Visual Computing Institute
Computer Vision

RWTH AACHEN UNIVERSITY

Global Keyfame-Based Optimization for a Direct Sparse Visual Odometry Approach

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RWTH Aachen
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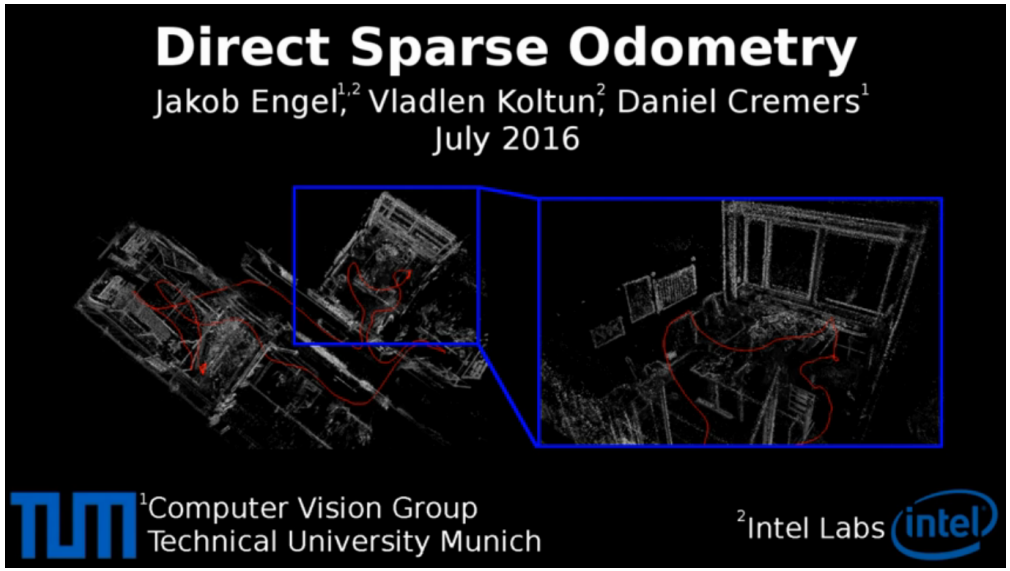
Bachelor Thesis Final Talk

Roadmap

Monocular Visual Odometry and SLAM

Monocular VO

- Direct image alignment
- Local window optimization of active keyframe poses
- Locally consistent map



Monocular Visual Odometry and SLAM

Monocular VO

- Direct image alignment
- Local window optimization of active keyframe poses
- Locally consistent map

Monocular SLAM

- Loop detection
- Global keyframe pose optimization
- Relocalization in case of lost tracking
- Globally consistent map

Roadmap

Monocular Visual Odometry and SLAM

Indirect and Direct Formulations

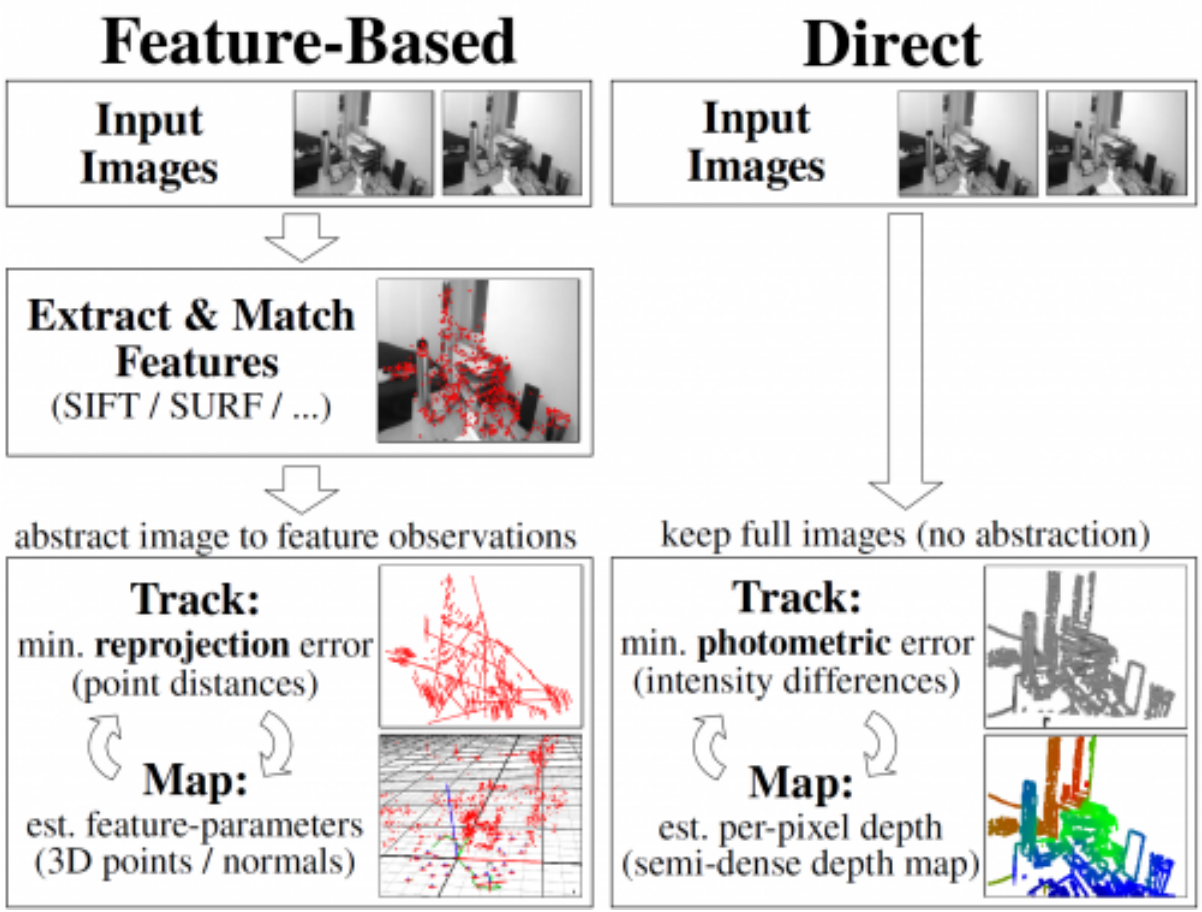
Global Optimization Layer Integration into DSO

