Piecewise Planar Object Reconstruction

Liangliang Nan

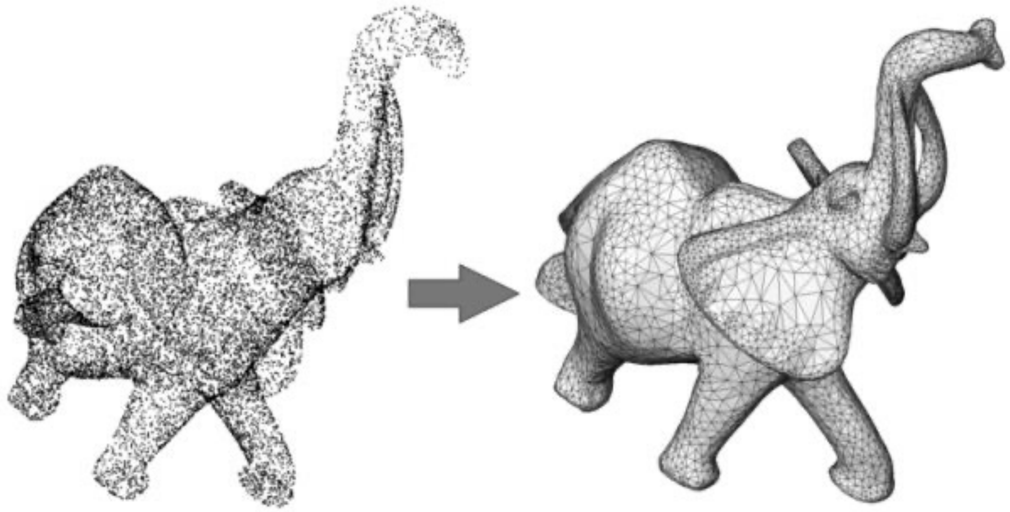
June 16th, 2022

Outline

- PolyFit: polygonal surface reconstruction
- Two extensions of PolyFit
  - LoD2 urban building reconstruction from airborne LiDAR data
  - LoD2 urban building reconstruction based on deep implicit fields
- Opportunities and future work
- Some thoughts about data

Reconstruction Methods

- Smooth surfaces
  - Fit noisy data; infer topology; fill (small) holes



Poisson Surface Reconstruction [Kazhdan *et al.* 06]

Reconstruction Methods

- Smooth surfaces
- Piecewise planar objects

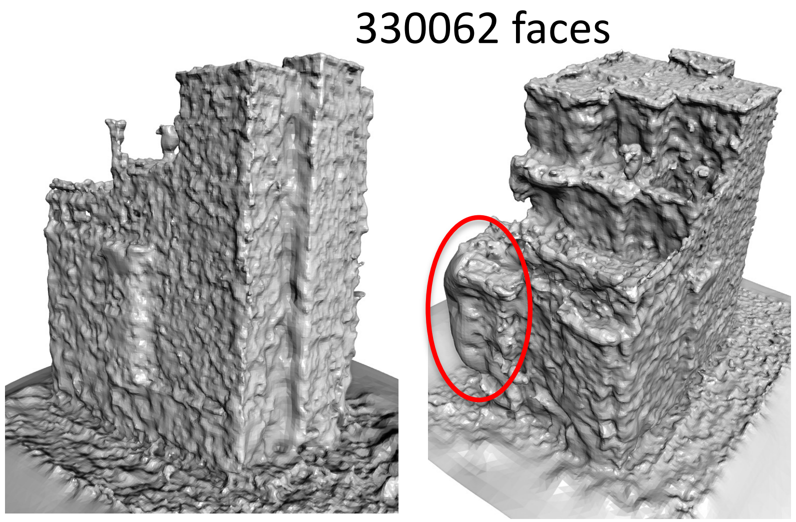



Reconstruction Methods

- Smooth surfaces
- Piecewise planar objects

Reconstruction Methods

- Smooth surfaces
- Piecewise planar objects



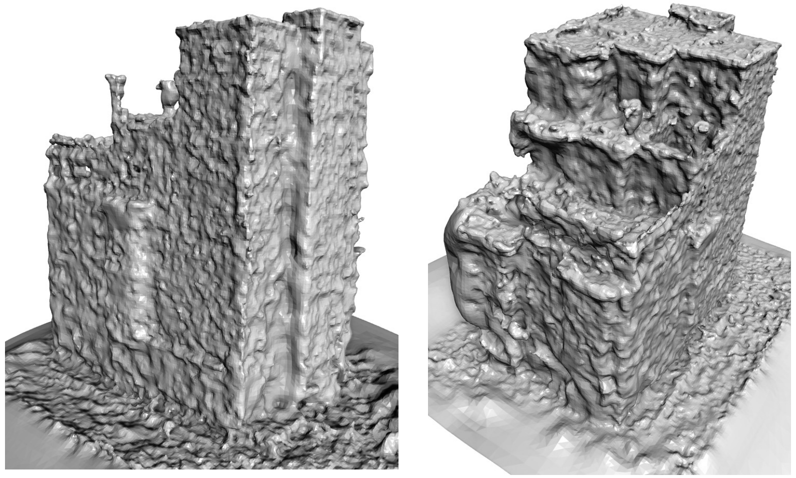
Result of [Kazhdan *et al.* 06]

- Unsatisfied results
  - Bumpy
  - Large number of faces
  - Unacceptable hole filling
- Rare direct applications
  - Post-processing required
    - Topologically correct
    - Simplified

Reconstruction Methods

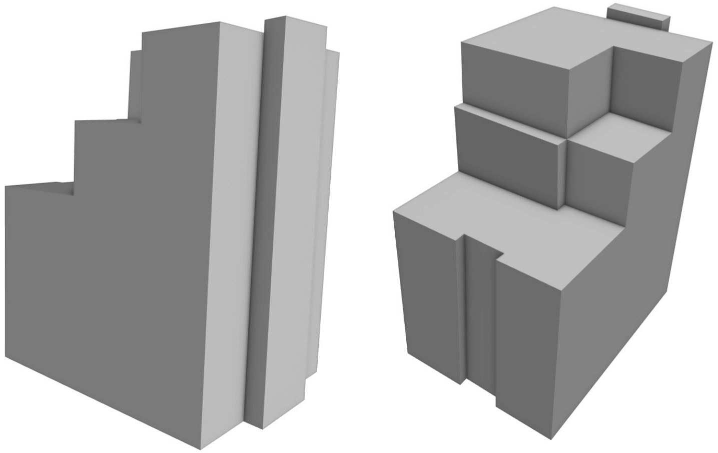
- Smooth surfaces
- Piecewise planar objects

330062 faces



Result of [Kazhdan *et al.* 06]

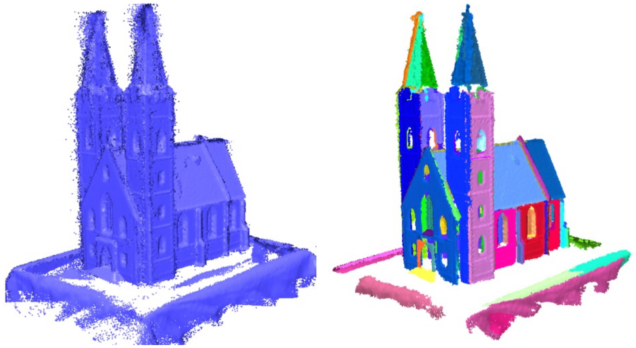
25 faces



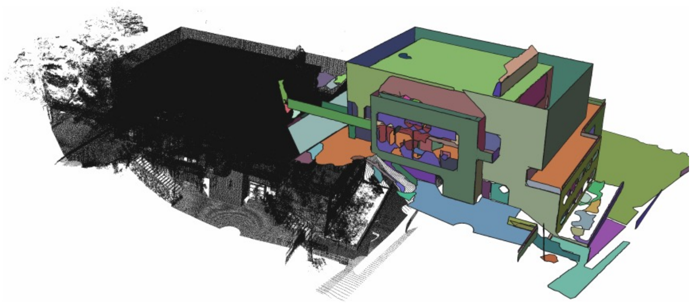
[Nan and Wonka 17]

Related work

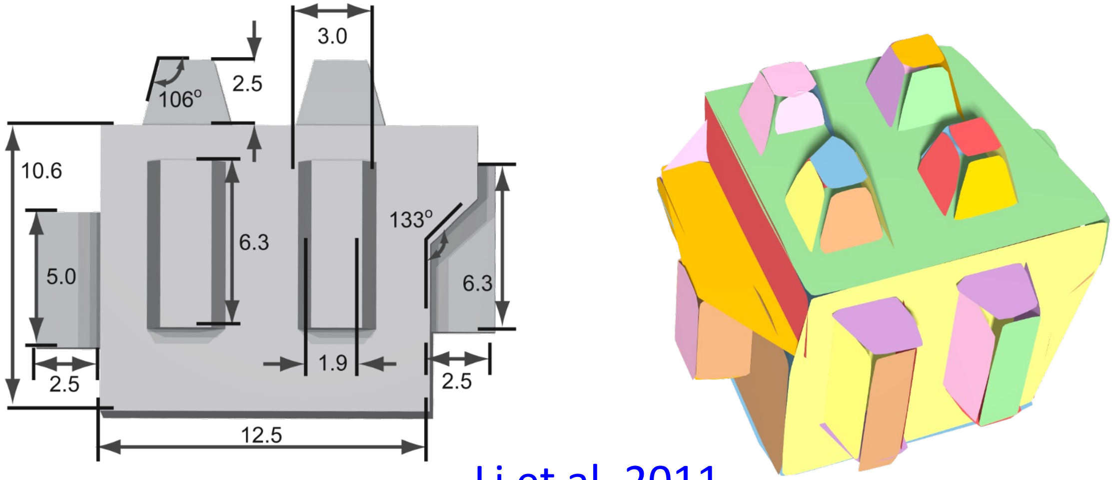
- Plane extraction
- Plane arrangement



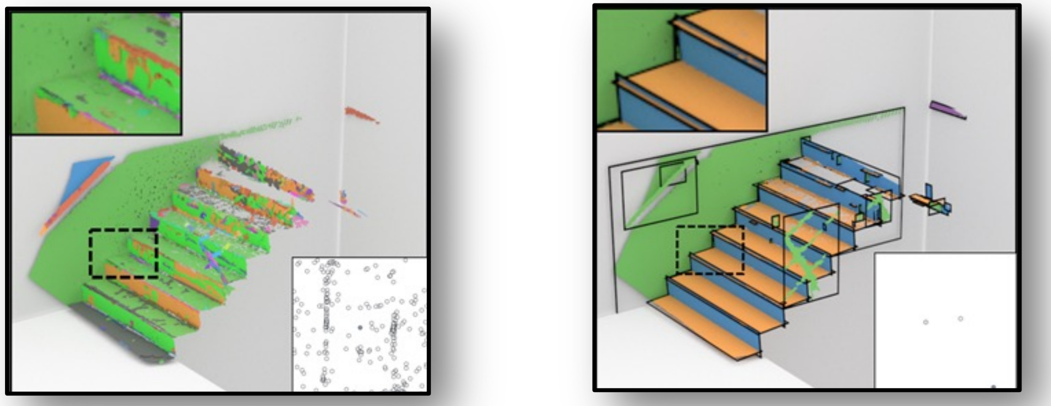
Schnabel et al. 2007



Oesau et al. 2015



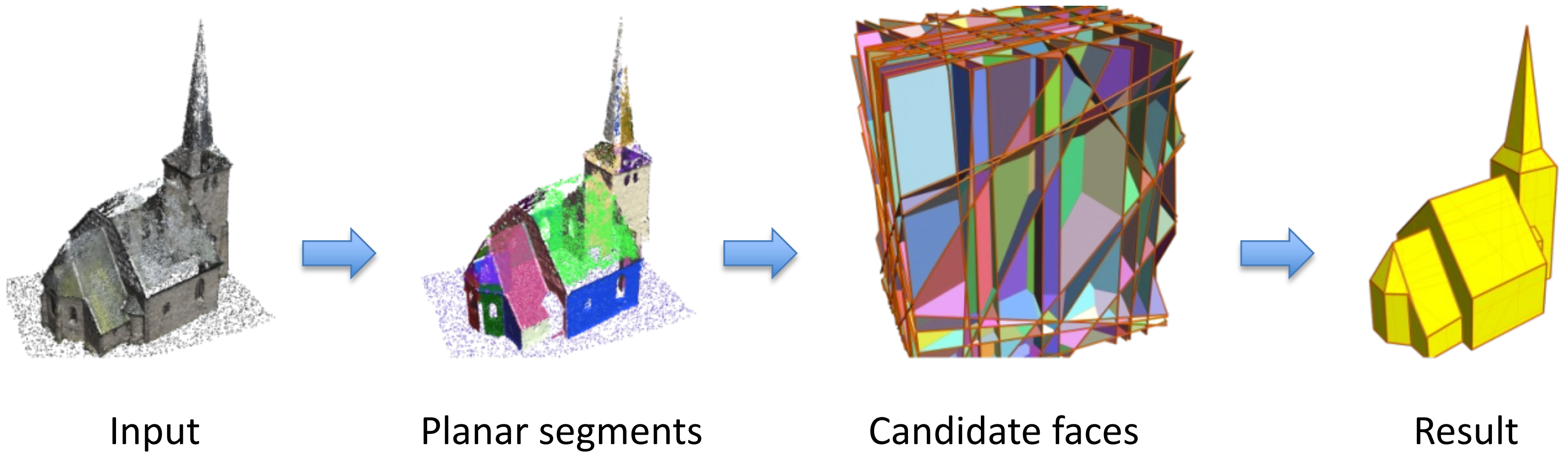
Li et al. 2011



Monszpart et al. 2015

Polygonal Surface Reconstruction

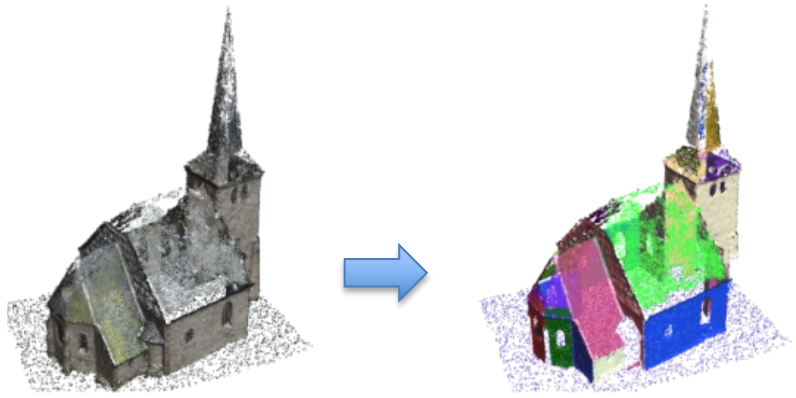
- Overview



Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Polygonal Surface Reconstruction

- Overview



Input

Planar segments

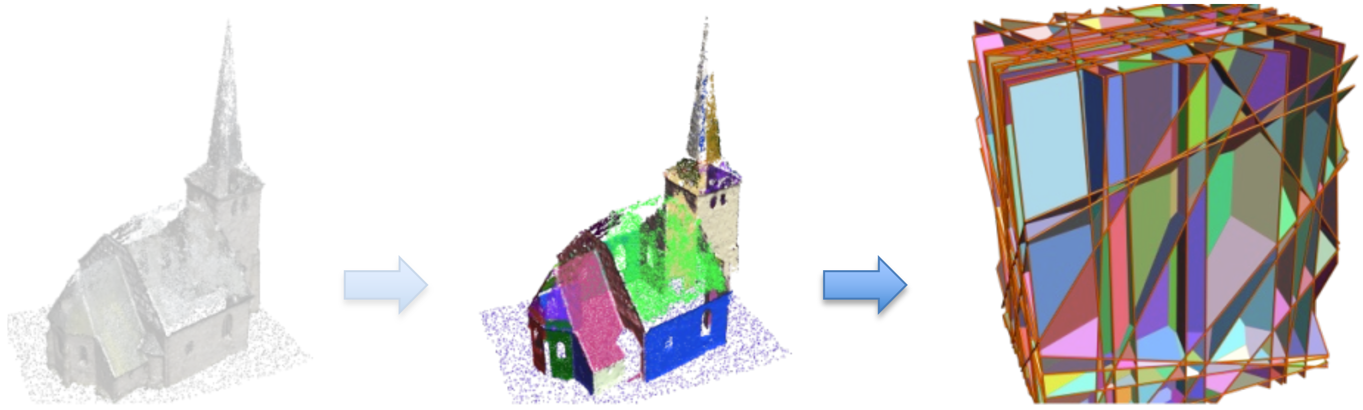
Idea of RANSAC

- Random 3 points -> plane
- Scoring, accept or reject
- Repeat
  - Plane from the remaining points
  - Stop if no plane can be extracted

Method used: Schnabel et al. 2007

Polygonal Surface Reconstruction

- Candidate Generation
  - Supporting plane clipping
  - Pairwise intersection

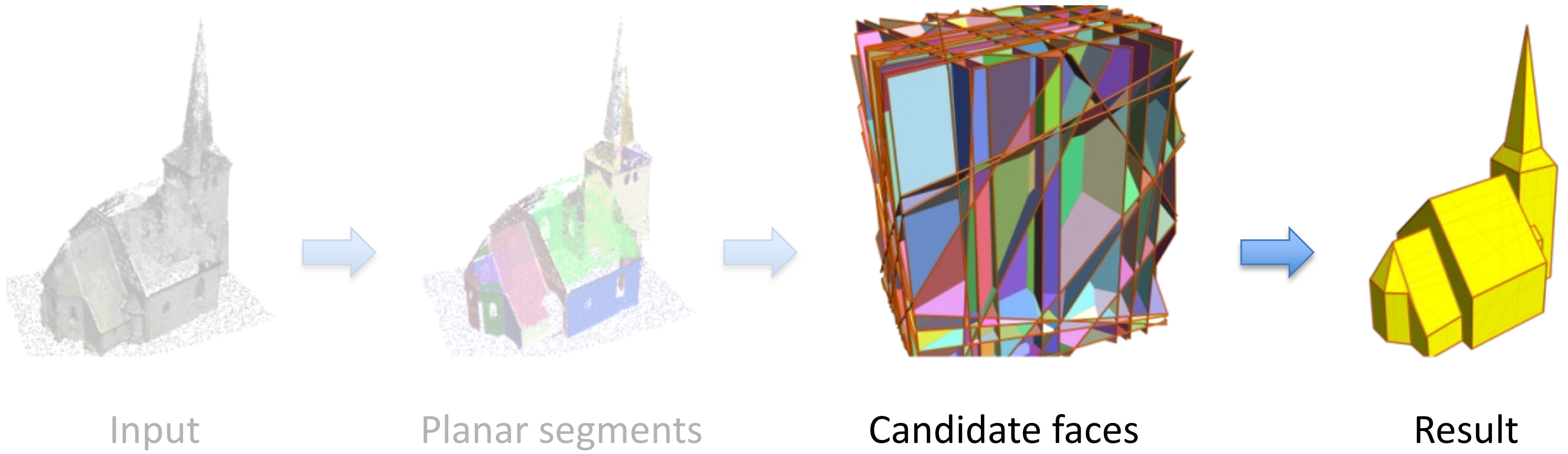


Input Planar segments Candidate faces

Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Polygonal Surface Reconstruction

