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

iLab @ HKURBANlab the urban big data lab

An efficient approach for symmetry detection in point clouds of constructions 建筑物点云中对称性识别的一类快速方法

VCC, SZU 深圳大学 可视计算研究中心
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*i*Lab, HKURBANlab, HKU 香港大学 HKURBANlab – iLab

Aim and scope

- Aim of this presentation 目的
  - To introduce the HKURBANlab – iLab 自报家门
  - To share our recent work 分享若干新进展
  - To promote collaborations 促进合作
  - To share job/PhD opportunities 分享机会
- Scope 范畴
  - Extension: 3D point cloud (BIM) 外延：三维点云（建筑）
  - Intention: Symmetry detection 内涵：对称性识别
  - Methods: Nonlinear optimization methods 方法：非线性优化方法

Outline

简介 1 Introduction to iLab

背景 2 Background & Opportunity

正文 3 DFO-based symmetry detection (Xue et al., 2018f)

讨论 4 Discussion

Section 1

INTRODUCTION TO ILAB

ILAB介绍

1.1 HKURBANlab

- Faculty of Architecture, HKU 建筑学院
  - 3 Departments: Arch., REC, DUPAD
  - 2 Divisions: Landscape Arch., Arch. Conservation
- HKURBANlab 实验中心
  - Newly branded research arm of FoA
  - 1 Academician (CAS), 10 full professors
  - 12 labs on

Urban planning;	Property rights;
Chinese architecture;	Rural;
Health;	Sustainability;
Fabrication and materials;	Conservation;
iLab (data and information);	Virtual Reality; ...

www.arch.hku.hk

1.1 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)

iLab @ HKURBANlab the urban big data lab

iLabHKU

fac.arch.hku.hk/iLab

1.1 The research team

- Lab director 主任
  - Dr. Wilson Lu
- Full-time team members 成员
  - 1 RAP, 1 PostDoc, 1 SRA, 3 RAs, 7 PhD candidates
- Research themes 主题
  - Urban big data (BIM, GIS, IoT, …)***
  - Construction project management *
  - Construction waste management *
  - International construction
    - Corporate social responsibility

(***: *involves CV*; *: *May involve CV*)

Lunch-time gathering

1.2 About myself

iLab

- A mixed background 背景
  - BEng in Automation — 2004
  - MSc in Computer Science — 2007
  - PhD in System Engineering — 2012
  - PDF/RAP in Construction / BIM — 2016
- Research interests 兴趣
  - Computation and urban semantics in BIM
  - Applied operations research
  - Machine learning and visualization for construction
- On-going research projects 在研
  - PI: RGC (17201717), HKU (201702159013, 201711159016)
  - Co-I: NSFC (71671156), NSSFC (17ZDA062), HKU PTF

→

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

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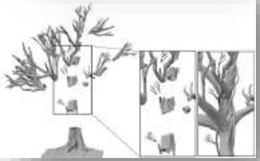
1.3 Job vacancies

- Research Assistant (2~4 openings)
  - $16,575/month + 5%/year 工龄
  - Transferable to PhD
  - Inquiry: Dr Frank Xue <xuef@hku.hk>
- PhD 博士
  - 100% funded scholarship
    - $16,330/month
  - HKU PhD Fellowship (UPF)
    - Above + $70,000 (one time)
  - HK PhD Fellowship Scheme (HKPF)
    - $20,000/month + $10,000/year conference + $42,100 (annual fee of 1st year)
  - Inquiry: Dr. Wilson Lu <wilsonlu@hku.hk>

Empty seats for you

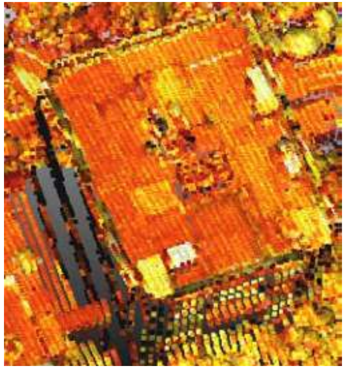
1.3 CV related research (e.g., GRF 17201717)



Relevant work at VCC
(image courtesy VCC)

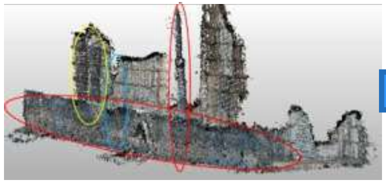
(Xue et al., 2018a; 2018b) Note: On RMSE (*xyz*) only, not using RGB

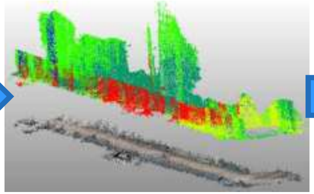
1.3 CV related research (e.g., PTF)

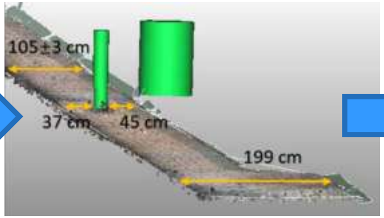


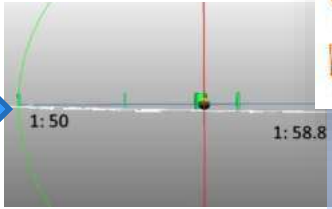
(Chen et al., 2018)

Relevant work at VCC (image courtesy VCC)









Walking characteristic	Calculated value	Type of pedestrians				
		Wheelchair	Stroller	Luggage	Senior	Exercise
No. of steps	0	OK	OK	OK	OK	OK
Slope grade*	1:50.0~58.8	OK	OK	OK	OK	OK
Tilt grade†	1:47.6~66.7	OK	OK	OK	OK	OK
Footway width‡	45~199 cm	Failed	Limited	Limited	OK	OK
Clearance	Good	OK	OK	OK	OK	OK
Overall walkability (the worst)		Failed	Limited	Limited	OK	OK

(Xue et al., 2018e)

