Multi-Scale Geometric Metrics and Feature Extraction for Benthic Habitat Surveying

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Ulysses Ecosystem Engineering

PICES 2026 Annual Meeting

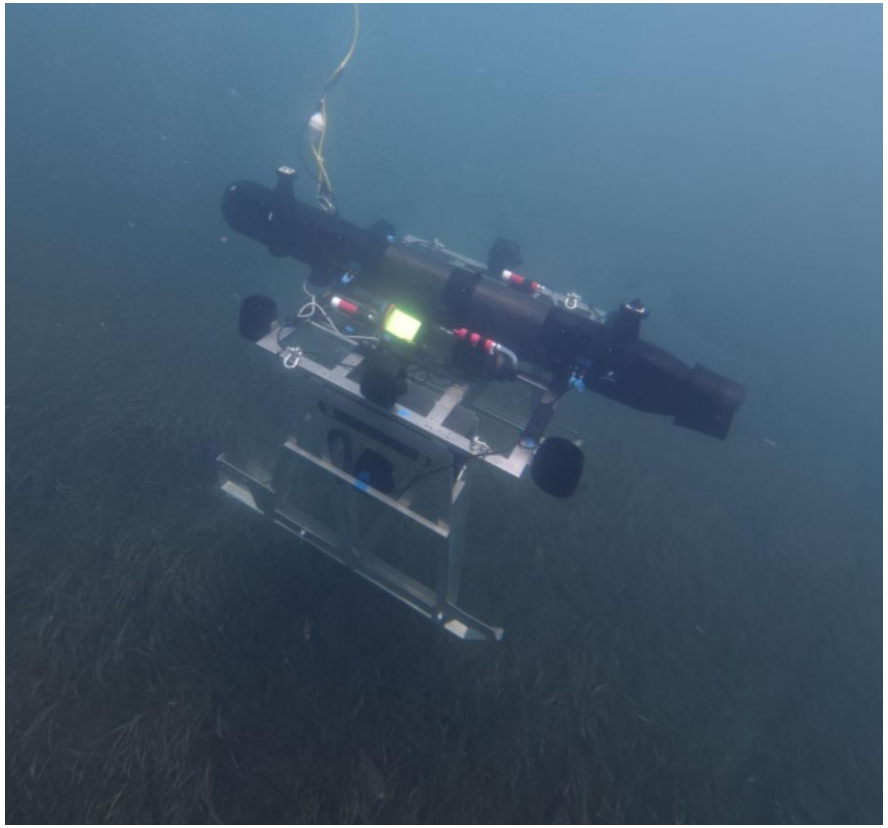


Introduction – Benthic Surveying

- Improve efficiency/quality of Underwater Surveys(e.g. Coral) via modern Photogrammetry techniques



[1]



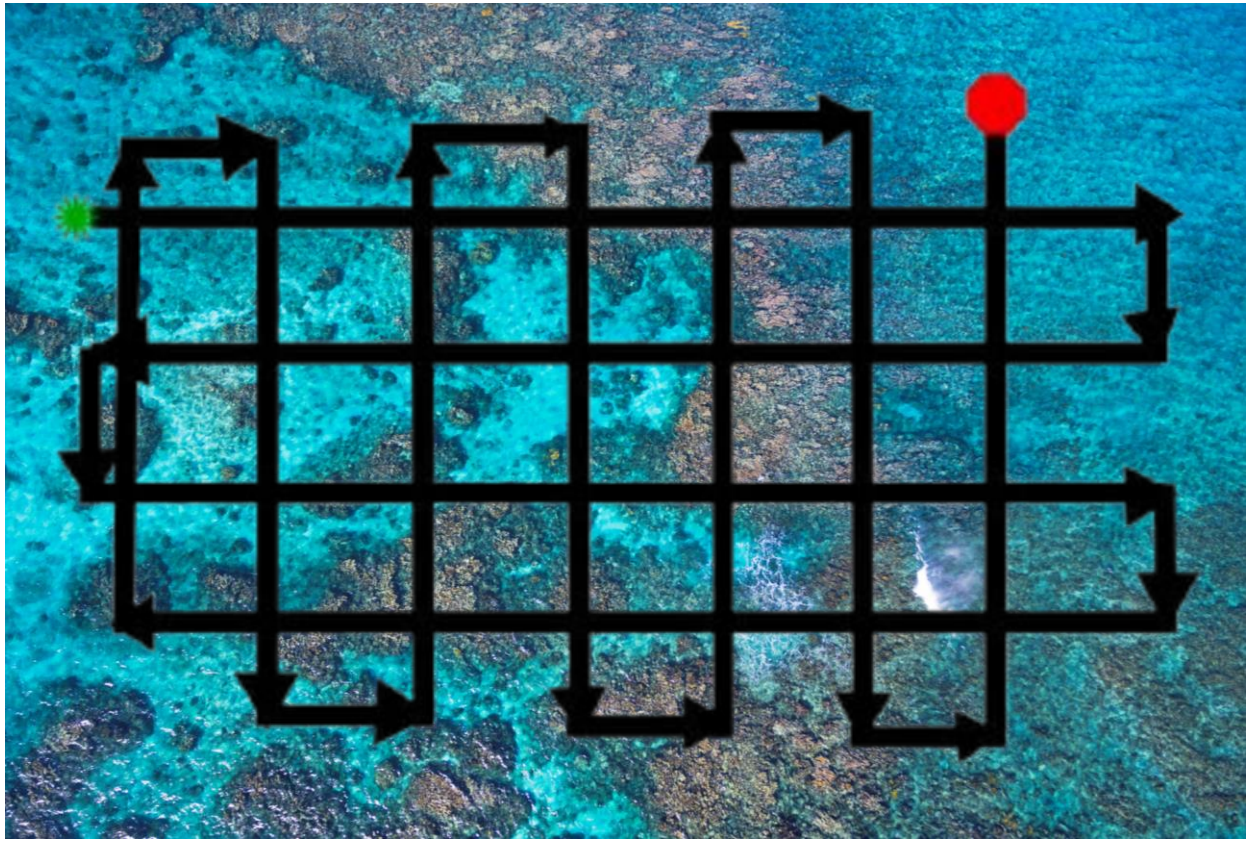
[2]

Project – Standard Operating Procedure

- Capture Coral Via Autonomous Drone, collect image set



[2]

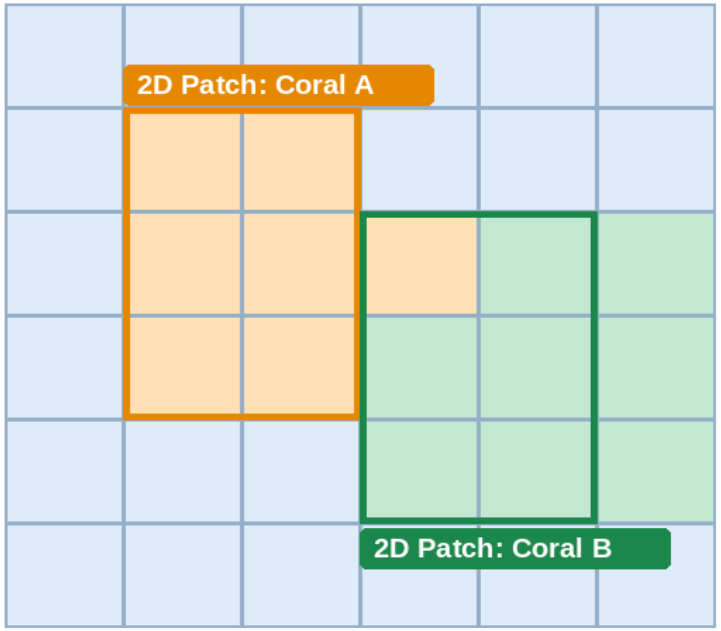


[3] [4]

Problem Statement

A. Flat 2D Video / Still Images: Lacks 3D Geometry & Height (z)

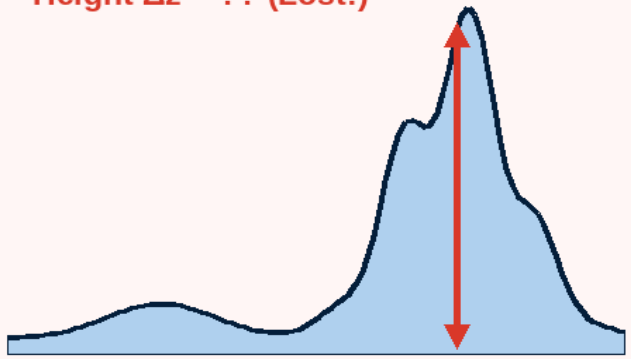
Underwater Video / Still Frames -> 2D Pixel or Patch Classification



Flat 2D Projection (x, y only)

Missing in 2D: Height (z) & Relief

Height Δz = ?? (Lost!)



Flat & tall colonies look identical from above
Overhangs, crevices & volume are invisible in 2D

2D Limitation: Abundant labeled 2D training sets, but blind to 3D reef structure

Key points

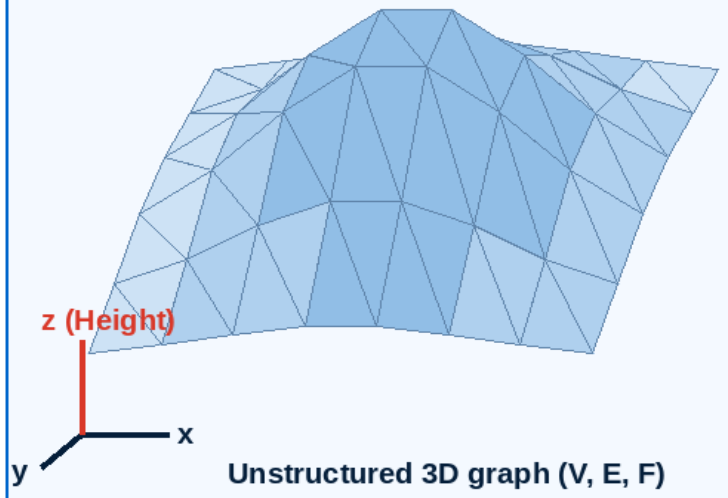
- Surveys collect overlapping images
- Labeling flat 2D pixels loses 3D geometry
- Cannot measure volumetric reliefs, overhangs, or structural complexity

Problem Statement

B. 3D Reconstructed Mesh: Richer Data, Higher ML Complexity

3D Triangular Mesh (x, y, z) -> Richer Geometry, Harder ML Learning Problem

3D Surface Mesh: +1 Full Dimension (z)



Unstructured 3D graph (V, E, F)

Why 3D ML Classifiers Struggle

1. Labeled Community Training Data:

2D Images — Abundant (Millions)

3D Meshes — Scarce!

