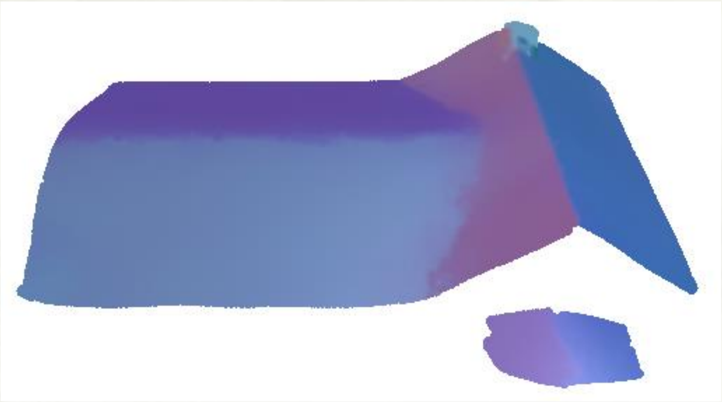
Feature-Enhancing Aerial LiDAR Point Cloud Refinement



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Outline

* Introduction
* Approach Overview
* Implementation Details
* Evaluation
* Conclusion and Future Work
* Acknowledgements

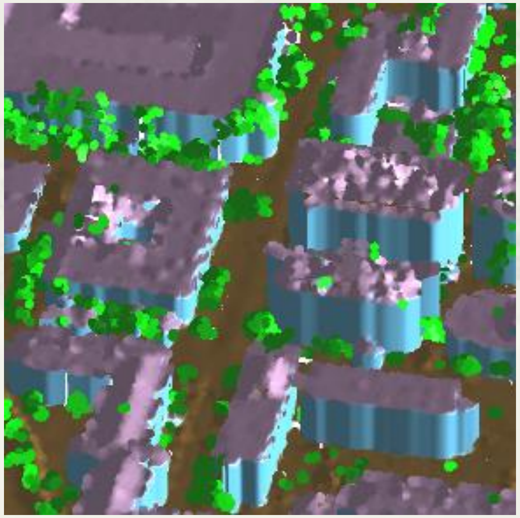
Why Refinement?

Defects of raw point clouds

* Noise
* Under-sampling

Visual artifacts in applications

* Grainy planes
* Gaps and holes
* Bumpy boundaries



Direct Rendering

Challenges of Aerial LiDAR Points

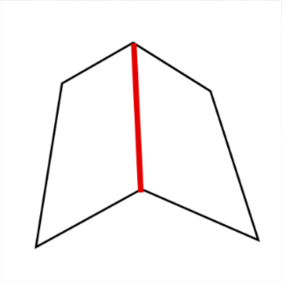
- Sparse sampling density
- 2.5D nature

Aerial LiDAR

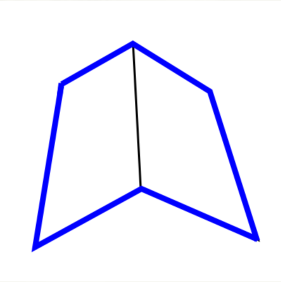
Image courtesy to Qian-Yi Zhou

Preliminary Definitions

- Normal discontinuous feature
  - Discontinuities in normals
  - The underlying surface is still continuous
- Position discontinuous feature
  - Discontinuities in positions
  - The underlying surface breaks



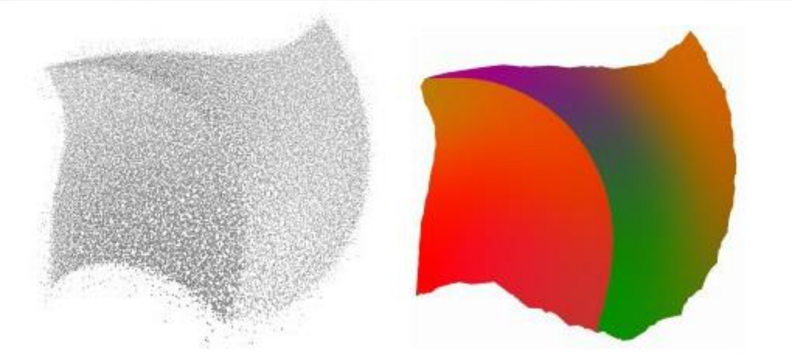
Normal discontinuous features



Position discontinuous features

Related Work

- Feature preserving bilateral filtering [Mederos2003] [Duguet2004] [Sun2007] [Nociar2010] [Huang2012]
  - Cannot handle position discontinuous features



From [Huang2012]

Raw Refined

- Explicit feature smoothing approaches [Pauly2003] [Daniels2007] [Zhou2008]
  - Replace points as lines/curves

Approach Overview

Input

* An unoriented, piece-wise smooth aerial LiDAR point cloud of a single building

Output

* A new set of oriented points
* Providing
  * Smoothed noise
  * Filled gaps and holes
  * Enhanced normal discontinuous features
  * Enhanced position discontinuous features

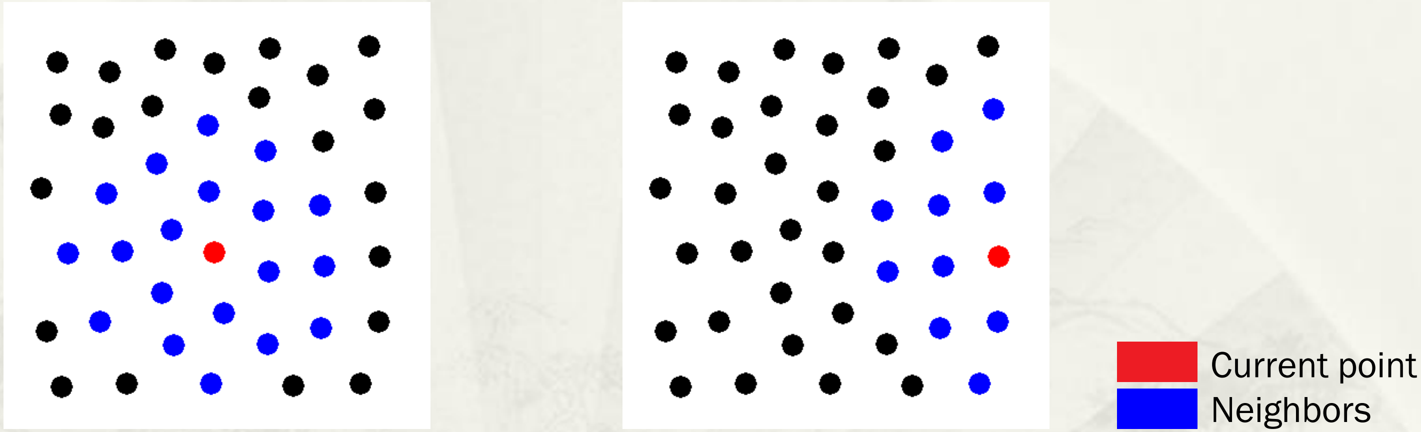
Approach Overview (Cont.)

