The Fourteenth International Conference on Learning Representations (ICLR) 2026

April 23rd - 27th, 2026

Rio de Janeiro, Brazil

Unsupervised Representation Learning for 3D Mesh Parameterization with Semantic and Visibility Objectives

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Objective

To **automate UV mapping** in 3D content creation in a way that satisfies the properties required by downstream tasks (e.g., texture synthesis), with the goal of **accelerating and simplifying the workflows of UV/layout and 3D modeling artists**

Advantages Our Method Offers

- **Semantic-Awareness:** 2D UV charts are aligned with meaningful 3D mesh surface regions so textures stay coherent and transferable across shapes
- **Visibility-Awareness:** Cutting seams are positioned in less visible areas to minimize noticeable artifacts after texturing and rendering

Core Idea: Train an MLP Backbone To Jointly Learn Geometry-Preserving and Perceptual Properties

1- Geometry-Preserving Objective Learning

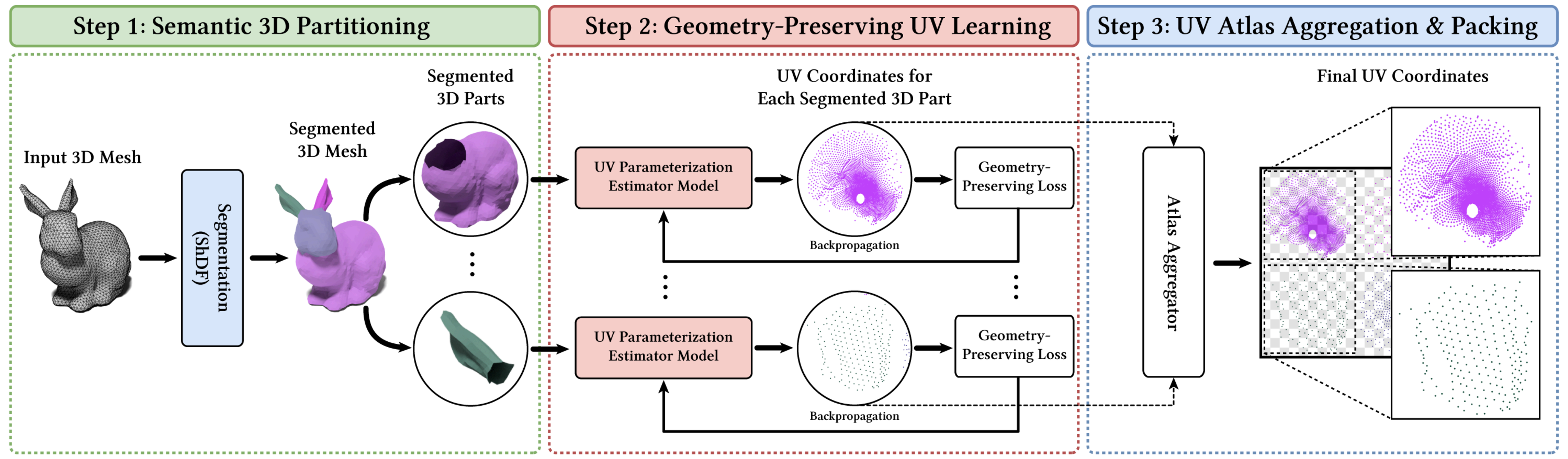
Similar to [1], we formulate bijectivity, isometricity, conformality, and equiareality as differentiable objectives and train an MLP to minimize their weighted sum.

2- Perceptual Objective Learning

- **Semantic-Aware UV:** Segment mesh into semantic 3D parts using Shape Diameter Function [2], learn a geometry-preserving UV for each part with the same MLP as in (1), and merge the resulting charts into one unified UV atlas.
- **Visibility-Aware UV:** Use Ambient Occlusion (AO) [3] as a proxy for viewer exposure to encourage seam placement in low-visibility regions.

