Structured 3D Modeling: Connecting Surface Detail with Internal Skeleton

Minglun Gong
School of Computer Science
University of Guelph

Outline

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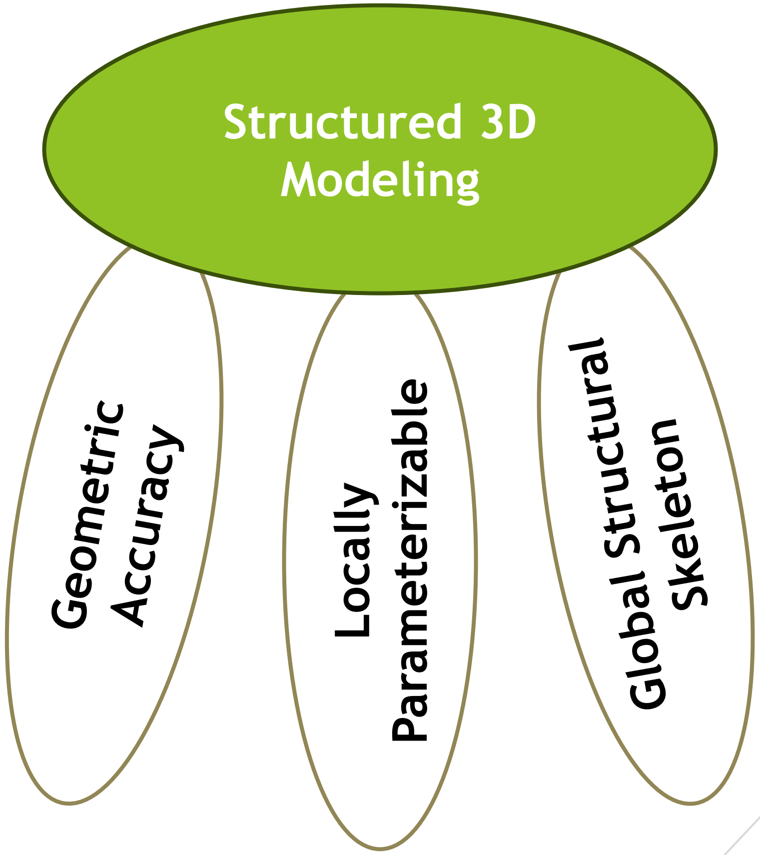
  - The three pillars for structured 3D modeling
- Skeletal-Anchored Dual Harmonics (SADH)
  - SADH representation
  - Staged optimization process
- Experimental Results
  - Surface reconstruction + skeletal structure
  - Robustness to incomplete point clouds
  - Unsupervised cross-Shape co-clustering
- Conclusions & Future Directions

What is Structured 3D Modeling?

- Definition:
  - Moving beyond raw geometric data (e.g., point clouds) to representations that encode explicit organization, hierarchy, and semantic meaning.
  - A unified representation that explicitly links the underlying topological skeleton (global structure/connectivity) to the physical surface (geometry and local manifolds).
  - It bridges the gap between "what the shape looks like" (geometry) and "how the shape is organized" (structure).
- Beyond the Status Quo:
  - It moves beyond raw point clouds and triangle meshes, which merely describe where matter is, but fail to encode how it is organized.
- The Implication:
  - The skeleton acts as a blueprint that governs the arrangement and parameterization of the local surface patches.

Three Pillars of Structured 3D Modeling

- A holistic model must simultaneously provide three distinct guarantees:
  - Geometric Accuracy - What does it look like? High-fidelity reconstruction of fine, anisotropic surface details.
  - Locally Parameterizable - How is it broken down? Decomposition into simple, disk-like 2D patches for compact representation.
  - Global Structural Skeleton - How is it connected? An internal anchor graph that preserves structural relationships and topology.



Accurate Surface Geometry

- Goal:
  - Precisely capture high-fidelity details (edges, curvatures, textures).
- Benefits:
  - Ensures visual realism and rendering quality.
  - Enables accurate physical collision/simulation.
  - Essential for high-precision reverse engineering.

Locally Parameterizable

- Goal:
  - Decompose the surface into clean, disk-like 2D patches that are locally parameterizable.
- Benefits:
  - Enables compact representation using efficient 2D functions.
  - Provides topological guarantees: each patch is homeomorphic to a disk.
  - Supports parallel processing: each patch can be fitted independently

Global Structural Skeleton

- **Goal:**
  - Recover the internal skeleton graph that governs global shape topology and part connectivity (e.g., branching of fingers/limbs).
- **Benefits:**
  - Preserves structural relationships between parts for semantic shape understanding.
  - Enables intuitive deformation and animation.
  - Supports topology-aware editing and segmentation

Importance in the Physical AI Era

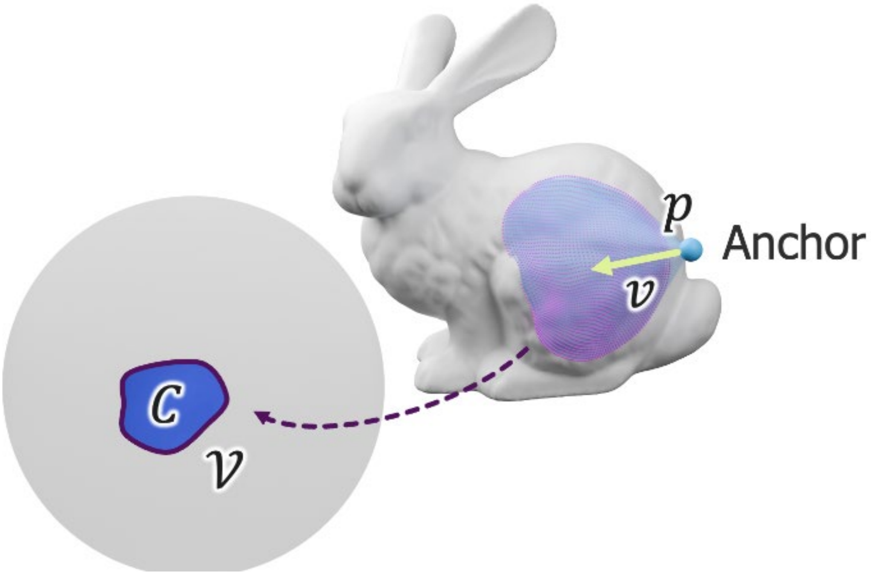
- AI is moving beyond 2D vision to actionable, physical understanding.
- Accurate Geometry:
  - High-fidelity surfaces enable accurate physics simulation—collision, friction, and dynamics—for realistic interaction.
- Parameterizable and Manifold:
  - Locally parameterizable patches provide a natural tokenization of 3D shapes, supporting shape analysis and generative modeling.
- Structural Skeleton:
  - A global structural skeleton acts as a semantic blueprint, enabling robots to understand articulation, part relationships, and plan grasping strategies.

