Evolutionary computation with applications in 3D urban reconstruction
进化计算在城市三维重建中的应用

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Outline

1 Evolutionary computation

2 Optimization-driven 3D reconstruction

3 Discussion

0.1 HKUrbanLab, HKU

iLab

- Faculty of Architecture, HKU 建筑学院
  - 3 Departments: Arch., REC, DUPAD
  - 2 Divisions: Landscape Arch., Arch. Conservation
- HKURBANlab 实验室集群
  - Newly branded research arm of FoA
  - 1 Academician (CAS), 12 full professors
  - 14 labs on
    - Urban planning; Property rights;
    - Chinese architecture; Rural;
    - Health; Sustainability;
    - Fabrication and materials; Conservation;
    - iLab (data and information); Virtual Reality; ...

HKURBAN lab

香港大學 建築學院

www.arch.hku.hk

0.1 iLab: The urban big data hub

- iLab 实验室
  - Urban big data hub
  - multi-dimensional and multi-disciplinary *urban big data* collection, storage, analysis, and presentation to inform decision-making in urban development
  - Focusing on information technology (IT)
    - *Geographical Information Systems* (GIS)
    - *Global Positioning Systems* (GPS)
    - *Urban Remote Sensing* (URS)
    - *Building Information Model* (BIM)
    - *Internet of Things* (IoT)
    - *virtual design and construction* (VDC)
    - *integrated project delivery* (IPD)

iLabHKU

fac.arch.hku.hk/iLab

0.1 iLab

iLab

- Director
  - Prof. Wilson Lu
- Members
  - 1 Assistant Professor, 1 Postdoc Fellow
  - 3 Research Assistants, 6 PhD students
- Themes 方向
  - Urban big data / urban computing
    - BIM, GIS, Digital Twin, Text mining, IoT, ...
  - Construction waste
    - Metrics, Behavioral analysis, policy
  - International construction
    - Corporate social responsibility

Lunch-time gathering

0.2 About myself

- A mixed background 背景
  - BEng in Automation, CAUC — 2004
  - MSc in Computer Science, CAUC — 2007
    - Advisor: Prof. W Fan
  - PhD in System Engineering, HKPU — 2012
  - PDF/RAP/AP in Construction IT — 2016
- Research interests 方向
  - Urban sensing and computing
  - Automation in construction
  - Applied operations research
  - Machine learning and data visualization

- Engineering
  - ISE, CEM, EIE
- Computer Science
  - AI, DFO, ML
- Economics
  - SCM

0.2 My research projects

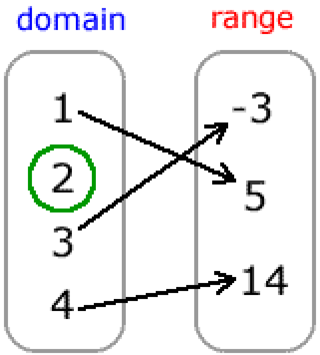
- On-going 在研
  - PI: HK RGC (17201717, 17200218), HKU-Tsinghua SPF (20300083), HKU (201811159177)
  - Co-PI: Key R&D Guangdong (2019B010151001), HKU PTF (102009741)
  - Co-I: NSFC (71671156), NSSFC (17ZDA062), HK SPPR (S2018.A8.010.18S), HK PPR (2018.A8.078.18D)
- Completed 完成
  - PI: HKU (201702159013, 201711159016)
  - Co-I: NSFC (60472123)
- Job vacancy – Research Assistant (2~3 openings)
  - $17,000/month, Transferable to PhD applicant (vision, performance)
  - New updates on my web page (QR code)

Section 1

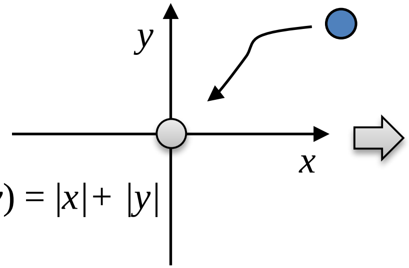
EVOLUTIONARY COMPUTATION

1.1 Fundamentals

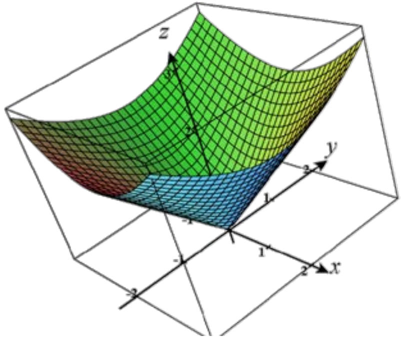
- **Function**
  - A mapping *f* from a domain set to a range set



- **Optimization problem**
  - the selection of a *best* element (with regard to some criteria) from *some* set of available alternatives
    - Optimality ← Objective function
    - “Best value” in range $\textbf{min}\ f : \mathbb{R}^n \longmapsto \mathbb{R}$
    - “Best element” in domain $\textbf{arg min}\ f$
- **Fitness landscape**
  - Appearance of *f*
  - Peaks/valleys contain the solutions
    - Extremum / extrema



min $f(x,y) = |x| + |y|$

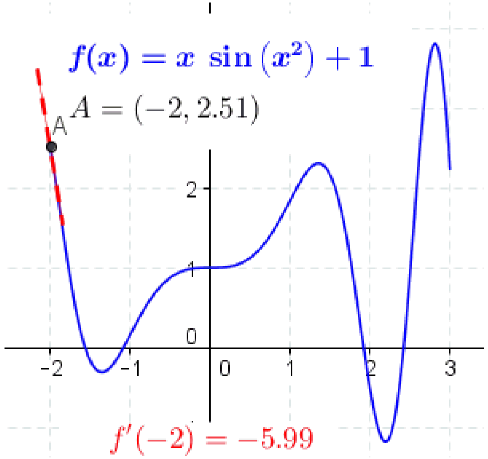


1.1 Fundamentals

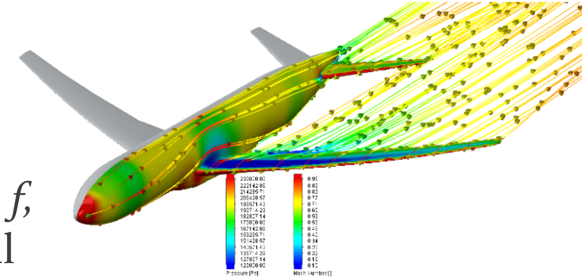
- Optimality guaranteed methods
  - Linear programming
    - Linear super plane of fitness landscape
  - Gradient-based
    - Stationary points, where the first derivative is zero
  - Brach-and-bound/cut
  - Exhaustive
- Non-guaranteed methods
  - Monte Carlo
  - Quasi-gradient / Surrogate
  - Heuristics (Fixed rules)
  - Evolutionary / metaheuristics (rules of rules)

