From geometric landscape to fitness landscape
As-built BIM reconstruction through optimization

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Outline

1. Background & Opportunities
2. The Method
3. Discussion
Section 1

BACKGROUND & OPPORTUNITIES
1.1 As-built modeling

As-built modeling (Volk et al. 2014)

- Increasingly important for AEC/FM†
  - Construction management
  - Facility management
  - Built env. conservation
  - Smart city
  - Self-driving car, etc.

Popular models and technologies

- Point clouds (Photogrammetry, laser scanning)
- Triangle mesh models (3D Maps)
- Volumetric as-built BIMs
  - Also: As-designed, as-planned, as-demolished
1.1 As-built BIM reconstruction

- Manual reconstruction?
  - Accurate, high-quality, & responsible
  - Expensive, tedious, or impractical for frequent update/cities

- Two paradigms of automatic reconstruction
  - (1) Semantic segmentation
    - Step 1: To cut and label data to small patches (objects) (e.g., slicing bridge piers/deck)
    - Step 2: To fit object parameters (e.g., width, height of a wall)
  - (2) Semantic registration
    - Step 1: To annotate standard BIM components E.g., online open BIM resources
    - Step 2: To register into the whole data
1.2 Geometric landscape in semantic registration

- Landscape
  - Land – scape: Appearance of land
  - Nature: Continuous surface
  - Peaks and valleys

- Geometric landscape in 3D data of building scenes
  - Also appearance
  - Nature: Point/surface polygon
    - Discrete, noisy, cluttered
  - Peaks and valleys
    - On building elements

(Landscape (Source: Wikipedia))

Geometric landscapes (non-repetitive and repetitive) in building scenes (Xue et al. 2019b; 2019c)
1.2 Problem: Fitness landscape in optimization

Optimization problem
- Find the best solution (e.g., $\min f(x) = |x|$)

Fitness landscape
- Appearance of $f$
  - Peaks/valleys contain the solutions
    - Where gradient $\nabla f = 0$

Fitness landscape for registering BIM
- Reflecting the geometric landscape
- Many methods are not working
  - Up to 9 degree-of-freedom (DoFs)
  - Continuous, jugged
  - Too expensive to calculate derivatives (V)

Fitness landscapes of registering BIM to 1 point (left) and real 3D point cloud (right)
1.3 Opportunity: Derivative-free optimization

- **Derivative-free optimization (DFO)** algorithms solve without explicit $\nabla$
  - Surrogate methods
    - CMA-ES and its variants are competitive
  - Trust-region methods
    - DIRECT, NEWUOA, etc.
  - Metaheuristics (GA, PSO, VNS, etc.)
  - Hyper-heuristics, data mining
  - … and Monte Carlo
- DFO can bridge the two landscapes
  - Accuracy? Efficiency?

Comparison of algorithms for BBOB-2009 (Black-Box Optimization Benchmarking, higher is better) (Auger et al., 2010) Image courtesy: Inria
Section 2

THE METHOD
2.1 Overview

Semantic registration through optimization

- Two inputs, BIM (pose/relationship) output
- Function: Minimize error (or maximize similarity)
- Variables: 3D transformation
- Subject to: Topological constraints

$$\min f(X) \quad \text{s.t. } C(X) \leq 0$$
2.2 Prototype demo \textit{(Xue et al., 2018; 2019b)}

- PCD/2D photos + BIM objects $\rightarrow$ as-built BIM
  - Automatic
  - Segmentation-free
  - Semantic
  - Accurate
  - Efficient

- COBIMG
  - DFO: CMA-ES

- A quick demo

\textit{(Language: C++, CLR; Data formats: Autodesk Revit, Stanford polygon)}
2.3.1 Case 1: An indoor office scene (Xue et al., 2019b)

\[
\begin{align*}
\min \quad & f(X) = \text{RMSE}(BIM(X), P_{in}) \\
\text{s.t.} \quad & C(X) \leq 0. \\
& f(X) = \text{RMSE}(BIM(X), P_{in}) \\
& \approx \text{RMSE}(P_X, P_{in}) \\
& \approx \text{RMSE}(P'_X, P'_{in}) \\
& = \sqrt{\frac{\sum_{p \in P'_{in}} \text{nn} \text{dist}^2(p, P'_X)}{m'}} \\
& \approx \text{RMSE}(P'_{in}, P'_X) \\
& = \sqrt{\frac{\sum_{p \in P'_X} \text{nn} \text{dist}^2(p, P'_{in})}{\|P'_X\|}} \\
\end{align*}
\]