2. Structural & Dimensional Complexity:

2D Grid — Regular 2D Pixels

3D Mesh — 3D Graph + Extra Dimension

3. Cross-Dataset Mesh Resolution:

Sparse vs. dense surveys need interpolation
& upsampling for uniform ML input!

-> High complexity + small training sets cause raw 3D ML classifiers to struggle

The 3D ML Paradox: Richer 3D data (a whole extra dimension), but far less training data

Key points

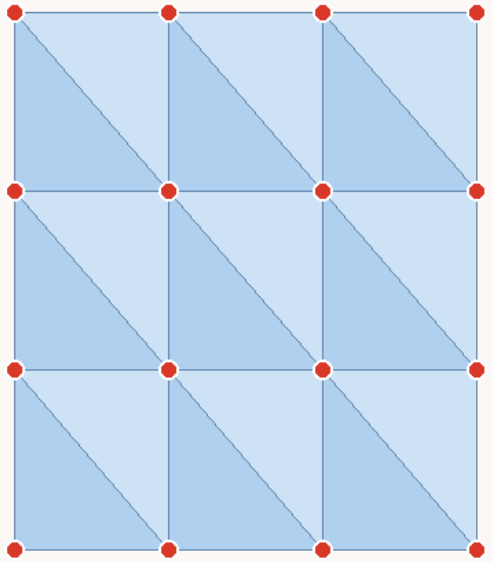
- Captures true height (z), relief and 3D colony architecture
- Far fewer labeled 3D training examples in the community
- Irregular vertex spacing across datasets challenges ML classifiers

Our Two-Fold Approach

1. SfM Mesh Interpolation & Upsampling: Cross-Dataset Uniformity

Interpolate & Upsample Sparse Meshes Instead of Downsampling to Lowest Denominator

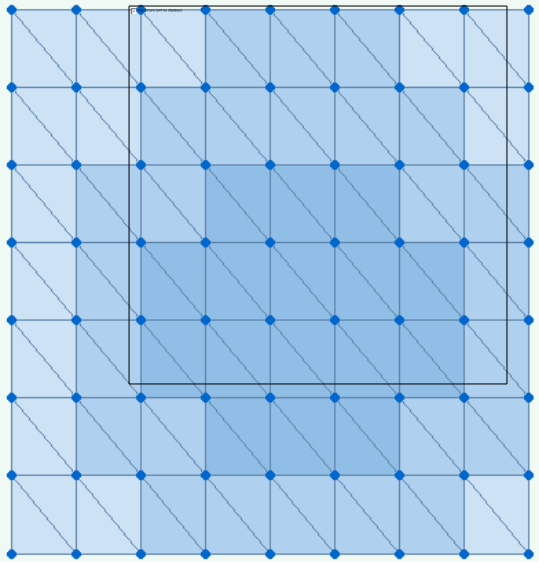
Sparse Mesh (Low-Res Survey)



Coarse triangles miss fine coral relief

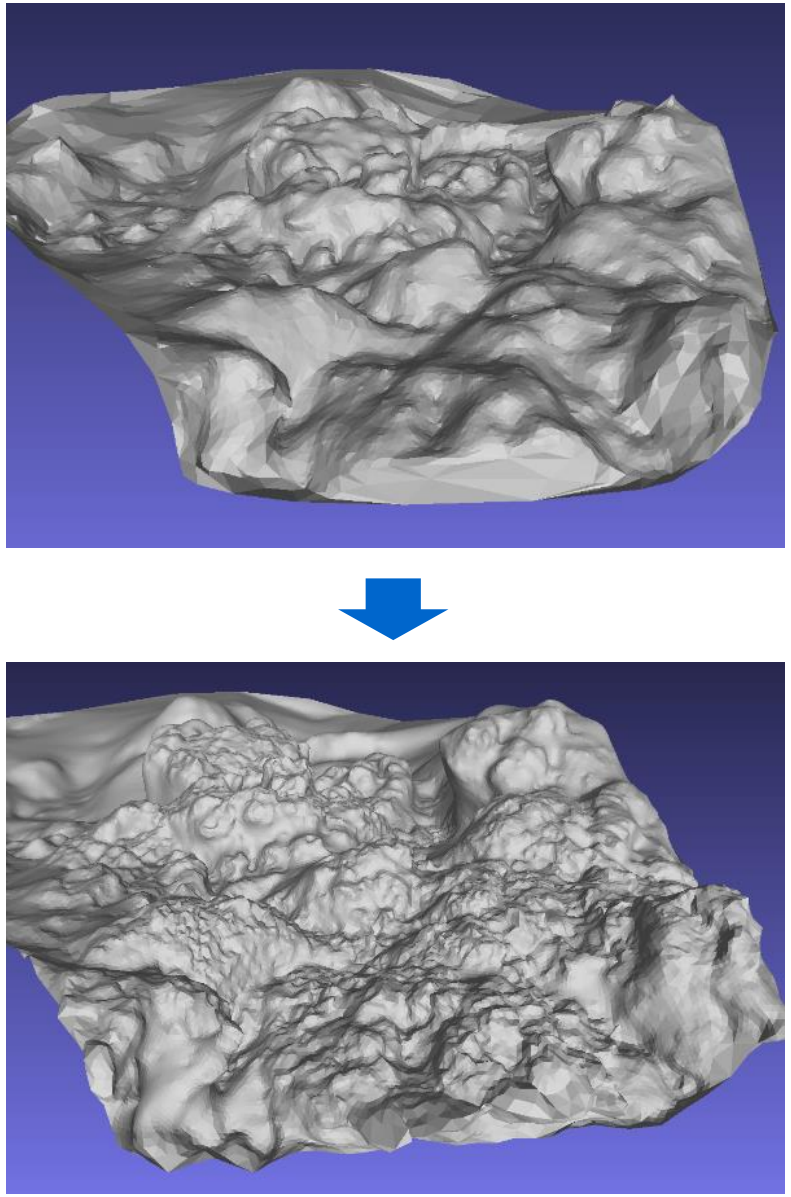
SfM + OpenMVS
Interpolate & Upsample

Upsampled Uniform Mesh



Uniform vertex density across datasets

Result: Standardized, high-resolution 3D meshes with uniform scale across surveys

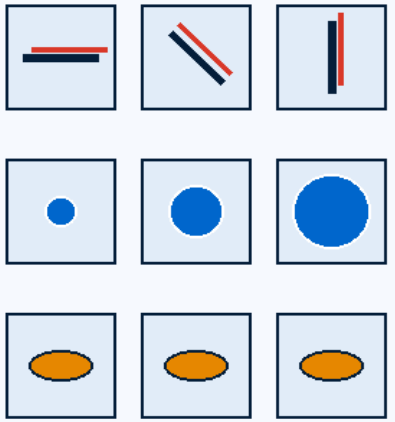


Our Two-Fold Approach

2. 3D Feature Augmentation: Strong Fundamentals in 2D Computer Vision

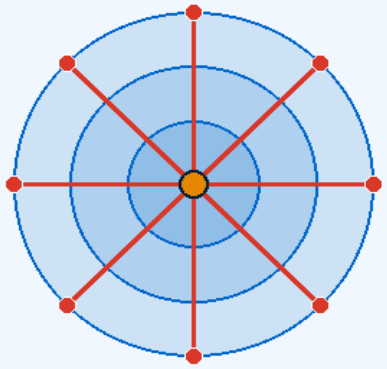
Augmenting Richer 3D Meshes with Multi-Scale Features Inspired by 2D Vision

2D CV Fundamentals
(Multi-Scale Filter Banks)



Edges, gradients & scales

3D-Native Mesh Analogs
(Computed at Every Vertex)



- Omnidirectional Rugosity (r)
- Vector Dispersion (r)

3D ML Classifier
(Feature-Augmented)

- Vertex (x, y, z)
- Rugosity (r = 1..k)
- Vec Dispersion (r = 1..k)
- Surface Normals n_i

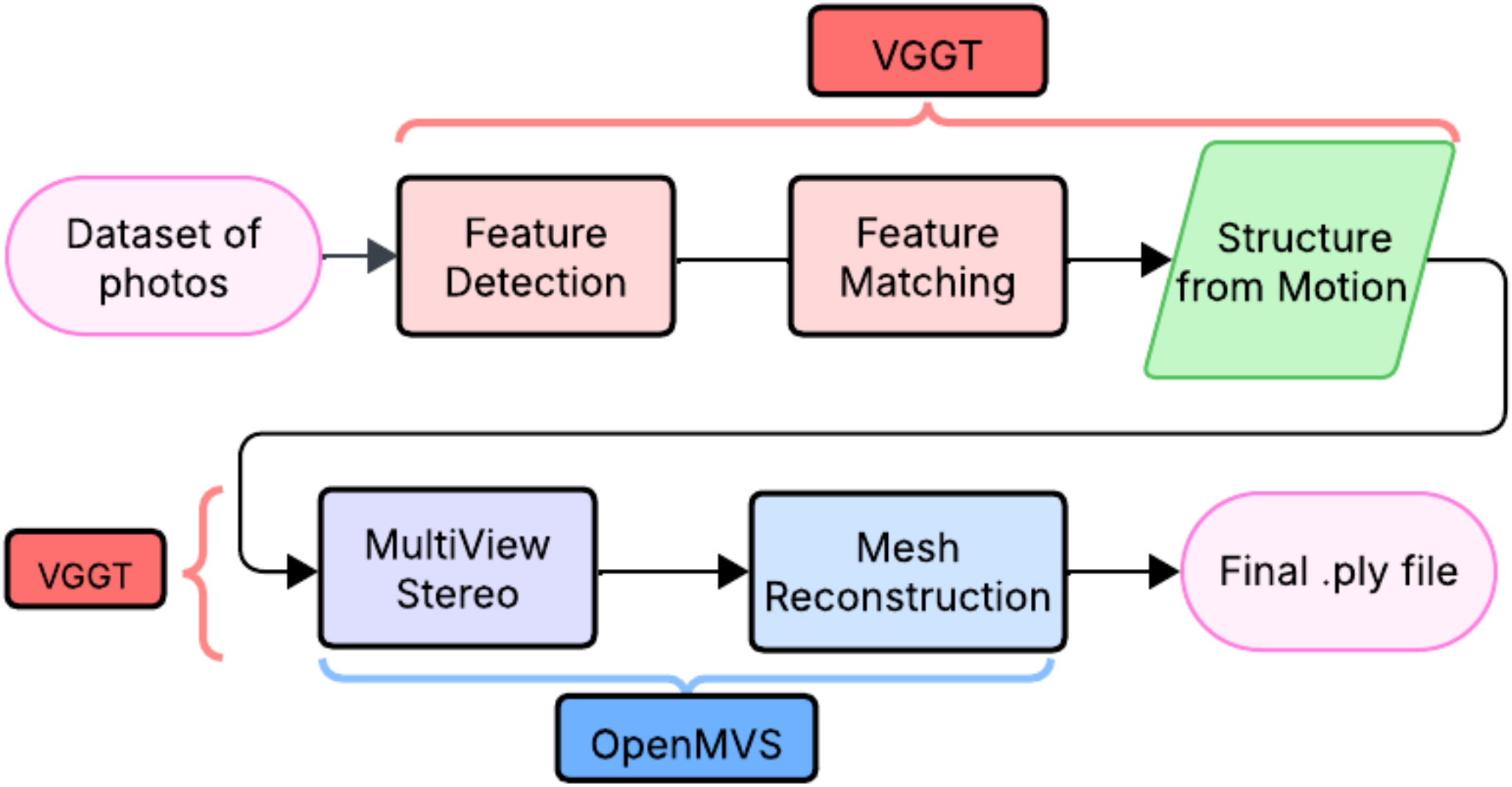
Accurate 3D Reef ML Classification

Result: Explicit multi-scale geometric features bridge the 3D ML training-data gap

