

THE UNIVERSITY OF HONG KONG 香港大學 **faculty of architecture 建築學院**



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

24 September 2019 Tianjin, China Civil Aviation University of China



www.frankxue.com

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Optimization-driven 3D reconstruction

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F. Xue: EO for 3D Reconstruction, CAUC, China



0.1 HKUrbanLab, HKU

◆ 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; Chinese architecture; Rural; 0 • Health; • Fabrication and materials;

• iLab (data and information);

Property rights; Sustainability; Conservation; Virtual Reality; ... **KURBAN**





0.1 iLab: The urban big data hub

� iLab **实验室**

iLab

- Urban big data hub
- multi-dimensional and multi-disciplinary *urban big data* collection, storage, analysis, and presentation to inform decisionmaking 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)

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0.1 iLab

Oirector

Prof. Wilson Lu

Members

- I 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 F. Xue: EO for 3D Reconstruction, CAUC, China



Lunch-time gathering

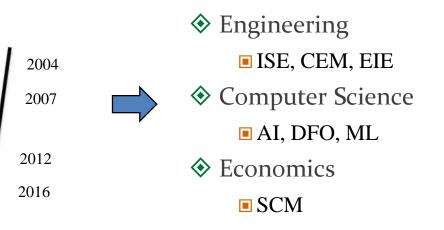


0.2 About myself

- ◇ A mixed background 背景
 BEng in Automation, CAUC
 MSc in Computer Science, CAUC

 Advisor: Prof. W Fan
 PhD in System Engineering, HKPU
 PDF/RAP/AP in Construction IT

 ◇ Research interests 方向
 - Urban sensing and computing
 - Automation in construction
 - Applied operations research
 - Machine learning and data visualization





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)
- Sob vacancy Research Assistant (2~3 openings)
 - \$17,000/month, Transferable to PhD applicant (vision, performance)
 - New updates on my web page (QR code)

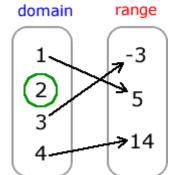


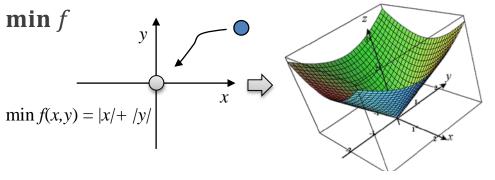
Section 1 EVOLUTIONARY COMPUTATION



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
 - \circ Optimality \leftarrow Objective function
 - "Best value" in range $\min f : \mathbb{R}^n \mapsto \mathbb{R}$
 - "Best element" in domain $\arg \min f$
- Fitness landscape
 - $\blacksquare Appearance of f$
 - Peaks/valleys contain the solutions ^{min}
 - Extremum / extrema

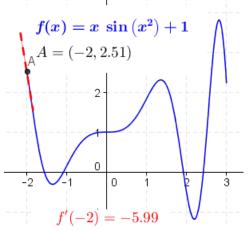






1.1 Fundamentals

- Optimality guaranteed methodsLinear 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)



First derivative and stationary points

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es of rules)
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Aerodynamics simulation *Picture source: mentor.com*



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1.2 Evolutionary computation

Evolutionary computation (EC) AS: • A.k.a. metaheuristics Harmony 2000 update with elitism Pheromone • A set of optimization algorithms stimation of distribution Ant-Q: Particle swarm optimization, GRASP • Iteration, population Ant colony optimization update like Q-learning Phero 1990 Often a meta-model "M" ACO: MMAS: P S > S Tabu search max & min limits, Simulated annealing \diamond A long History tism and frequency update Pheromone 1980 neighborhood-based From bio-inspiration half-greedy rp Genetic algorithm e s LS: ACS: P To meta-model 1970 leighborhood none • With many variants **Evolution concepts** GA: CACO: • see AC 1960 Crossover Local search update Mutation romone ret Mutation

