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

iLab @HKURBANlab the urban big data lab

Architectural symmetry detection from 3D urban point clouds

A derivative-free optimization (DFO) approach

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Outline

1. Background & Opportunity
2. DFO-based symmetry detection
3. Discussion

Section 1

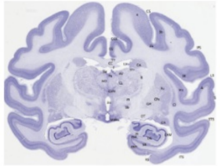
BACKGROUND & OPPORTUNITY

1.1 Symmetry

“The chief forms of beauty are order and symmetry and definiteness, which the mathematical sciences demonstrate in a special degree.”

▣ Aristotle, *Metaphysics*, 3-1078b

◈ Symmetry is fundamental, from quarks to animals to galaxies

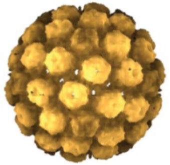


Human brain

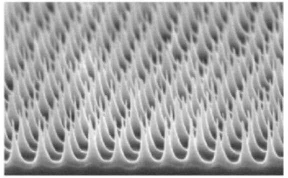
Starfish

Steam turbine

Nautilus shell

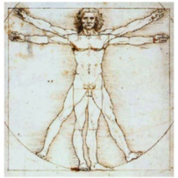


Simian virus



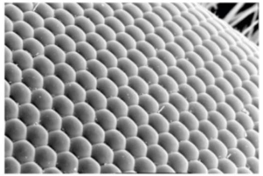
Silicon nanostructures

Taj Mahal



Vitruvian Man

Spiral galaxy



Insect eye

Geodesic dome

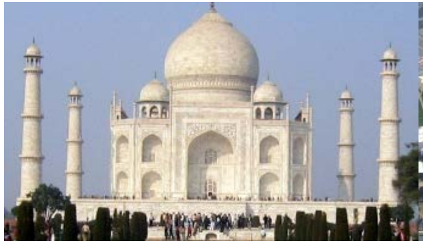
Persian carpet

Symmetry (Photo source Mitra et al. (2013))

1.1 Symmetry in constructions

◇ Universal

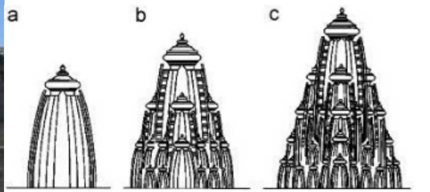
- Across various eras, continents, and cultures



(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

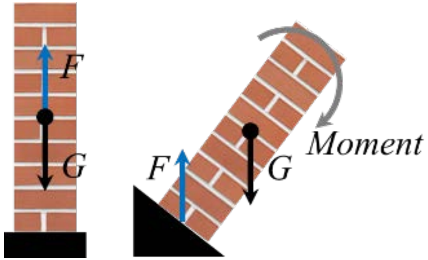
(e) Scaling × rotation
(The Pantheon dome, Italy)

(f) Rotation × translation
(The Gherkin, UK)

(g) Translation × reflection
(Sugar Hill Project, USA)

1.1 Reasons for the symmetry in constructions

- Not accidental, but the results of
  - Mechanics
    - e.g., vertical plane axis of reflection for loads and stability
  - Functions and climate
  - Economics and manufacture, and
  - Aesthetics, psychology, and cognition



(a) Gravity (*e.g.*, moment can pull down a leaning wall)