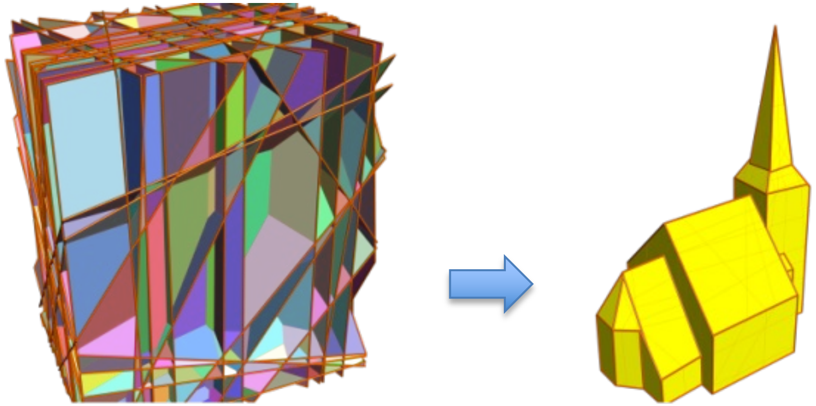
- Face Selection



Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Polygonal Surface Reconstruction

- Face Selection
  - Labeling problem
  - Linear integer program



Candidate faces Result

N candidate faces $F = \{f_i | 1 \leq i \leq N\}$

$$\text{Variables: } x_i = \begin{cases} 1, & \text{face } f_i \text{ will be chosen} \\ 0, & \text{face } f_i \text{ will } \textbf{not} \text{ be chosen} \end{cases}$$

Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Polygonal Surface Reconstruction

- Objective Function
  - Data fitting
    - Favors selecting faces with more support
    - Percentage of unused points

$$E_f = 1 - \frac{1}{|P|} \sum_{i=1}^{N} x_i \cdot support(f_i)$$

Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Polygonal Surface Reconstruction

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  - Data fitting
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    - Percentage of unused points

$$E_f = 1 - \frac{1}{|P|} \sum_{i=1}^{N} x_i \cdot support(f_i)$$

Confidence weighted number of supporting point

$$support(f) = \sum_{p,f|dist(p,f)<\varepsilon} (1 - \frac{dist(p,f)}{\varepsilon}) \cdot conf(p)$$

Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Polygonal Surface Reconstruction

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Confidence weighted number of supporting point

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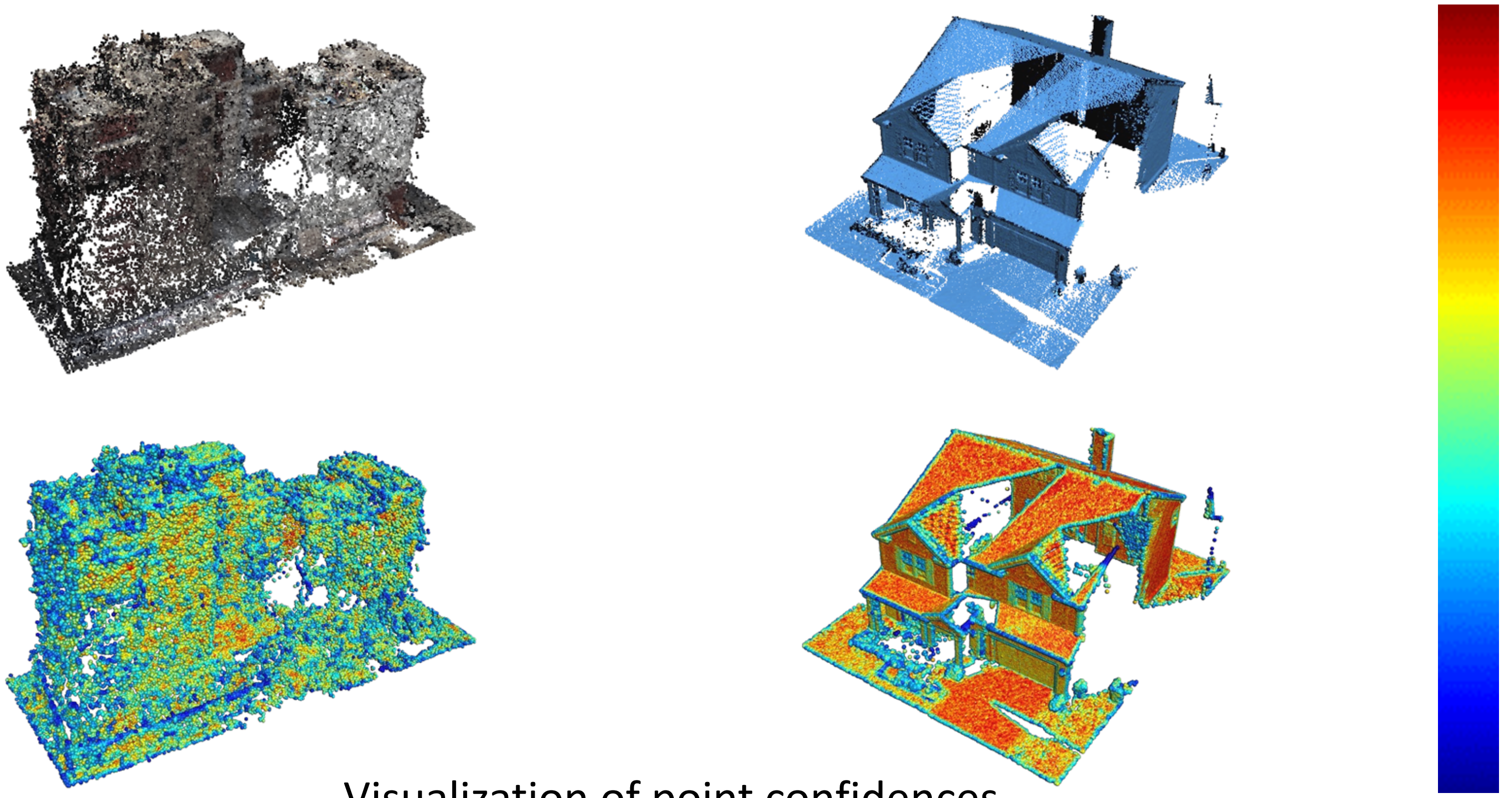
Point confidence

$$conf(p) = \frac{1}{3}\sum_{i=1}^{3} \underbrace{\left(1 - \frac{3\lambda_i^1}{\lambda_i^1 + \lambda_i^2 + \lambda_i^3}\right)}_{\text{quality of plane fitting}} \cdot \underbrace{\frac{\lambda_i^2}{\lambda_i^3}}_{\text{sampling uniformity}} \qquad \lambda_i^1 \le \lambda_i^2 \le \lambda_i^3$$

Polygonal Surface Reconstruction

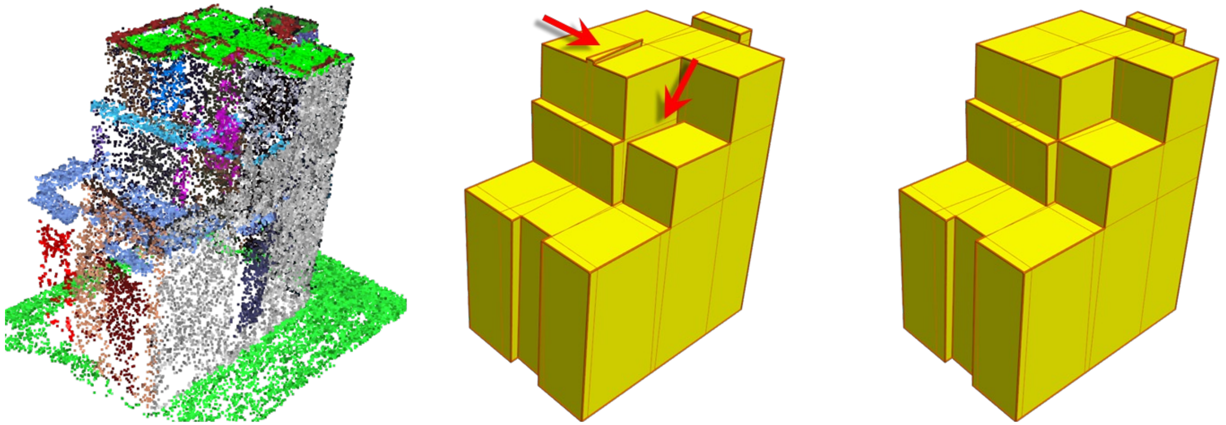
- Objective Function
  - Data fitting



Visualization of point confidences

Polygonal Surface Reconstruction

- Objective Function
  - Data fitting
  - Model complexity
    - Penalize sharp corners



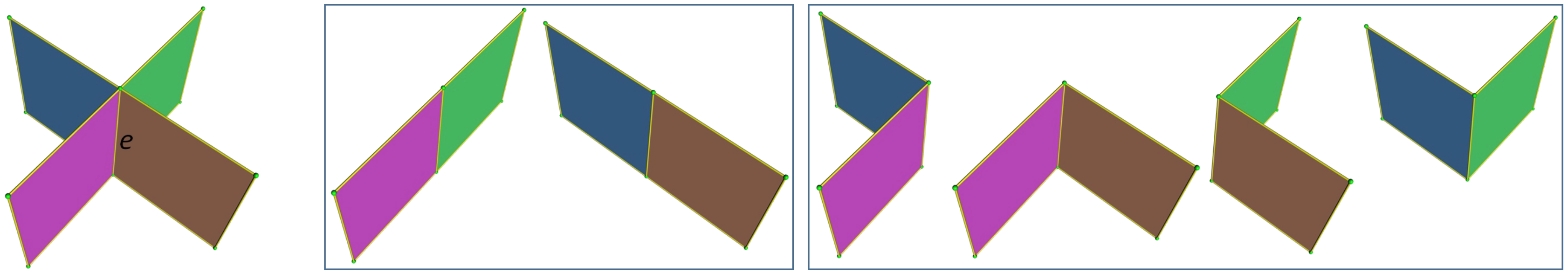
(a) (b) (c)

Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Polygonal Surface Reconstruction

- Objective Function
  - Data fitting
  - Model complexity
    - Penalize sharp corners

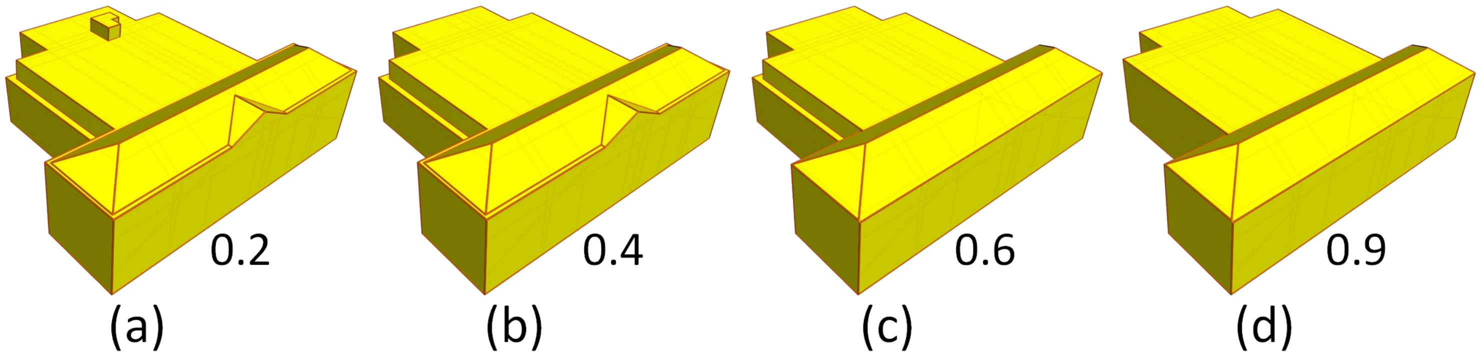
$$E_m = \frac{1}{|E|} \sum_{i=1}^{|E|} corner(e_i)$$



Intersecting two faces

Polygonal Surface Reconstruction

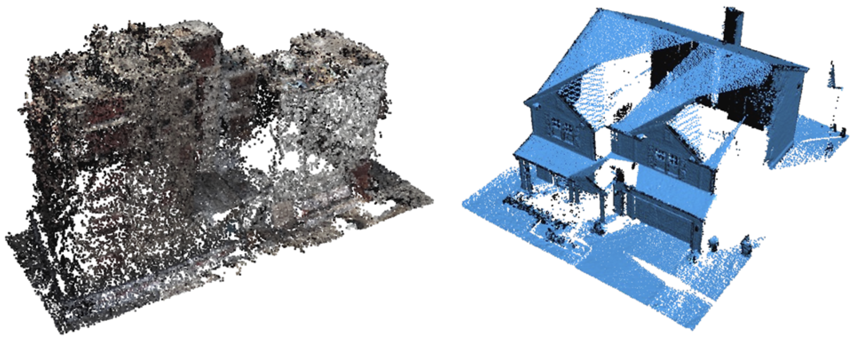
- Objective Function
  - Data fitting
  - Model complexity
    - Penalize sharp corners

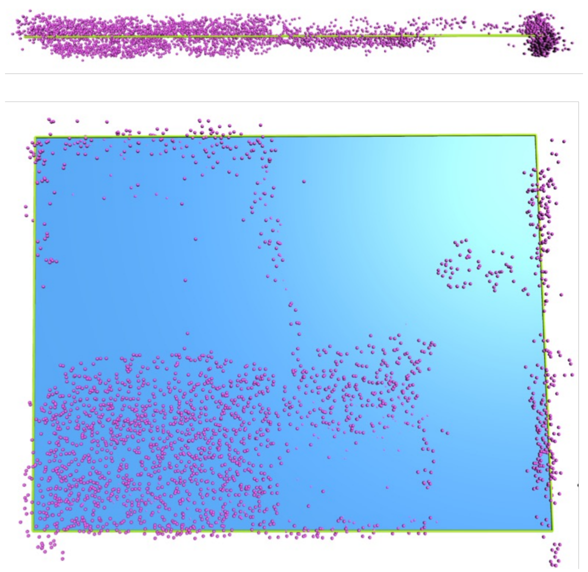


Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Polygonal Surface Reconstruction

- Objective Function
  - Data fitting
  - Model complexity
  - Point coverage



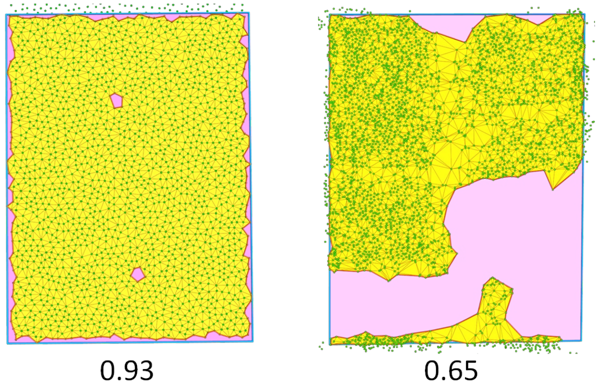


Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Polygonal Surface Reconstruction

- Objective Function
  - Data fitting
  - Model complexity
  - Point coverage

$$E_c = \frac{1}{area(M)} \sum_{i=1}^{N} x_i \cdot (area(f_i) - area(M_i^{\alpha})),$$



Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Polygonal Surface Reconstruction

- Face Selection
  – Linear integer program

$$\min_{\mathbf{x}} \quad \lambda_f \cdot \underline{E_f} + \lambda_m \cdot \underline{E_m} + \lambda_c \cdot \underline{E_c}$$

Data fitting

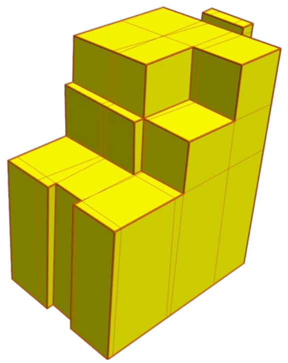
Model complexity

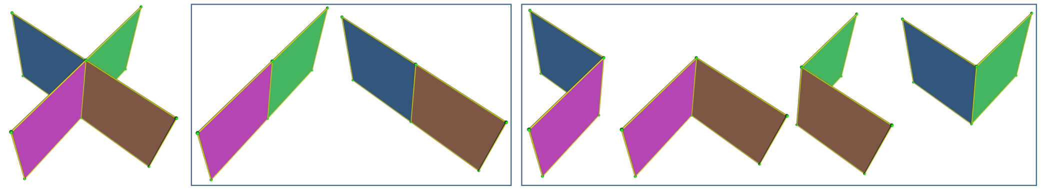
Point coverage

Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Polygonal Surface Reconstruction

- Face Selection
  - Linear integer program
    - Constraints
      - Watertight
      - Manifold





$$\min_{\mathbf{x}} \quad \lambda_f \cdot E_f + \lambda_m \cdot E_m + \lambda_c \cdot E_c$$

$$\text{s.t.} \quad \begin{cases} \sum_{j \in \mathcal{N}(e_i)} x_j = 2 \quad \text{or} \quad 0, & 1 \leq i \leq |E| \\ x_i \in \{0, 1\}, & 1 \leq i \leq N \end{cases}$$

Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Polygonal Surface Reconstruction

- Face Selection
  - Linear integer program
    - Constraints
    - Solvers (SCIP, CBC, GLPK, Gurobi…)