“Trade-off” in Existing Modeling Methods

Representation	Representative Methods	Geometry Detail	Parameterizable Patches	Global Structure
Neural Implicit Fields	DeepSDF [2019] OccNet [2019]	Excellent	Limited (Hard to extract patches)	Poor (No underlying connectivity)
Local / Patch	ARO-Net [2023] MASH [2025]	Excellent	Excellent	Poor (Fails to connect patches semantical)
Skeletal	DPC [2015] Coverage Axis++ [2024]	Poor (Loses fine surface detail)	Limited (Hard to map back to simple patches)	Excellent
Coupled Surface-Skeleton	PAM [2014] MSD [2024]	Good to Excellent	Limited (Primitive-based)	Excellent

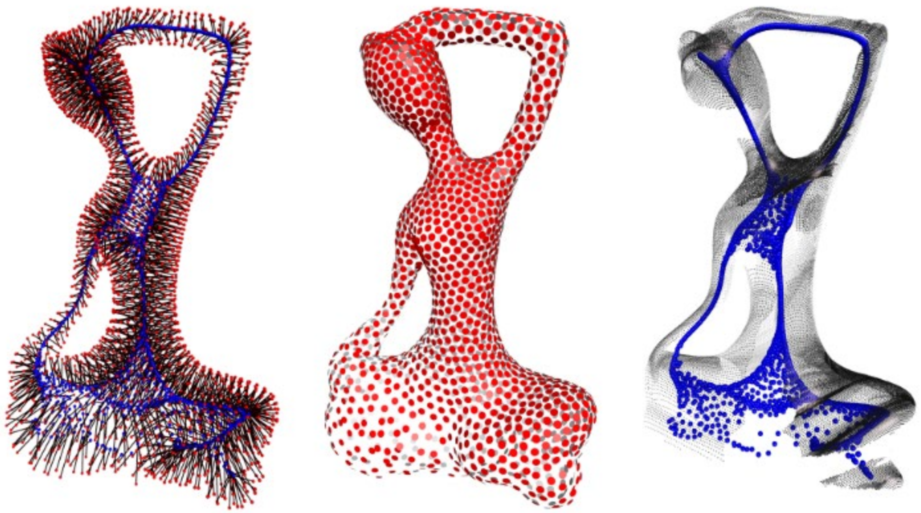
Masked Anchored Spherical Distances (MASH) [2025]

- Key Innovations:
  - Patches encoded using spherical harmonics (SH) for compactness (L=2 balances accuracy and efficiency)
  - Generalized view cone with parameterized base masks spatial extent of each spherical function for locality
  - Differentiable optimization converts point clouds to MASH representation
  - Handles arbitrary geometry and topology (open surfaces, complex internal structures)



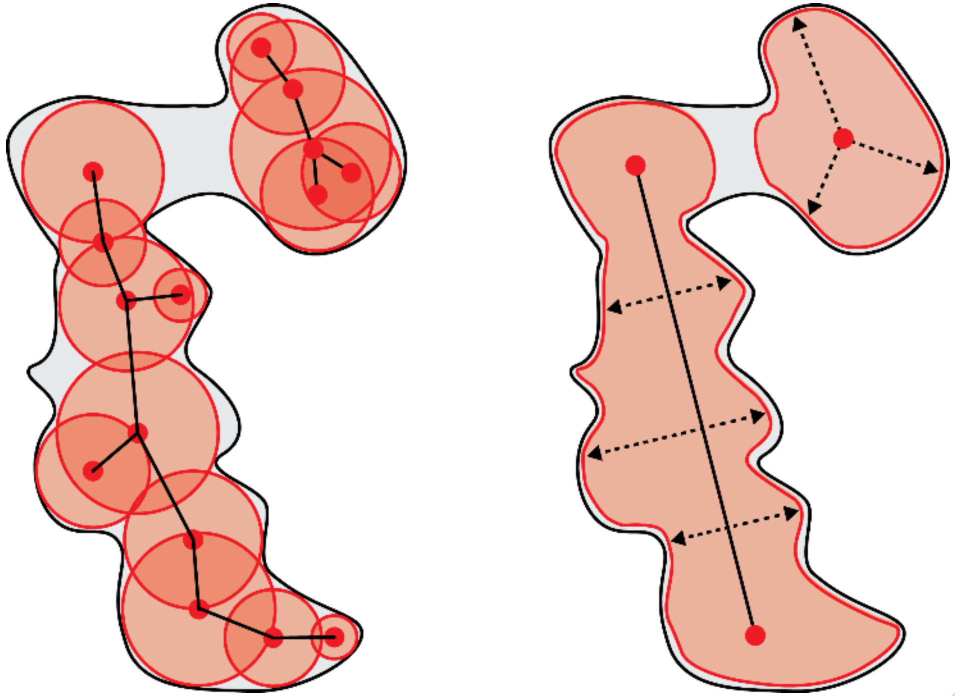
Deep Points Consolidation (DPC) [2015]

- Key Innovations:
  - Joint optimization of surface points (outer) and skeletal points (inner) in a unified framework
  - Inner points form a coherent meso-skeleton (mixture of curves and sheets)
  - Outer points consolidate and complete missing regions
  - Representation encodes both local and non-local geometric information



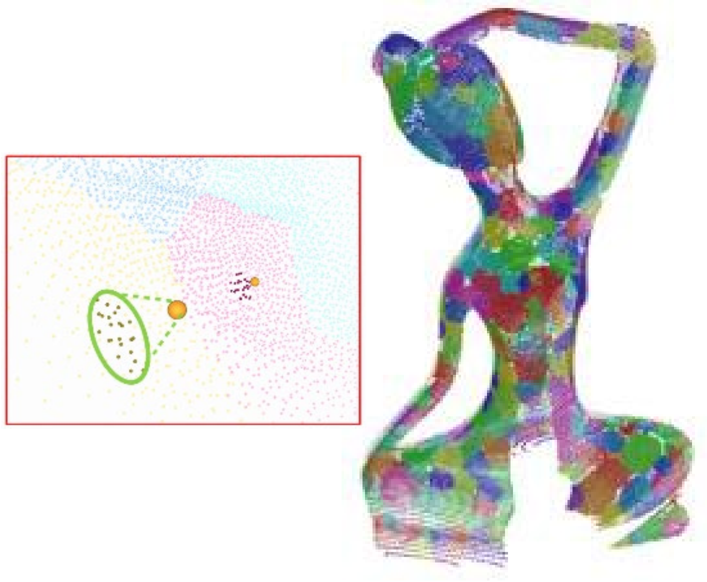
Medial Skeletal Diagram (MSD) [2024]

- Key Innovations:
  - Generalized enveloping primitives (anisotropic, direction-dependent radii)
  - Skeleton remeshing via Restricted Voronoi / Delaunay
  - Global optimization for minimal primitive count
  - Feature-preserving refinement for exact mesh alignment