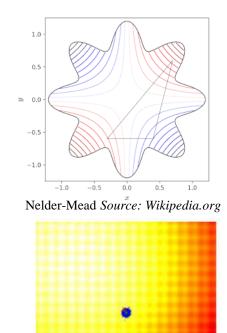
Derivations of AC (Xue 2012)

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



1.3 Benchmark performance

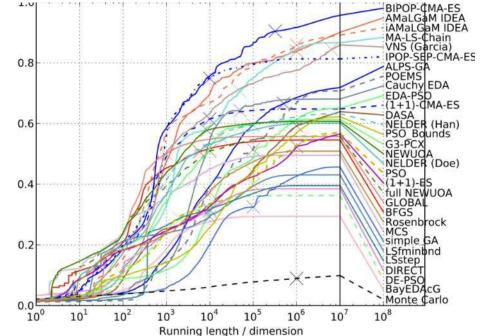
♦ Black-Box Optimization Benchmark solving without explicit ∇

Surrogate methods

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- 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.)

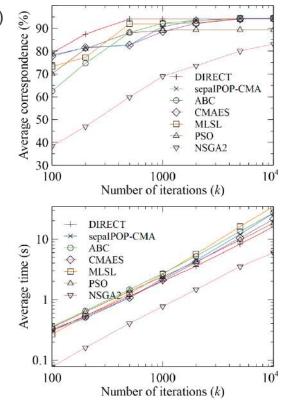
Symmetry detection in 3D point clouds (Xue et al. 2019a)

- Among 7 algorithms
 - All with default parameters
- DIRECT was the best
- NSGA2 was the worst
- $\boldsymbol{\diamondsuit}$ So, overall, we say

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- Quasi-derivative + evolutionary' > Quasi-derivative > evolutionary
- Due to the characteristics of real world problems



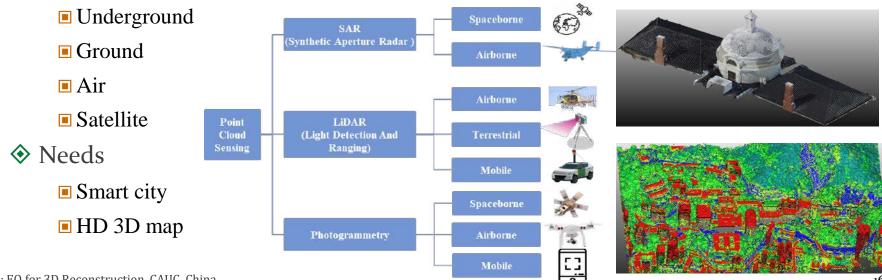
Section 2 OPTIMIZATION-DRIVEN 3D RECONSTRUCTION

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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





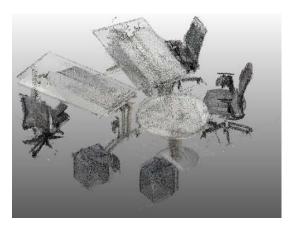
2.2 An indoor case (Xue et al. 2019b)

- Input: 3D point cloud
- Traditional methods
 - Non-semantic: Photogrammetry, 3D mesh
 - $\blacksquare \text{ Semantic: Segment} \rightarrow \text{features} \rightarrow \text{class, parameters}$

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
- $\blacksquare f = \text{RMSE}(model(x), input)$
 - \circ min f
 - **s.t.** *x* in Boundary, $C(x) \le 0$

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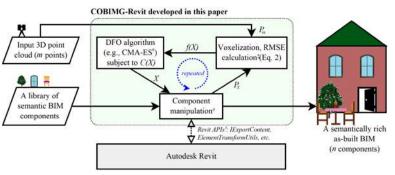


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2.2.2 The overall flow

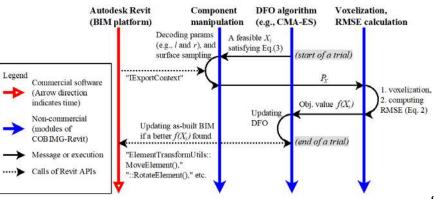
- ♦ Two inputs
- ♦ One output
- Four modules
 - Autodesk Revit
 - Component op. (Revit plugin) / C++ CLR
 - DFO algorithm (CMA-ES) / C++11
 - f evaluation / C++11
 - (See the message sequencing chart)