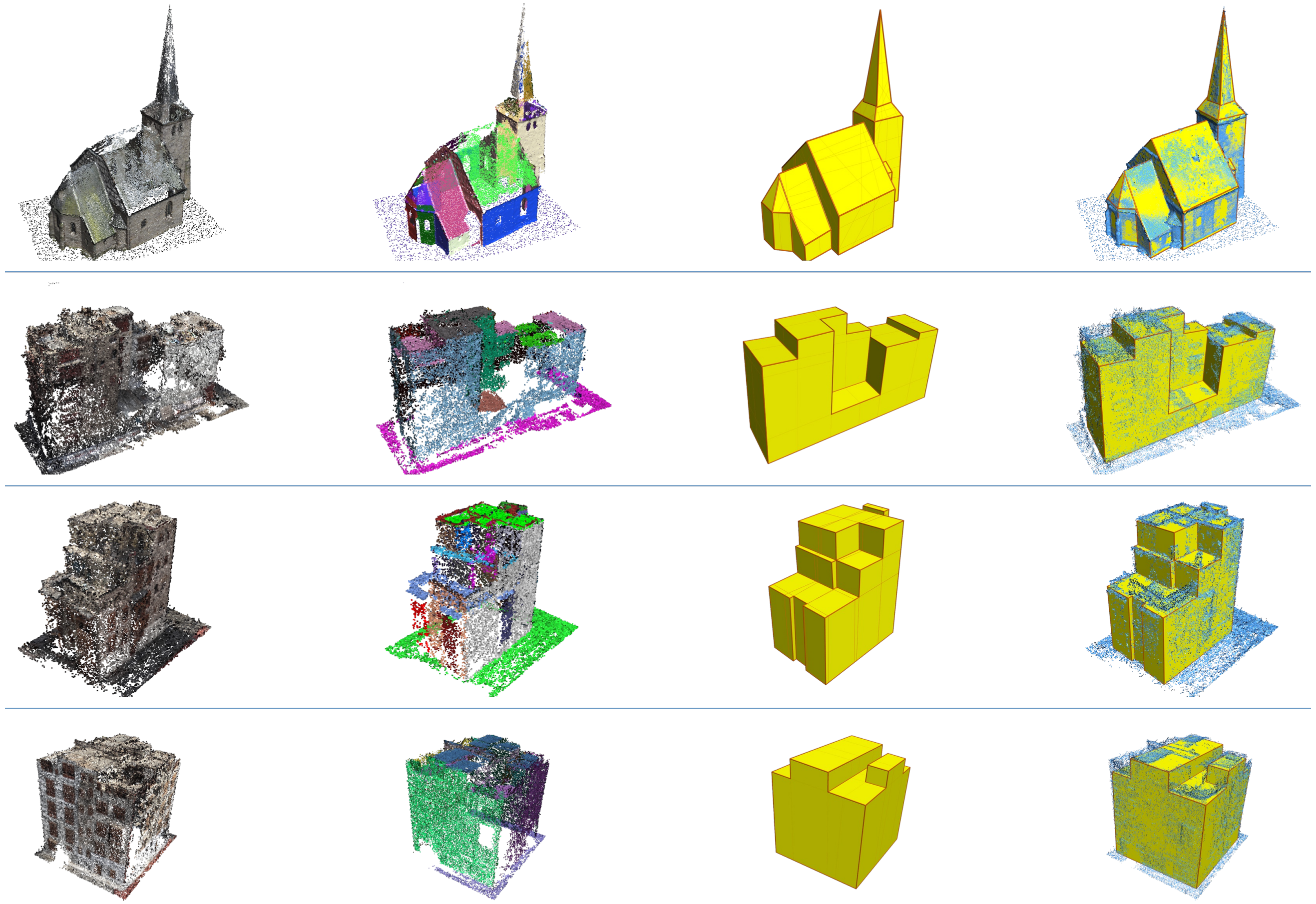
$$\min_{\mathbf{x}} \quad \lambda_f \cdot E_f + \lambda_m \cdot E_m + \lambda_c \cdot E_c$$

$$\text{s.t.} \quad \begin{cases} \sum\limits_{j \in \mathcal{N}(e_i)} x_j = 2 \quad \text{or} \quad 0, & 1 \leq i \leq |E| \\ x_i \in \{0, 1\}, & 1 \leq i \leq N \end{cases}$$

Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Polygonal Surface Reconstruction

- Reconstruction Results



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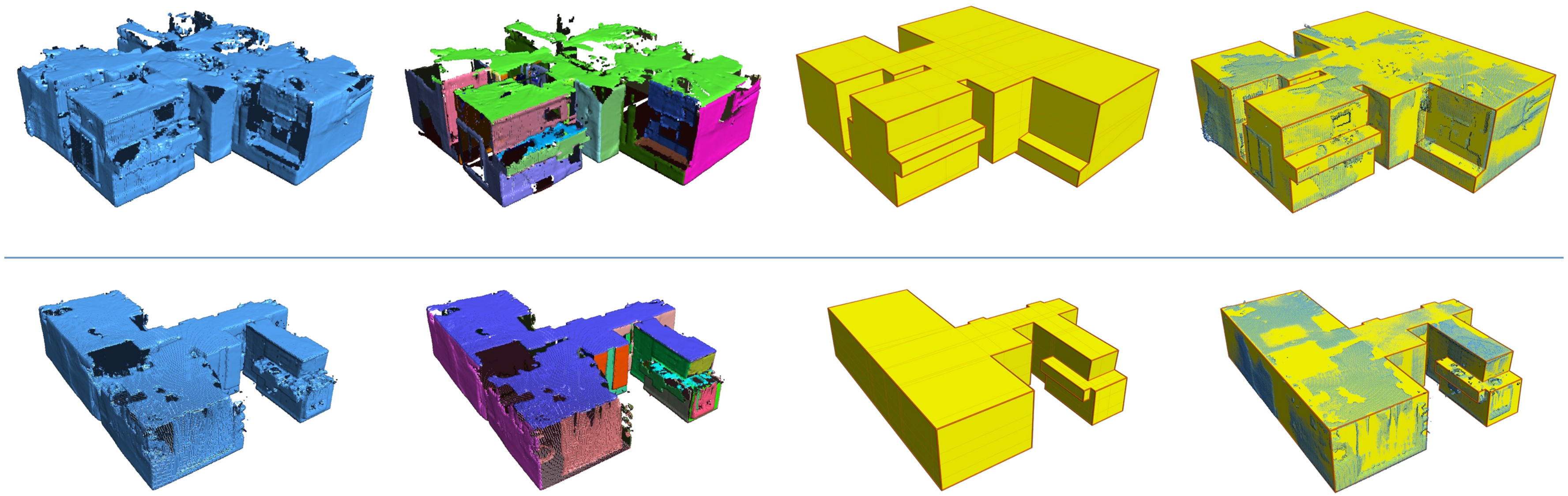
Polygonal Surface Reconstruction

- Reconstruction Results



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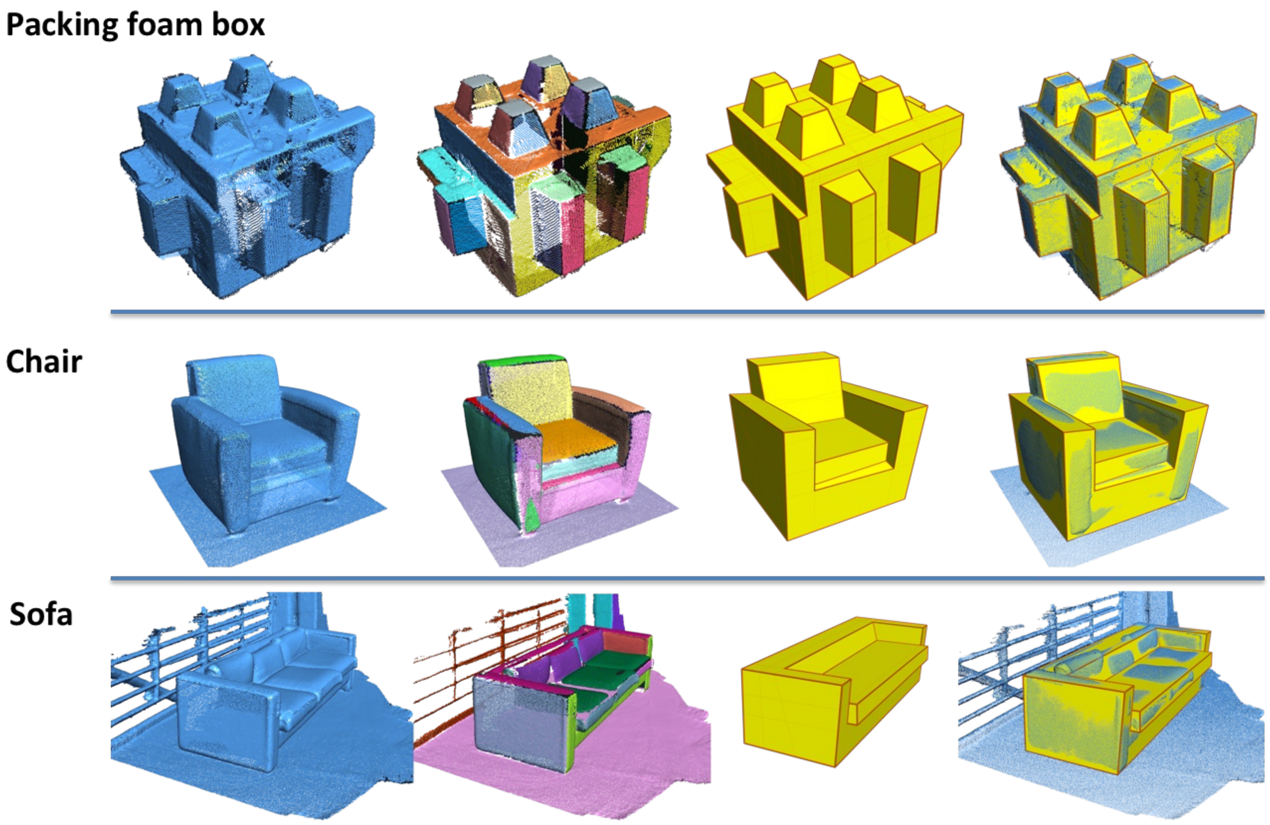
Polygonal Surface Reconstruction

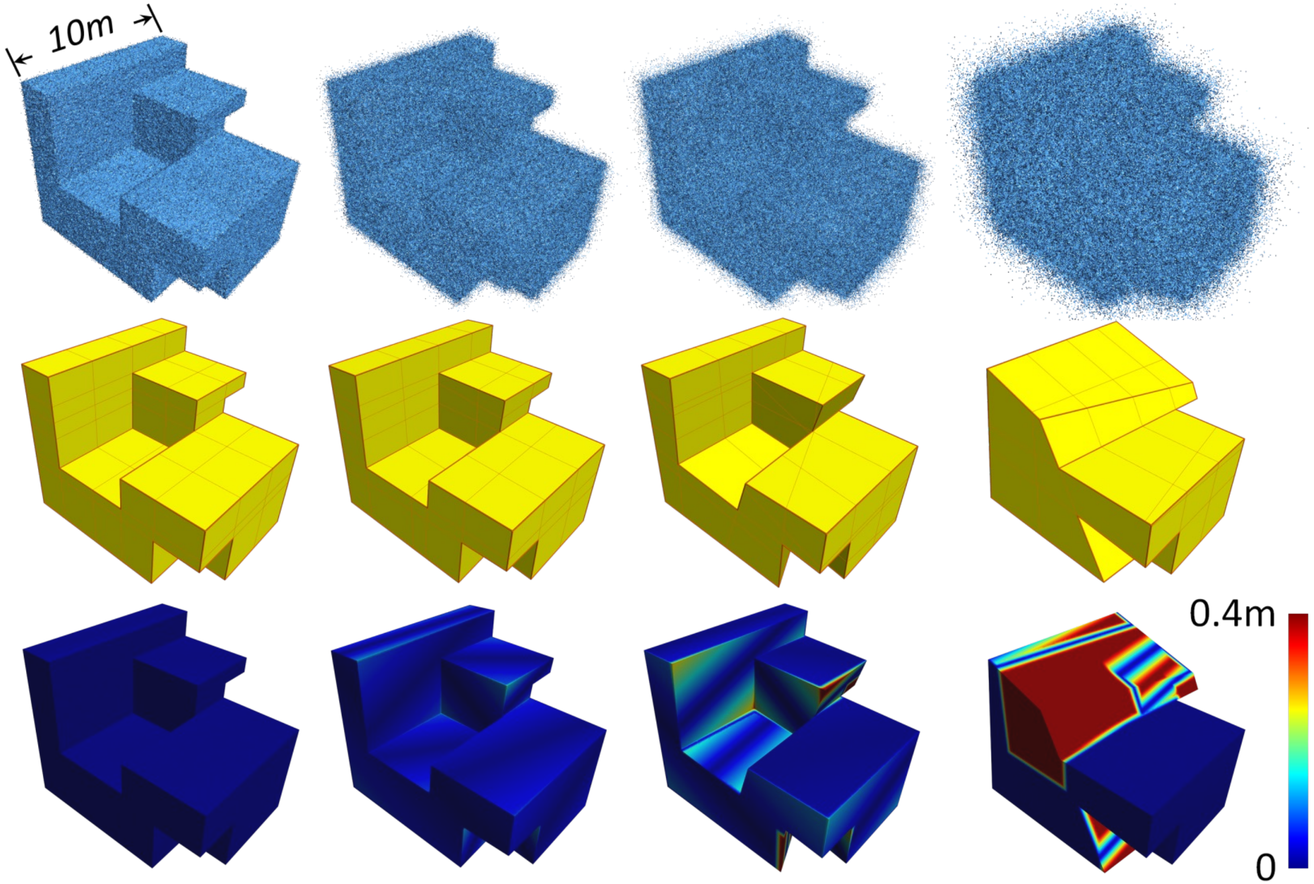
- Reconstruction Results



Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Polygonal Surface Reconstruction

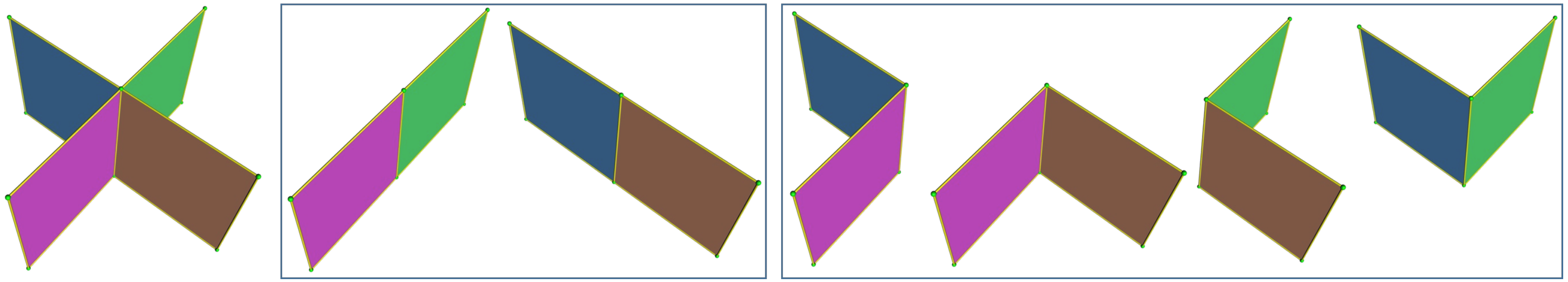
- Robustness to noise



(a) $\sigma = 0.1m$ (b) $\sigma = 0.4m$ (c) $\sigma = 0.6m$ (d) $\sigma = 0.8m$

Limitations

- Open surfaces



$$\text{s.t.} \quad \begin{cases} \sum_{j \in \mathcal{N}(e_i)} x_j = 2 \quad \text{or} \quad 0, & 1 \leq i \leq |E| \\ x_i \in \{0, 1\}, & 1 \leq i \leq N \end{cases}$$

Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Limitations

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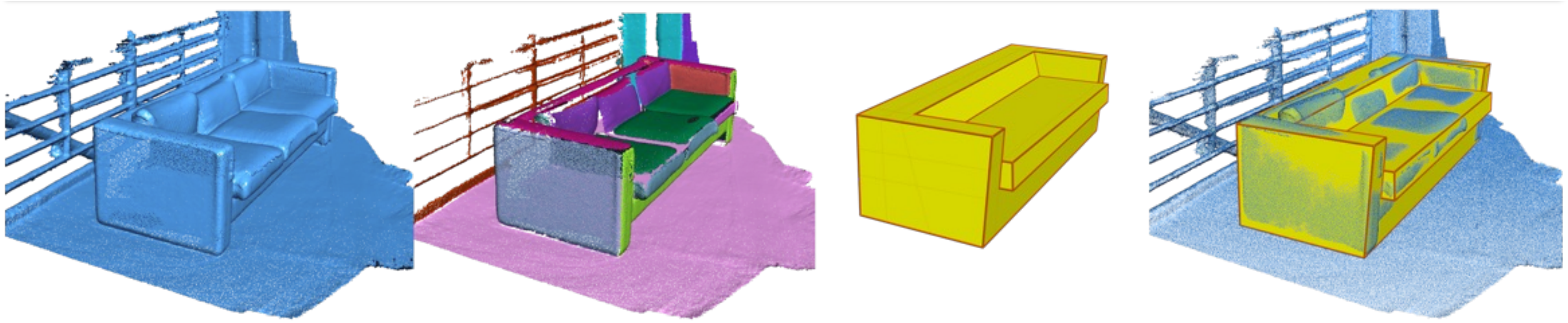

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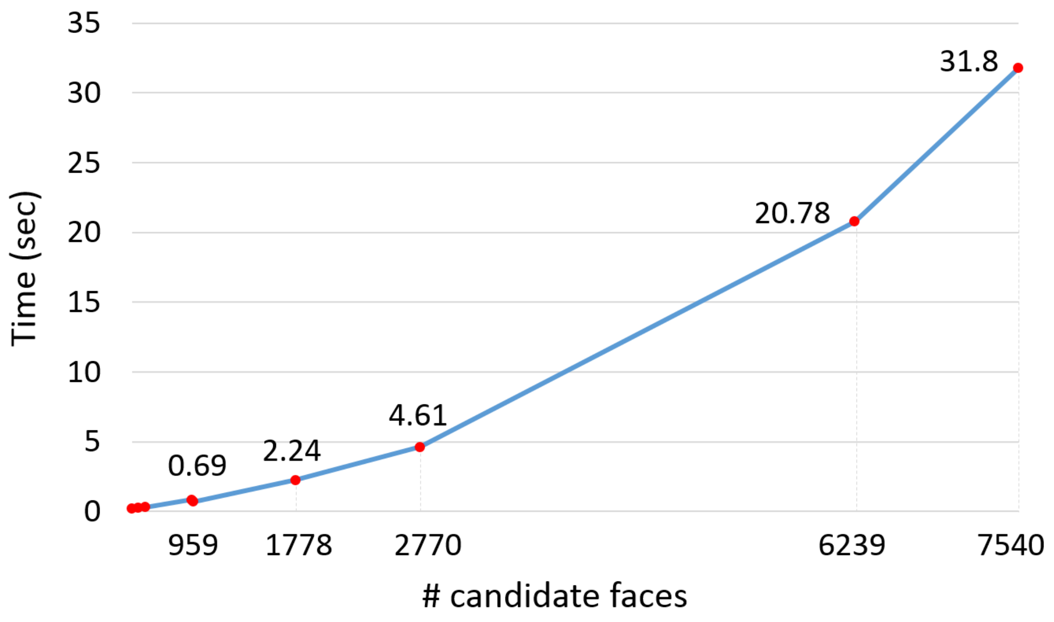
Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Limitations