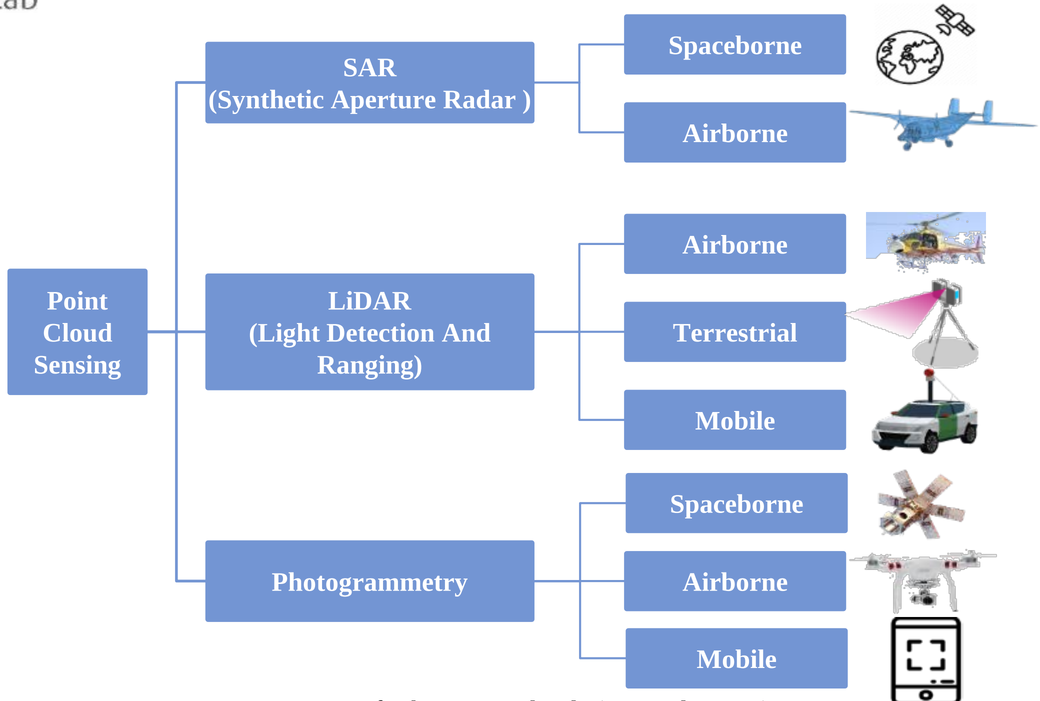
(b) Local climate (*e.g.*, tropical roofs and stilts against rains)

(c) Required functions (*e.g.*, strongholds for defense)

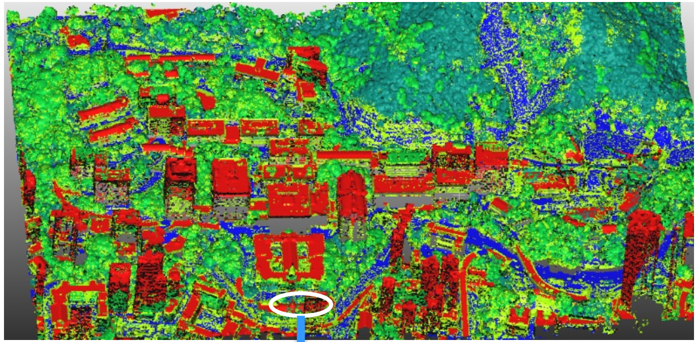
(Note: Some photos are adapted from wikipedia.org, original work shared by Mr. Wabu and Mikehume, licensed under CC-BY-SA 2.0/3.0)

1.2 Data: Point clouds of constructions

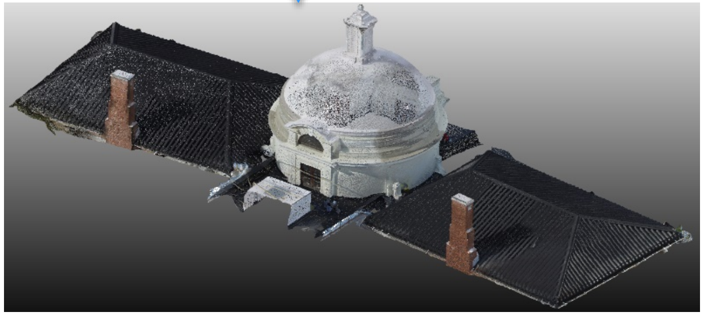
◇ Increasingly affordable, large-scale urban point clouds



A taxonomy of urban point clouds (Xu et al., 2018)



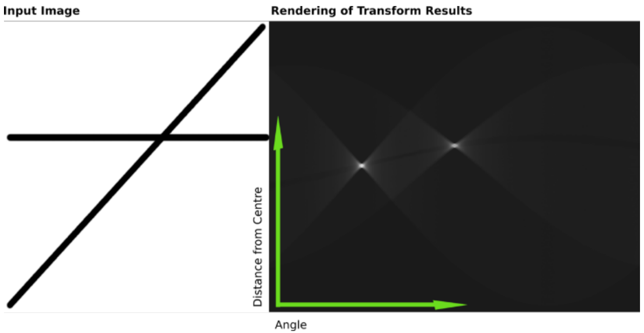
HKU Campus, 4 points/m² (Chen et al. 2018a)



The HHY Building, HKU, > 2,000 points/m²

1.3 Existing methods for symmetry detection

- Three categories, according to the methodology
  - Pairwise voting-clustering
    - Hough-like transform parameter space
  - Heuristic feature matching
  - Parameter optimization
    - Hill climbing on the parameter space



