Processing 3D Laser Scanner Data for Automotive Styling Design

Ph.D. Thesis Proposal

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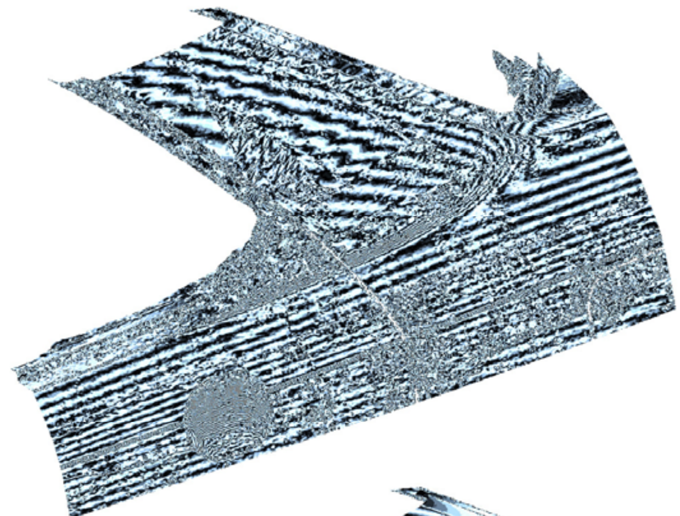
May 6, 2005



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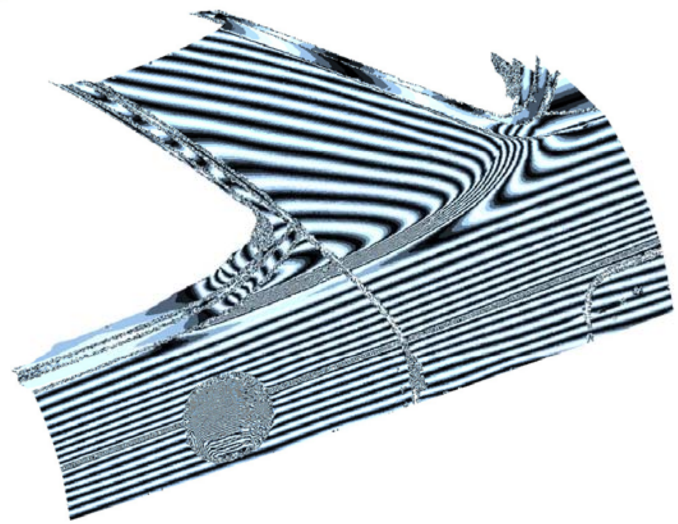
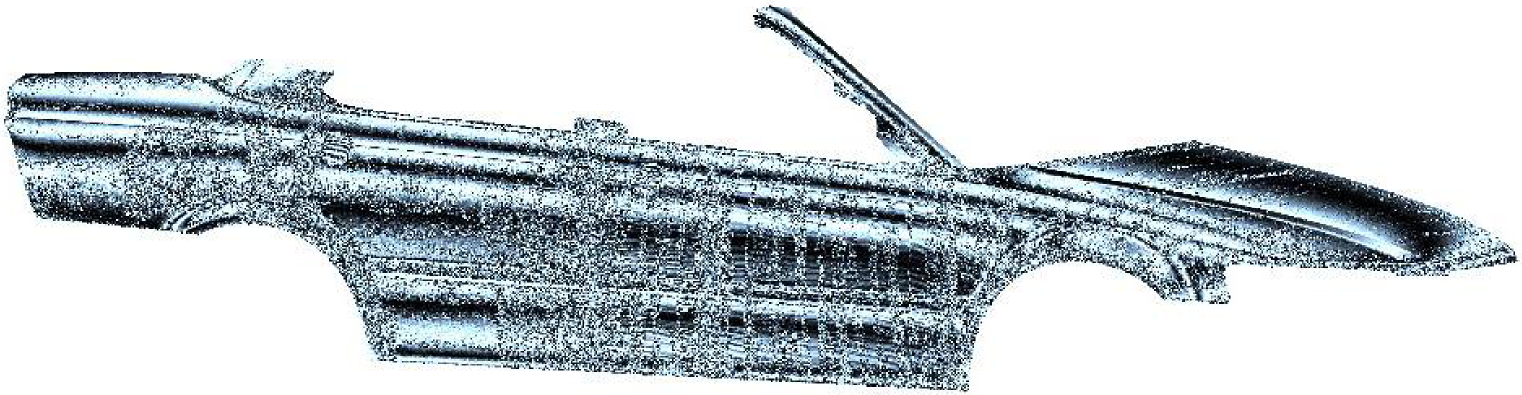


Laser Scanner Technology

http://www.steinbichler.de

- Can quickly measure 3D surface coordinates without contact
- Accurate and easy to use
- Used in automotive styling design to digitize models
- Scanned data can be used for:
  - Testing engineering requirements
  - Aesthetic interrogation
  - Surfacing the final part



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Problem Statement

- Laser-scanner data often needs significant preprocessing before it is useful
- Automotive styling design issues are not addressed by existing algorithms
  - How to remove geometric noise from the data without deforming it or smoothing sharp edges?
  - How to group the points into regions closely approximated by single surfaces?
  - Can we create a piecewise-smooth reconstruction of the part that satisfies both aesthetic and engineering constraints?

Automotive Design Requirements

- Design Constraints
  - Scanner accuracy
  - Tolerances required for design and manufacture
  - These bound the deformation of the data and the accuracy of surface fitting and surface reconstruction
- Aesthetic Constraints
  - A k differentiable surface has k-1 differentiable reflection lines: smooth reflection lines require a twice differentiable surface
  - Character lines are sharp edges that create a distinctive shape – these sharp edges must be preserved
  - Principle of simplest shape: the resulting surface must be free of unnecessary undulations

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Thesis Contributions

- Mesh Smoothing
  - Creates an aesthetically pleasing surface
  - Minimizes mesh deformation
  - Preserves sharp edges
- Surface Extraction
  - Estimates curvatures and noise levels on the data
  - Detects sharp edges
  - Segments data into regions approximated by single surfaces
  - Fits surfaces to a specified tolerance
- Surface Reconstruction (proposed)
  - Will reconstruct objects with large smooth surfaces, smooth blends between surfaces, and sharp edges
  - Will bound the accuracy and geometric continuity of the reconstructed object

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Algorithms

- Mesh Smoothing
- Surface Extraction from Meshes
- Surface Extraction from Point-Sampled Data
- Surface Reconstruction Proposal
- Summary

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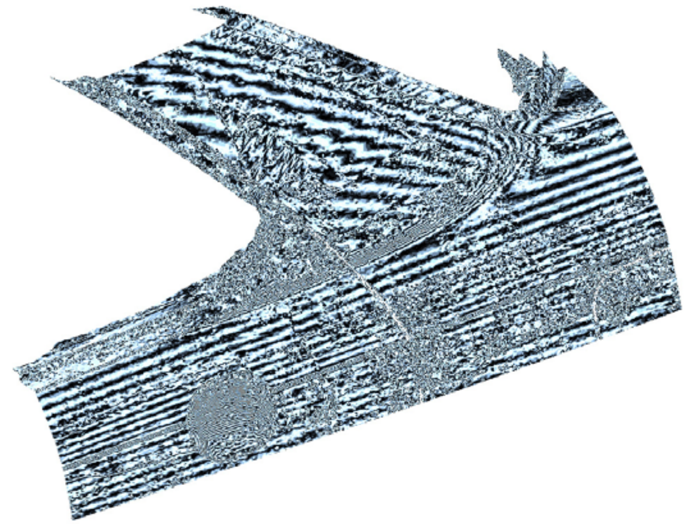
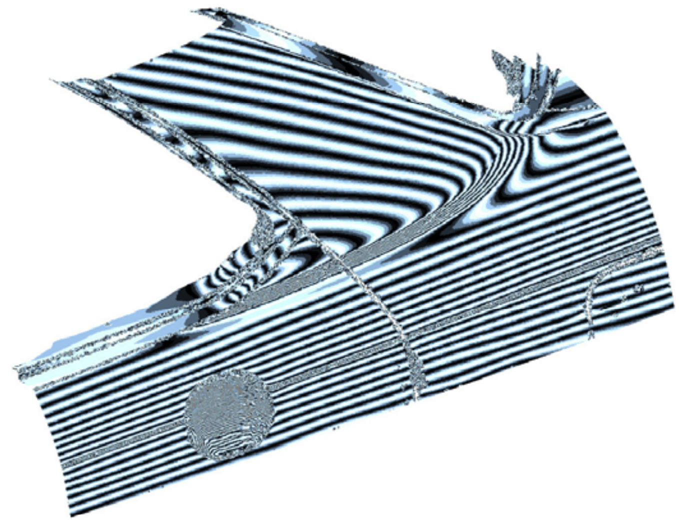
Problem Statement

- Goal: remove geometric noise from a mesh with edge preservation and minimal deformation

- Deformation must be within laser-scanner and design tolerances
- Result must be smooth over large scales with sharp edges preserved
- The smoothed mesh will be used for aesthetic interrogation and patch fitting for design





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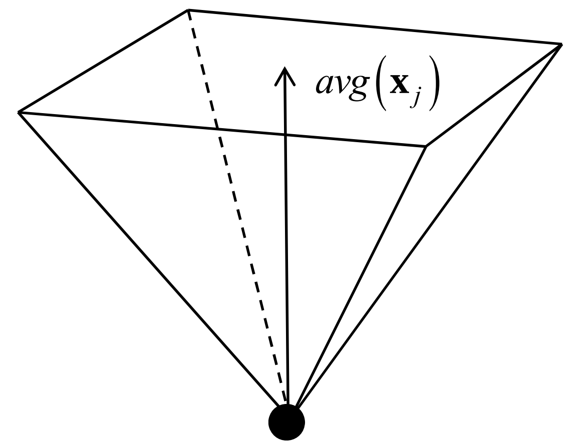
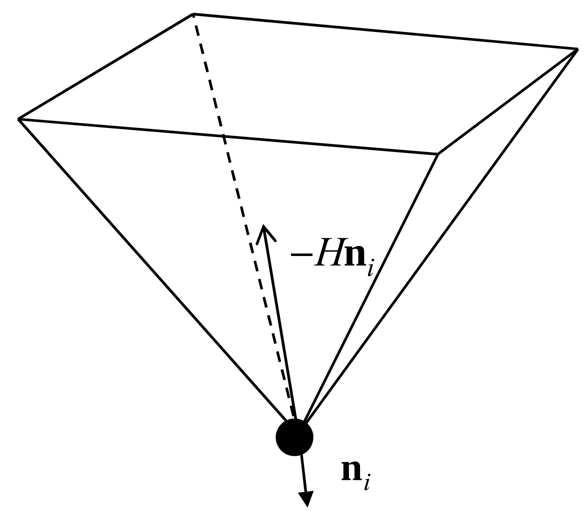
Existing Smoothing Methods

- Diffusion: move each vertex to a weighted average of the positions of its neighbors [1]
- Curvature Flow: move each vertex in its normal direction a distance equal to the mean curvature [2]
  - Both these methods can cause distortion, so using them requires a compromise
- Normal Maps: smooth the normals first, then find vertex positions that satisfy the normal field [3]

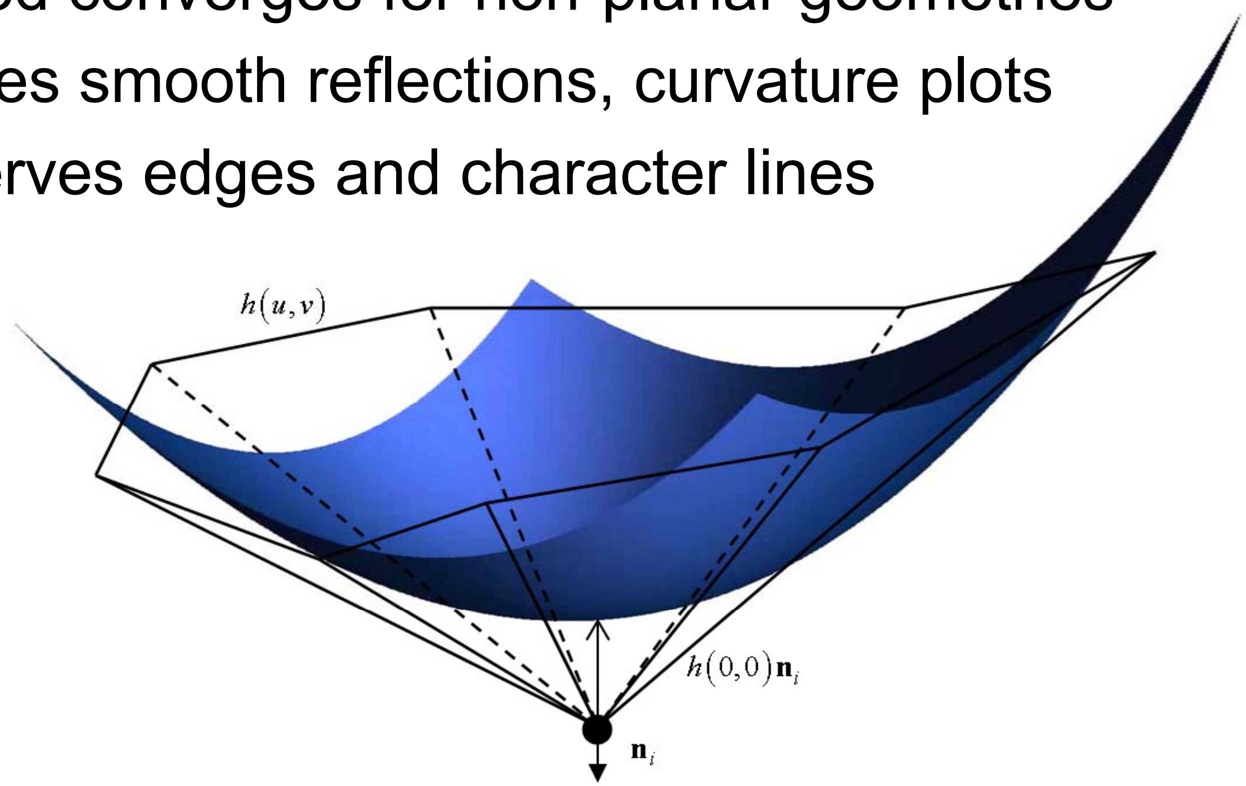




[1] Kobbelt, et al., *Geometric Modeling Based on Polygonal Meshes (tutorial), EUROGRAPHICS 2000.*
[2] Desbrun, et al., *Implicit Fairing of Irregular Meshes Using Diffusion and Curvature Flow, SIGGRAPH 99.*
[3] Tasdizen, et al., *Geometric Surface Smoothing via Anisotropic Diffusion of Normals, IEEE Visualization 2002.*