Approach

- Explicitly extract and regularize position discontinuous features
- Two-step framework
  - Smoothing: handles noise
  - Up-sampling: handles under-sampling

Position Discontinuous Feature Refinement

- Detection: local environment analysis



Interior

Boundary

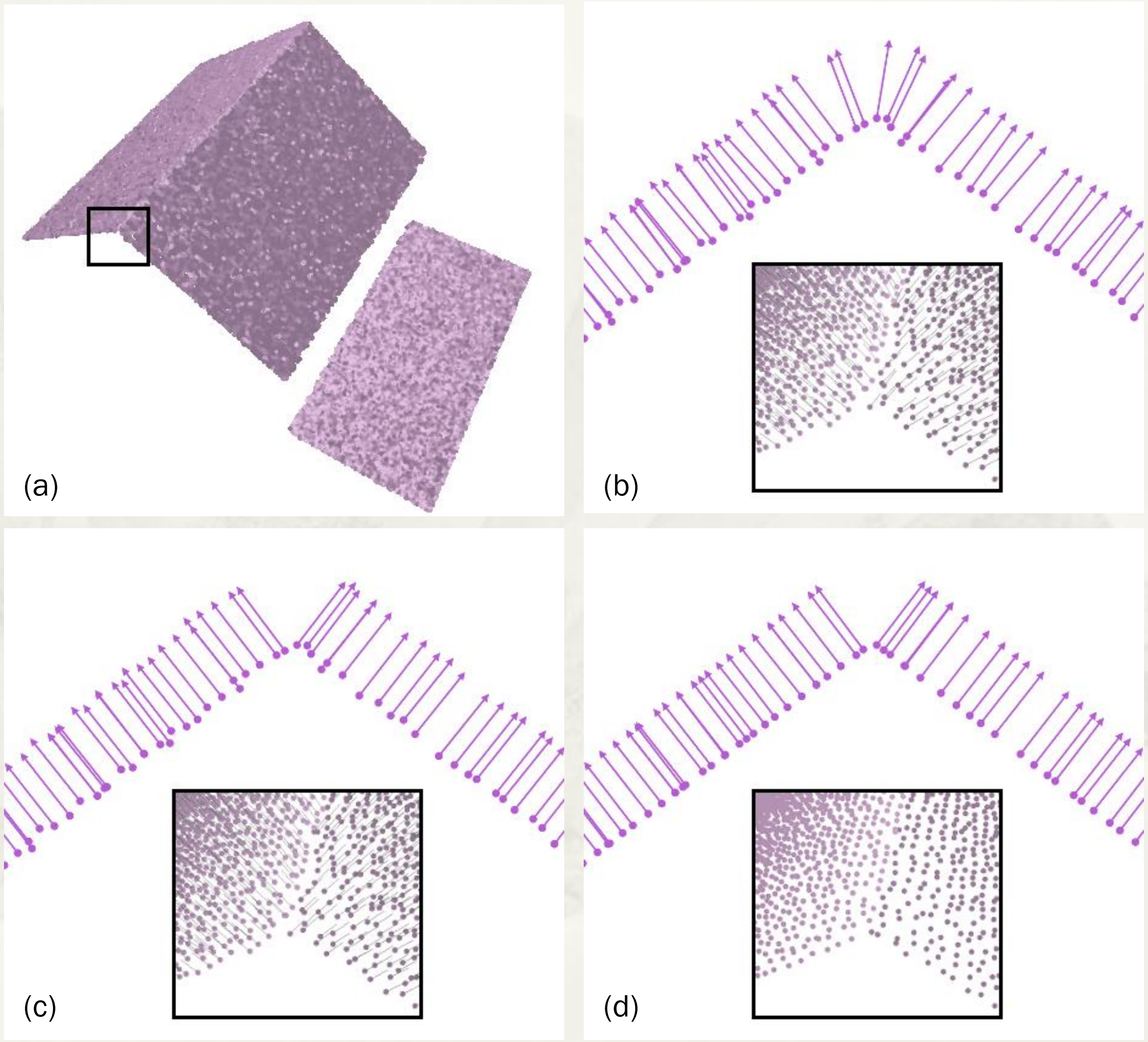
- Boundary direction (B. direction) estimation
  - The direction of the underlying line formed by boundary points only
  - PCA over neighbors