Systematic Approach to The UV Parameterization Learning Problem

Semantic-Aware UV Parameterization Learning



Visibility-Aware UV Parameterization Learning

(1) Compute per-vertex AO values on the input mesh

$$V(p,\omega)=\begin{cases}1, & \text{if the ray starting at } p \text{ in direction } \omega \text{ does not intersect the surface (unoccluded)}\\ 0, & \text{otherwise (occluded)}\end{cases}$$

The binary visibility function $V(p,\omega)$ measures whether direction ω is visible from a point p on the mesh surface with unit normal vector $n(p)$

$$AO(p) = \frac{1}{\pi}\int_{\Omega^+(p)} V(p,\omega)\,(n(p)\cdot\omega)\,\mathrm{d}\omega$$

By this convention, $AO(p) = 1$ indicates a fully exposed point (no occlusion) and $AO(p) = 0$ indicates a fully occluded point

(2) Apply a base UV-parameterization backbone to obtain candidate UV islands

Intuitively, the **bi-directional cycle mapping** [1] enforces that projecting a 3D surface patch into 2D UV coordinates and re-projecting those UVs back onto the 3D mesh yields the original data.

(3) Extract UV boundary points corresponding to cutting seams

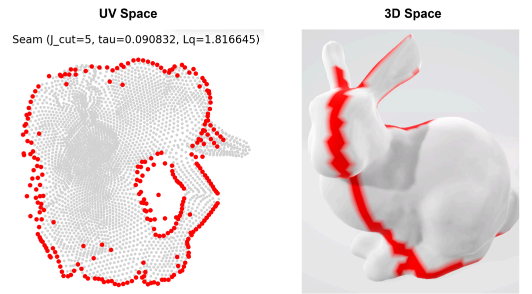
$$\eta_i = \max\left(\|q_i - q_{i,j}\|_2\right)_{j=1}^{N} \longrightarrow s_i = \sigma\big(\beta(\eta_i - \tau)\big)$$

Each point in UV space

N nearest neighbor UV coordinates

Per-vertex seam membership score

A threshold based on the UV domain size $\leftarrow \tau = \tau_{\text{scale}}\, L(Q) \rightarrow$ The side length of bounding square of the UV map



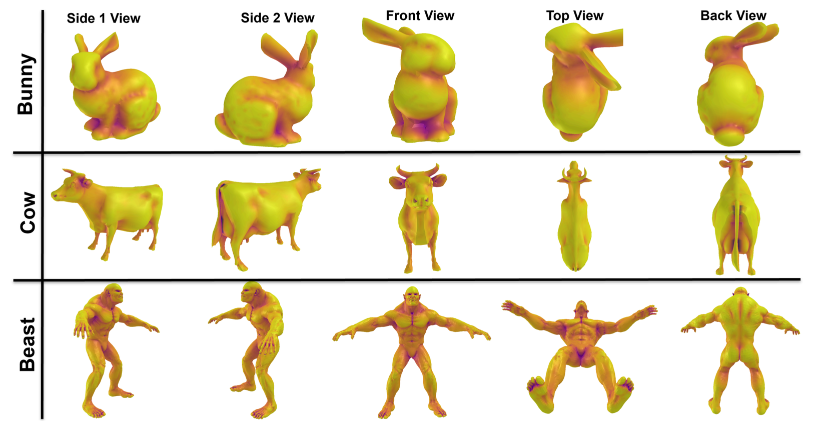
(4) Minimize the AO-weighted average over the associated 3D vertices

$$\mathcal{L}_{\text{AO}} = \frac{\sum_i s_i\, AO_i}{\sum_i s_i + \varepsilon} \longrightarrow \mathcal{L}_{\text{vis}}(\theta) = \mathcal{L}_{\text{wrap}} + \mathcal{L}_{\text{cycle}} + \mathcal{L}_{\text{repel}} + \mathcal{L}_{\text{dist}} + \lambda_{\text{vis}}\,\mathcal{L}_{\text{AO}}$$

