

大规模复杂场景三维重建与理解

申抒含

中国科学院自动化研究所

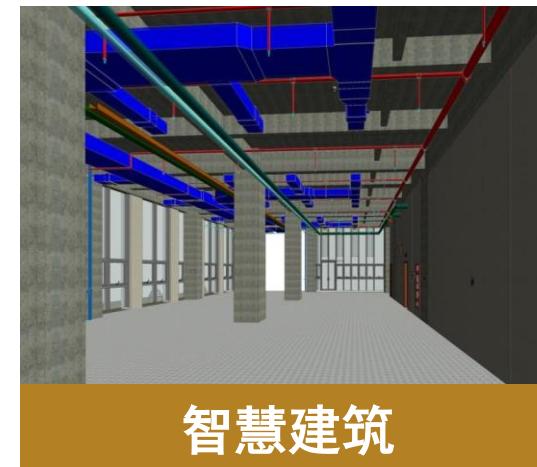
大规模复杂场景三维重建与理解



数字城市



无人系统



智慧建筑



导航定位

共性需求：室内外场景三维重建与理解（低成本、高精度、全自动、高效率）

大规模复杂场景三维重建与理解



相机标定
三维重建
场景理解
...

计算机视觉

Structure from Motion
Multiple View Stereo
Semantic Segmentation
Scene Completion

计算机图形学

Mesh Modeling
Mesh Optimization
Texture Mapping
Rendering

几何优化
可视化
VR/AR/XR
...

大规模复杂场景 三维重建与理解

GIS
BIM
实景三维
...

摄影测量

Oblique Photograph
Aerial Triangulation
Tin Mapping
DSM/DEM/DTM

机器人

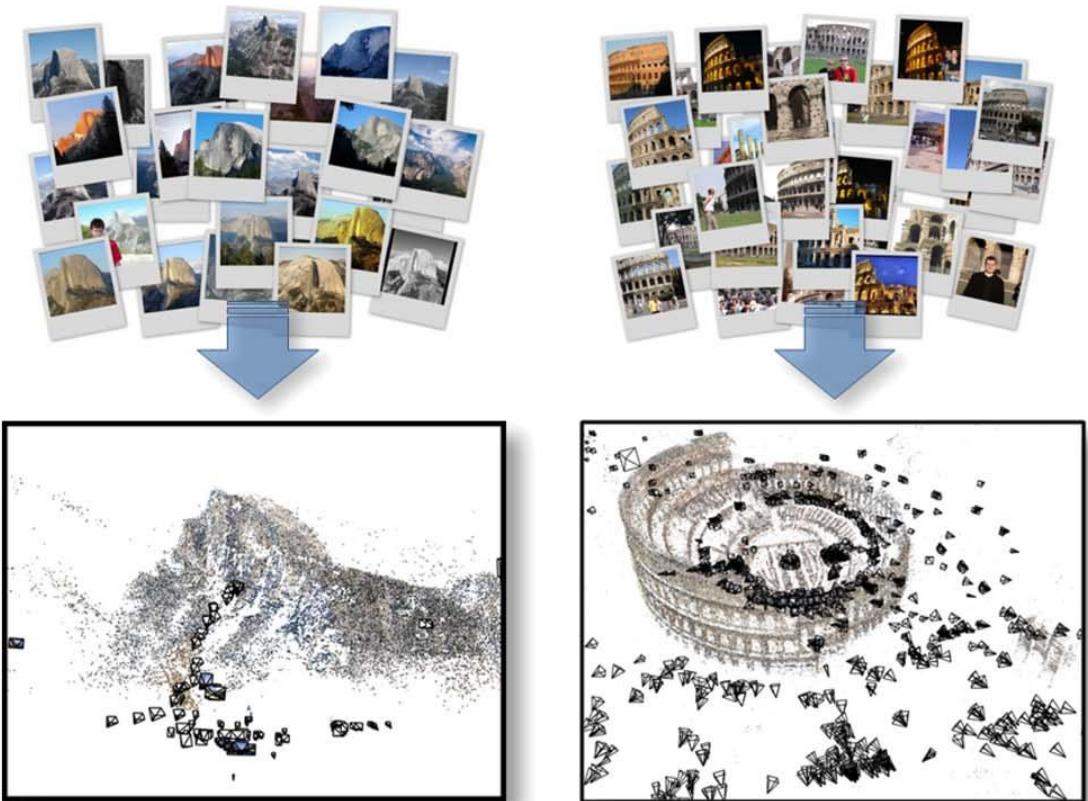
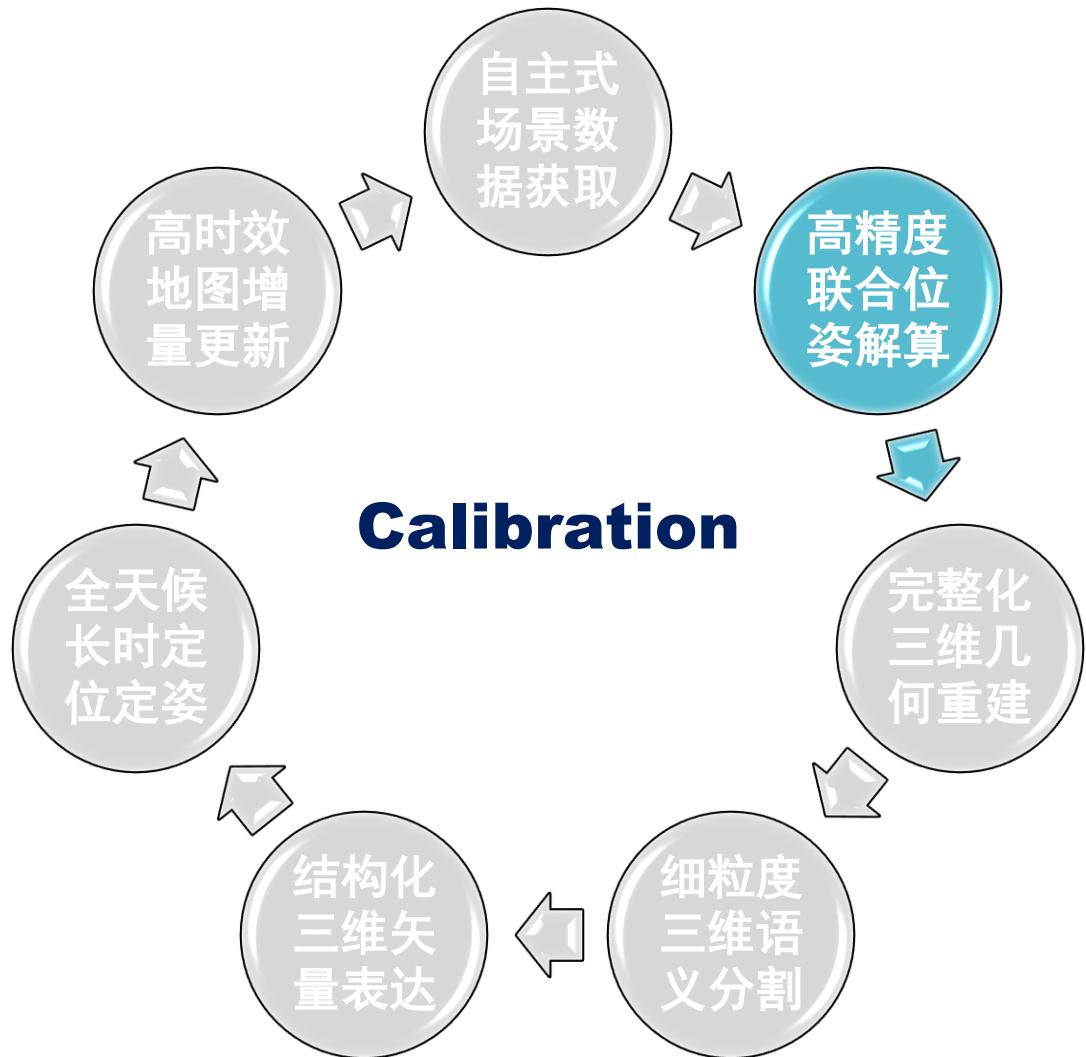
SLAM
Odometry
Re-Localization
Planning

构图定位
路径规划
导航避障
...

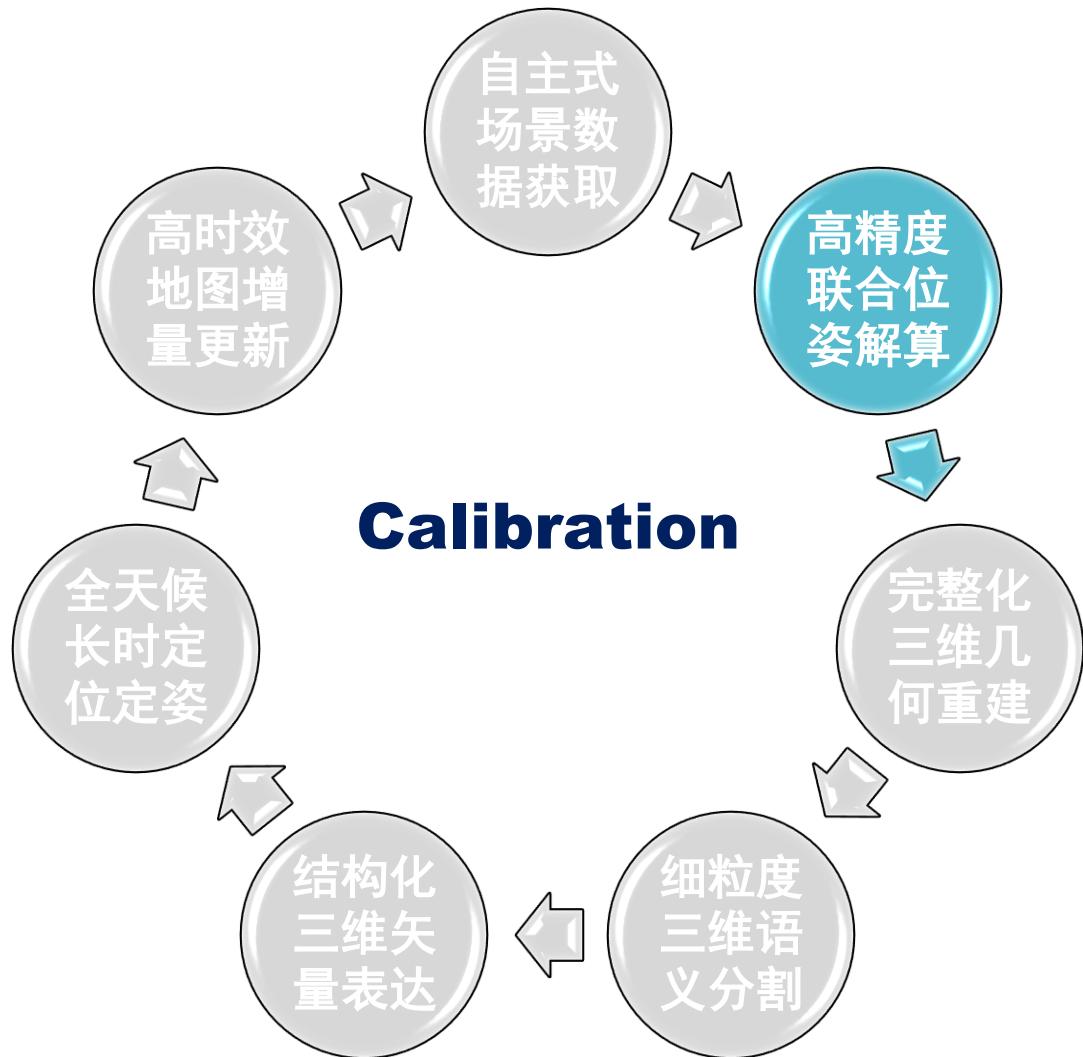
大规模复杂场景三维重建与理解系统



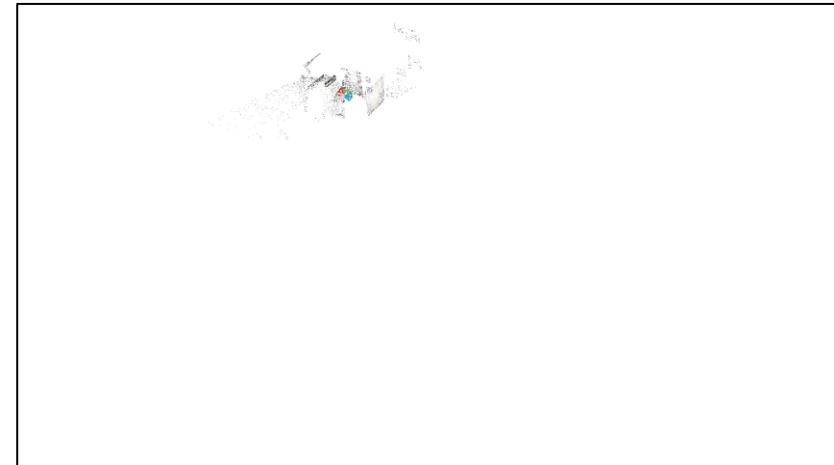
高精度联合位姿解算



高精度联合位姿解算



Structure-from-Motion, SfM



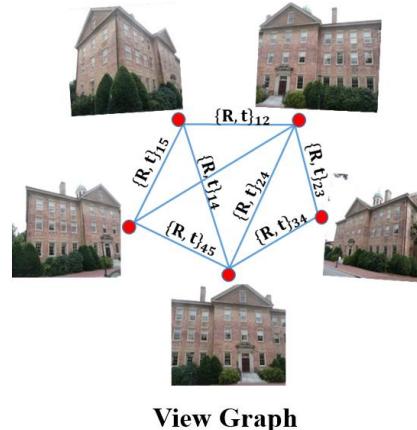
Simultaneous Localization and Mapping, SLAM

高精度联合位姿解算 — Structure-from-Motion



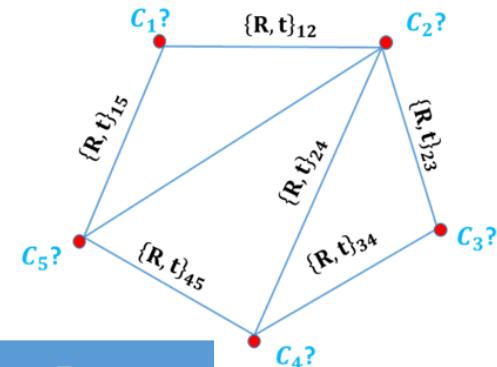
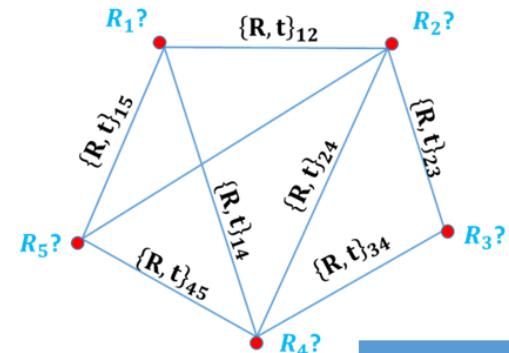
Incremental Structure-from-Motion (增量式):

- 两视图种子图像重建
- — 增量注册新图像
- 重新三角化场景点
- 局部Bundle adjustment
- 全局Bundle adjustment



Global Structure-from-Motion (全局式):