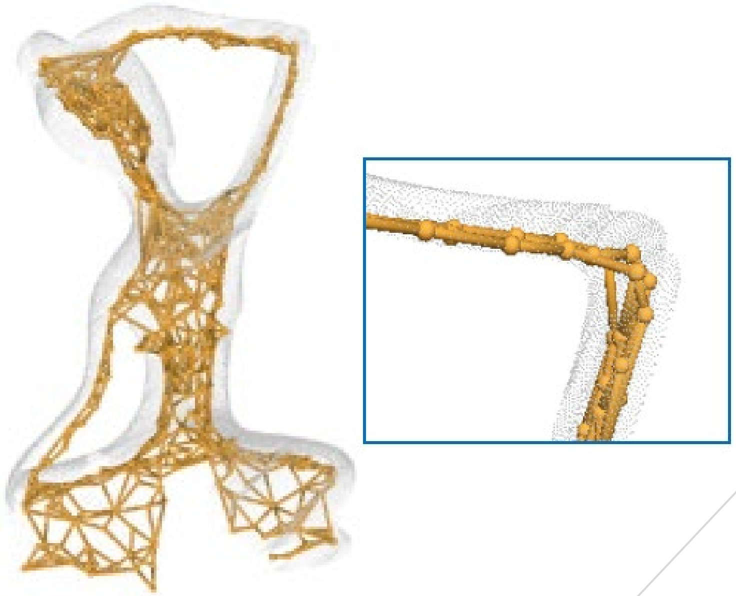


The Missing Link

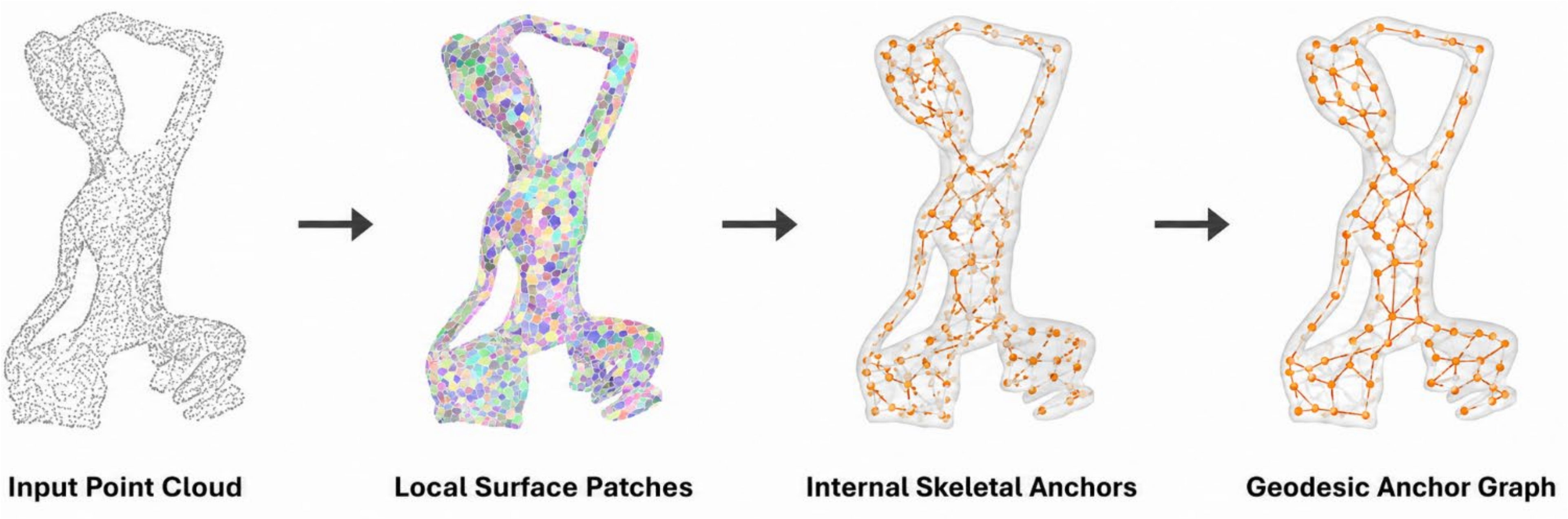
- Local Parameterizable Surface Patches
  - Expressive geometry
  - Compact representation
  - High fidelity
- Global Meso-skeleton
  - Global organization
  - Connectivity
  - Semantic blueprint



How to couple them?



Skeletal-Anchored Dual Harmonics (SADH)

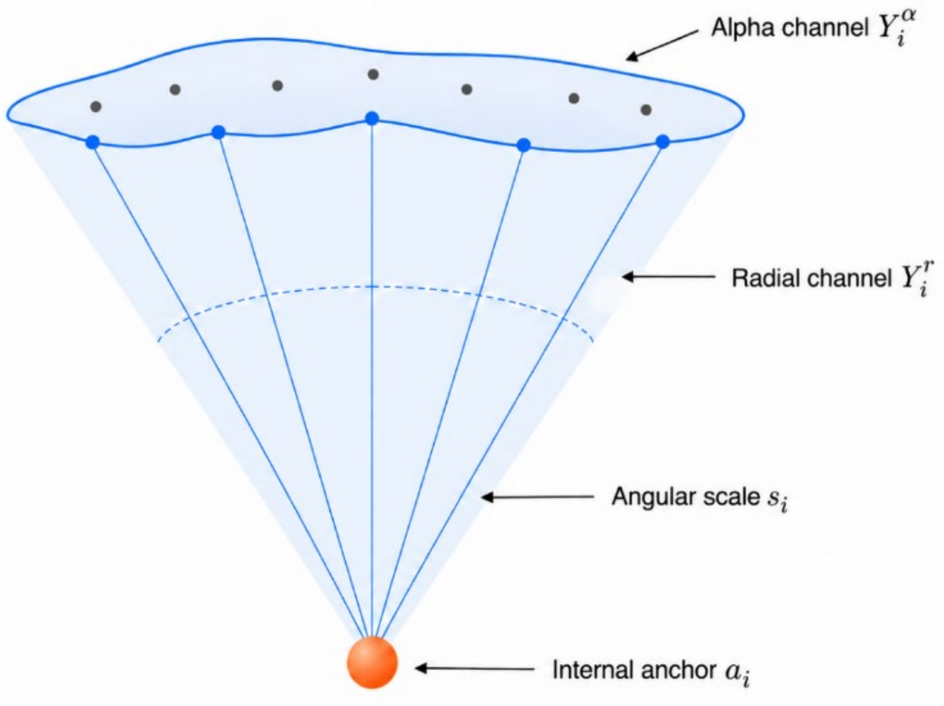


Use of Anchor Graph in Other Domains

Method	Uses Surface Patches?	Uses an Anchor/ Internal Graph?	Domain / Application
AG²aussian	No (uses 3D Gaussians)	Yes (Anchor-graph)	3D Scene Understanding & Editing
ScaffoldAvatar	No (uses 3D Gaussians)	Yes (Anchors bound to patch centers)	Avatar Reconstruction & Animation
LAKe-Net	No (uses sparse keypoints)	Yes (Surface-skeleton)	Topology-Aware Point Cloud Completion
Patch-based Skinning	Yes	No (Patches are on the surface)	Character Animation
SADH	Yes	Yes (Geodesic anchor graph)	Structured 3D Shape Modeling

SADH Patch Representation

- $P_i = \left(a_i, R_i, s_i, Y_i^{\langle r,\alpha \rangle}\right)$
  - Anchor Position $(\boldsymbol{a_i} \in \boldsymbol{R}^3)$
  - Local Frame $(\boldsymbol{R_i} \in \boldsymbol{SO}(3))$ Defines the outward-facing orientation of the patch.
  - Angular Scale$(\boldsymbol{s_i} \in [\mathbf{0}, \mathbf{1}])$ Controls the opening angle of the viewing cone.
  - Dual-Channel Spherical Harmonics $(\boldsymbol{Y_i^{\langle r,\alpha \rangle}})$
    - $(\boldsymbol{Y_i^r})$: ***models radial distance from the anchor to the surface.***
    - $(\boldsymbol{Y_i^\alpha})$: ***defines the active support region of the patch.***



Dual Harmonics: Geometry + Support

- Dual harmonics decouple surface geometry from patch support
- Radial Channel Y_i^r models surface geometry
  - For each direction (ϕ, θ), $Y_i^\alpha(\phi, \theta)$ determines the radial distance from the anchor to the surface.
- Alpha Channel Y_i^α defines patch support
  - A sample is active when $Y_i^\alpha(\phi, \theta) \geq \tau_\alpha$
  - Determines which directions inside the viewing cone belong to the patch.