: In C++, supported by libemaes (version 0.9.5, available at: https://github.com/beniz/libemaes)

\$: In C++, supported by PCL (version 1.8.1, with FLANN, available at: http://pointclouds.org)

: In C+++compatible CLR, supported by Autodesk Revit (version 2015 Educational, documents available at: http://www.revitapidocs.com)





2.2.3 *f* evaluation

- f is still too expensive
 - Computing *m* points against thousands of triangles
- \diamond An effective approximation
 - Component point cloud dense sampling (pre-iteration

 $O(n' \log m')$

O(n')

- $O(m \log m)^{**}$ Input cloud down sampling
- Iteration
 - Transform component with *x* O(n)
 - Octree voxel down sampling
 - *nndist* for n' points
 - Compute *f*
 - Meta-model Evolution

 $f(X) = RMSE(BIM(X), P_{in})$ $\approx RMSE(P_X, P_{in})$ $\approx RMSE(P'_{Y}, P'_{in})$ $= \sqrt{\sum_{p \in P'_{\text{in}}} nndist^2(p, P'_X)/m'}$ $\approx RMSE(P'_{in}, P'_X)$ $= \sqrt{\sum_{p \in P'_X} nndist^2(p, P'_{in})} / ||P'_X||$ $O(n \log n)^{**}$

Octree search for 3D space/points Source: apple.com 19

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**: optional

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2.2.3 Implementation with GUI

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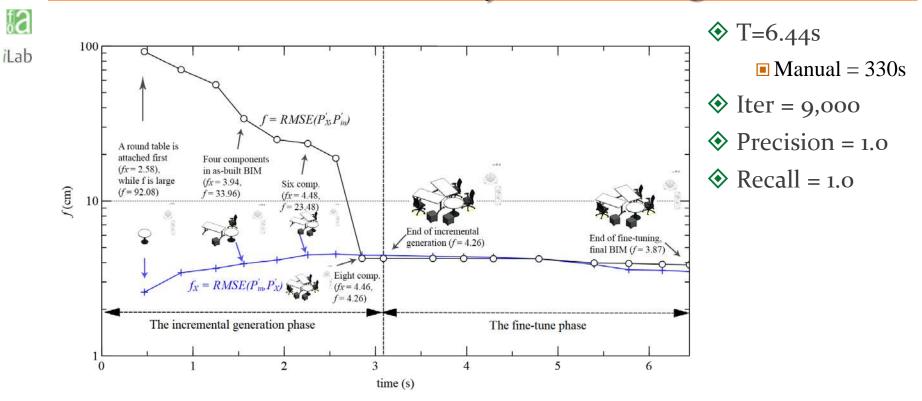
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2.2.4 3D reconstruction as *f* descending









(a) A screenshot of the 3D view of the output asbuilt BIM (b) A visual comparison between the input (grey points) and the output BIM

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2.2.4 Demo video (another scene)



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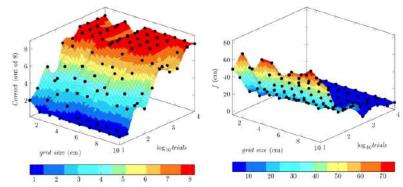
2.2.5 Parameter sensitivity analysis

- Two major parameters
 - Iterations per component (*trails*)
 - Grid size of octree voxelization
- ♦ Indicators

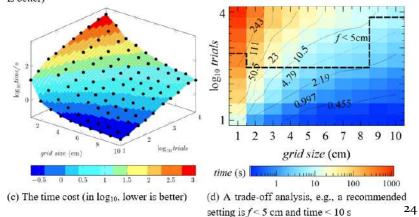
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- (a): correctness
- (b):*f*
- (c): time consumption
- (d): trade-off between (a) and (c)