- 全局旋转平均(Rotation Averaging)
- 全局平移平均(Translation Averaging)
- 三角化场景点
- 全局Bundle adjustment



$$R_{ij} = R_j R_i^T$$
$$\lambda_{ij} t_{ij} = R_j(C_i - C_j)$$

高精度联合位姿解算 — Global SfM



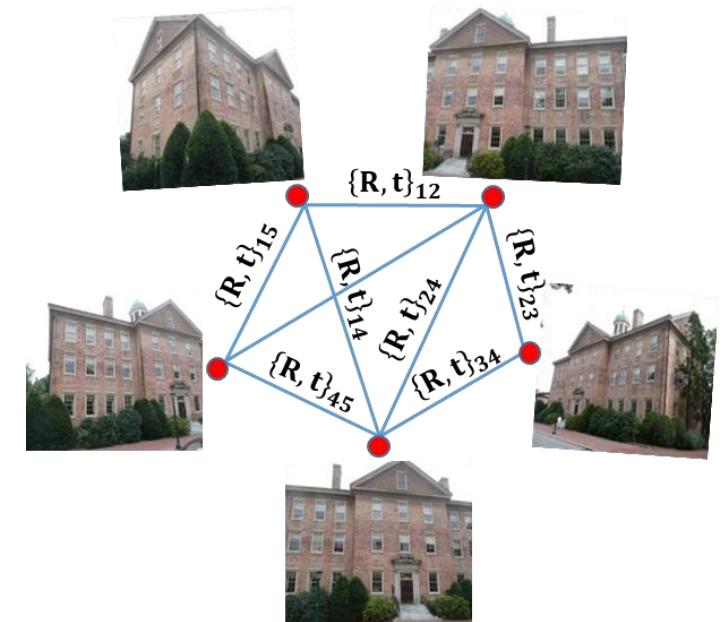
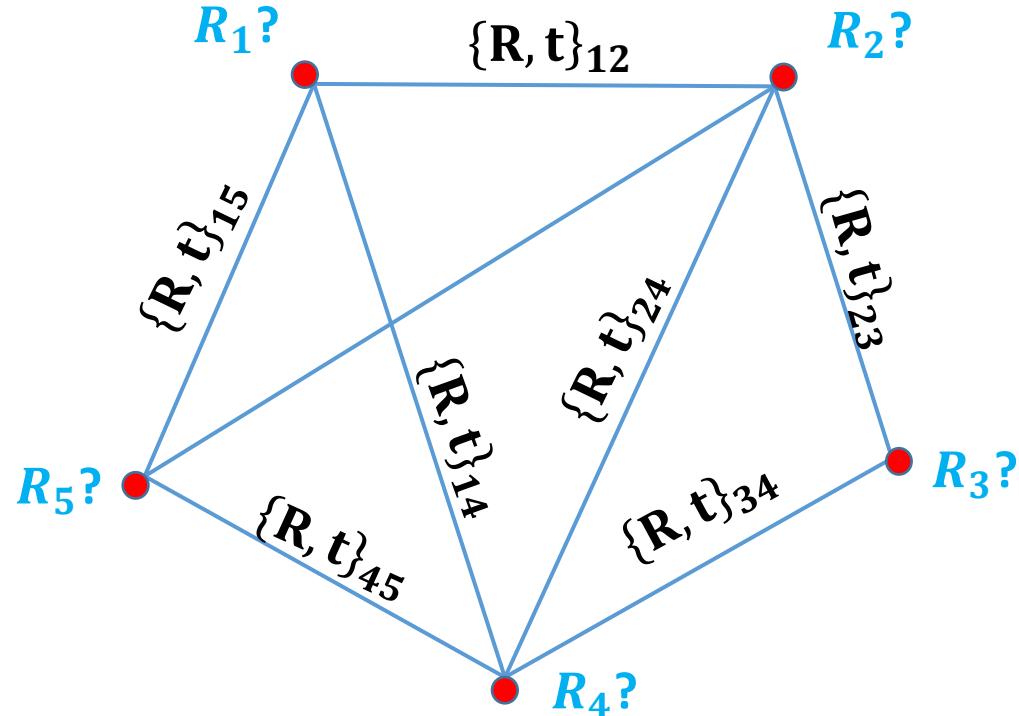
Global Rotation Averaging

$$R_{ij} = R_j R_i^T$$



$$\min_R \|R_{ij} - R_j R_i^T\|^2$$

Solver: Lie algebra in $\mathfrak{so}(3)$ $\rightarrow \mathcal{L}1$ averaging $\rightarrow \mathcal{L}2$ averaging

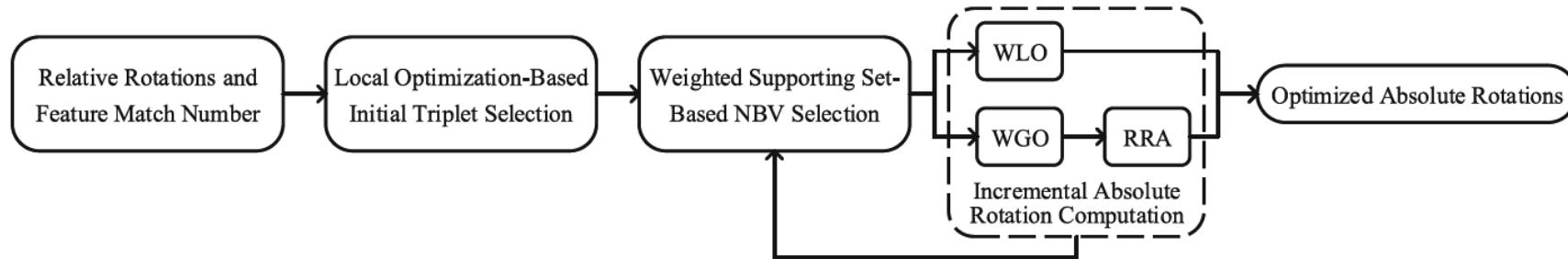


View Graph

Incremental Rotation Averaging

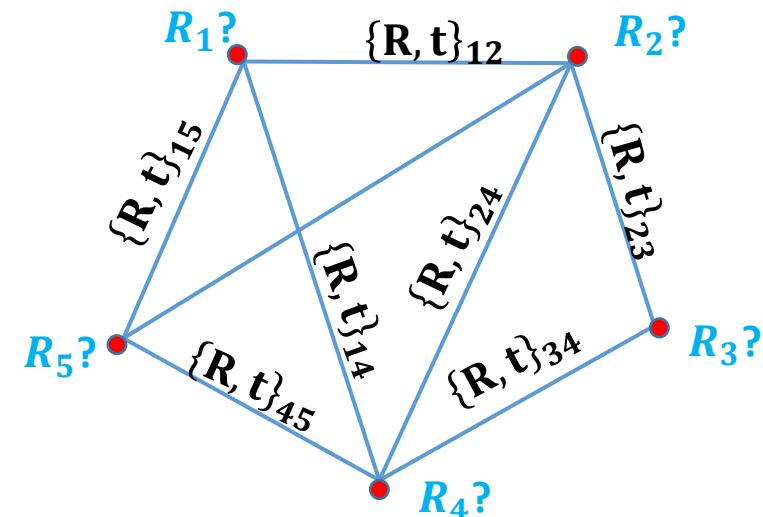
Xiang Gao, Lingjie Zhu, Zexiao Xie, Hongmin Liu, Shuhan Shen

International Journal of Computer Vision 2021



主要思想：

- Instead of estimating all rotations $\{R_i\}$ **simultaneously**, they are estimated in an **incremental** way.
- Local Optimization-Based Initial Triplet Selection.
- Weighted Supporting Set-Based NBV Selection.
- Weighted Local/Global Optimization.
- Re-Rotation Averaging.



高精度联合位姿解算 — IRA

➤ Weighted Supporting Set-Based NBV Selection

\mathcal{V}_1 and \mathcal{V}_2 : vertex sets currently absolute rotations estimated or not, i.e. $\mathcal{V}_1 \cup \mathcal{V}_2 = \mathcal{V}$.

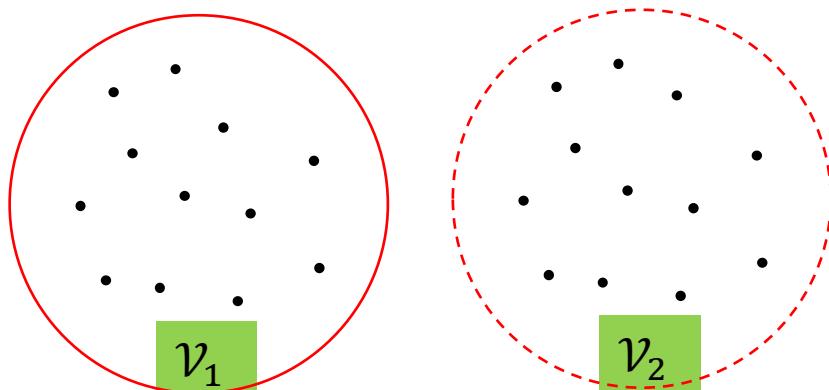
\mathcal{E}_{1m} : edge set between a vertex v_m in \mathcal{V}_2 and the vertices in \mathcal{V}_1 .

Initialize the absolute rotation of v_m with \mathcal{E}_{1m} by: $\{\mathbf{R}_m^i = \mathbf{R}_{im} \mathbf{R}_i | e_{im} \in \mathcal{E}_{1m}\}$.

Compute the selection cost by: $c_m^i = \sum_{e_{jm} \in \mathcal{E}_{1m}} \cos(d_\theta(\mathbf{R}_m^i, \mathbf{R}_m^j))$.

Select the dominant edge for v_m by: $e_{i^*m} = \arg \max \{c_m^i | e_{im} \in \mathcal{E}_{1m}\}$.

Select the vertex as NBV by: $v_{m^*} = \arg \max \{c_m^{i^*} | v_m \in \mathcal{V}_2\}$.



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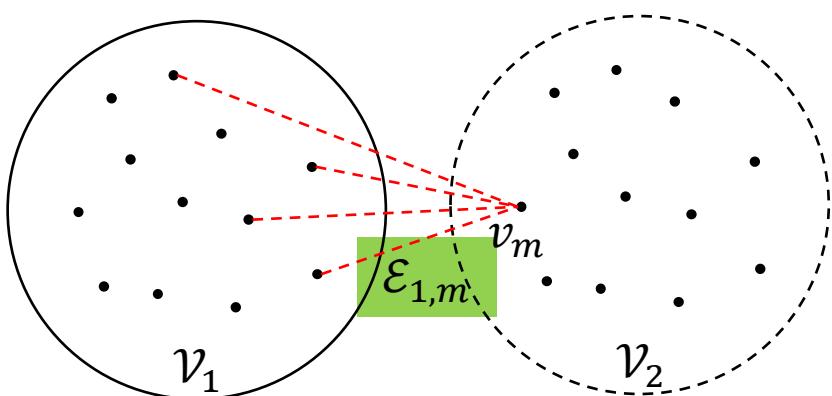
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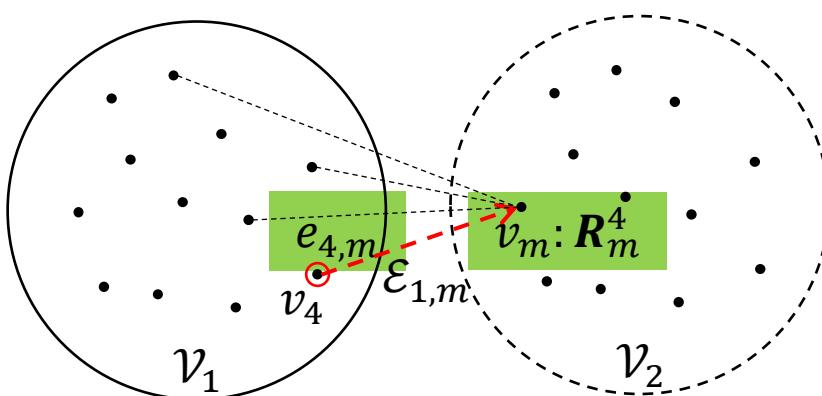
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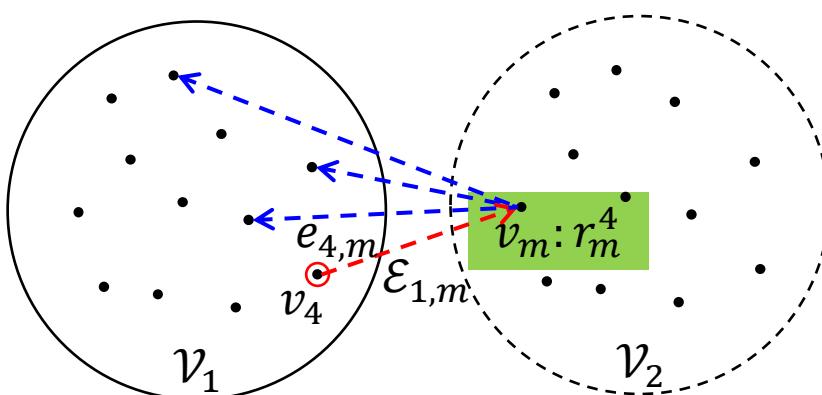
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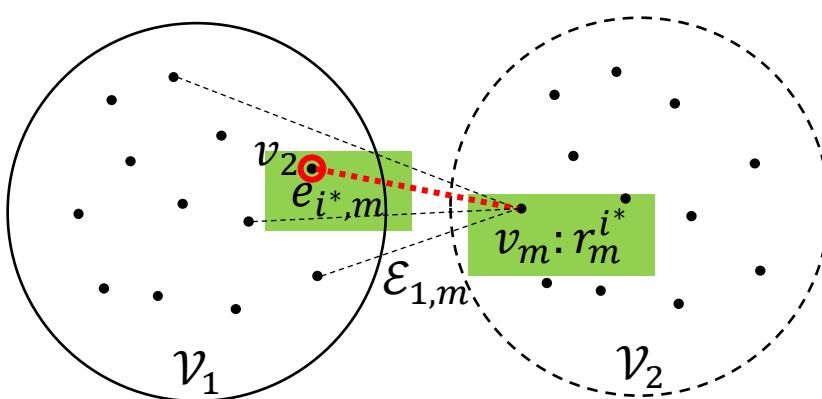
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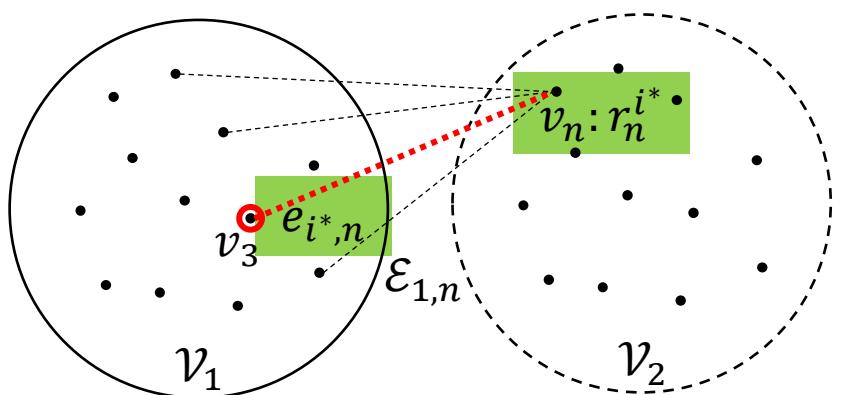
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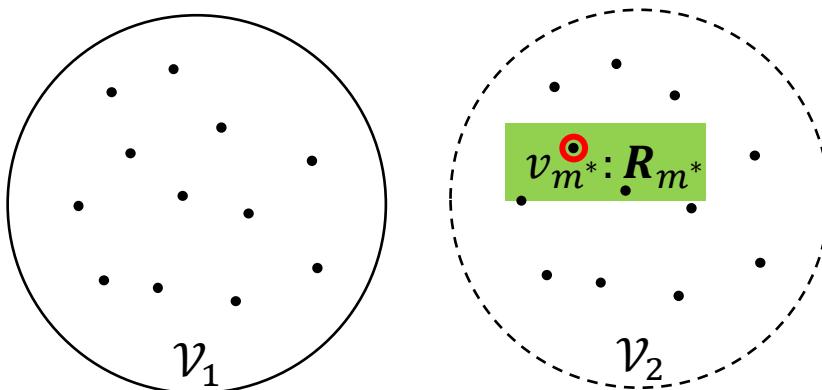
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高精度联合位姿解算 — IRA



COMPARATIVE RESULTS IN ROTATION AVERAGING ACCURACY ON THE 1DSFM DATASET: FIRST SECOND THIRD FORTH .