Key points

- Adds geometric information at every vertex, so classifiers don't learn 3D from scratch
- Grounded in 2D computer vision: multi-scale filter banks
- Rugosity and vector dispersion at any edge radius r

Design & Methods – VGGT: 3D Point Cloud

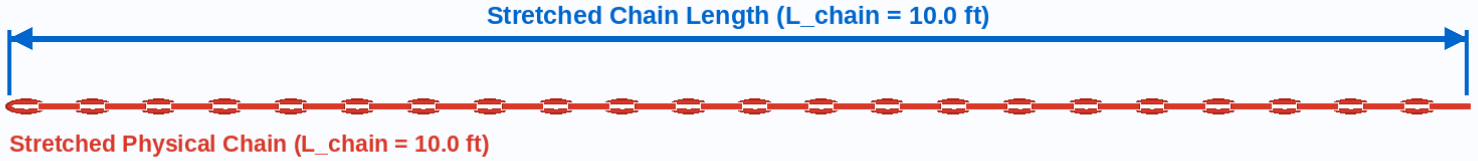


VGGT [5]; OpenMVS [6]

Linear Rugosity

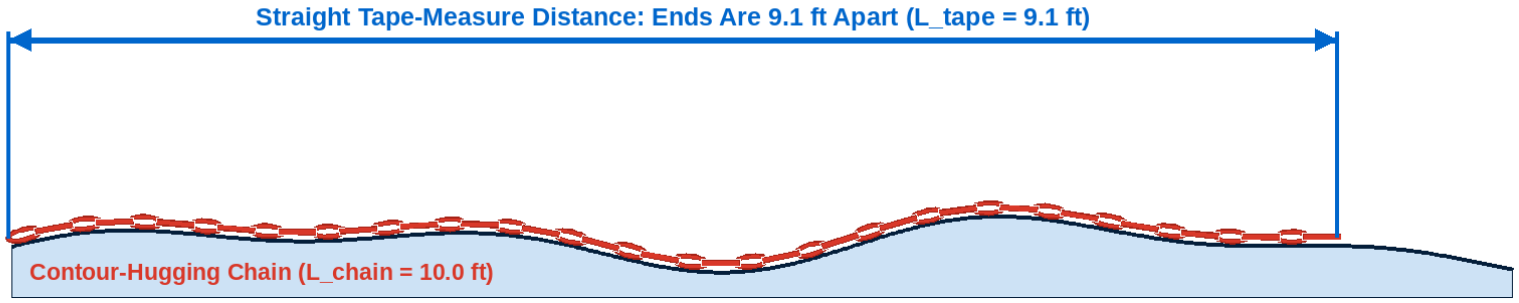
Physical Chain Transect Concept: Fixed 10.0 ft Chain on Flat vs. Complex Reef Surfaces

1. Stretched-Out Chain-Link Chain (Total Chain Length L_chain = 10.0 ft)



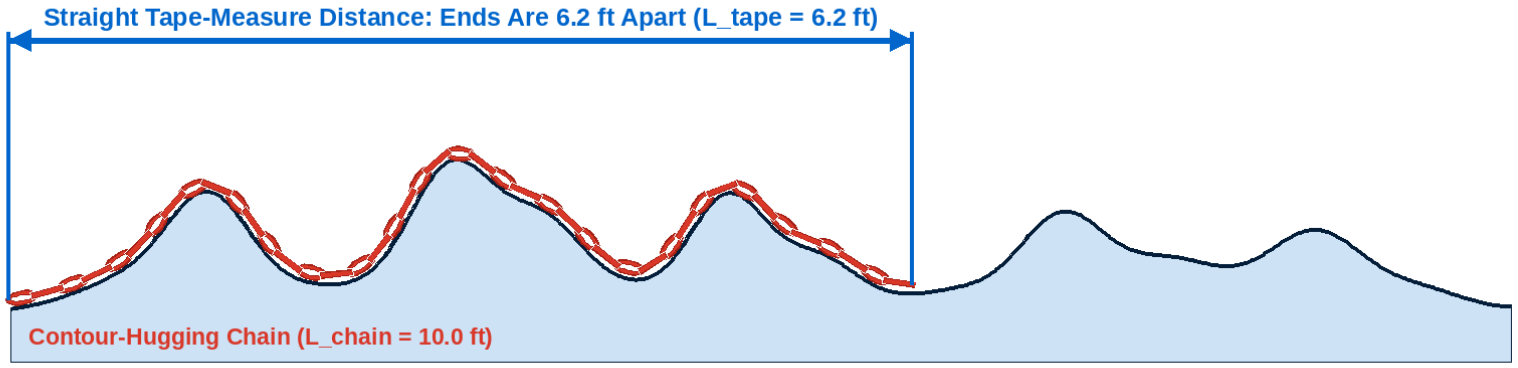
Stretched Reference
L_chain = 10.0 ft

2. Nearly Flat Seafloor: Same 10.0 ft Chain Laid on Gently Sloping Substrate



Nearly Flat Surface
L_chain = 10.0 ft | L_tape = 9.1 ft
R_linear = 10.0 / 9.1 = 1.10

3. Complex Coral Reef: Same 10.0 ft Chain Drapes Over High-Relief Coral Heads

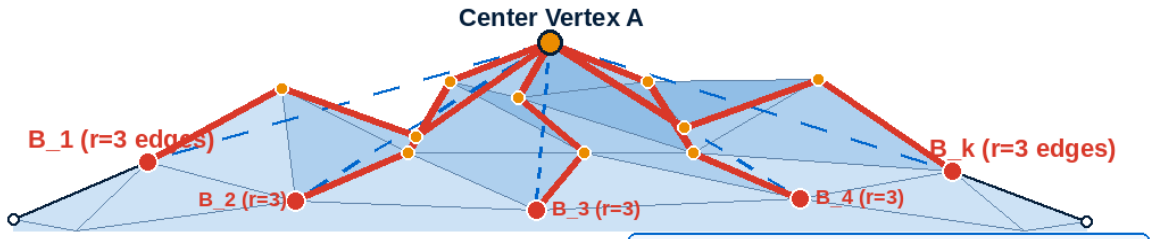


Complex Coral Reef
L_chain = 10.0 ft | L_tape = 6.2 ft
R_linear = 10.0 / 6.2 = 1.61

Methods - Omnidirectional Rugosity (ODR)

B. Omnidirectional 3D Mesh Rugosity (Our Implementation)

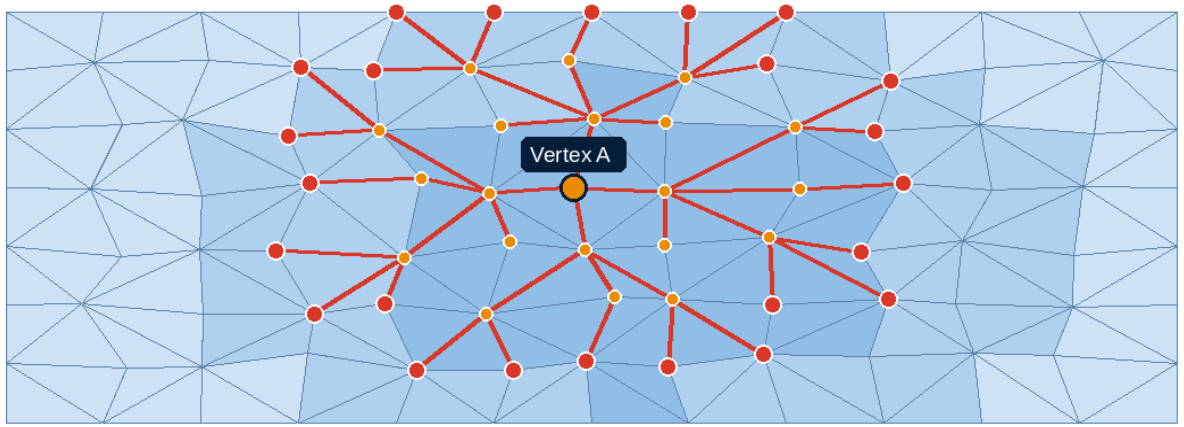
Mesh Graph Paths (r Triangular Edges) vs. 3D Euclidean Chords



3D Paths L_edges(A->B_i) vs. Chords L_euclid(A,B_i)

rugosity_r(A) = mean [L_edges / L_euclid]

Top-Down Reef Mesh: 360° BFS Graph Neighborhood (Radius r) at Every Vertex



- Omnidirectional (360°): Zero directional bias; captures all surrounding relief
- Computed at Every Point in the Mesh: Full-survey continuous mapping
- Arbitrary Edge Radius r: Evaluates both micro & macro scales intractable in-situ

- **Construct a Weighted graph G = (V, E)] edge weights are 3D Euclidean lengths**
- **Run Breadth-First Search (BFS) from each center vertex A out to an arbitrary radius r of triangular edges: obtain ring** $S_r(A)$

$$S_r(A) = \{ B \in V : d_{\text{hop}}(A, B) = r \}$$

$$R_r(A) = \frac{1}{|S_r(A)|} \sum_{B \in S_r(A)} \frac{L_{\text{chain}}(A \to B)}{\| \mathbf{x}_A - \mathbf{x}_B \|}$$

