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Elastic LiDAR Fusion: Dense Map-Centric CT-SLAM

Chanoh Park(Ph.D. Student), Peyman Moghadam, Soohwan Kim, Alberto Elfes, Clinton Fookes, Sridha Sridharan

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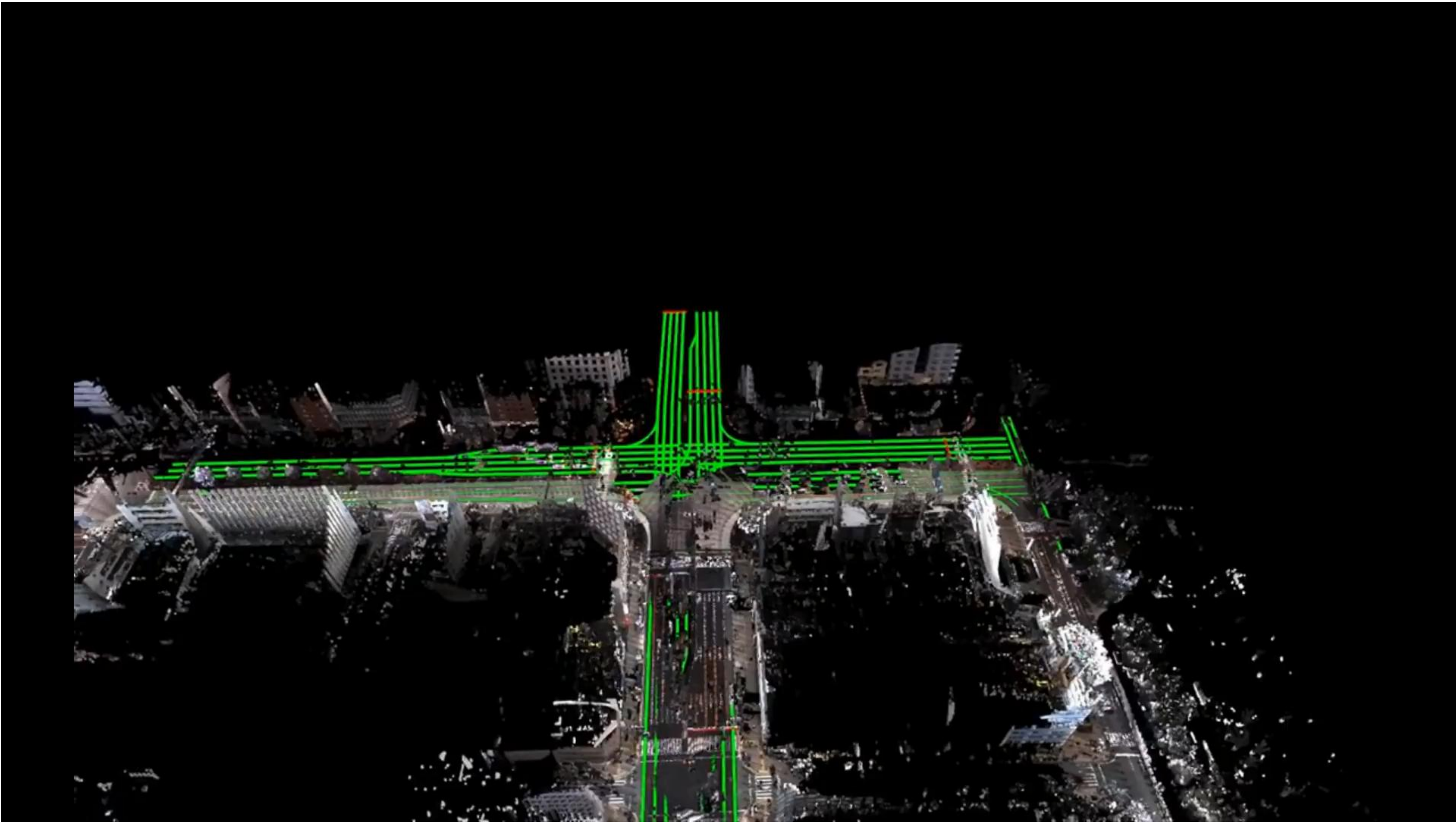
www.data61.csiro.au

CSIRO Supervisors: Peyman Moghadam, Alberto Elfes
QUT Supervisors: Sridha Sridharan, Clinton Fookes, Jonathon Roberts

QUT CSIRO

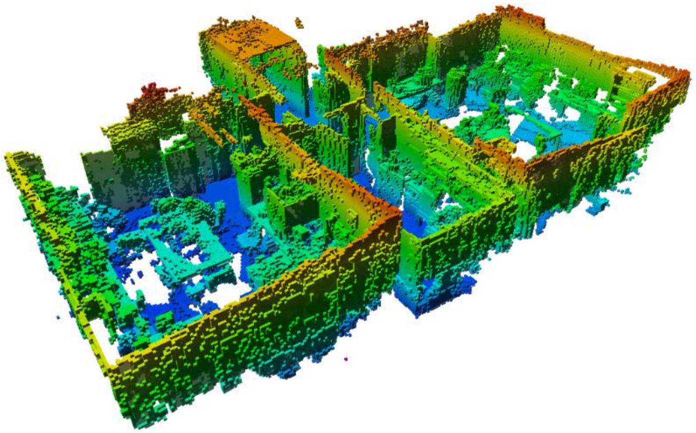
Introduction



Ref: https://youtu.be/gGrKbeLMGUU?list=PLObjxz0SzcZwAFJs-kZgLkkAL5dVNqBcC

State of the art in LiDAR SLAM

- Plenty have limitations
  - Trajectory-centric
    - No online loop closure
    - Offline operation
    - No fusion of redundant observations
    - Non-scalable
  - Difficulties in multi-modal sensor fusion
  - Map is discretised or full of redundant elements