Polynomial Fitting Solution

- Each vertex is moved onto a polynomial surface approximating its neighborhood
- User can control polynomial order, neighborhood size, and threshold angle
- Method converges for non-planar geometries
- Creates smooth reflections, curvature plots
- Preserves edges and character lines



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Differential Geometry

- The neighborhood of every point on a smooth surface is defined by a 2D Taylor series in a local coordinate system:

$$h(u,v) = \sum_{k=2}^{n} \frac{1}{k!}\left(u\frac{\partial}{\partial u} + v\frac{\partial}{\partial v}\right)^{k} h(0,0)$$

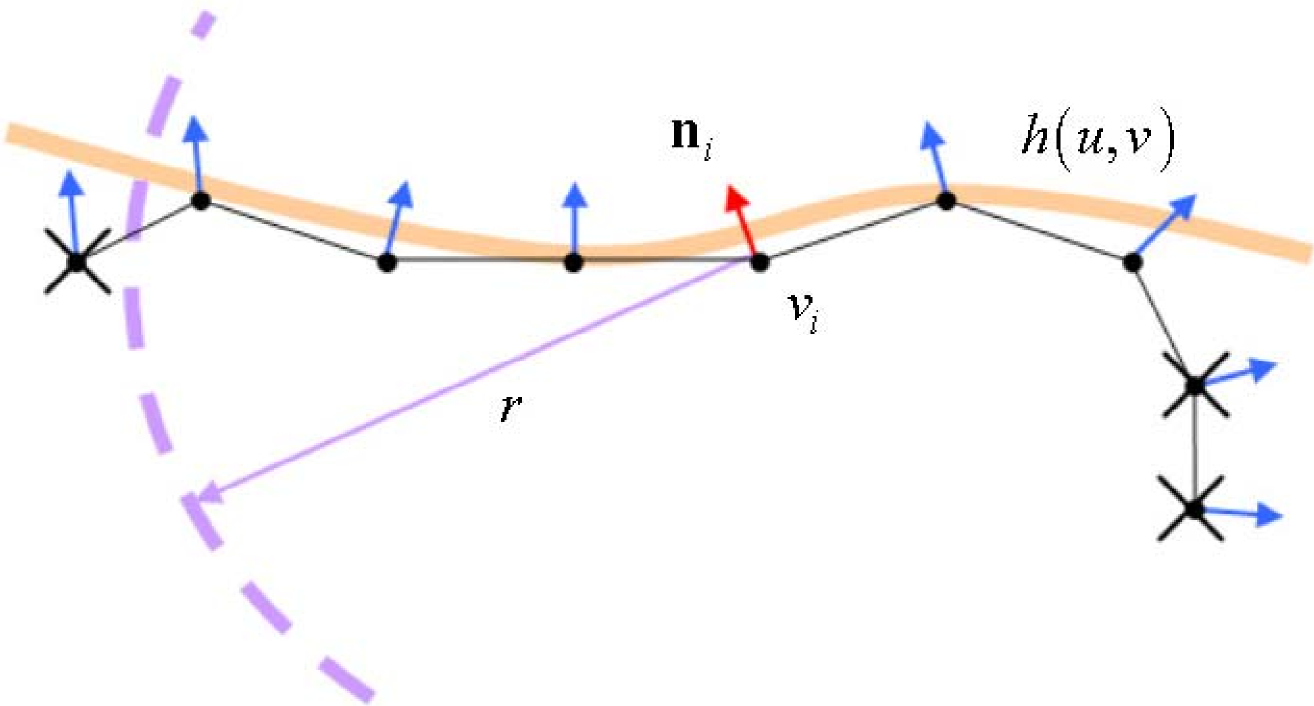
- The Taylor series determines the differentiability of the surface at the point
- We find the coefficients of truncated approximation of the Taylor series

$$h(u,v) = a_{00} + a_{10}u + a_{01}v + a_{20}u^2 + a_{11}uv + a_{02}v^2$$

- Approximating polynomial is found with a linear least-squares problem solved by Cholesky decomposition

Vertex Neighborhoods

- Create a neighborhood by adding vertices with positions and normals close to that of the target vertex
- This creates pseudo-planar neighborhoods that don't include sharp edges



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Implementation

- For each vertex
  - Grow a neighborhood using breadth-first search with distance and normal-deviation constraints
  - Find neighborhood vertex positions in local coordinate system
  - Least squares fit a polynomial to the vertices in the local coordinate system
  - Move the target vertex onto the polynomial
- User selects neighborhood width, polynomial order, and threshold angle