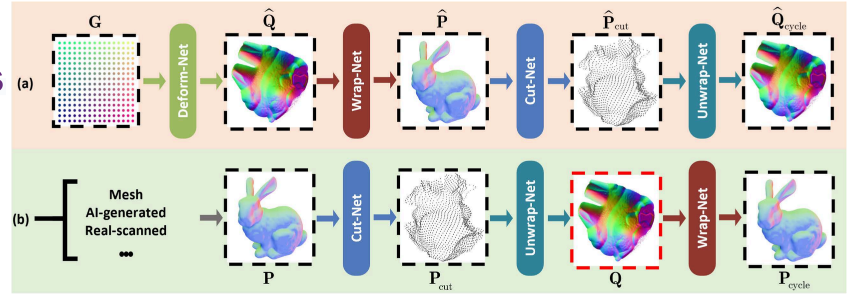
AO_i → Per-vertex ambient occlusion

ε → A small constant to avoid division by zero

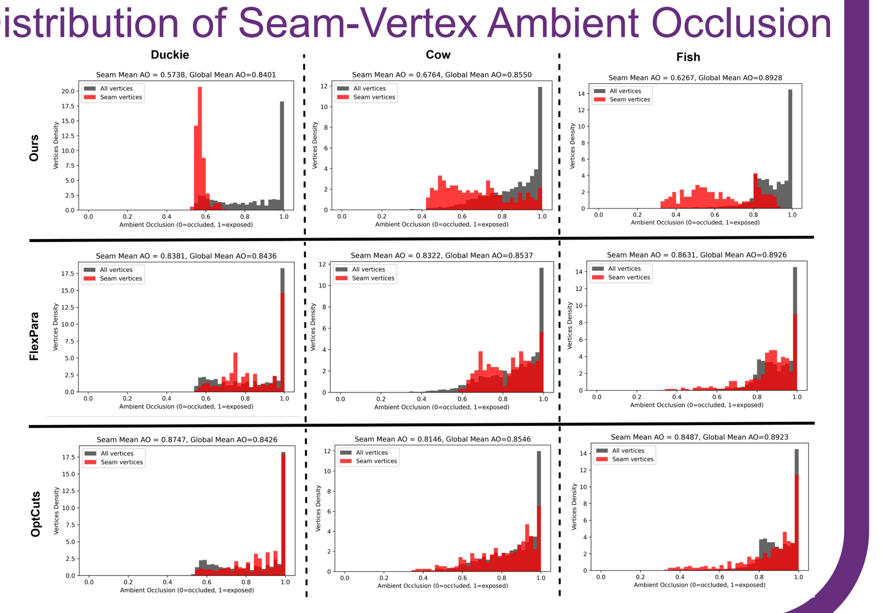
Per-Vertex Ambient Occlusion Visualization



Bidirectional Cycle Mapping [1]