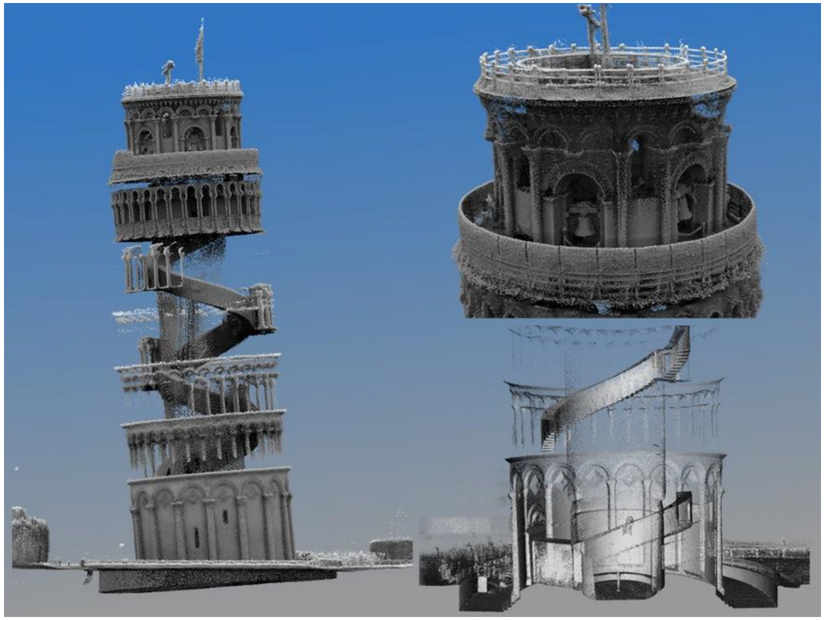


State of the art

- Zebedee(2012), V-LOAM(2015)
  - Nicely handle LiDAR motion distortion

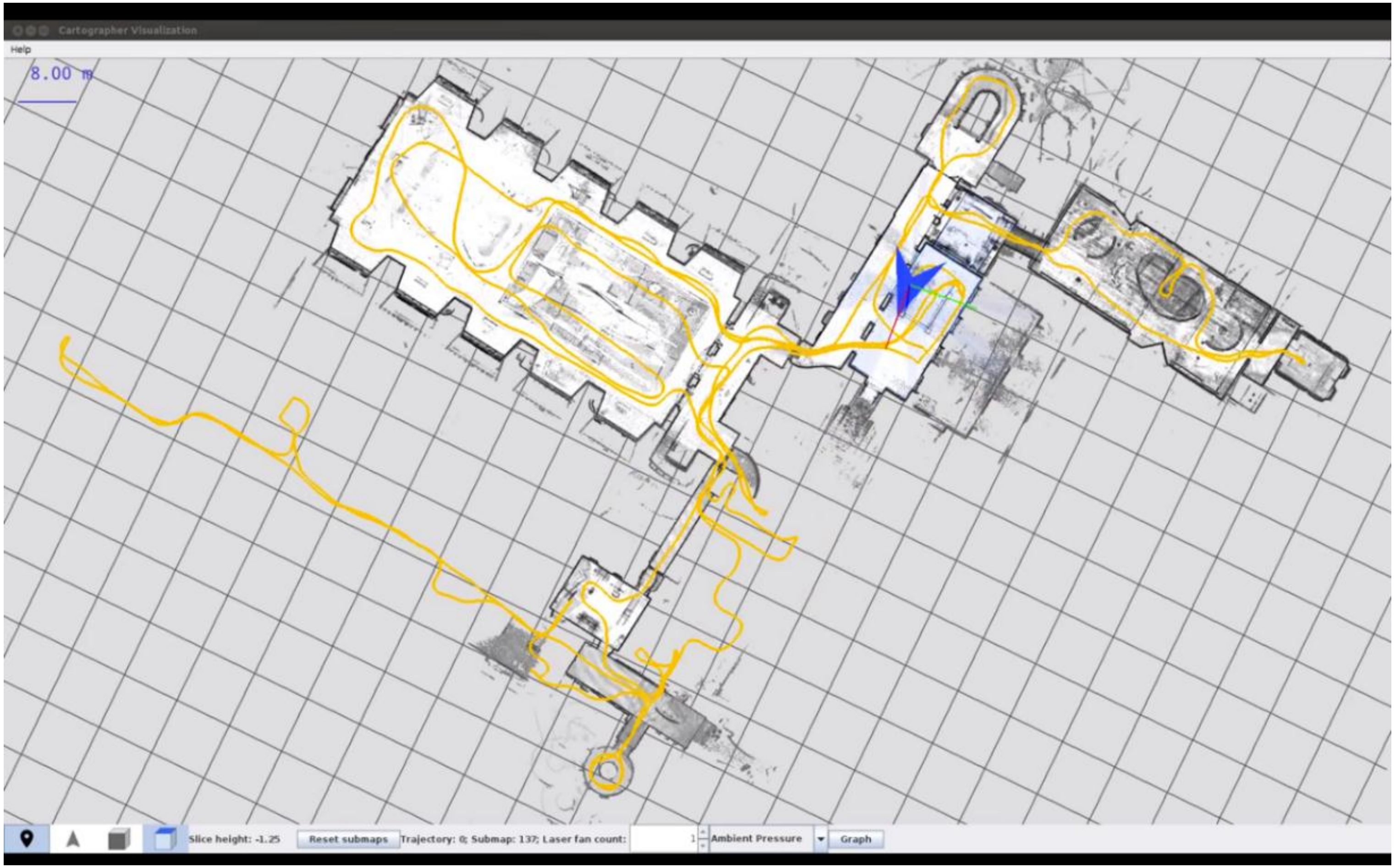
Demo(2016)

Zebedee(2012)



State of the art

- Google Cartographer(2014)

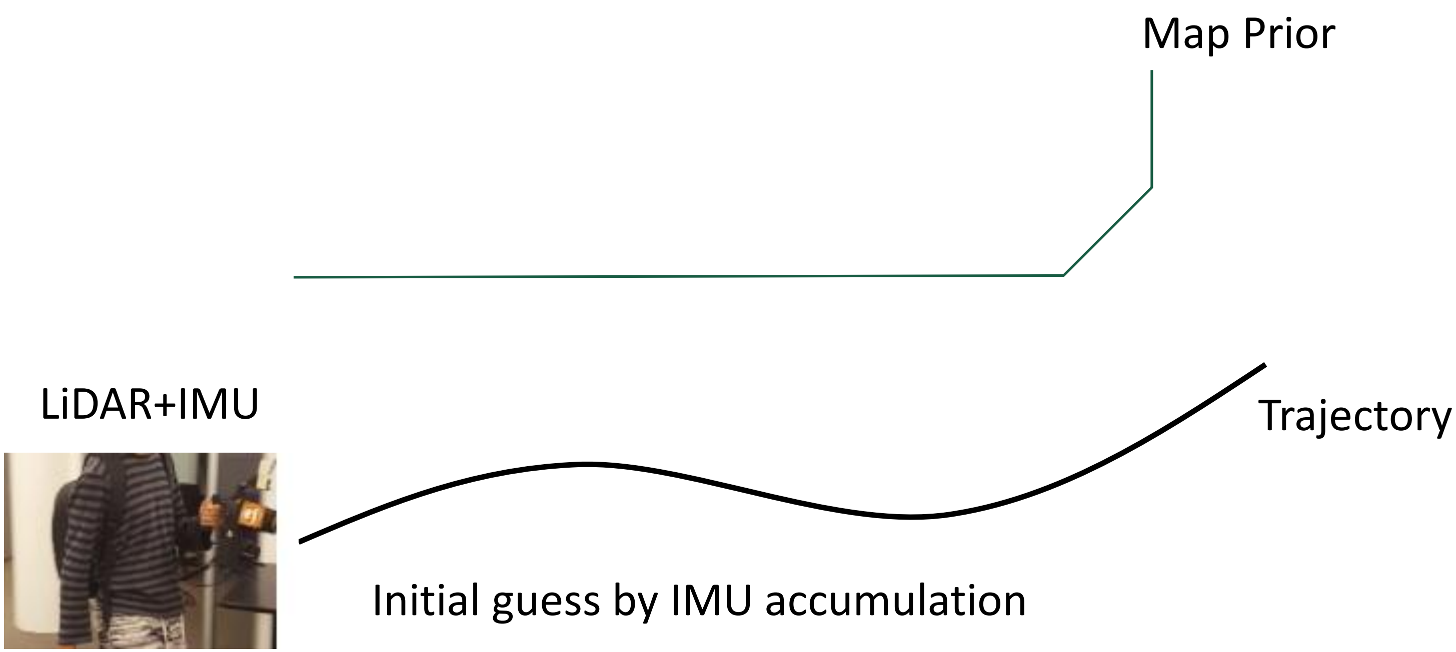


Introducing Elastic LiDAR Fusion

- First LiDAR based map-centric approach
  - Loop closure by map
  - Fuse all the measurements
- Easy multi-modal sensor fusion
  - We combine CT-SLAM with a map-centric approach
  - LiDAR-Inertial fusion is proposed