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Automobile C-Pillar

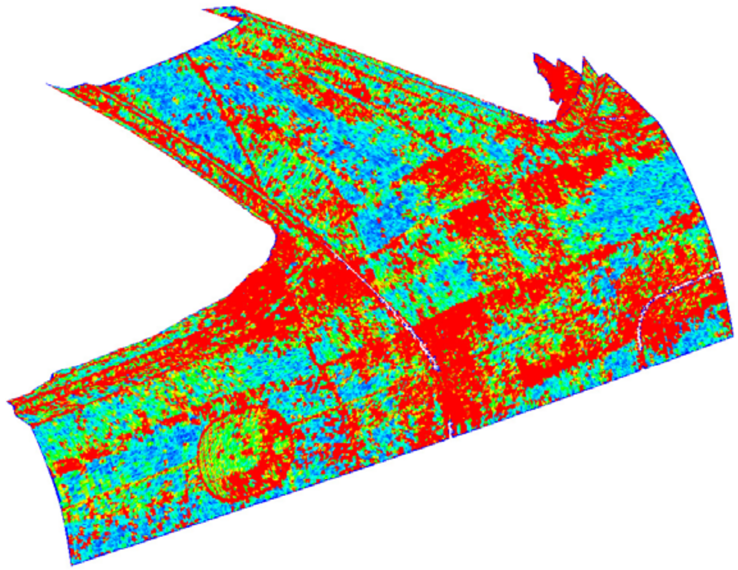
99,790 vertices

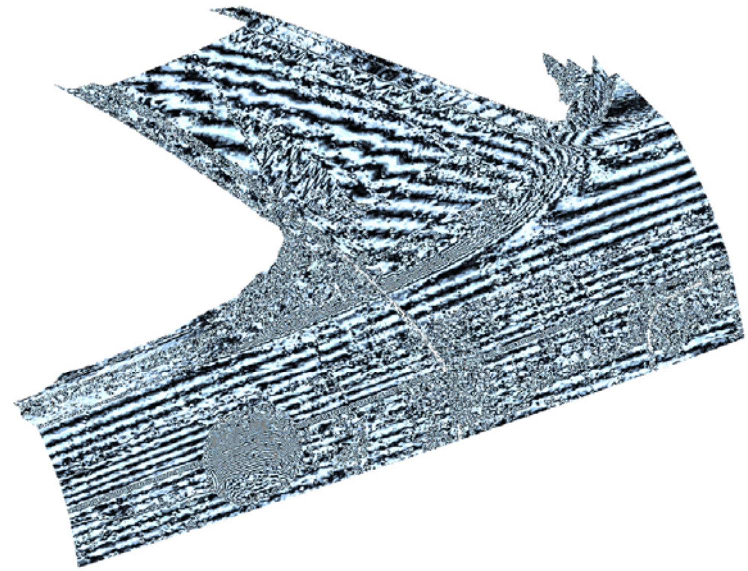
Results

Curvature

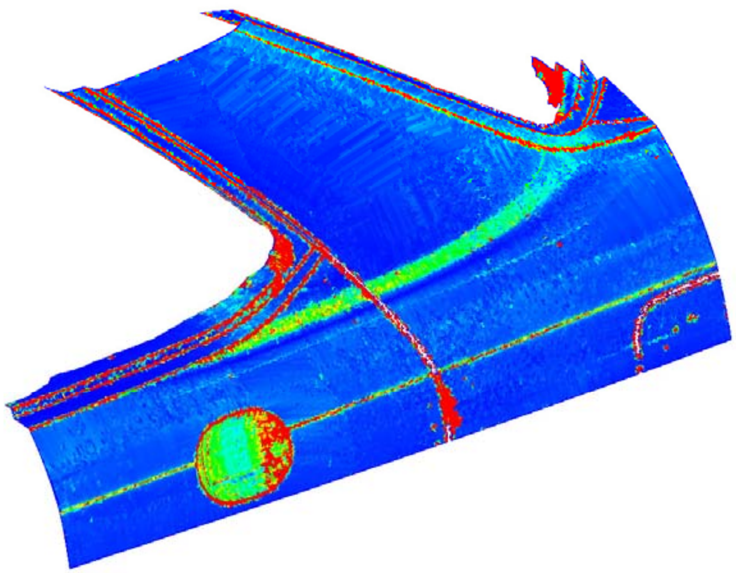
Reflections

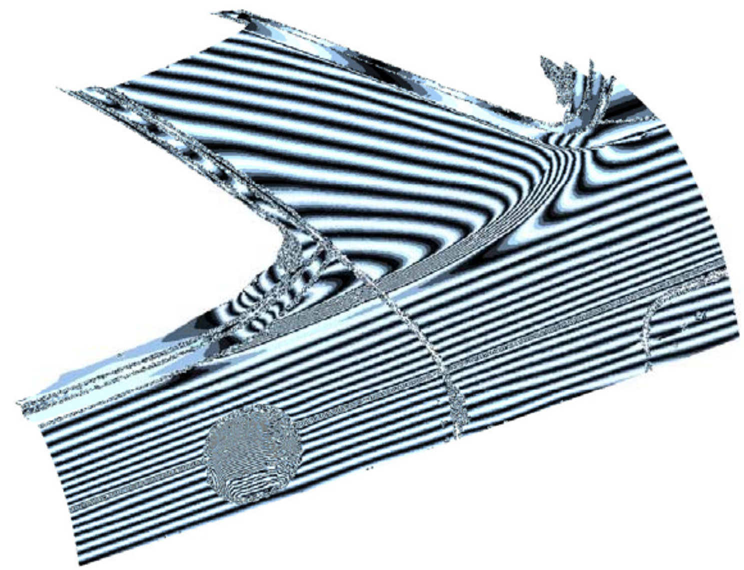
Original





Smoothed

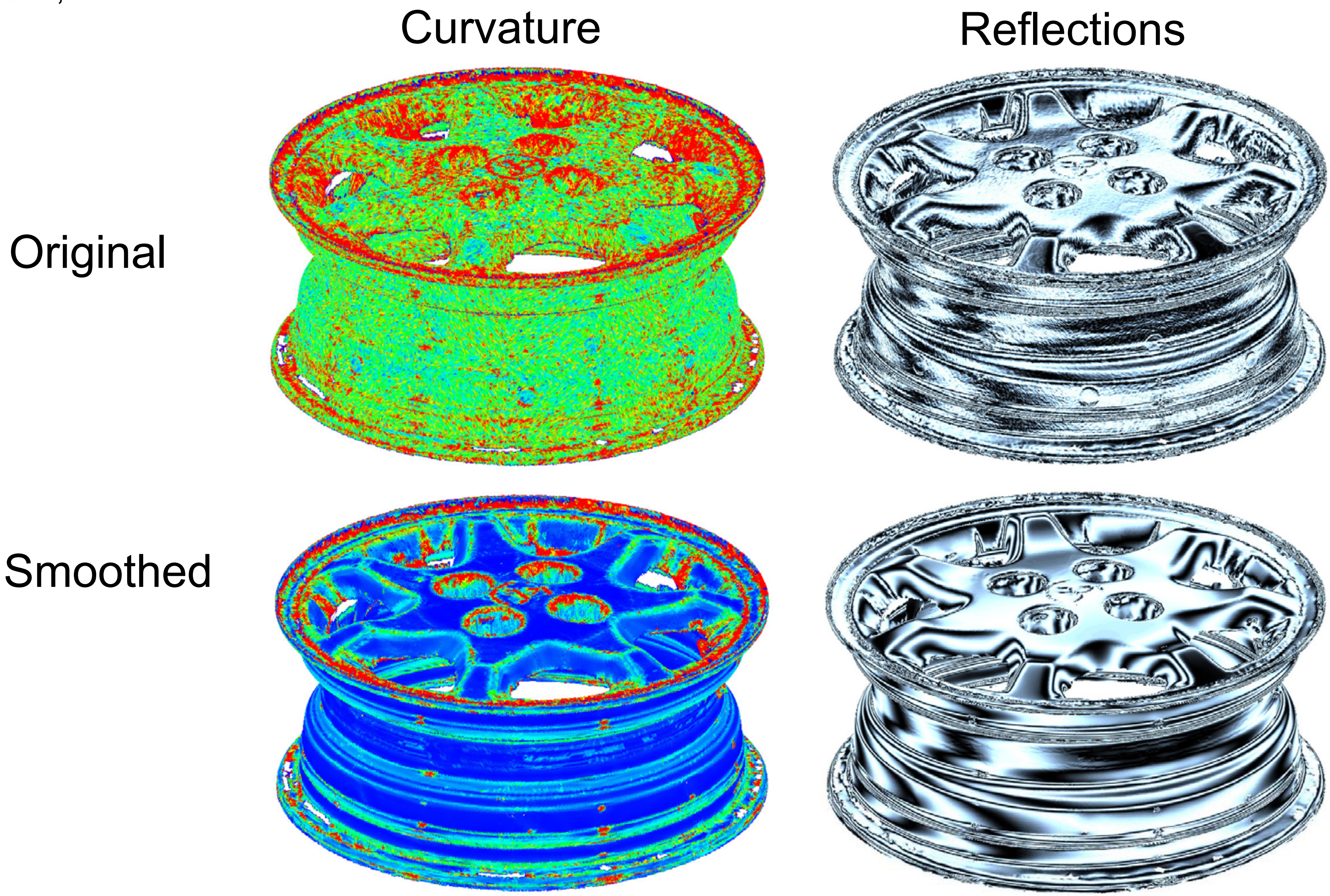




Wheel Rim

366,920 vertices

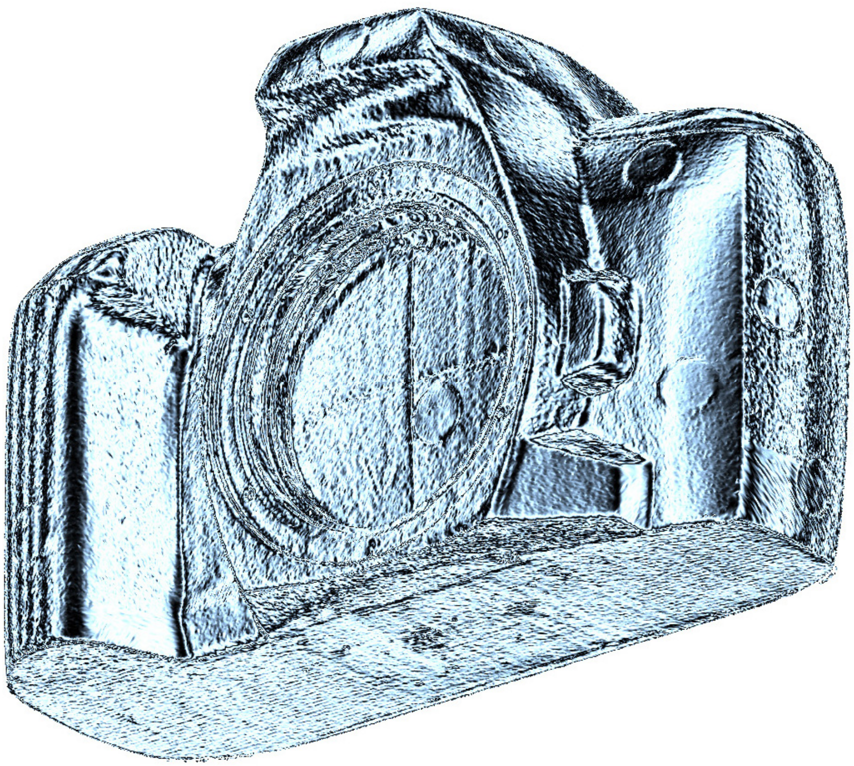
Results



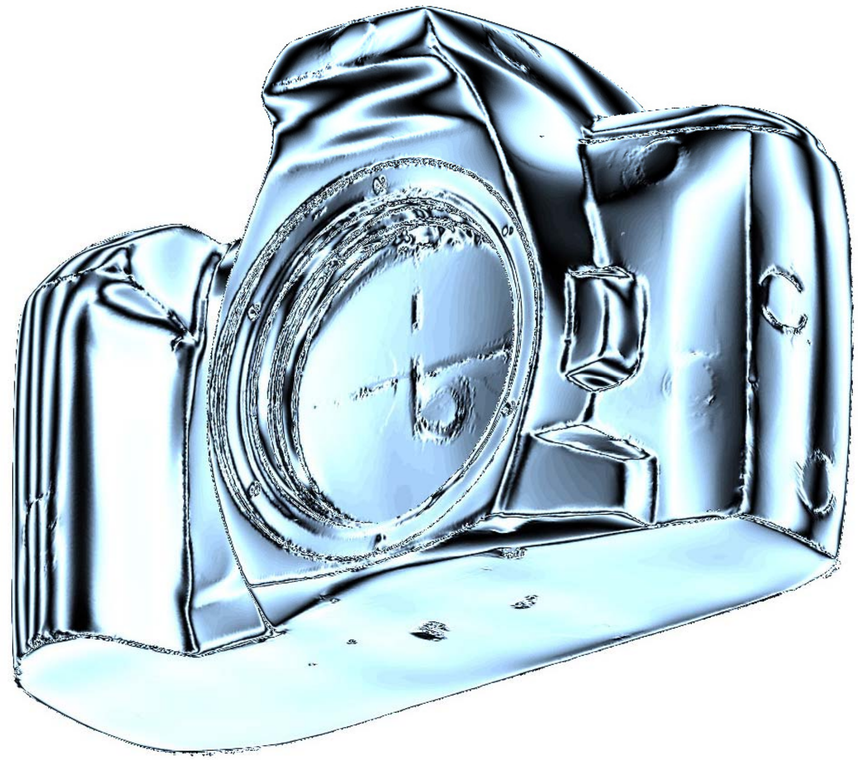
SLR Body

606,254 vertices

Results



Original



Smoothed

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Algorithms

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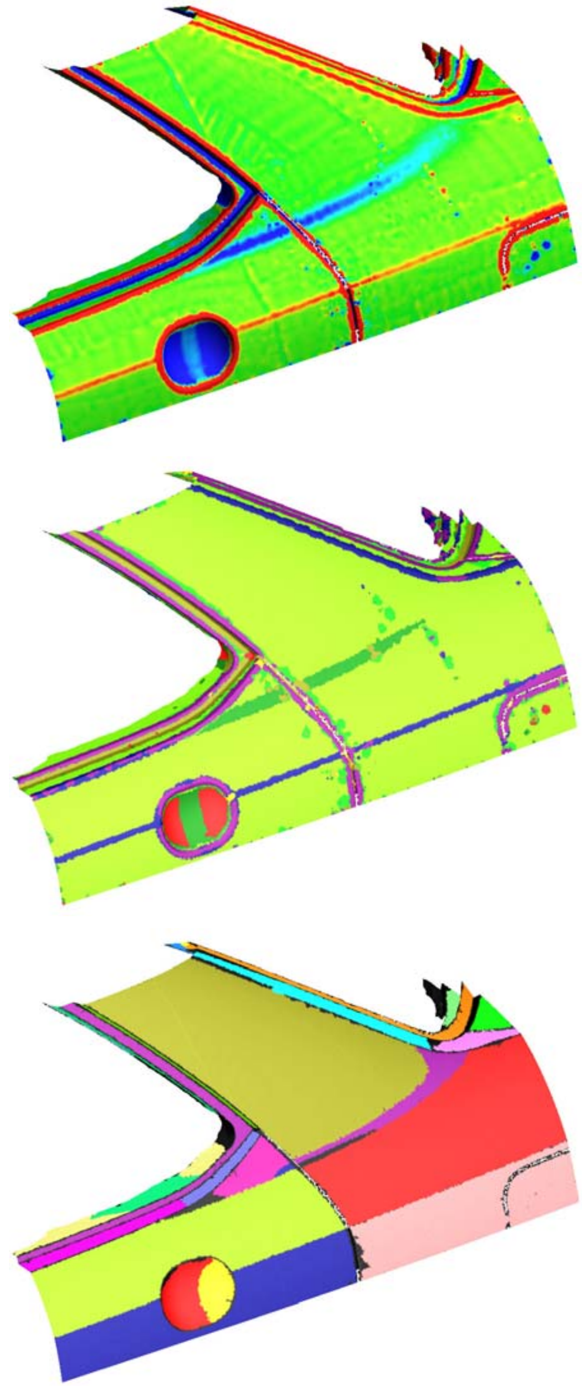
Problem Statement

- Must create a concise surface-based representation of the object from the scanned data
- This is a manually intensive and time-consuming procedure
- How can we automatically segment a dense, noisy mesh into groups of vertices approximated by single surfaces and then output the surfaces themselves?
  - Segments should be as large as possible
  - Surface approximations must be accurate
- A designer can easily modify the extracted surfaces to create a final design

Algorithm Summary

- Approximate vertex neighborhoods with polynomials
  - Estimate surface curvatures
  - Estimate noise levels
  - Detect sharp edges
- Filter curvatures and label vertices by curvature-signs
- Contract labeled regions to create seed regions
- Grow seed regions by iterating between region growing and surface fitting
- Regions are grown by testing vertices for geometric compatibility with the approximating surfaces



Related Work

- Besl and Jain introduced region growing for images and range data [1]
  - We generalize this approach to dense, noisy, unstructured data
- Direct segmentation: hierarchical subdivision by testing neighborhoods for compatibility with increasingly complex analytic surfaces [2]
  - Not clear how to use with freeform surfaces
- Recover-and-select: simultaneously grow randomly placed regions while culling non-optimal models [3,4]
  - We place seed regions carefully for computation efficiency

[1] Besl and Jain. *Segmentation Through Variable-Order Surface Fitting*. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 1988.
[2] Benkő and Várady. *Segmentation Methods for Smooth Point Regions of Conventional Engineering Objects. Computer-Aided Design Journal*, 2004.
[3] Leonardis, et al. *Superquadrics for Segmenting and Modeling Range Data. IEEE Transactions on Pattern Analysis and Machine Intelligence*, 1997.

Noise and Curvature Estimation

- We approximate the points within a ball centered at each vertex with a quadric polynomial

$$h(u,v) = a_{00} + a_{10}u + a_{01}v + a_{20}u^2 + a_{11}uv + a_{02}v^2$$

- From this polynomial we calculate the Gaussian, mean, and principal curvatures
- The G^0 noise is calculated by $\varepsilon_i^0 = |a_{00}|$
- The G^1 noise is calculated by $\varepsilon_i^1 = \cos^{-1}(\mathbf{n} \cdot \mathbf{n}_i)$
- For the G^0 and G^1 noise, we find the value that is larger than that of a certain percentage of the other vertices
- These values will be the compatibility thresholds for region growing

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Sharp Edge Detection

- If the smallest radius of curvature at a vertex is small compared to the mesh density, a sharp edge is indicated
- We do not grow regions from sharp edges
- Mathematically, a sharp edge is likely if $\dfrac{1}{\left|\kappa_{\max,\,i}\right|} < 10\ l_{avg,\,i}$

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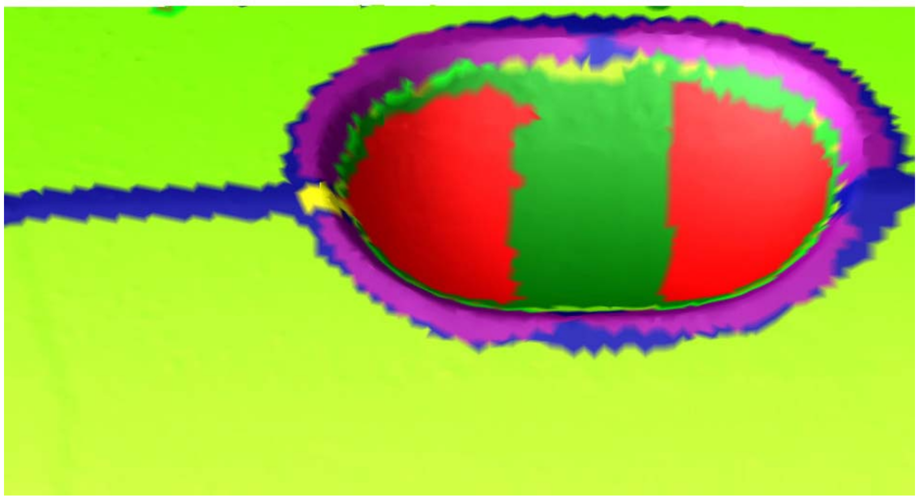
Surface-Type Labeling

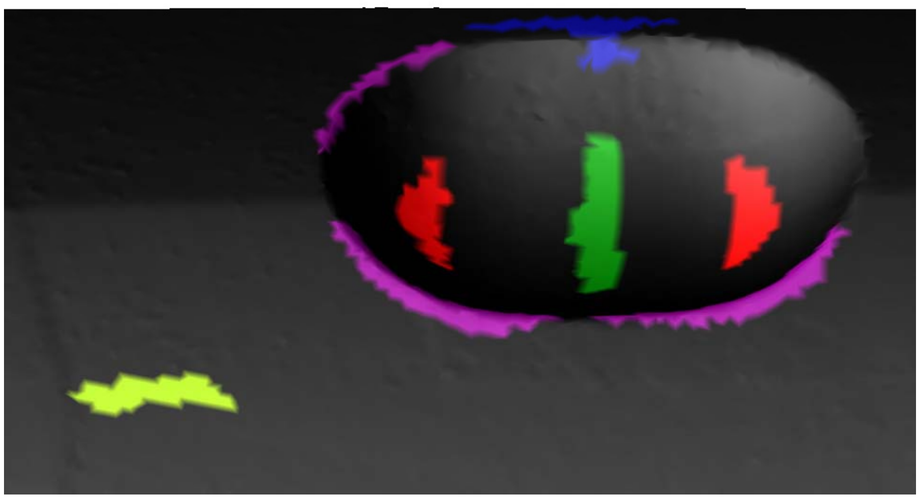
- We apply median and mean filters to the curvatures to despeckle and smooth them
- Then we use the signs of the filtered Gaussian and mean curvature to label the vertices