Hough transform (image source Wikipedia)

Category	General methodology	Accuracy (less geometric error)	Efficiency (Using less time)	Types of symmetries
Pairwise voting-clustering	Collection of pairwise votes of all the points in the parameter space	+	−	**All (++)**
Heuristic feature matching	Matching features (e.g., lines, planes, spheres) to infer symmetries	−	**++**	Limited by the features (−)
Parameter optimization	Solving abstracted optimization models over the parameter space	**++**	+	**All (++)**

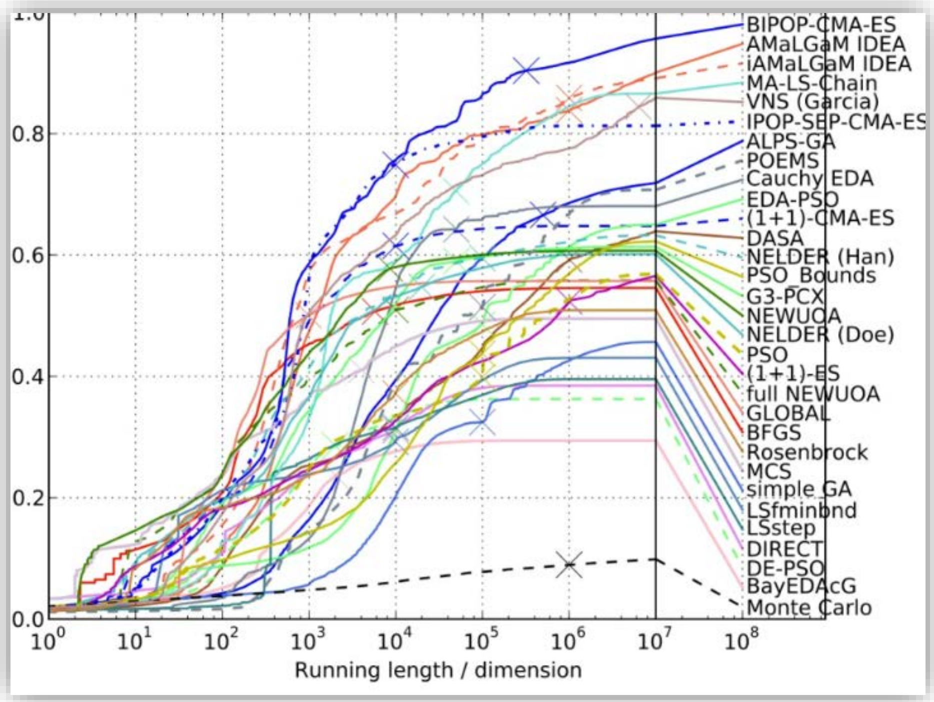
++: Very satisfactory; **+**: satisfactory; **−**: not satisfactory.

1.3 Challenges

- Pairwise voting-clustering
  - inherited proneness to noise of Hough-like (Brown, 1983),
  - ineffective recognition of local symmetries (Bokeloh et al., 2009),
  - low efficiency (exponential to the number of parameters), and
  - limited cardinality *n* (Berner et al., 2008)
- Heuristic feature matching
  - availability of *a priori* rules of the point clouds, and
  - abundance of suitable features (Lipman et al., 2010)
- Parameter optimization
  - very complex (*e.g.*, $n > 10^6$) and expensive (time-consuming in evaluation) in the dense point clouds of real architectures

1.4 Opportunity: Derivative-free optimization (DFO)

- Derivatives are often too expensive
  - Many known methods are not working
- Where *Derivative-free optimization* (DFO) algorithms may help
  - 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 source: Inria*

1.5 Aim and contribution of this research

- Aim
  - A novel DFO approach for
    - architectural symmetry detection (ASD),
    - processing of large-scale point clouds of constructions
- Contribution
  - A novel formulation of ASD
    - With effective approximation
  - Evaluation with a modern DFO algorithm
  - For BIM/CIM, and related disciplines

Section 2

DFO-BASED SYMMETRY DETECTION

2.1 Preliminary formulas

◈ Symmetry group

$$G = \langle \mathcal{T}, \circ \rangle,$$ *The symmetry group* $\circ$: *function composition*

$$\mathcal{T} = \{T | T(\mathcal{C}) = \mathcal{C}, T \text{ is affine on } \mathbb{R}^3\},$$ *The set of all symmetries* (1)

$$\mathcal{C} = \{p_1, p_2, \ldots, p_n\} \subset \mathbb{R}^3, n > 0,$$ *A given point cloud*