Step 1: Smoothing

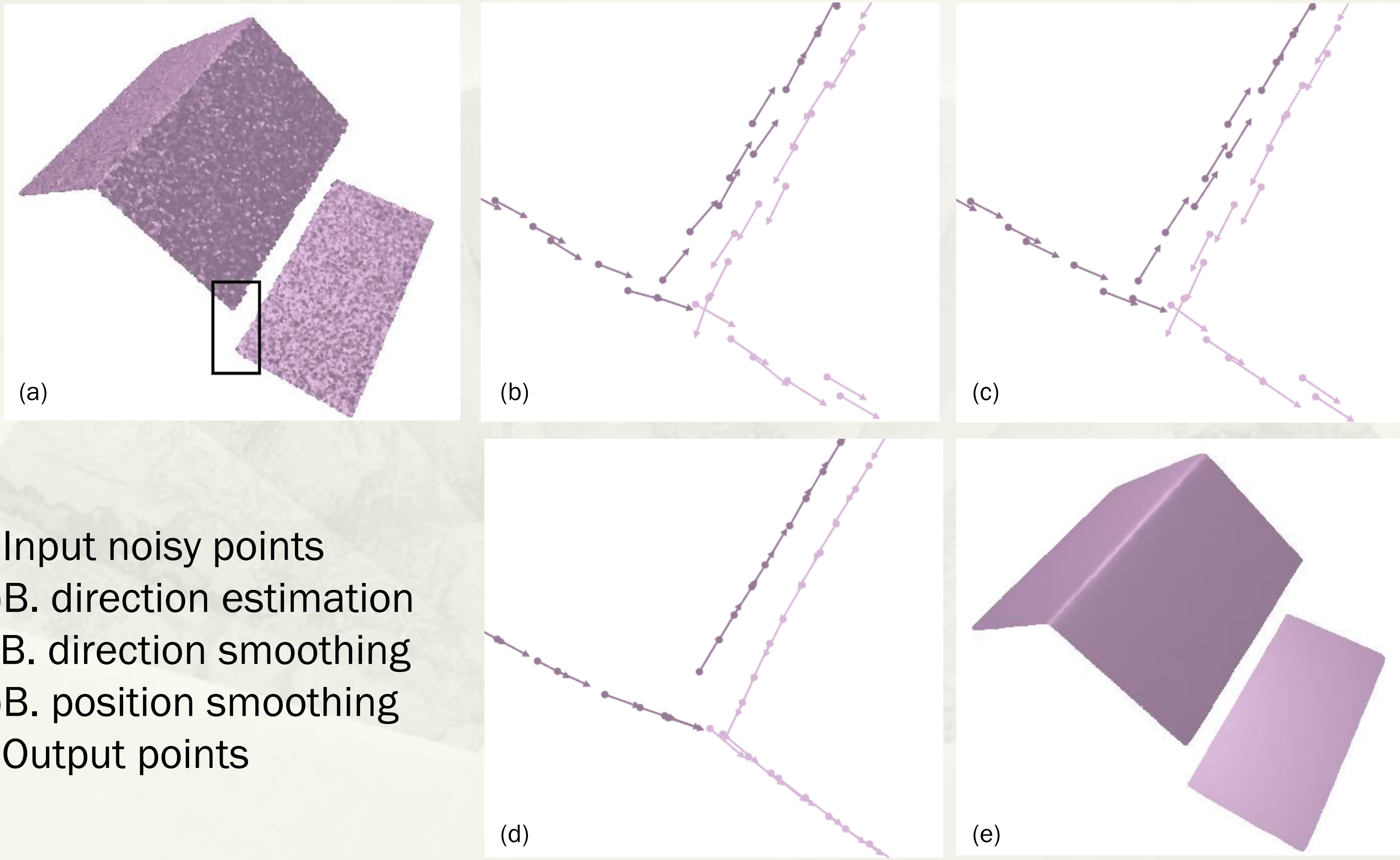
- Bilateral filtering
  - The estimate for a point is the weighted average of prediction from neighboring points
  - The weight of a neighbor depends on
    - Spatial distance (spatial weight)
    - Normal/B. direction difference (influence weight)
- Two stage:
  - Smooth normals/B. directions
  - Smooth positions under the guidance of the filtered normals/B. directions

Smoothing for All Points

(a)Input noisy points
(b)Normal estimation
(c)Normal smoothing
(d)Position smoothing



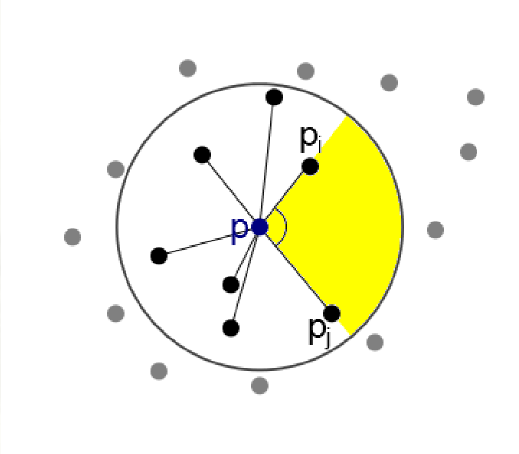
Smoothing for Boundary Points



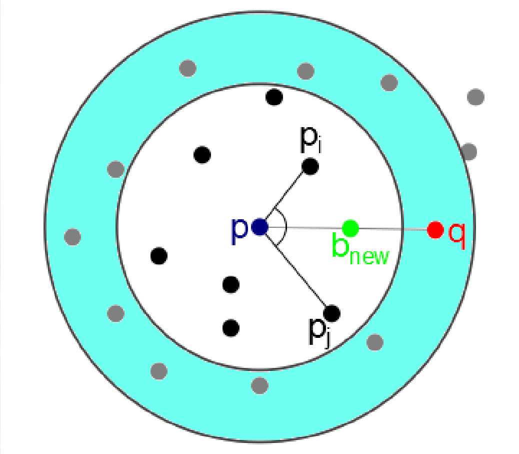
(a)Input noisy points
(b)B. direction estimation
(c)B. direction smoothing
(d)B. position smoothing
(e)Output points

Step 2: Up-sampling

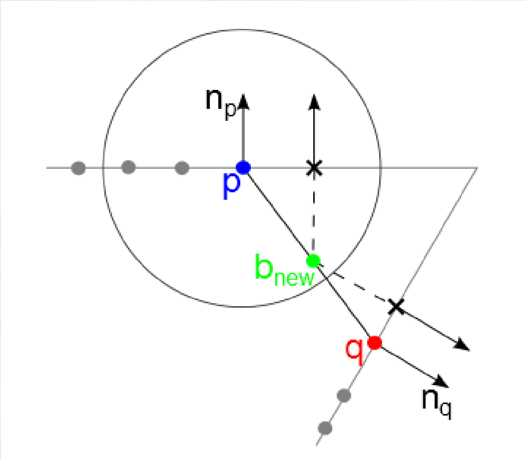
- Local gap detector: local environment analysis
- Bilateral projection operator: preserve features