	$K > 0$	$K = 0$	$K < 0$
$H < 0$	Peak	Ridge	Saddle Ridge
$H = 0$	(none)	Flat	Minimal Surface
$H > 0$	Pit	Valley	Saddle Valley

Seed Regions

- Region growing is most effective when vertices on the boundary of the growing region are geometrically compatible with those already in the region
- Cluster points with the same surface-type labels
- Contract these clusters to form seed regions





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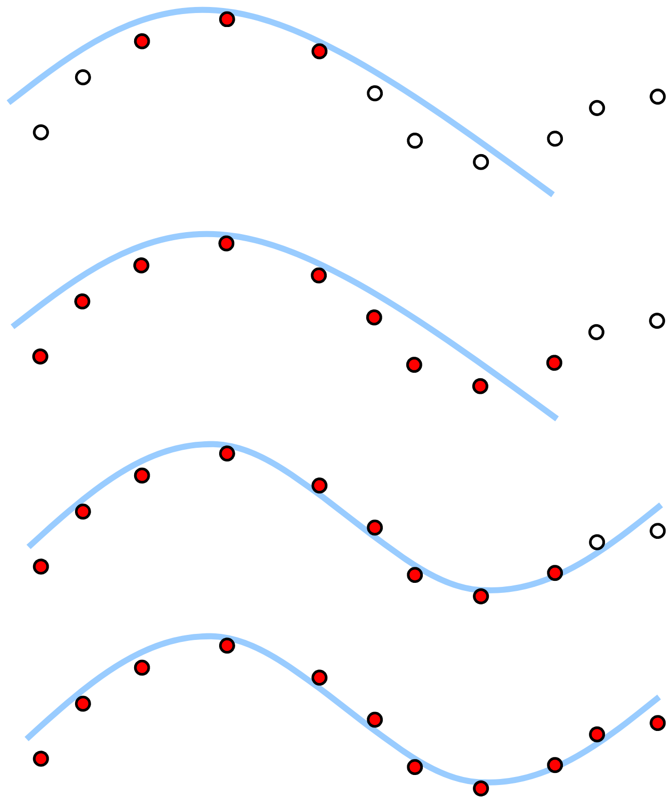
Region Growing

- Seed regions lie within large groups of vertices with identical geometric properties
- A surface approximating the seed region likely approximates the nearby vertices well



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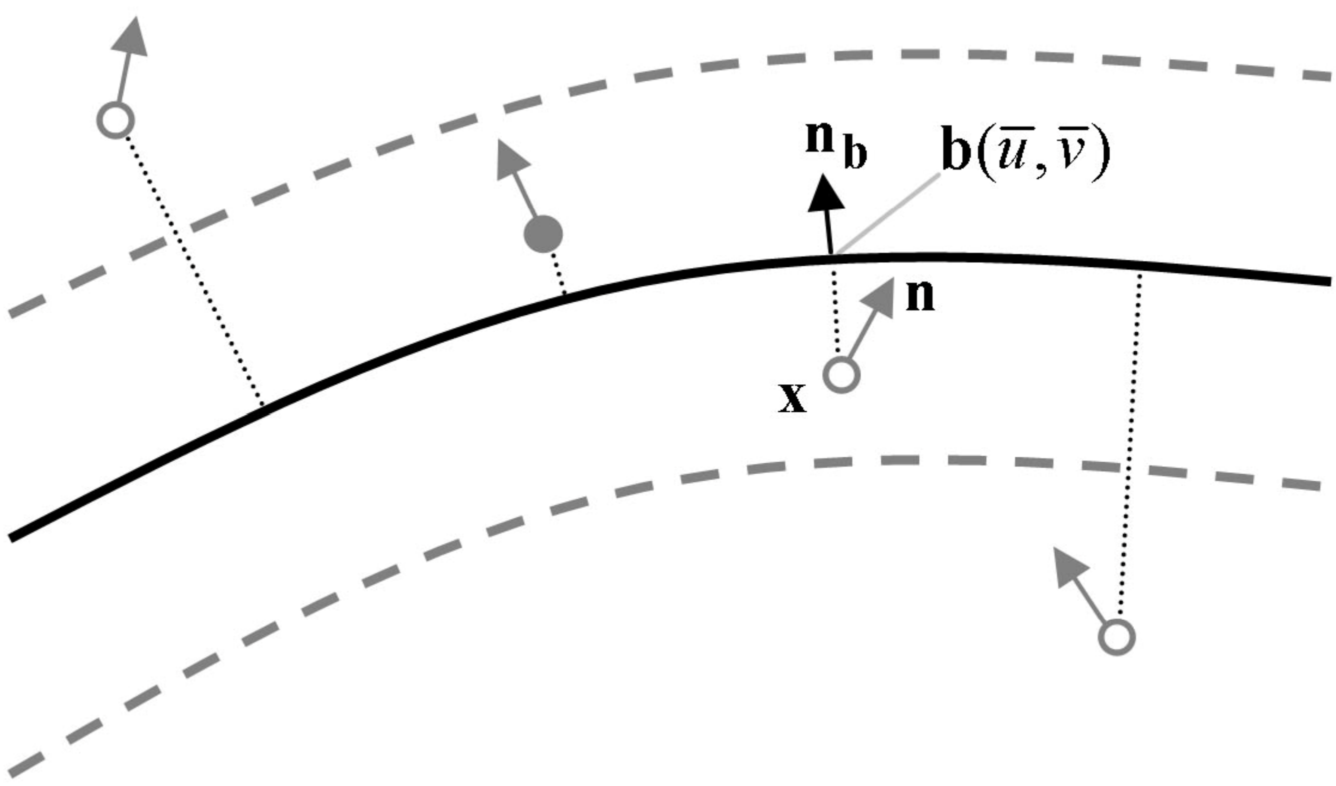
Geometric Compatibility

- We fit a surface to the seed region
- Given a point $\mathbf{x}$ and a parametric surface $\mathbf{b}(u,v)$
  - $\mathbf{x}$ is G^0-compatible if $\| \mathbf{x} - \mathbf{b}(\bar{u},\bar{v}) \| < \varepsilon^0$
  - $\mathbf{x}$ is G^1-compatible if $\cos^{-1}(\mathbf{n},\mathbf{n_b}) < \varepsilon^1$



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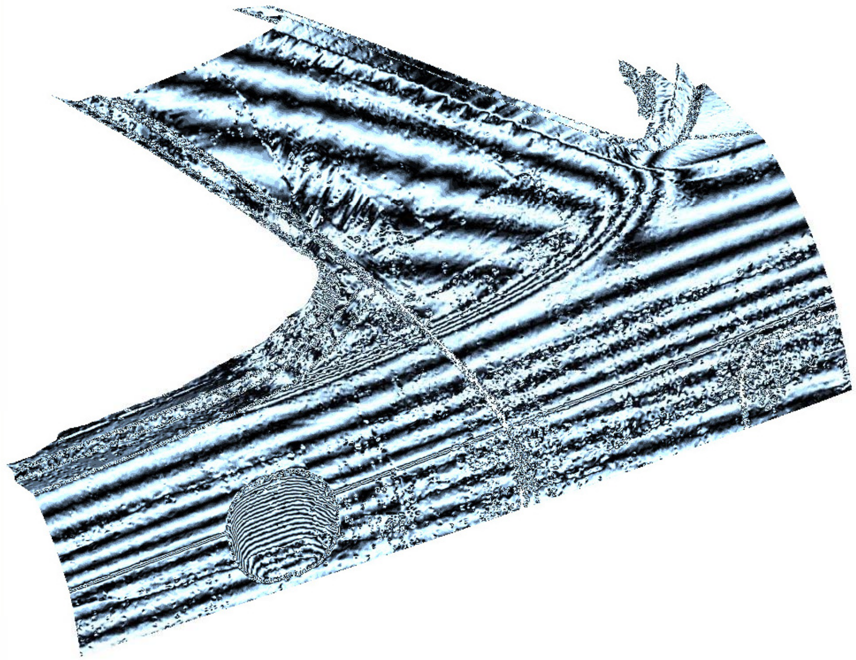
Surface Fitting

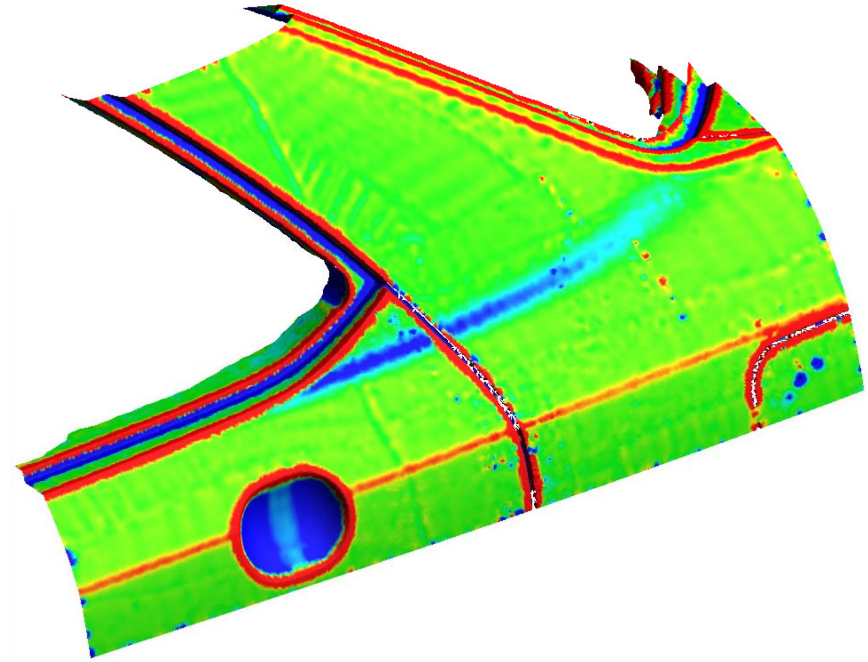
- The region-growing algorithm can be used with any class of surfaces that allows
  - approximation (surface fitting)
  - differentiation
  - point projection (testing geometric compatibility)
- We use bicubic Bézier surfaces

$$\mathbf{b}(u,v) = \sum_{i=0}^{3}\sum_{j=0}^{3} \mathbf{p}_{i,j} B_i^3(u) B_j^3(v), \quad 0 \le u,v \le 1$$

- First we get an initial parameterization for the region
- Then we iterate between surface fitting and parameterization to get a good fit

Results





- Simulated reflection lines on the raw mesh show how noisy the geometry is
- The estimated curvatures are shown on the right