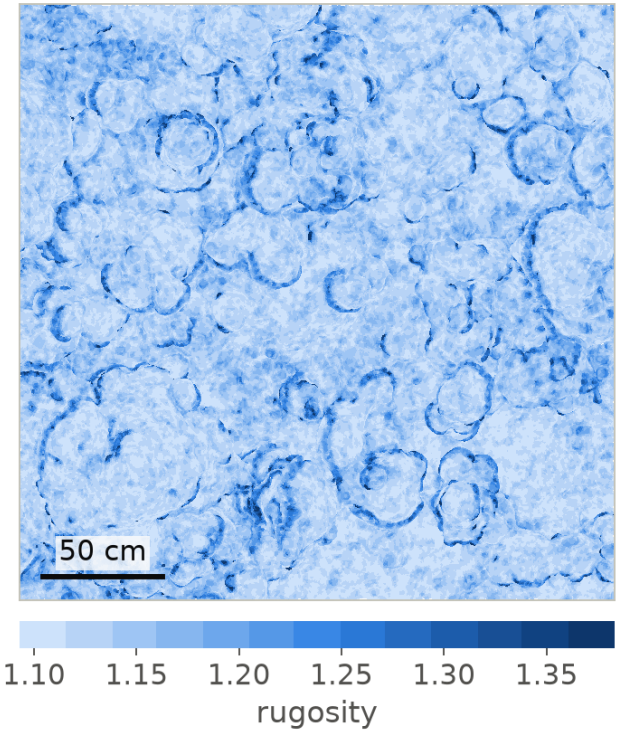
- **Compute ODR at vertex A by averaging surface-to-Euclidean distance ratios across all boundary vertices B in** $S_r(A)$

- Building on Young et al. [7], we extend rugosity and vector dispersion to every point of the mesh, in every direction

Multi-Scale Radius – Small & Large Scales

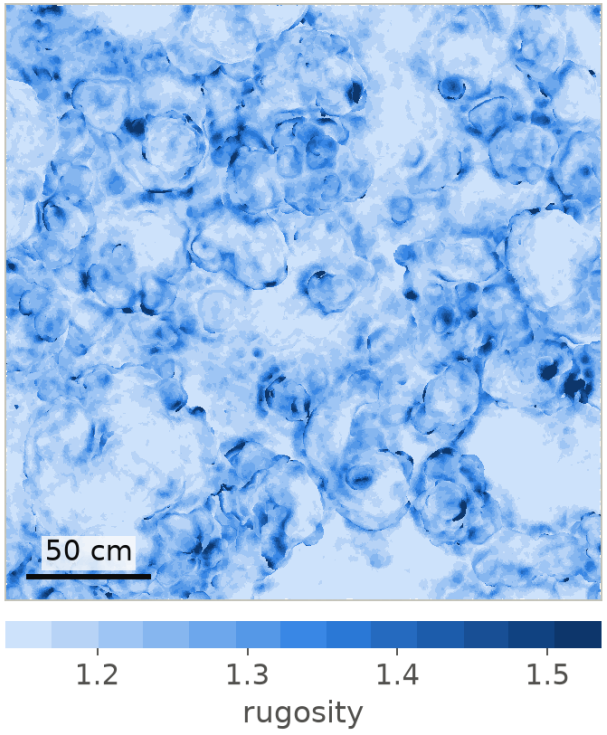
- **Radius = number of triangle edges × edge length, chosen freely. Like a 2D multi-scale filter bank [8], each radius adds a feature. Example: Soneva reef, 1 cm mesh**

≈ 3 cm radius (r = 3)



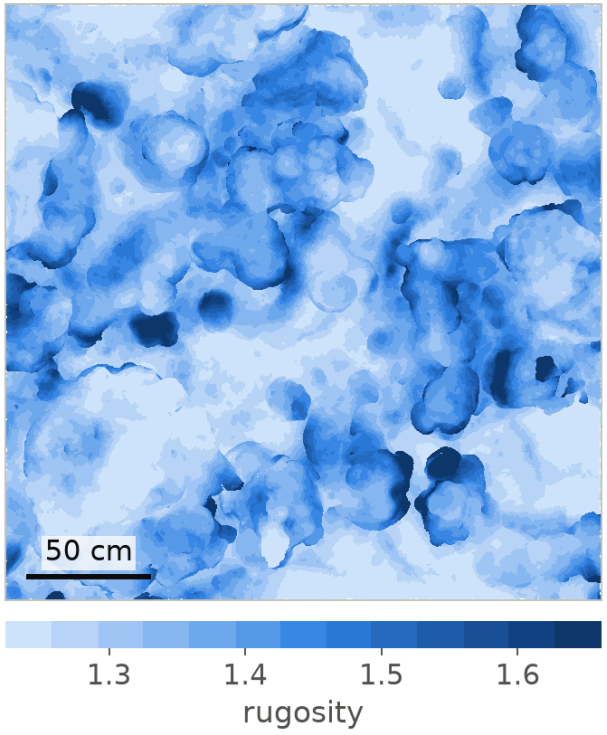
Surface texture: colony rims and edges; finer than a chain can follow

≈ 9 cm radius (r = 10)



Colony structure: the scale of a chain transect, but in every direction

≈ 33 cm radius (r = 40)



Reef topography: whole colonies against sand, at every point

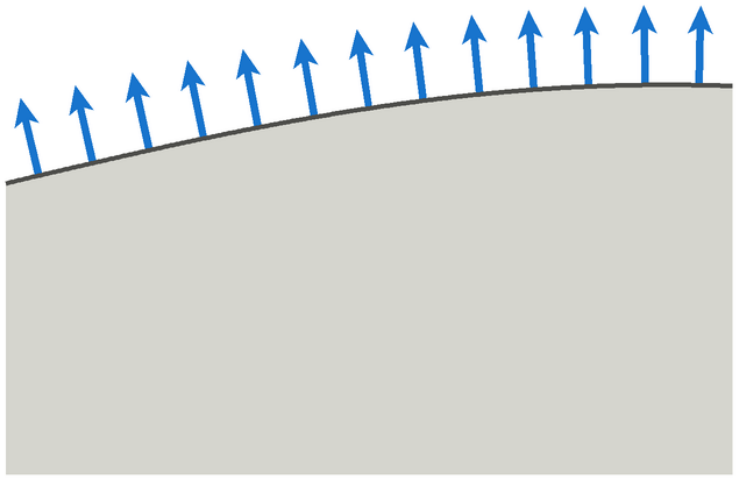
Methods – Vector Dispersion

- Following Young et al. [7]: how scattered the surface directions are around a point

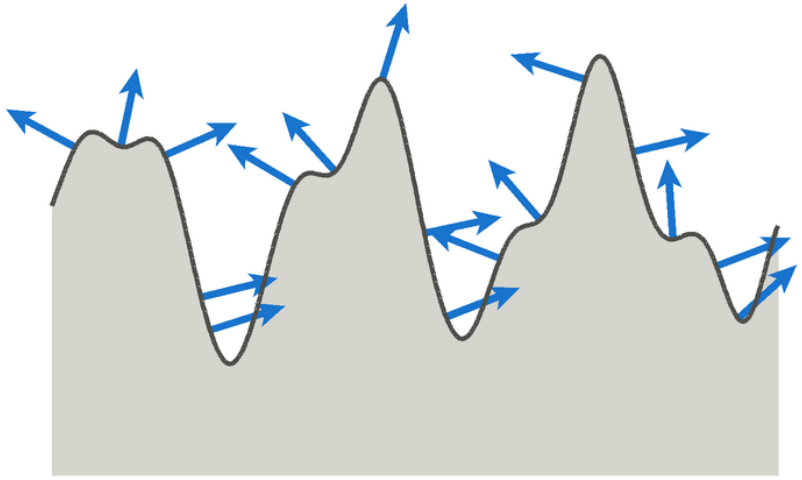
- Omnidirectional, at every vertex, over the N unit face normals $\hat{n}_i$ within r edges (0 = all aligned, 1 = fully scattered):

$$\mathrm{VD}_r(A) = \frac{N - R}{N - 1}, \qquad R = \| \sum_i \hat{\mathbf{n}}_i \|$$

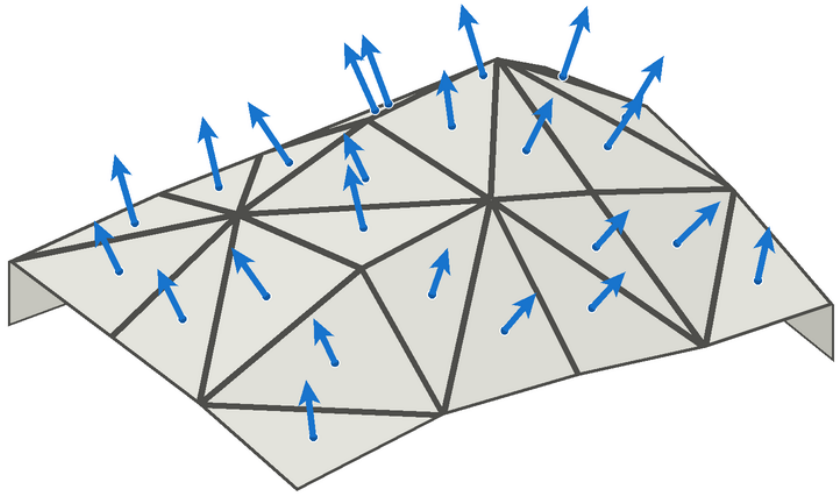
smooth or uniformly sloping: VD ≈ 0



complex coral: VD = 0.36



3D triangular mesh: face normals



Making It Work on Real Meshes

- Sparse graph + parallel search: every vertex, every radius, on a 16-core laptop

< 1 min

10-million-vertex coral scan at one radius -> Largely condensed with parallel BFS

r → cm

every mesh remeshed to one edge length, so radius = r × edge

masked

mesh borders, cut mounting bases and loose fragments are left out of the statistics

Into Practice

From concepts to a real reef and real corals

Ulysses Ecosystem Engineering

Evan Garcia & Jeffrey S. Ellen, Ph.D.