Section 2

BACKGROUND & OPPORTUNITY

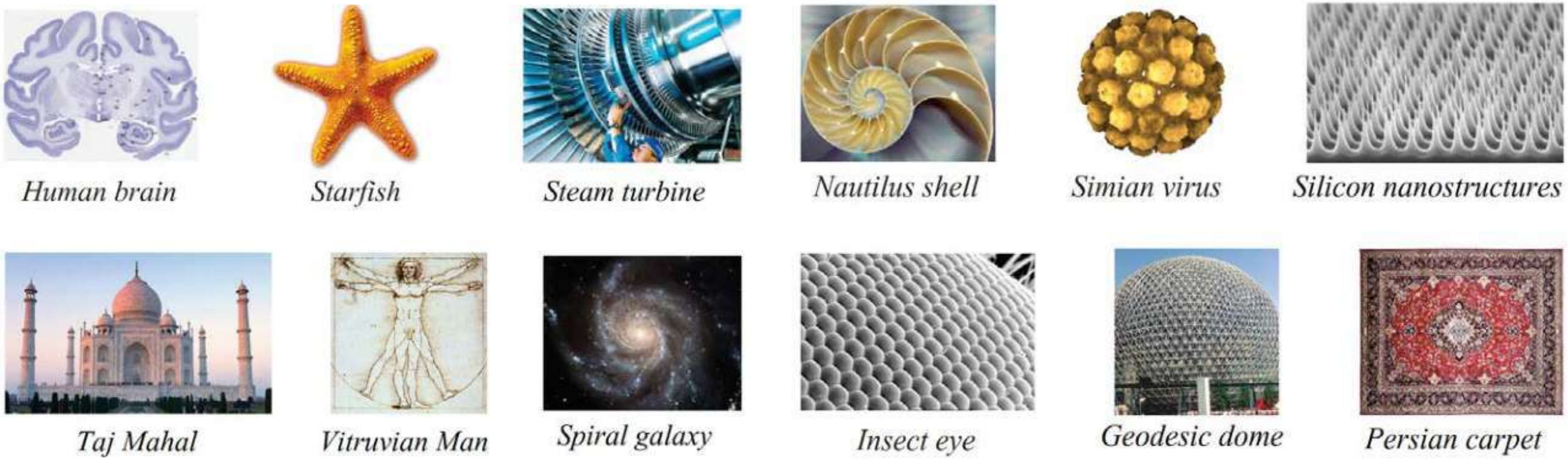
背景和机遇

2.1. 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



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

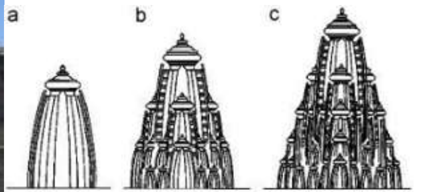
2.1 Symmetry in constructions

- 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)

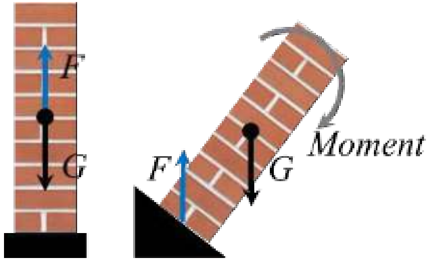
(f) Rotation × translation
(The Gherkin, UK)

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

(Note: Some photos are adapted from wikipedia.org, original work shared by Yann, Livioandronico2013, D. B. Gleason, Evancahill, Ashish Nangia, and Aurelien Guichard, licensed under CC-BY-SA 2.0/3.0/4.0)

2.1 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)

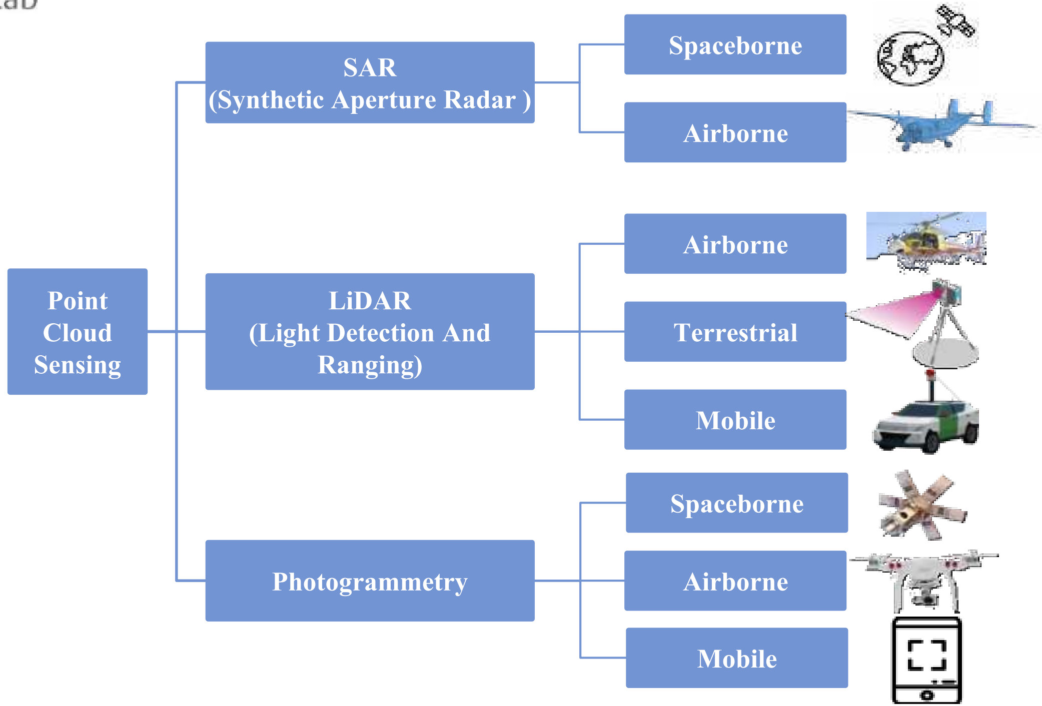
(b) Local climate (*e.g.*, tropical roofs and stilts against rains)