Data	IRLS-GM [15]	IRLS- $\ell_{\frac{1}{2}}$ [16]	MPLS [18]	OMSTs [35]	HRRA [26]	HARA [21]	NeuRoRA [17]	MSPRA [19]	RAGO [22]	IRA [23]	IRA++ [24]	IRAv3
ALM	2.12°	2.14°	1.16°	1.26°	1.03°	1.15°	1.16°	1.07°	0.88°	0.83°	0.80°	0.73°
ELS	1.08°	1.15°	0.88°	0.75°	0.59°	0.62°	0.64°	0.83°	0.46°	0.51°	0.46°	0.44°
GDM	35.83°	28.20°	9.87°	45.15°	4.04°	63.74°	2.94°	3.69°	2.68°	5.32°	2.88°	1.99°
MDR	4.52°	3.08°	1.26°	1.12°	2.54°	1.50°	1.13°	1.09°	1.03°	0.85°	0.83°	0.75°
MND	0.77°	0.71°	0.51°	0.68°	0.62°	0.51°	0.60°	0.50°	0.46°	0.51°	0.50°	0.44°
NYC	1.43°	1.40°	1.24°	1.30°	1.24°	1.37°	1.18°	1.12°	0.71°	1.00°	0.95°	0.82°
PDP	2.16°	2.62°	1.93°	1.73°	0.92°	0.92°	0.79°	0.76°	0.63°	0.90°	0.75°	0.72°
PIC	4.14°	3.12°	1.81°	1.41°	4.87°	3.22°	1.91°	1.80°	0.58°	1.67°	1.70°	1.50°
ROF	1.62°	1.70°	1.37°	1.85°	2.48°	2.42°	1.31°	1.19°	1.10°	1.51°	1.24°	1.09°
TOL	2.59°	2.45°	2.20°	2.10°	2.05°	2.36°	1.46°	1.25°	1.20°	2.45°	1.33°	1.44°
TFG	1.94°	2.03°	—	2.63°	4.88°	2.06°	2.25°	—	1.53°	3.30°	1.74°	1.49°
USQ	4.93°	4.97°	3.48°	3.83°	3.77°	4.78°	2.01°	1.85°	1.92°	4.40°	3.70°	3.27°
VNC	4.87°	4.64°	2.83°	3.30°	1.84°	1.49°	1.50°	1.10°	0.89°	1.02°	0.94°	0.86°
YKM	1.70°	1.62°	1.45°	1.55°	1.57°	1.65°	0.99°	0.91°	0.92°	1.57°	1.38°	1.36°
Rank	10.64	10.29	7.46	8.21	8.00	8.50	5.93	4.23	2.00	5.93	3.36	1.93

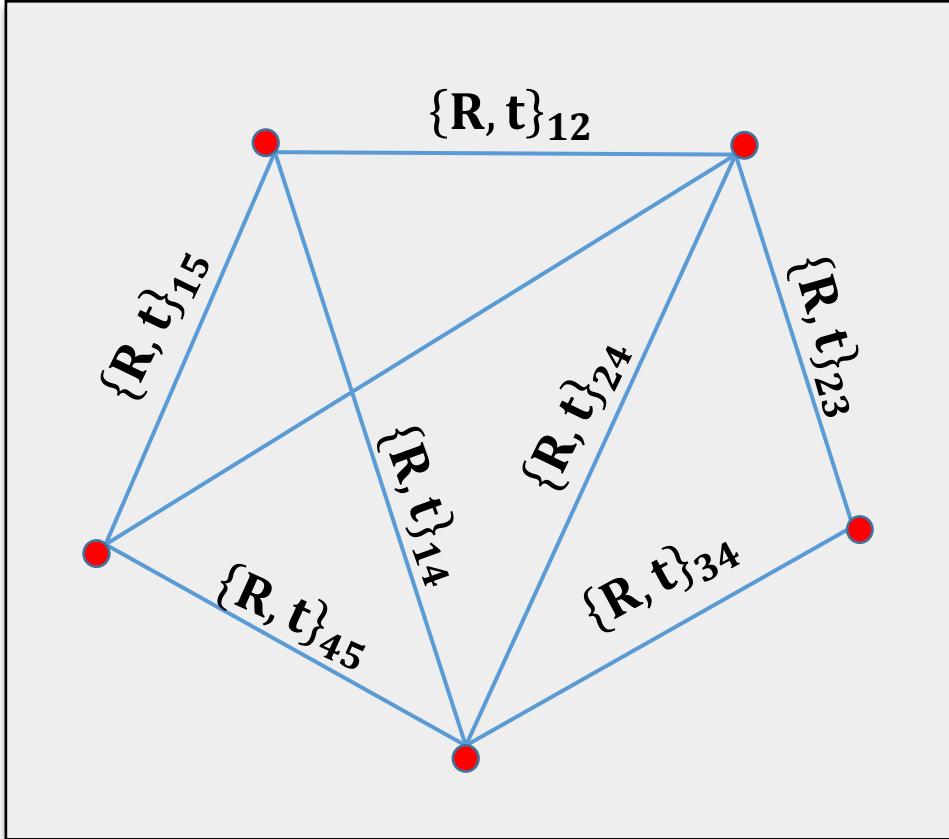
MPLS: Y. Shi and G. Lerman, Message passing least squares framework and its application to rotation synchronization, *ICML* 2020.

OMSTs: H. Cui et al., Efficient and robust large-scale structure-from-motion via track selection and camera prioritization. *ISPRS JPRS* 2019.

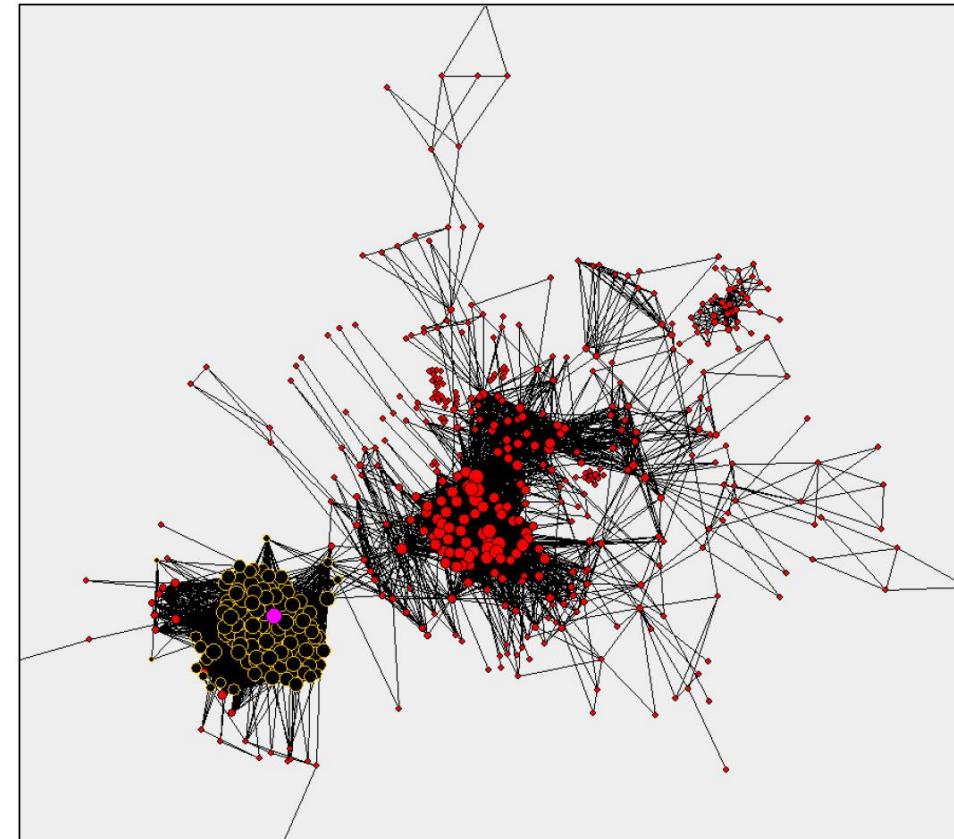
HARA: S. H. Lee and J. Civera, HARA: A hierarchical approach for robust rotation averaging, *CVPR* 2022.

RAGO: H. Li, et al., RAGO: Recurrent graph optimizer for multiple rotation averaging. *CVPR* 2022.

高精度联合位姿解算 — IRA



Easy



Hard

高精度联合位姿解算 — IRA++ / IRAv3 / ITA

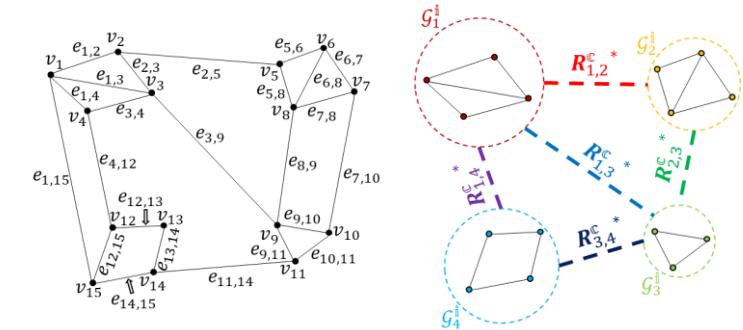


IRA++: Distributed Incremental Rotation Averaging

Xiang Gao, Lingjie Zhu, Hainan Cui, Zexiao Xie, Shuhan Shen

IEEE Transactions on Circuits and Systems for Video Technology 2022

主要思想: View Graph自适应分组, 抑制误差传播

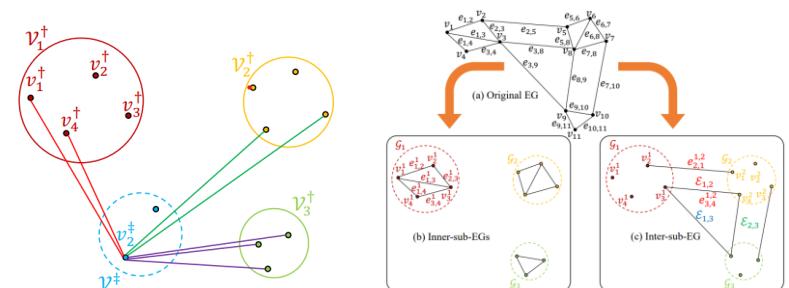


IRAv3: Hierarchical Incremental Rotation Averaging on the Fly

Xiang Gao, Hainan Cui, Menghan Li, Zexiao Xie, Shuhan Shen

IEEE Transactions on Circuits and Systems for Video Technology 2022

主要思想: View Graph动态分组, 抑制图初始误差

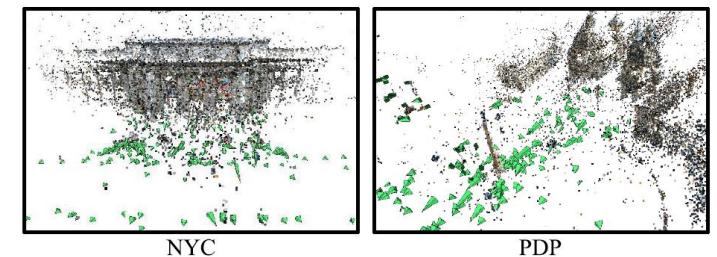


Incremental Translation Averaging

Xiang Gao, Lingjie Zhu, Bin Fan, Hongmin Liu, Shuhan Shen

IEEE Transactions on Circuits and Systems for Video Technology 2022

主要思想: 增量式平移平均, 实现完整重建



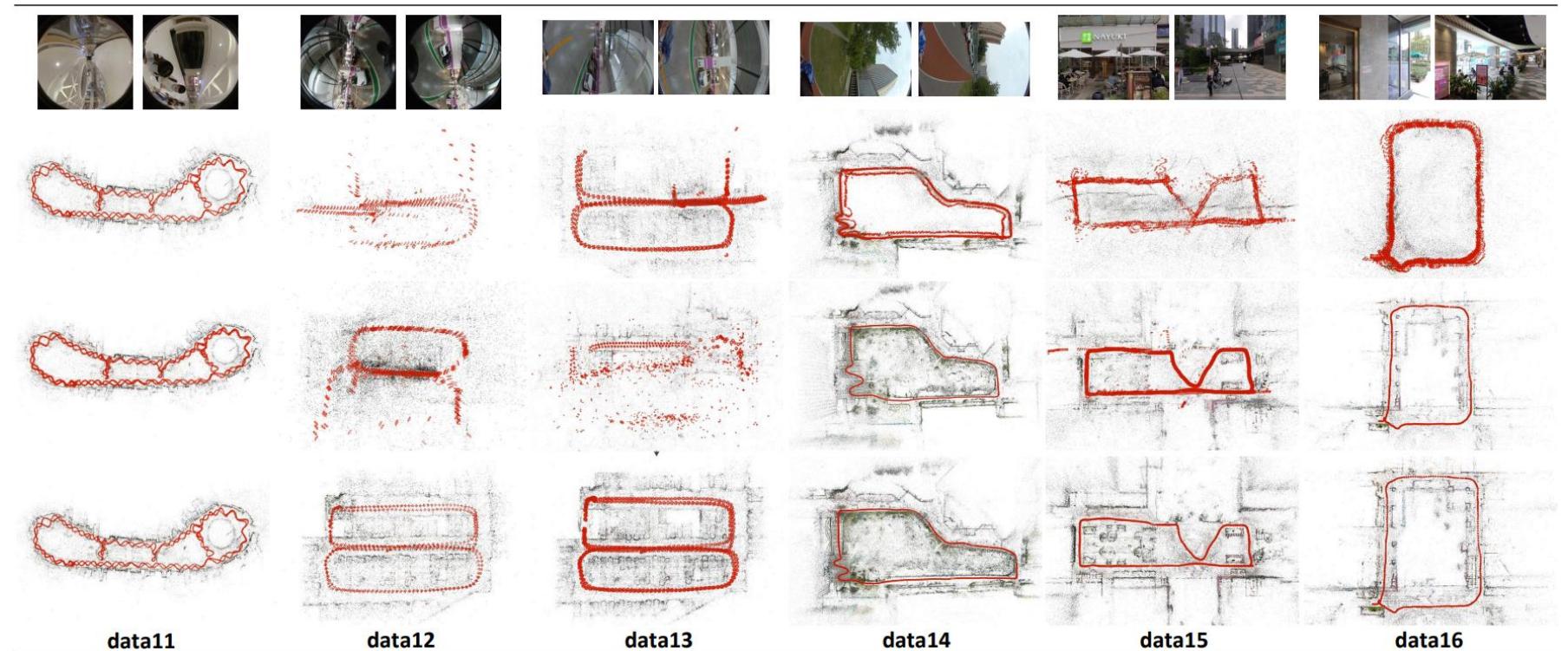
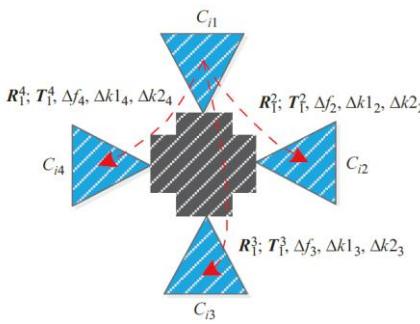
高精度联合位姿解算 — MMA



MMA: Multi-camera Motion Averaging

Hainan Cui, Shuhan Shen

AAAI 2022



Dual-fisheye

Six-fisheye

Eight-perspective

高精度联合位姿解算 — Global SfM



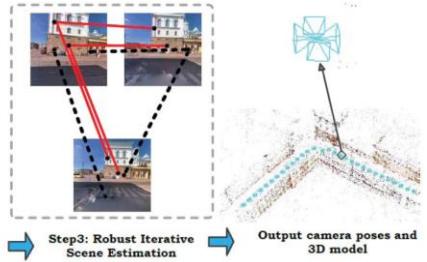
IRA / IRA++ / IRAv3 / ITA / MMA, and many other Global SfM methods

- 😊 效率很高、一致性更好、
- 😢 鲁棒性有限、场景缺失、

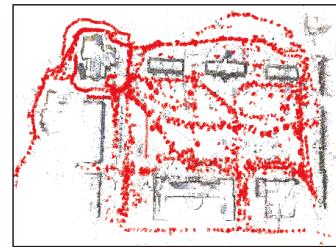
Incremental SfM methods

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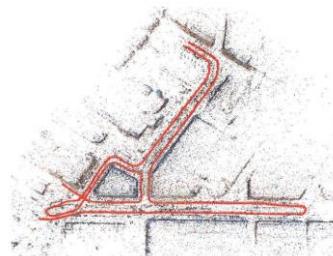
高精度联合位姿解算 — Efficient Incremental SfM