How it works:

Continuous-time local trajectory estimation



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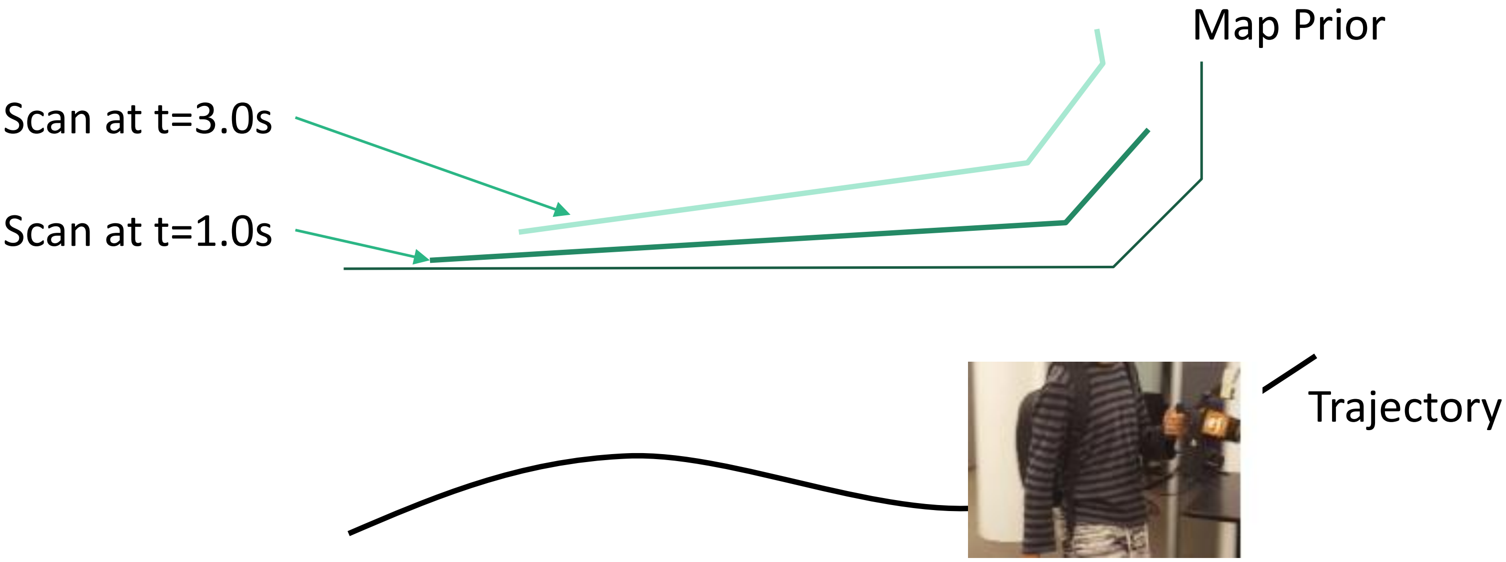

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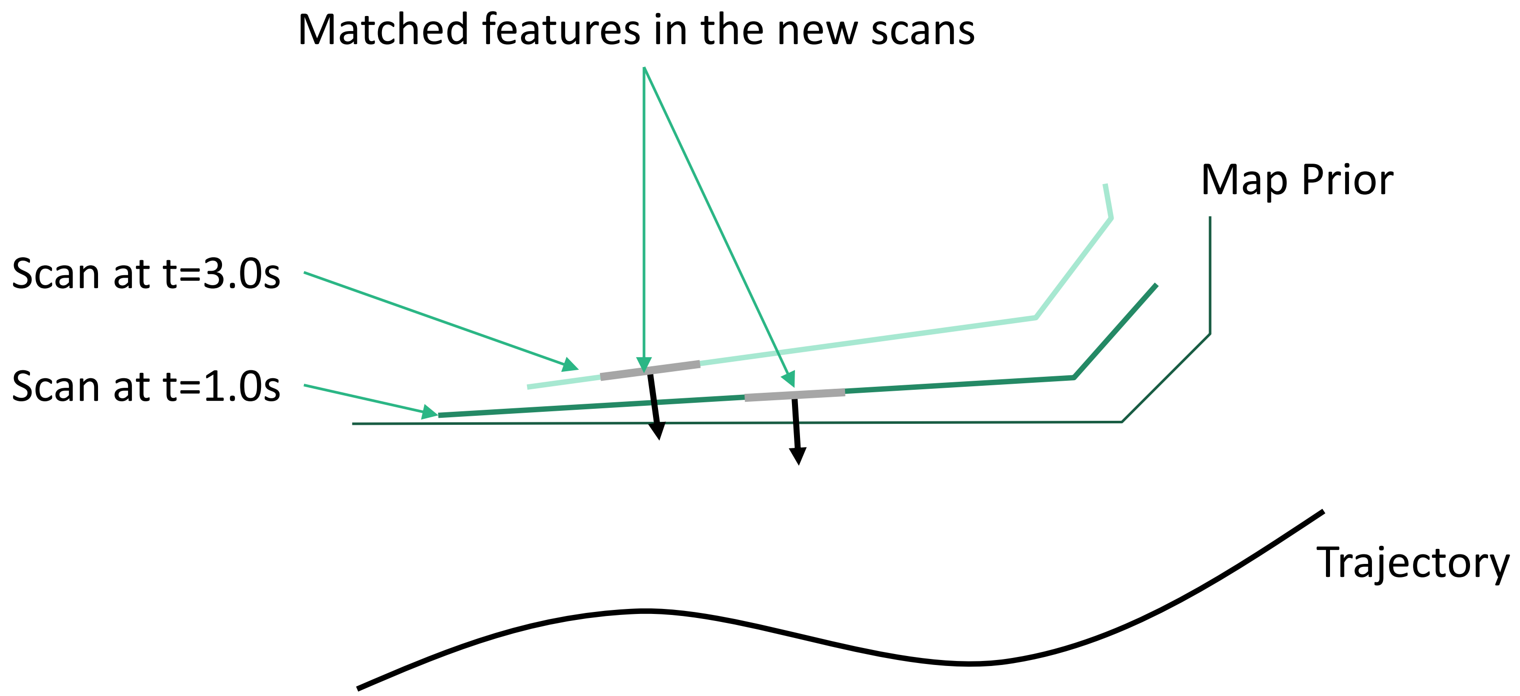