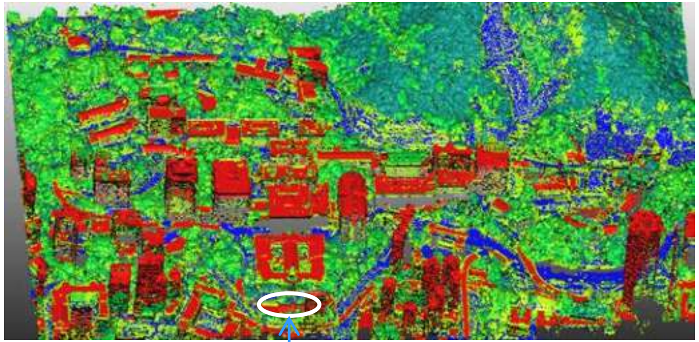
(c) Required functions (*e.g.*, strongholds for defense)

(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)

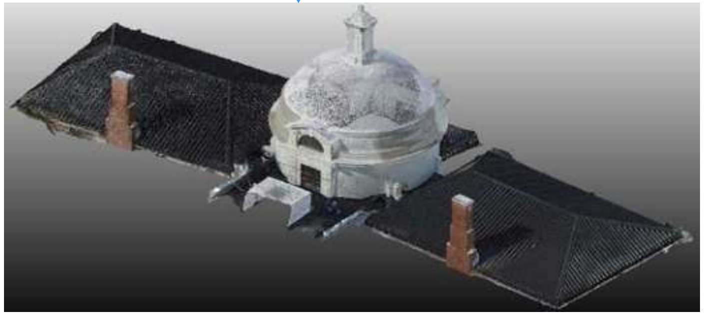
2.2 Data: Point clouds of constructions

◇ Increasingly affordable, large-scale urban point clouds (Xu et al., 2018)





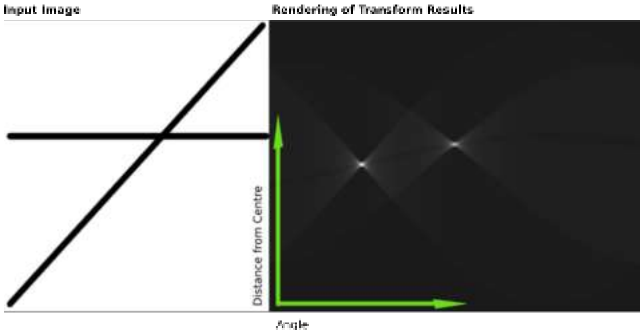
Central Western District around HKU, 4 points/m²



The HHY Building, HKU, > 2,000 points/m² (Xue et al., 2018d)

2.3 Symmetry detection methods for point clouds

- 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



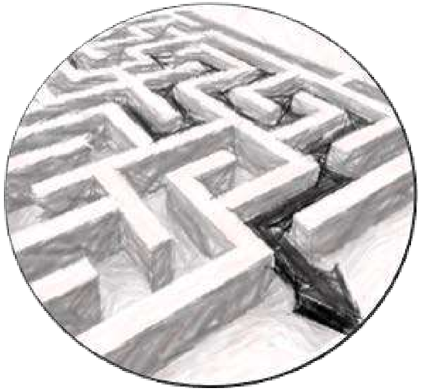
Hough transform (image courtesy Wikipedia)

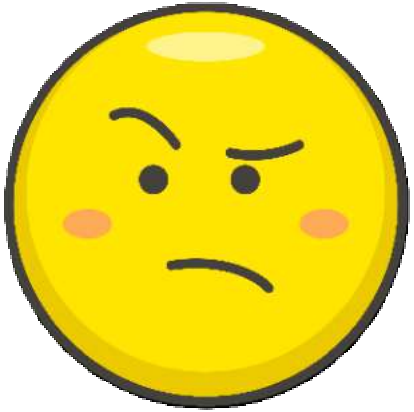
Category	General methodology	Accuracy (less geometric error)	Efficiency (Using less time)	Types of symmetries
Pairwise voting-clustering	Collection of pairwise votes of all the points in the parameter space	+	−	**All (++)**
Heuristic feature matching	Matching features (e.g., lines, planes, spheres) to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

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

2.3 Challenges

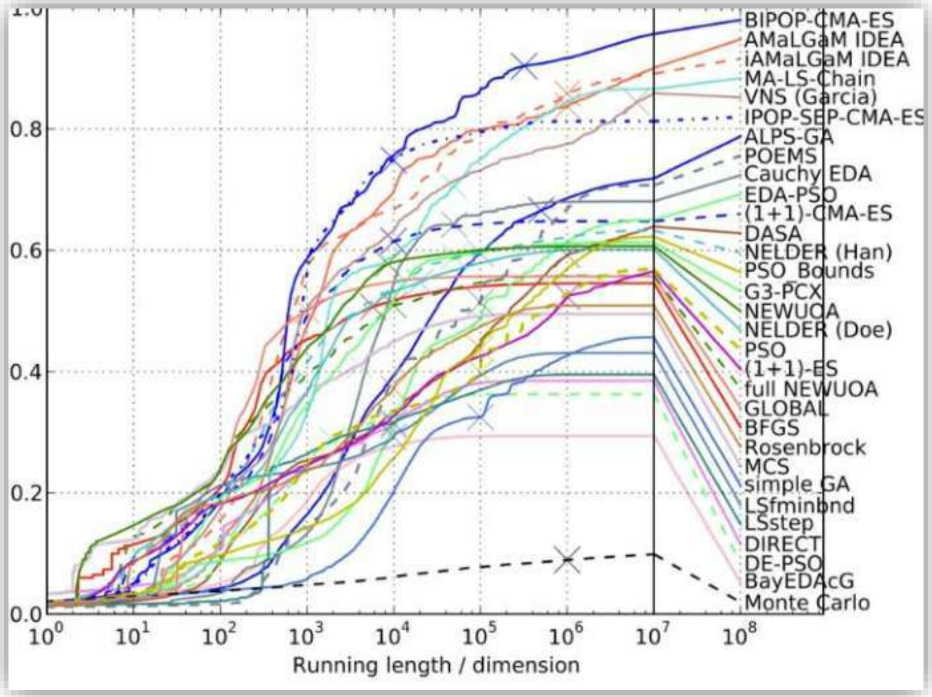
- Pairwise voting-clustering
  - inherited proneness to noise of Hough-like (Brown, 1983),
  - ineffective recognition of local symmetries (Bokeloh et al., 2009),
  - low efficiency (exponential to the number of parameters), and
  - limited cardinality n (Berner et al., 2008)
- Heuristic feature matching
  - 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