(a) Locate gap



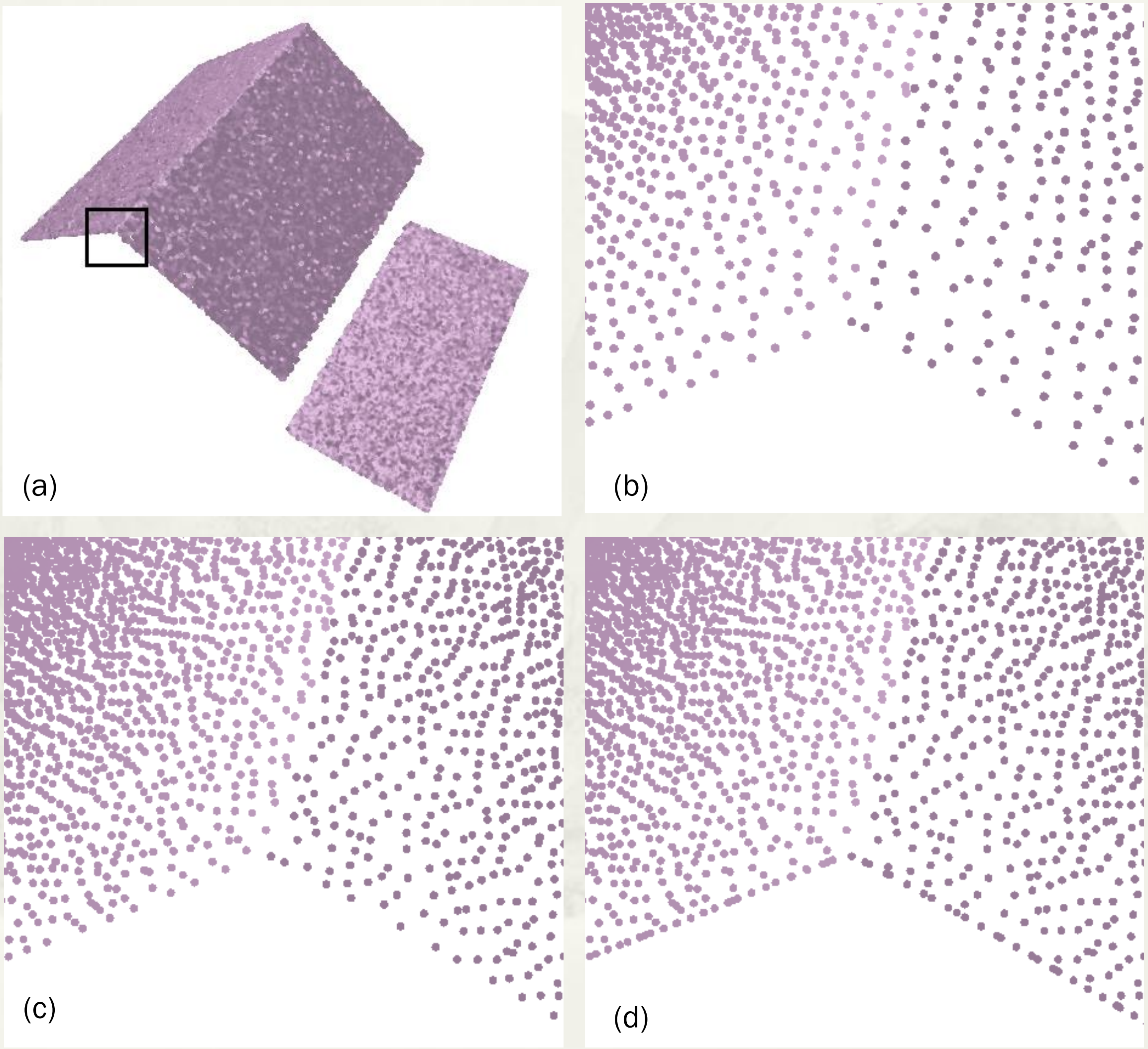
(b) Find end point



(c) Interpolate new point

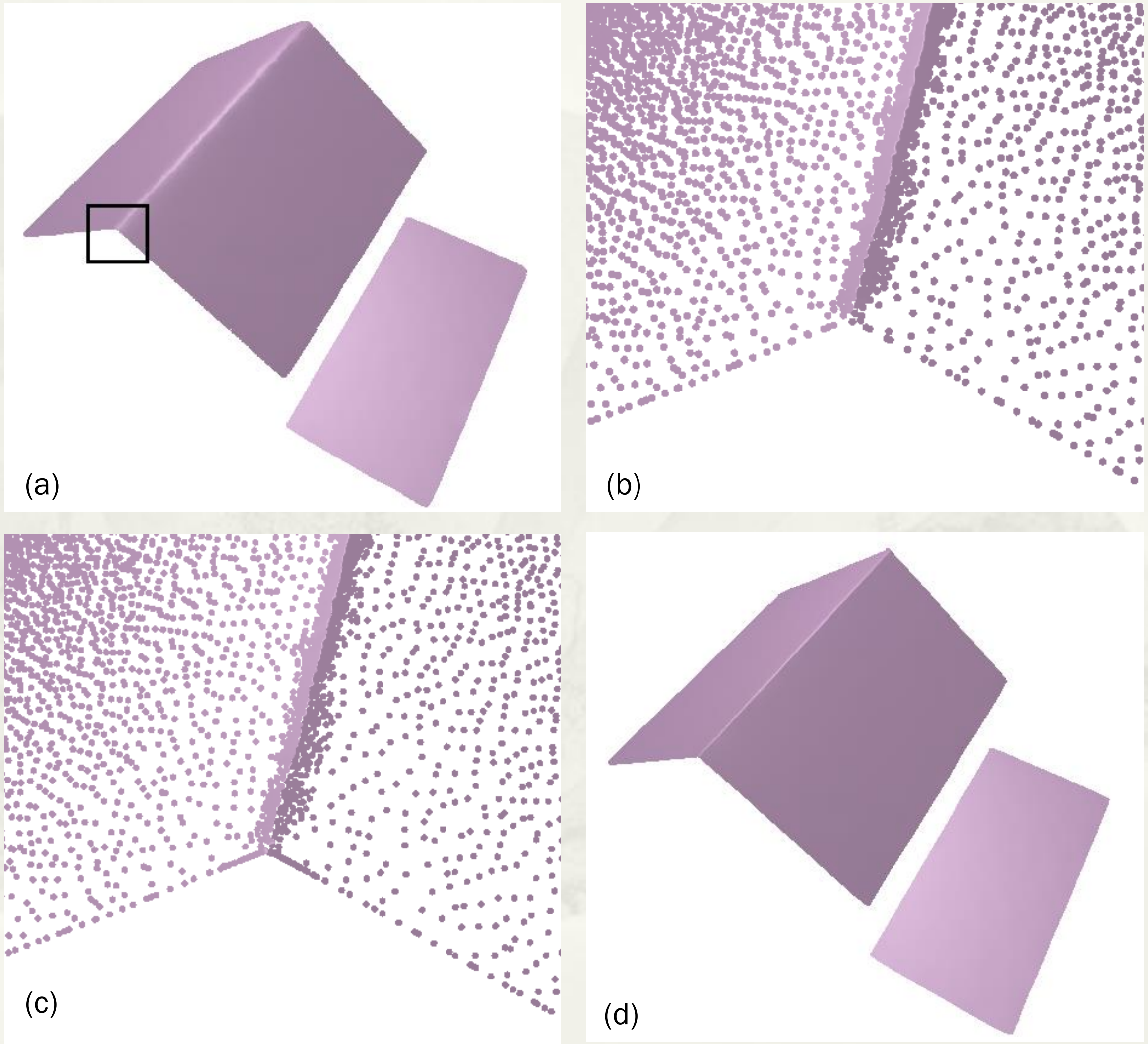
Up-sampling

(a)Input noisy points
(b)Smoothed points
(c)Interior up-sampling
(d)Boundary up-sampling



Feature Enhancing Up-sampling

Features can be enhanced if up-sampling is Restrained to regions near features



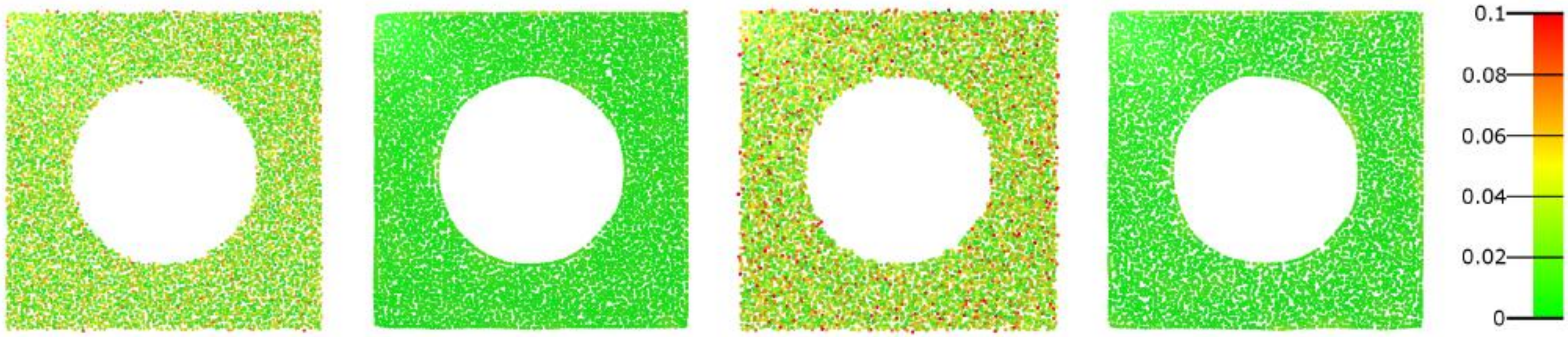
(a)Smoothed points