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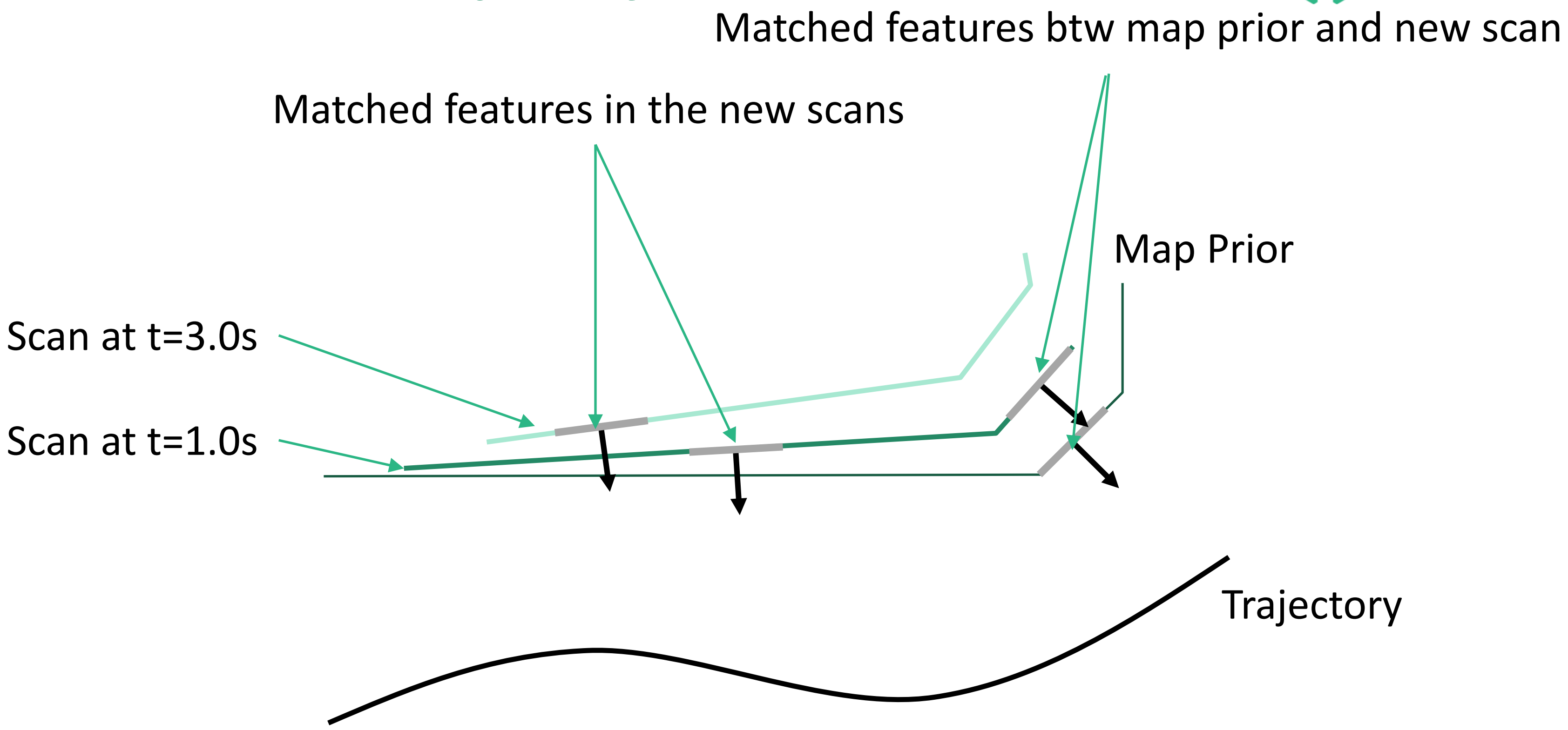
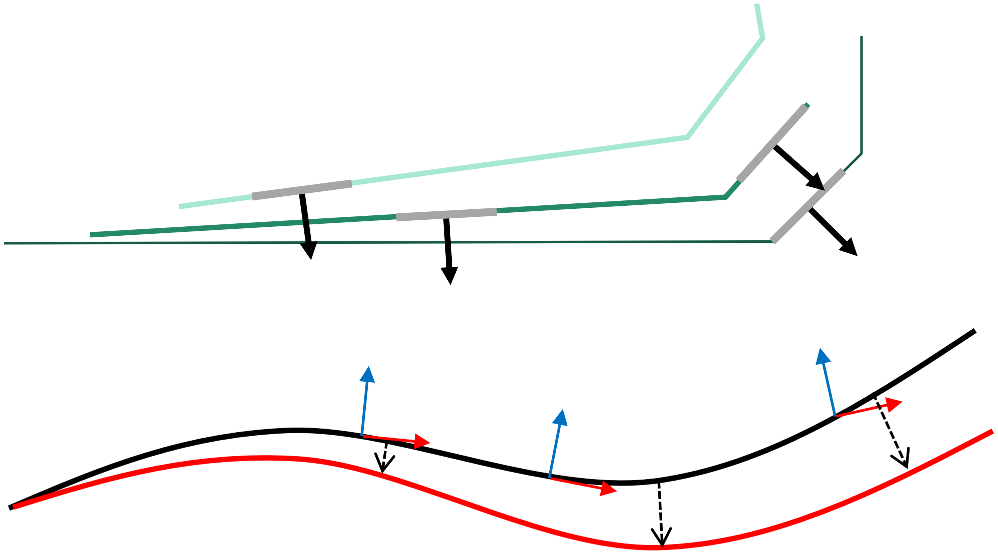


How it works:

Continuous-time local trajectory estimation

1. Find a new trajectory

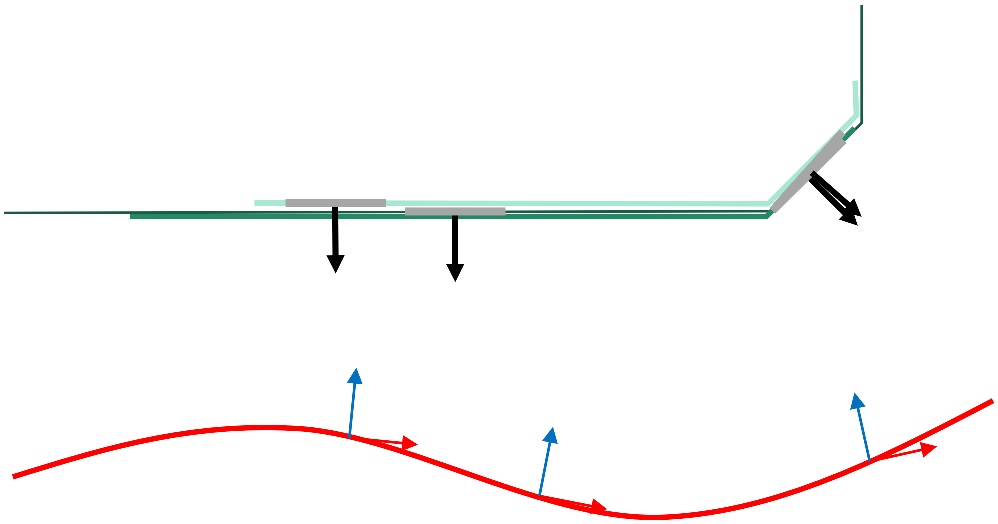


Corrected Trajectory

How it works:

Continuous-time local trajectory estimation

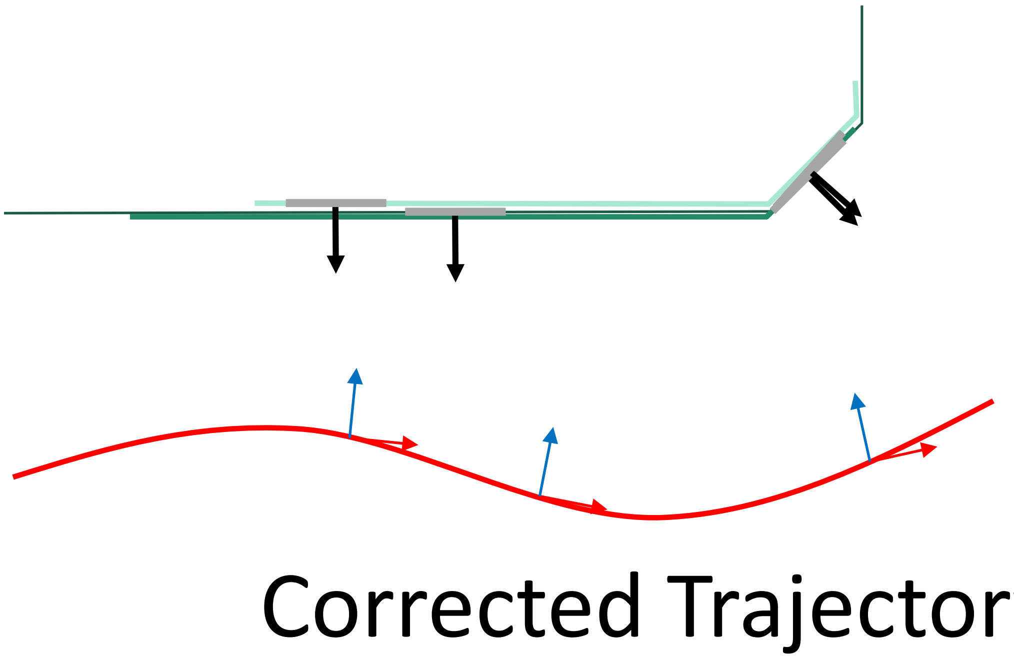
1. Find a new trajectory
2. Reproject points cloud



Corrected Trajectory

How it works:
Continuous-time local trajectory estimation

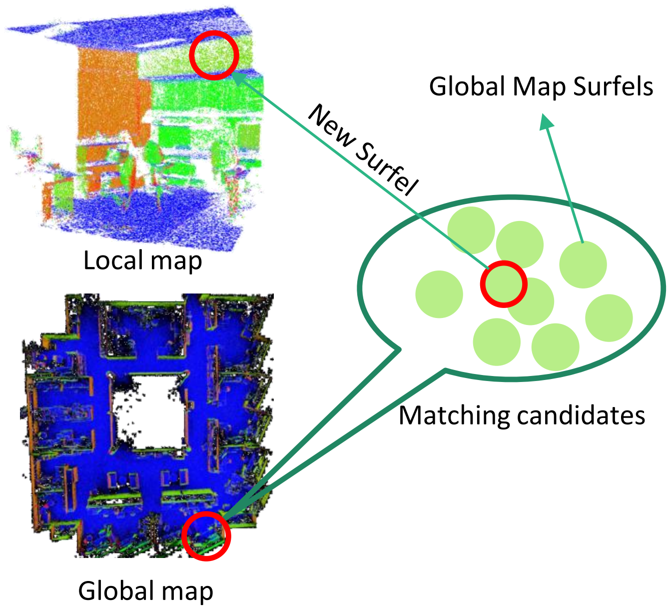
1. Find a new trajectory
2. Reproject points cloud
3. New scans become another map prior

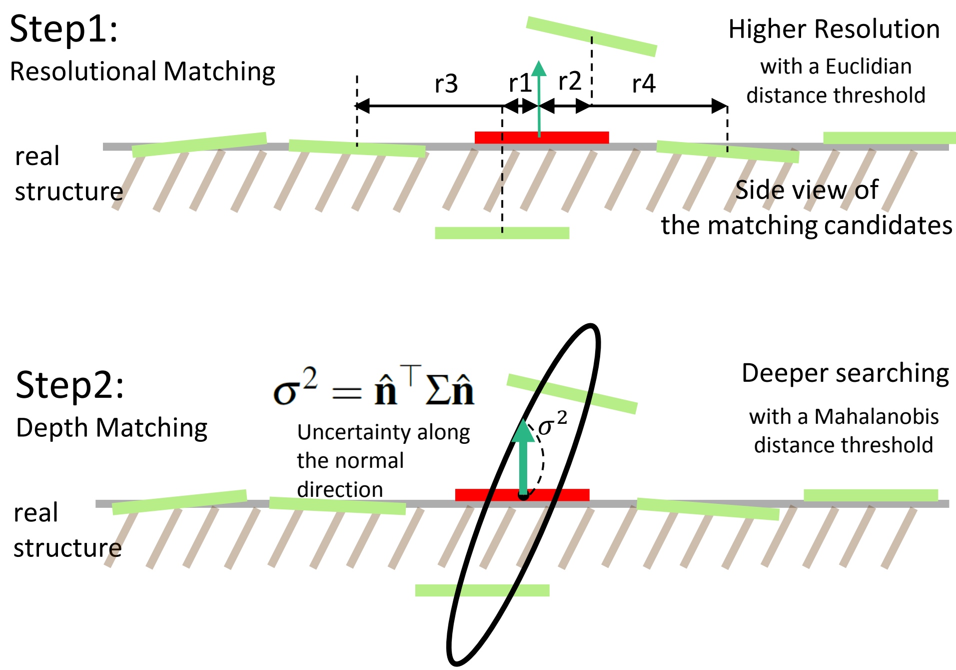


How it works:

Surfel Fusion

- Fuses surfels from the local window into the global map
  - Data association





- Surfel fusion
  - Normal, Centre, Colour with Bayesian Fusion

How it works:

Loop closure by deformation

- Previous two stages just keep building map
  - What about the loop closure?