2.4 Opportunity: Derivative-free optimization (DFO)

- Derivatives are 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 courtesy: Inria*

2.5 Aim and contribution of this research

- Aim
  - A novel DFO-based architectural symmetry detection (ASD) approach for processing large-scale point clouds of constructions
- Contribution
  - A novel formulation of ASD
    - With effective approximation
  - Evaluated and benchmarked modern DFO algorithms
    - For ASD, and related disciplines
  - An open source scientific library *libodas*
    - On *Github*
    - (to be streamlined after paper submission)

Section 3

DFO-BASED SYMMETRY DETECTION (XUE ET AL., 2018F)

基于無導數优化的对称性识别

3.1 Preliminary formulas

- Symmetry group

$G = \langle \mathcal{T}, \circ \rangle$, — G: *the symmetry group* ∘ 复合算子

$\mathcal{T} = \{T \mid \underline{T(\mathcal{C}) = \mathcal{C}}, T \text{ is affine on } \mathbb{R}^3\}$, — $\mathcal{T}$: *the set of all global symmetries* (1)

$\mathcal{C} = \{p_1, p_2, \ldots, p_n\} \subset \mathbb{R}^3, n > 0$, — $\mathcal{C}$: *the cloud of n points in 3D* ($\mathbb{R}^3$)

- Practical descriptors for noisy clouds from real world

(relaxed condition)

$d_T(p, \mathcal{C}) = \| T(p) - N(T(p), \mathcal{C}) \|$ — *Distance to* $\mathcal{C}$ *of p after a transform T* (2)

$\frac{1}{n} |\{p \mid p \in \mathcal{C}, \underline{d_T(p, \mathcal{C}) < \varepsilon\, diagonal_{\mathcal{C}}}\}|$, or — *Correspondence* (3)

$[\frac{1}{n} \Sigma_{p\in\mathcal{C}}\, d_T(p, \mathcal{C})^2]^{1/2}$ — *Root-mean-square distance (RMSD)* (4)

- Architectural symmetry (a subgroup)

$\mathcal{T}_A = \{T \mid \mathcal{A}_g(T) + \mathcal{A}_t(T) < \varepsilon_A, T \in \mathcal{T}\} \subseteq \mathcal{T}$, — $\mathcal{T}_A$: *the set of all architectural symmetries*

$\mathcal{A}_g(T) \geq 0$, — $\mathcal{A}_g$: *the violations of geometric regularity* (5)

$\mathcal{A}_t(T) \geq 0$, — $\mathcal{A}_t$: *the violations of topology*

3.2 The problem of ASD

- ASD

$$
\begin{aligned}
&\textbf{min } f(x) = f_{\mathcal{C}}(x) + \omega \mathcal{A}(x) && f\text{: the objective function to minimize} \\
&\textbf{s.t. } x = (x_1, x_2, \ldots, x_m) \in \mathbb{R}^m, && x\text{: the } m \text{ parameters of a symmetry} \\
&f_{\mathcal{C}} : \mathbb{R}^m \to \mathbb{R}^+ \cup \{0\}, \textit{ see } \text{Eqn. (2) - (4)}, && f_{\mathcal{C}}\text{: the penalty (or error) against } \mathcal{C} \qquad (6) \\
&\mathcal{A} : \mathbb{R}^m \to \mathbb{R}^+ \cup \{0\}, \textit{ see } \text{Eqn. (5)}, && \mathcal{A}\text{: the penalty against the style} \\
&\omega \in \mathbb{R}^+ \cup \{0\}, && \omega\text{: the relative weight of } \mathcal{A}
\end{aligned}
$$

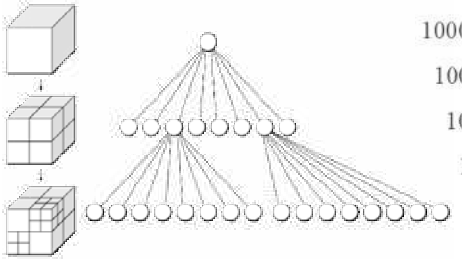
- Computational complexity
  - O(k n log n), still too high, e.g., n = 1M
    - k iterations, O(n log n) for each iteration (using $k$dtree-based FLANN)
- Performance metrics of problem-solving
  - f
  - Computational time
  - Correspondence (Eq. 3)

3.2 The approximated problem of ASD

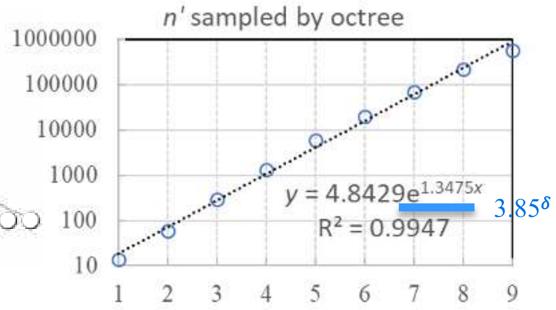
- ASD approximated by octree

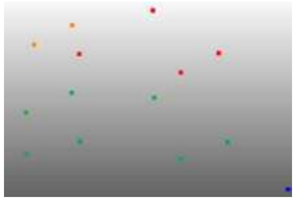
$$\min f(x) = f_{\mathcal{C}_O}(x) + \omega \mathcal{A}(x)$$

- Computational complexity
  - $O(k\, 4^{\delta} \log n)$
    - δ: depth of octree, constant

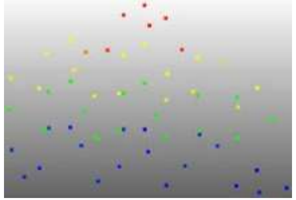


Octree (image courtesy Wikipedia)