From Local Patches to a Global Structure

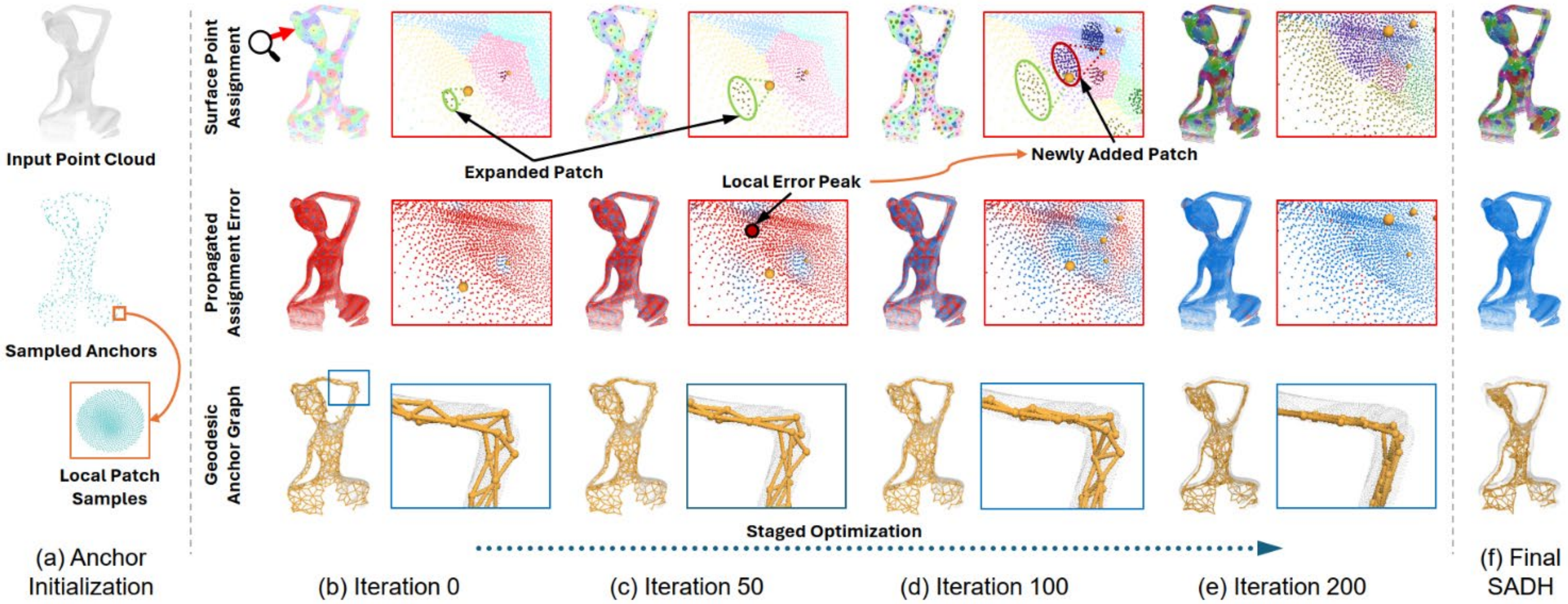
- Local Surface Representation
  - Each patch models a compact local surface region.
  - Each patch is rooted at an internal anchor.
  - Surface points are assigned to their best-fitting patch.
- Global Structural Organization
  - Adjacent surface patches induce connections between their anchors.
  - These connections form a geodesic anchor graph.
  - The graph preserves structural relationships across the whole shape.
- Key distinction: Anchors are connected only when their patches are adjacent—spatial proximity alone does not imply connectivity.

SADH Optimization

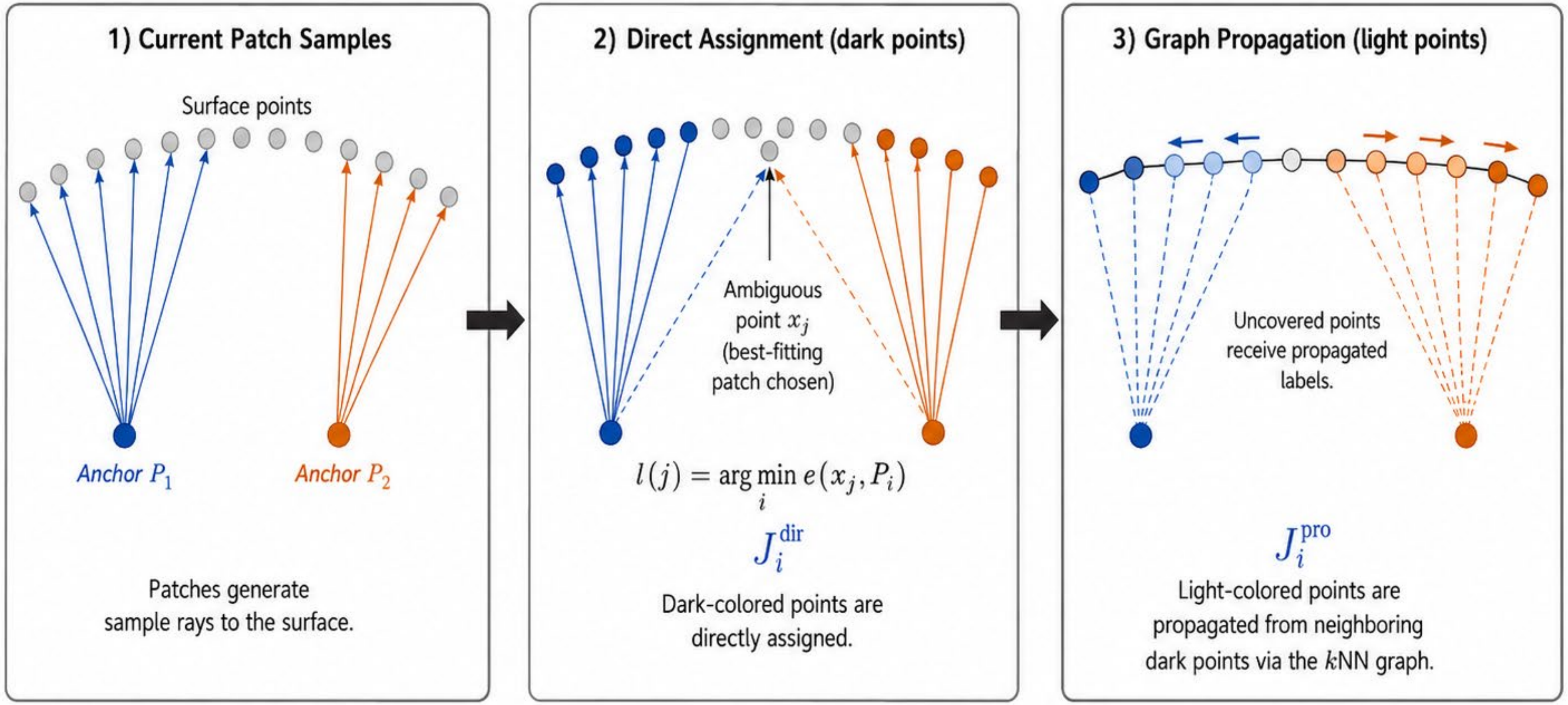
- Given: Oriented point set $S = \{(x_j, n_j)\}_{j=1}^{N}$
- Optimize: A set of SADH patches $\{P_i\}_{i=1}^{M}$ under three coupled objectives:
  - Reconstruction - Each patch accurately fits its surface region.
  - Skeletal Coherence - Anchors form a coherent internal skeleton capturing global topology.
  - Coverage - The union of all patches covers the entire surface.