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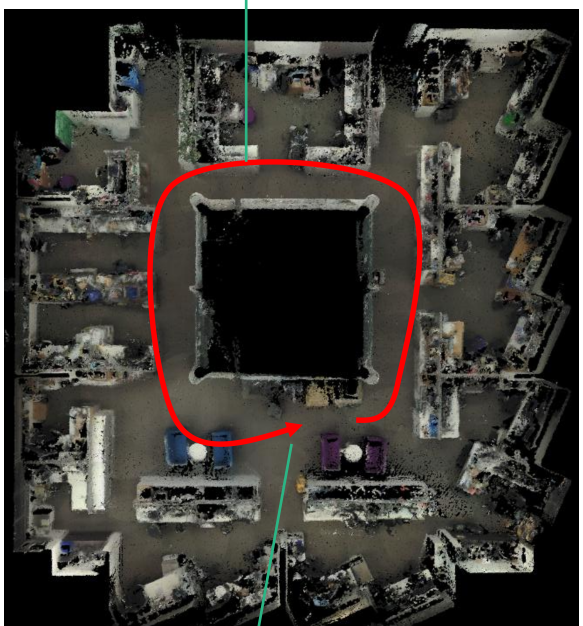
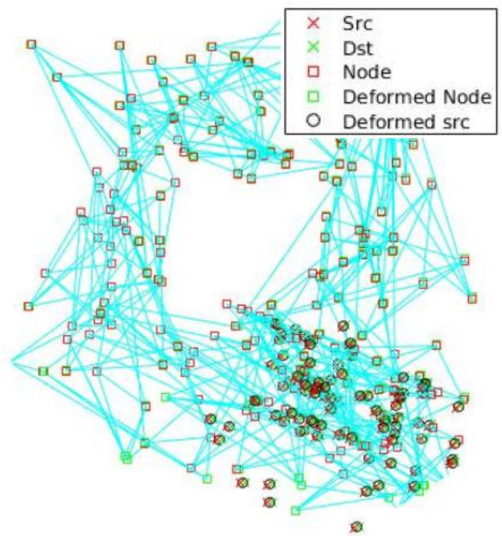
Trajectory





$$\mathbf{e}_{loop} = \sum \|\mathbf{p}'_{src} - \mathbf{p}_{dest}\|^2$$

$$\mathbf{e}_{pin} = \sum \|\mathbf{p}'_{dest} - \mathbf{p}_{dest}\|^2$$

$$\mathbf{e}_{reg} = \sum_{j}^{m} \sum_{k \in \mathbb{V}(\mathbf{g}_j)} \|\mathbf{R}_j(\mathbf{g}_k - \mathbf{g}_j) + \mathbf{g}_j + \mathbf{t}_j - \mathbf{g}_k - \mathbf{t}_k\|^2$$

$$[\hat{\mathbf{R}}_j, \hat{\mathbf{t}}_j] = \underset{\mathbf{R}_j, \mathbf{t}_j \in SE(4)}{\operatorname{argmin}} \; \omega_{reg}\mathbf{e}_{reg} + \omega_{pin}\mathbf{e}_{pin} + \omega_{loop}\mathbf{e}_{loop}$$

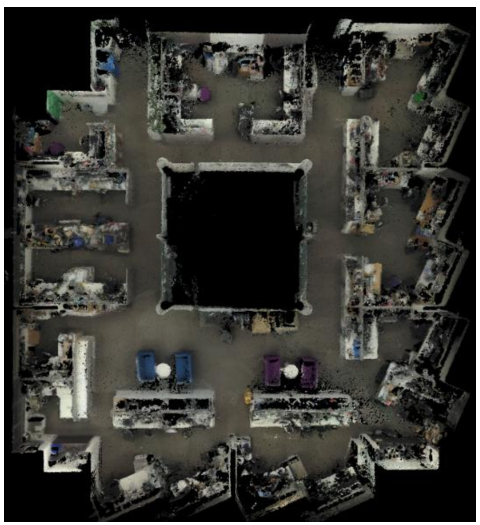
Loop closure detection | Graph for a deformation | Deformation constraints

Experiment results

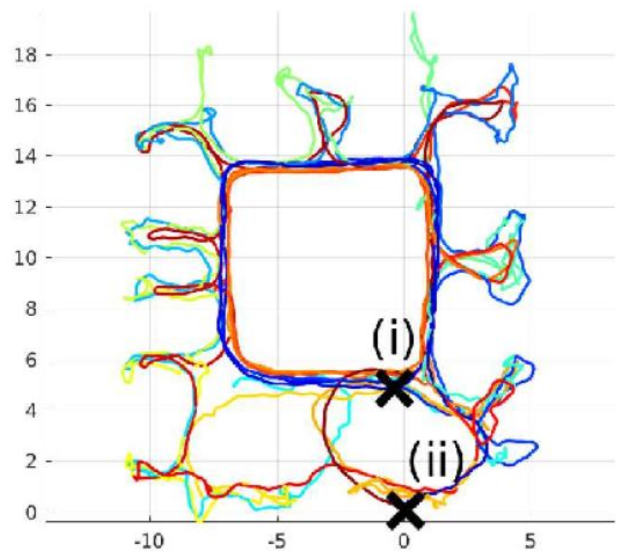
Loop Closure Cost Comparison

How fast is our method?

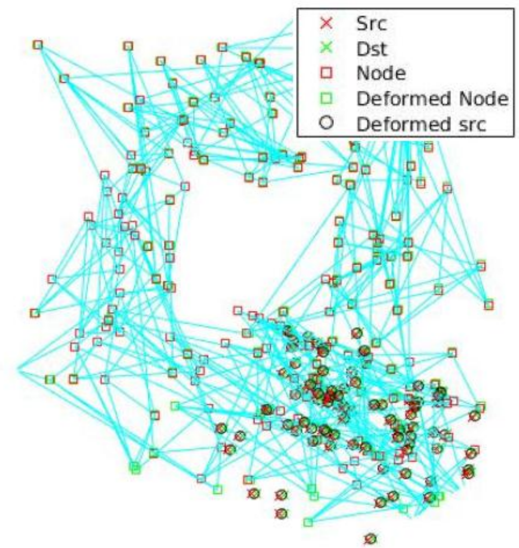
Types	Optimization*	No.State	Elapsed Time (sec)
Proposed	Fig. 5 (i)	192	0.12
CT-SLAM [6]	Fig. 5 (ii)	3396	195.4