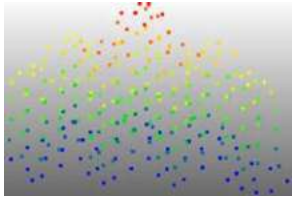




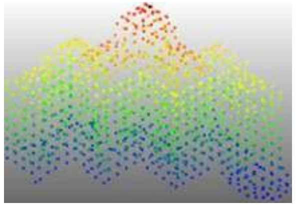
δ = 1 (14)



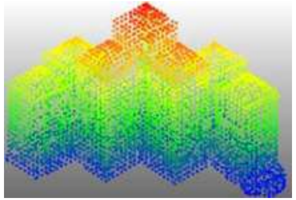
δ = 2 (58)



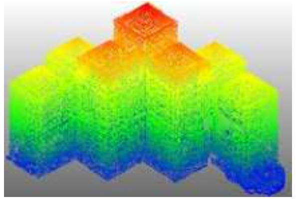
δ = 3 (295)



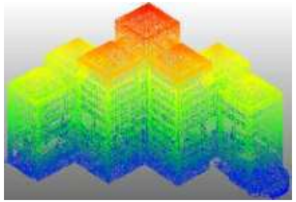
δ = 4 (1.3K)



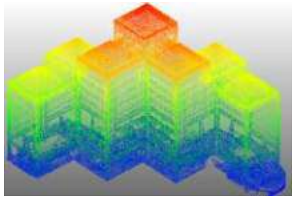
δ = 5 (5.8K)



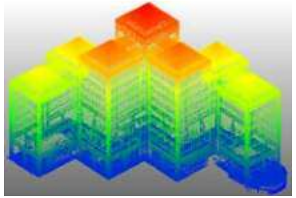
δ = 6 (0.02M)



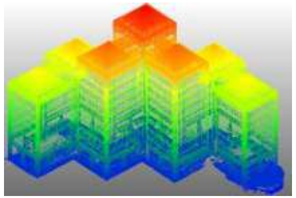
δ = 7 (0.07M)



δ = 8 (0.22M)



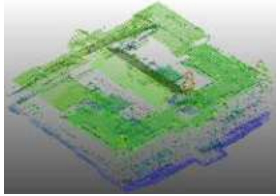
δ = 9 (0.57M)

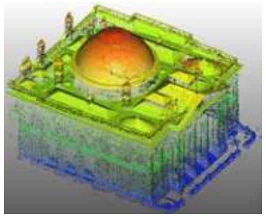


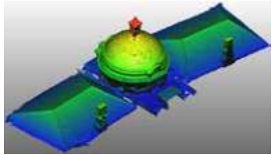
Original (1.2M)

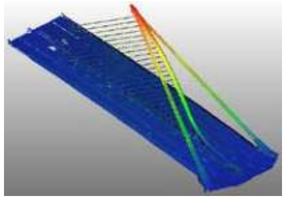
3.3 The experimental settings

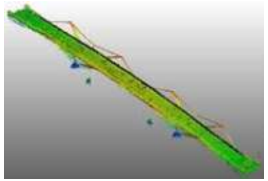
- Detecting the global symmetry of 9 cases
  - 3 heritage buildings, 3 modern, and 3 infrastructures
    - From Hong Kong and Dublin
    - n from 0.01M to 1.4M
    - Density from 4 to 2,000 points/m^2
  - With best-known correspondences (**%)
  - $\varepsilon = 0.005$

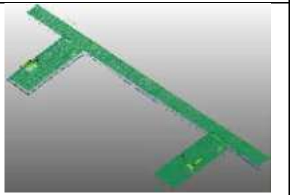

Main Building, University of Hong Kong[*] (29,756; 86.56%)

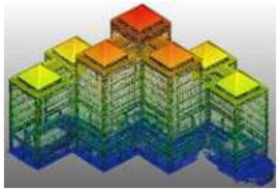

Dublin City Hall[†] (459,386; 86.14%)

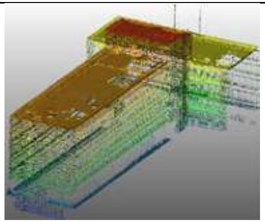

Hung Hing Ying Building, University of Hong Kong[‡] (1,413,211; 96.04%)

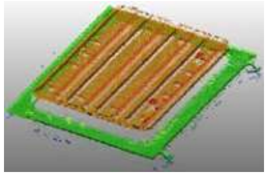

Samuel Beckett Bridge, Dublin[†] (570,338; 97.52%)


Seán O'Casey Bridge, Dublin[†] (223,213; 99.55%)


Two piers at Victoria Harbor, Hong Kong[*] (12,631; 94.84%)


One George's Quay Plaza, Dublin[†] (1,170,122; 95.50%)


47-51 O'Connell Street Upper, Dublin[†] (395,818; 97.18%)