(b)Interior enhancing
(c)Boundary enhancing
(d)Output points

Evaluation Outline

- Robustness
- Stability
- Versatility
- Extensibility
- Comparison with previous work
- Performance
- Applications

Robustness to Noise

- The smoothing quality does not degrade much as the noise increases



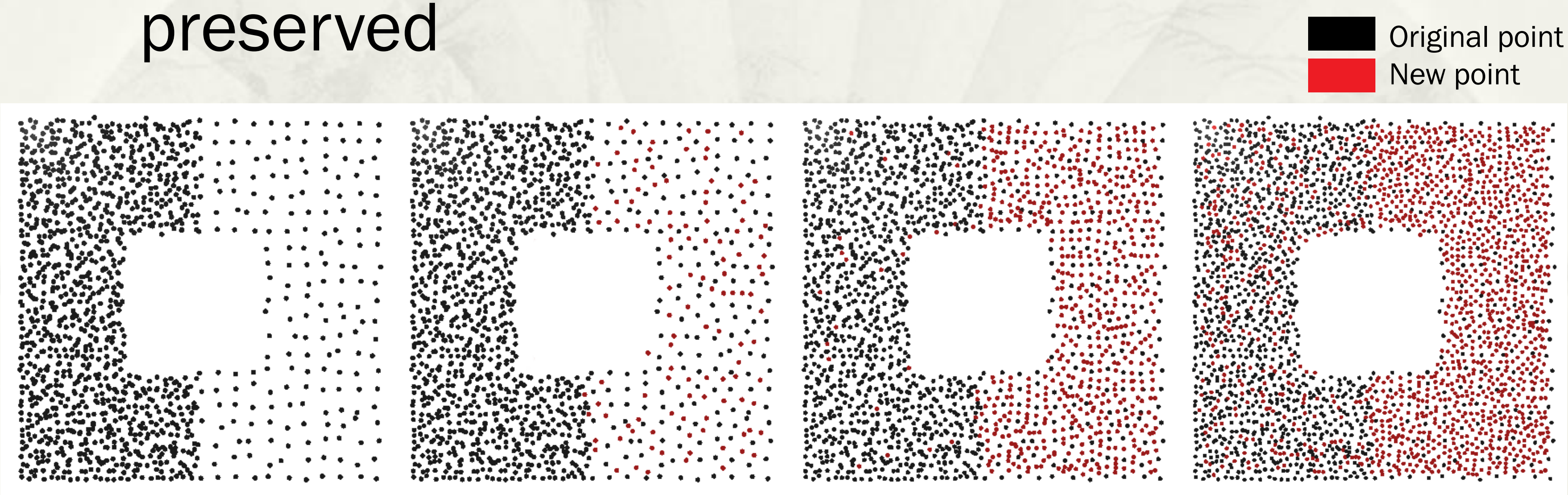
(a) 50% noise, original (b) 50% noise, smoothed (c) 100% noise, original (d) 100% noise, smoothed