Office map



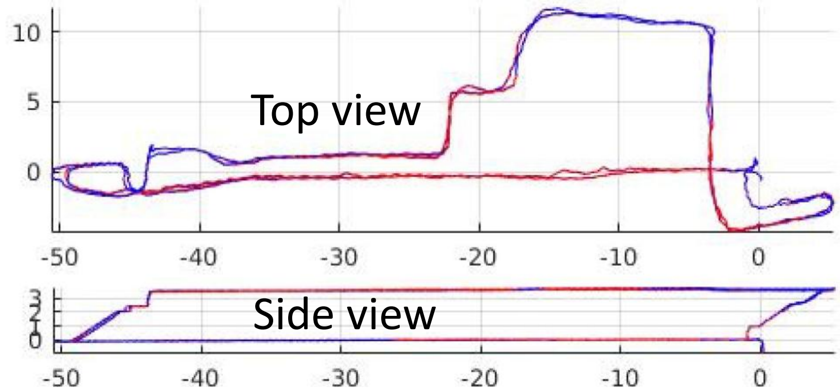
Trajectory map



Deformation graph

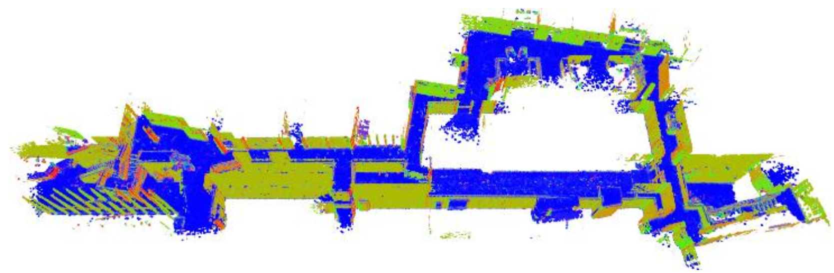
Trajectory Estimation Error

Trajectory



Blue: trajectory by an offline batch optimization
Red: Proposed method

Map

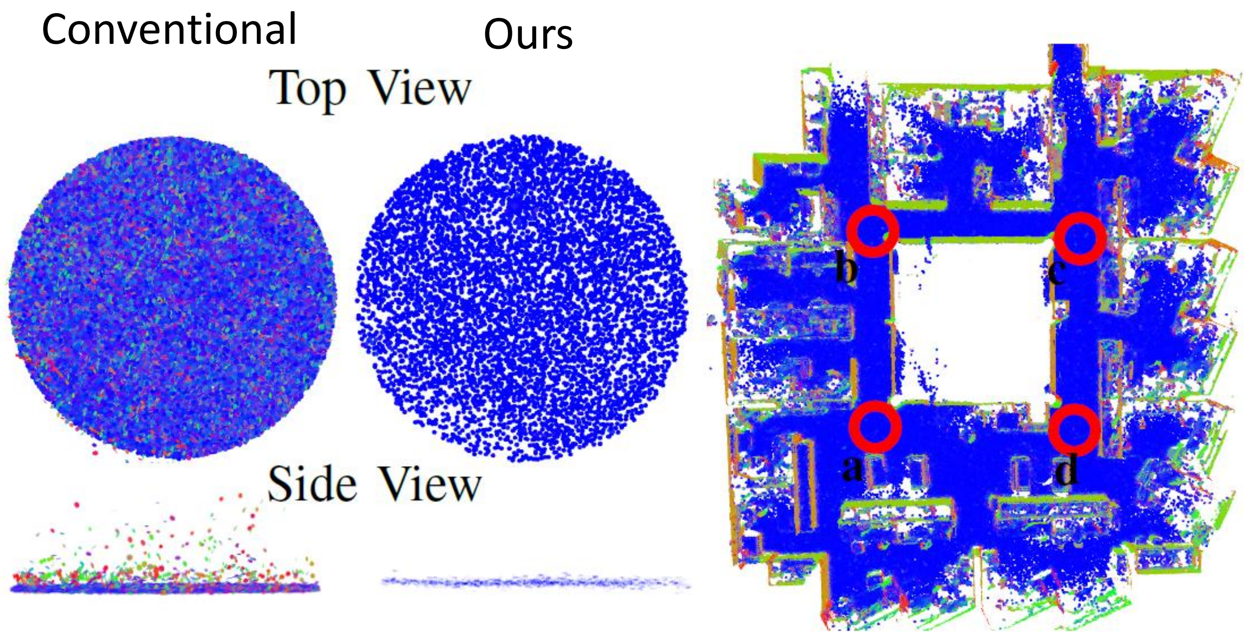


Difference

Dataset	Traj Error(m)	Length(m)	Time(min)	Size(m)
Fig. 1	0.047	330	14.6	20×20
Fig. 7 (i)	0.041	130	6.1	10×6
Fig. 7 (ii)	0.056	300	11.4	55×20
Fig. 7 (iii)	0.076	360	9.1	60×25

Only small difference!

Surface Estimation Error



Location	No.Points	No.Surfel	CT-Err	Prop (mm)
a	47.8×10^4	3.7×10^3	16.08	**7.72**
b	37.8×10^4	4.1×10^3	15.78	**5.79**
c	40.6×10^4	3.8×10^3	16.43	**10.39**
d	56.3×10^4	3.8×10^3	19.40	**13.07**

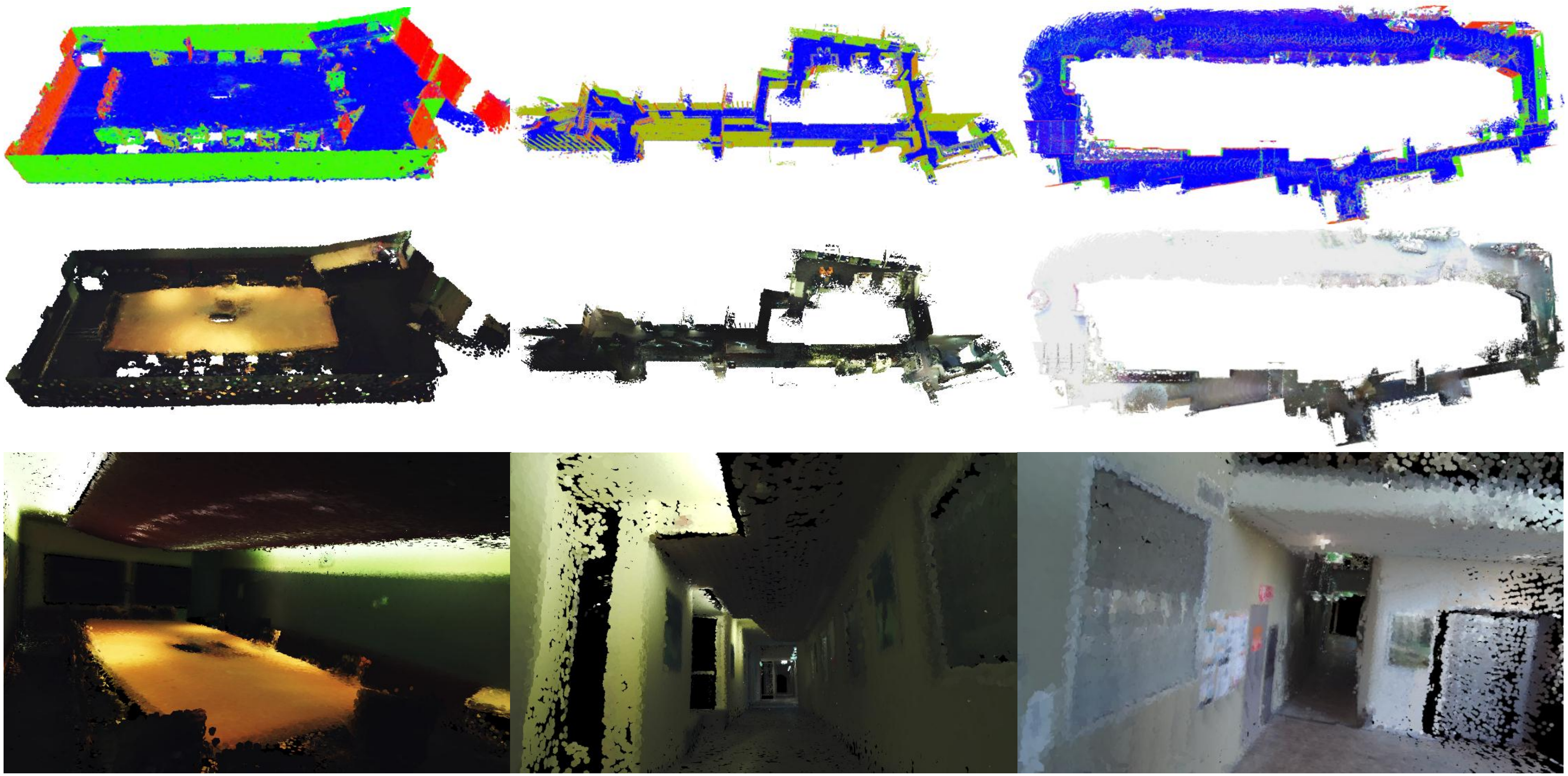
10 times less map elements **Less noise**