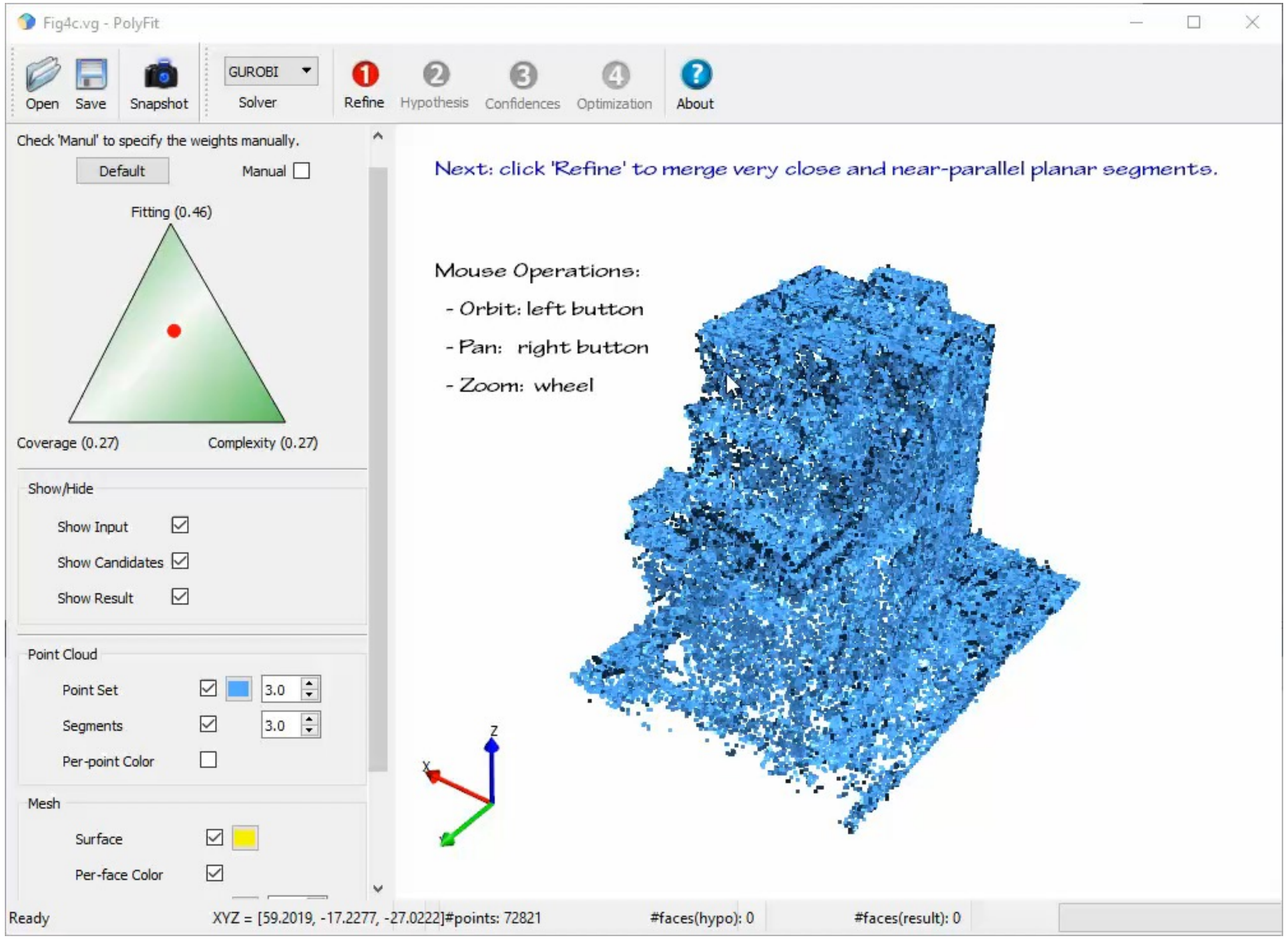
- Open surfaces
- Complexity of the algorithm
  - Finer surface details cannot be recovered
    - Fence
    - Façade decorations
    - Door handle
    - …



Nan and Wonka. PolyFit: Polygonal Surface Reconstruction from Point Clouds. ICCV 2017

Polygonal Surface Reconstruction

- Demo



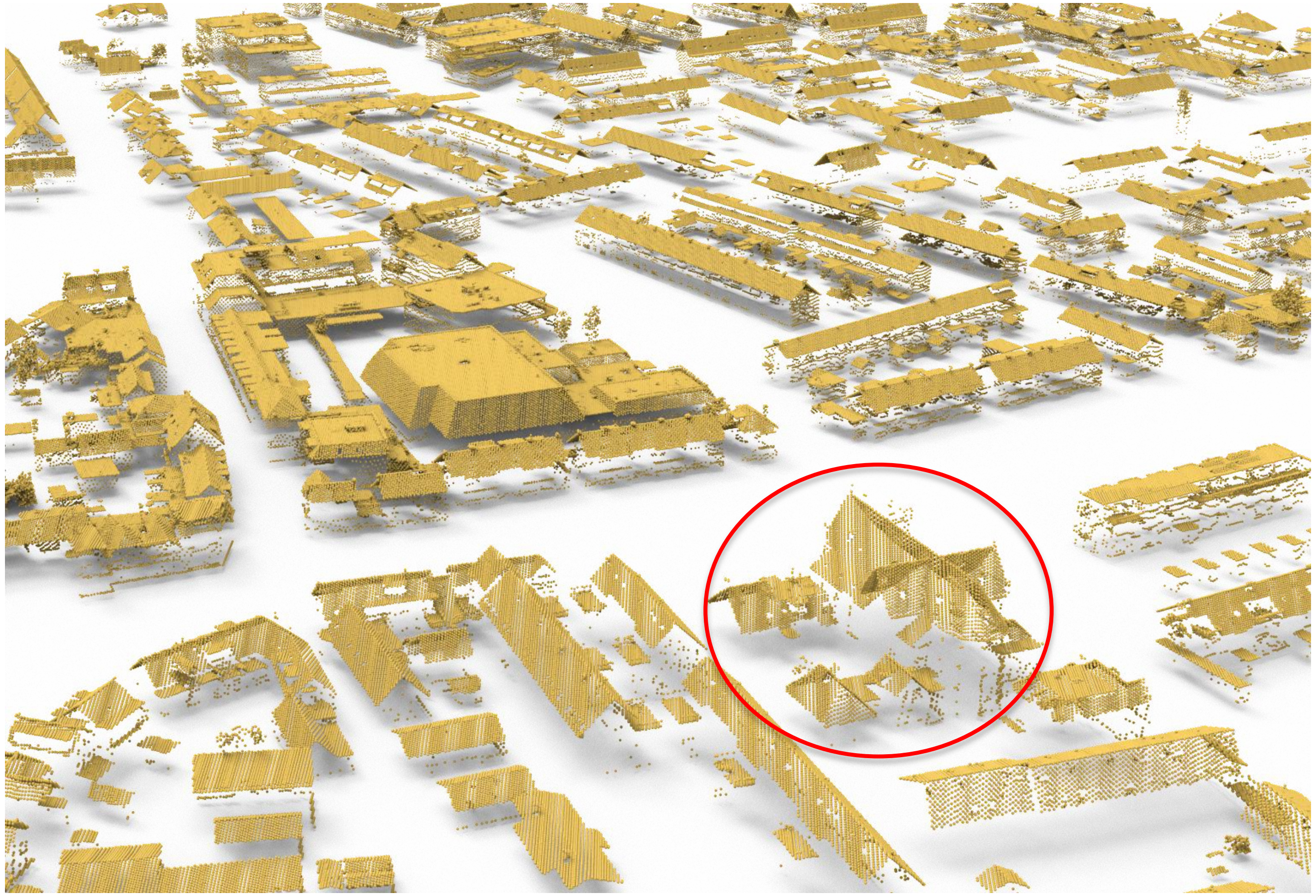
Source Code (in C++) https://github.com/LiangliangNan/PolyFit

Outline

- PolyFit: polygonal surface reconstruction
- Two extensions of PolyFit
  - LoD2 urban building reconstruction from airborne LiDAR data
  - LoD2 urban building reconstruction based on deep implicit fields
- Opportunities and future work
- Some thoughts about data

LoD2 Building Reconstruction from LiDAR

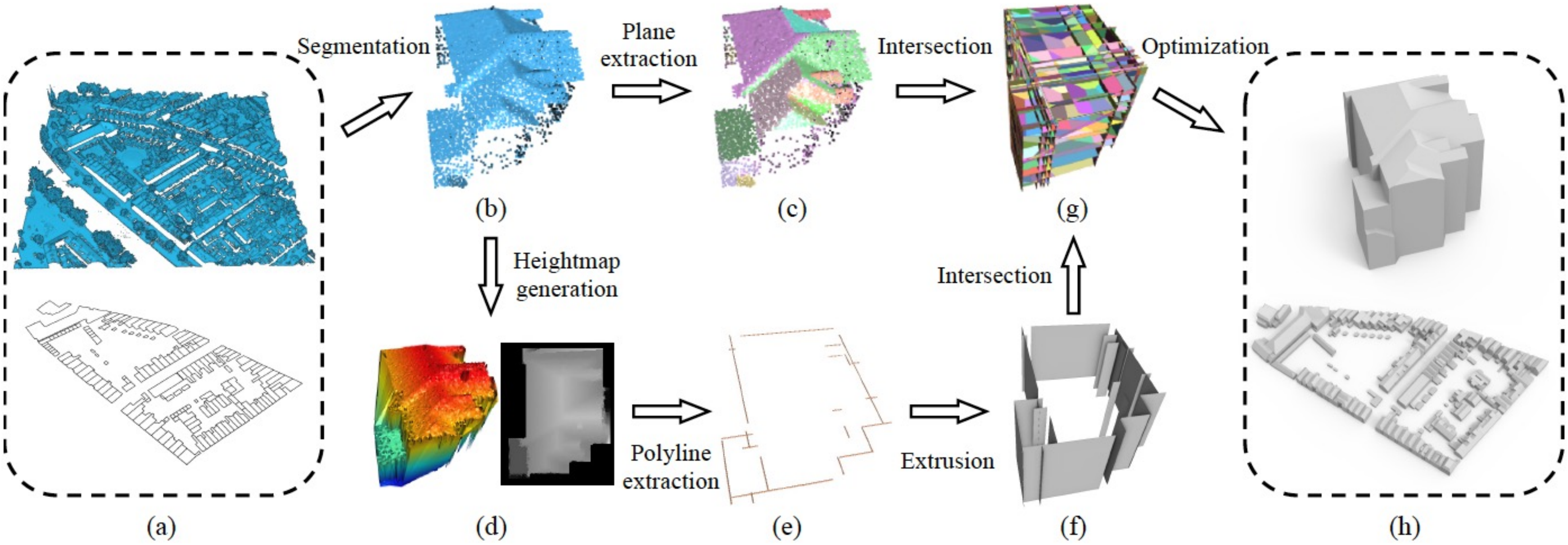
- LiDAR point clouds



Huang et al., City3D: Large-Scale Building Reconstruction from Airborne LiDAR Point Clouds. *Remote Sensing*. 2022; 14(9):2254.

LoD2 Building Reconstruction from LiDAR

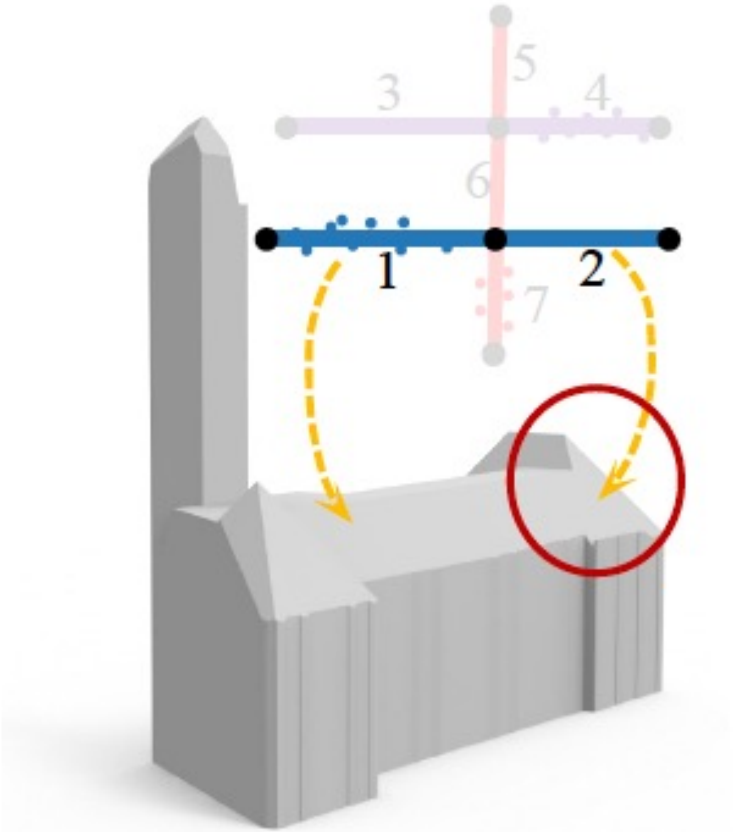
- Pipeline



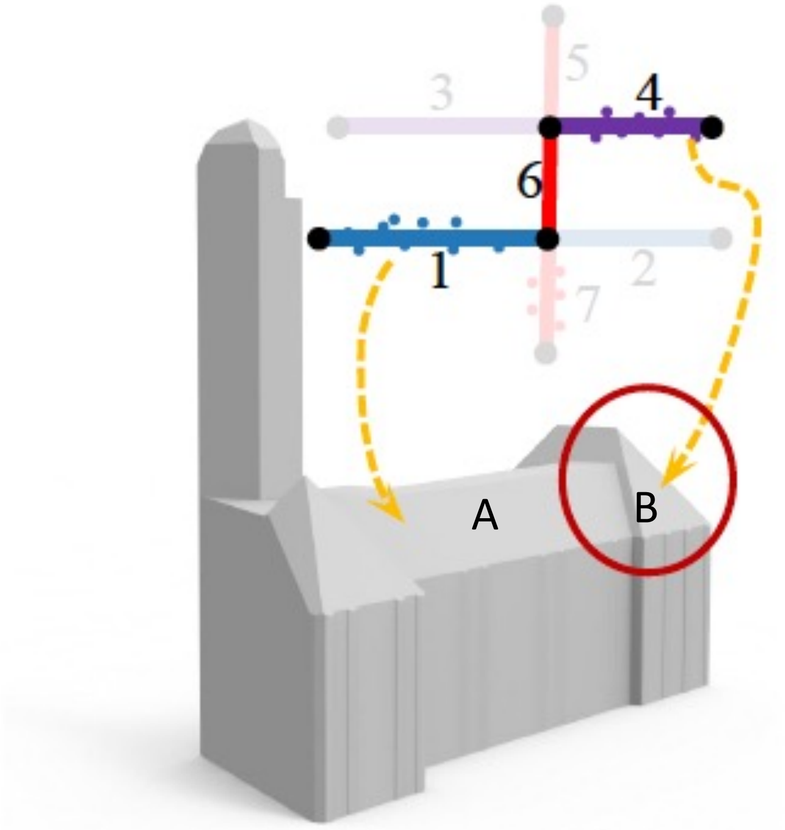
Huang et al., City3D: Large-Scale Building Reconstruction from Airborne LiDAR Point Clouds. *Remote Sensing*. 2022; 14(9):2254.

LoD2 Building Reconstruction from LiDAR

- New constraints: face prior



Without face prior constraint

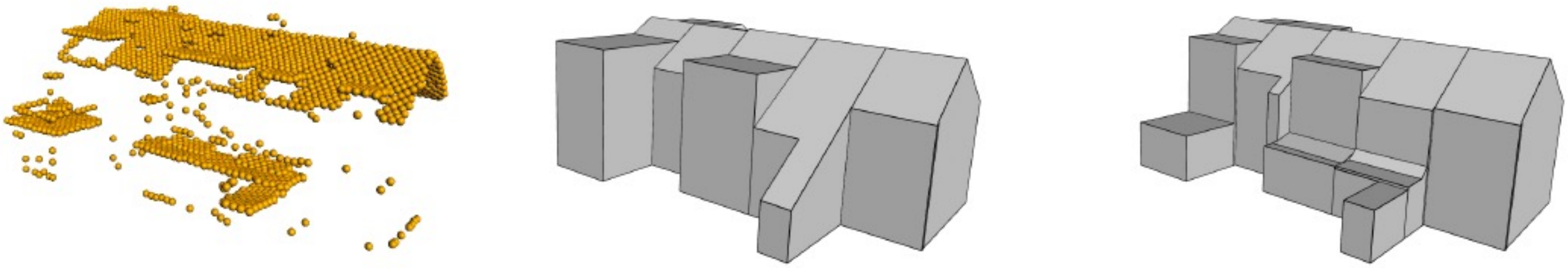


With face prior constraint

Huang et al., City3D: Large-Scale Building Reconstruction from Airborne LiDAR Point Clouds. *Remote Sensing*. 2022; 14(9):2254.

LoD2 Building Reconstruction from LiDAR

- Comparison with PolyFit

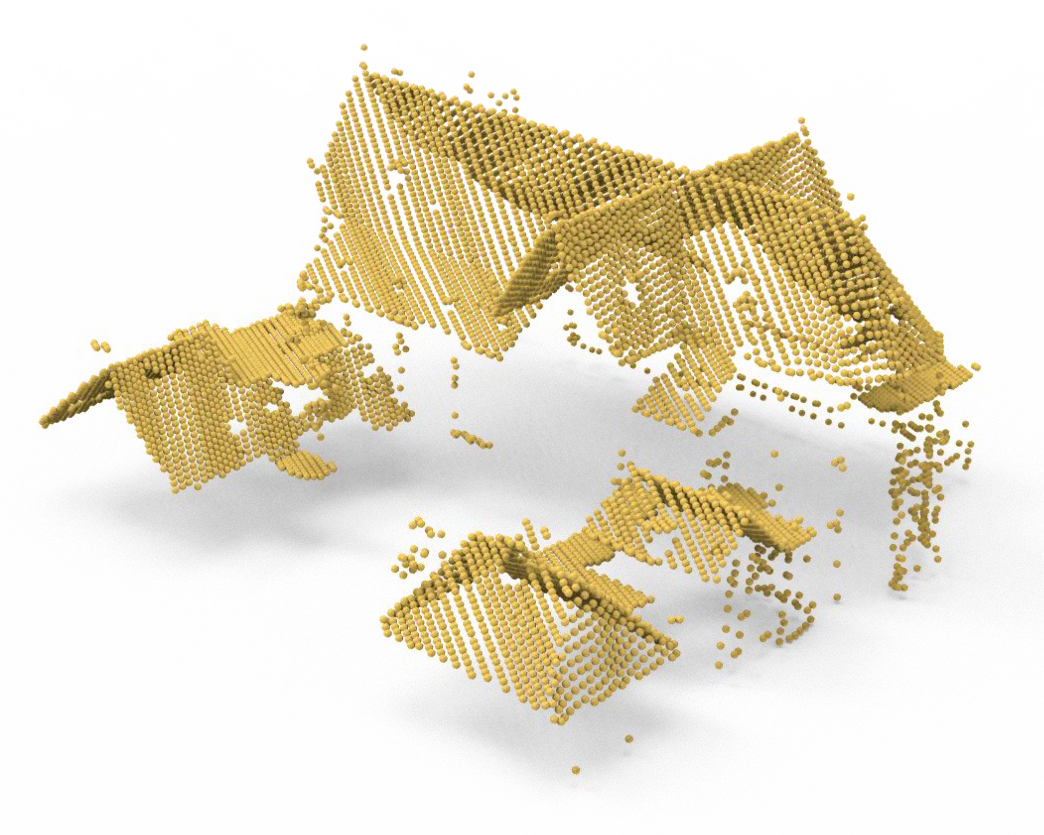


(a) Input point cloud (c) PolyFit (58 faces) (d) Ours (86 faces)

Huang et al., City3D: Large-Scale Building Reconstruction from Airborne LiDAR Point Clouds. *Remote Sensing*. 2022; 14(9):2254.