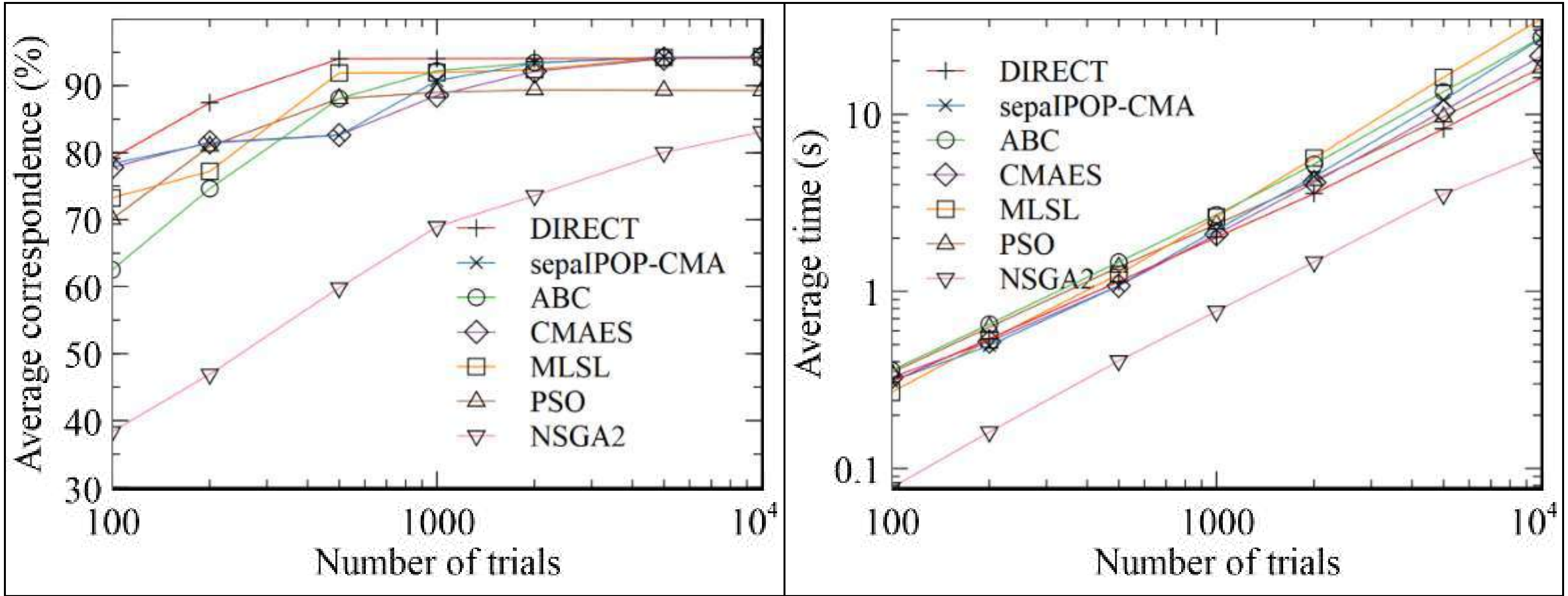

Western District Fruits Wholesale Market, Hong Kong (44,699; 96.97%)

3.3 The test DFO algorithms in *libodas*

Algorithm library	Algorithm	Description	Reference
libnsga2 **(version 0.2, available at: https://github.com/dojeda/nsga2-cpp)**	NSGA2	Non Sorting Genetic Algorithm II	(Deb et al., 2002)
popot **(version 2.13, available at: https://github.com/jeremyfix/popot)**	PSO	Particle Swarm Optimization	(Poli et al., 2007)
	ABC	Artificial Bee Colony	(Karaboga & Basturk, 2007)
libcmaes **(version 0.9.5, available at: https://github.com/beniz/libcmaes)**	CMAES	Covariance Matrix Adaptation Evolution Strategy	(Hansen et al., 2003)
	sepaIPOP-CMA	A variant of CMAES for noisy problems	(Hansen, 2009)
nlopt **(version 2.4.2, available at: https://github.com/stevengj/NLopt/)**	DIRECT	DIviding RECTangle	(Jones et al., 1993)
	MLSL-LDS	Multi-Level Single-Linkage using Low-Discrepancy Sequence	(Kucherenko & Sytsko, 2005)
(None)	Voting-clustering	Pairwise voting-clustering	(Mitra et al., 2006)

3.4 Comparison of DFO methods ($\delta = 4$)

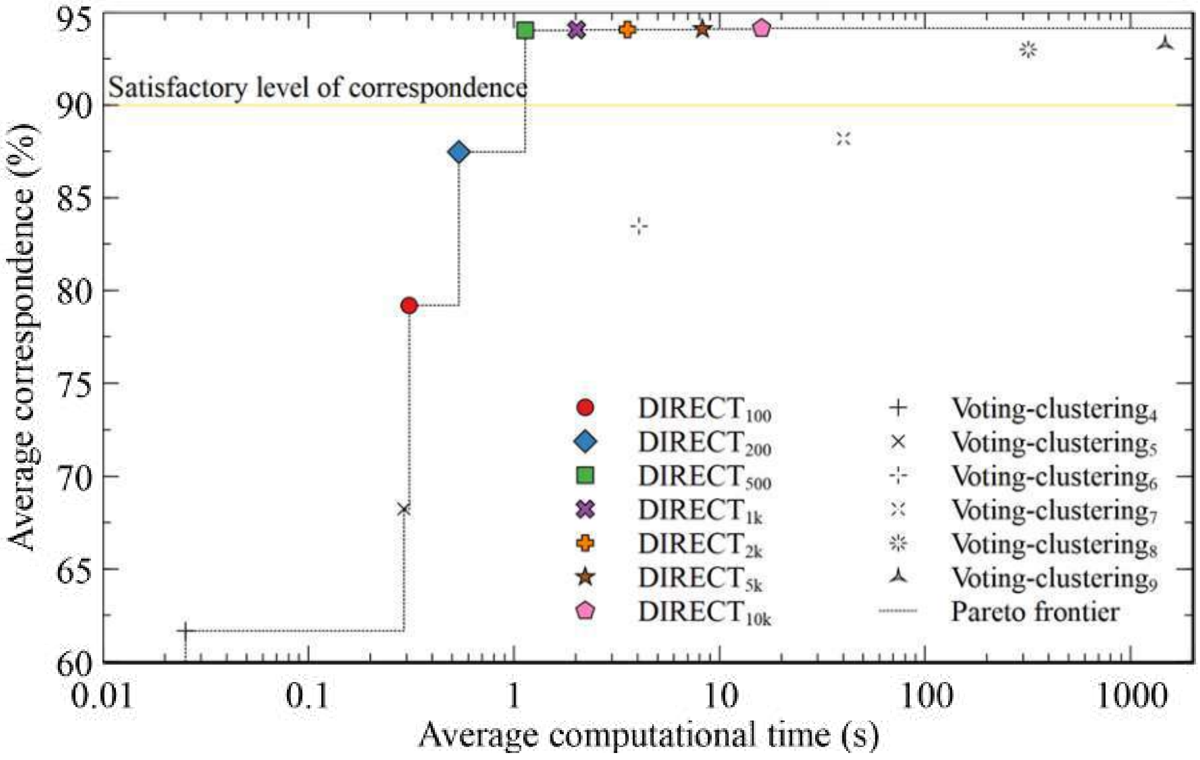
- DIRECT is the best when k < 2,000
- CMAES, sepaIPOP-CMA, ABC, MLSL are slightly better when k > 5,000