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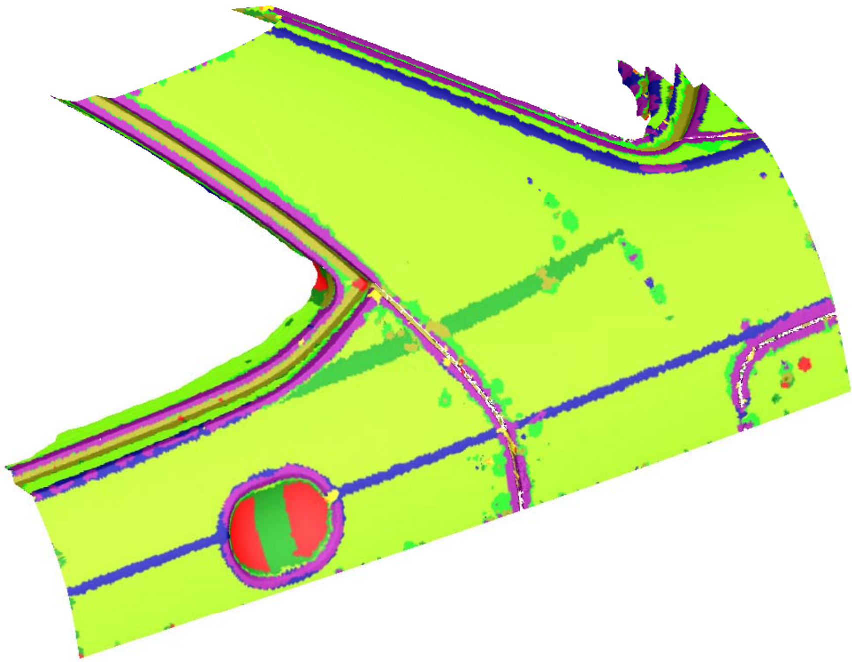
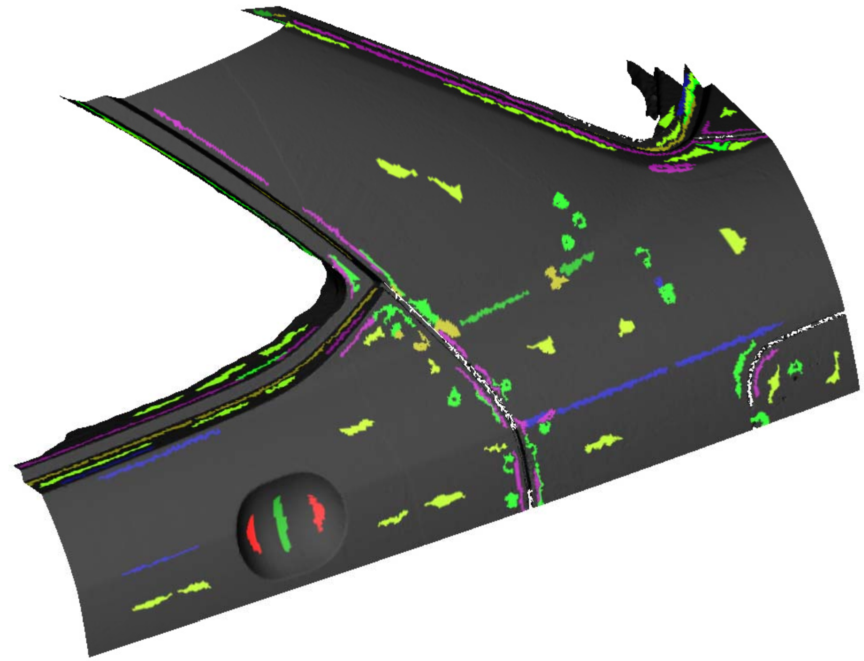
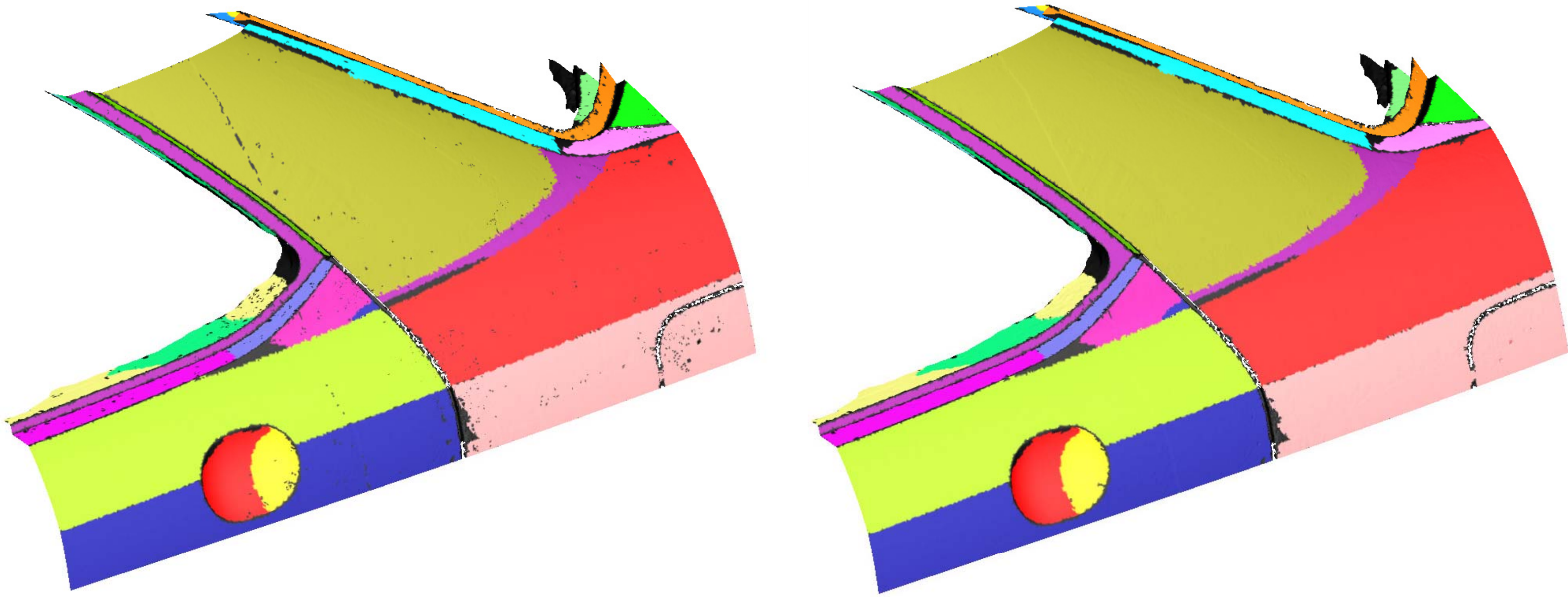
Results





- We label vertices using the signs of the Gaussian and mean curvatures
- Then we contract the labeled regions to form seed regions

Results



- Each color corresponds to a region of vertices approximated by a single surface
- As a last step, we remove holes in the segmentation caused by outlier noise

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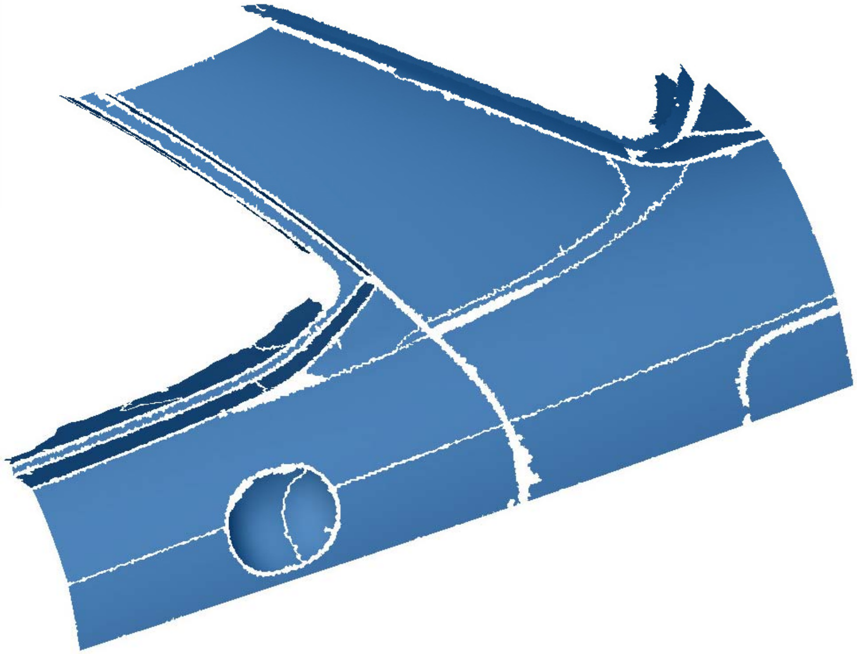
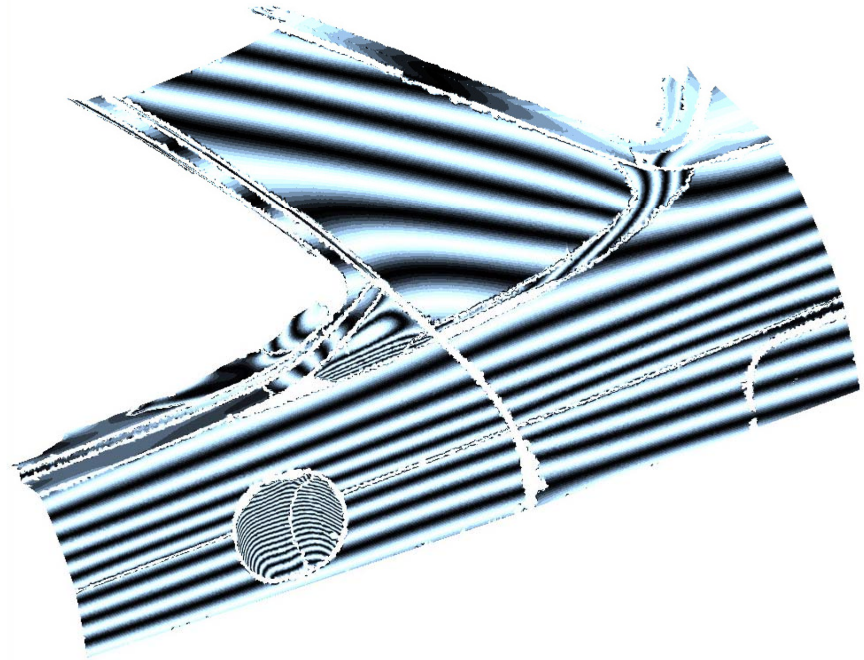
Results





- Here we projected the segmented vertices onto the extracted surfaces
- Note the smooth reflection lines on the extracted surfaces

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Algorithms

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- Surface Reconstruction Proposal
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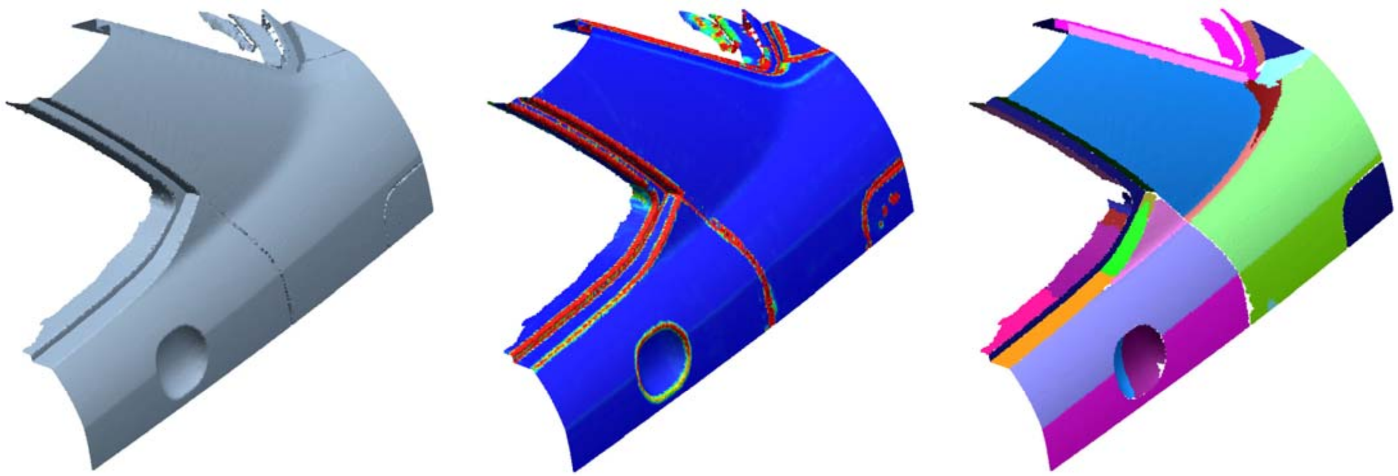
Motivation



- Using a mesh for surface extraction requires too much computer memory
- Can we modify the algorithm and reduce the data representation so we can process very large models?
- When the data is very dense, we can replace topology with spatial proximity!

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Algorithm

- Grow regions from seed points in in order of increasing surface variation
- Region Growing
  - Use points near the seed point to fit an initial surface approximation for region growing
  - Grow the region by adding points that are geometrically compatible with the underlying surface
  - Once all compatible points have been added, fit a new surface to the region to improve the approximation
  - Use the new surface to re-grow the region
- Repeat until region size stops increasing

Surface Variation

- Estimates local surface properties on point clouds
- Like finding the mean and variance of a 1D distribution
- Let $\mathbf{N}(\mathbf{x}_i)$ be the *k*-nearest neighbors of a point $\mathbf{x}_i$
- Then the covariance matrix of the points is

$$\mathbf{C} = \sum_{\mathbf{y} \in \mathbf{N}(\mathbf{x}_i)} (\mathbf{y} - \overline{\mathbf{x}}) \cdot (\mathbf{y} - \overline{\mathbf{x}})^T$$

- The eigenvalues of this matrix measure the variance of $\mathbf{N}(\mathbf{x}_i)$ in the directions of the eigenvectors
- The surface variation is

$$\sigma_k(\mathbf{x}_i) = \frac{\lambda_0}{\lambda_0 + \lambda_1 + \lambda_2}$$

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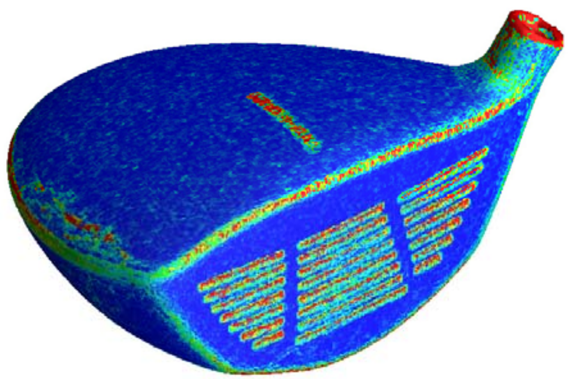
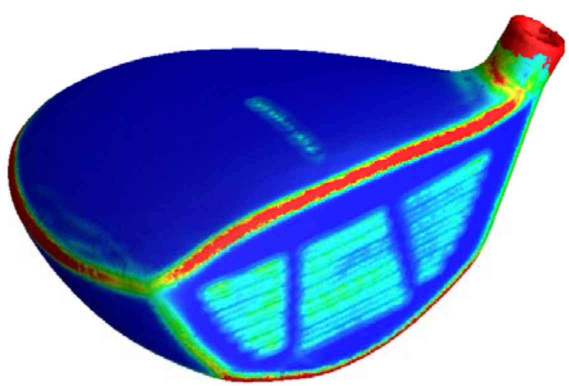
Surface Variation

Input point cloud (200,000 points)