LoD2 Building Reconstruction from LiDAR

- Allows the use of available footprint data



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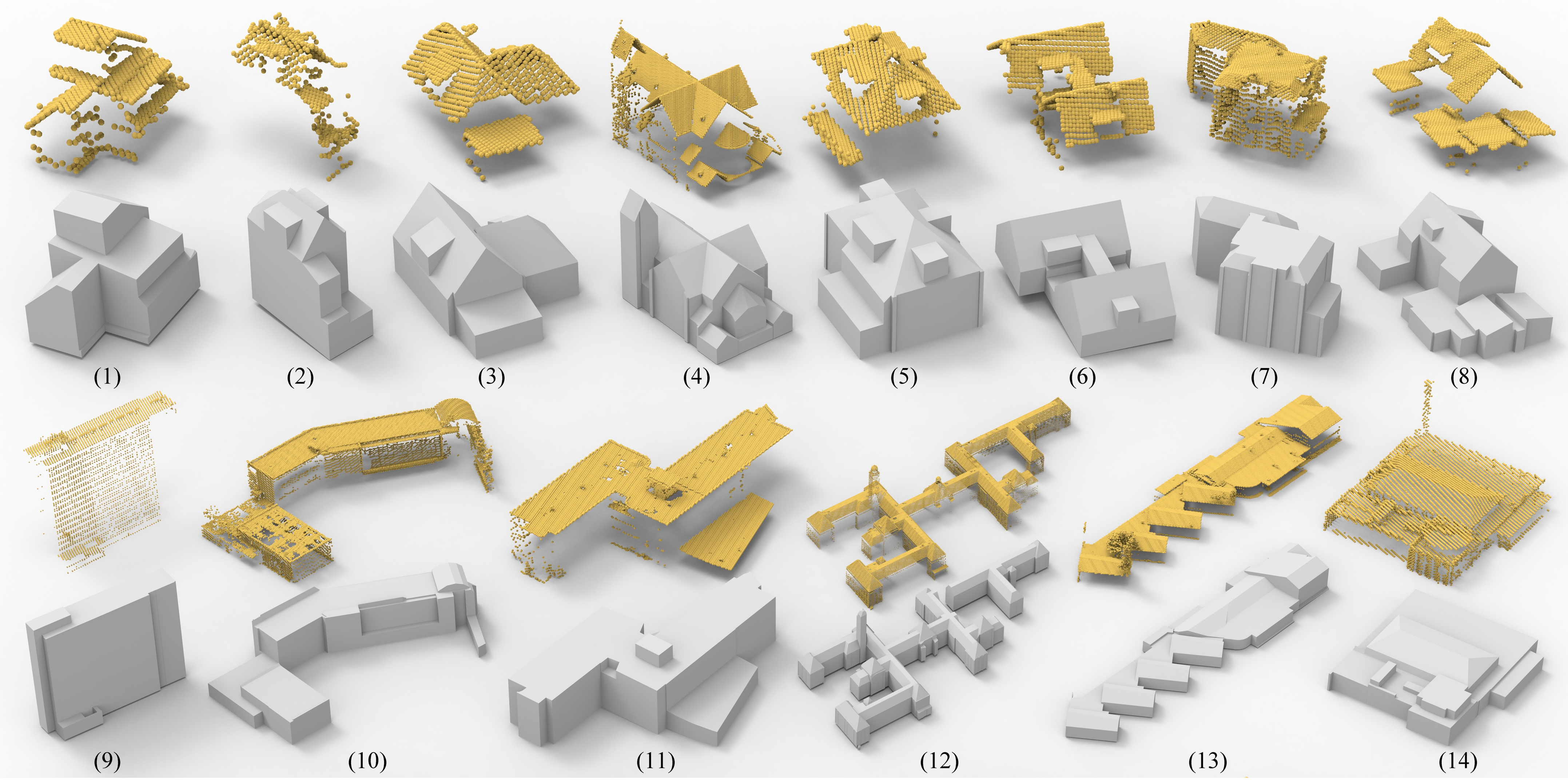
LoD2 Building Reconstruction from LiDAR



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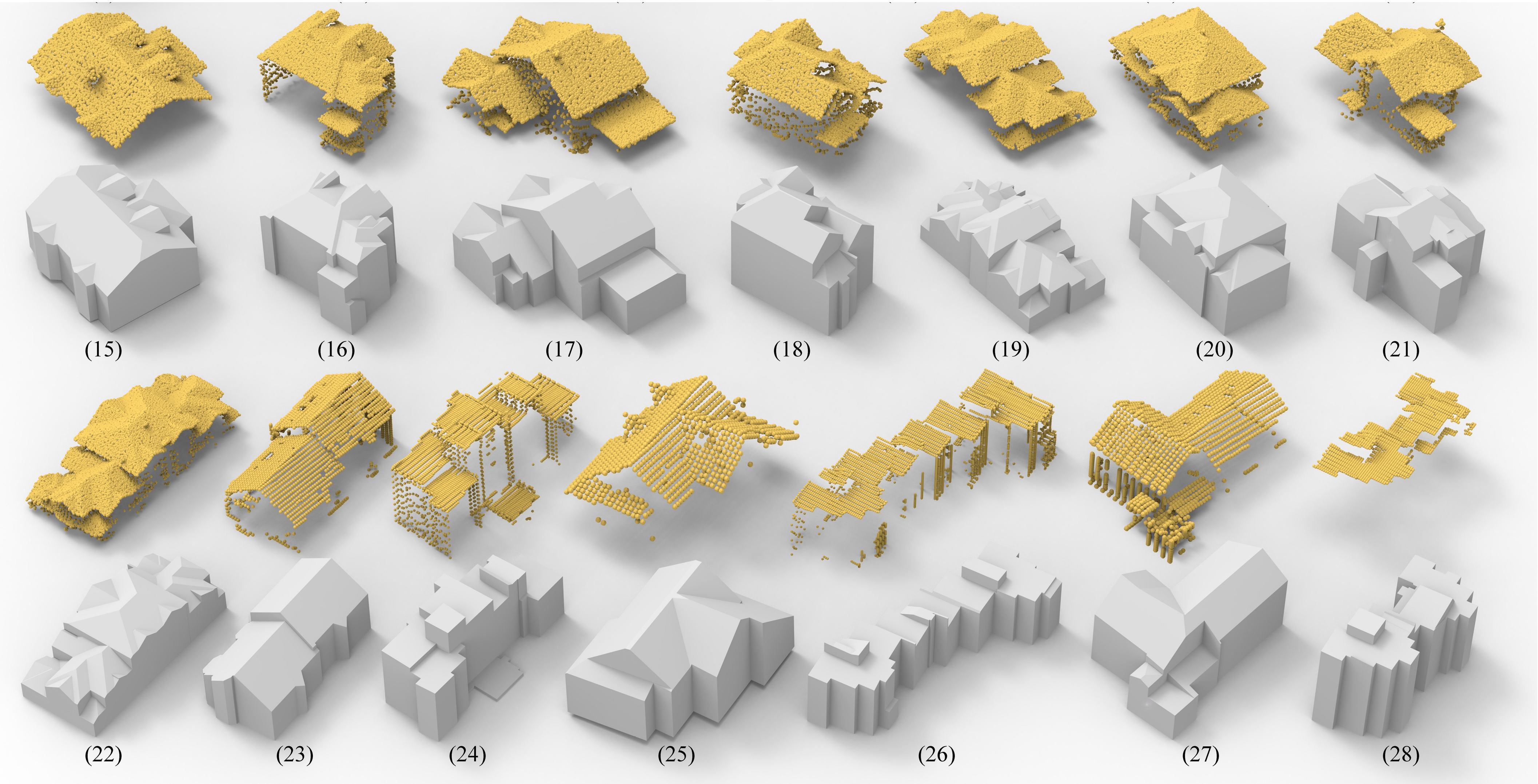
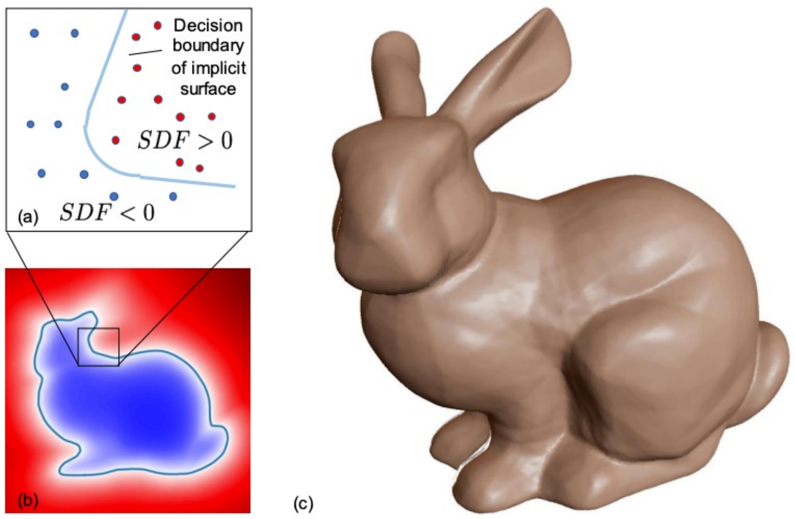
LoD2 Building Reconstruction from LiDAR



Huang et al., City3D: Large-Scale Building Reconstruction from Airborne LiDAR Point Clouds. *Remote Sensing*. 2022; 14(9):2254.

LoD2 from Deep Implicit Fields

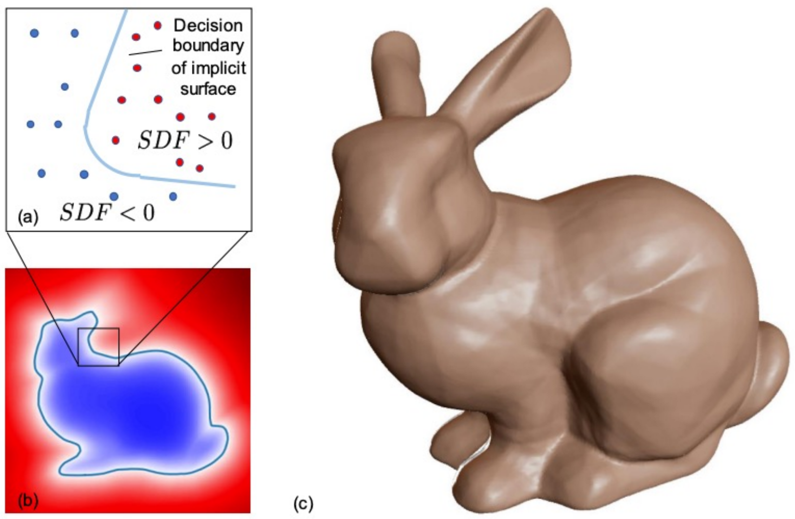
- Deep implicit fields
  - Surface representation using a continuous volumetric field

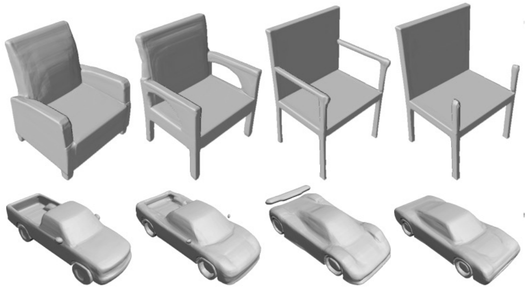


Park et al. DeepSDF: Learning Continuous Signed Distance Functions for Shape Representation. CVPR 2019.

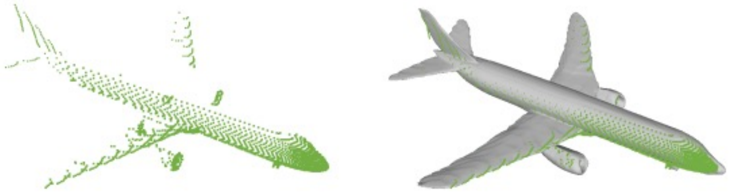
LoD2 from Deep Implicit Fields

- Deep implicit fields
  - Surface representation using a continuous volumetric field
    - Boundary: zero-level-set of the learned function





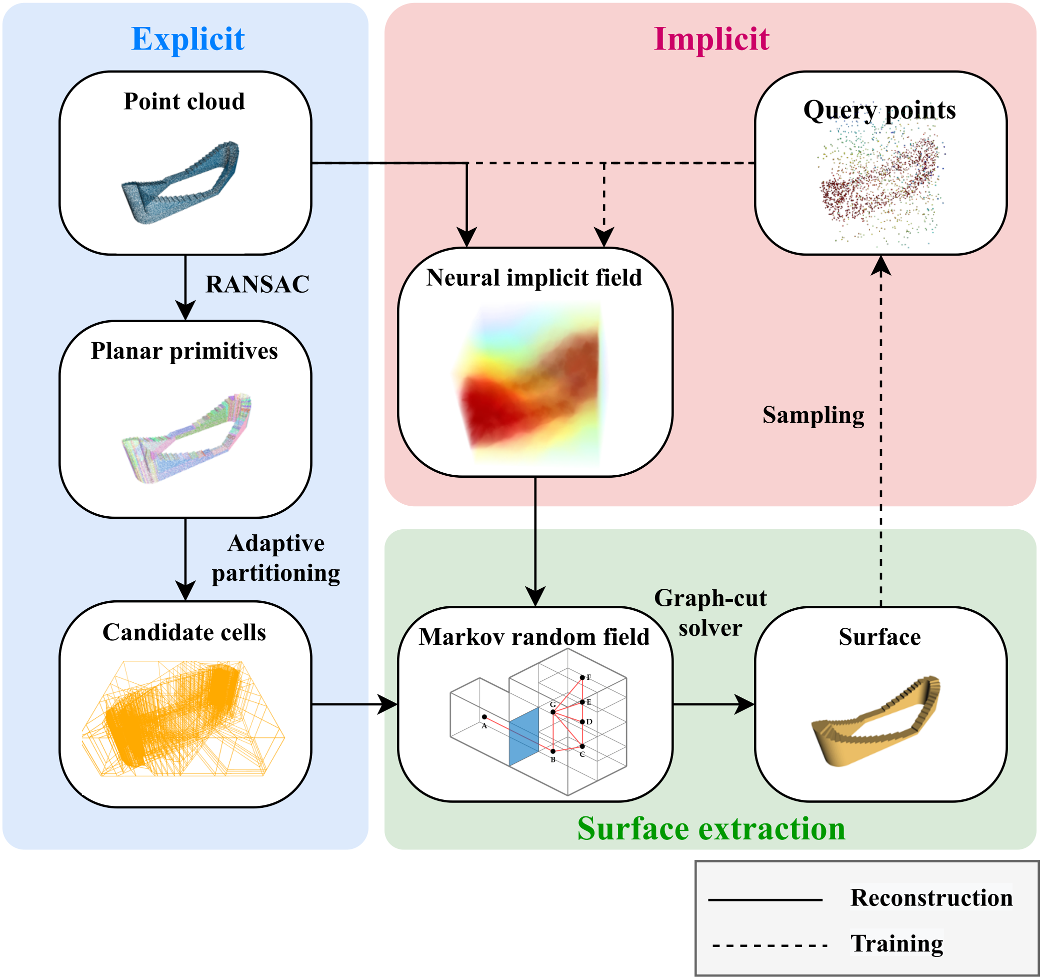
shape interpolation



shape completion

Park et al. DeepSDF: Learning Continuous Signed Distance Functions for Shape Representation. CVPR 2019.

LoD2 from Deep Implicit Fields



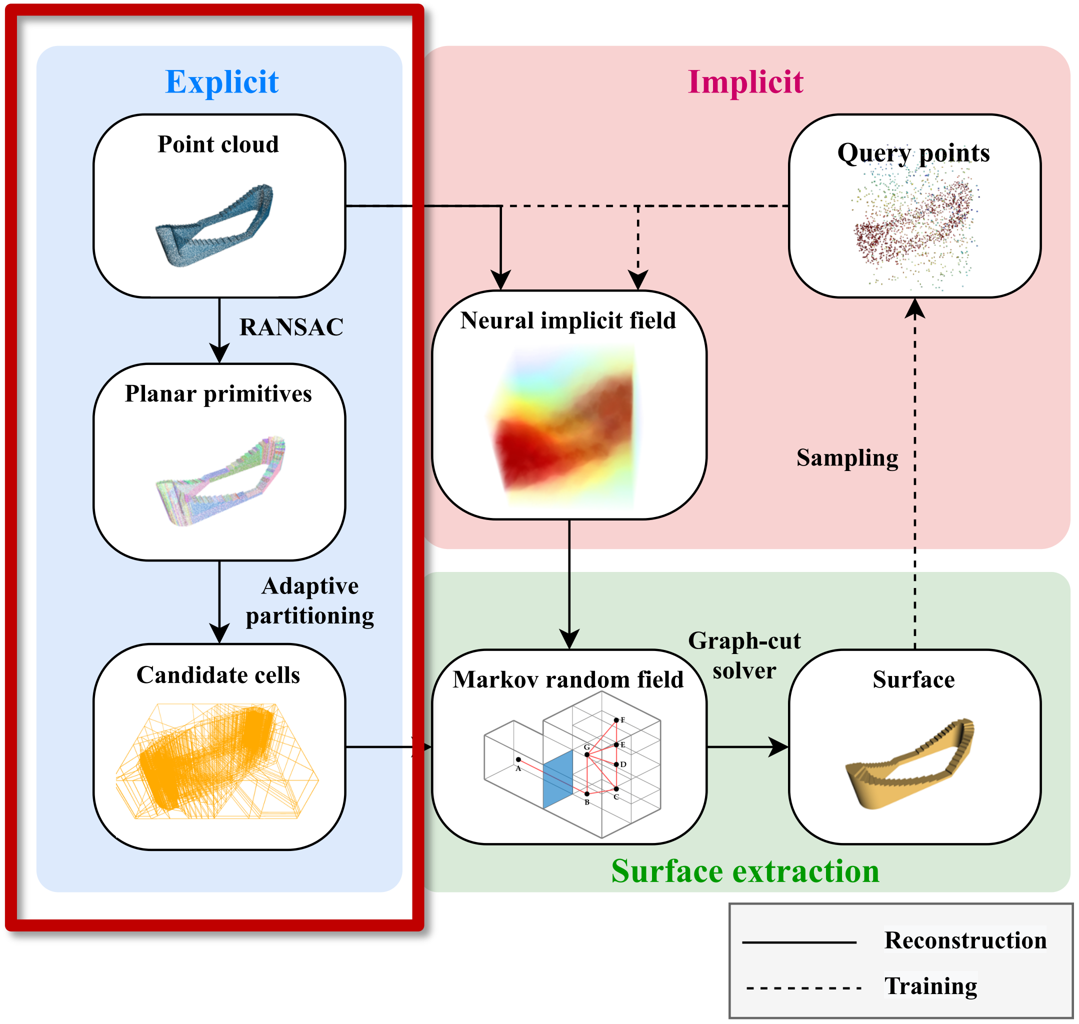
Explicit
Candidate generation by partitioning