(a) Average correspondence (higher is better) | (b) Average computational time (lower is better)

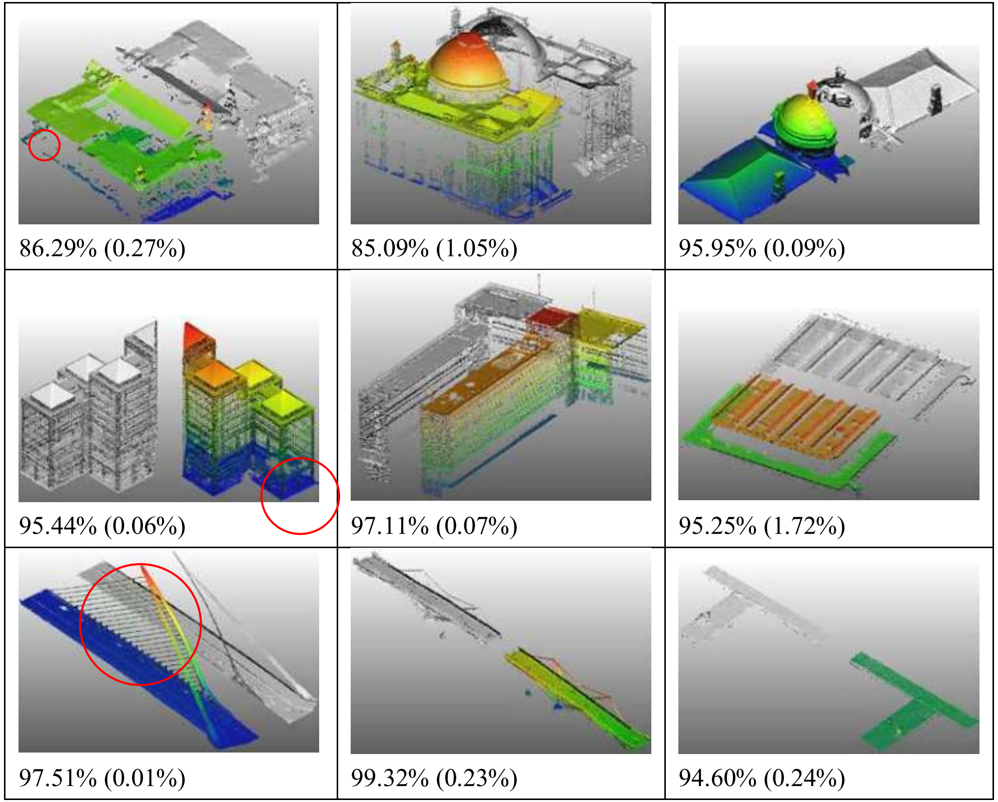
3.4 Comparison with voting-clustering

- DIRECT dominates voting-clustering
  - More accurate
  - When saving over 99.9% time
  - For a satisfactory (90%) level of correspondence
  - Except for the very unsatisfactory part (e.g., < 75% correspondence)



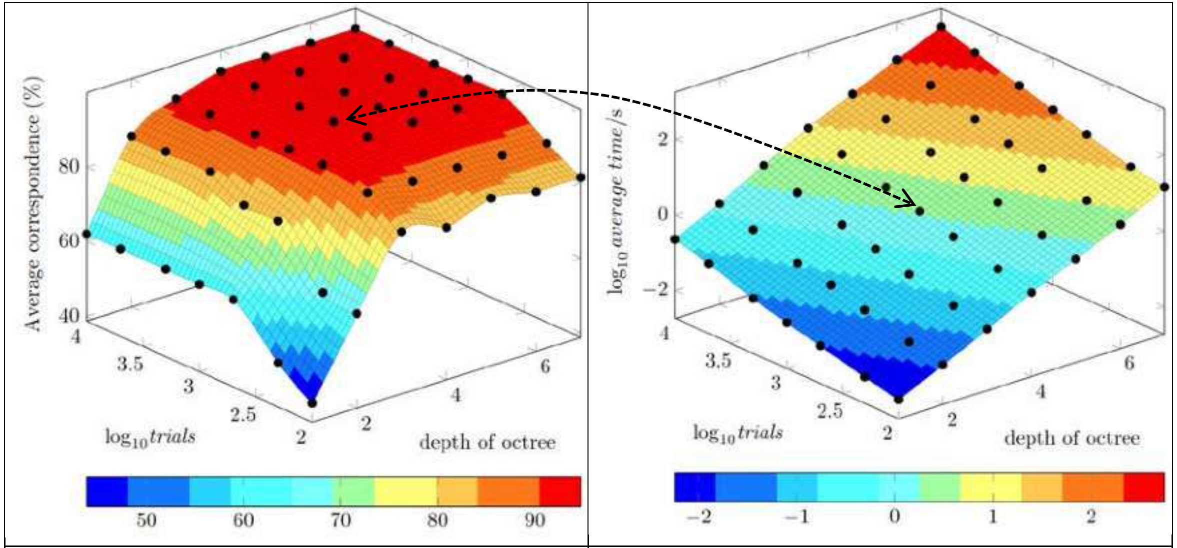
3.4 Results

- Segmentation by the detected global symmetry
  - Informative for building modeling
- All correctly detected
  - 0.01~1.72% gap to best known
  - In 0.2~4.8s
- Real objects are not perfectly symmetric, sometimes
  - As circled
  - Due to geo-location, vegetation, design, deformation, etc.