Monte Carlo, Quasi-gradient / Surrogate: Expensive f

Heuristics, Evolutionary / metaheuristics: Inexpensive f, escape "local optima"

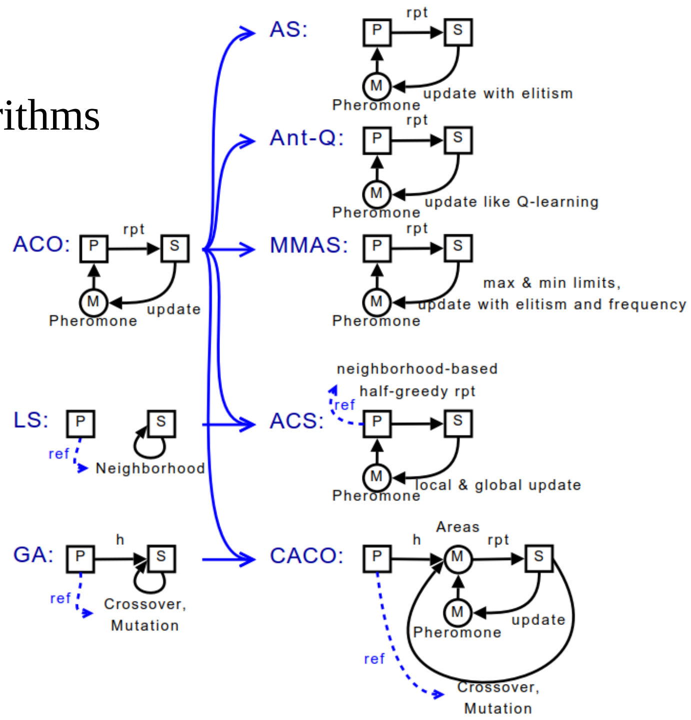


First derivative and stationary points

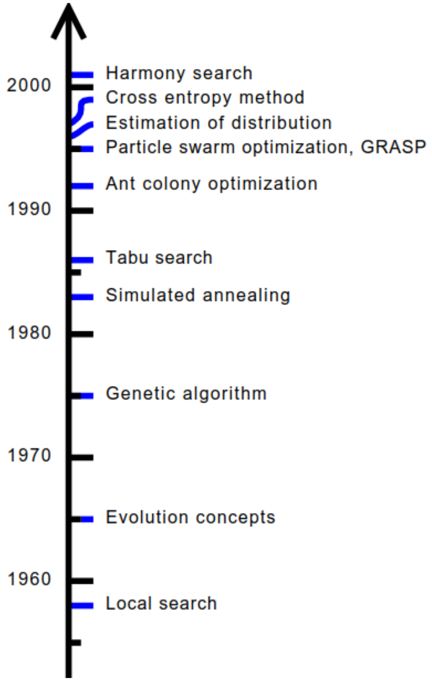

Aerodynamics simulation
Picture source: mentor.com

1.2 Evolutionary computation

- Evolutionary computation (EC)
  - A.k.a. metaheuristics
  - A set of optimization algorithms
    - Iteration, population
  - Often a meta-model “M”
- A long History
  - From bio-inspiration
  - To meta-model
  - With many variants
    - see AC



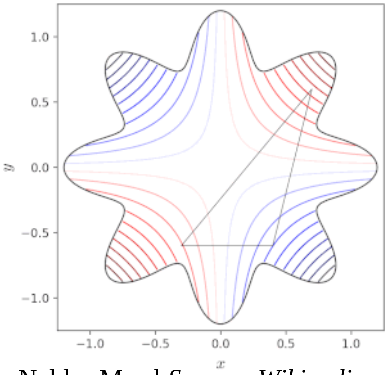
Derivations of AC (Xue 2012)



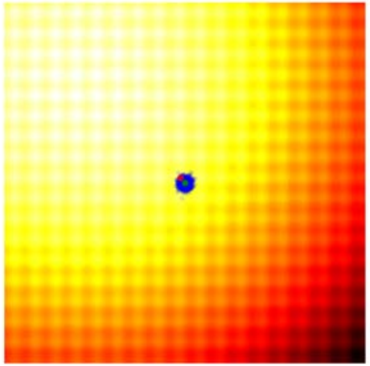
Timeline of early EC (Xue 2012)

1.2 Evolutionary computation (cont.)

- Some recent ones with quasi-gradient meta-model
  - For expensive *f*
  - Escaping local optima
  - Approximately a.k.a. derivative-free optimization (DFO)
- Examples
  - CMA: Covariance Matrix Adaptation
    - CMA-ES; Variants of CMA-ES
    - CMA-VNS (Xue & Shen, 2017)
  - IDEA: Iterated Density Estimation EA
  - Nelder—Mead (downhill simplex)
  - NEWUOA: New Unconstrained Optimization w. quadratic Approxir
  - DIRECT: DIviding RECTangles