Step	What It Optimizes
Patch Initialization	Initial anchor placement and patch setup
Surface Point Assignment	Assign points to best-fitting patches
Dual-Harmonic Surface Fitting	SH parameters $Y^{(r,\alpha)}$ (local geometry)
Skeletal Regularization	Anchor locations a_i (global structure)
Coverage Optimization	Anchor orientations and angular scales $\{R, s\}$ (patch support)

Staged Optimization Pipeline



Step 1: Surface Point Assignment



Step 2: Dual-Harmonic Surface Fitting

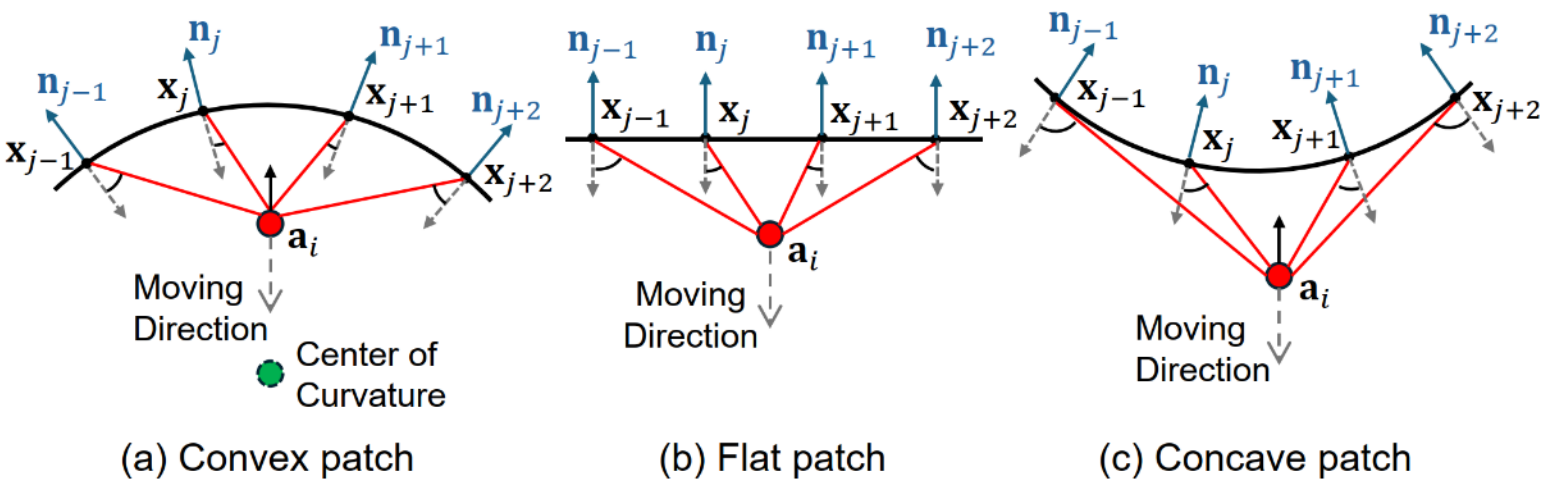
- Fitting Loss — Where should the surface be?
  - Each active patch sample is fitted to its nearest input surface point
  - Purpose: improve the geometric accuracy of the radial channel
- Coverage Loss — How far should the patch extend?
  - The assigned/colored surface points indicate where the patch should expand.
  - Purpose: increase the angular scale so that the viewing cone covers its assigned surface region.
- Alpha Loss — Which direction should stay active?
  - Learn which directions should remain active inside the viewing cone.

Step 3: Skeletal Regularization

- The anchor points are pushed onto the meso-skeleton.
  - First generate geodesic anchor graph through patch adjacency.
  - Then optimize anchor point locations using three terms:
    - *Meso-skeleton Loss*
    - *Centering Loss*
    - *Opposing-Anchor Repulsion Loss*
- Meso-skeleton Loss
  - Encourages each anchor to lie on the meso-surface formed by its neighboring anchors in the geodesic anchor graph.
  - Penalize the signed distance between each anchor and the tangent plane at its neighbor anchors.

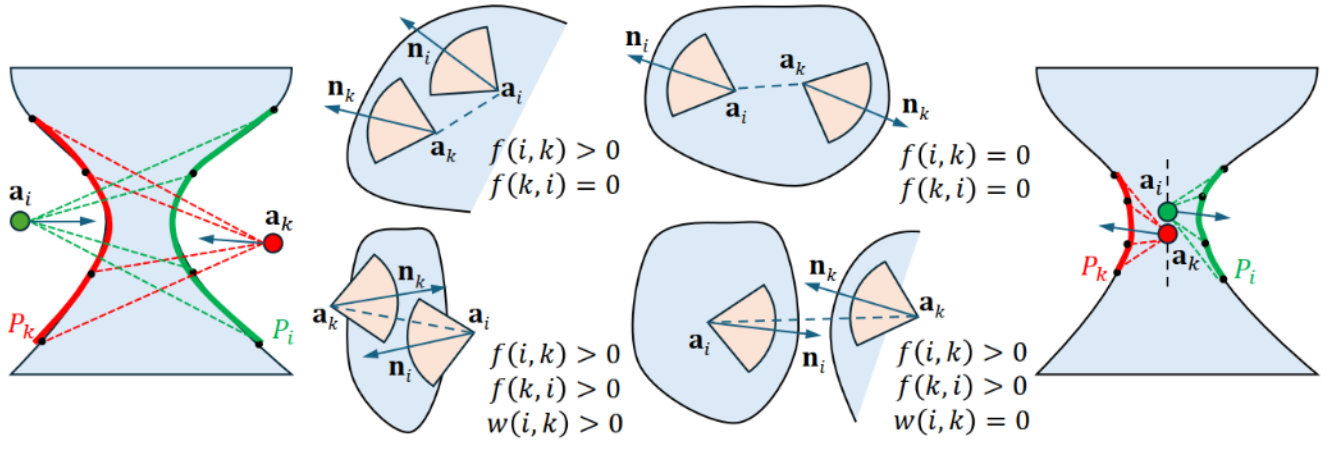
Step 3: Centering Loss

- Centering Loss
  - Penalizes the angular deviation between the vector from a surface point to its anchor and the inward normal direction.
  - For a convex patch, places the anchor near the center of curvature.
  - For a flat or concave surfaces, the constraint alone pushes the anchor toward infinity