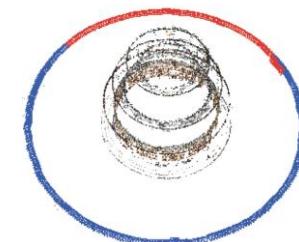
Auxiliary SfM
IEEE TIP 2015
GNSS辅助稀疏重建



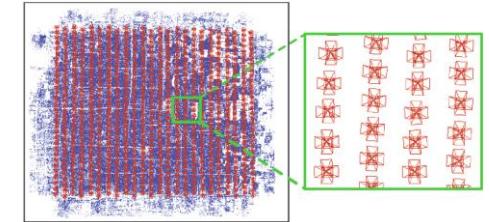
Batched SfM
3DV 2017
批量式稀疏重建



Hybrid SfM
CVPR 2017
混合式稀疏重建



Progressive SfM
3DV 2018
渐进式稀疏重建



Tracks Selection in SfM
ISPRS JPRS 2019
匹配序列约简重建



Aerial and Ground Fusion
ISPRS JPRS 2018
天地图像融合重建

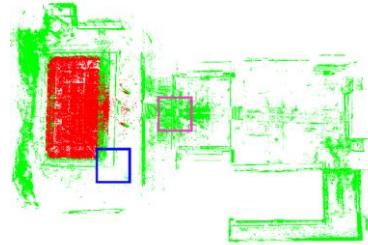
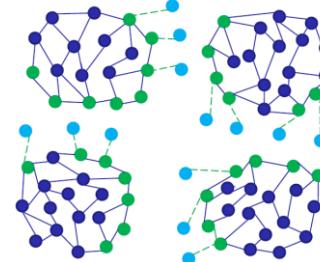
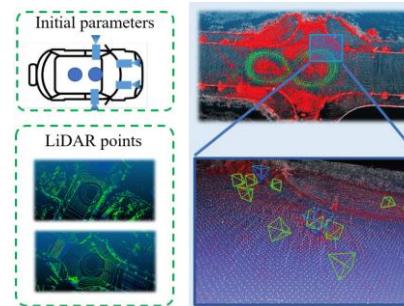


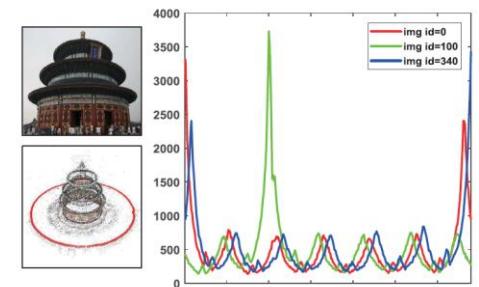
Image and Laser Fusion
IEEE TCSVT 2020
图像-激光融合重建



Parallel SfM
PR 2020
分布式稀疏重建



Multi-Camera-LiDAR SfM
IROS 2022
多相机-多激光稀疏重建

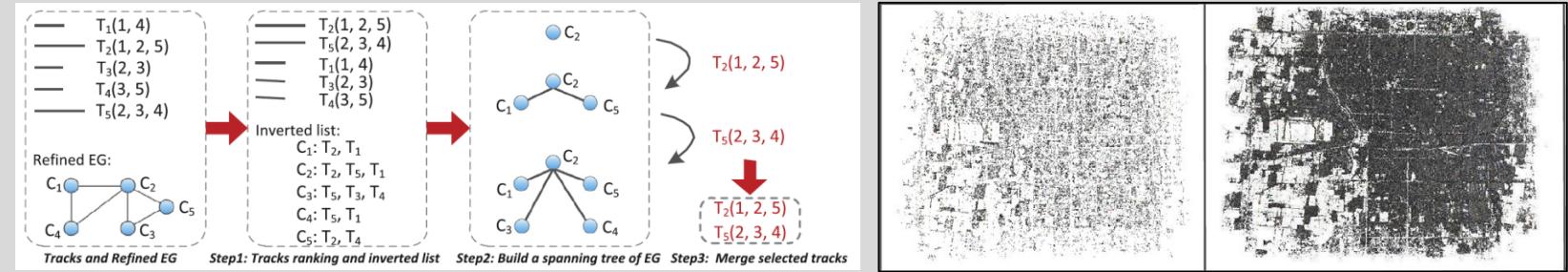


VidSfM
IEEE TIP 2022
多视频序列稀疏重建

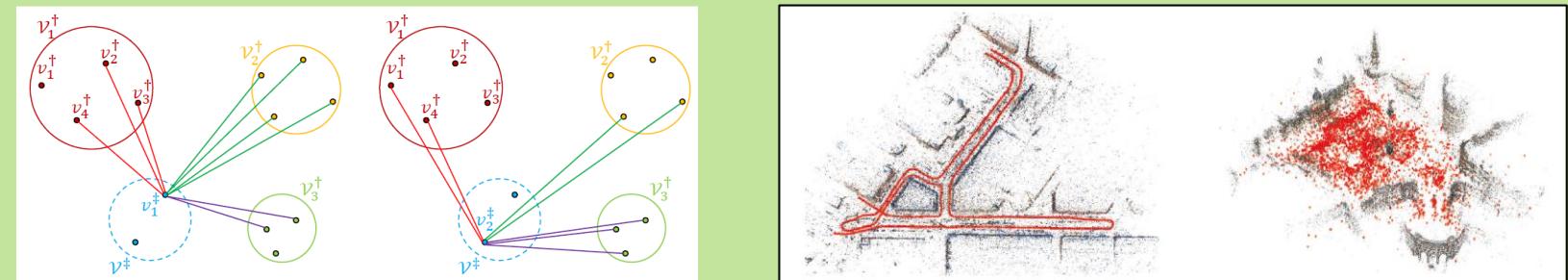
高精度联合位姿解算 — Efficient Incremental SfM



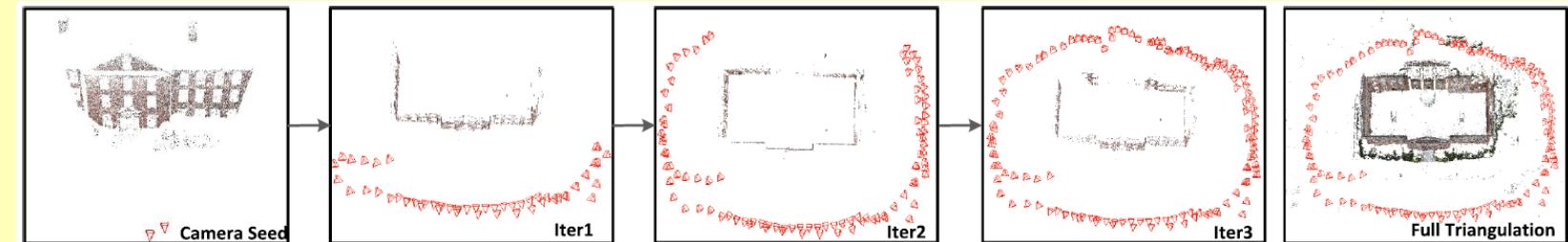
● Tracks Selection



● RA Supervision



● Camera Prioritization



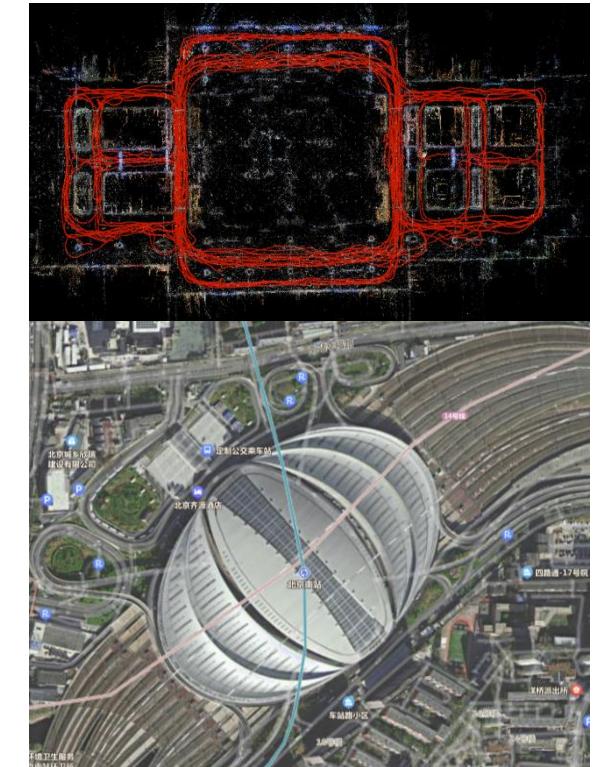
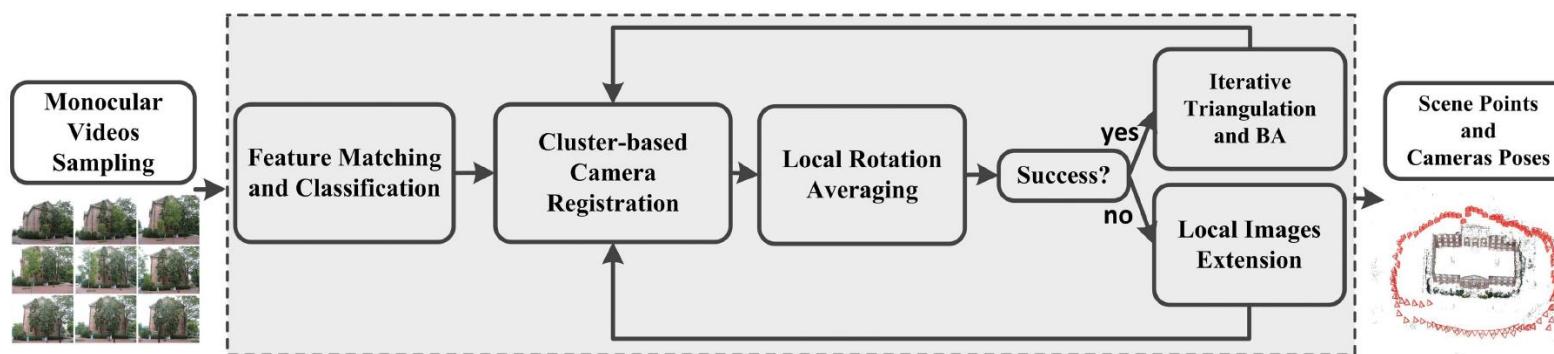
高精度联合位姿解算 — VidSfM



VidSfM: Robust and Accurate Structure-from-Motion for Monocular Videos

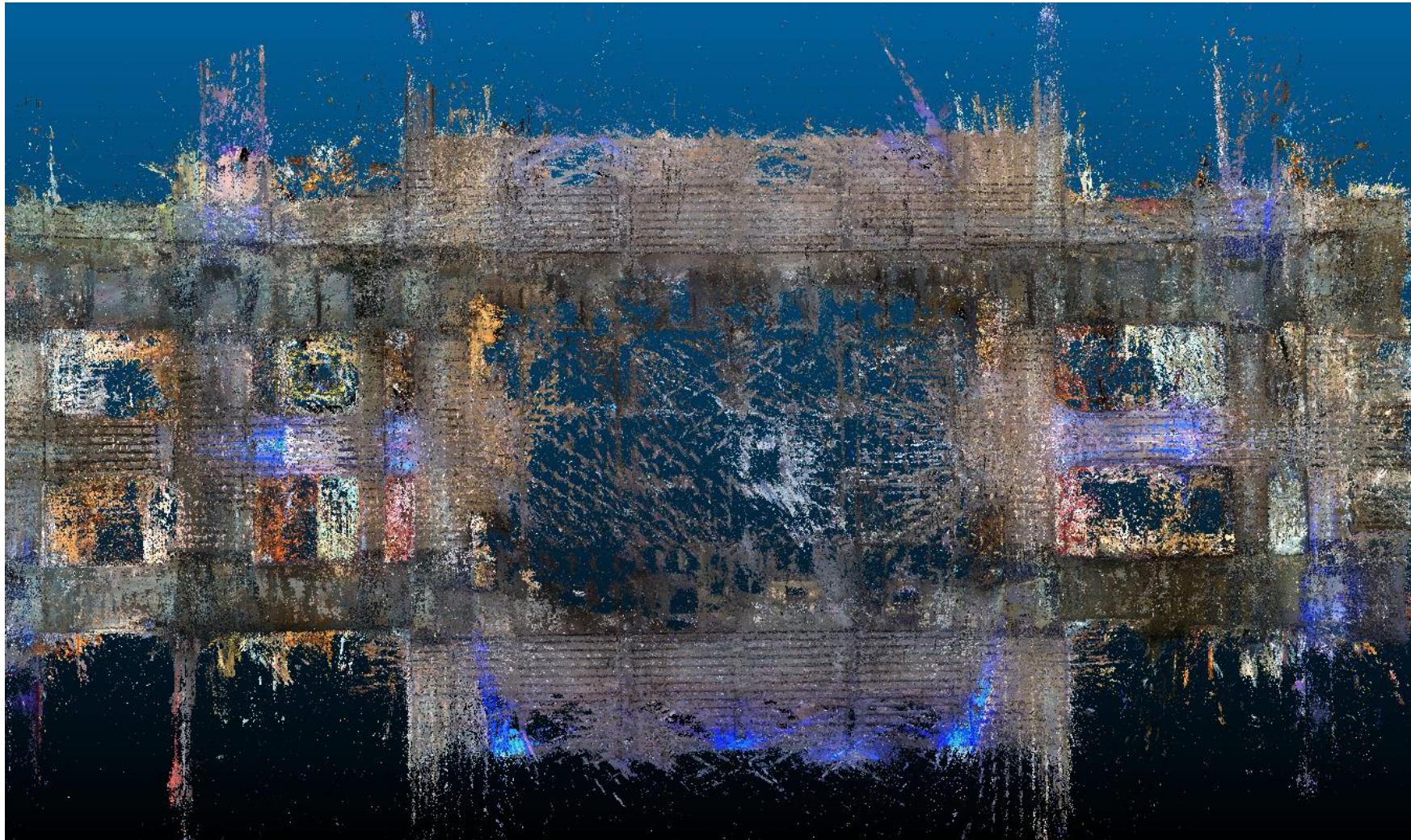
Hainan Cui, Diantao Tu, Fulin Tang, Pengfei Xu, Hongmin Liu, Shuhan Shen