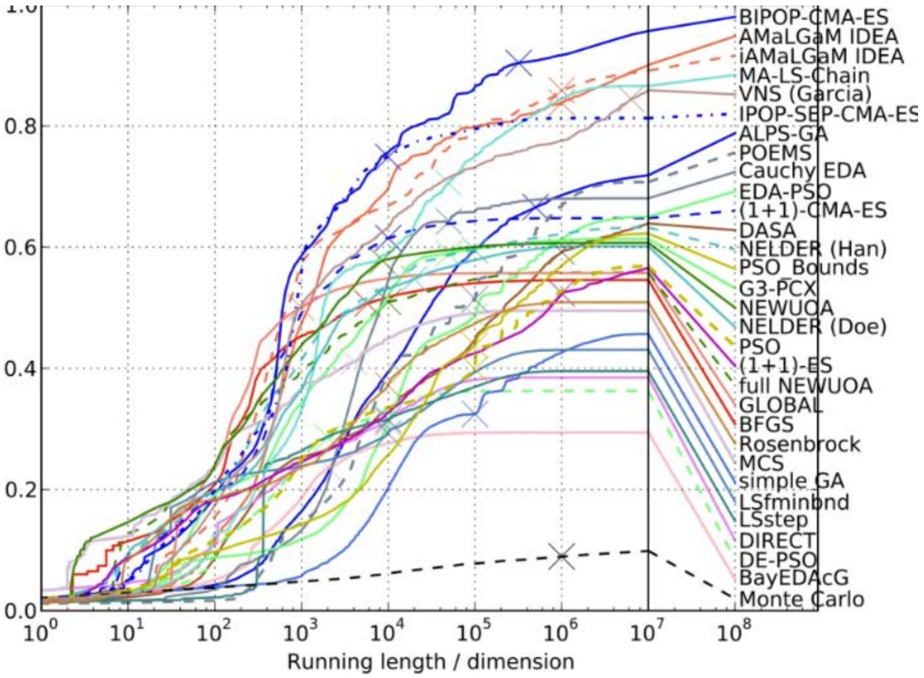
Nelder-Mead *Source: Wikipedia.org*



CMA-ES *Source: otoro.net*

1.3 Benchmark performance

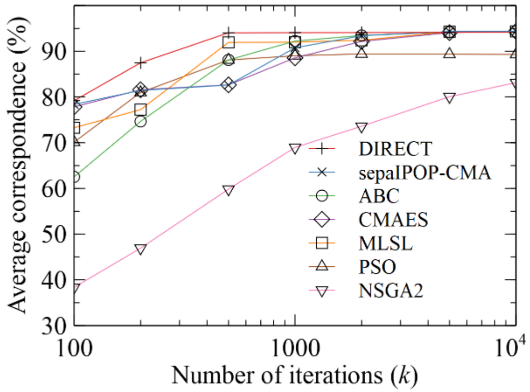
- *Black-Box Optimization Benchmark* solving without explicit ∇
  - Surrogate methods
    - CMA-ES and its variants are competitive
  - Trust-region methods
    - DIRECT, NEWUOA, etc.
  - Metaheuristics (GA, PSO, VNS, *etc.*)
  - Hyper-heuristics, data mining
  - … and Monte Carlo

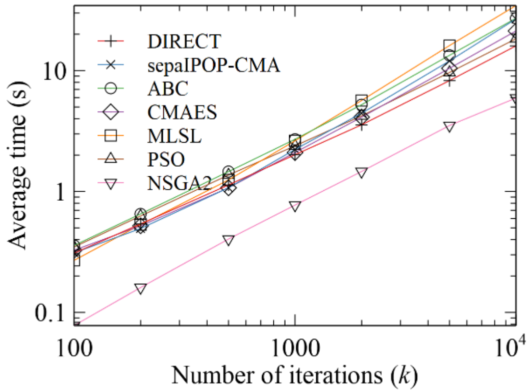


Comparison of algorithms for BBOB-2009 (Black-Box Optimization Benchmarking, higher is better) (Auger et al., 2010) *Image courtesy: Inria*

1.3 Benchmarking performance (cont.)

- Symmetry detection in 3D point clouds (Xue et al. 2019a)
  - Among 7 algorithms
    - All with default parameters
  - DIRECT was the best
  - NSGA2 was the worst
- So, overall, we say
  - 'Quasi-derivative + evolutionary' > Quasi-derivative > evolutionary
  - Due to the characteristics of real world problems



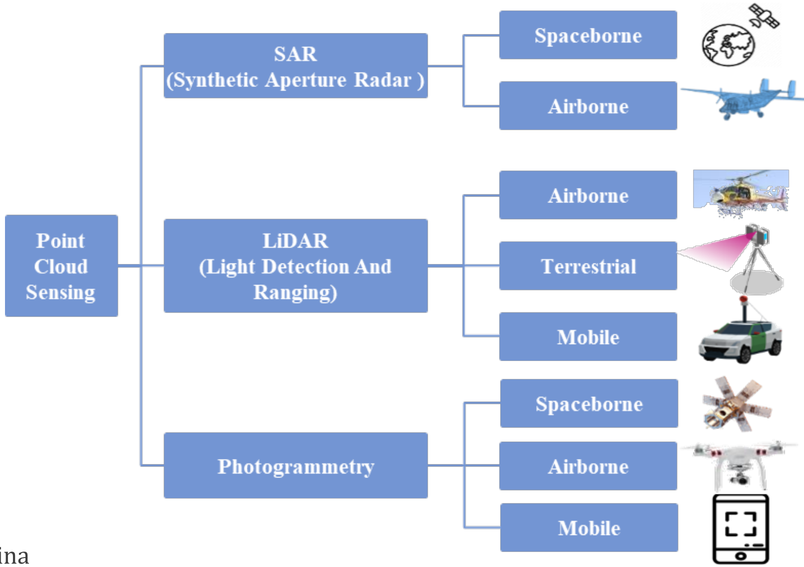


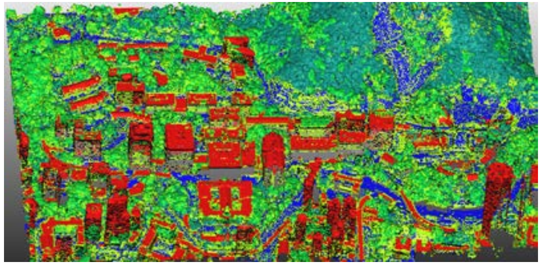
Section 2

OPTIMIZATION-DRIVEN 3D RECONSTRUCTION

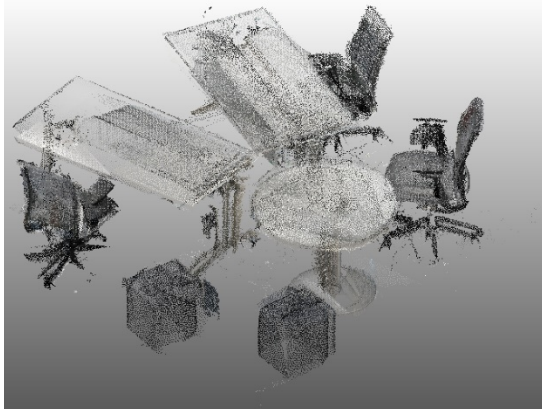
2.1 3D urban reconstruction

- 3D Reconstruction
  - Capturing the shape and appearance of real objects to cyber space
- Abundant 2D/3D urban data from sensors
  - Underground
  - Ground
  - Air
  - Satellite
- Needs
  - Smart city
  - HD 3D map