Datasets

Normal map

Colour map

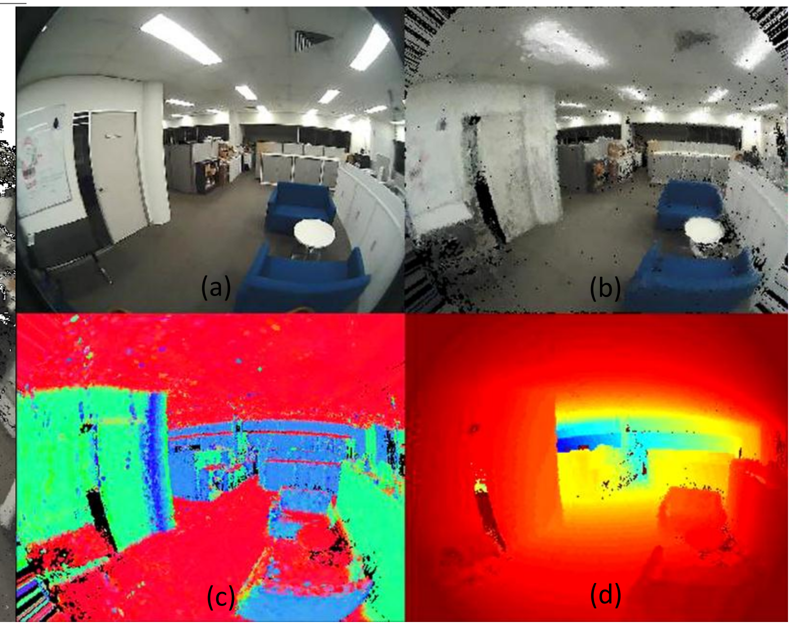
Details



Small map | Multi-Floors | Indoor outdoor mixed

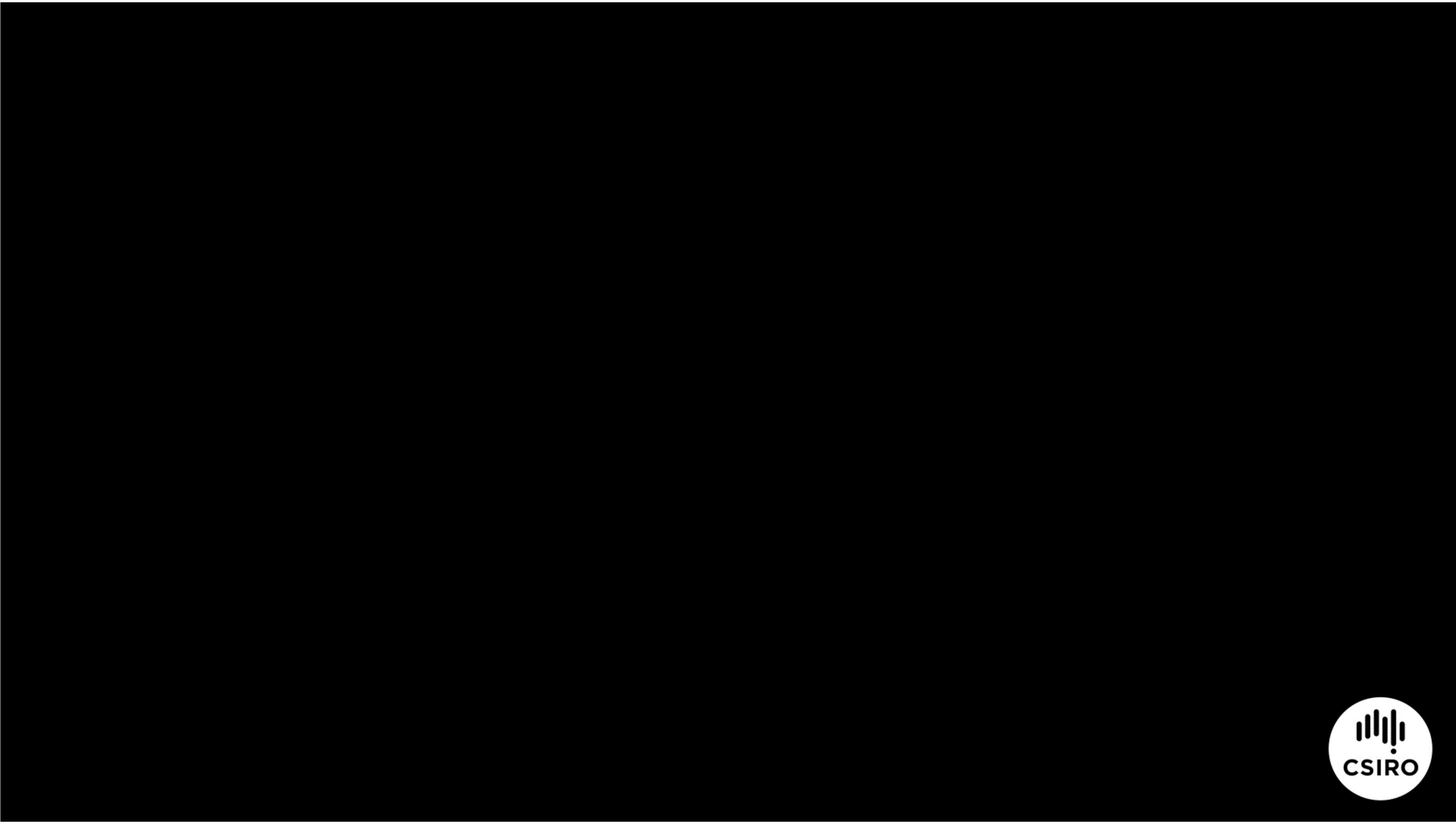
Surfel Scene Representation

Colour Img   Synthesized Img



Normal map   Disparity map

Demo video



Summary

- Long-term mapping
  - Loop closure by map deformation
    - – No global batch optimization at the end
  - Fusion of LiDAR estimations
    - – Map size is dependent on space. Not time!
    - – Accurate map estimation
- Easy handling of asynchronous, high-rate sensor fusion and motion distortion

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Question?

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Surfel Scene Representation