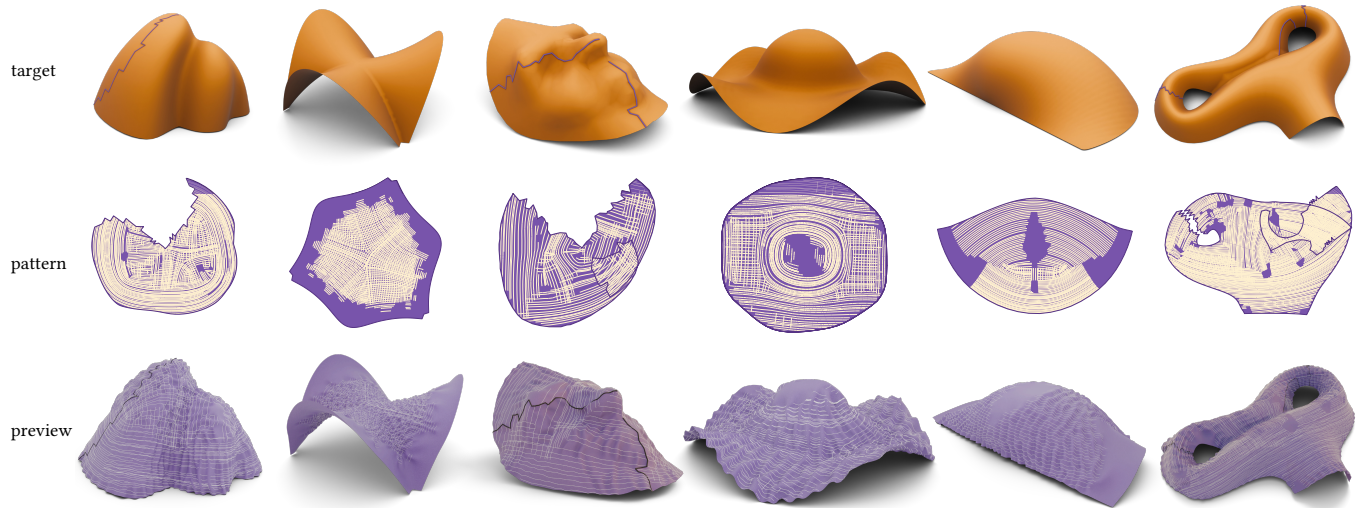


Fig. 8. Optimized stitching pattern and virtual preview of the expected fabrication result. Top row: input surface; middle row: optimized pattern generated by the algorithm; bottom row: virtual preview of the fabrication. Note that while the virtual preview tool is agnostic to overlaps in the stitching pattern, for practical fabrication they must be eliminated by cutting the pattern into patches that must be stitched together before deployment.

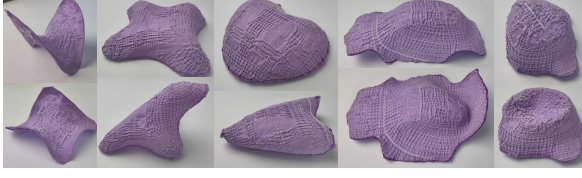


Fig. 9. Fabricated examples without support structure. In the top row, the fabrications stand in the configuration approximating the target surface. The bottom row showcases the flexibility of the fabric, as the shapes can transform into other configurations.

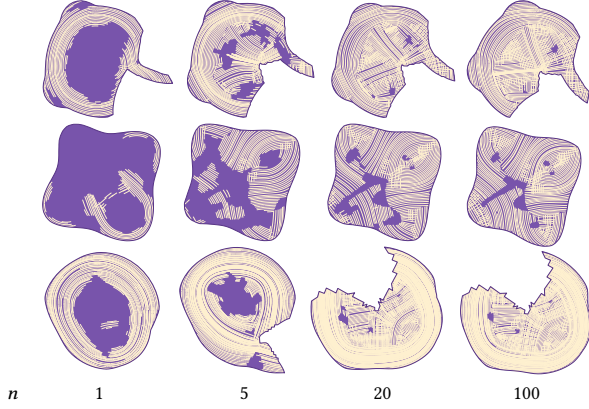


Fig. 10. Evolution of the pattern during the optimization: We show intermediate results at different numbers of iterations  $n$ .



Fig. 11. Influence of smoothness: the result of increasing  $\lambda_{\text{smooth}}$  is visualized. It can be seen that with low value, the pattern is very irregular, highlighting the effect of  $E_{\text{smooth}}$ . The colors visualize the associated magnitudes of  $S$ , with blue corresponding to 1 and red to  $1/z$ .