Step 3: Opposing-Anchor Repulsion Loss

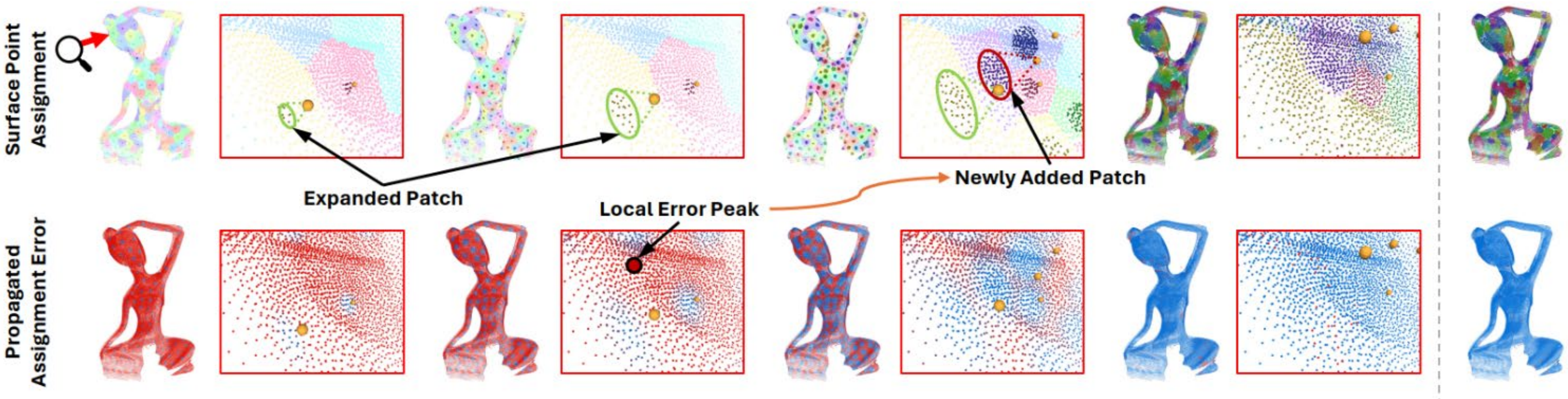
- In thin structures, anchors may pass through each other rather than forming a medial structure.
  - The repulsion term encourages the anchors to settle on a common medial sheet or axis
  - It is activated only for nearby anchors whose outward axes face each other



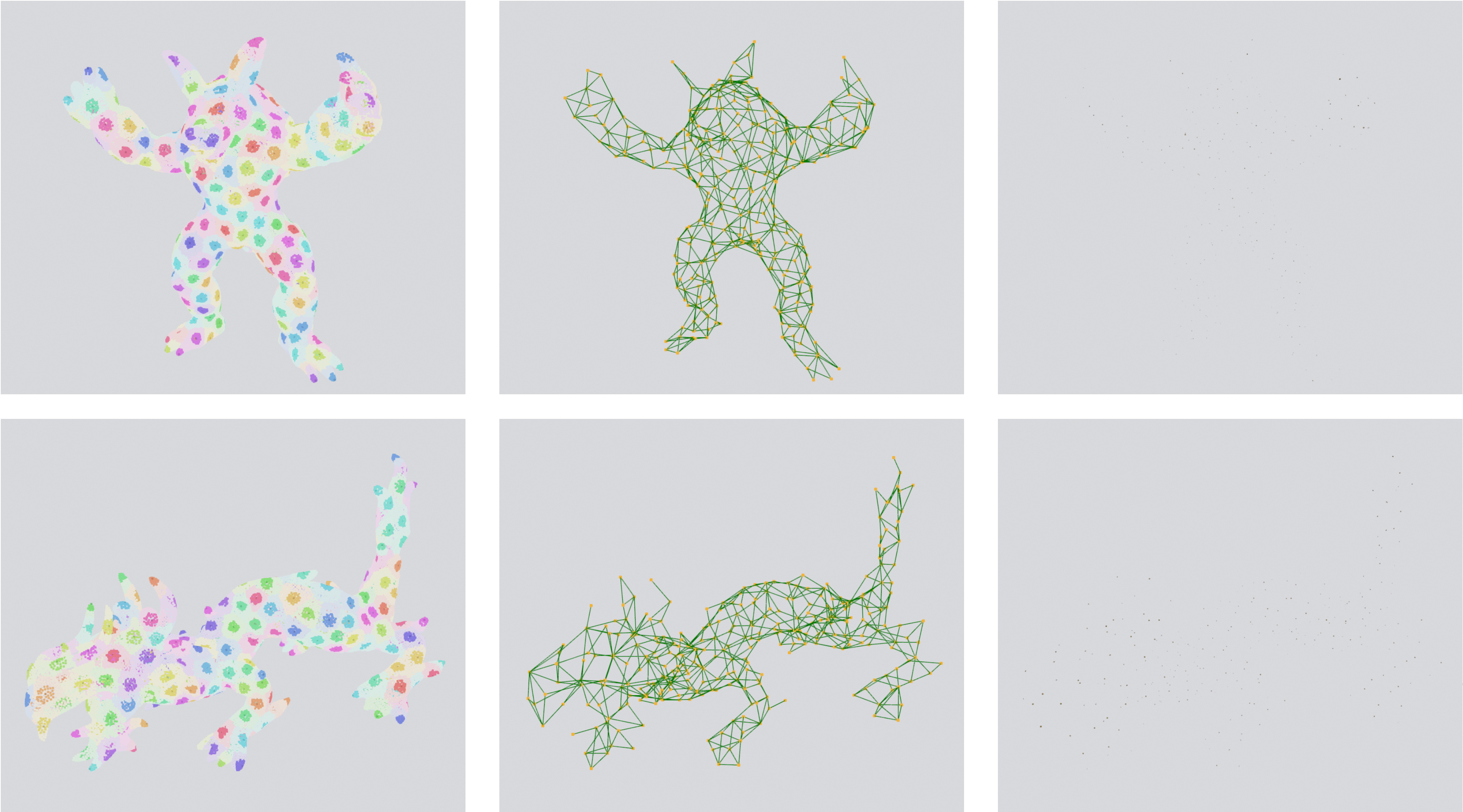
(a) Without $\mathcal{L}_{\text{repel}}$ (b) Valid and invalid opposing pairs (c) With $\mathcal{L}_{\text{repel}}$

Step 4: Coverage Optimization

- Achieved by:
  - Gradually adjusting the orientation and angular scale of individual patches $\{R, s\}$.
  - Removing patches that do not contribute sufficiently to the surface representation.
  - Inserting new anchor points in poorly represented surface regions.