Data set	Interior-MD	Interior-SD	Boundary-MD	Boundary-SD
(a)	0.028482	0.018486	0.051923	0.027182
(b)	0.003169	0.003243	0.025885	0.015879
(d)	0.036123	0.026051	0.060937	0.031821
(e)	0.004458	0.004472	0.030655	0.019828

MD: mean distance
SD: standard deviation

Robustness to Non-homogeneous Point Density

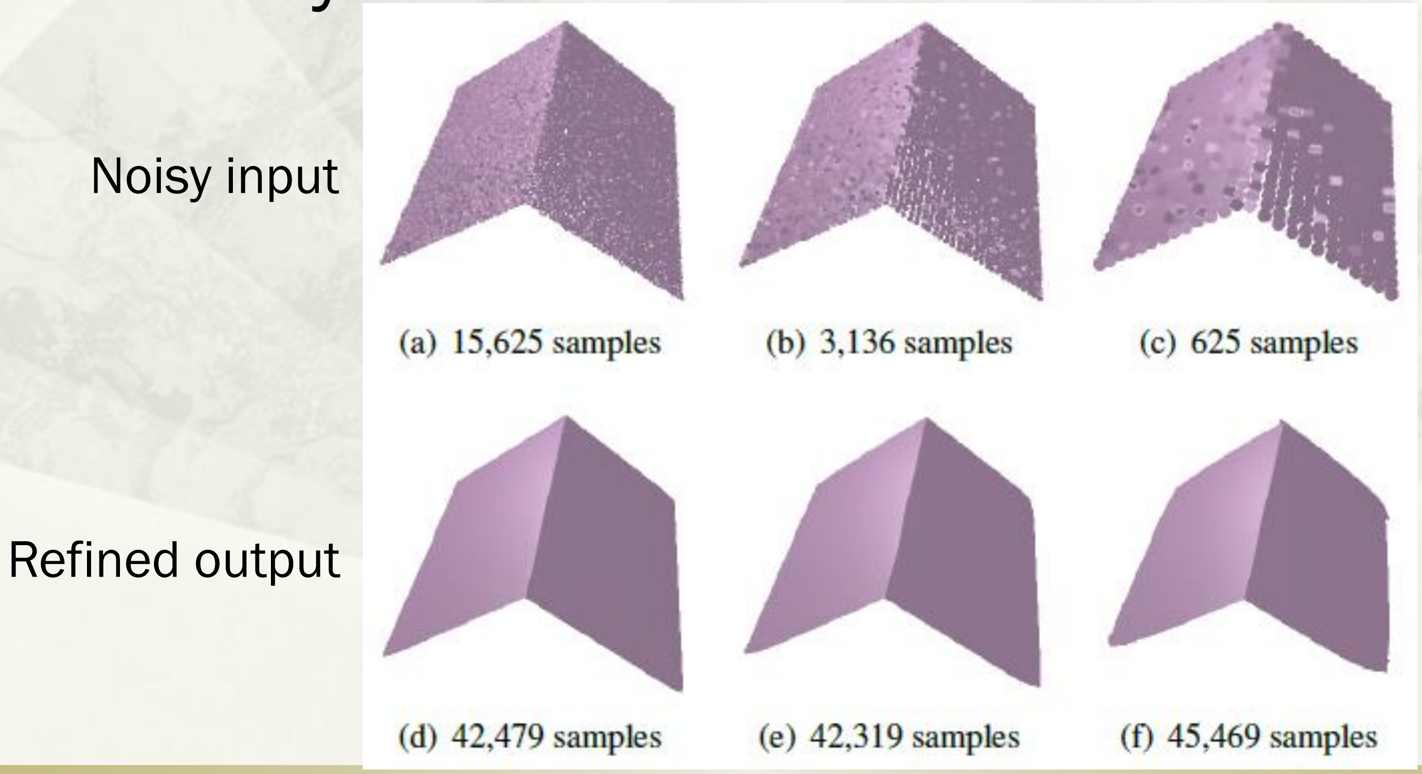
* Achieve global uniform sampling with a single parameter
* Both inner and outer boundaries are well preserved