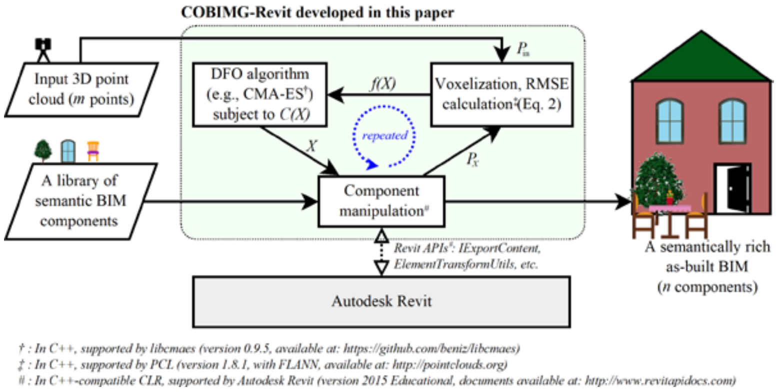
2.2 An indoor case (Xue et al. 2019b)

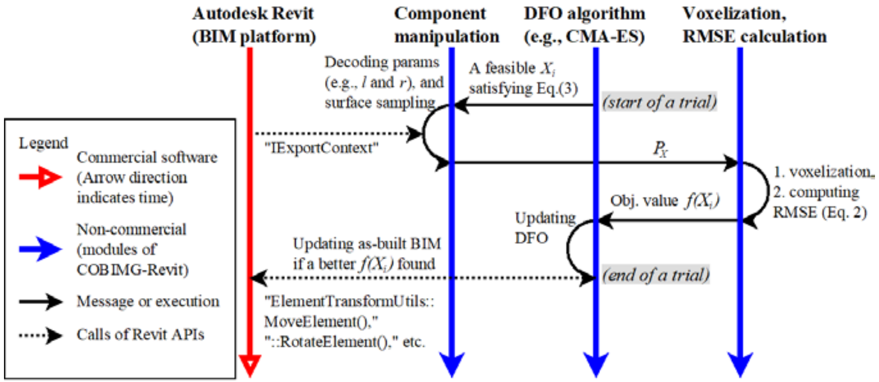


- Input: 3D point cloud
- Traditional methods
  - Non-semantic: Photogrammetry, 3D mesh
  - Semantic: Segment → features → class, parameters
- Modeling *f* for EC
  - Available 3D components from manufacturer/WWW
  - Best model = best fitting
    - Fitting parameters: 3D location (t_z, t_z, t_z), 3D rotation (r_z)
    - $x = (t_z, t_z, t_z, r_z)$, DoF(x) = 4
  - f = RMSE(*model*(x), *input*)
    - **min** f
    - **s.t.** x in Boundary, $C(x) \leq 0$

2.2.2 The overall flow

- Two inputs
- One output
- Four modules
  - Autodesk Revit
  - Component op. (Revit plugin) / C++ CLR
  - DFO algorithm (CMA-ES) / C++11
  - *f* evaluation / C++11
  - (See the message sequencing chart)

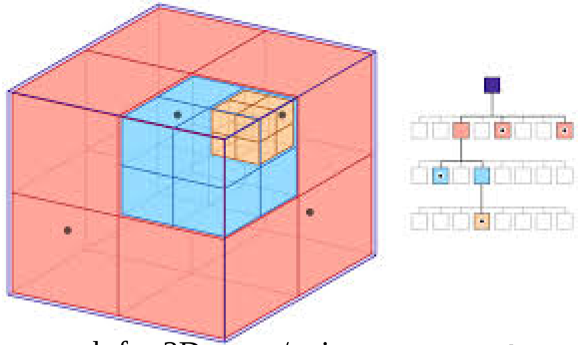




2.2.3 *f* evaluation

- *f* is still too expensive
  - Computing *m* points against thousands of triangles
- An effective approximation
  - Component point cloud dense sampling (pre-iteration
  - Input cloud down sampling — $O(m \log m)$**
  - Iteration
    - Transform component with *x* — $O(n)$
    - Octree voxel down sampling — $O(n \log n)$**
    - *nndist* for n' points — $O(n' \log m')$
    - Compute *f* — $O(n')$
    - Meta-model Evolution

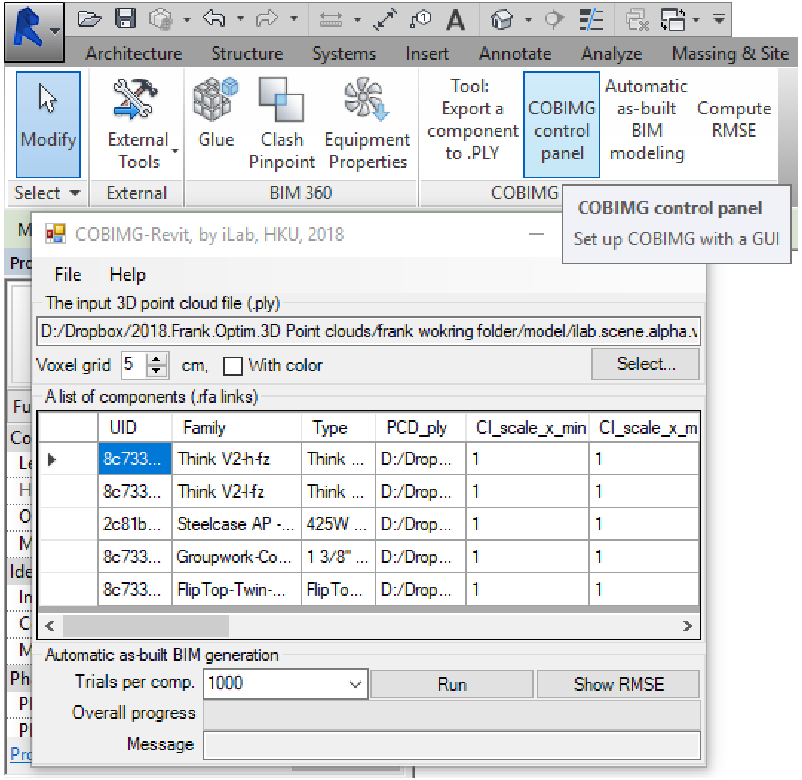
$$
\begin{aligned}
f(X) &= RMSE(BIM(X), P_{\text{in}}) \\
&\approx RMSE(P_X, P_{\text{in}}) \\
&\approx RMSE(P'_X, P'_{\text{in}}) \\
&= \sqrt{\textstyle\sum_{p \in P'_{\text{in}}} nndist^2(p, P'_X)/m'} \\
&\approx RMSE(P'_{\text{in}}, P'_X) \\
&= \sqrt{\textstyle\sum_{p \in P'_X} nndist^2(p, P'_{\text{in}})/\|P'_X\|}
\end{aligned}
$$