IEEE Transactions on Image Processing 2022



Beijing South Railway Station
60,000 m²

高精度联合位姿解算 — VidSfM



北京南站B1层到达区（2.5小时手机视频，6万平方米室内区域）

高精度联合位姿解算—多类型三维重建系统



自主式
场景数
据获取

高精度
联合位
姿解算



航拍三维建模系统



地面全景三维建模系统

勾化
准矢
表达

细粒度
三维语
义分割

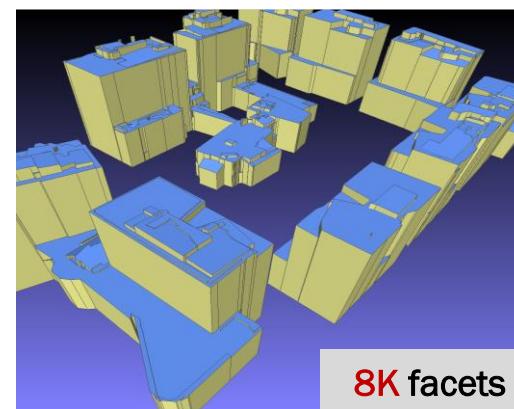
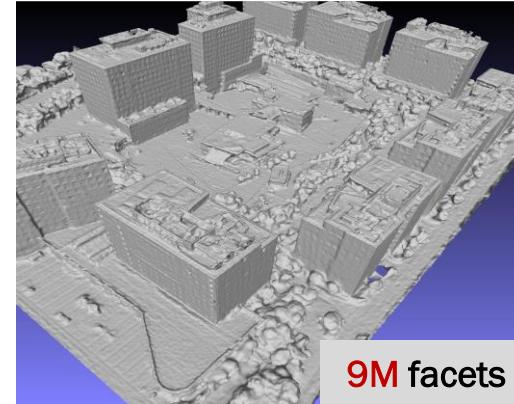
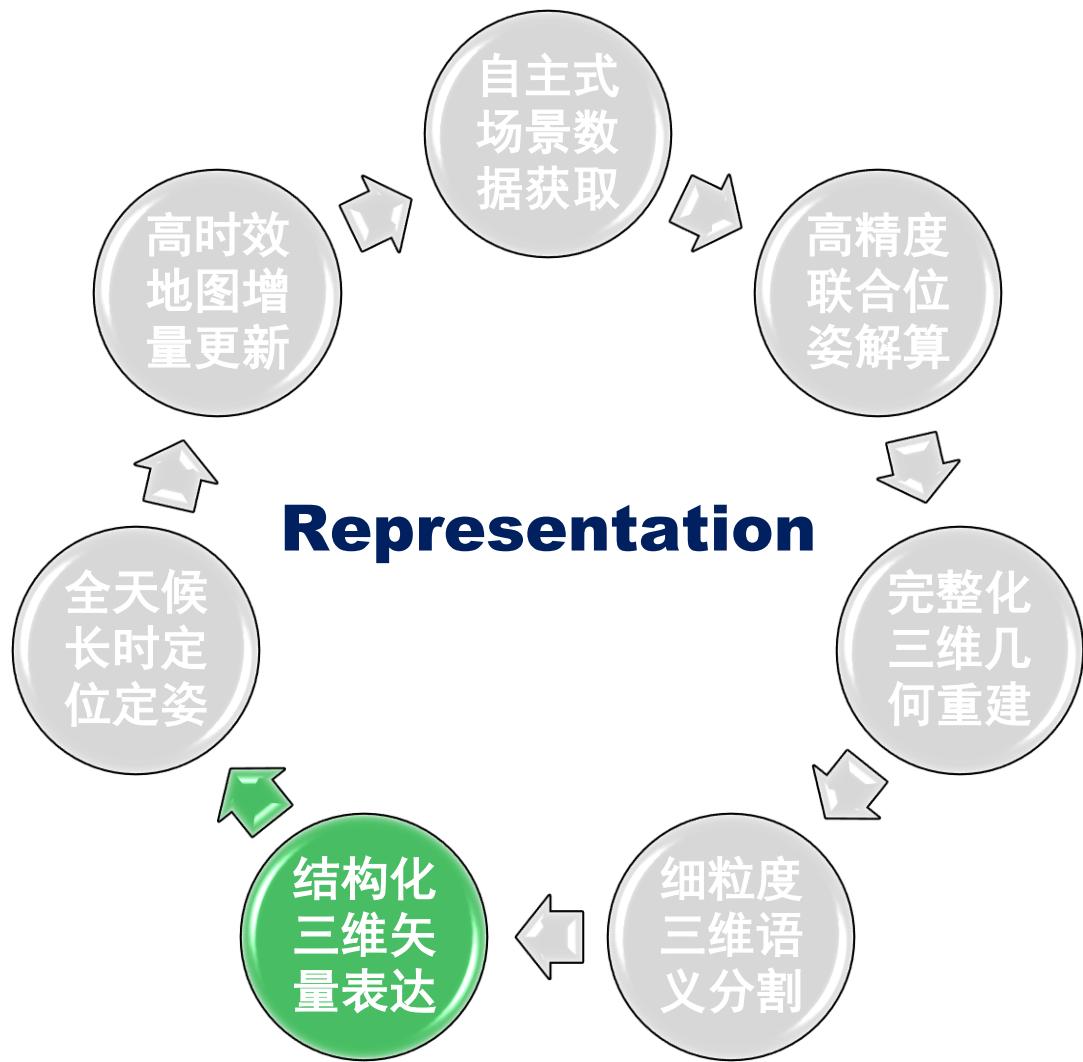


道路三维建模系统

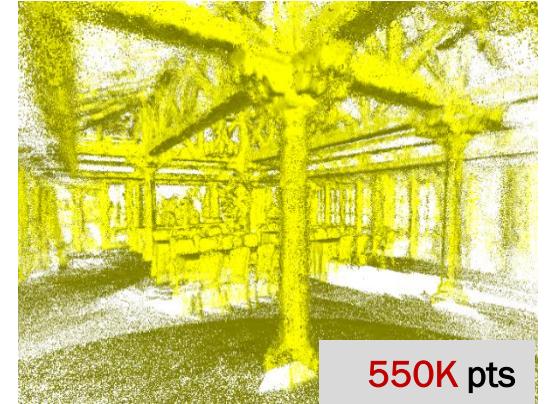


中国古建三维建模系统

结构化三维矢量表达

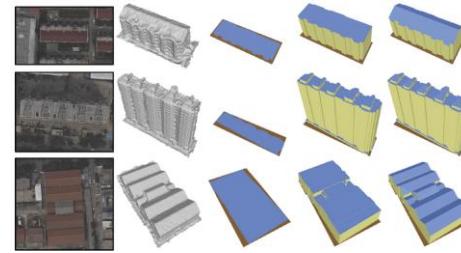
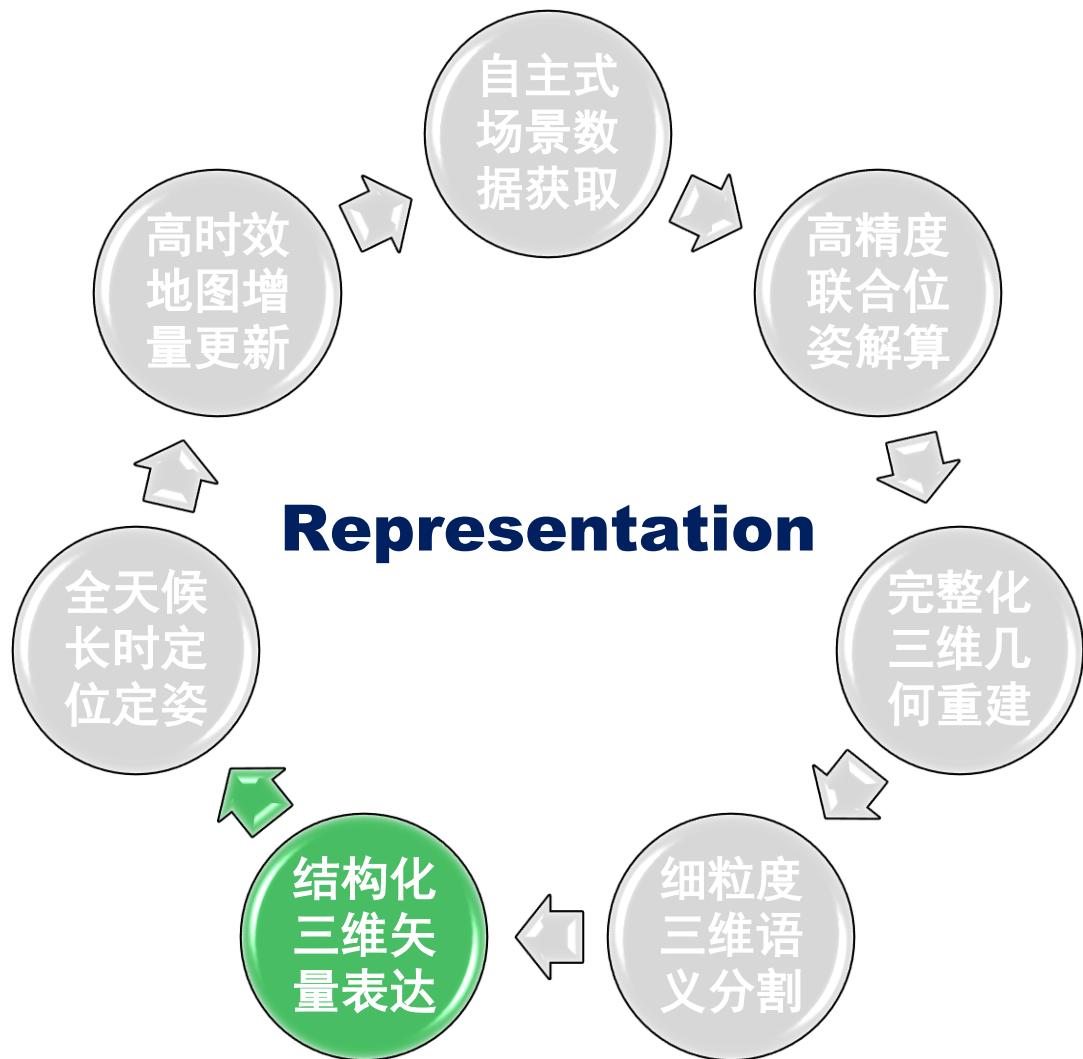


室外场景三维矢量表达

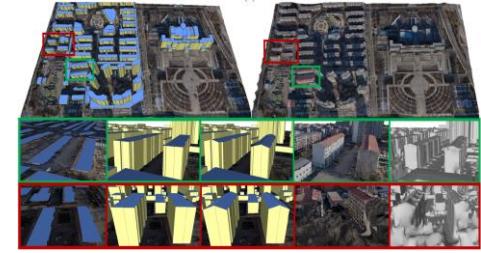


室内场景三维矢量表达

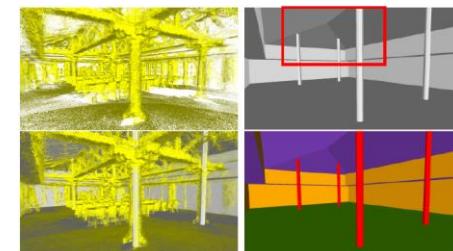
结构化三维矢量表达



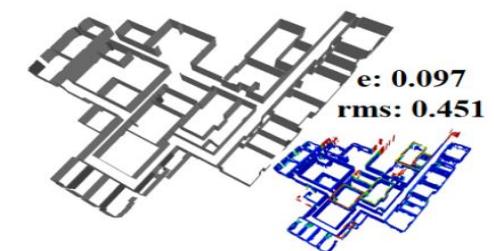
Urban LOD2 Modeling
ECCV 2018
LOD2室外矢量建模



Urban LOD2 Modeling
IEEE TIP 2021
LOD2室外矢量建模



Indoor LOD2 Modeling
ISPRS JPRS 2021
LOD2室内矢量建模



Indoor LOD2 Modeling
ISPRS JPRS 2022
LOD2室内矢量建模

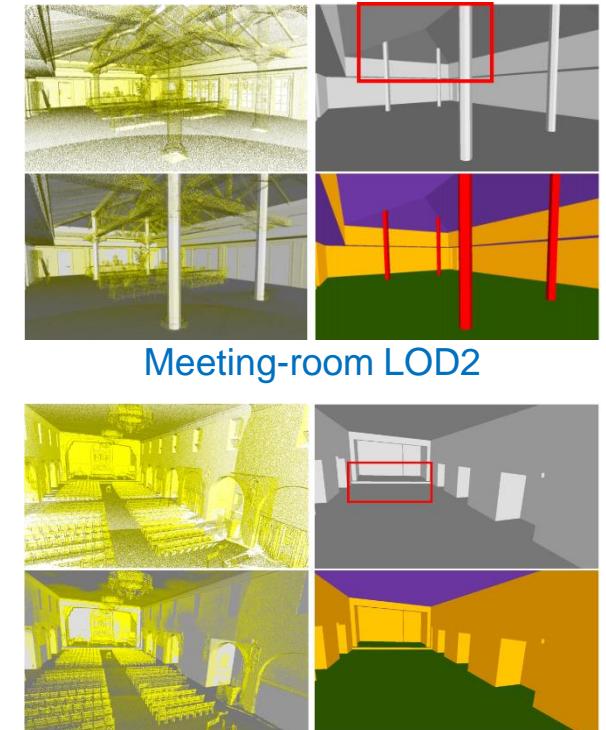
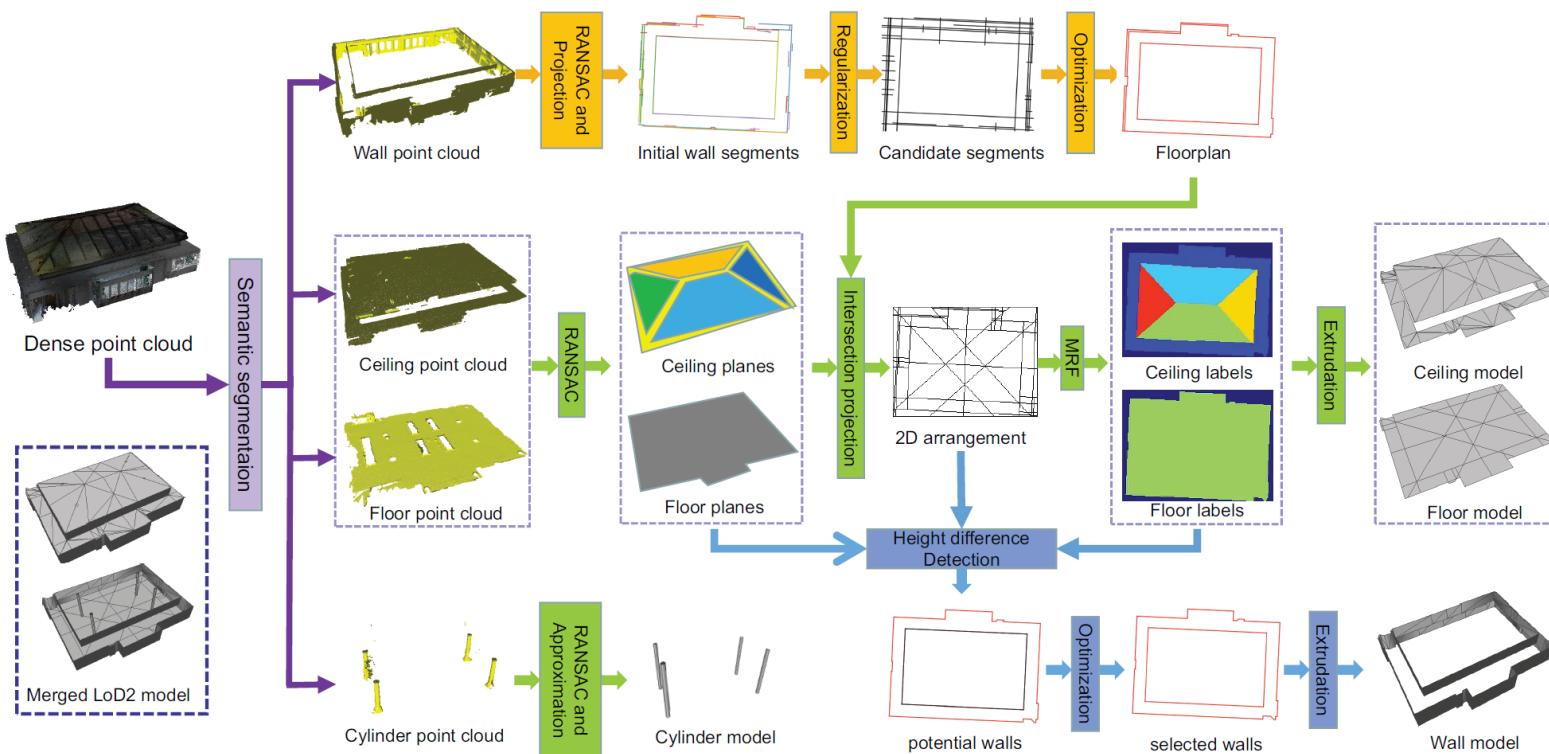
结构化三维矢量表达 — VecIM



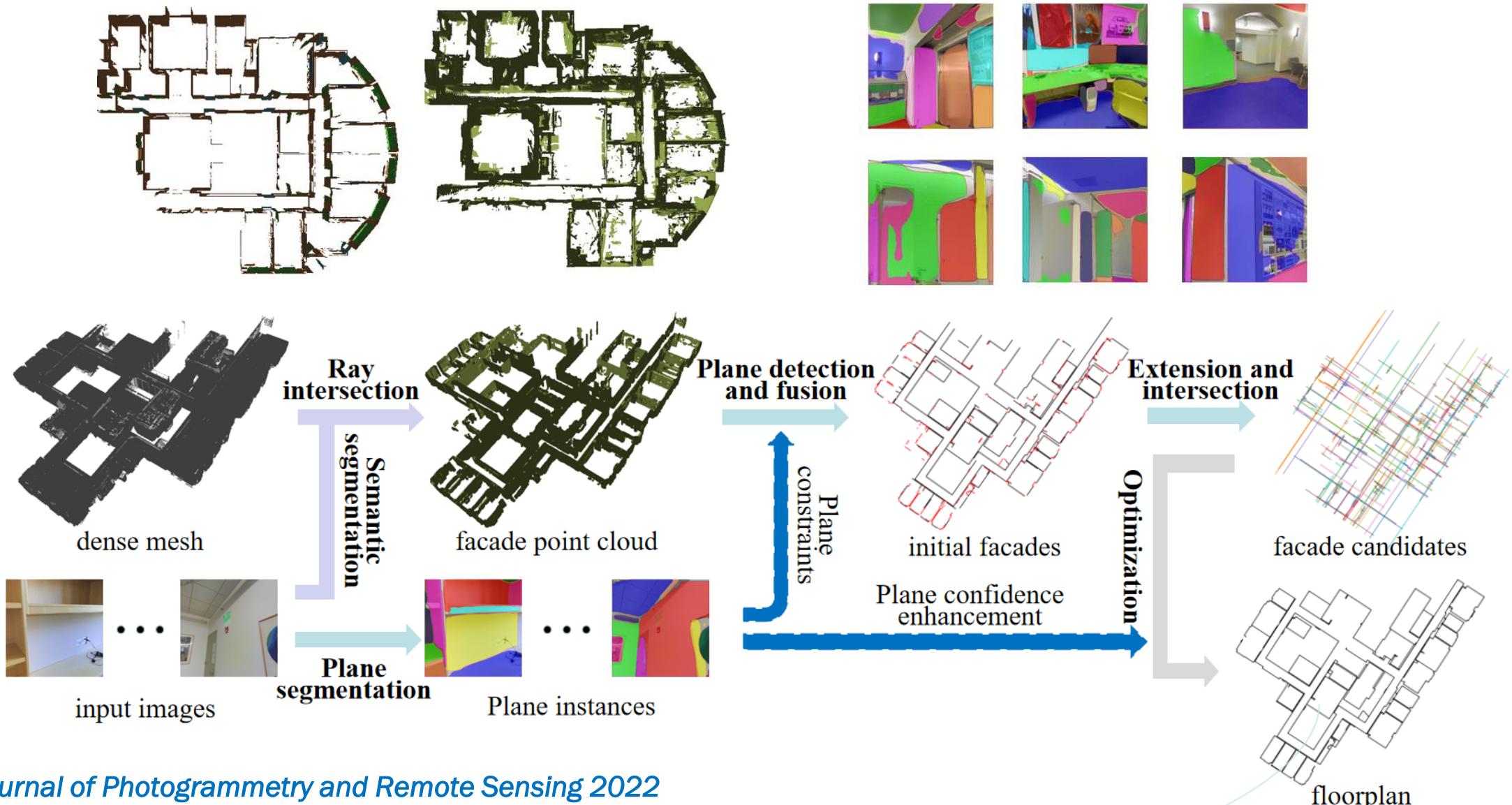
Vectorized Indoor Surface Reconstruction from 3D Point Cloud with Multistep 2D Optimization