Surface variation using few nearest neighbors



Surface variation using many nearest neighbors

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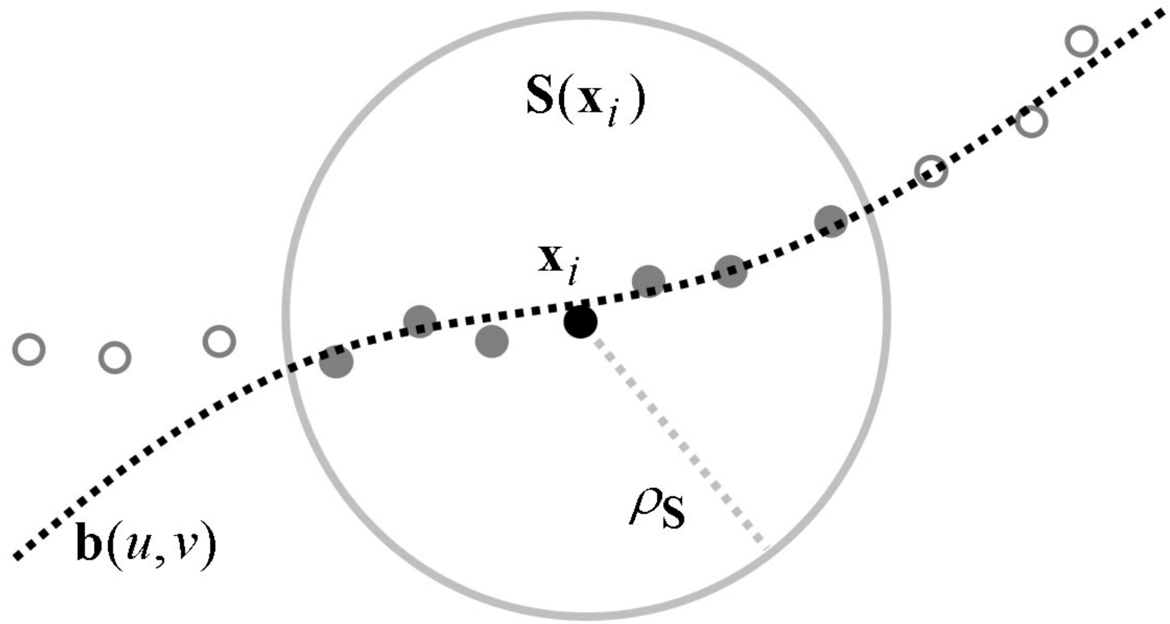
Seed Regions



- If $\mathbf{x}_i$ has already been assigned to a region, skip it
- Otherwise, construct a seed region $\mathbf{S}(\mathbf{x}_i)$ of all the unlabeled points within a radius ρ_S of $\mathbf{x}_i$

$$\mathbf{S}(\mathbf{x}_i) = \left\{ \mathbf{x} \in \mathbf{X} \;\middle|\; \|\mathbf{x} - \mathbf{x}_i\| < \rho_S \;\; and \;\; \mathbf{x} \; is \; unlabeled \right\}$$

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Results

- We used a threshold distance of 0.3 mm
- Uses about 80 bytes per point, a fraction of the RAM required for processing a mesh
- Processes very large models in a few minutes

Model	Num. Points	Thresh. Angle	Peak RAM	Time (secs)
C-pillar	99,790	5°	25 MB	24
Golf Club	209,779	5°	33 MB	25
Rear Fender	1,065,886	6°	90 MB	255
Front Door	1,497,459	5°	125 MB	288

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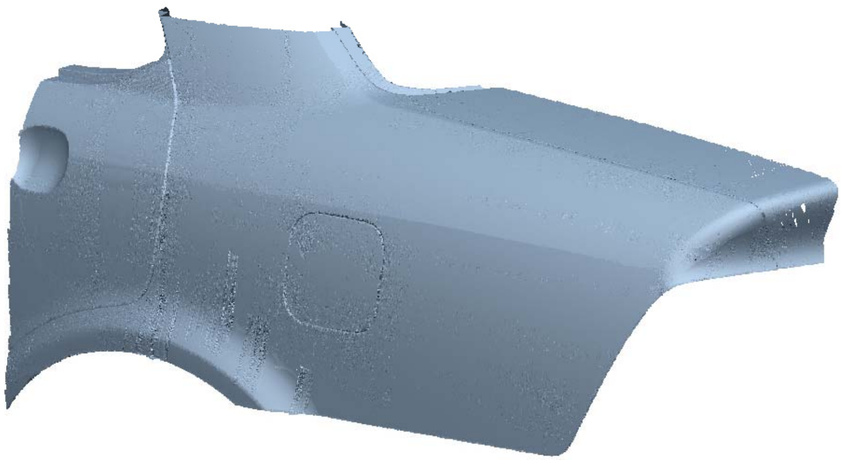
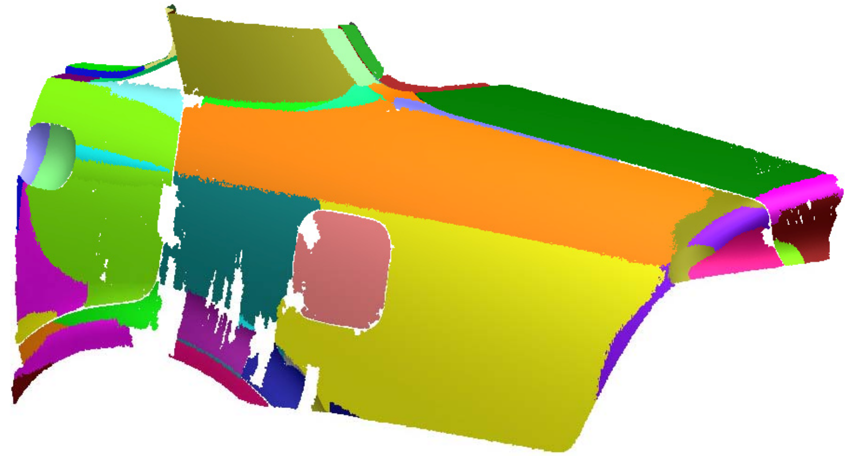
Results – Rear Fender





- 1,065,886 points
- 90 MB peak RAM
- 255 secs

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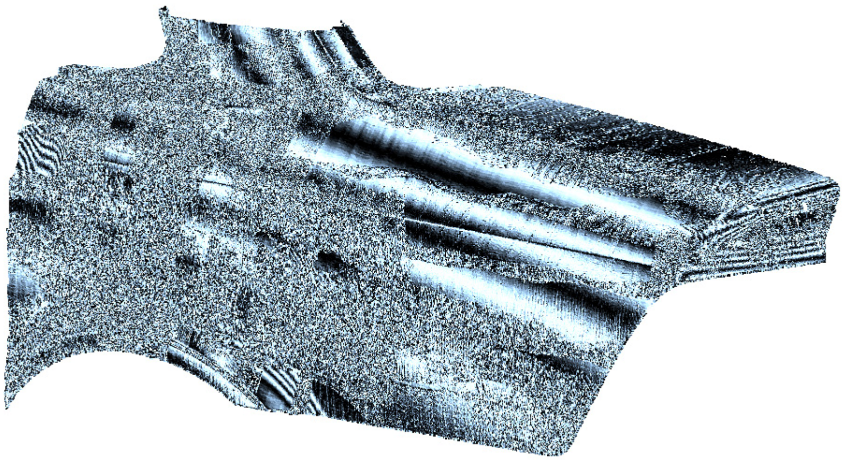
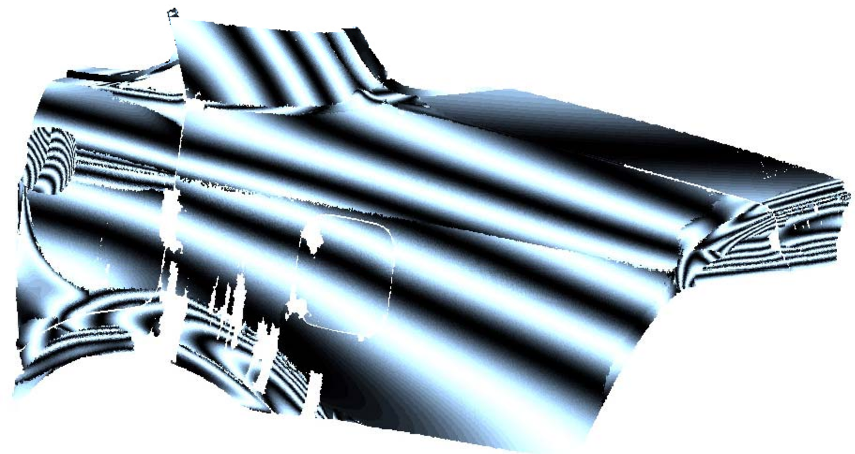
Results – Rear Fender





- Simulated reflection lines on raw data and extracted surfaces

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Motivation

- Can we blend and intersect the extracted surfaces?
- Can we create a piecewise-smooth reconstruction?
- The reconstructed model must:
  - Approximate the data to engineering tolerances
  - Be free of unnecessary undulations (principle of simplest shape)
  - Preserve sharp edges and character lines
- Reconstruction useful for: aesthetic interrogation, engineering analysis, manufacturing

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Proposed Work Outline

- Extract surfaces from point data
- Subdivide the object's bounding box into cells
- Find surface approximations in each cell
- Convert surfaces into an implicit representation
- Intersect surfaces at sharp edges
- Use the **Partition of Unity Method** to blend the approximations in each cell
- Reconstructed surface is the solution of a single implicit equation
- Established methods to polygonize the surface

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Related Work

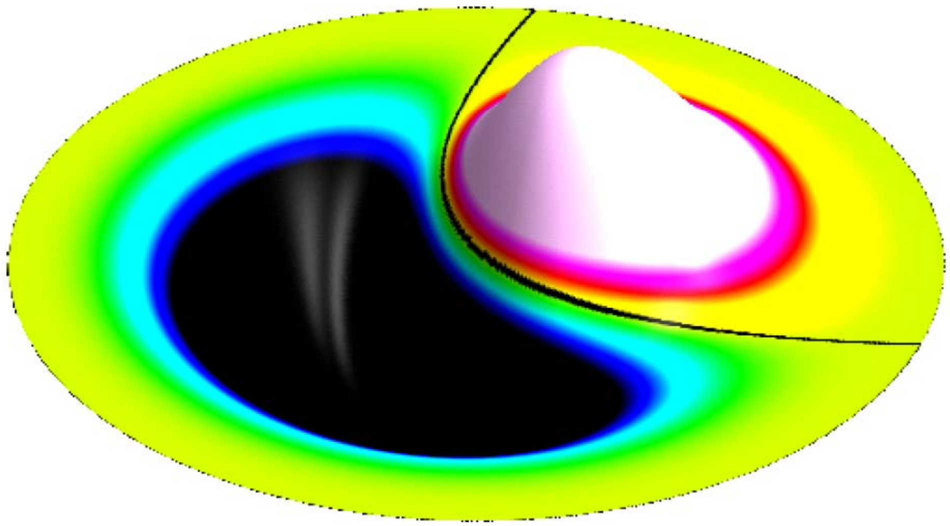
- An implicit surface is the locus of 3D points such that $F(\mathbf{x})=0$ for some scalar-valued function $F(\mathbf{x})$
- Blending and intersecting surfaces becomes trivial [1]
- Used to create meshes from point clouds [2,3]:
  - Compute a signed distance function as the distance from each point to the tangent plane of the closest point in the point cloud
  - Extract the surface by meshing the zero level set of the signed distance function
- Implicit representations have also been used to create C^1-smooth reconstructions with B-splines [4]

[1] Bloomenthal. *Introduction to Implicit Surfaces.* Morgan Kaufmann Publishers, 1997.
[2] Hoppe, et al. *Piecewise Smooth Surface Reconstruction, SIGGRAPH 94.*
[3] Curless & Levoy. *A Volumetric Method for Building Complex Models from Range Images, SIGGRAPH 96.*
[4] Bajaj, et al. *Automatic Reconstruction of Surfaces and Scalar Fields from 3D Scans, SIGGRAPH 95.*

Related Work - RBFs

- Approximate the points around various centers near the point cloud with a polynomial $h(u,v)$ and set $g_i(\mathbf{x})=w-h(u,v)$
- Sum the products of these local approximations with radial basis functions

$$f(\mathbf{x}) = \sum_i [g_i(\mathbf{x}) + \lambda_i]\phi_\sigma(\|\mathbf{x} - \mathbf{p}_i\|)$$



Ohtake, Y., Belyaev, A., and Seidel, H.-P. *A Multi-scale Approach to 3D Scattered Data Interpolation with Compactly Supported Basis Functions. Shape Modeling International 2003, pp. 153-161.*

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Related Work - PUM

- Partition of unity methods integrate locally defined approximations into a global approximation
  - Partition the global domain into small subdomains
  - Approximate the data in each subdomain
  - Blend the local solutions together with smooth weights that sum to one everywhere on the domain
- Originally developed to solve PDEs
- Used for computer graphics [1,2]
- Uses local representations that can be created and evaluated quickly

[1] Ohtake, et al. *Multi-Level Partition of Unity Implicits, SIGGRAPH 2003.*
[2] Tobor, et al. *Efficient Reconstruction of Large Scattered Geometric Datasets using the Partition of Unity and Radial Basis Functions, WSCG 2004.*

Related Work Summary

- We need to blend and intersect extracted surfaces
  - Difficult to automate with explicit representation
  - Impossible with RBFs
- Methods developed for computer graphics ignore constraints of automotive styling design
- Can we use partition of unity methods to satisfy accuracy or geometric continuity constraints?
- How can we ensure that the surfaces and edges of the reconstructed object satisfy the principle of simplest shape?