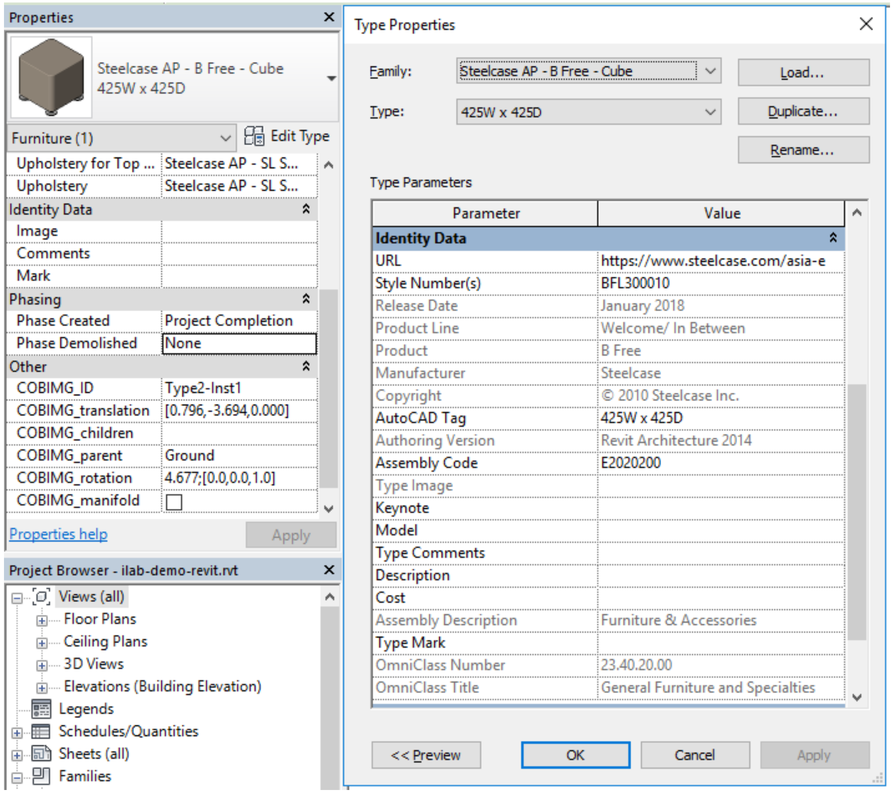


Octree search for 3D space/points *Source: apple.com*

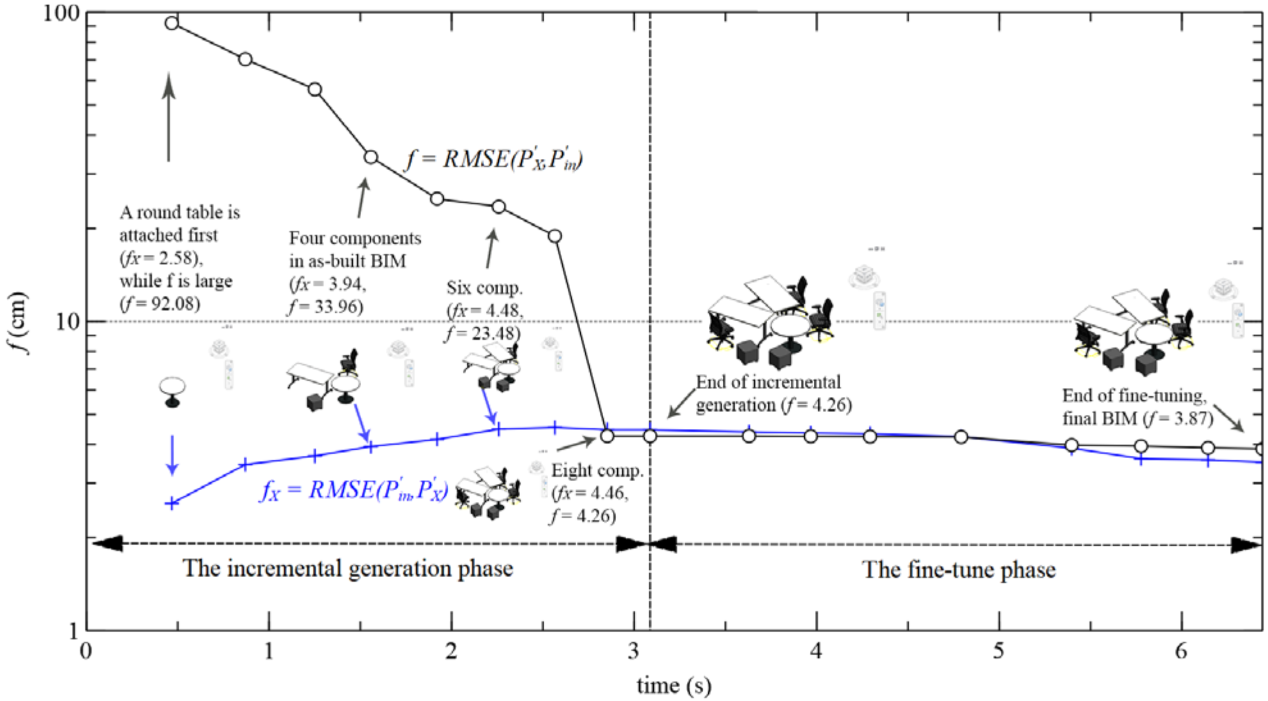
**: optional

2.2.3 Implementation with GUI



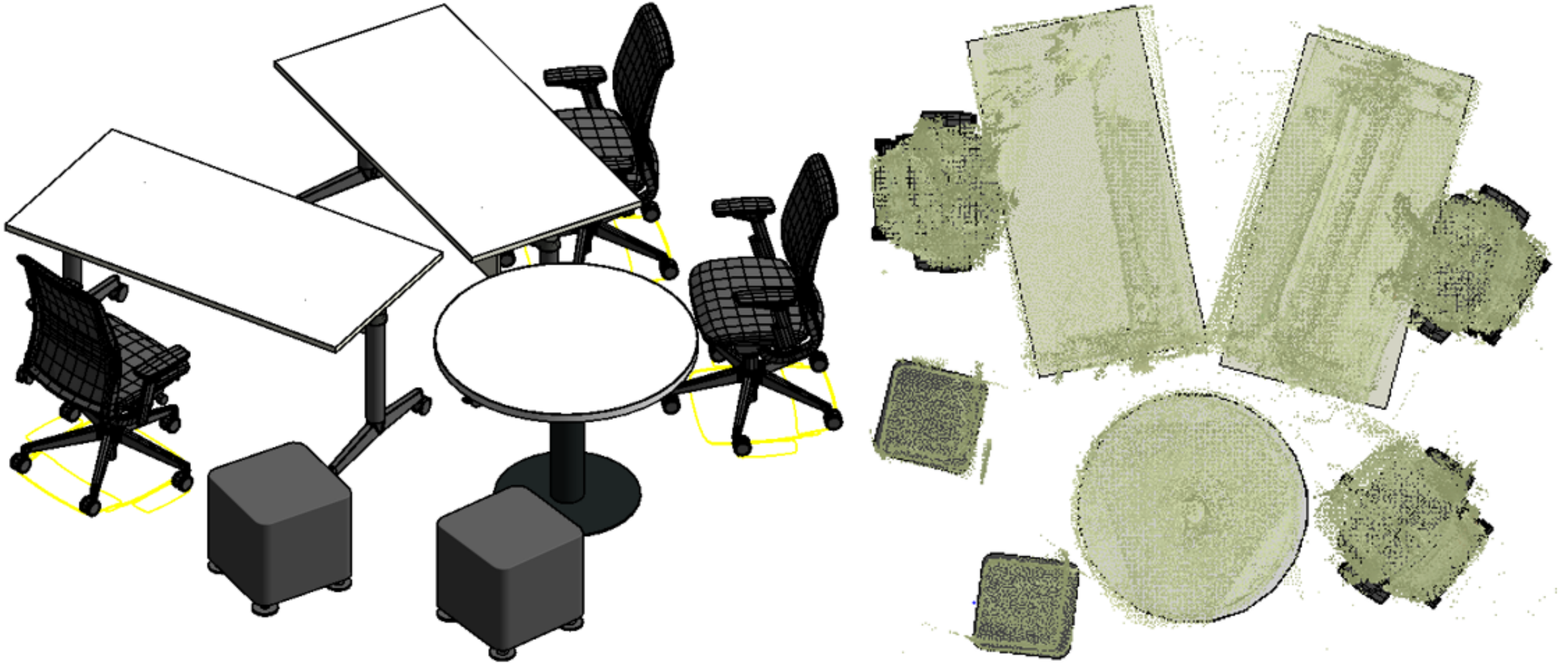


2.2.4 3D reconstruction as *f* descending



- T=6.44s
  - Manual = 330s