Jiali Han, Mengqi Rong, Hanqing Jiang, Hongmin Liu, Shuhan Shen

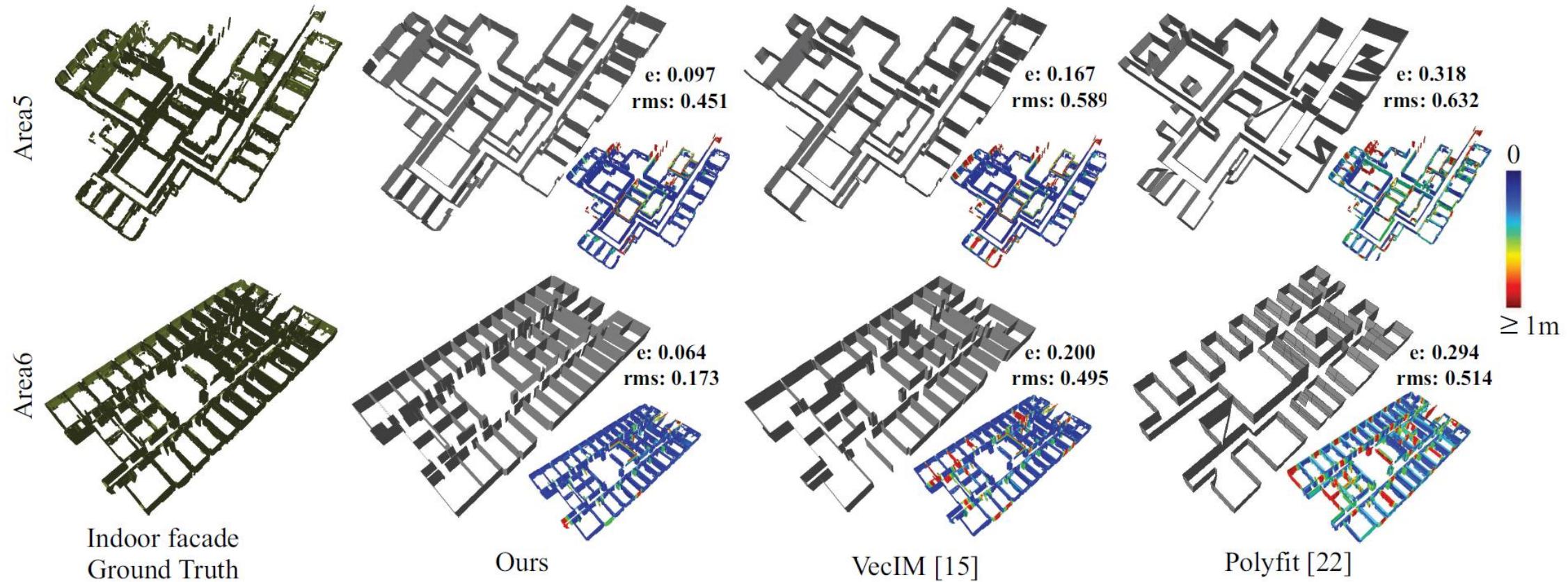
ISPRS Journal of Photogrammetry and Remote Sensing 2021