◈ Practical descriptors for noisy clouds from real world

(relaxed condition)

$$\mathrm{PCR} = \frac{1}{n} |T(\mathcal{C}) \cap \mathcal{C}| > 1 - \varepsilon,$$ *(Approximate) point correspondence rate* (2)

$$\mathrm{MSE} = \frac{1}{n} \sum_{p \in \mathcal{C}} ||T(p) - N(T(p), \mathcal{C})||^2 < \varepsilon d^2,$$ *Mean-squared error* (3)

◈ Architectural symmetry

$$\mathcal{T}_{\mathcal{A}} = \{T | \mathcal{A}(T) = \mathcal{A}_g(T) + \mathcal{A}_t(T) < \varepsilon_{\mathcal{A}}, T \in \mathcal{T}\} \subseteq \mathcal{T},$$ *The target subset* (4)

$$\mathcal{A}_g(T) \geq 0,$$ *Geometric regularity*

$$\mathcal{A}_t(T) \geq 0,$$ *Topological requirements*

2.2 The problem of ASD

- ASD

$$
\begin{aligned}
\textbf{min} \quad & f(x) = f_{\mathcal{C}}(x) + \omega\mathcal{A}(x) \\
\textbf{s.t.} \quad & x = \{x_1, x_2, \ldots, x_m\} \in \mathbb{R}^m, \\
& f_{\mathcal{C}} : \mathbb{R}^m \mapsto \mathbb{R}^+ \cup \{0\}, \qquad \text{see Eq. (2–3)}, \\
& \mathcal{A} : \mathbb{R}^m \mapsto \mathbb{R}^+ \cup \{0\}, \qquad \text{see Eq. (4)}, \\
& \omega \in \mathbb{R}^+ \cup \{0\},
\end{aligned}
\tag{5}
$$

A weighted sum objective

- Computational complexity
  - O(k n log n)
    - k iterations, O(n log n) for each iteration (using $k$dtree-based FLANN)
- Performance metrics of problem-solving
  - f
  - Computational time
  - PCR (Eq. 32)

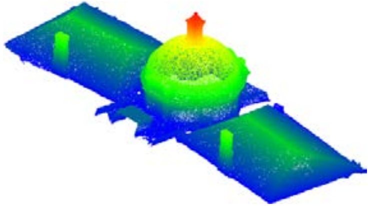
2.3 A pilot study

- The HHY Building at HKU campus (Fig. (a))
  - 250 photos taken by a UAV (Fig. (b))
  - 1.4 million points (Fig. (c)) obtained by Autodesk ReCap
  - Two-storey neoclassical redbrick building
    - Symmetry axes/planes are vertical ($\mathcal{A}_g$)

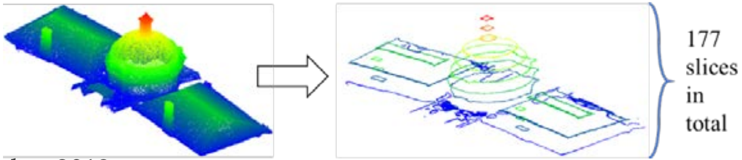
      Approximated using *z*-slices (Fig. (d))
  - Formulation in Fig. (e)
- Algorithm
  - CMA-ES (Hansen 2009)
  - Default parameters
    - Iteration = 200

(a) The Hung Hing Ying Building at HKU main campus

(b) 250 aerial photos taken with a UAV (model: *DJI Inspire 1*)