- Iter = 9,000
- Precision = 1.0
- Recall = 1.0

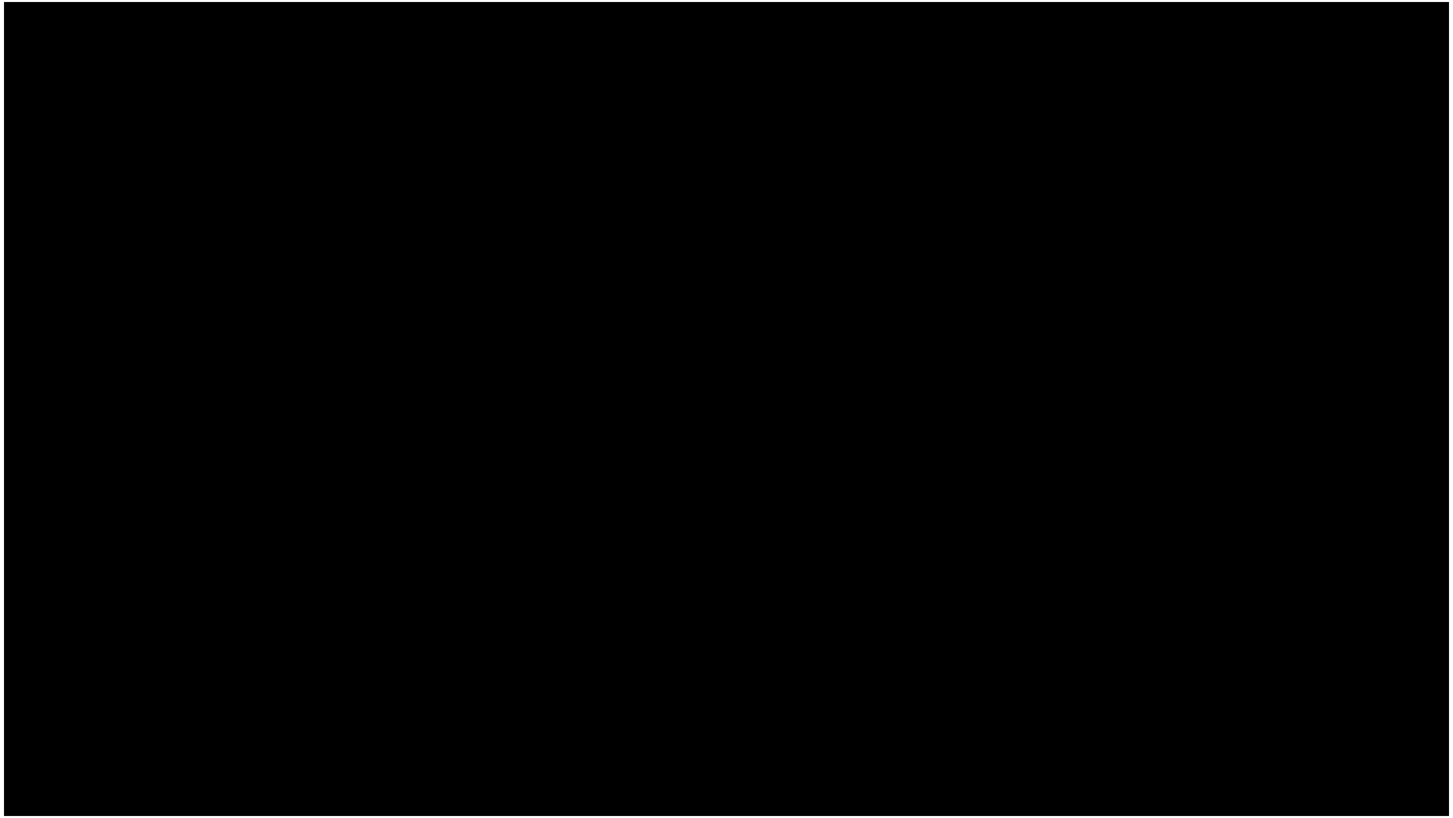
2.2.4 Result BIM



(a) A screenshot of the 3D view of the output as-built BIM

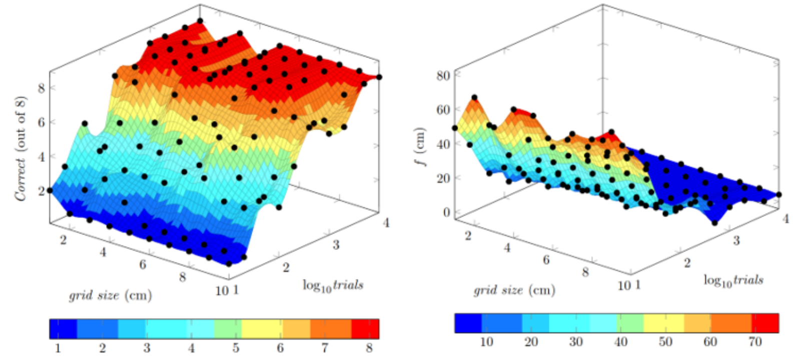
(b) A visual comparison between the input (grey points) and the output BIM