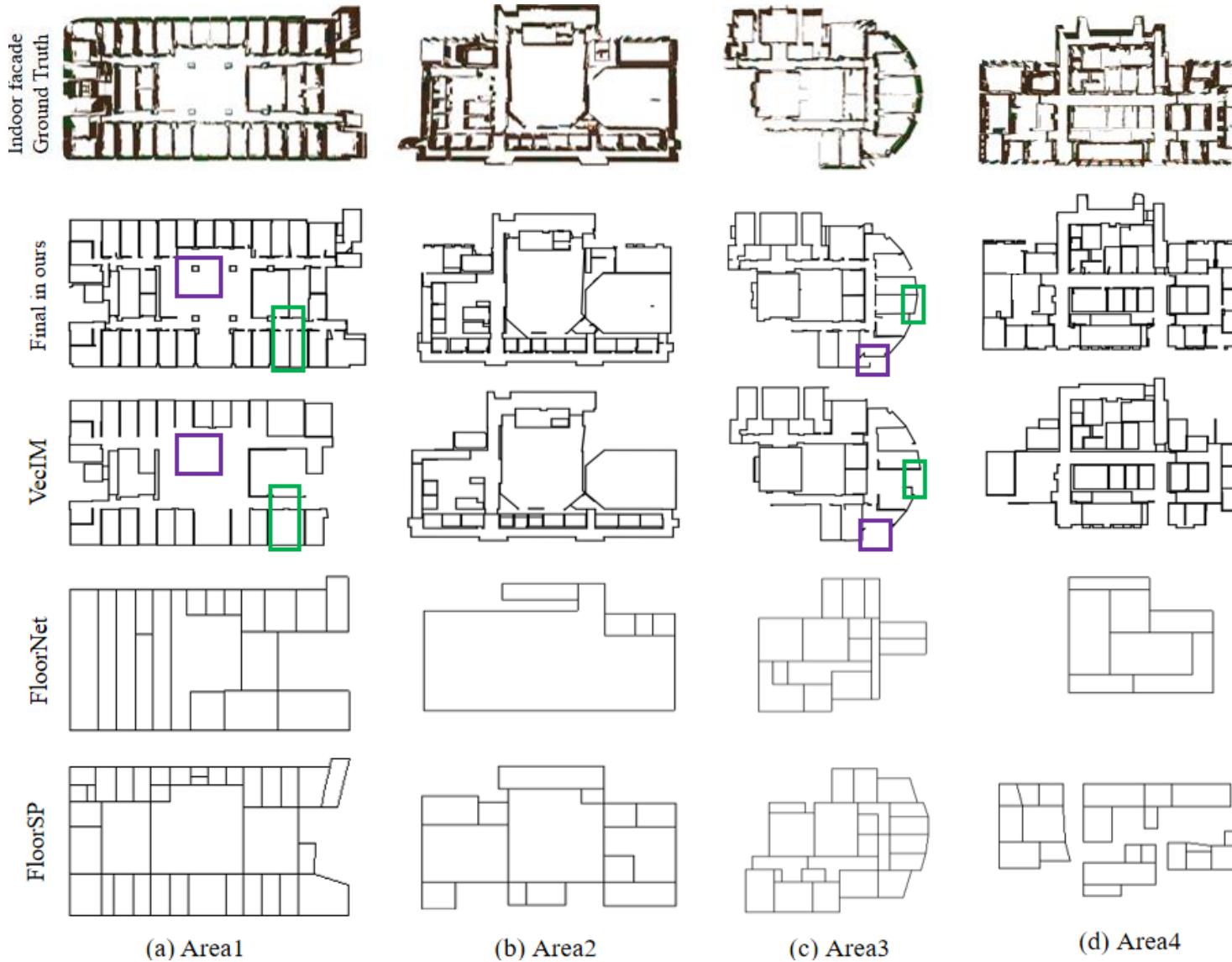
结构化三维矢量表达 — FloorUSG



结构化三维矢量表达 — FloorUSG



结构化三维矢量表达 — FloorUSG



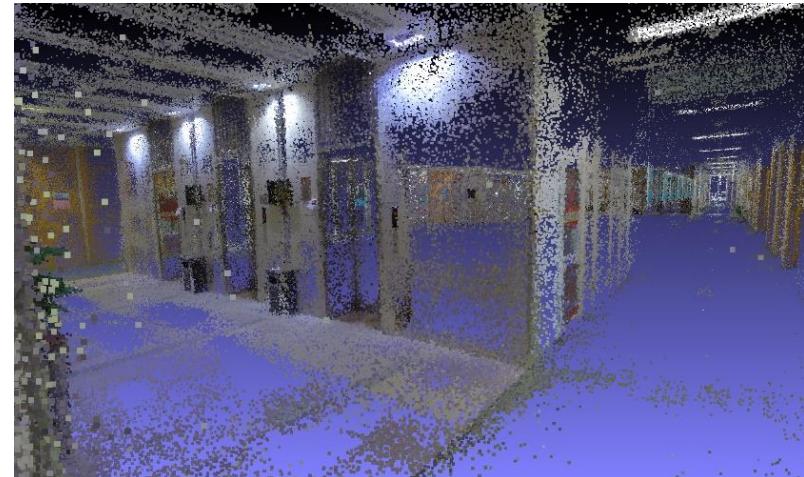
结构化三维矢量表达



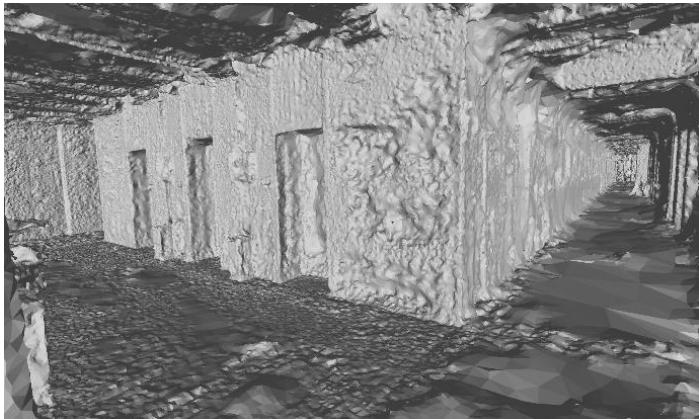
Insta360 Pro2



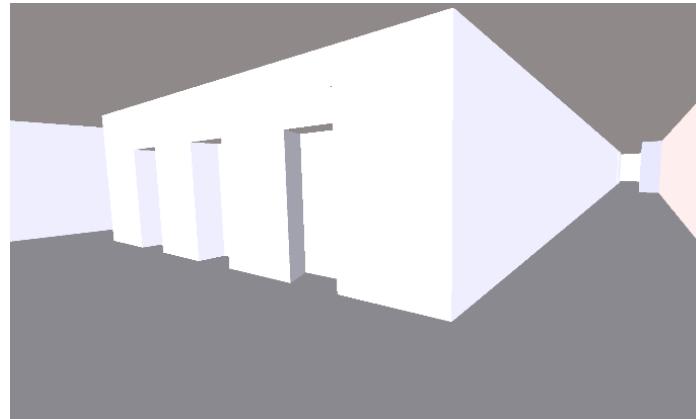
6分钟全景相机视频, 960平方米



稠密三维点云, 1000万三维点



三角网格模型, 300万面片



LOD2级矢量模型, 930面片



纹理矢量模型

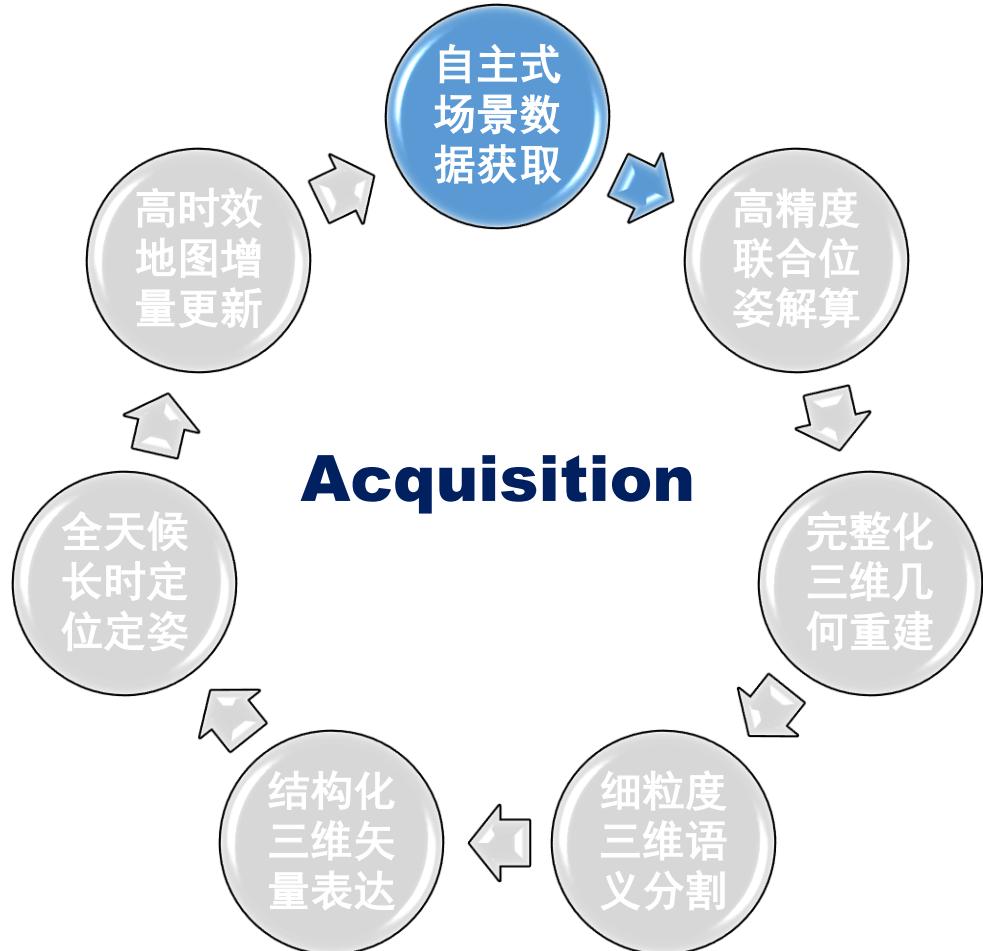
结构化三维矢量表达



大规模复杂场景三维重建与理解系统

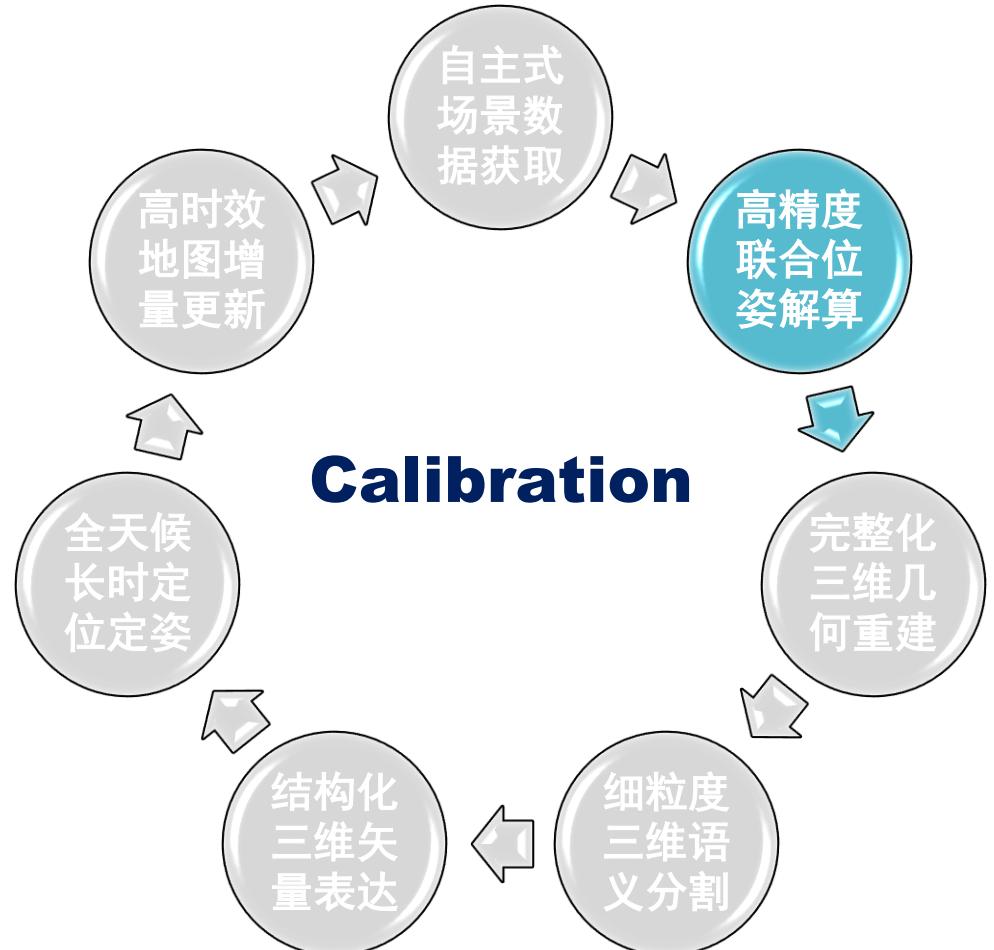


自主式场景数据获取



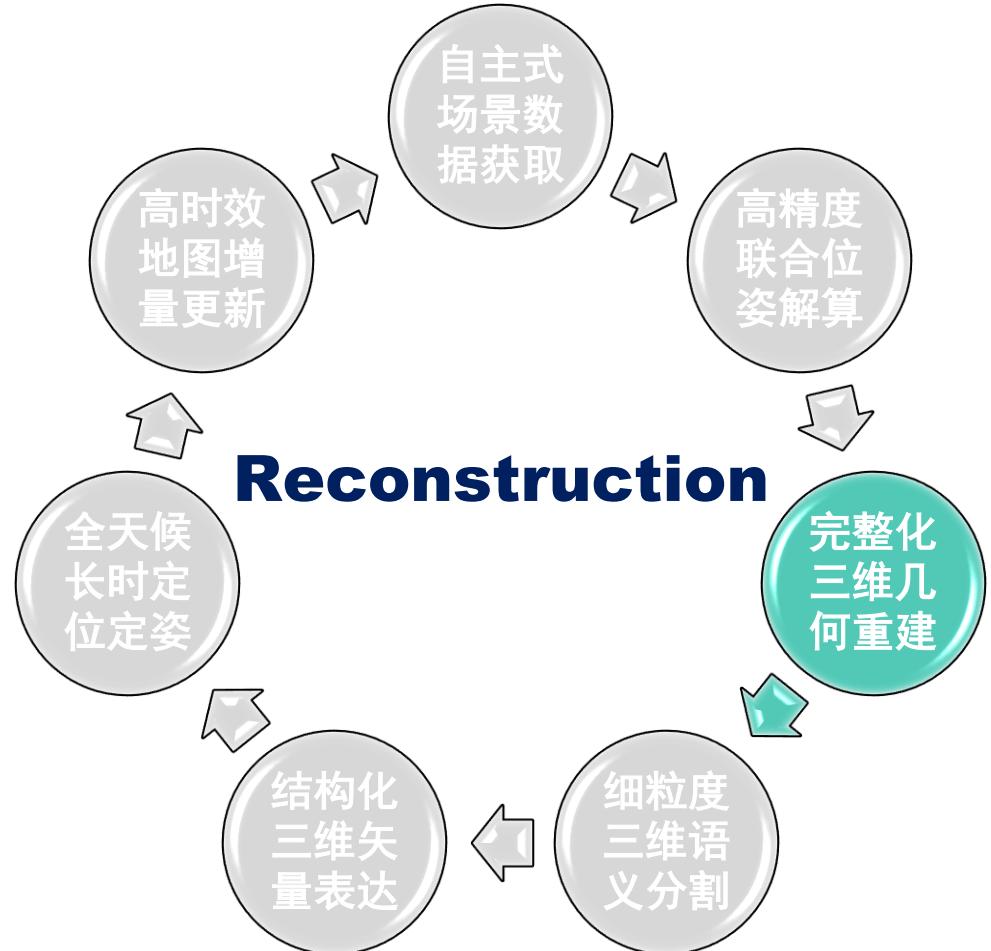
基于全局地图的场景探索式数据获取

高精度联合位姿解算



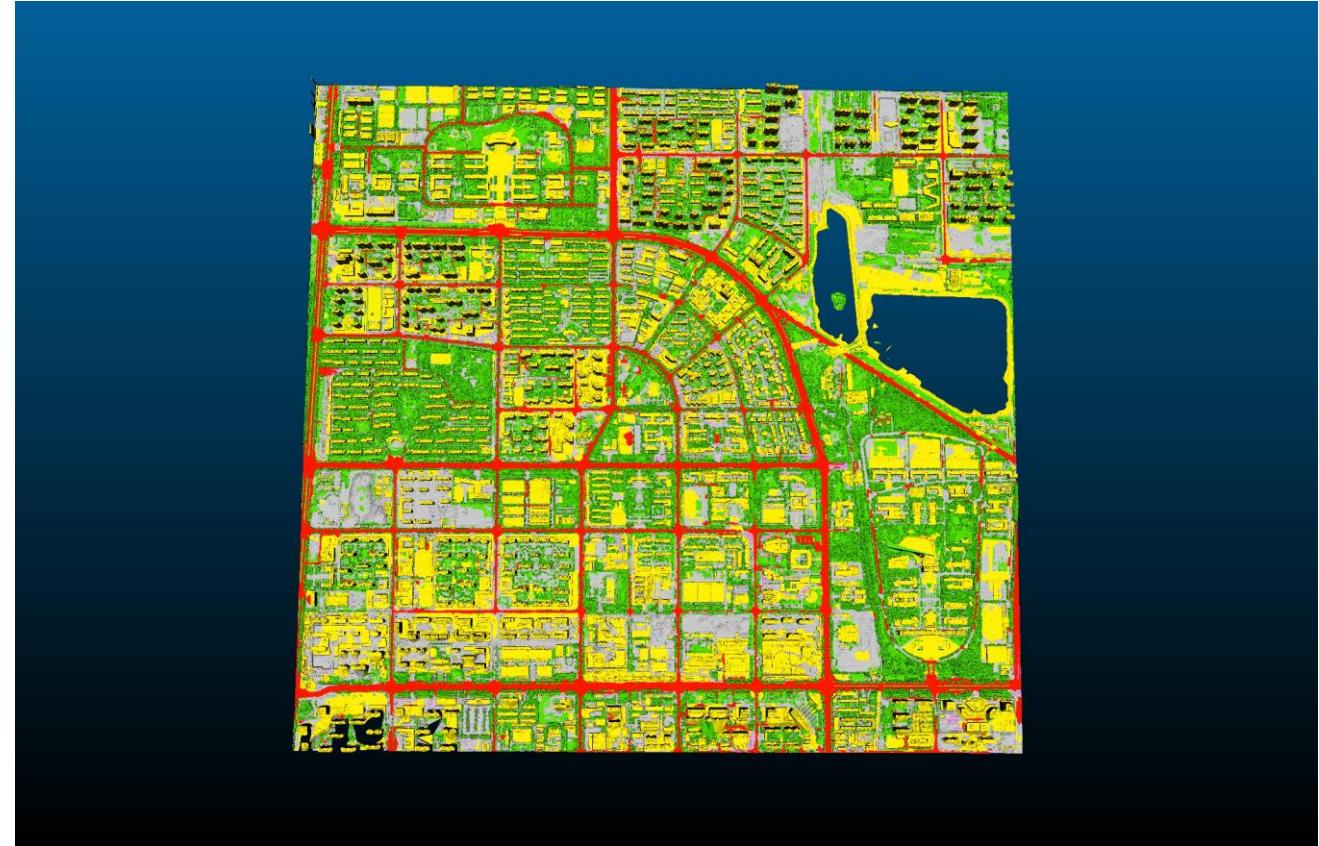
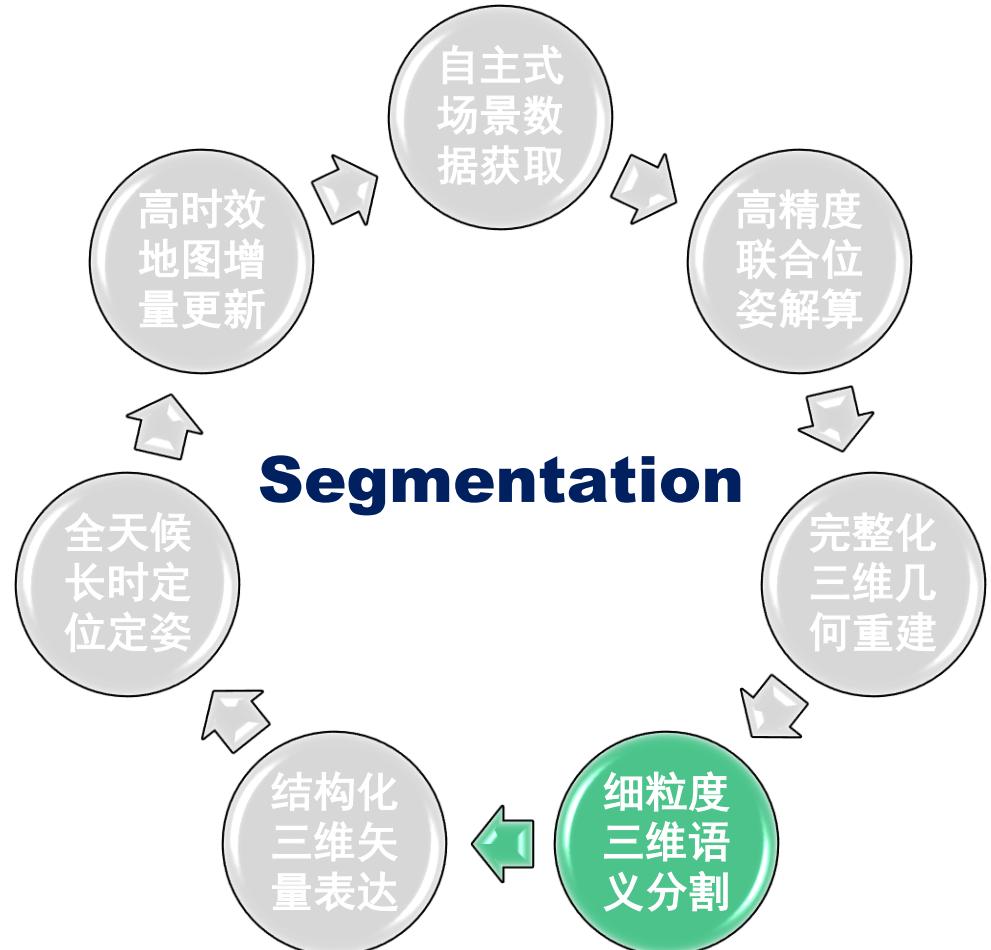
航拍图像相机位姿解算

完整化三维几何重建



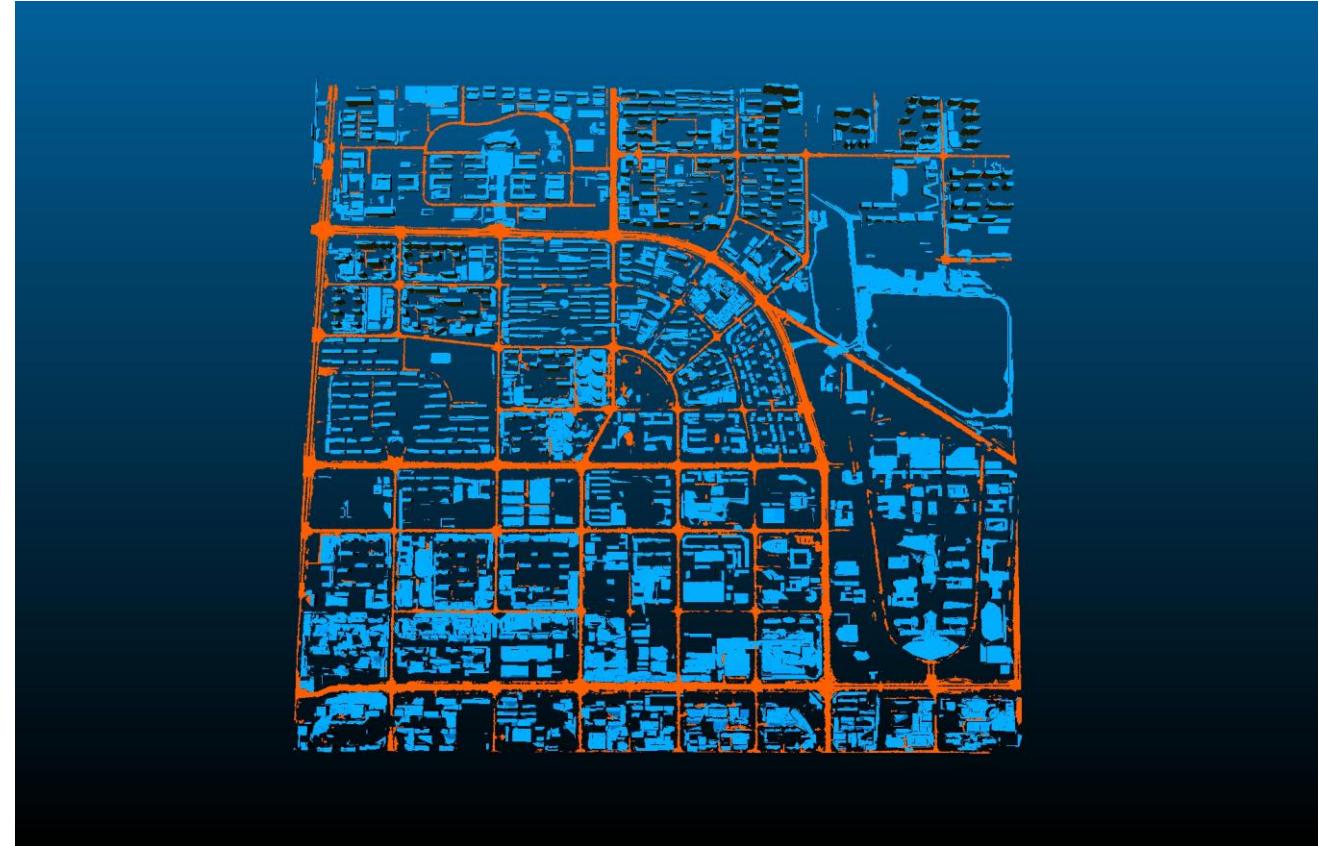
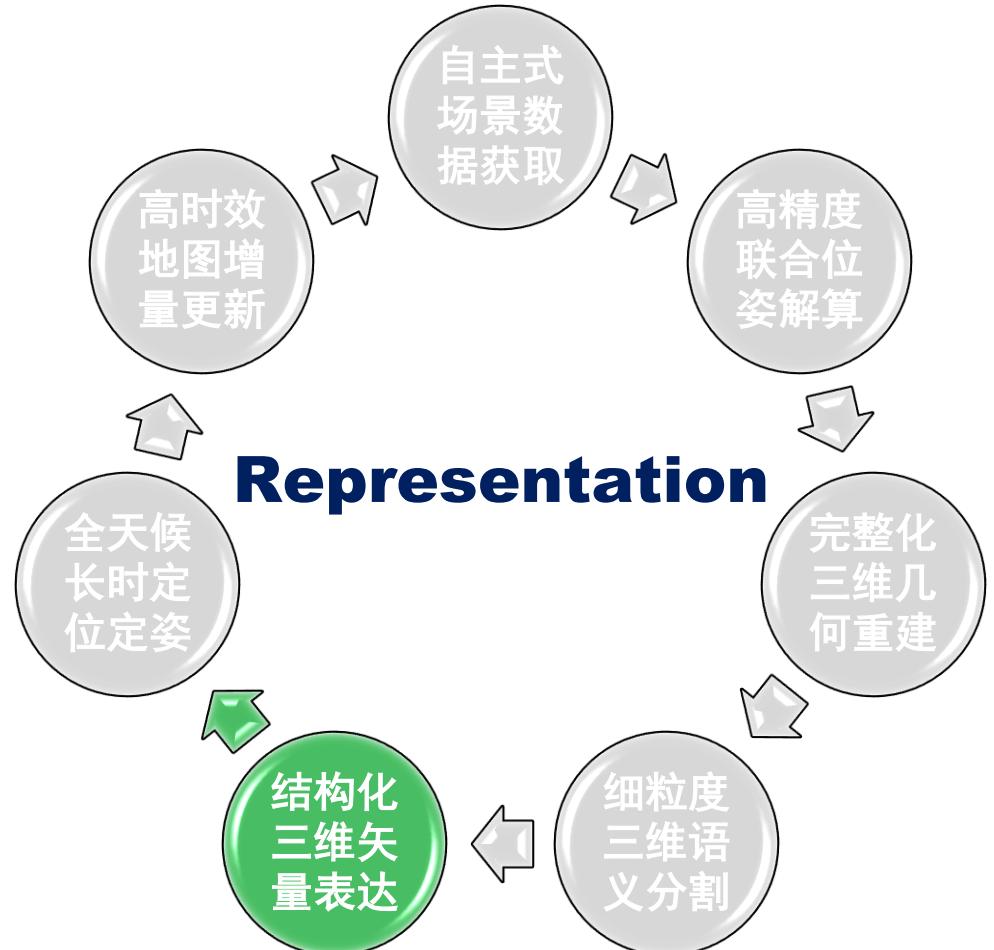
倾斜摄影三维几何重建