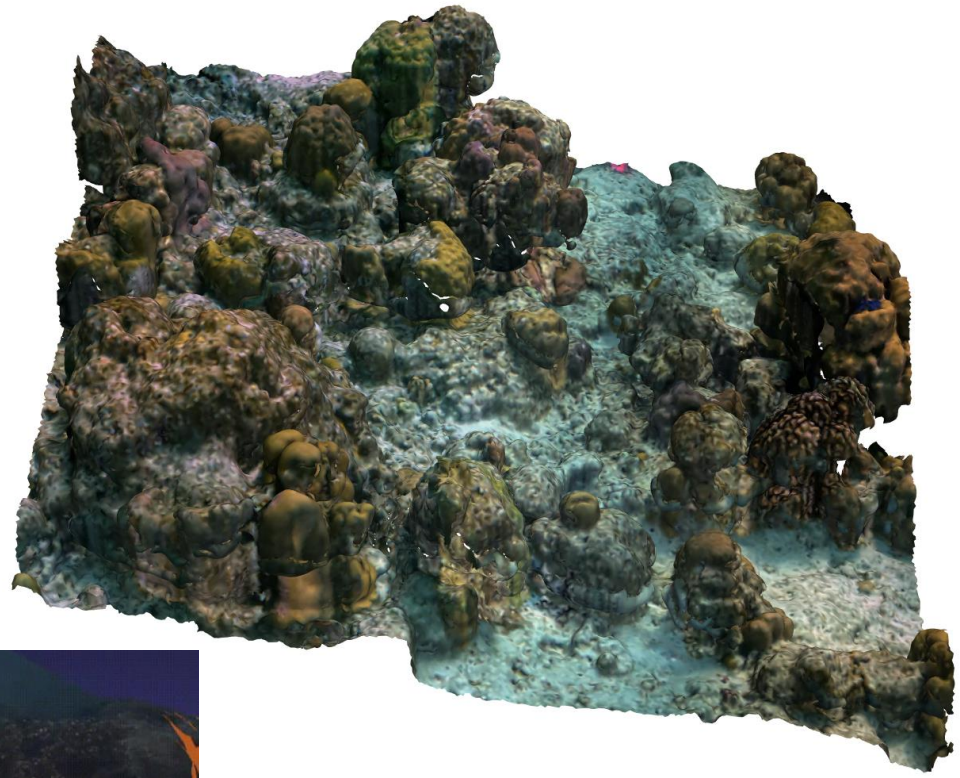
Reef Scale – Models



Guam OCC-GUA-024, 3 × 3 m
classical SfM (COLMAP); [9]



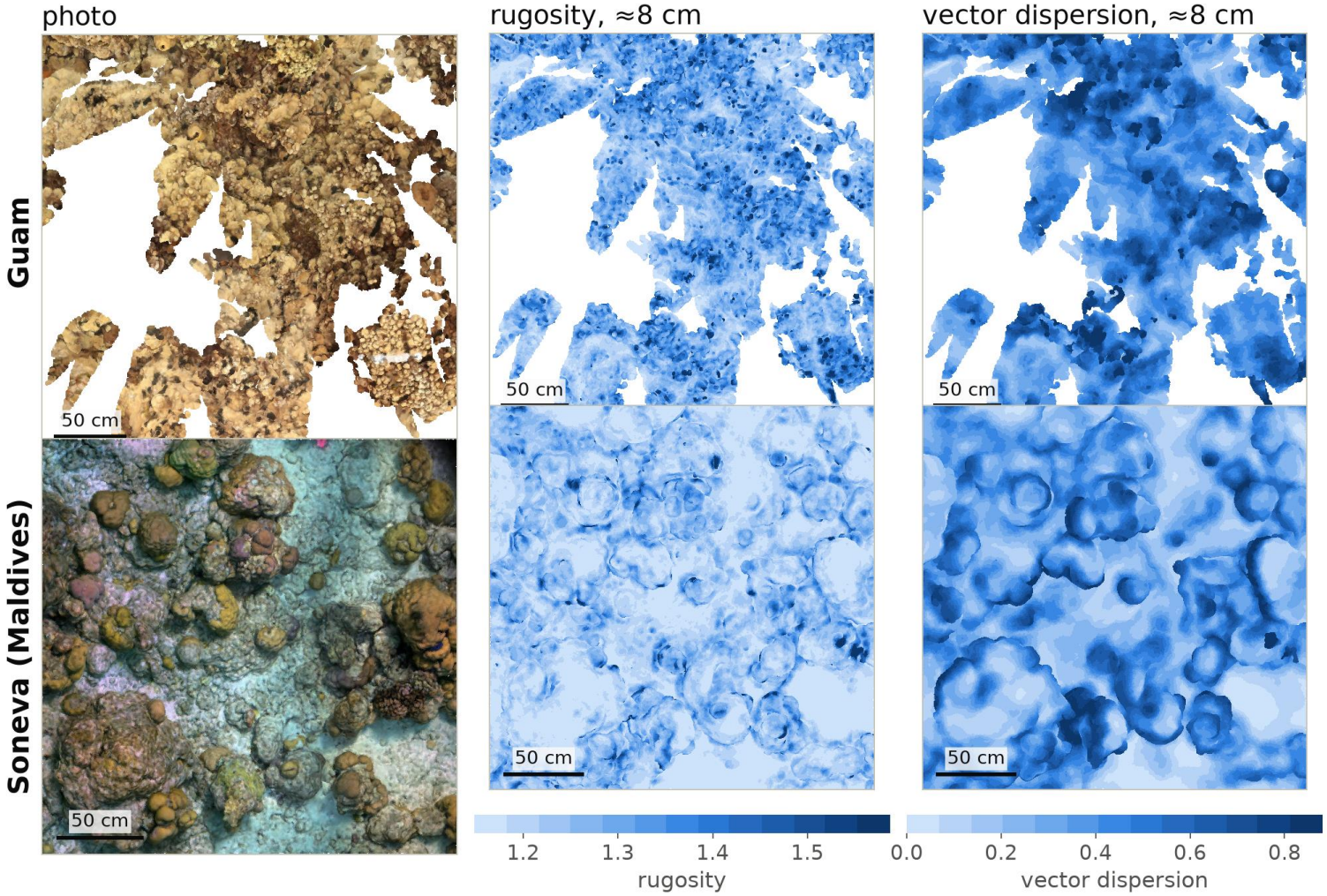
VGGT reconstruction: our pipeline, in progress

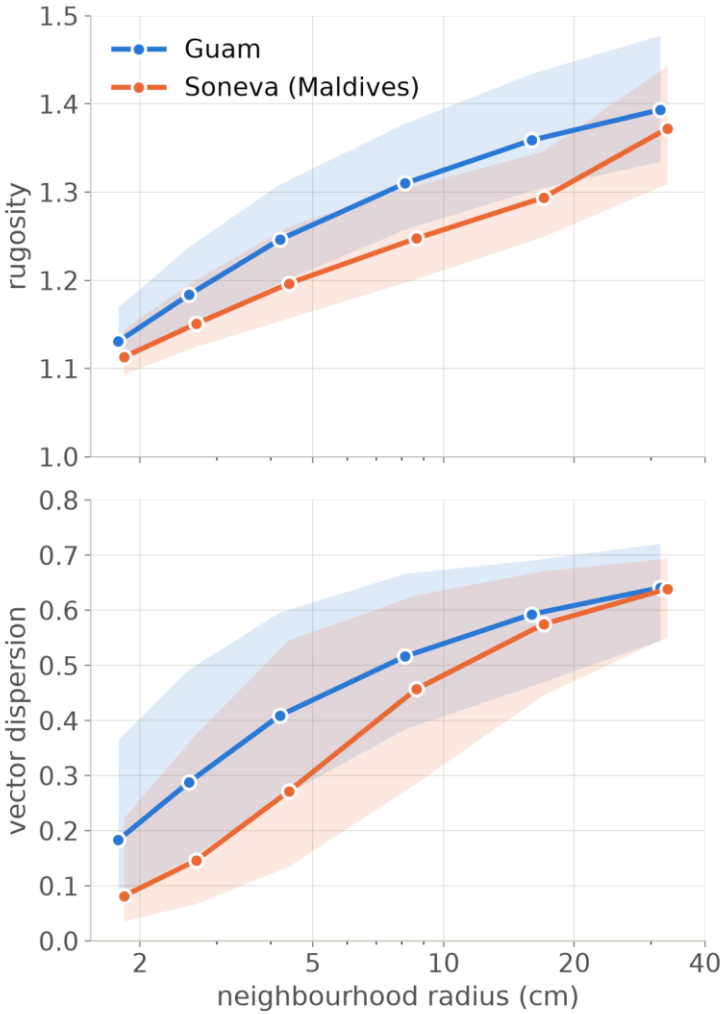


Soneva Host Beach, 2.5 × 2.5 m
classical SfM (COLMAP); [10]

Reef Scale – Metrics Mapped on Real Reefs

- **Two 1 cm reef meshes: Guam is rougher at every scale; the gap closes by ~30 cm**





Imagery: NOAA PIFSC ESD, Guam site OCC-GUA-024, 2022 [9]; Wildflow soneva-corals, Soneva Host Beach, 2025, CC BY 4.0 [10]. Meshes: J. Ellen.