Partition of Unity Method

- On a bounded domain Ω, we want a set of nonnegative functions $\{\varphi_i\}$ with compact support such that
$$\sum_i \varphi_i = 1 \text{ on } \Omega$$
- Given a local approximation $V_i(x)$ in each subdomain, the global approximation is
$$f(x) = \sum_i \varphi_i(x) V_i(x)$$
- Given a set of nonnegative compactly supported functions $\{w_i(x)\}$ that cover the domain
$$\Omega \subset \bigcup_i \operatorname{supp}(w_i)$$
- This equation generates the partition of unity functions
$$\varphi_i(x) = \frac{w_i(x)}{\sum_j w_j(x)}$$

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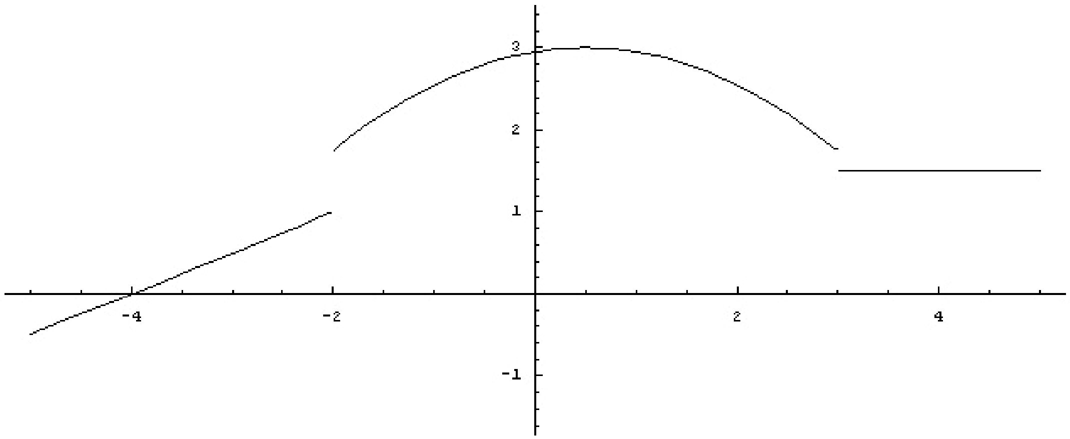
PUM – 1D Example

- Consider three $V_i(x)$ on the domain Ω=(5,5)

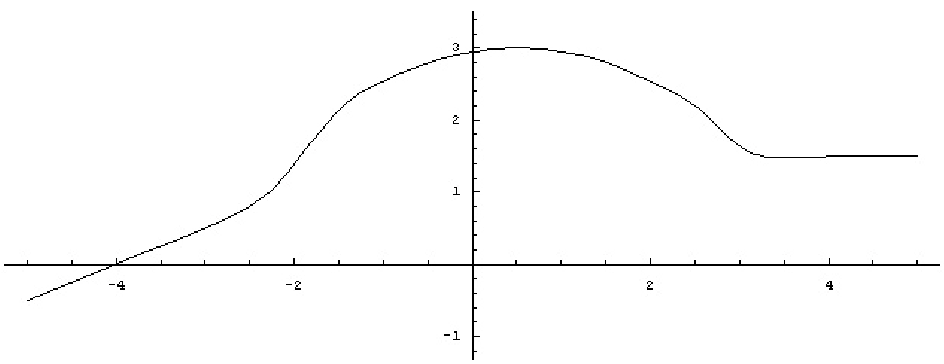


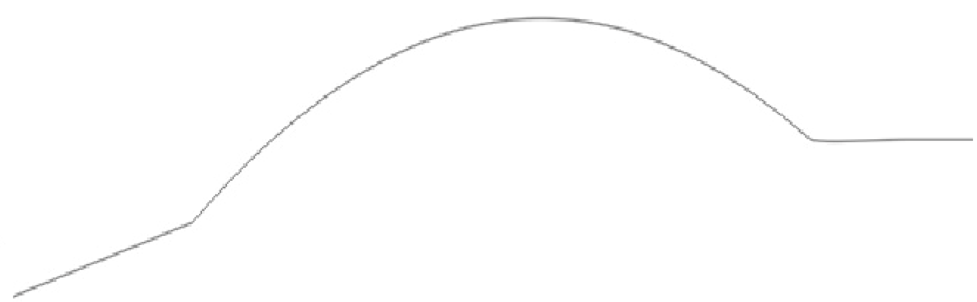
$$V_1(x) = \frac{x}{2} + 2 \qquad \text{for} \quad -5 < x < -2$$

$$V_2(x) = -\frac{1}{5}\left(x - \frac{1}{2}\right)^2 + 3 \qquad \text{for} \quad -2 < x < 3$$

$$V_3(x) = \frac{3}{2} \qquad \text{for} \quad 3 < x < 5,$$

- How can we easily blend and intersect them?





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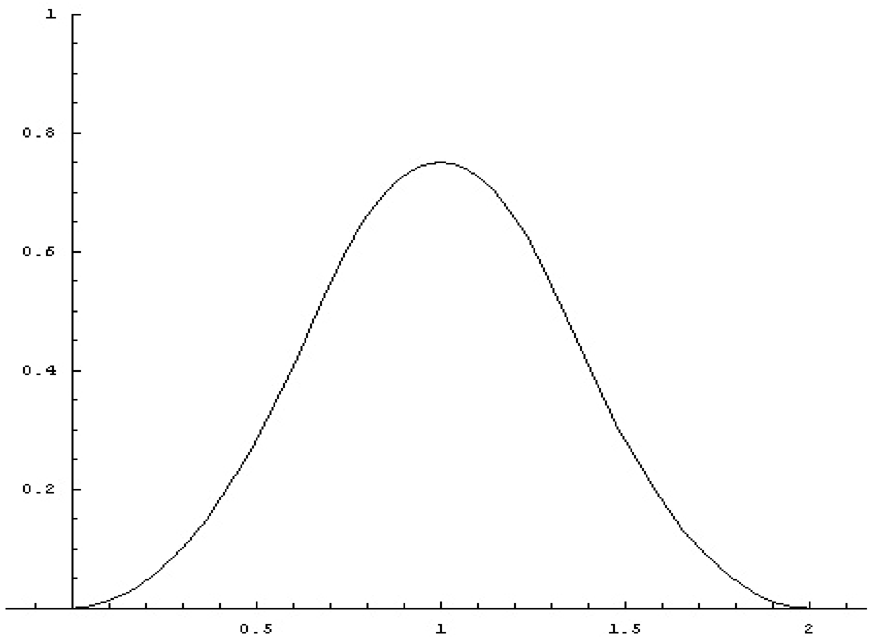
PUM – 1D Example

- The partition of unity functions $\{\varphi_i\}$ are generated from the C^1 function



$$w(x,R)=\begin{cases}\frac{9}{8}\frac{x^2}{R^2}+\frac{9}{4}\frac{x}{R}+\frac{9}{8} & \text{for } -R\le x<-\frac{R}{3}\\ -\frac{9}{4}\frac{x^2}{R^2}+\frac{3}{4} & \text{for } -\frac{R}{3}\le x<\frac{R}{3}\\ \frac{9}{8}\frac{x^2}{R^2}-\frac{9}{4}\frac{x}{R}+\frac{9}{8} & \text{for } \frac{R}{3}\le x<R.\end{cases}$$

- We can use any positive functions with compact support
- The reconstruction inherits the continuity of the $\{\varphi_i\}$

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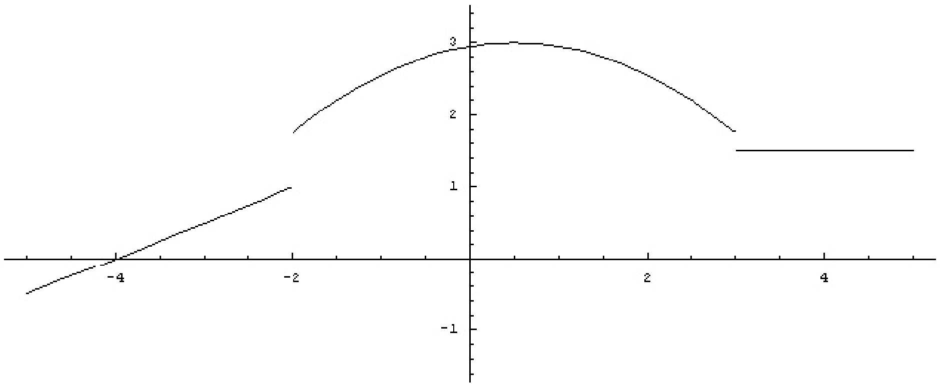
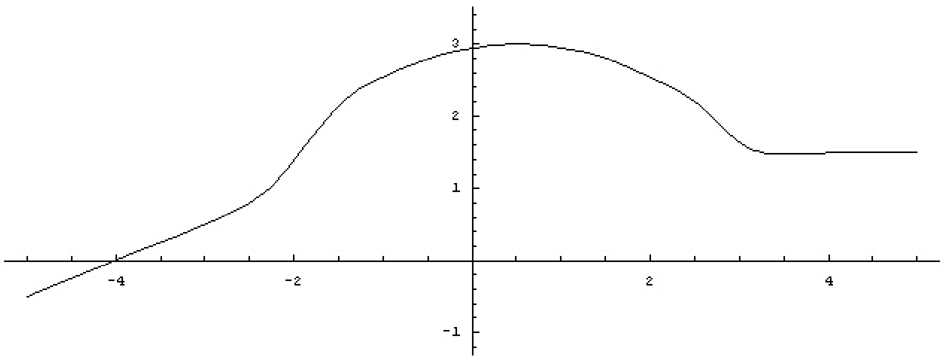
PUM – 1D Example

- The blended global approximation is simply

$$f(x) = \frac{w_1 V_1 + w_2 V_2 + w_3 V_3}{w_1 + w_2 + w_3}$$



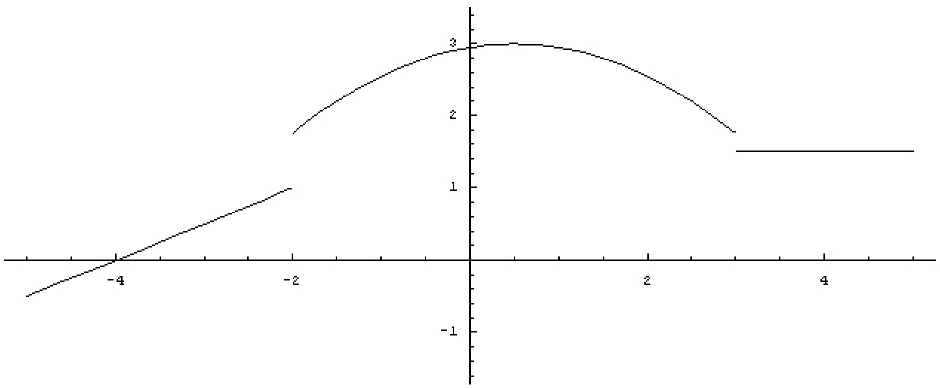


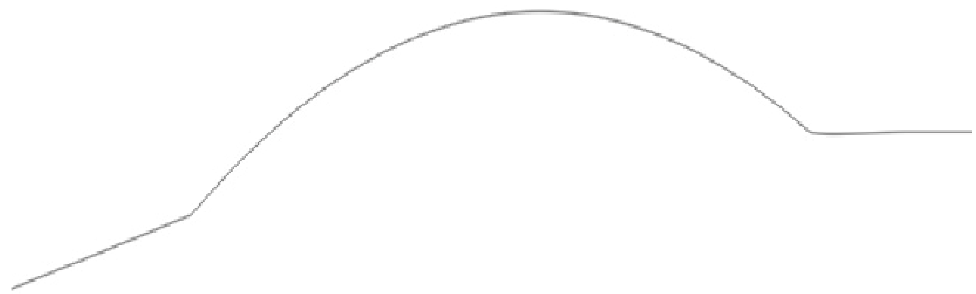
- We can control the strength of the blending by changing the parameter R of the $w_i(x,R)$

PUM – Implicit 1D Example

- Replace the $V_i(x)$ with y-$V_i(x)$ to define the blended function implicitly
- Now it's trivial to intersect the functions

$$\frac{\min[w_1(y-V_1),\ w_1(y-V_2)]+w_2(y-V_2)+\min[w_3(y-V_2),\ w_3(y-V_3)]}{w_1+w_2+w_3}=0$$





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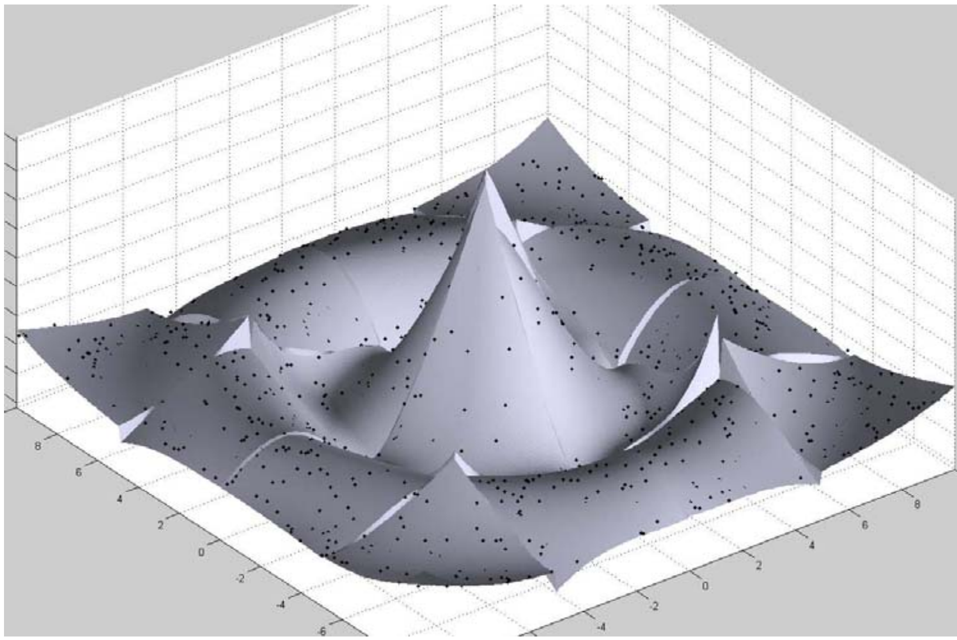
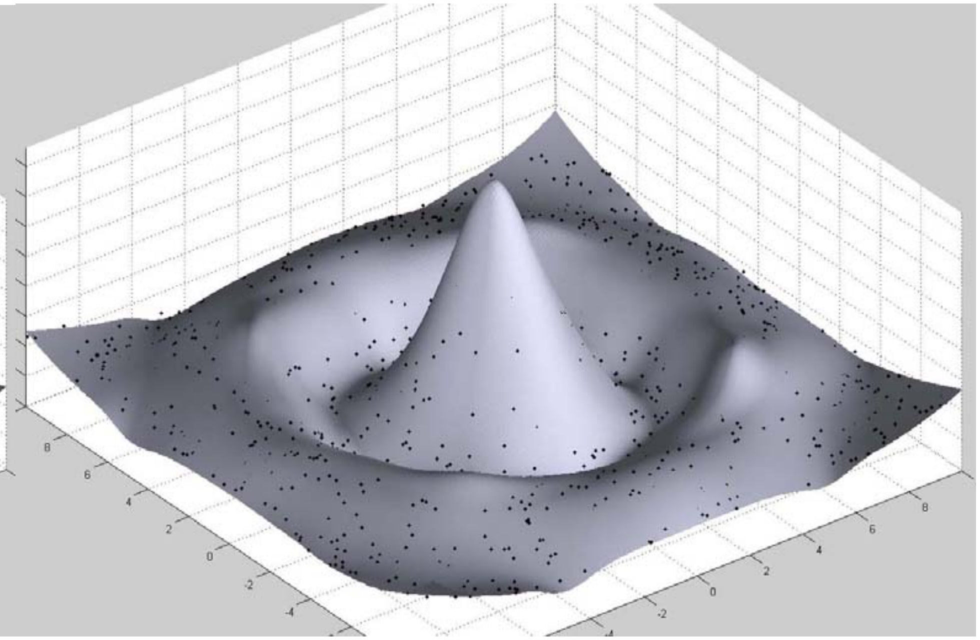
PUM – 2D Example