(c) A dense cloud of 1,413,211 points of the building rooftop



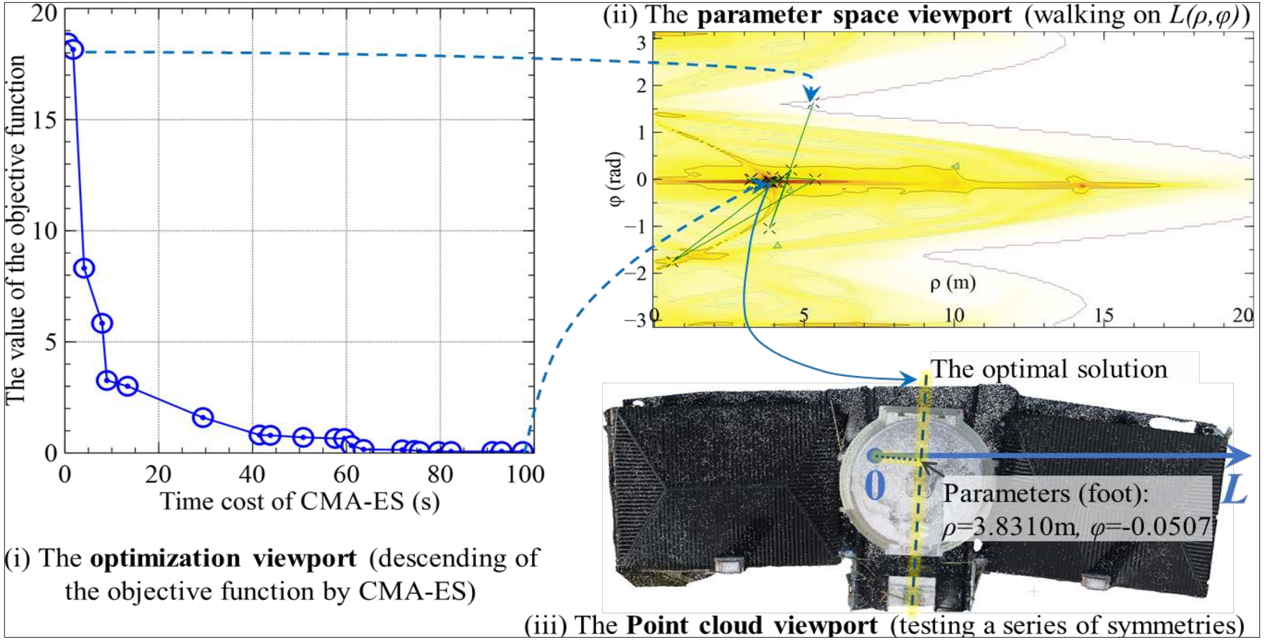
(d) The slices for fast verifying reflections on rooftop in the pilot case

$$\begin{aligned} \textbf{min } f(x) &= f_{\mathcal{C}}(x) + 10\mathcal{A}(x) \\ &= \frac{1}{n}\Sigma_{i=1}^{177}|\mathcal{C}_i|\cdot MNND_{\mathcal{C}_i}(x) \\ &\quad +10\,[\,\mathcal{A}_g(x) + \mathcal{A}_t(x)\,] \\ \textbf{s.t. } x &= (\rho, \varphi), \\ &\rho \in \mathbb{R}^+ \cup \{0\}, \varphi \in (-\pi, \pi]. \end{aligned}$$

(e) The formulated problem

2.4 The automatic ASD process, visualized

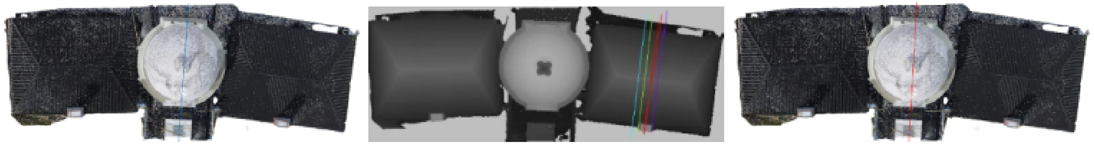
- Was a descent of objective value of the problem (e)
  - Figure (i)
- Also a hill-climbing in the parameter setting landscape
  - Figure (ii)
- Also an adaptive ASD from points
  - Figure (iii)

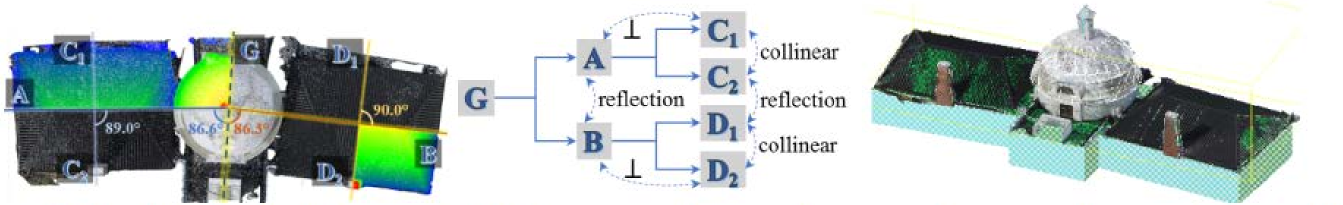


(i) The **optimization viewport** (descending of the objective function by CMA-ES)