Three Growth Forms

Seriatopora



Meandrina meandrites



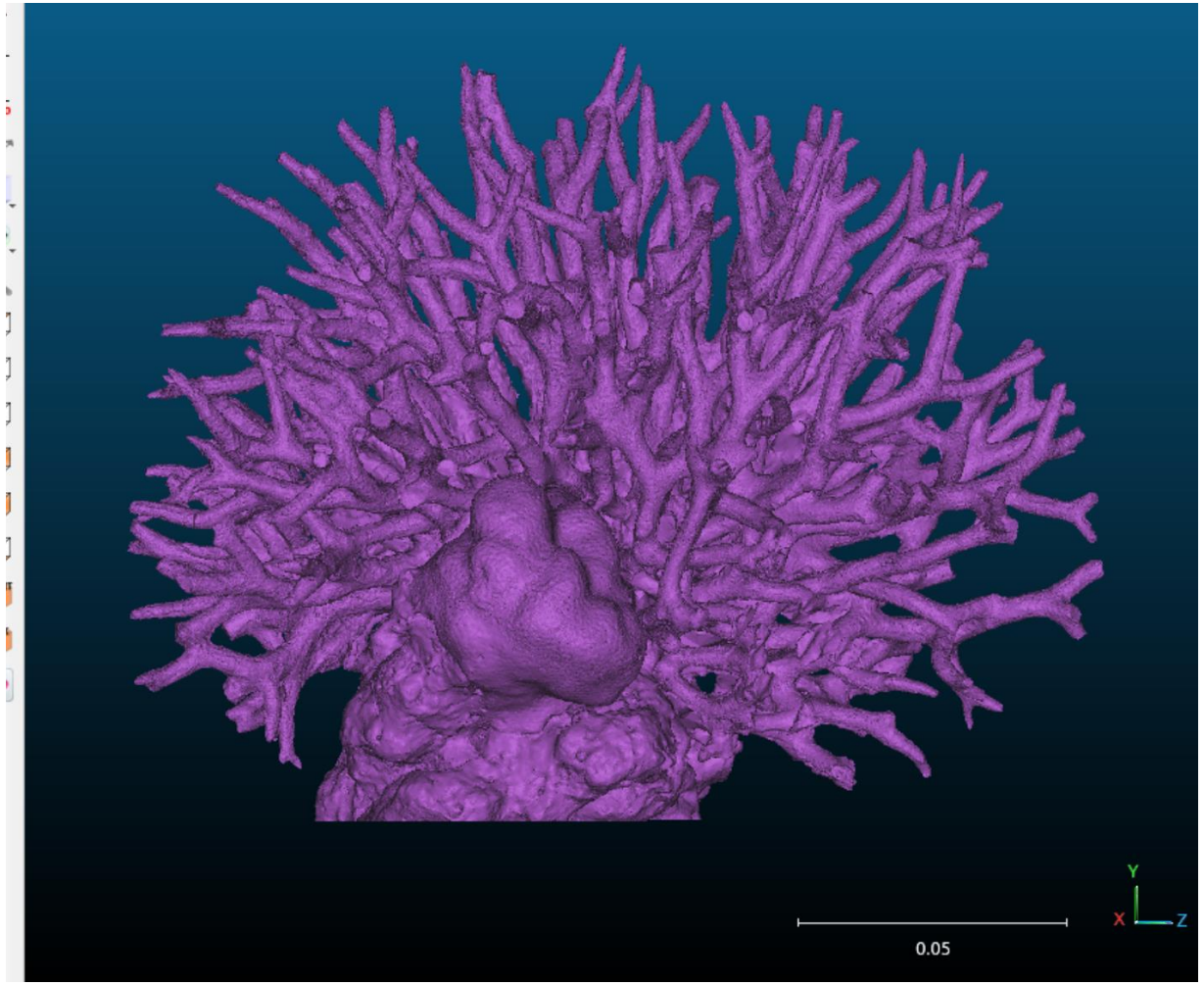
Gemmipora brassica



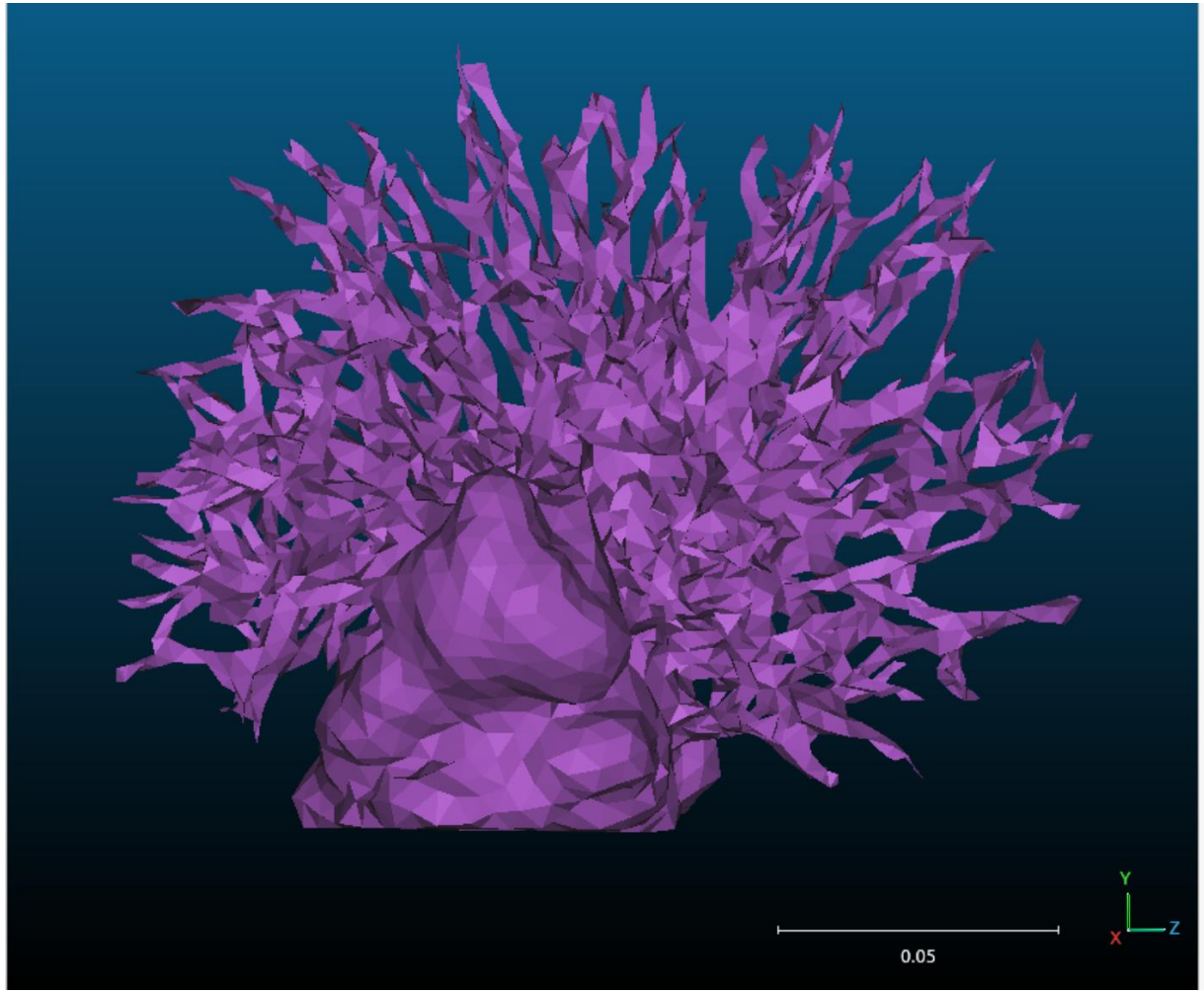
Smithsonian

[11]

Coarse Remeshing – Normalize edges



Original scan (0.13 mm edges)