细粒度三维语义分割



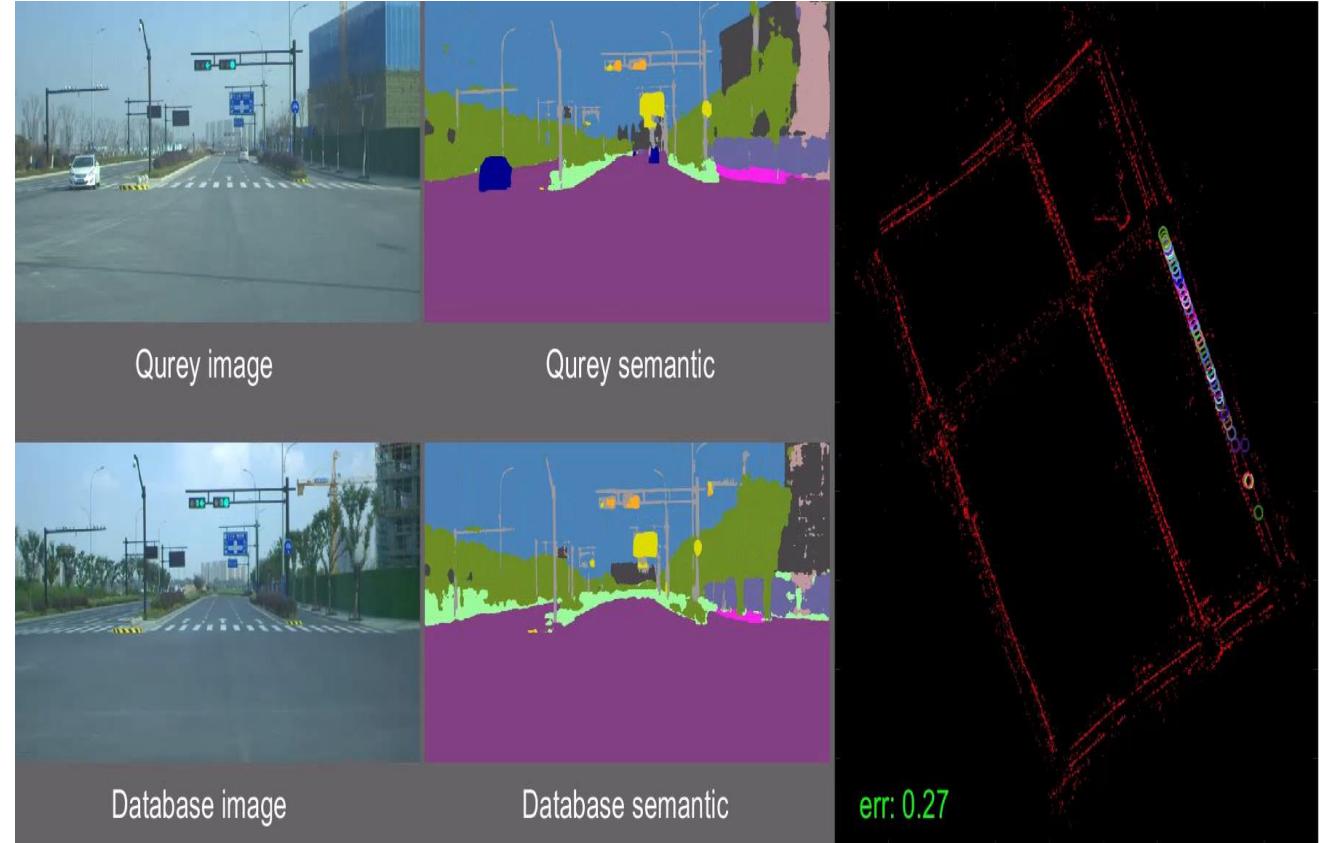
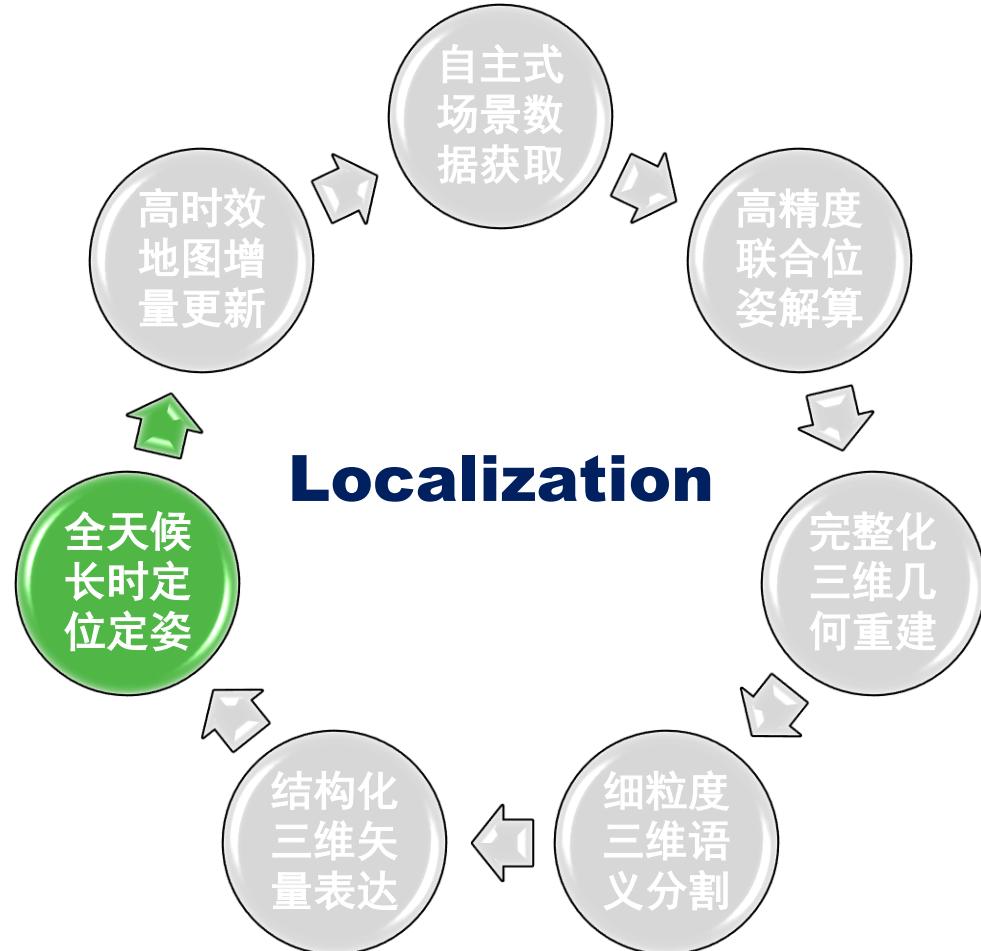
城市场景地物三维语义分割

结构化三维矢量表达



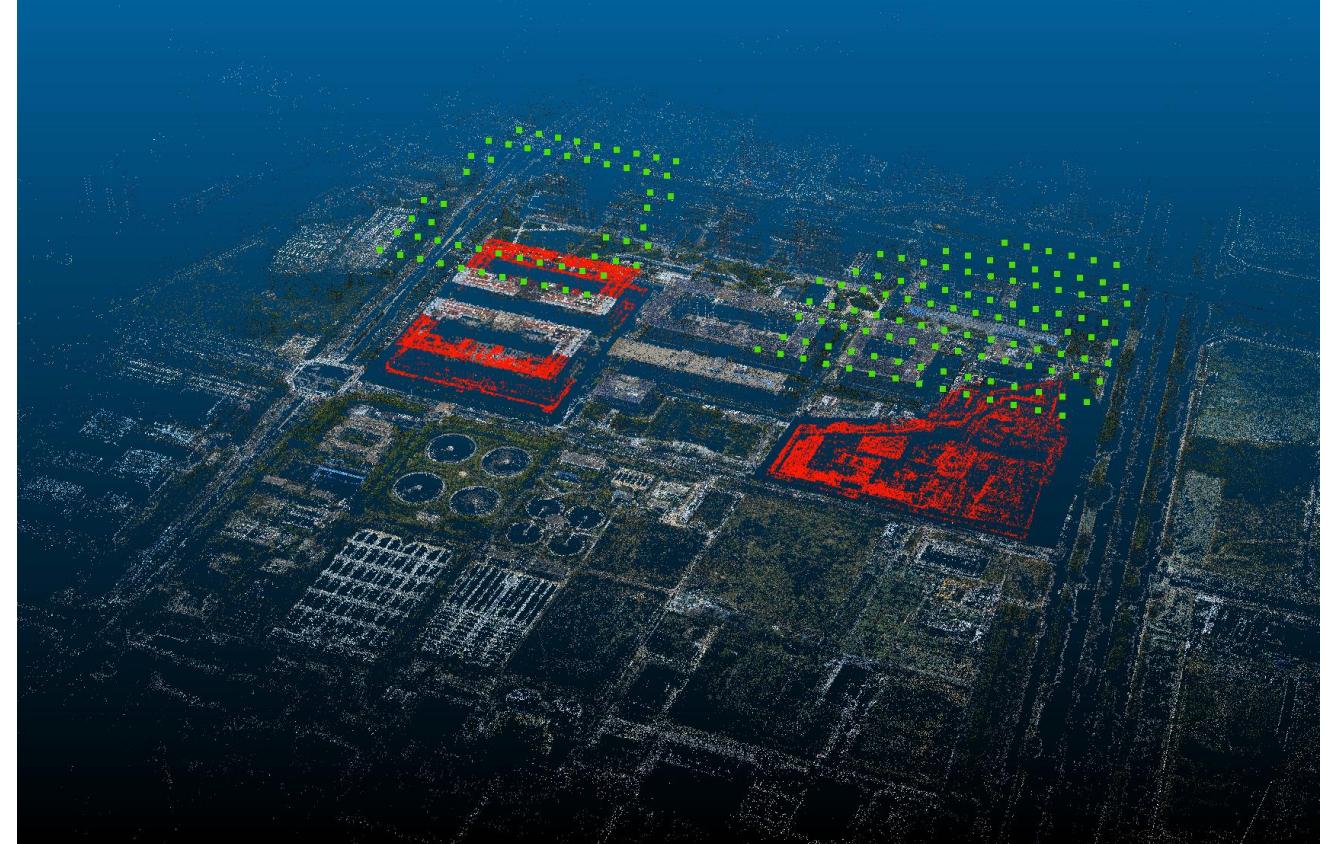
建筑物轻量化三维矢量表达

全天候长时定位定姿



基于三维地图的无人车长时定位定姿

高时效地图增量更新



三维场景变化检测与增量更新

大规模复杂场景三维重建与理解系统



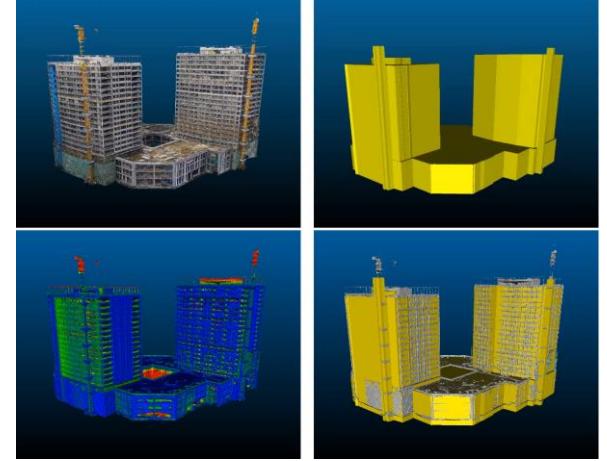
大场景三维重建与理解系统应用



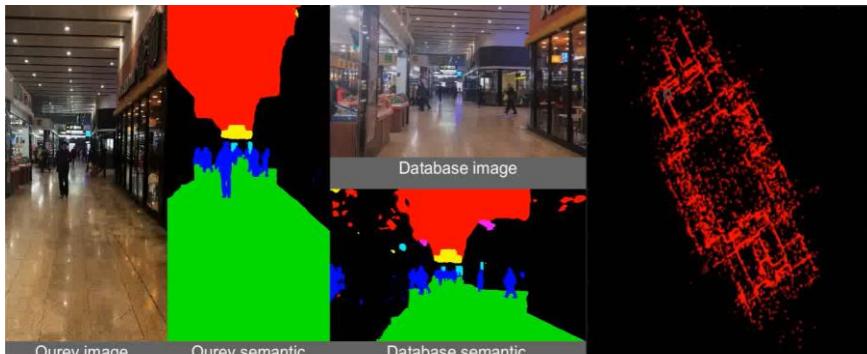
量产车视觉三维矢量地图



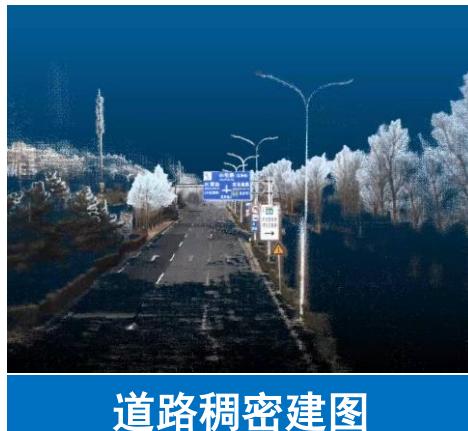
建筑三维数字孪生



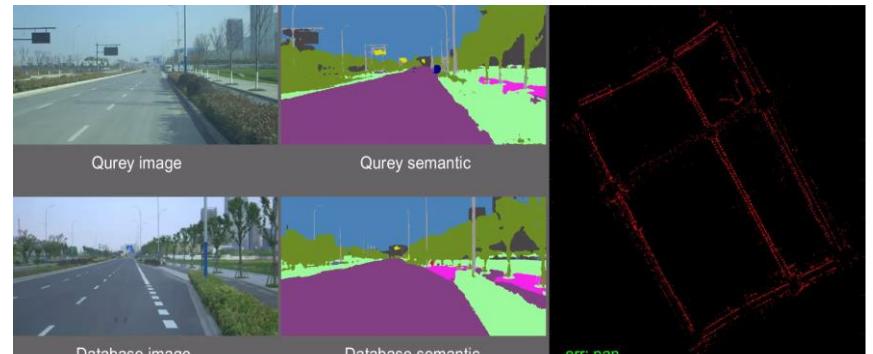
城市实景三维建模



室内视觉三维建图与单目定位



道路稠密建图



无人车视觉三维建图与单目定位

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Thanks! Q&A