3.5 Parameter sensitivity (k, δ) (using DIRECT)

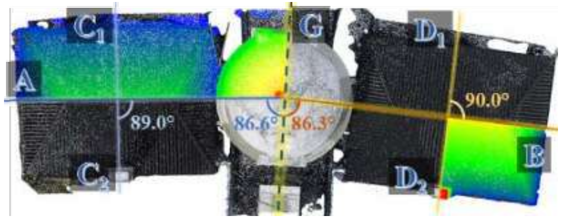
- A favorable flat plateau when $k \geq 500$, $\delta \geq 4$
- Time cost perfectly matched the complexity
  - $k = 1{,}000$, $\delta = 4$ is recommended



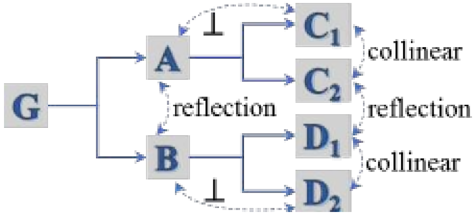
(a) Correspondence (higher is better)	(b) Computational time (lower is better)

3.6 The next steps

- From global symmetry to symmetry hierarchy (Xue et al., 2018d)
  - Emphasizing more on $\mathcal{A}(x)$ in Eq. (6)
  - Co-hierarchy analysis (collinear, perpendicular, symmetry of symmetry, etc.)
- Applications
  - Modeling buildings
    - With semantics
  - As well as cities



(b) The detected major reflections



(c) The symmetry hierarchy

(d) A symmetry-guided rooftop model

3.7 Summary

- Presented a new method for global ASD
  - For large-scale point clouds with certain noises
  - Implemented in an open source library
- Accuracy
  - better than conventional voting-clustering
  - 0.01%~1.7% gap to best-known correspondence
- Automation and efficiency
  - Fully, inexpensive (e.g., saving 99.9% time)
  - Very fast (*s* level)
- Results
  - Useful for building/city modeling and beyond

Section 4

DISCUSSION

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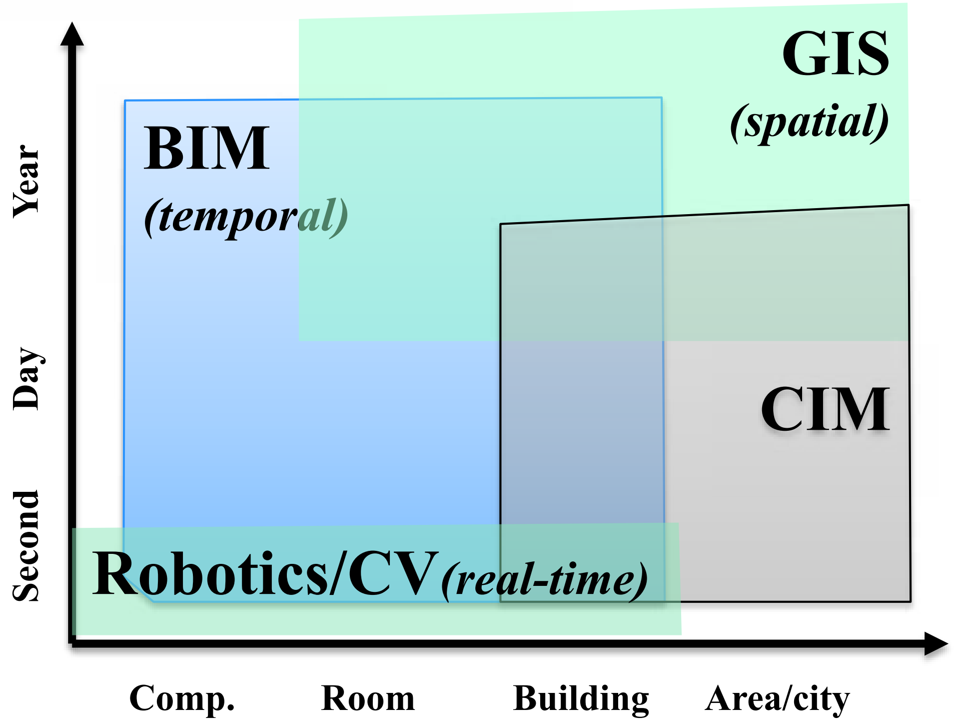
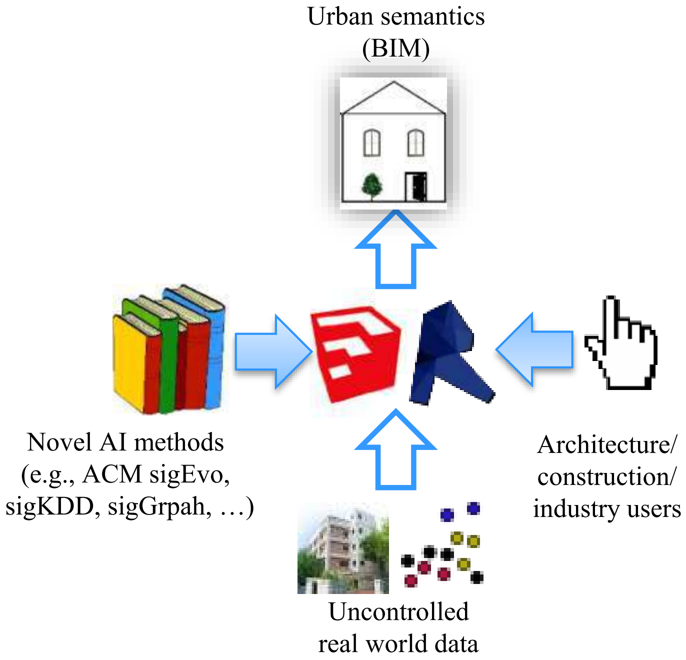
4.1 Discussion



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



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

4.2 Potential collaborations

- Inter-disciplinary inter-institutional research
  - BIM, GIS, CV, RS, AR, …
- Joint research funding
  - Hong Kong
    - **HK ITF Midstream Research Fund (MRF)**
      \$5~10 millions (<50% can go to Mainland)
    - **HK RGC Collaborative Research Fund (CRF)**
    - NSFC/RGC Joint Research Scheme
      ~\$1M + RMB 0.8M
  - Shenzhen
    - Guangdong - Hong Kong Technology Cooperation Funding Scheme (TCFS)
  - Greater Bay Area
    - 重点技术联合创新基金 (still inception)

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Thank You !

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