- These ideas extend to 2- and 3-dimensions



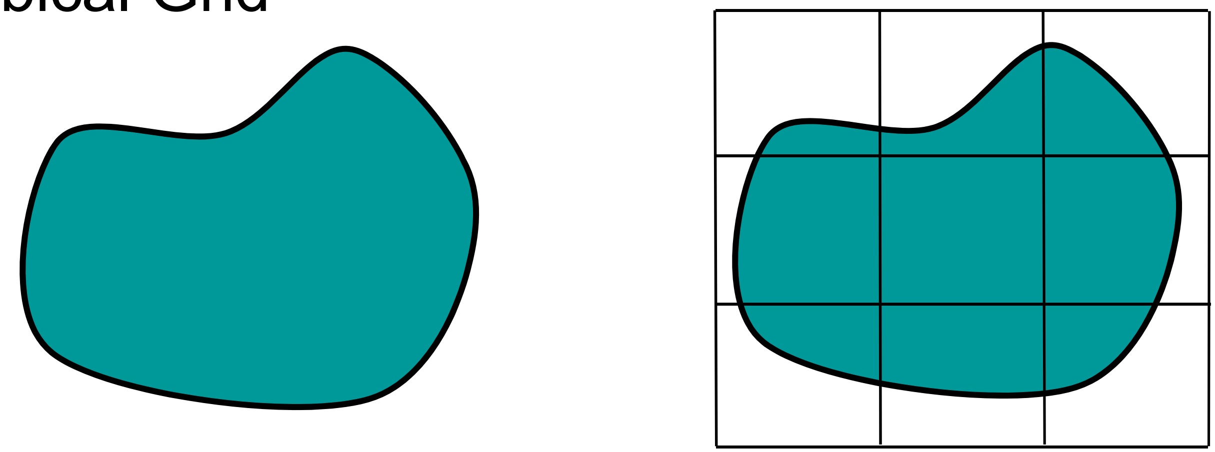


- 16 cubic surfaces approximating synthetic noisy data

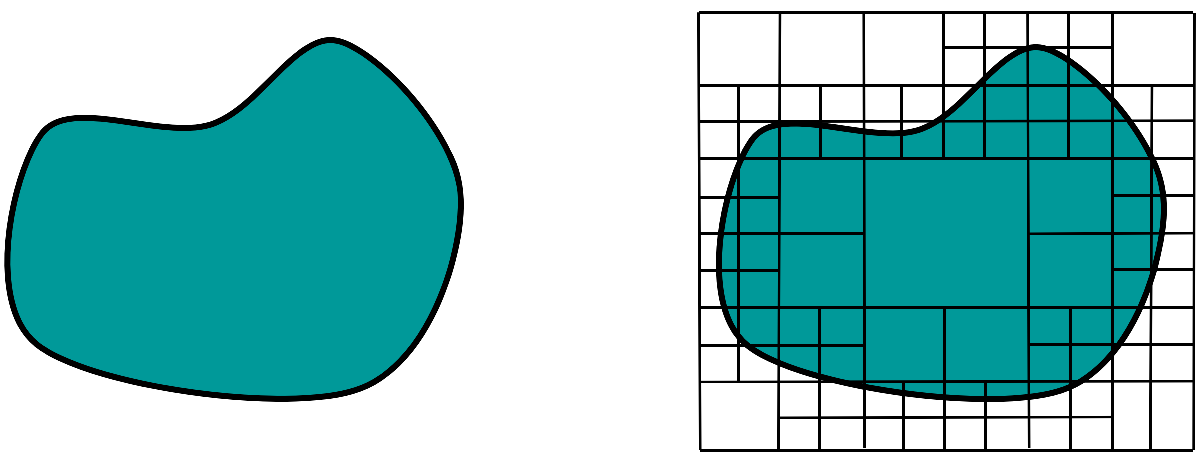
- C^2 blend of the 16 surfaces

Proposed Research – Domain Subdivision

- First step is to subdivide the domain into small cells
- Cubical Grid



- Octree Subdivision



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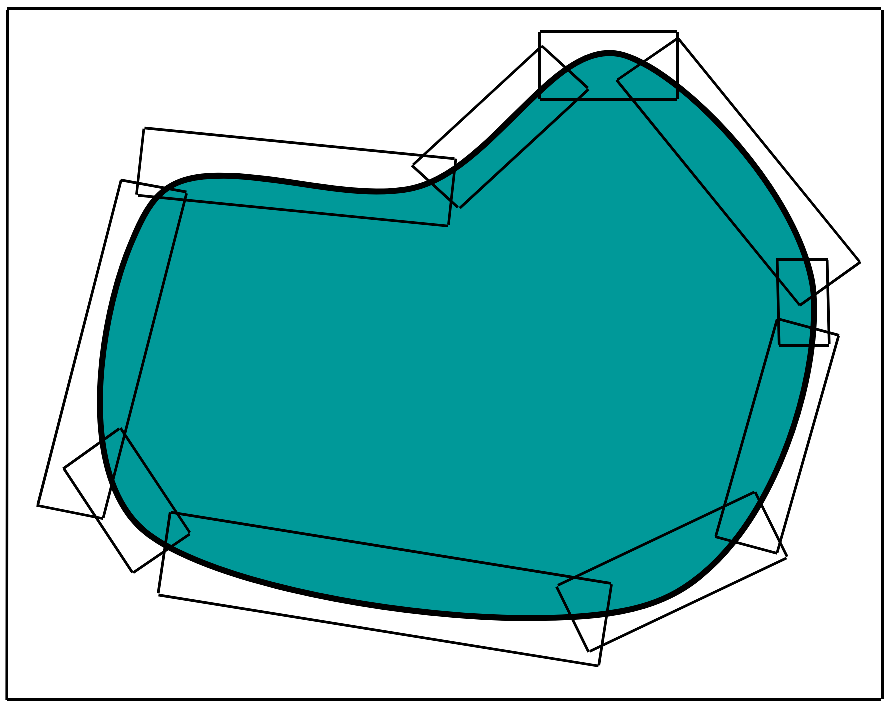
Proposed Research – Domain Subdivision

- Geometry-adaptive cells
  - Quality of the reconstructed surface varies with the size and orientation of the subdivision cells
  - We can use local geometry information to determine the size and orientation of the cells on the point cloud



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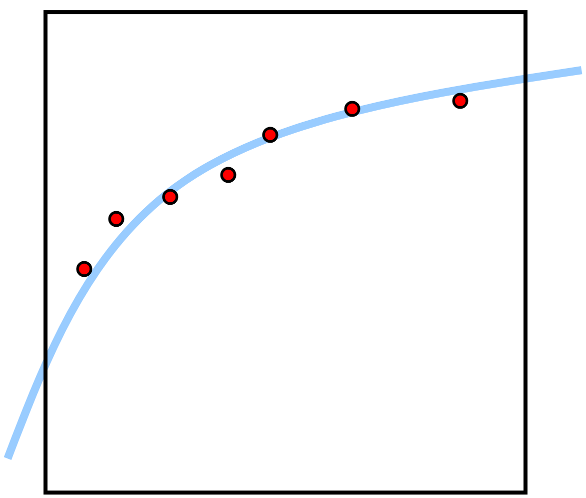
Proposed Research – Domain Subdivision

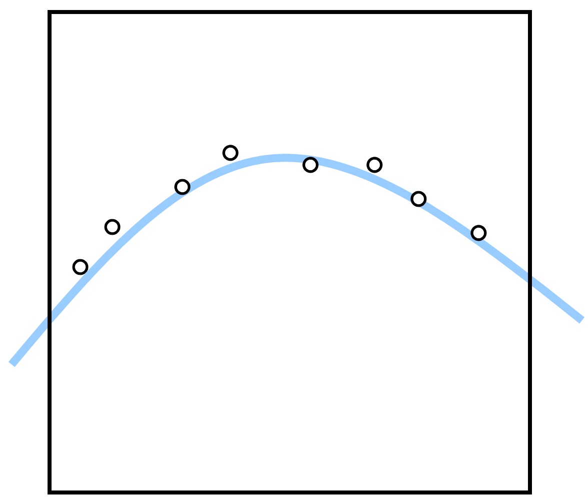
- Questions we will address:
  - Can we make cells that vary in size and orientation according to the object geometry?
  - How do we ensure the cells overlap?
  - How do we integrate them with the rest of the domain?
  - Will the computational cost and difficulty of finding the geometry-adaptive cells by justified by the improved quality of the reconstruction?

Proposed Research – Local Approximations

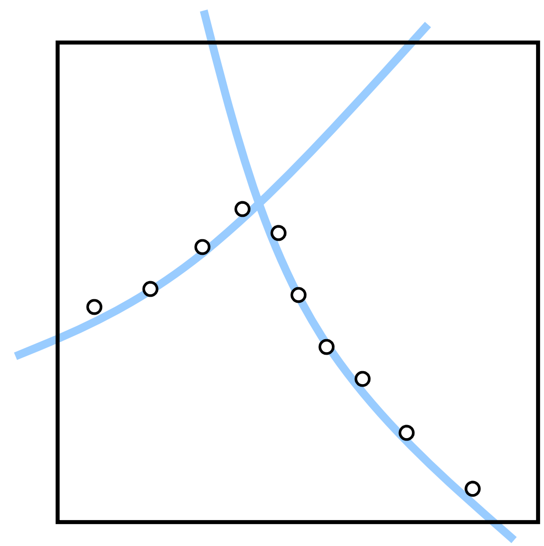
- Then we use the following information to determine the local approximations in each cell
  - Does it contain less than a certain number of points?
  - How many extracted surfaces are defined inside it?
  - Does it contain a sharp edge or corner?



Points already segmented



Points not segmented



Sharp edge detected

Proposed Research – Local Approximations

- Questions we will address:
  - How can we integrate geometry-adaptive cells with this approach?
  - What recursive subdivision rules will give the best results?
  - How will we deal with outlier noise?
  - How reliably can we detect sharp edges or corners and fit separate surfaces to the points around them?

Proposed Research – Isosurface Extraction

- The reconstructed surface is the zero level set of a signed distance function
- Extract isosurfaces from implicit functions
- Convert the approximation in each cell to implicit forms
- Multiply the approximations by the partition of unity functions and sum them over the domain
- For cells that do not contain points, we can estimate the signed distance function by finding the nearest point to the cell and examining its normal

Algorithms

- Mesh Smoothing
- Surface Extraction from Meshes
- Surface Extraction from Point-Sampled Data
- Surface Reconstruction Proposal
- Summary

Expected Contributions

- Mesh Smoothing
  - Creates an aesthetically pleasing surface
  - Minimizes mesh deformation
  - Preserves sharp edges
- Surface Extraction
  - Estimates curvatures and noise levels on the data
  - Detects sharp edges
  - Segments data into regions approximated by single surfaces
  - Fits surfaces to a specified tolerance
- Surface Reconstruction (proposed)
  - Will reconstruct objects with large, smooth surfaces, smooth blends between surfaces, and sharp edges
  - Will bound the accuracy and geometric continuity of the reconstructed object

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Publications

- Mesh Smoothing
  - M. Vieira, K. Shimada, and T. Furuhata. *Local Least Squares Fitting for Surface Mesh Fairing in Automobile Panel Design, ASME DETC / DAC*. 2002, Montreal, Canada.
  - M. Vieira, K. Shimada, and T. Furuhata. *Smoothing of Noisy Laser Scanner Generated Meshes Using Polynomial Fitting and Neighborhood Erosion, ASME Journal of Mechanical Design*, May 2004.
- Surface Extraction
  - M. Vieira, K. Shimada. *Segmentation of Noisy Laser-Scanner Generated Meshes With Piecewise Polynomial Approximations, ASME DETC / DAC*. 2004, Salt Lake City, Utah. (Winner DAC Best Paper Award)
  - M. Vieira, K. Shimada. *Surface Mesh Segmentation and Smooth Surface Extraction Through Region Growing, Computer Aided Geometric Design Journal*, (accepted; submitted July 2004).
  - M. Vieira, K. Shimada. *Surface Extraction from Point-Sampled Data through Region Growing, International Journal of CAD/CAM*, (submitted).