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





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

Problem

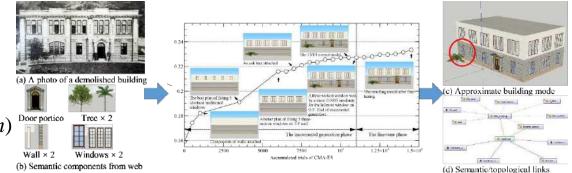
■ To fit 3D object to 2D

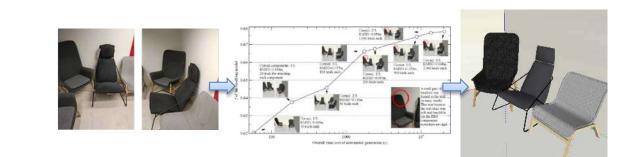
f = dissimilarity

• arg max f(x)=SSIM(t(x), m)

♦ Algorithm

CMA-ES





Performance

Good

 \blacksquare ~1 trails/s

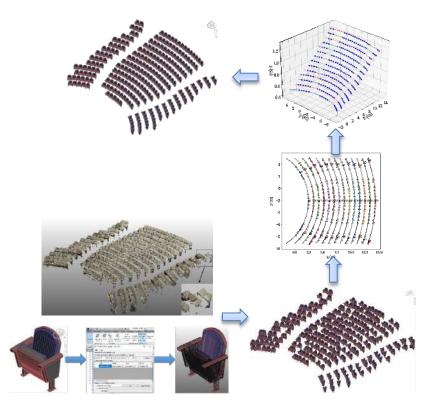


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2.3.2 Opt in algorithms (Xue et al. 2019c)

- Problem
 - Reconstructing repetitive objects
- \odot Same *f* to 2.2
- ♦ Algorithm
 - $\blacksquare \rightarrow$ Multi-Modal Optimization (MMO)
 - NMMSO
- Performance
 - \blacksquare Recall \rightarrow + 10%
 - Precision \rightarrow + 10%
 - \blacksquare Time $\rightarrow -35\%$



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

Problem

- Detecting symmetry in point cloud
- f = distance

• arg min $f = \text{RMSE}(C(\mathbf{x}), C) \approx \text{RMSE}(C'(\mathbf{x}), C')$

Algorithm CMA-ES (a) The detected reflections (b) Symmetry hierarchy (c) A symmetry-guided model (a) Reflection (Mirror) (b) Rotation (c) Translation (d) Translation × scaling (The Tai Mahal India) (The Pentagon, USA) (The Great Wall, China) (Fractal-like) (Hindu temples ♦ Performance (ii) The parameter space viewport (walking on $L(\rho, \varphi)$ \blacksquare Time = 98.6s (e) Scaling × rotation (f) Rotation × translation (g) Translation × reflection (h) Cluster of homogeneous (Sugar Hill Project, USA) symmetries (Tulou, China) (The Pantheon dome, Italy) (The Gherkin, UK) $\blacksquare PCR = 93.7\%$ The optimal solution 60 80 40 Parameters (foot) Time cost of CMA-ES (s) 3.8310m, @==0.050 (i) The optimization viewport (descending of (a) The building (b) Photos by a drone (c) A dense point cloud the objective function by CMA-ES) (iii) The Point cloud viewport (testing a series of symmetries)



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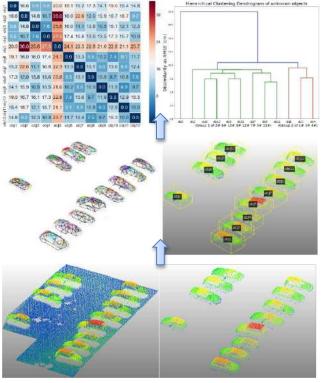
2.3.4 Clustering similar objects (Xue et al. 2019e)

Problem

- To cluster similar cloud patches
- f = dissimilarity
 - $\blacksquare \min f = \text{RMSE}(C_1(\mathbf{x}), C_2)$
- Algorithm

CMA-ES

- Performance
 - \blacksquare ~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
 - $\circ~$ 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
- \diamond To analyze parameter sensitivity



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References

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Thank you !

Q&A time



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