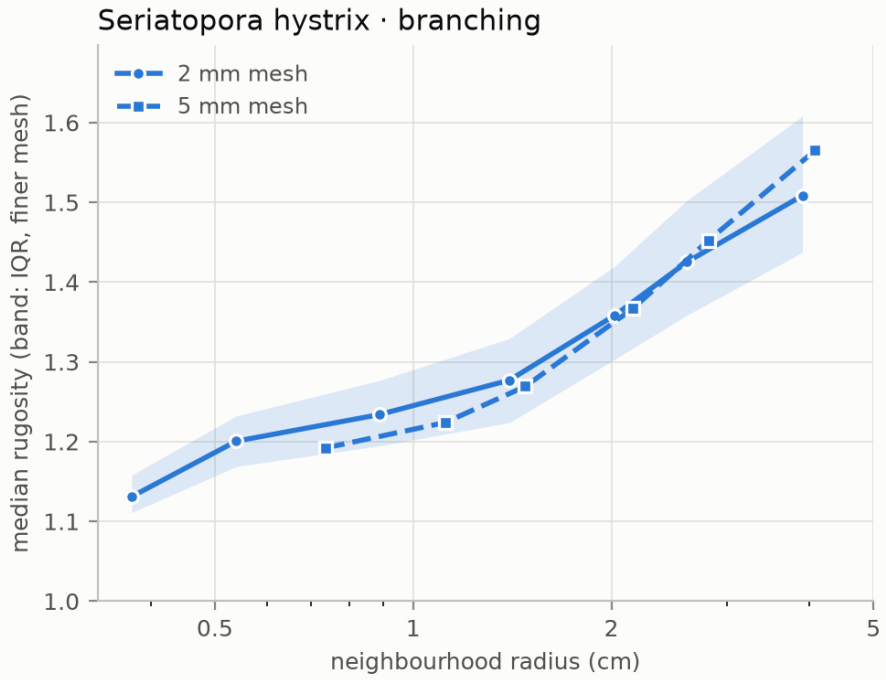


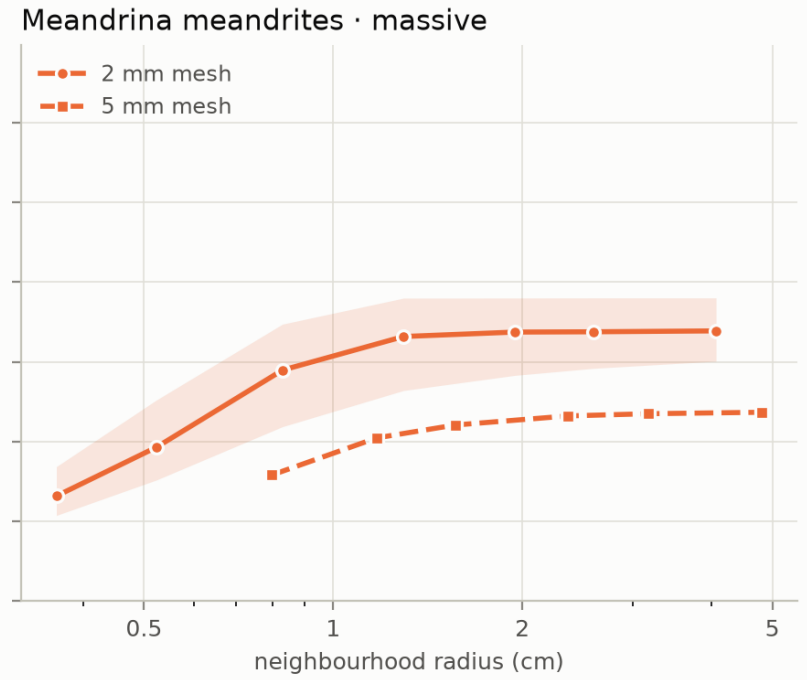
Remeshed: uniform 5 mm edges

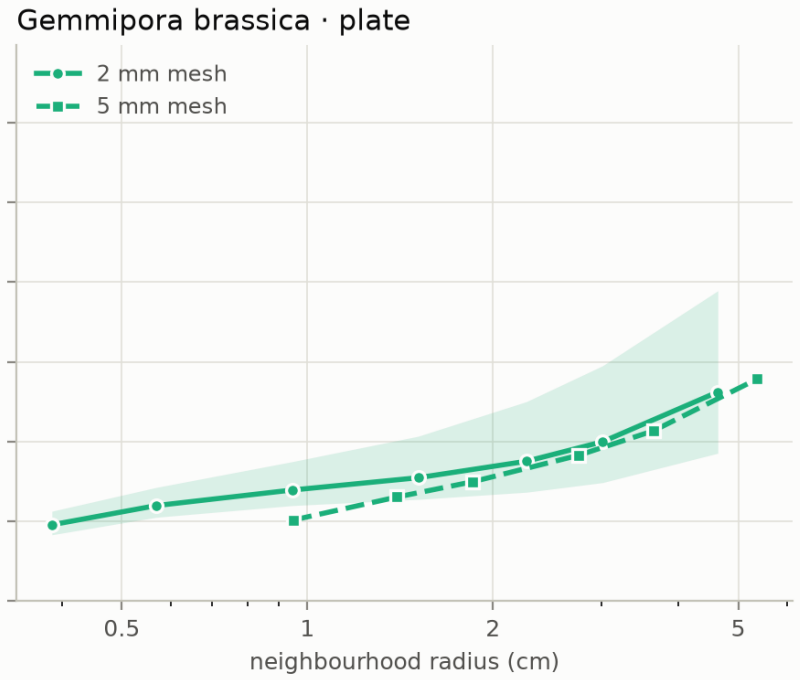
ODR Signatures by Growth Form

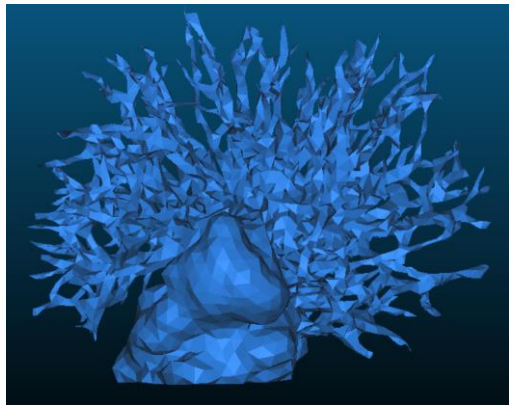
Rugosity signatures at two mesh resolutions

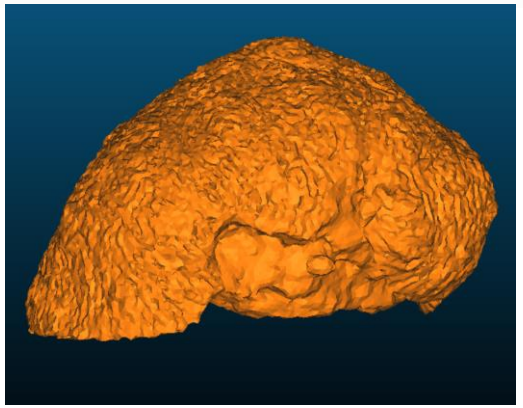
solid = 2 mm, dashed = 5 mm; same coral, same colour

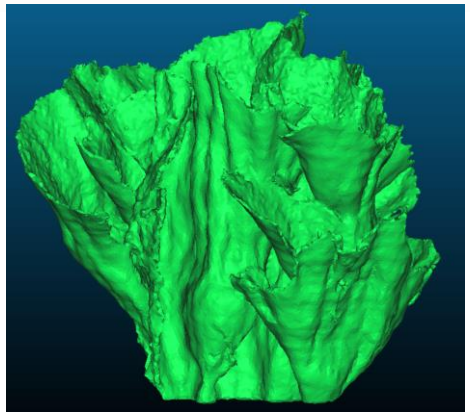








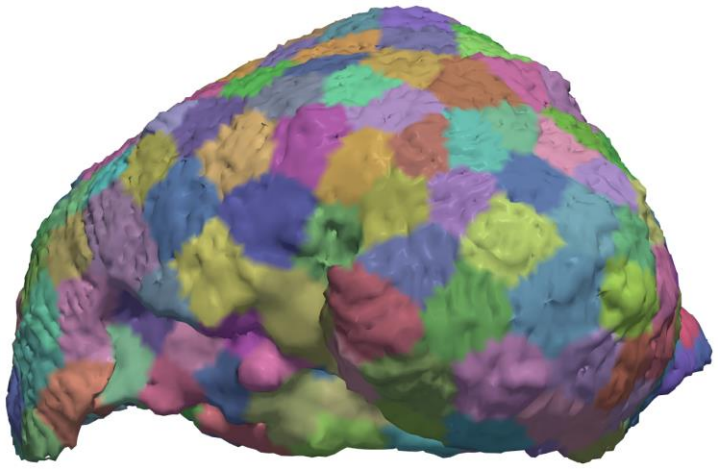




Preliminary Classification of Growth Forms

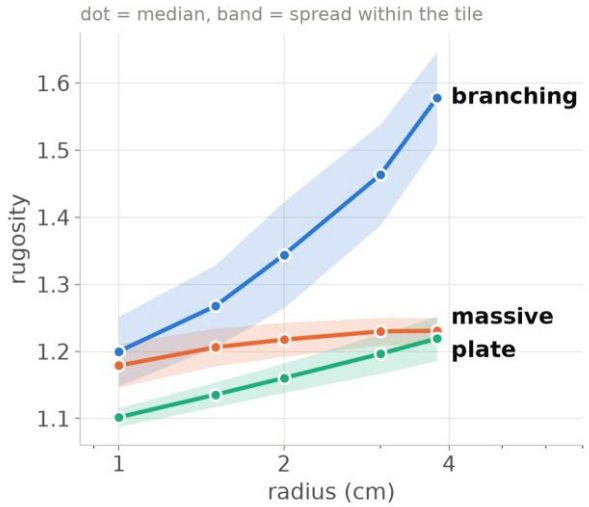
- Logistic regression on tiles of coral, training ODR curves, tested on unseen regions

1 Cut into tiles



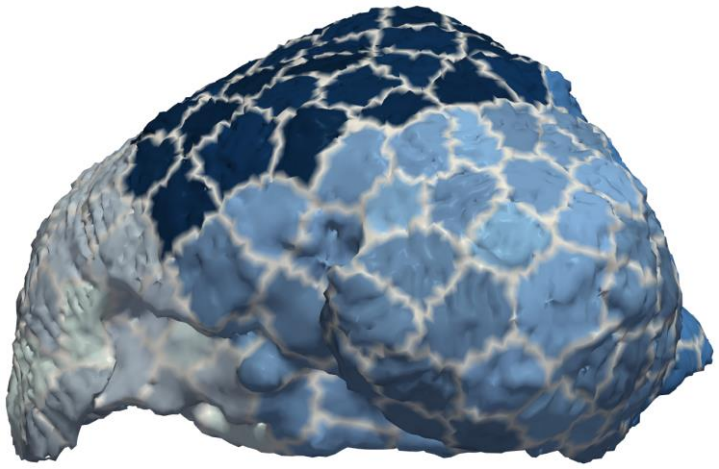
Each coral is split into equal-area surface tiles, **about 4 × 4 cm**.

2 Describe each tile



10 numbers per tile: median rugosity and its spread at 1, 1.5, 2, 3 and 3.8 cm.

3 Train and test by region



5 regions of neighboring tiles. Hold one out (dark), train on the rest, predict each of its tiles; repeat for all 5.

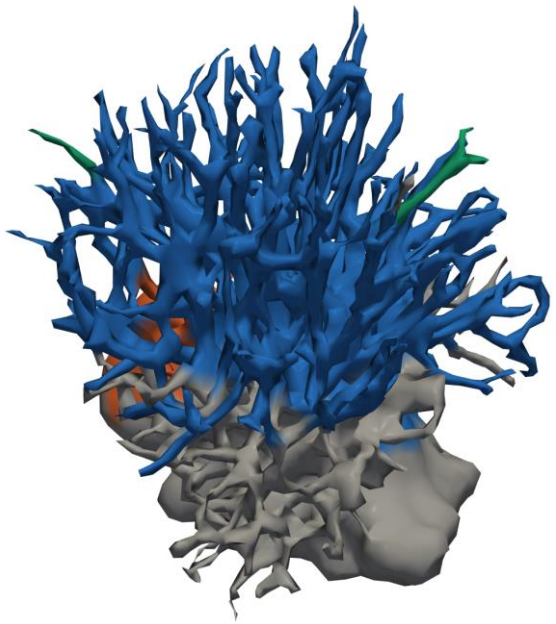
Why whole regions?

– Neighboring tiles share surface, so a random split would unfairly gather information about unseen parts of the topology all throughout and inflate accuracy.

ODR Alone: 88% of Tiles

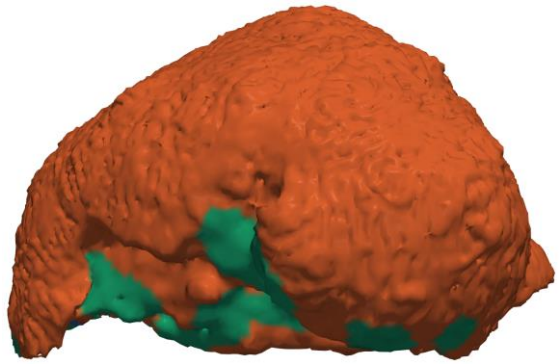
PRELIMINARY · 3 specimens

- Color = predicted growth form for regions the model has not seen



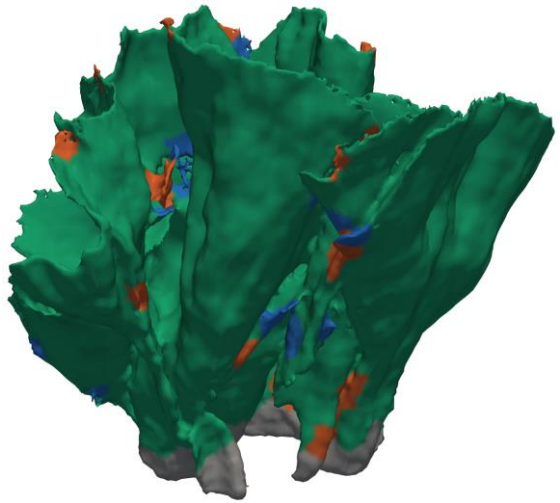
92%

of branching tiles (36)



83%

of massive tiles (259)



90%

of plate tiles (905)