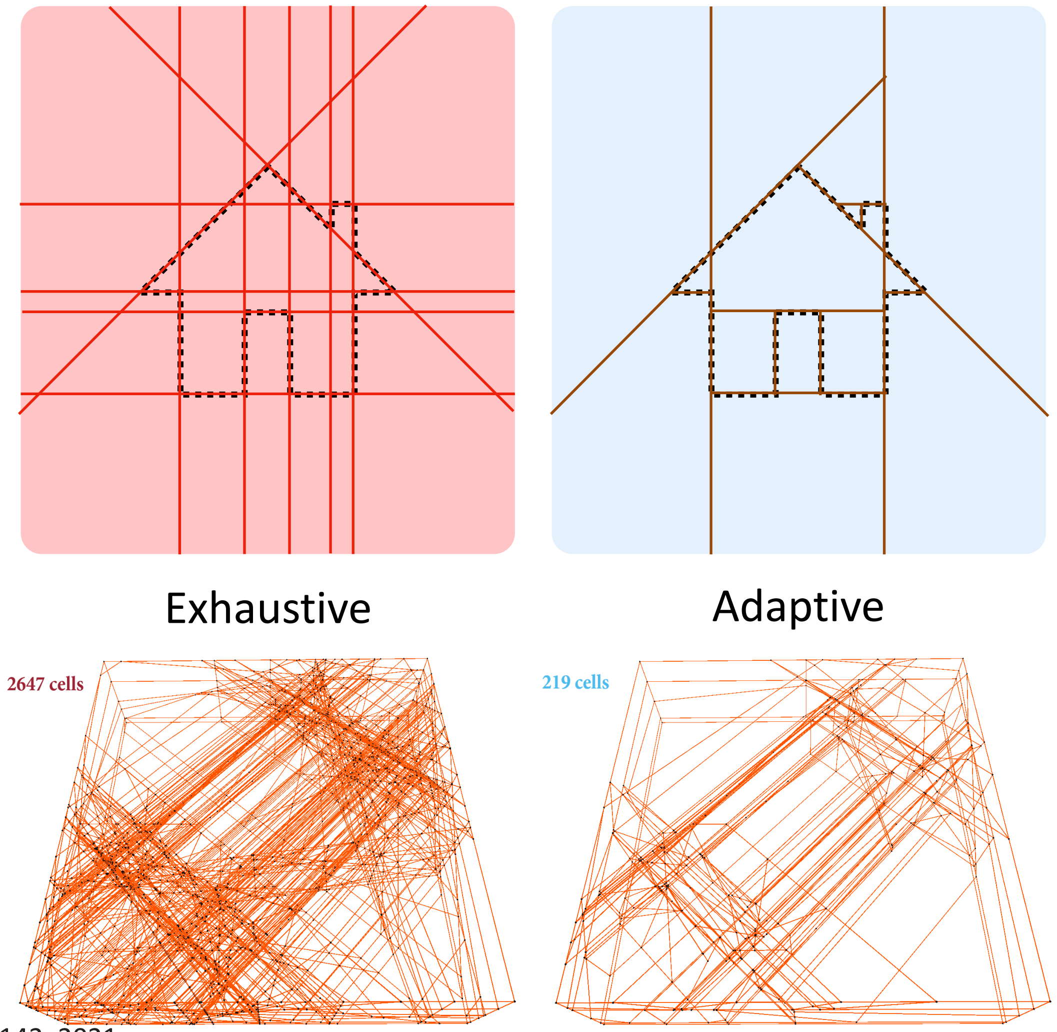
Implicit
Occupancy indication by deep learning

Surface extraction
Surface extraction by graph-cut optimisation

Chen at al. Reconstructing Compact Building Models from Point Clouds Using Deep Implicit Fields. arXiv:2112.13142, 2021

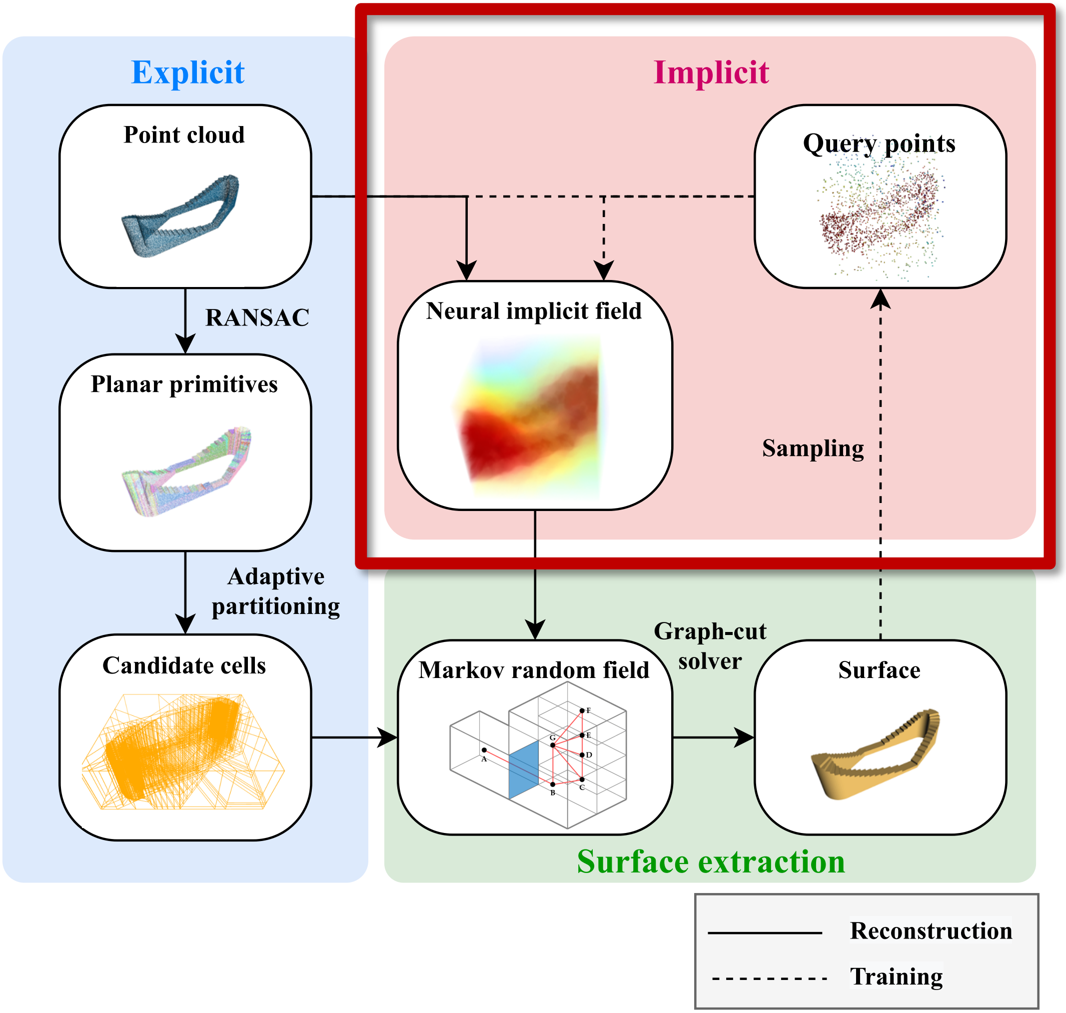
LoD2 from Deep Implicit Fields





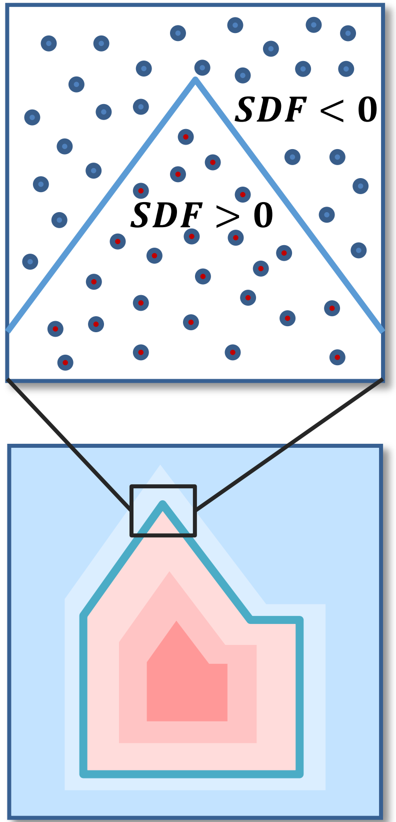
Chen at al. Reconstructing Compact Building Models from Point Clouds Using Deep Implicit Fields. arXiv:2112.13142, 2021

LoD2 from Deep Implicit Fields



Signed distance function $SDF(\mathbf{x}) = s : \mathbf{x} \in \mathbb{R}^3, s \in \mathbb{R}.$

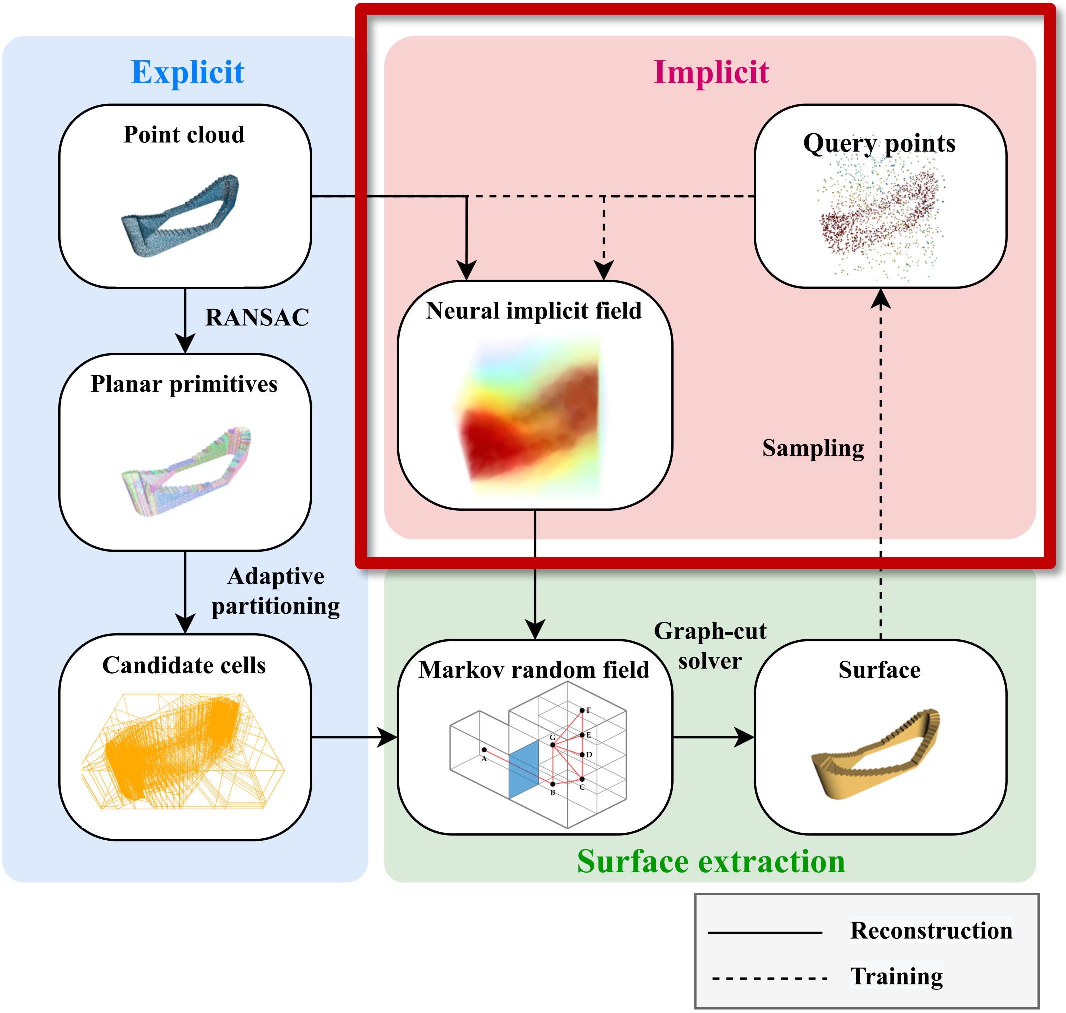
Surface at $SDF(\cdot) = 0$



Method used: *Erler et al. 2020*

Chen at al. Reconstructing Compact Building Models from Point Clouds Using Deep Implicit Fields. arXiv:2112.13142, 2021

LoD2 from Deep Implicit Fields



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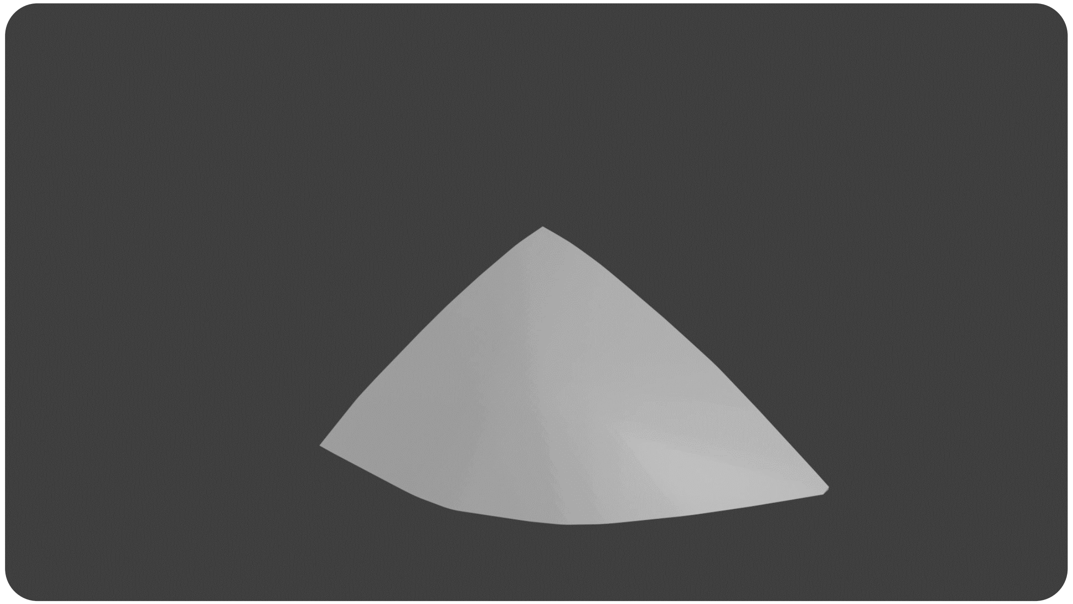
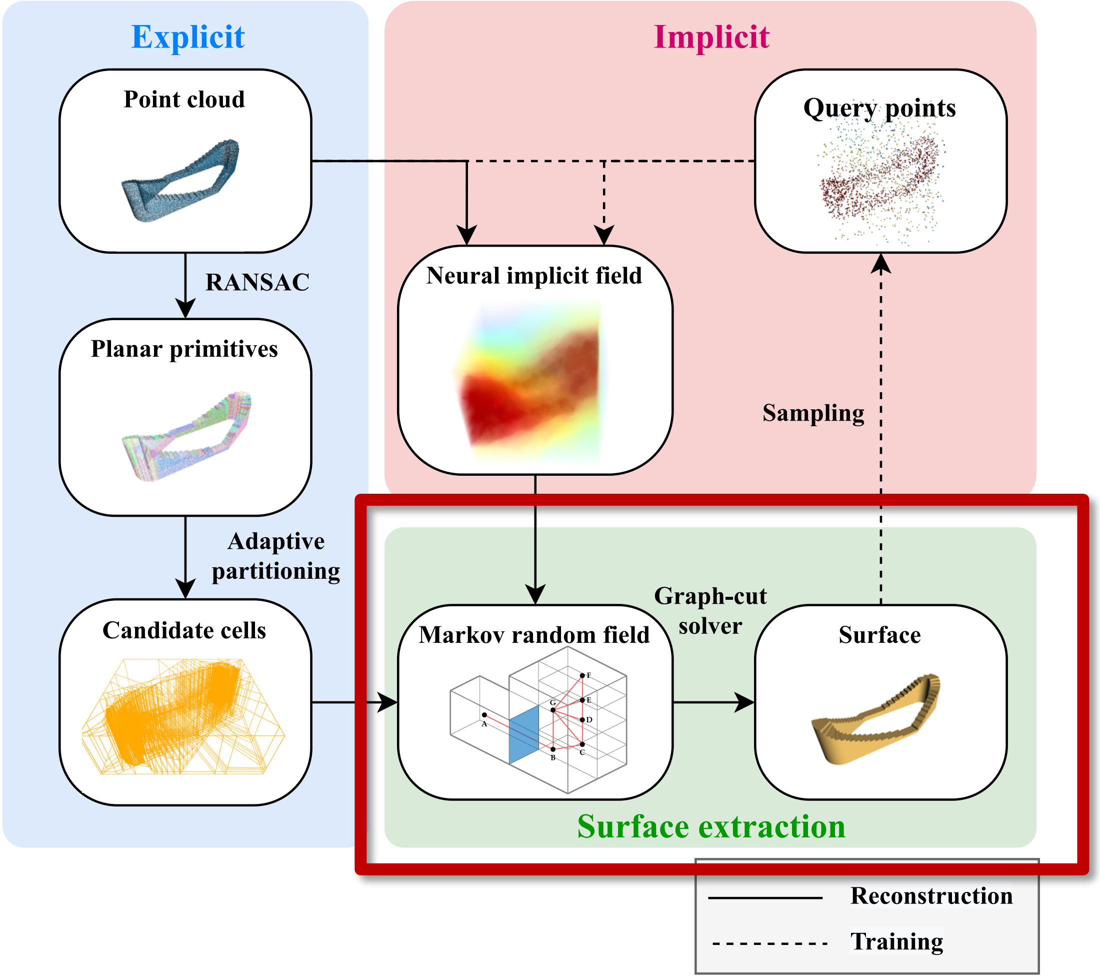


The learned implicit field approaches the building surface with training iterations

Chen at al. Reconstructing Compact Building Models from Point Clouds Using Deep Implicit Fields. arXiv:2112.13142, 2021