(a) Original (b) γ=2.0 (c) γ=1.3 (d) γ=1.0

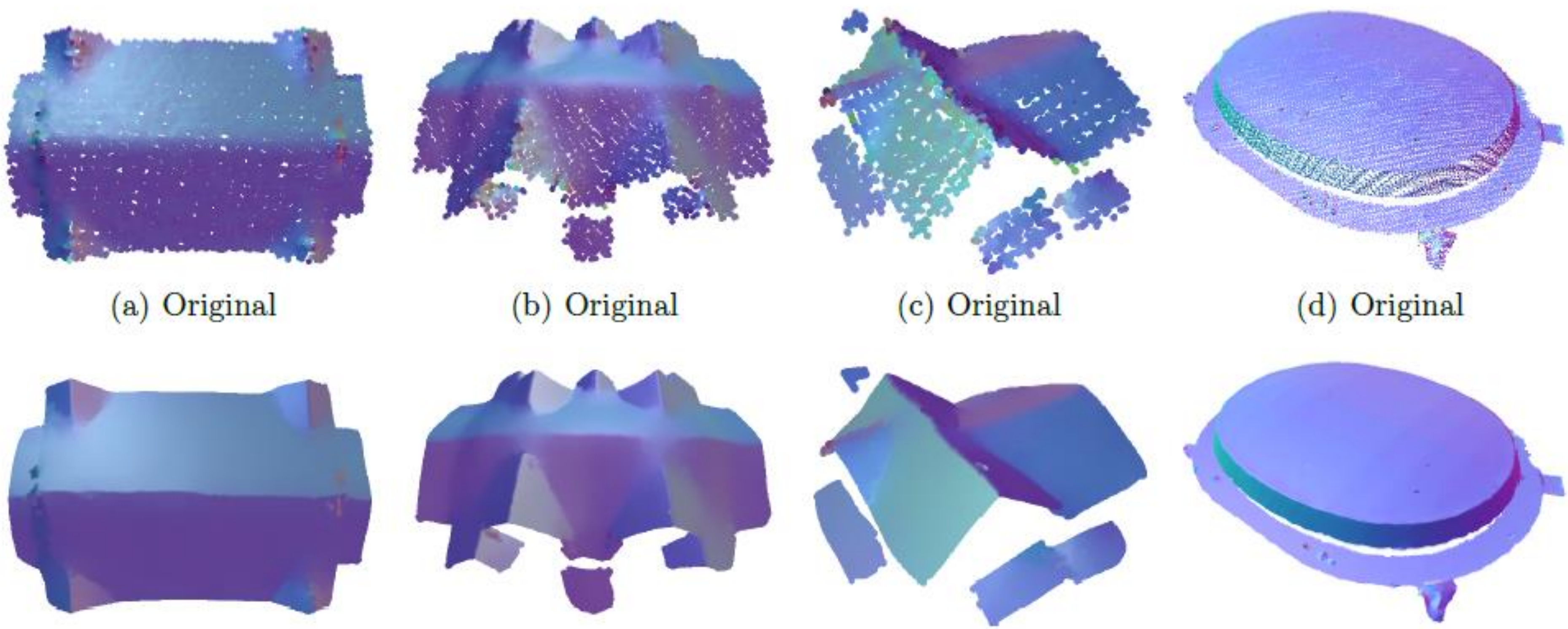
Stability

* Most normal and position discontinuous features are sharply recovered for data sets with vastly different densities