88%

Score = share of tiles labeled correctly, averaged over the three forms

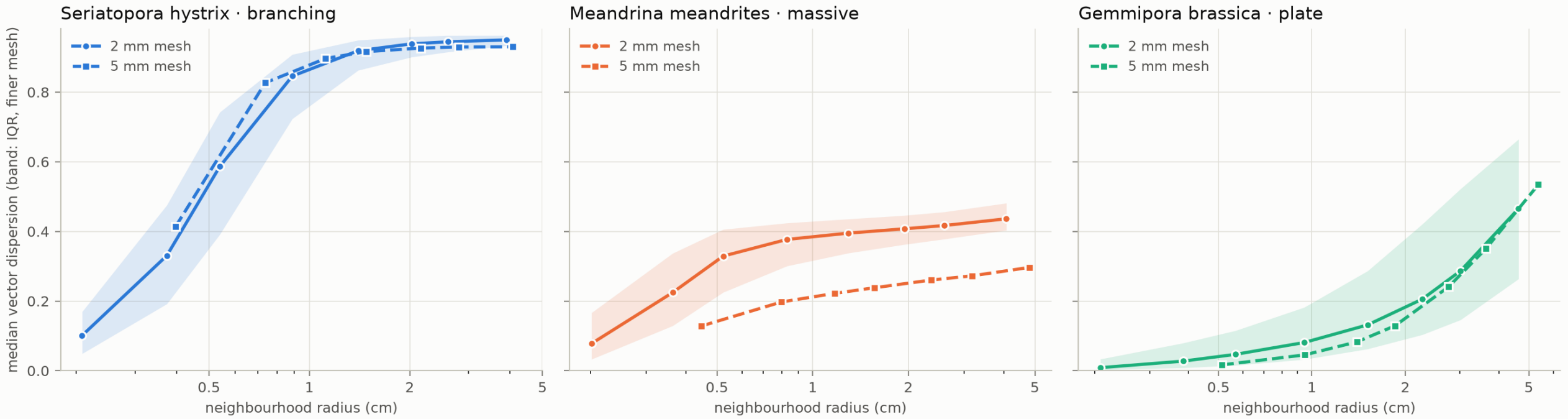
- branching
- massive
- plate
- not scored (base)

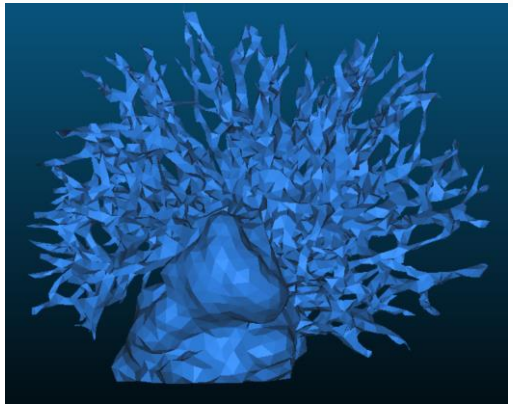
Note: Tile counts are uneven (36 branching vs. 905 plate), so the branching score rests on few tiles and is less certain. Future work will balance tile count across growth forms.

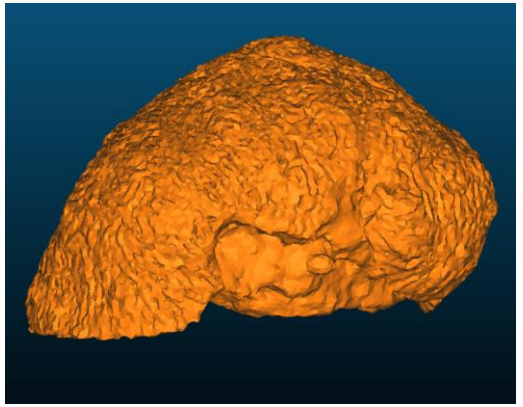
VD Signatures by Growth Form

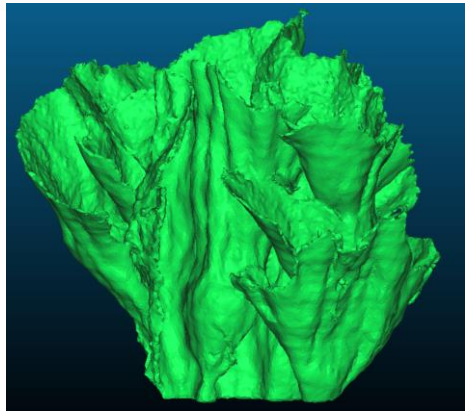
Vector dispersion signatures at two mesh resolutions

solid = 2 mm, dashed = 5 mm; same coral, same colour





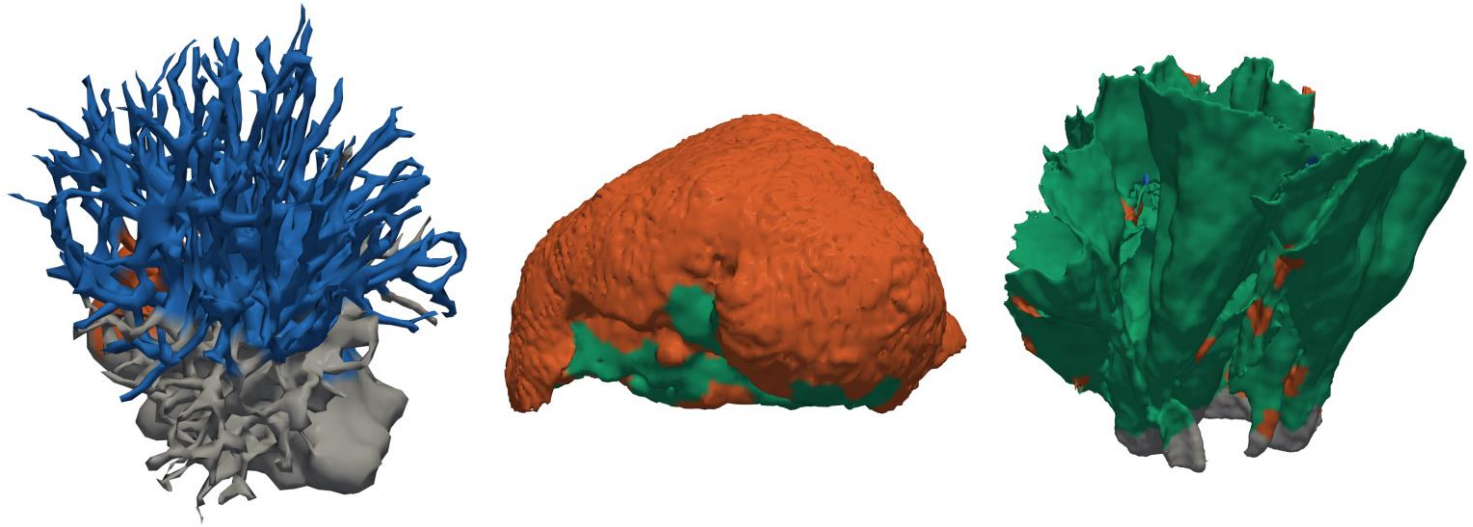




ODR + VD: 92% of Tiles

PRELIMINARY · 3 specimens

- Combining both curves beats either one alone

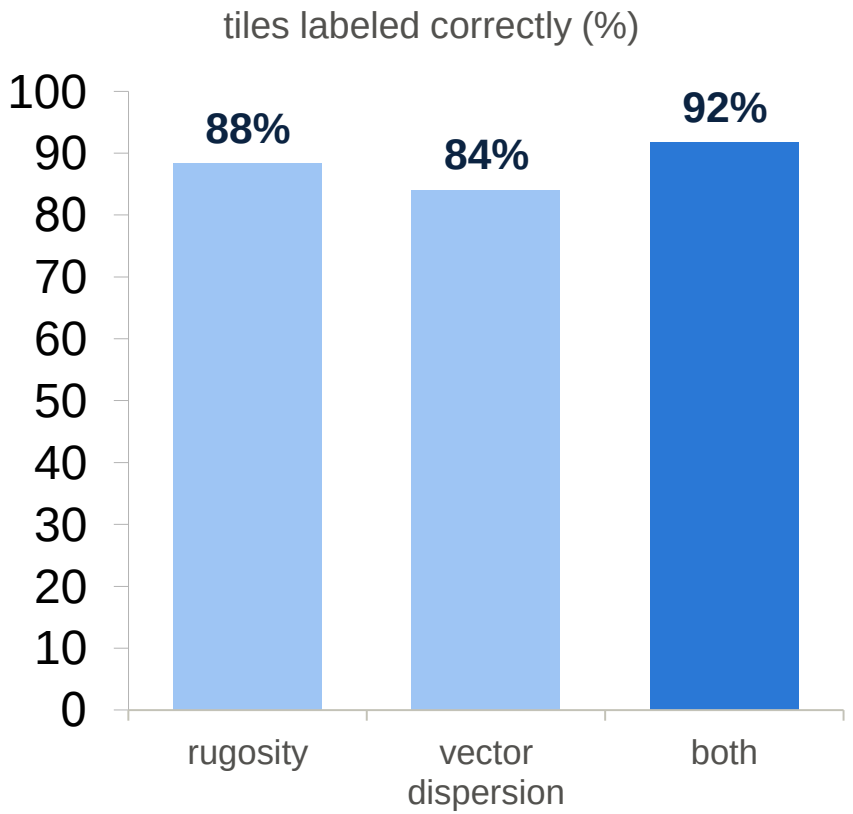


97%
of branching tiles (36)

85%
of massive tiles (259)

93%
of plate tiles (905)

branching massive plate not scored



Three colonies, one per growth form: a teaser, not yet a general classifier. Spatially blocked cross-validation, 5 mm meshes.

Note: Tile counts are uneven (36 branching vs. 905 plate), so the branching score rests on few tiles and is less certain. Future work will balance tile count across growth forms.

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Ulysses Ecosystem Engineering

Project # HIP-25-034

Conclusions

1. Virtual Analogs to Real-World Reef Measurements

Building on Young et al. [7], who showed digital chain rugosity matches in-situ transects, we compute rugosity and vector dispersion on 3D SfM meshes without dive-time limits.

2. Omnidirectional & Multi-Scale Across the Entire Mesh

Every point, every direction, any radius from millimetres to tens of centimetres, including scales a chain cannot measure.

3. Early Evidence: Signatures Carry Growth-Form Information

On three museum specimens [11], the curves separated growth forms (92% of tiles): a promising start, not yet proof. Next: many more colonies per form, then growth-form maps of whole reefs.

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