LoD2 from Deep Implicit Fields



Markov random field formulation

$$E(x) = D(x) + \lambda V(x) \qquad x_i = \{in, out\}$$

Data term (unary potential)

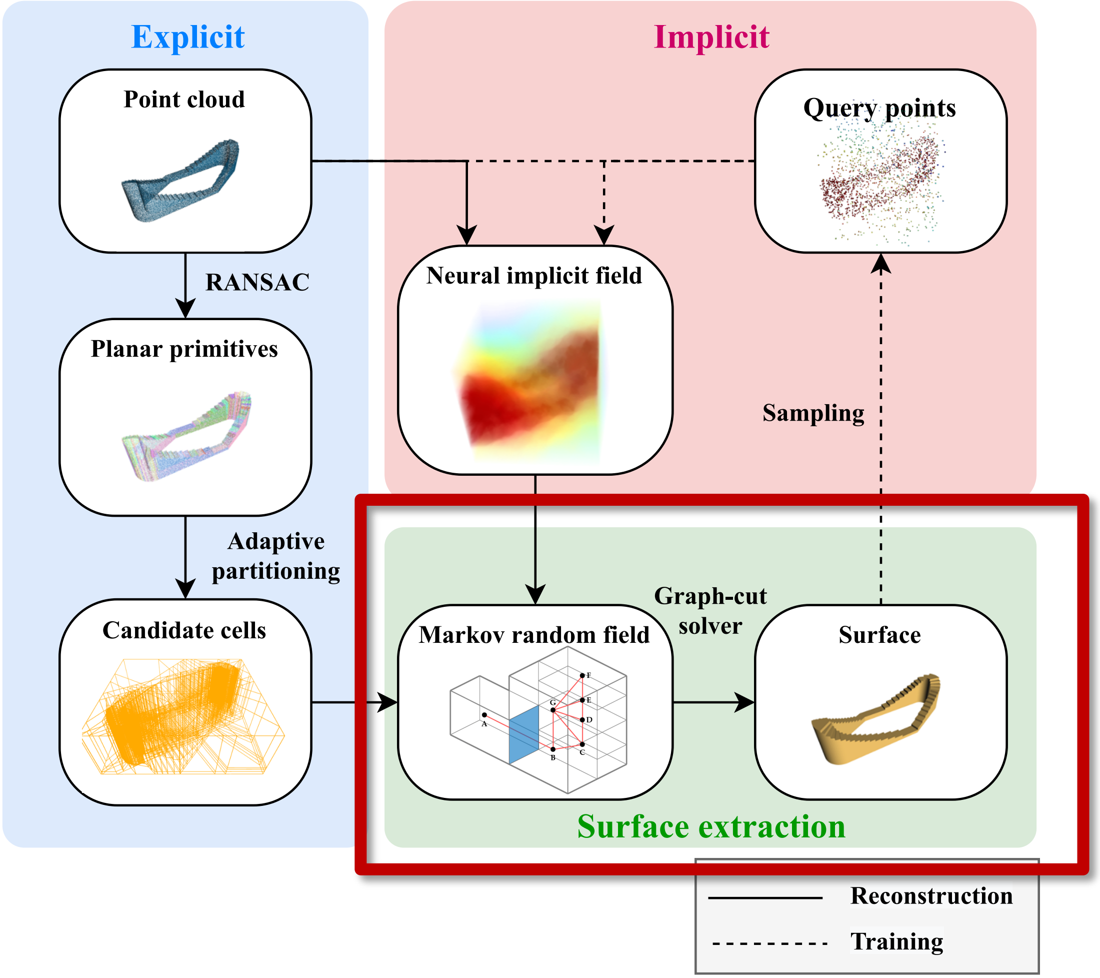
$$D(X) = \frac{1}{|C|} \sum_{i \in C} d_i(C_i, x_i)$$

$$d_i(C_i, x_i) = |probability(C_i) - x_i|$$

Basic idea
- classify all cells into interior and exterior
- outer shell of the interior cells gives surface model

Chen at al. Reconstructing Compact Building Models from Point Clouds Using Deep Implicit Fields. arXiv:2112.13142, 2021

LoD2 from Deep Implicit Fields



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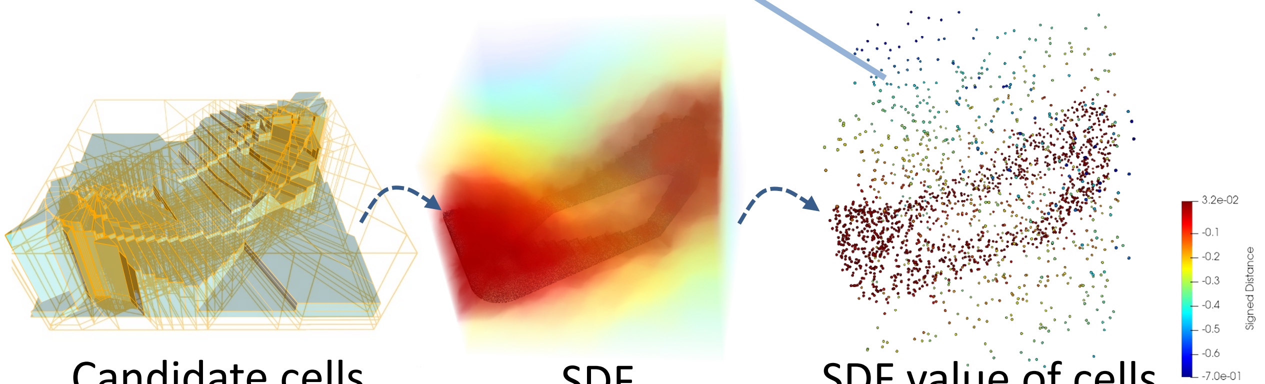

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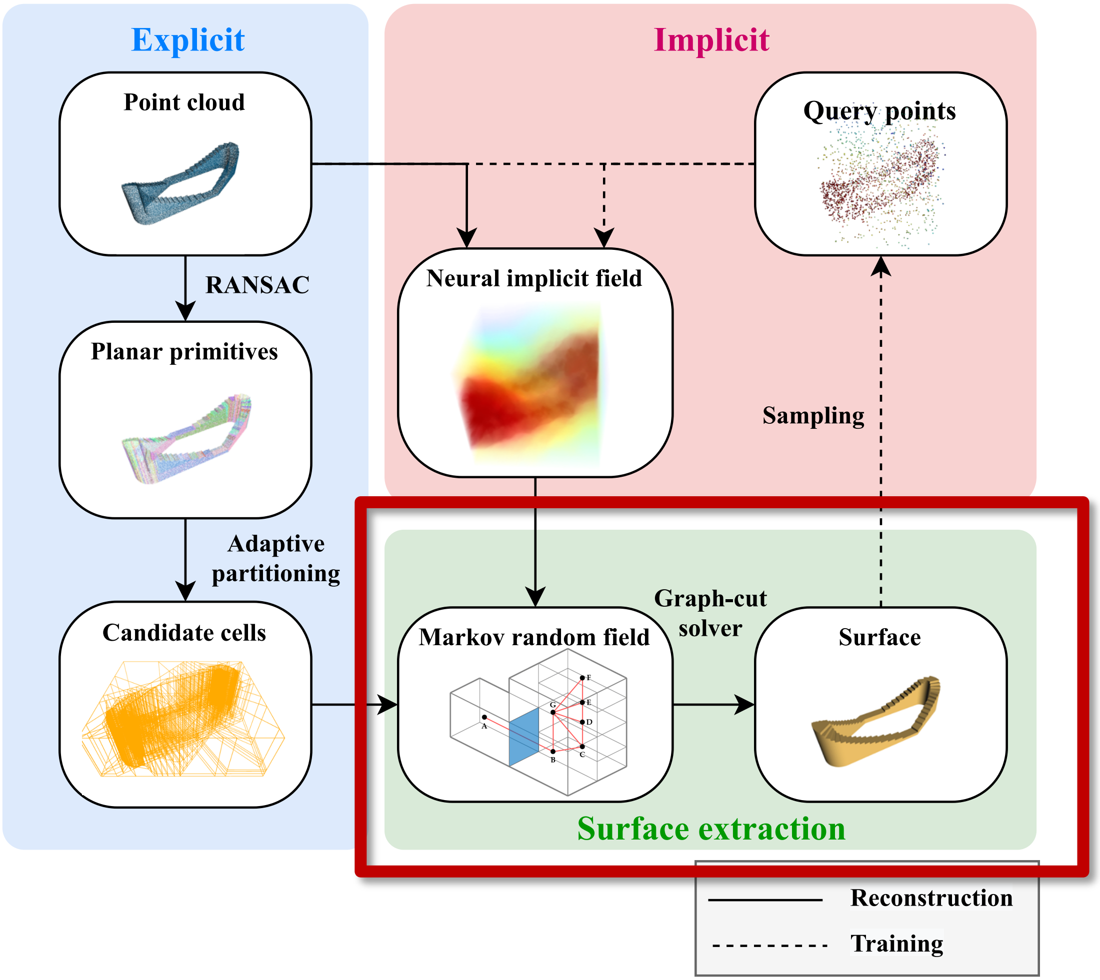
LoD2 from Deep Implicit Fields



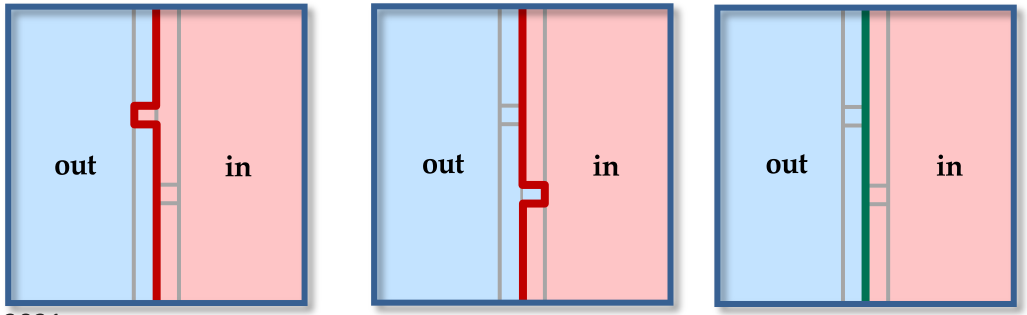
Markov random field formulation

$$E(x) = D(x) + \lambda V(x) \qquad x_i = \{in, out\}$$

Smoothness term (pairwise potential)

$$V(X) = \frac{1}{A} \sum_{\{i,j\} \in C} a_{ij} \cdot 1_{x_i \neq x_j}$$

- $\{i, j\} \in C$ represents adjacent polyhedra
- a_{ij} denotes the shared area



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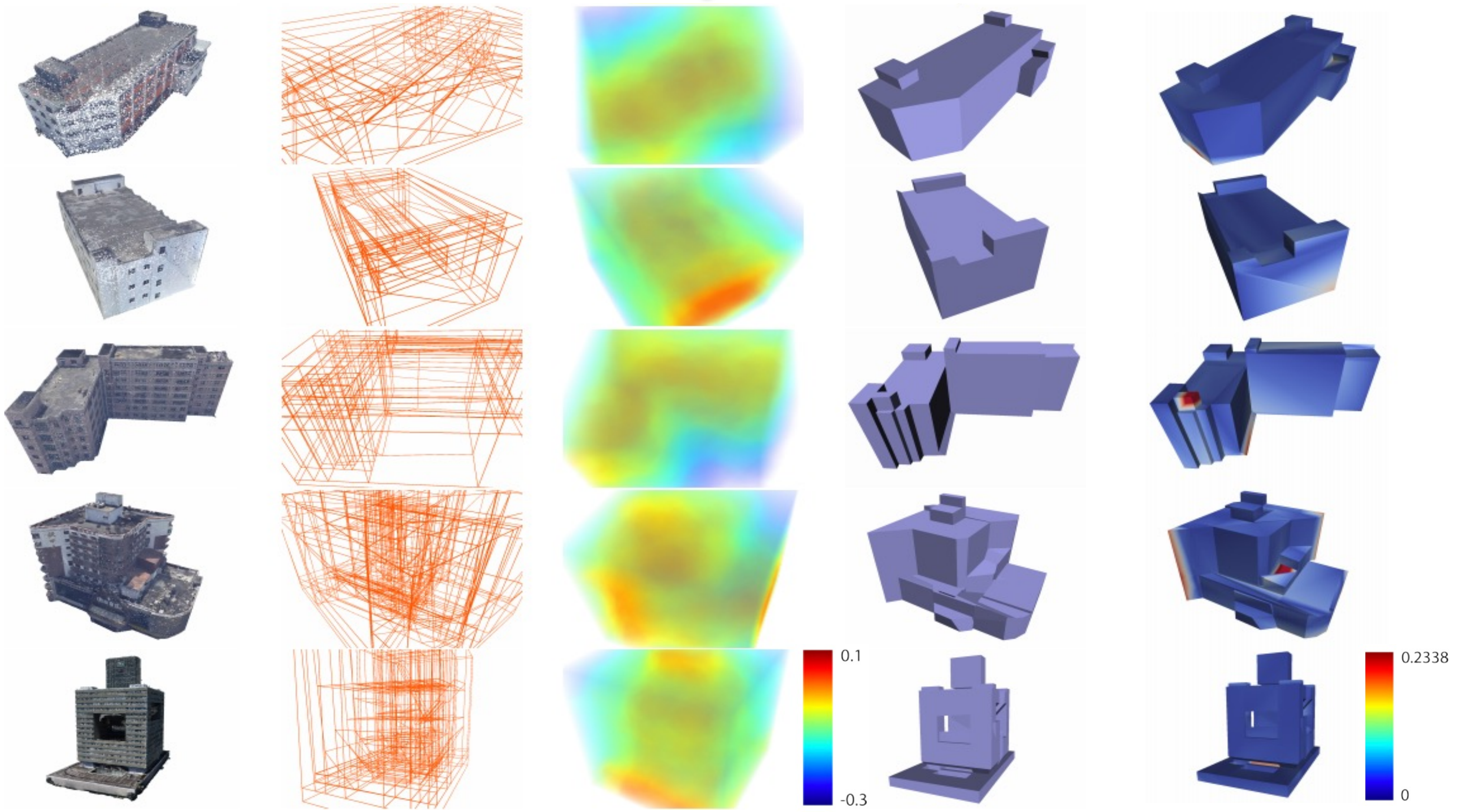
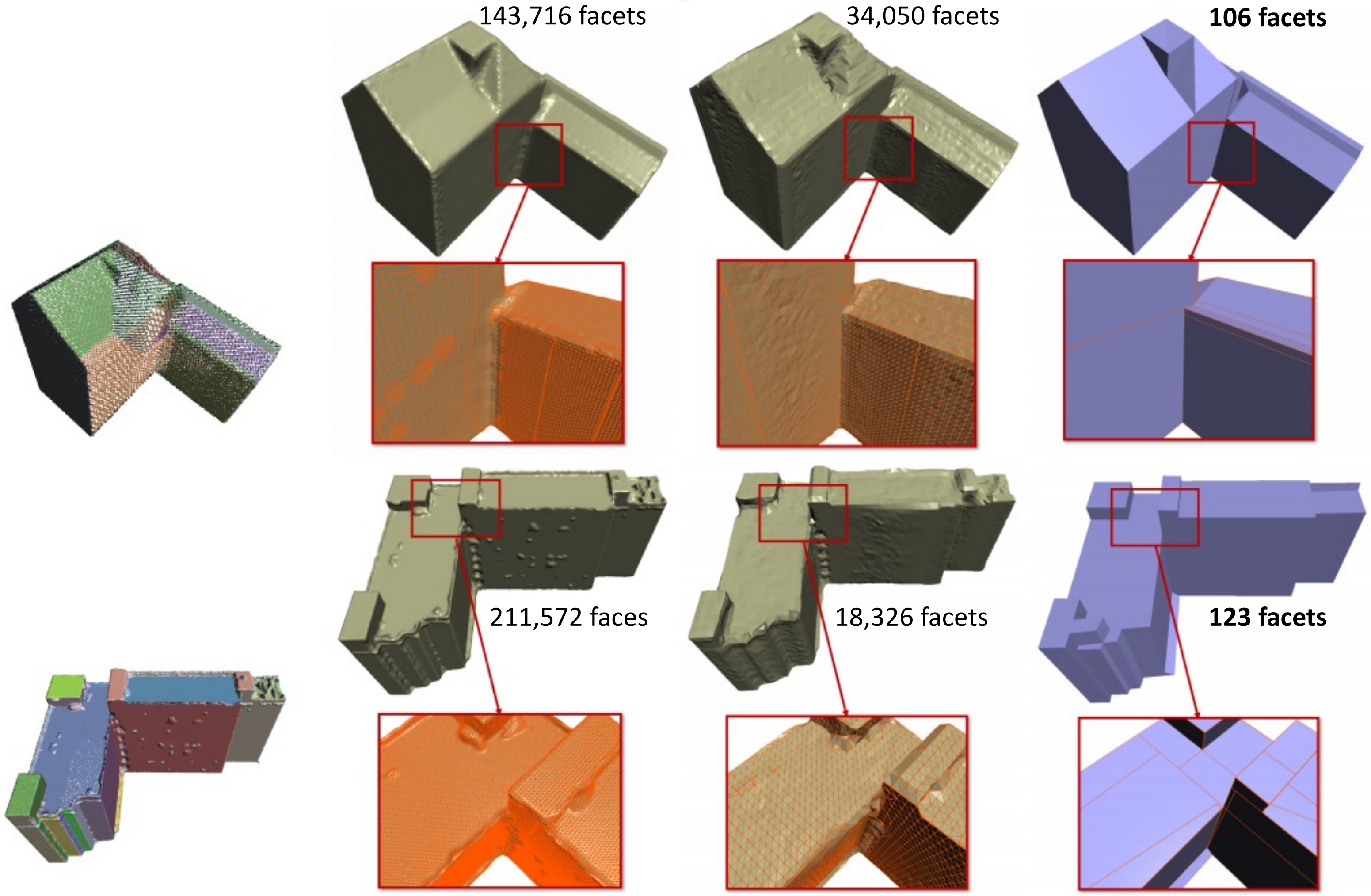
LoD2 from Deep Implicit Fields