(iii) The **Point cloud viewport** (testing a series of symmetries)

2.5 The results

	Mitra and Pauly [16]	Cicconet *et al.* [18]	The DFO approach
Type	Voting-clustering	Voting-clustering	Parameter optim.
PCR†	90.7% (grid center)	9.77% (the best one)	**93.7%**
MSE† (m²)	0.091	19.164	**0.086**
Plane	$19.983x - y = 78.033$	$7.914x - y = 71.718$	$19.708x - y = 75.596$
Correct?†	**Yes**	No (local only)	**Yes**
Time† (s)	140.7	837.7	**98.7**
Top view			

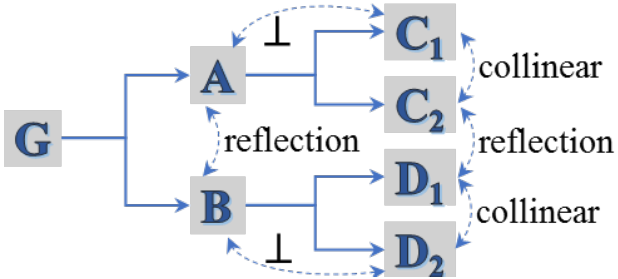


(a) The detected reflections (b) Symmetry hierarchy (c) A symmetry-guided model

- ◈ Encouraging
  - ▣ Outperformed existing methods
    - o Correctness
    - o Accuracy
    - o Time
- ◈ Application in BIM
  - ▣ Useful in building modeling
    - o Applied to Chen et al. (2018)

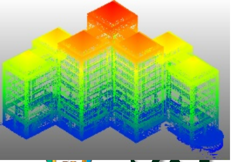
2.6 Summary

- A new method for ASD
  - For large-scale point clouds with certain noises
- Accuracy
  - better than conventional methods
- Automation and efficiency
  - Fully, inexpensive, very fast
- Applications
  - Building/city modeling and beyond
- Intrinsic knowledge discovered
  - Symmetry of symmetries
  - Co-hierarchy analysis
  - Design “genes”