(Language: C++, CLR; Data formats: Autodesk Revit, Stanford polygon)
## 2.3.1 Case 1

### Indoor modeling
- Accurate: 3.87 cm, 100% recall
- Fast: 6.44 s
- Rich semantics: Product, assembly, etc.

<table>
<thead>
<tr>
<th>Modeler No.</th>
<th>Experience</th>
<th>Correctness (out of 8)</th>
<th>RMSE (cm)</th>
<th>Time cost (s)</th>
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</thead>
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<tr>
<td>1</td>
<td>Expert (3 years)</td>
<td>8</td>
<td>3.79</td>
<td>363.9</td>
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<tr>
<td>2</td>
<td>Average (1 year)</td>
<td>8</td>
<td>3.90</td>
<td>335.4</td>
</tr>
<tr>
<td>3</td>
<td>Beginner</td>
<td>8</td>
<td>4.22</td>
<td>691.1</td>
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<tr>
<td>COBIMG-Revit</td>
<td></td>
<td>8</td>
<td>3.87</td>
<td>6.44</td>
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<tr>
<td>COBIMG-Revit + annotation</td>
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<td>8</td>
<td>3.87</td>
<td>~ 246.0</td>
</tr>
</tbody>
</table>
Case 2: A lecture hall (Xue et al. 2019c)

- RMSE= 8.97cm, time = 1,155s
- 99% precision, 98% recall
Case 3: Architectural symmetry (Xue et al. 2019a)

(i) The optimization viewport (descending of the objective function by CMA-ES)
(ii) The parameter space viewport (walking on $L(\rho, \phi)$)
(iii) The Point cloud viewport (testing a series of symmetries)

<table>
<thead>
<tr>
<th>Id</th>
<th>Thumbnail of input point cloud</th>
<th>Normal(^a) Segmented</th>
<th>Symmetric parts(^b)</th>
<th>PCR (%)</th>
<th>Time (s)</th>
<th>Intrinsic(^c) asymmetry</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>![Image 1]</td>
<td>![Image 2]</td>
<td>![Image 3]</td>
<td>96.29</td>
<td>0.81</td>
<td>As circled</td>
</tr>
<tr>
<td>2</td>
<td>![Image 4]</td>
<td>![Image 5]</td>
<td>![Image 6]</td>
<td>85.22</td>
<td>1.79</td>
<td>As circled</td>
</tr>
<tr>
<td>3</td>
<td>![Image 7]</td>
<td>![Image 8]</td>
<td>![Image 9]</td>
<td>95.99</td>
<td>3.68</td>
<td>As circled</td>
</tr>
<tr>
<td>4</td>
<td>![Image 10]</td>
<td>![Image 11]</td>
<td>![Image 12]</td>
<td>95.44</td>
<td>2.77</td>
<td>As circled</td>
</tr>
<tr>
<td>5</td>
<td>![Image 13]</td>
<td>![Image 14]</td>
<td>![Image 15]</td>
<td>97.11</td>
<td>2.21</td>
<td>As circled</td>
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<td>6</td>
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<td>![Image 18]</td>
<td>96.96</td>
<td>0.60</td>
<td>As circled</td>
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<td>7</td>
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<td>![Image 21]</td>
<td>97.51</td>
<td>3.05</td>
<td>As circled</td>
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Section 3

DISCUSSION
3.1 Discussion

 Semantic registration for as-built BIM
  - Converts geometric landscape to fitness landscape
  - Reuses online open BIM resources
  - Finds optima (objects in as-built BIM) using DFO
    - Automatic
    - Segmentation-free
    - Accurate
    - Efficient
    - Good for complex-shaped objects

 Drawbacks
  - Require annotations beforehand
  - Killer (downstream) applications
References

- Xue, F., Lu, W., Chen, K., & Webster, C. J. (2019c). BIM reconstruction from 3D point clouds: A semantic registration approach based on multimodal optimization and architectural design knowledge, Advanced Engineering Informatics, (under revision)
Thank You!

謝謝！