Point cloud | Candidate cells (wireframe shown) | SDF | Reconstruction | Error

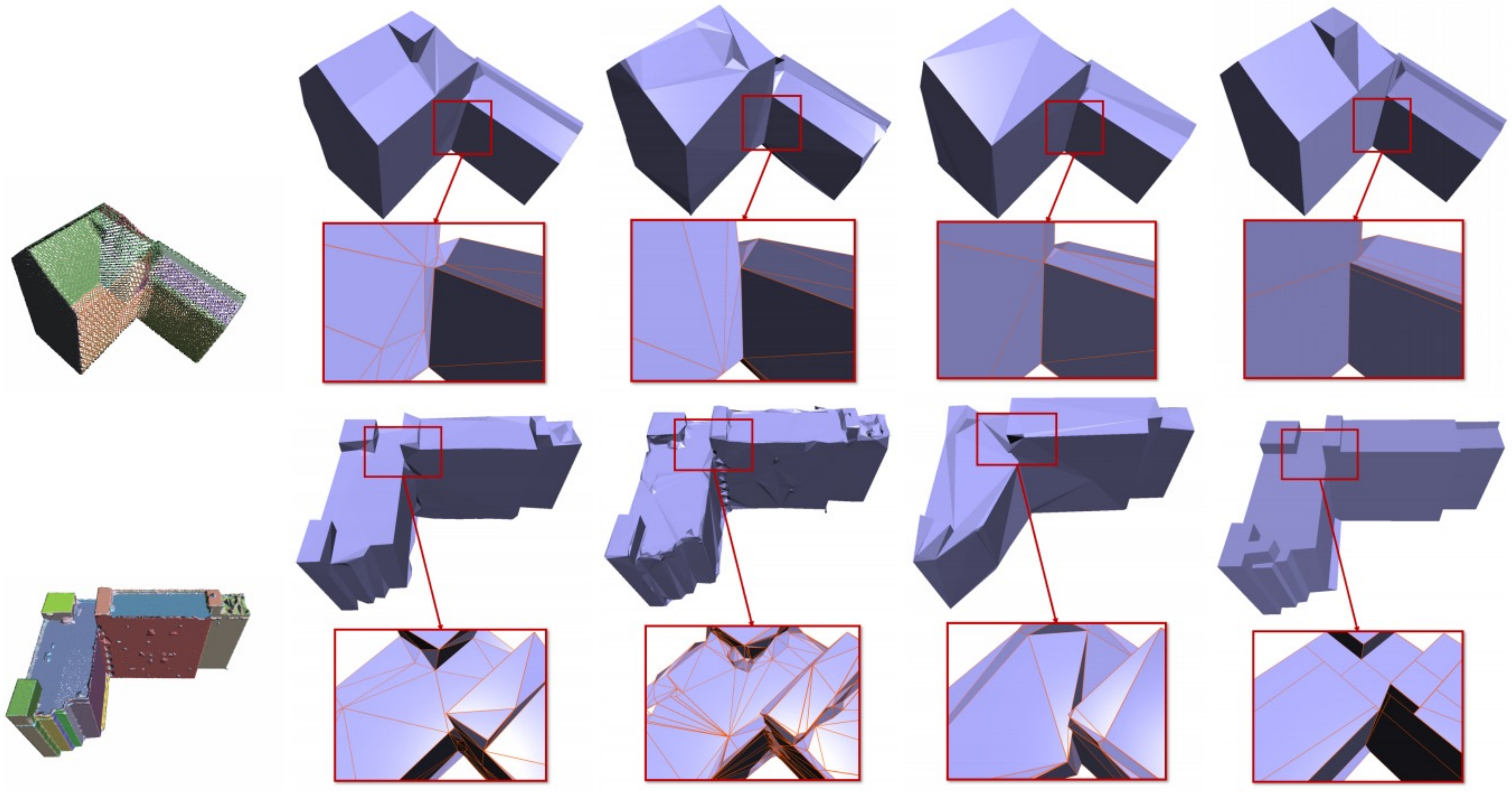
Chen at al. Reconstructing Compact Building Models from Point Clouds Using Deep Implicit Fields. arXiv:2112.13142, 2021

LoD2 from Deep Implicit Fields



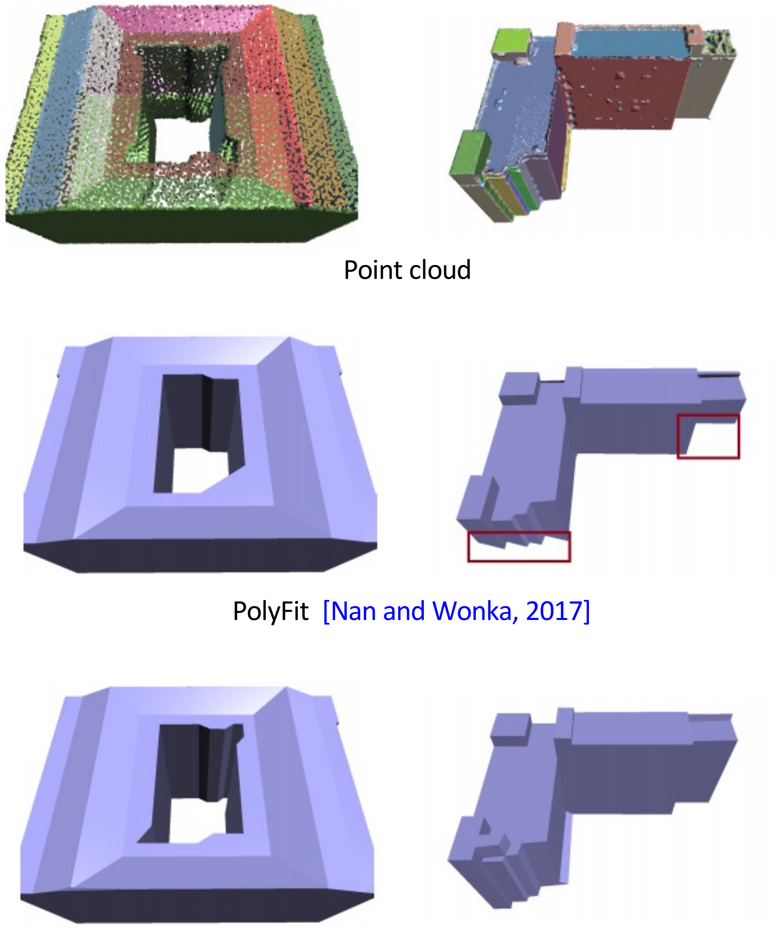
Point cloud [Kazhdan et al., 2006] [Erler et al., 2020] Ours

LoD2 from Deep Implicit Fields



Point cloud | QEM [Garland and Heckbert, 1997] | SAMD [Salinas et al., 2015] | VSA [Cohen-Steiner et al., 2004] | Ours

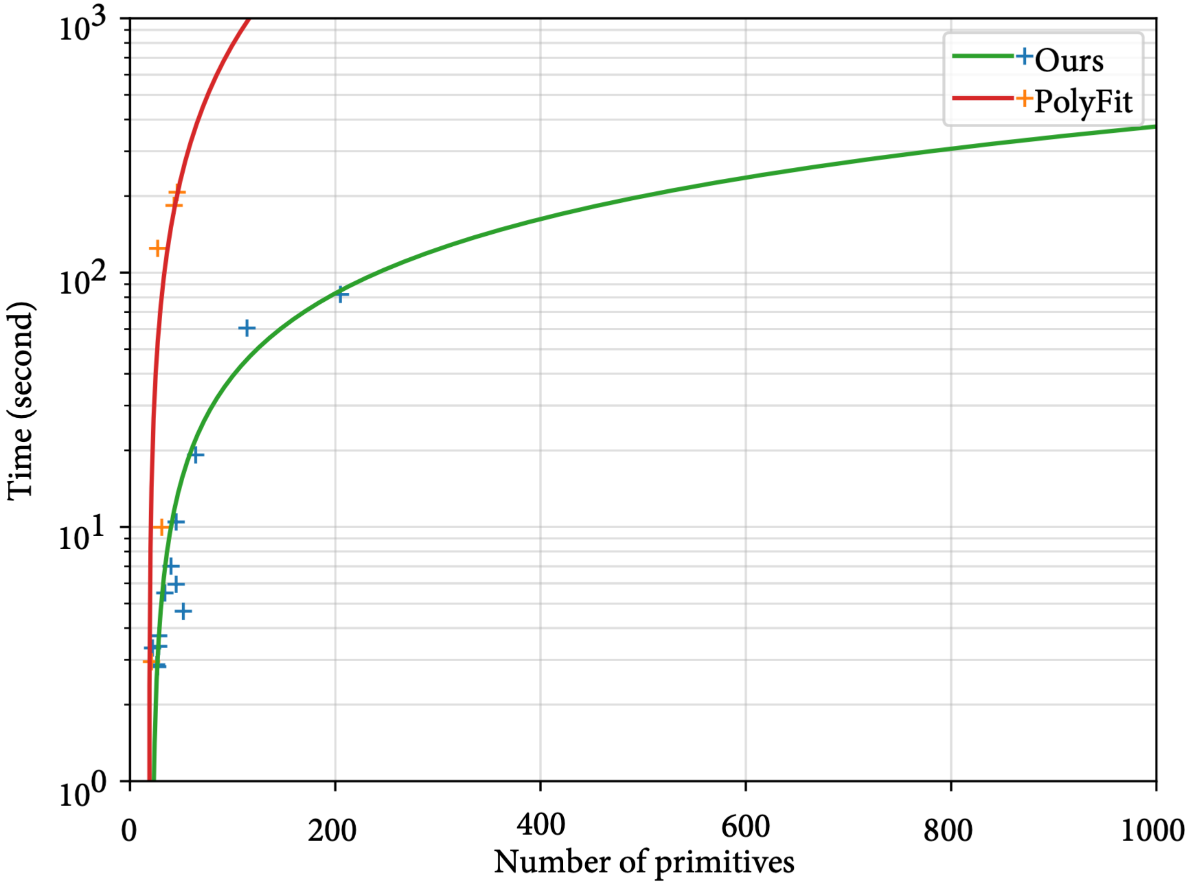
LoD2 from Deep Implicit Fields



Point cloud

PolyFit [Nan and Wonka, 2017]

Ours



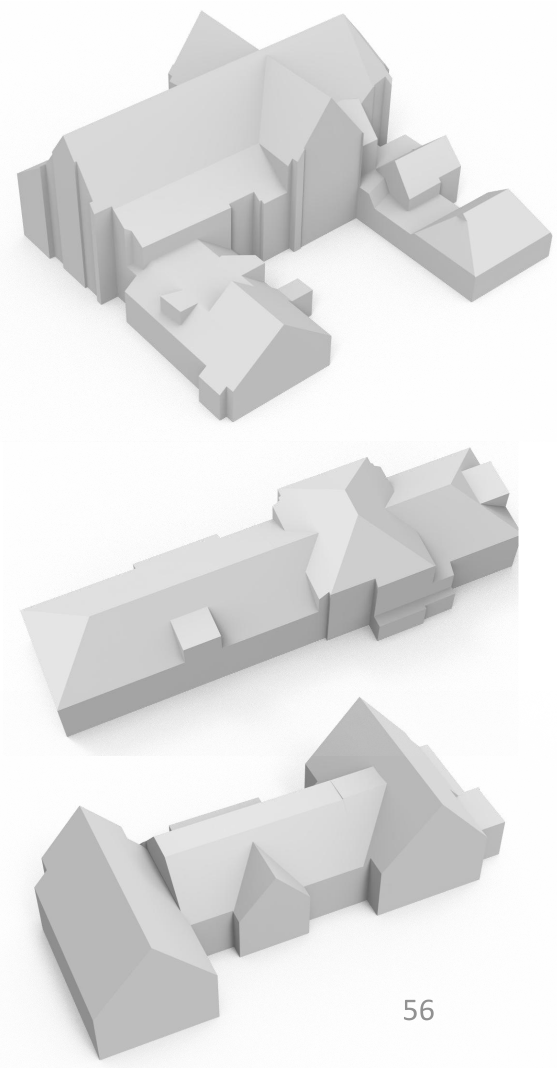
Chen at al. Reconstructing Compact Building Models from Point Clouds Using Deep Implicit Fields. arXiv:2112.13142, 2021

Outline

- PolyFit: polygonal surface reconstruction
- Two extensions of PolyFit
  - LoD2 urban building reconstruction from airborne LiDAR data
  - LoD2 urban building reconstruction based on deep implicit fields
- Opportunities and future work
- Some thoughts about data

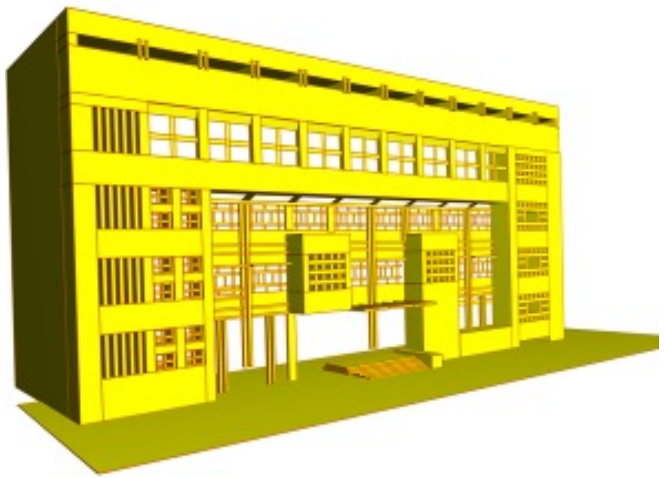
Opportunities and future work

- Large-scale
  - Instance segmentation



Opportunities and future work

- Large-scale
- Finer levels of detail

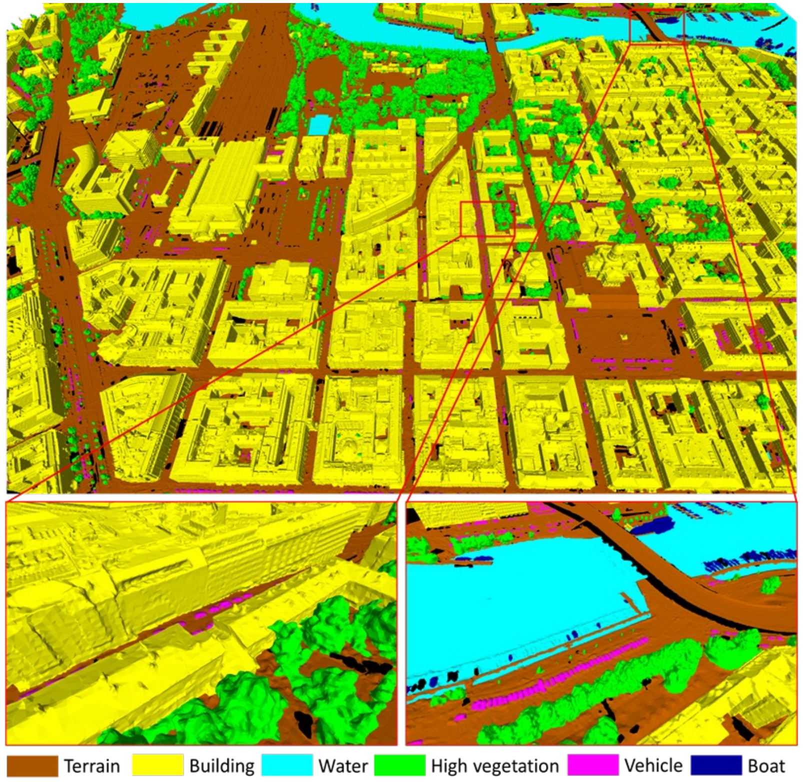


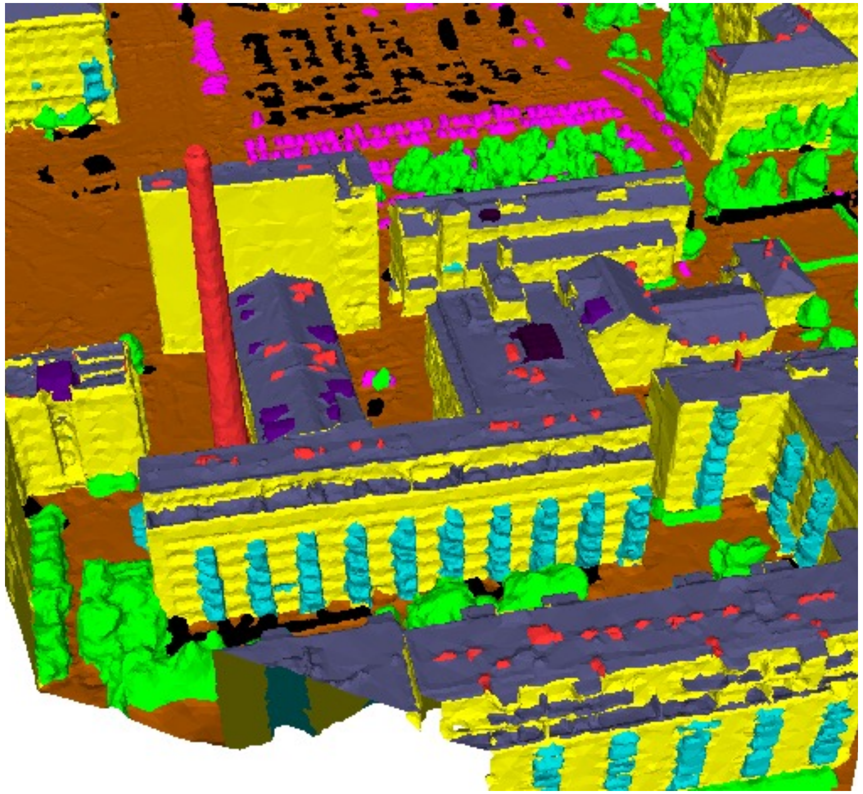
Nan at al. SmartBoxes for Interactive Urban Reconstruction. SIGGRAPH 2010

Nan at al. Template Assembly for Detailed Urban Reconstruction. EUROGRAPHICS 2015

Opportunities and future work

- Large-scale
- Finer levels of detail
  - SUM dataset



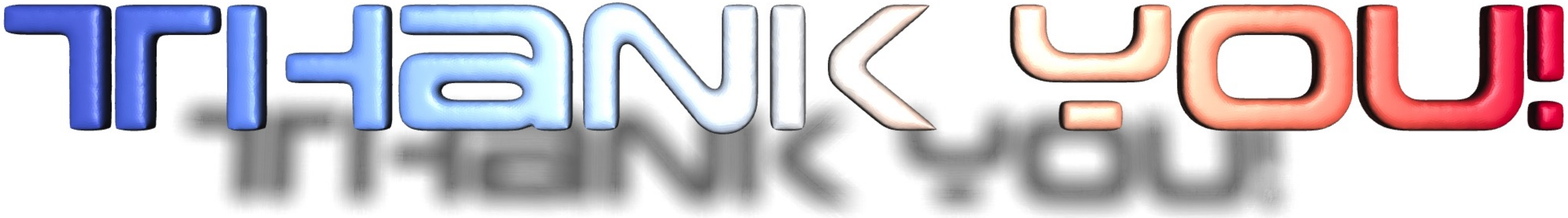


Gao et al. SUM: A Benchmark Dataset of Semantic Urban Meshes . *ISPRS Journal of Photogrammetry and Remote Sensing* 179 (2021) 108-120.

Some thoughts about data

开放, 共享!!!

荷兰(全国)机载LiDAR点云数据下载链接 (左键点击感兴趣区域会出现下载链接，例如AHN4 Puntenwolk (LAZ))：
https://www.arcgis.com/apps/mapviewer/index.html?layers=77da2e9eeea8427aab2ac83b79097b1a



https://3d.bk.tudelft.nl/liangliang/