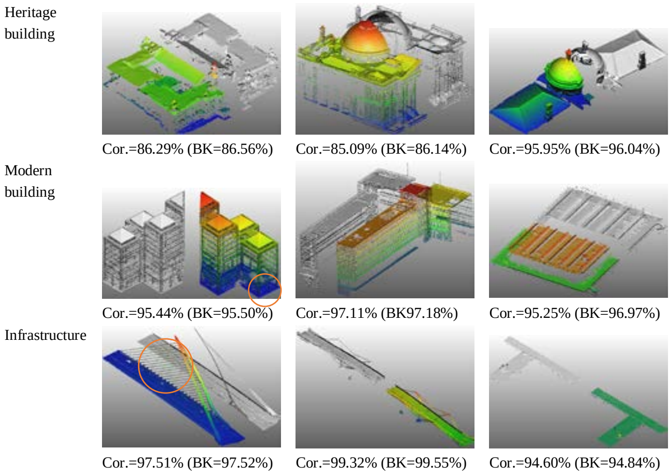
Section 3

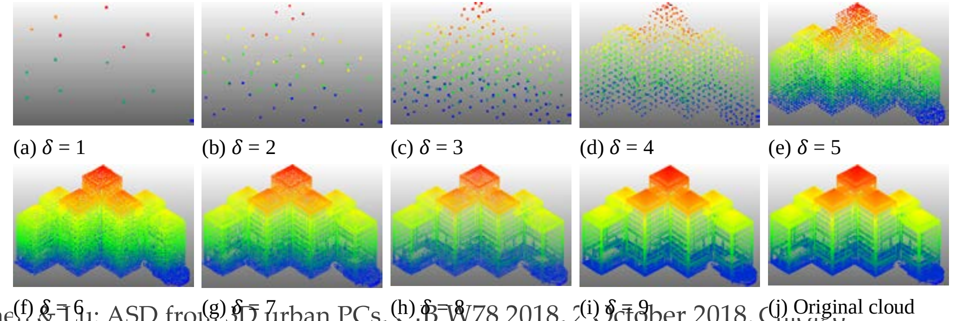
DISCUSSION

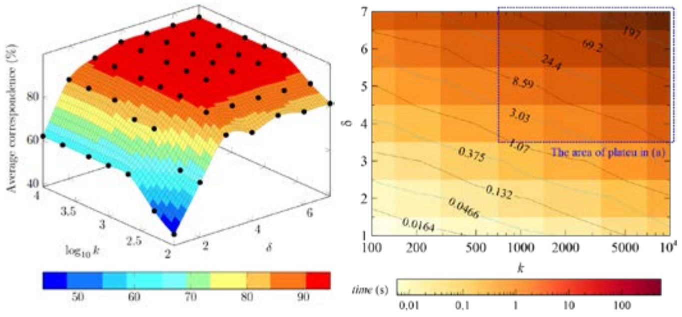


Recent progress of the research

- A systematic determination of voxel size (δ)
- Adapted more than 40 DFO algorithms
- Benchmarked on a test set of 9 constructions
- Parameters' sensitivity analysis
  - Adoption recommendation
- It is open source now
  - https://github.com/ffxue/odas



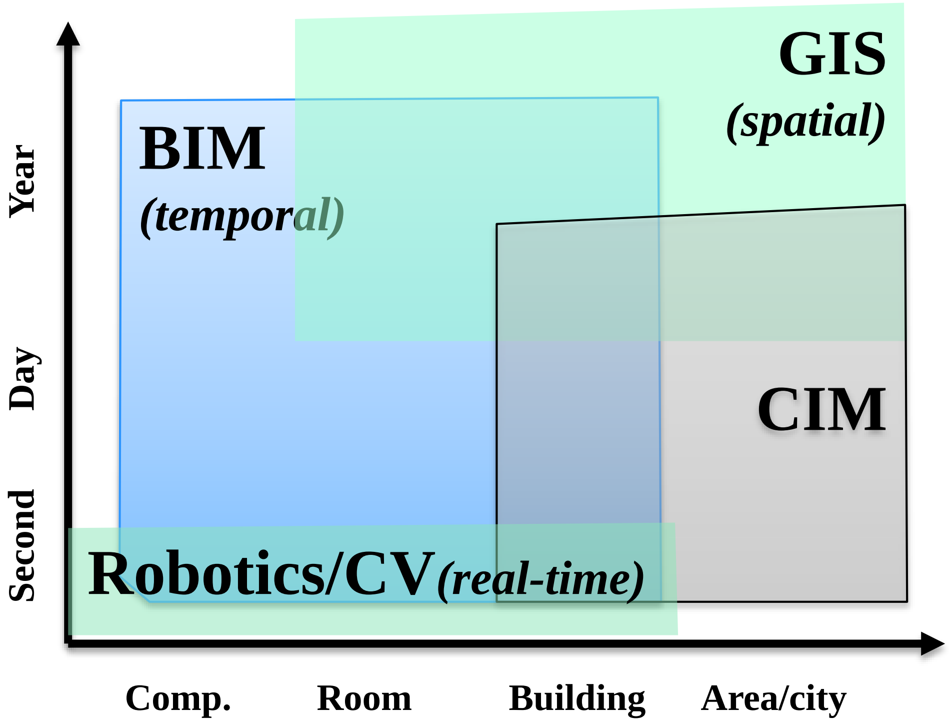




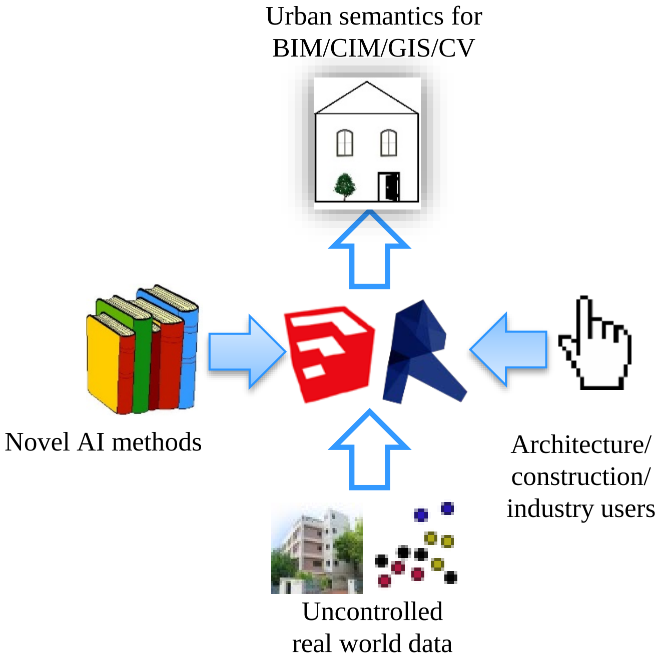
(a) Average correspondence (higher is better)