2.2.4 Demo video (another scene)

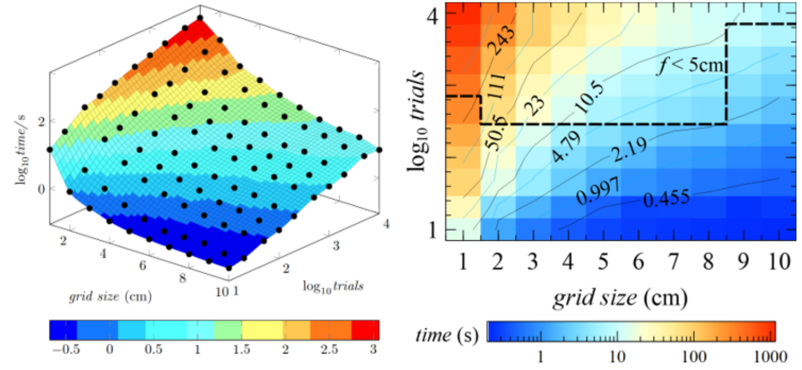


2.2.5 Parameter sensitivity analysis

- Two major parameters
  - Iterations per component (*trails*)
  - *Grid size* of octree voxelization
- Indicators
  - (a): correctness
  - (b): f
  - (c): time consumption
  - (d): trade-off between (a) and (c)



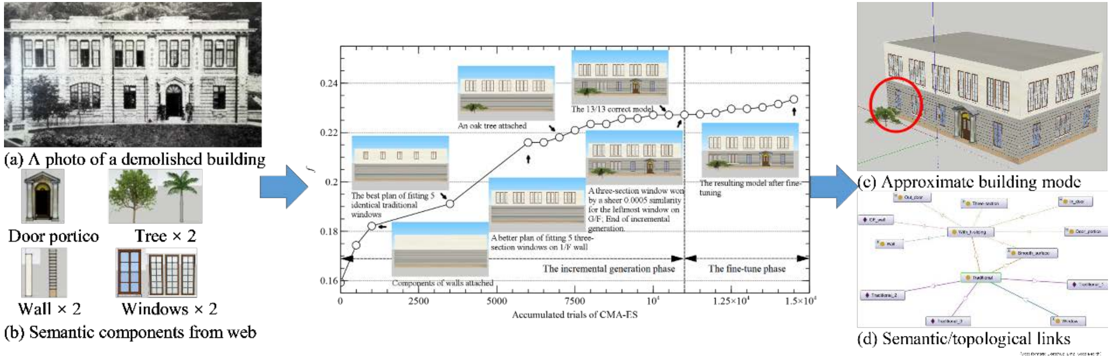
(a) The number of correct components (higher is better) (b) The objective function (lower is better)

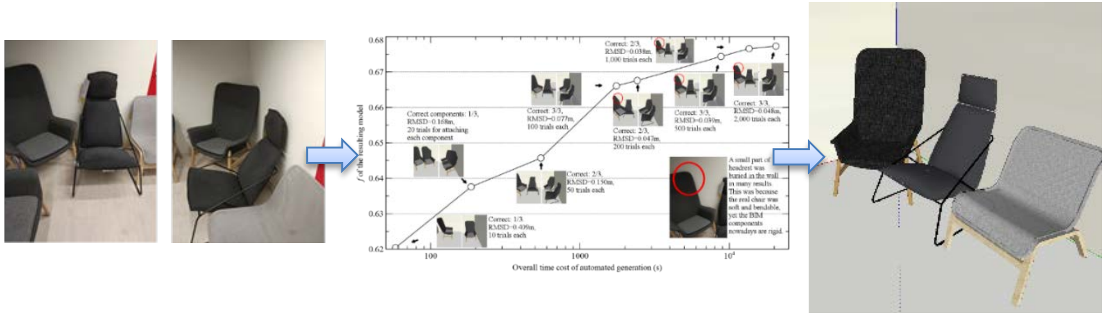


(c) The time cost (in $\log_{10}$, lower is better) (d) A trade-off analysis, e.g., a recommended setting is f < 5 cm and time < 10 s

2.3.1 Image-based reconstruction (Xue et al. 2018)

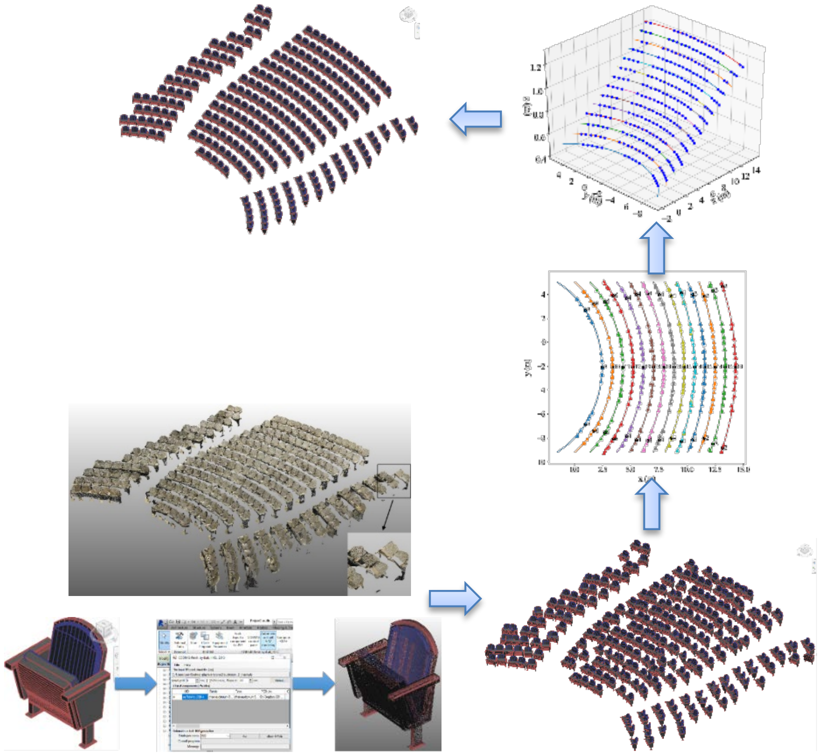
- ◇ Problem
  - ▣ To fit 3D object to 2D
- ◇ *f* = *dissimilarity*
  - ▣ arg max $f(x)=\text{SSIM}(t(x), m)$
- ◇ Algorithm
  - ▣ CMA-ES
- ◇ Performance
  - ▣ Good
  - ▣ ~1 trails/s