Versatility

- Effective to buildings with various roof shapes and complexity

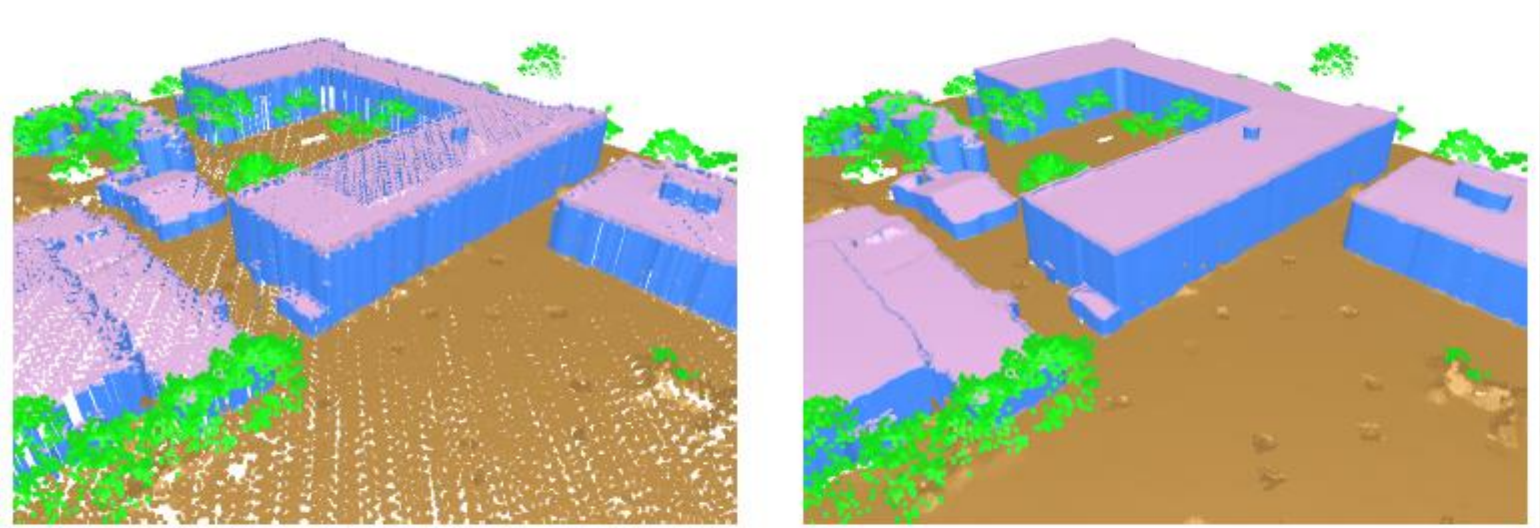


(a) Original (b) Original (c) Original (d) Original

(e) Refined (f) Refined (g) Refined (h) Refined

Extensibility

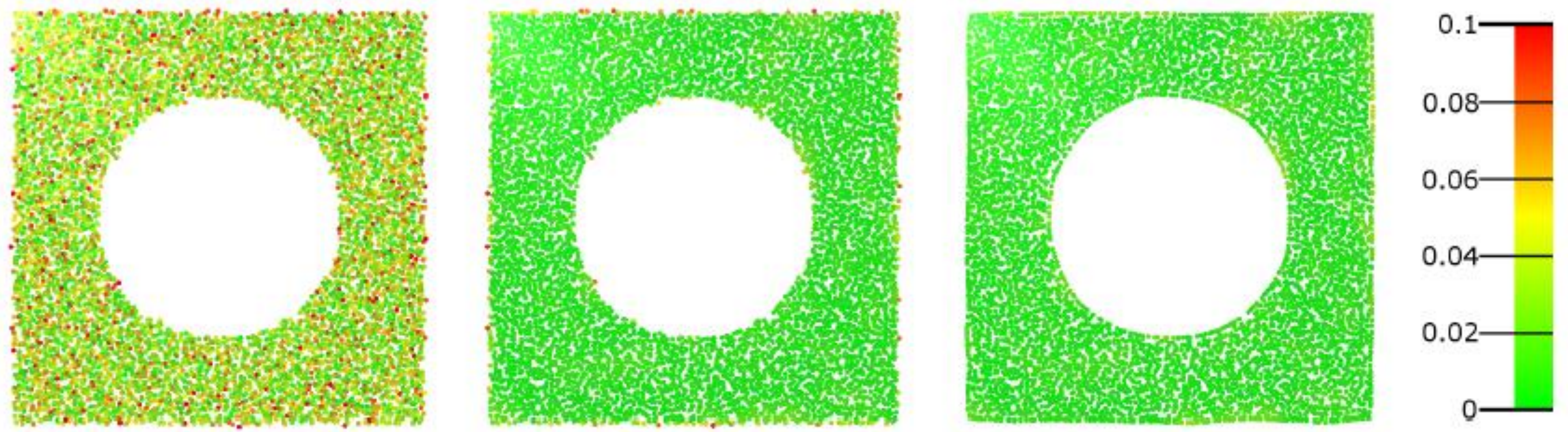
- Extensible to objects other than buildings
- Extensible to large-scale data



(a) Original (b) Refined

Comparison with Point-Based Refinements

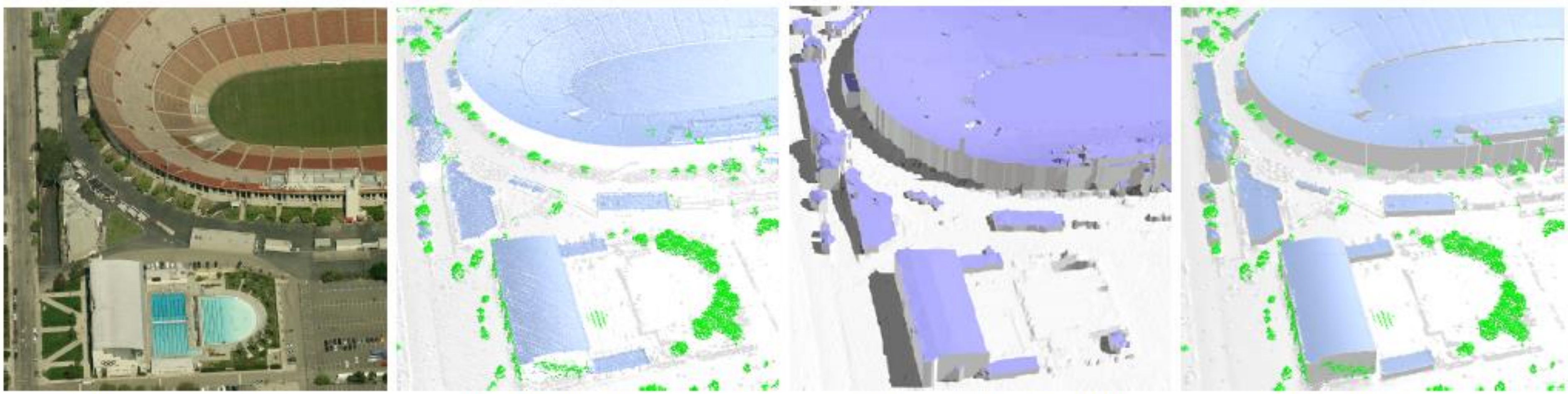
- Comparable quality on non-boundary points
- Obviously less errors on boundaries



(a) 100% noise, original (b) After RIMLS smoothing (c) After our smoothing

Comparison with Geometry Modeling

* Comparable quality on straight boundaries
* Better quality on curved boundaries



(a) Ground truth image (b) Original points (c) Geometry models (d) Refined points

Performance

- Smoothing and up-sampling are fast

Data set	IP-N	SM-T	US-T	US-N	EU-T	OP-N
Figure 1 (b)	5,594	0.57	1.37	11,597	2.36	16,590
Figure 6 (f)	23,500	2.07	5.84	52,303	2.57	57,461
Figure 11 (e)	9,079	1.23	1.68	15,603	5.80	25,720
Figure 11 (f)	7,546	1.12	1.18	12,146	4.11	21,409
Figure 11 (g)	4,658	0.49	0.99	9,248	3.45	16,532
Figure 11 (h)	119,310	11.06	40.44	298,164	105.36	450,279
Figure 15 (b)	4,498	0.76	0.54	6,403	0.70	7,913

IP-N: number of input points; NE-T: time for normal estimation; SM-T: time for smoothing; US-T: time for up-sampling; UP-N: number of points after up-sampling; EU-T: time for feature enhancement up-sampling; OP-N: number of output points. Time is measured in seconds.

Applications

- Our approach provides
  - smoother planes
  - no gaps
  - sharpened both normal and position discontinuous features
- It is a useful pre-process to improve visual quality of
  - direct point rendering
  - surface reconstruction (e.g. APSS and RIMLS)

(a) Before: points (b) After: points (c) Before: APSS (d) After: APSS (e) Before: RIMLS (f) After: RIMLS

Conclusion

- Explicitly extract and regularize position discontinuous features
- The smoothing step filters noise while preserves features
- The up-sampling step fills gaps while enhance features
- Experiments show improved rendering and surface reconstruction results

Future Work

- To improve performance: parallelize each refinement operation
- To improve quality:
  - incorporate other information such as aerial images
  - add more restricted geometric assumptions as in urban modeling
- Incorporate refinement into real-time city-scale point cloud visualization

Acknowledgements

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