(b) Average computational time (lower is better)

3.2 Urban semantics in a broader view



The spatial-temporal matrix of the interests of BIM, GIS, CIM, CV



The inter-disciplinary view of smart, resilient development for humanity

References

- Auger, A., Finck, S., Hansen, N., and Ros, R. (2010). BBOB 2009: Comparison tables of all algorithms on all noisy functions, INRIA.
- Chen, K., Lu, W., **Xue, F**., Tang, P., & Li, L. H. (2018a). Automatic building information model reconstruction in high-density urban areas: Augmenting multi-source data with architectural knowledge. Automation in Construction, 93, 22-34.
- Chen, K., Lu, W. S. ., **Xue, F**, Zheng, L. Z., & Liu, D. D. (2018b). Smart Gateway for Bridging BIM and Building. In Proceedings of the 21st International Symposium on Advancement of Construction Management and Real Estate (pp. 1307-1316). Springer, Singapore.
- Deb, K., Pratap, A., Agarwal, S. & Meyarivan, T.A.M.T., (2002). A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE transactions on evolutionary computation, 6(2), pp.182-97.
- Hansen, N., (2009). Benchmarking a BI-Population CMA-ES on the BBOB-2009 Function Testbed. In Workshop Proceedings of the GECCO Genetic and Evolutionary Computation Conference., 2009. ACM.
- Hansen, N., Müller, S.D. & Koumoutsakos, P., (2003). Reducing the time complexity of the derandomized evolution strategy with covariance matrix adaptation (CMA-ES). Evolutionary computation, 11(1), pp.1-18.
- Hough, P.V., (1959). Machine analysis of bubble chamber pictures. In Proceedings of International Conference on High Energy Accelerators and Instrumentation (HEACC 1959). Geneva, 1959. CERN.
- Jones, D.R., Perttunen, C.D. & Stuckman, B.E., (1993). Lipschitzian optimization without the Lipschitz constant. Journal of Optimization Theory and Applications, 79(1), pp.157-81.
- Karaboga, D. & Basturk, B., (2007). A powerful and efficient algorithm for numerical function optimization: artificial bee colony (ABC) algorithm. Journal of global optimization, 39(3), pp.459-71.
- Kucherenko, S. & Sytsko, Y., (2005). Application of deterministic low-discrepancy sequences in global optimization. Computational Optimization and Applications, 30(3), pp.297-318.

References (cont.)

- Mitra, N.J., Guibas, J. & Pauly, M., (2006). Partial and approximate symmetry detection for 3D geometry. ACM Transactions on Graphics, 25(3), pp.560-68.
- Mitra, N.J., Pauly, M., Wand, M. & Ceylan, D., (2013). Symmetry in 3D geometry: Extraction and applications. Computer Graphics Forum, 32(6), pp.1-23.
- National Institute of Building Sciences. (2015). National Building Information Modeling Standard. Version 3, Retrieved from https://www.nationalbimstandard.org/
- Poli, R., Kennedy, J. & Blackwell, T., (2007). Particle swarm optimization. Swarm intelligence, 1(1), pp.33-57.
- Xu, J., Chen, K., **Xue, F**., & Lu, W. (2018). 3D point clouds for architecture, engineering, construction, and operation: A SWOT analysis. Working paper
- **Xue, F**., Lu, W., Chen, K. (2018a). Automatic generation of semantically rich as-built building information models using 2D images: A derivative-free optimization approach. Computer-Aided Civil and Infrastructure Engineering, in press.
- **Xue, F**., Lu, W., Chen, K. & Zetkulic, A. (2018b). From 'semantic segmentation' to 'semantic registration': A derivative-free optimization-based approach for automatic generation of semantically rich as-built building information models (BIMs) from 3D point clouds. Journal of Computing in Civil Engineering. Under review
- **Xue, F**., Chen, K., Lu, W., Huang, GQ. (2018c). Linking radio-frequency identification to Building Information Modeling: Status quo, development trajectory and guidelines for practitioners. Automation in Construction, in press.
- **Xue, F**., Chiaradia, A., Webster, C., Chen, K., Lu, W. (2018d). Personalized Walkability Assessment for Pedestrian Paths: An As-built BIM Approach Using Ubiquitous Augmented Reality (AR) Smartphone and Deep Transfer Learning. CRIOCM 2016. to appear.

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