2.3.2 Opt in algorithms (Xue et al. 2019c)

- Problem
  - Reconstructing repetitive objects
- Same *f* to 2.2
- Algorithm
  - → Multi-Modal Optimization (MMO)
  - NMMSO
- Performance
  - Recall → + 10%
  - Precision → + 10%
  - Time → –35%

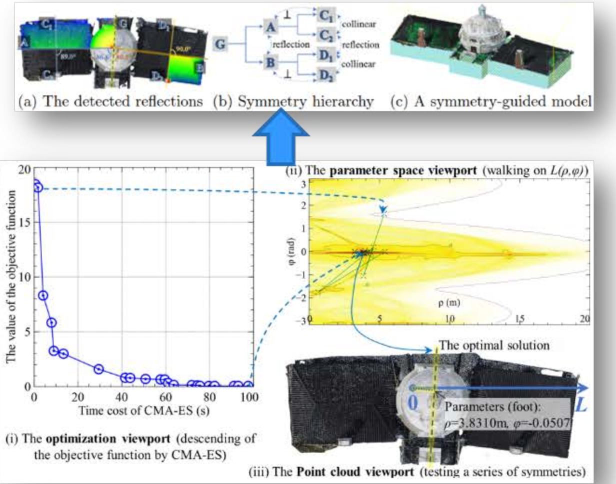


2.3.3 Topology reconstruction: Symmetry (Xue et al. 2019d)

- Problem
  - Detecting symmetry in point cloud
- *f* = distance
  - arg min *f* = RMSE(*C*(x), *C*) ≈ RMSE(*C'*(x), *C'*)
- Algorithm
  - CMA-ES
- Performance
  - Time = 98.6s
  - PCR = 93.7%


(a) Reflection (Mirror) (The Taj Mahal, India) (b) Rotation (The Pentagon, USA) (c) Translation (The Great Wall, China) (d) Translation × scaling (Fractal-like) (Hindu temples) (e) Scaling × rotation (The Pantheon dome, Italy) (f) Rotation × translation (The Gherkin, UK) (g) Translation × reflection (Sugar Hill Project, USA) (h) Cluster of homogeneous symmetries (Tulou, China)

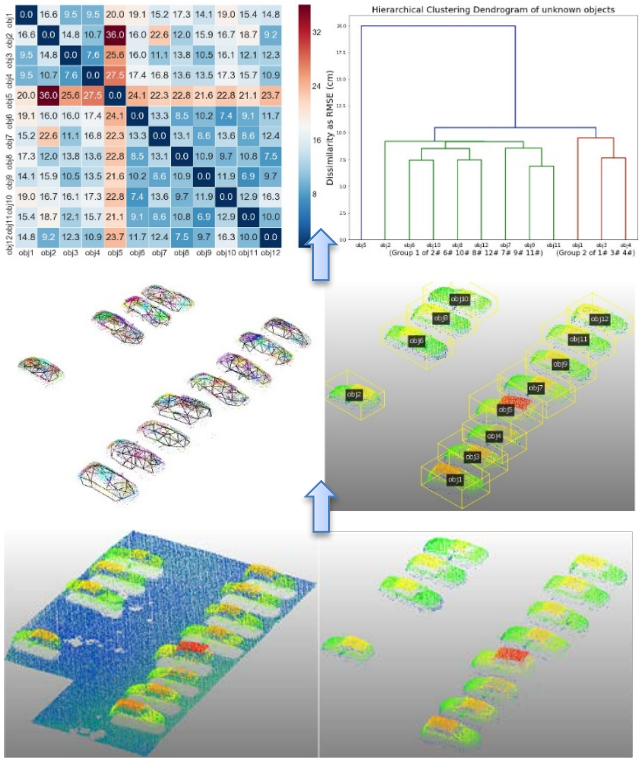

(a) The building (b) Photos by a drone (c) A dense point cloud



(a) The detected reflections (b) Symmetry hierarchy (c) A symmetry-guided model
(i) The optimization viewport (descending of the objective function by CMA-ES)
(iii) The Point cloud viewport (testing a series of symmetries)

2.3.4 Clustering similar objects (Xue et al. 2019e)

- Problem
  - To cluster similar cloud patches
- f = *dissimilarity*
  - $\min f = \mathrm{RMSE}(C_1(x), C_2)$
- Algorithm
  - CMA-ES
- Performance
  - ~0.6s for each pair



城市点云中的目标聚类

Section 3

DISCUSSION

3.1 A recap

- “Any evidence-based decision making can be formulated as an optimization problem”
- Evolutionary computation
  - A long history
  - Still a thriving domain
    - Conferences: GECCO, IEEE CEC
  - Good to handle expensive, complex tests
    - E.g., 3D urban reconstruction
    - Especially recent algorithms

3.2 Modeling for EC

- To design *f*
  - Supporting functions
- To set up domain
- To validate range
- To apply EC
- To analyze parameter sensitivity

References

- **Xue, F**., Lu, W., Chen, K. (2018). Automatic generation of semantically rich as-built building information models using 2D images: A derivative-free optimization approach. *Computer-Aided Civil and Infrastructure Engineering*, *33*(11), 926-942.
- **Xue, F.**, Lu, W., Webster, C. J., & Chen, K. (2019a). A derivative-free optimization-based approach for detecting architectural symmetries from 3D point clouds. *ISPRS Journal of Photogrammetry and Remote Sensing*, *148*, 32-40.
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- **Xue, F.**, Chen, K., & Lu, W. (2019e). Understanding unstructured 3D point clouds for creating digital twin city: An unsupervised hierarchical clustering approach. *CIB World Building Congress 2019*.

Thank you !

Q&A time

www.frankxue.com