Convergence Visualization (400 Anchors)



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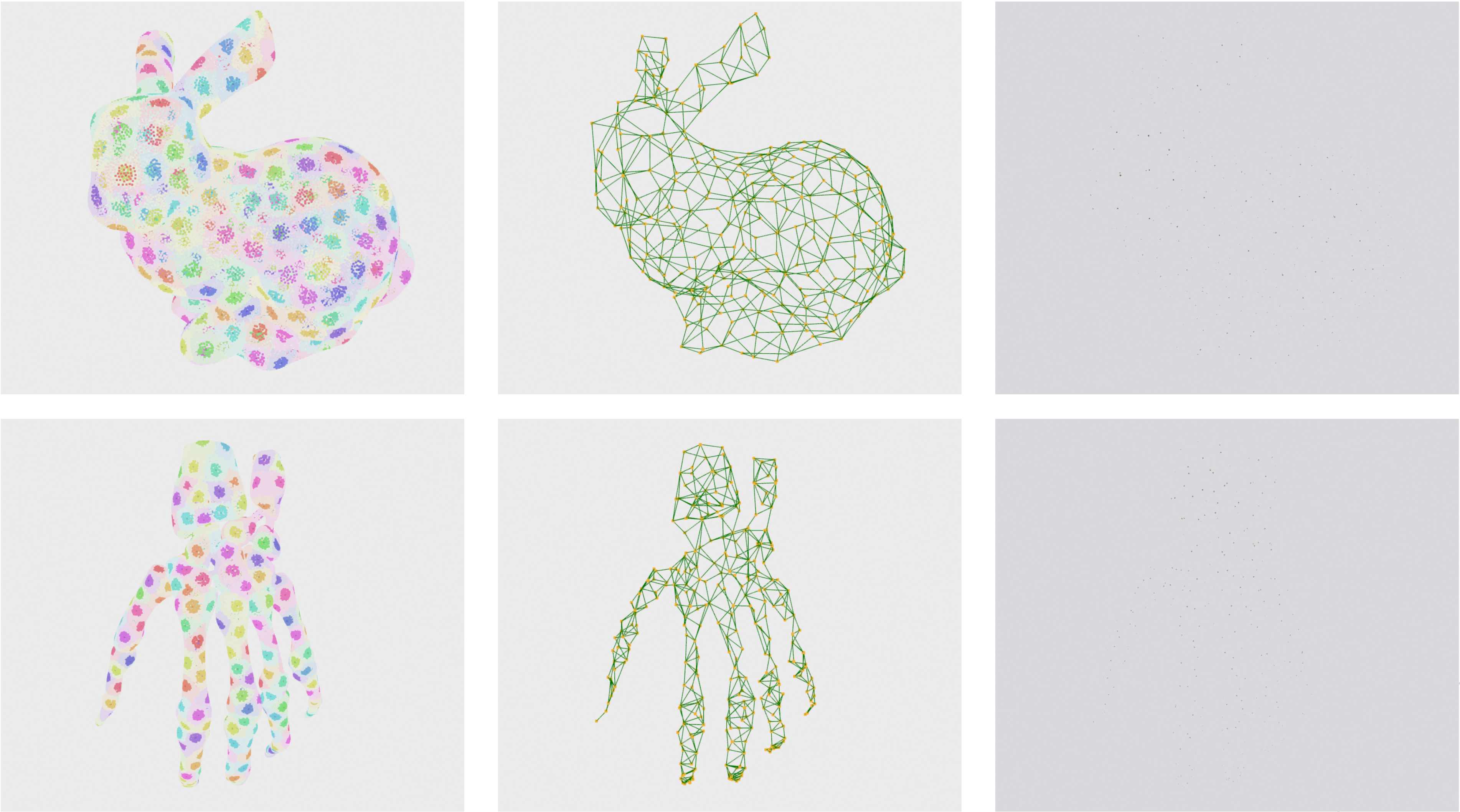
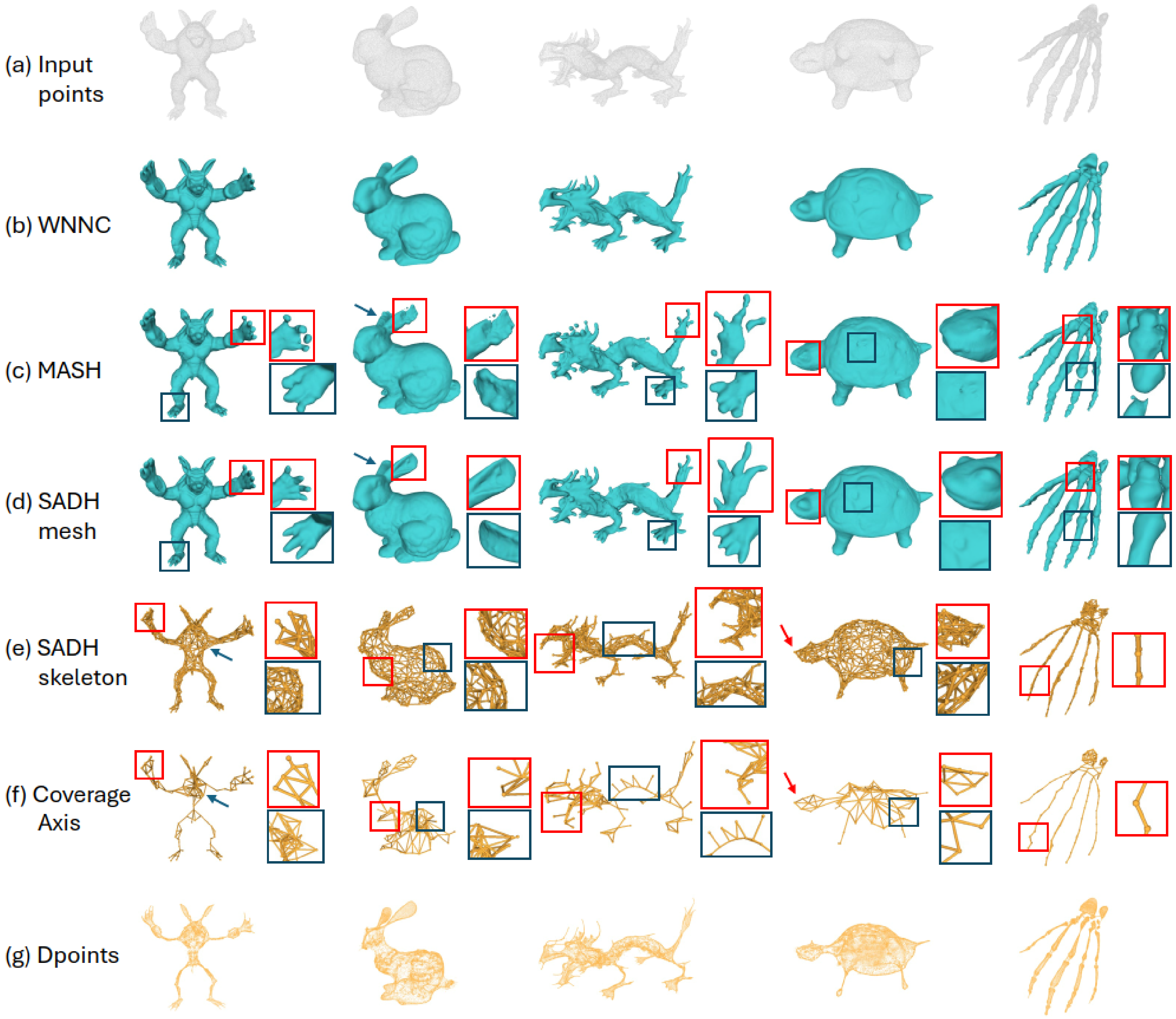