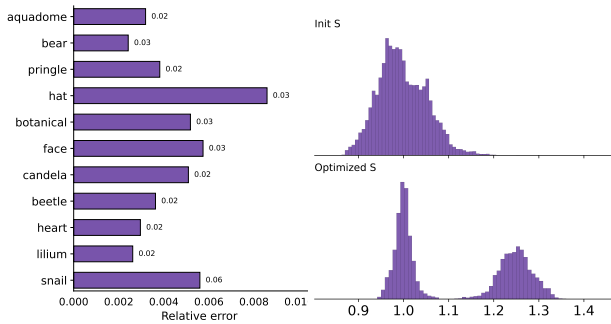


Fig. 12. Error graphs: We show the relative error of the digital preview vs. the original target surface (left), where the average relative error is displayed by the bars, and we also note the maximum error on top. We also show the histograms of the vector magnitudes in the stitching field  $S$  at initialization and after optimization for the *lilium* mesh (right), exhibiting two distinct peaks at the allowed stretching values 1 and  $\frac{1}{z}$ .

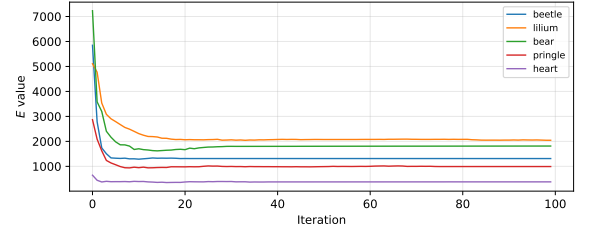


Fig. 13. Convergence of the total energy (dominated by the stretch energy) for all fabricated models. Depicted are the first 100 iterations.

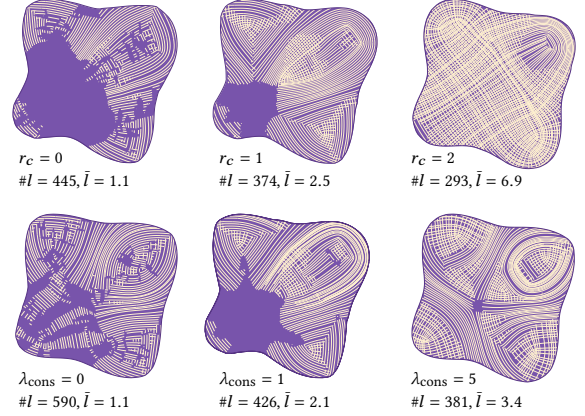


Fig. 14. Consistency influence: the resulting embroidery patterns (without minimum length and jump filtering in the final step) are shown with different consistency radii  $r_c$  and strengths of the consistency term  $\lambda_{\text{cons}}$ . For the  $r_c$  experiments,  $\lambda_{\text{sing}}$  is set to 0 as this makes the difference bigger, however the effect remains visible under higher Jacobian smoothness, as shown in the second row. We also report the number of stitch lines  $\#l$  and average line length  $\bar{l}$  for each pattern.

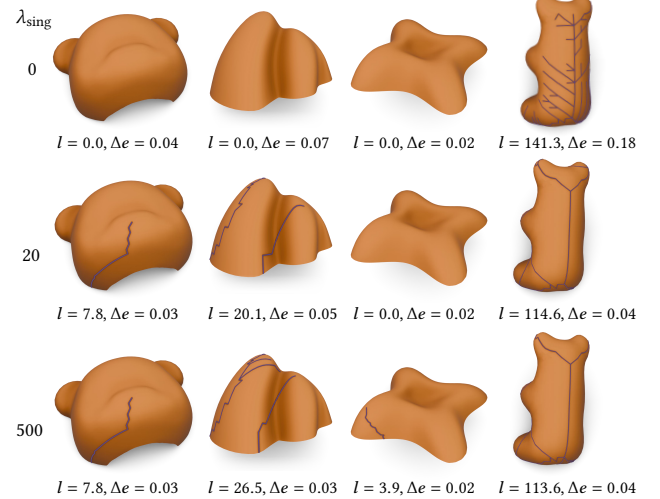


Fig. 15. Singularities arising with different weights  $\lambda_{\text{sing}}$  of the singularity term  $E_{\text{sing}}$ . A higher value introduces new seams in high-curvature regions and can merge seams in low-curvature regions. We report the total length  $l$  of the cut, as well as the average stretching error  $\Delta e$ . The model bear is edited from *DS\_Design\_1774304* on printables under CC BY-SA.