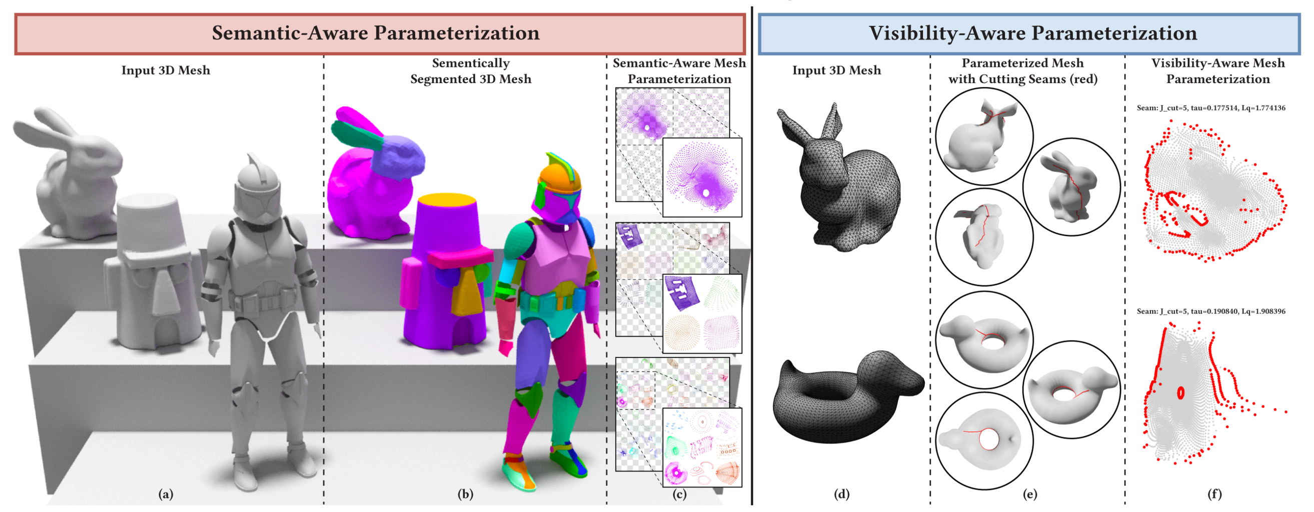


Distribution of Seam-Vertex Ambient Occlusion

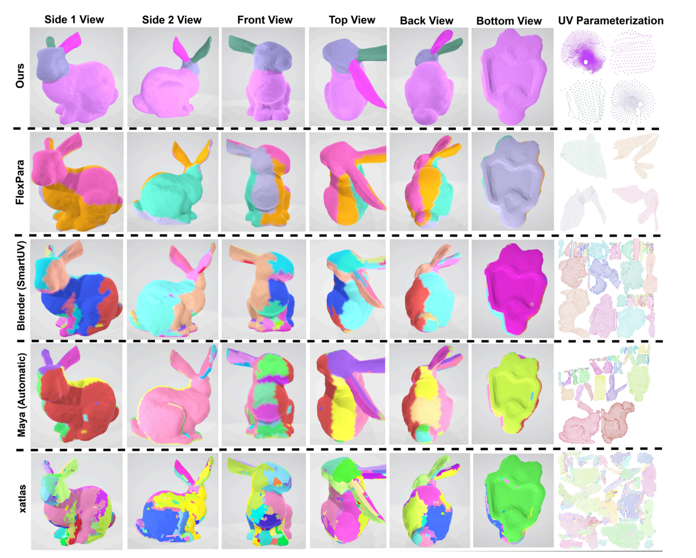


Simulation Results

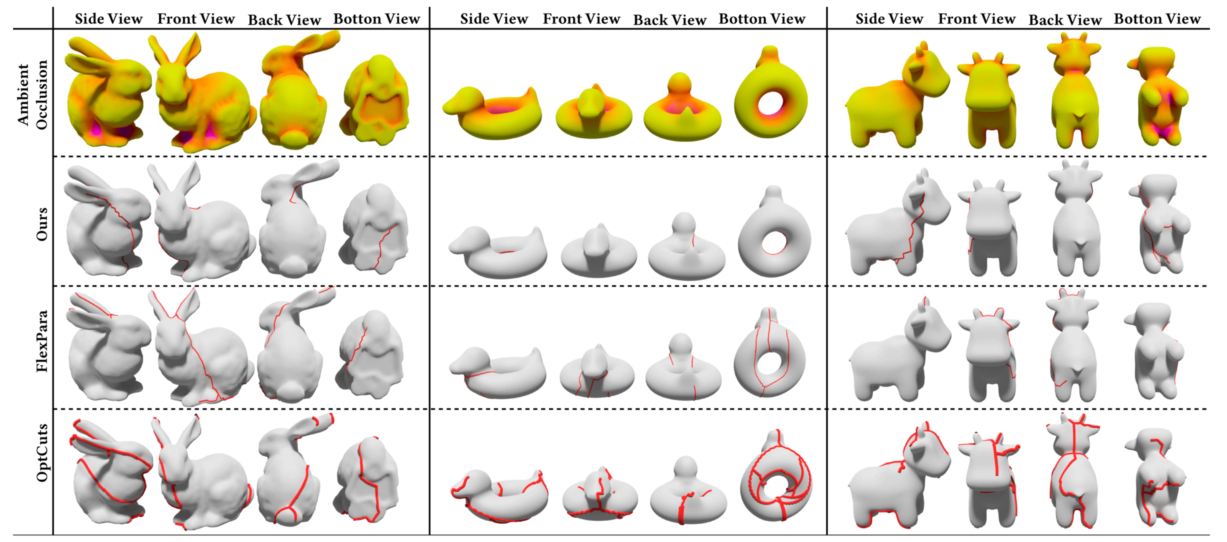
3D Mesh Parameterization Generated by Our Proposed Pipelines