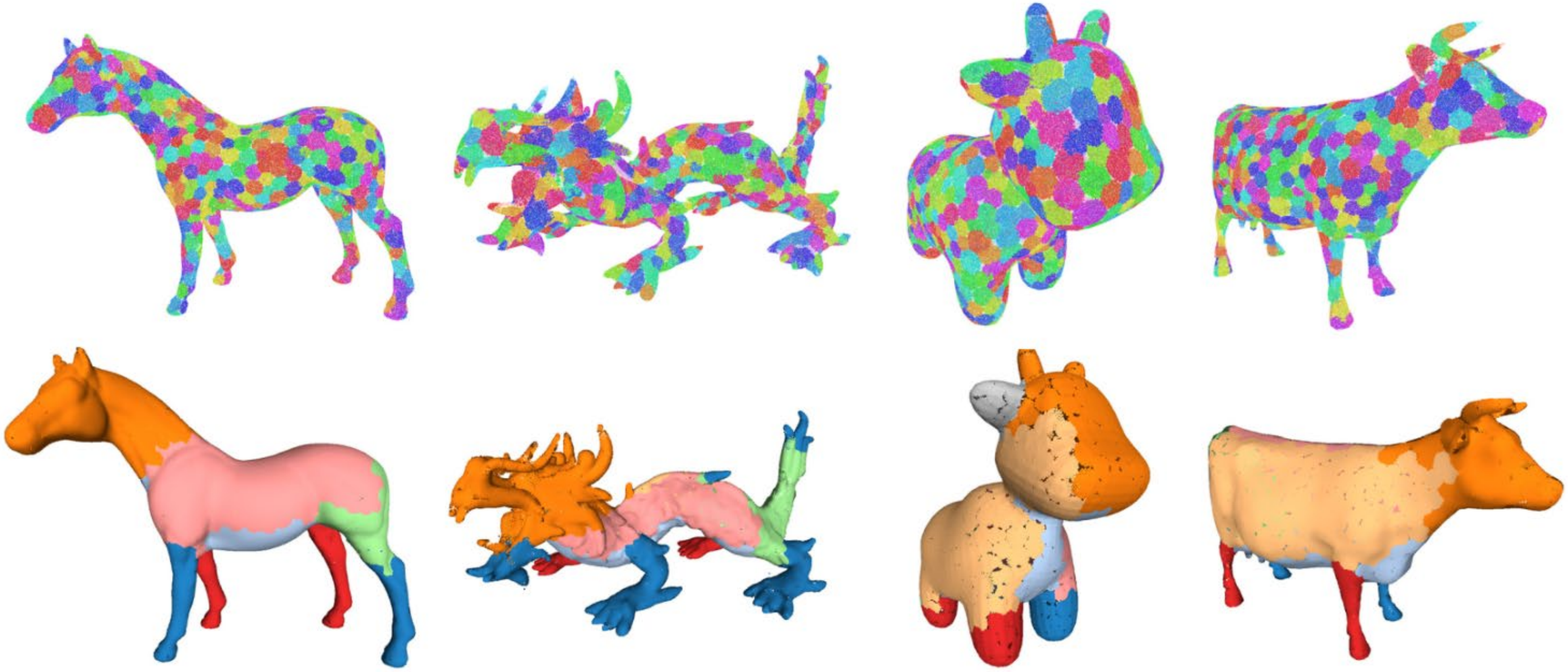
Experimental Setup

Setting	Dataset / Input	What We Evaluate	Baselines / Method
Surface Reconstruction + Skeletal Structure	Famous dataset (22 shapes) Oriented point cloud, N = 40,000	Surface accuracy + Skeletal-anchor coherence	Comparison to PGR, WNNC, etc.
Robustness to Incomplete Point Clouds	Partial point clouds	Patch decomposition Anchor graph stability under missing data	Coverage Axis (spurious branches) DPC (dense sampling)
Unsupervised Cross-Shape Co-Clustering	Multiple animal shapes No semantic labels	Part discovery via spectral clustering on global patch graph	Patch descriptor: anchor + SH + neighbor relations


(a) Input points
(b) WNNC
(c) MASH
(d) SADH mesh
(e) SADH skeleton
(f) Coverage Axis
(g) Dpoints

(a) Incomplete Input Point Cloud (b) SADH Patch Partition (c) SADH Reconstruction (d) Geodesic Anchor Graph (e) Coverage Axis (f) Dpoints

Unsupervised Cross-shape Patch Co-clustering



Conclusions

- We introduced SADH, a structured 3D shape representation that couples local surface geometry with internal skeletal organization.
- Key Contributions:
  - Locally Parameterizable - Decomposes surfaces into compact, disk-like patches using dual-channel spherical harmonics.
  - Geometric Accuracy - Captures anisotropic surface details with high fidelity.
  - Global Structural Skeleton - Anchors patches to an internal graph that preserves structural relationships and topology.
- SADH bridges the gap between local surface modeling and global structure, enabling downstream tasks such as deformation, animation, topology-aware editing, and semantic shape understanding.

Future Directions

Direction	Description
Adopt Anisotropic Basis	Replace spherical harmonics with ellipsoid basis functions for better representation of directional details
Cross-Shape Correspondence	Enable semantic mapping between shapes via anchor graph alignment
Shape Deformation & Editing	Leverage the anchor graph for intuitive, structure-preserving deformation (drag a node; surface follows)
Dynamic Shape Capture	Extend SADH to time-varying sequences (e.g., human motion, facial expressions) with temporally coherent anchor graphs
Multi-Modal Fusion	Combine SADH with images, text, or depth for richer shape understanding
AI-Based Shape Generation	Use SADH patches + anchor graph as structured tokens for diffusion or transformer-based generative models

QUESTIONS?

Thank you for your attention

Abstract

- We introduce SADH, a new approach to 3D shape modeling that connects external surface geometry with internal structural organization. The core idea is simple: represent a shape using small, flexible surface patches that are attached to anchor points inside the object's volume—much like how skin is supported by an underlying skeleton. Each patch is described using a compact mathematical formulation that captures both its local shape and its directional properties, allowing it to adapt to complex, detailed regions efficiently. Starting from raw 3D point clouds, our method jointly optimizes the surface patches, their anchor positions, and their connections through a step-by-step process, ultimately forming a coherent internal structure. The resulting representation not only reconstructs surfaces accurately but also preserves meaningful relationships between neighboring parts, making it naturally useful for tasks like shape deformation and editing. Experiments across diverse 3D shapes demonstrate that SADH achieves both high-quality surface reconstruction and robust structural organization.