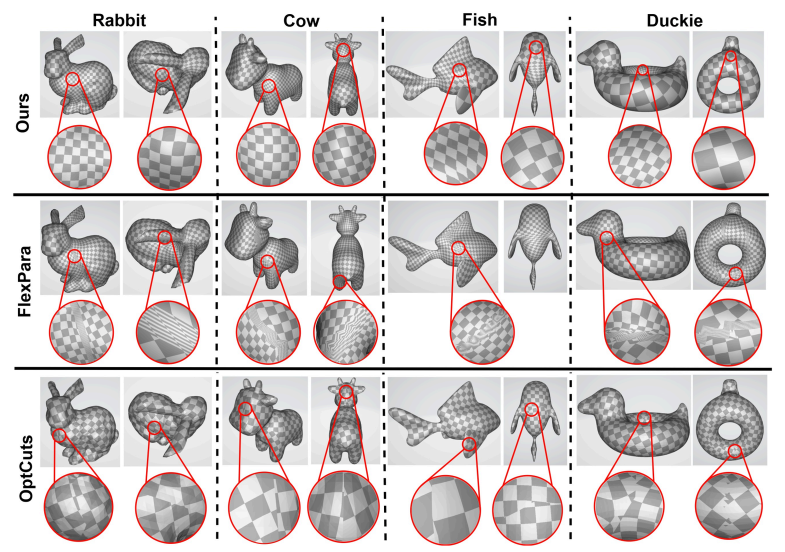
Comparison of Semantic-Aware UV Parameterization



Comparison of Visibility-Aware UV Parameterization



Comparison of Checkerboard Texturing



Quantitative Comparison of Semantic-Aware UV Parameterization

Method	Semantic Awareness		Conformality ↑	Equiareality ↑	Inference Time (sec) ↓
	Hamming Distance ↓	Rand Index ↑			
xatlas [5]	0.8896	0.7023	**0.9792**	**0.9341**	12
Blender [7]	0.8634	0.7173	0.9289	0.9023	< 1
Maya [6]	0.8615	0.7125	0.9272	0.8746	< 1
FlexPara (Multi-Chart) [1]	0.5980	0.6902	0.9592	0.7606	2
Ours - Semantic-Aware Param	**0.3188**	**0.8151**	0.9123	0.6707	15
Ours - Semantic+Visibility-Aware Param	0.3212	0.8087	0.9153	0.6369	15

Quantitative Comparison of Visibility-Aware UV Parameterization

Method	Visibility ↓	Conformality ↑	Equiareality ↑	Time (s) ↓
OptCuts [4]	0.7855	**0.9341**	**0.8934**	240
FlexPara (Single-Chart) [1]	0.8604	0.9097	0.6759	2
Ours - Visibility-Aware Param	**0.6065**	0.9175	0.6093	2
Ours - Semantic+Visibility-Aware Param	0.6534	0.9153	0.6369	15

User Study with 45 Expert Participants

Method	Expert User Preference Percentage
Visibility-Awareness Evaluation	
OptCuts [4]	1.48 %
FlexPara (single-Chart) [1]	4.81 %
Ours - Visibility-Aware Param	**93.70 %**
Semantic-Awareness Evaluation	
xatlas [5]	2.66 %
Blender [7]	5.33 %
Autodesk Maya [6]	8.44 %
FlexPara (multi-Chart) [1]	3.33 %
Ours - Semantic-Aware Param	**80.22 %**

References

[1] Zhao, et al. "FlexPara: Flexible Neural Surface Parameterization," IEEE TPAMI 2025.
[2] Shapira, et al. "Consistent Mesh Partitioning and Skeletonisation using The Shape Diameter Function," The Visual Computer 2008.
[3] Zhukov, et al. "An Ambient Light Illumination Model," Eurographics Workshop on Rendering Techniques 1998.
[4] Li, et al. OptCuts: Joint Optimization of Surface Cuts and Parameterization.
[5] xatlas: Mesh Parameterization and UV Unwrapping Library, https://github.com/jpcy/xatlas
[6] Autodesk Maya, https://www.autodesk.com/products/maya/overview
[7] Blender, https://www.blender.org/