Global Photometric Error Formulation and Optimization

Evaluation

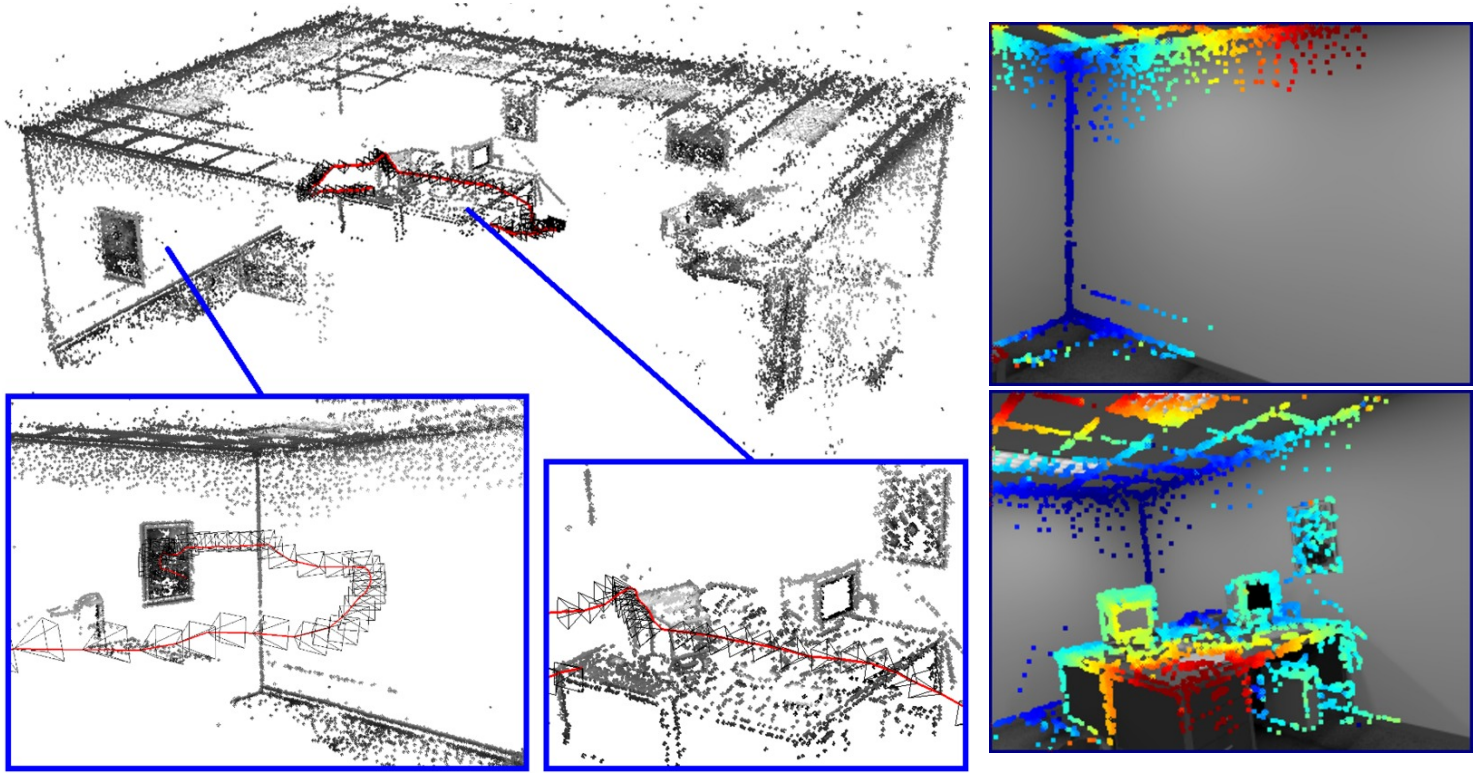
Conclusion and Future Work

Indirect and Direct Formulations



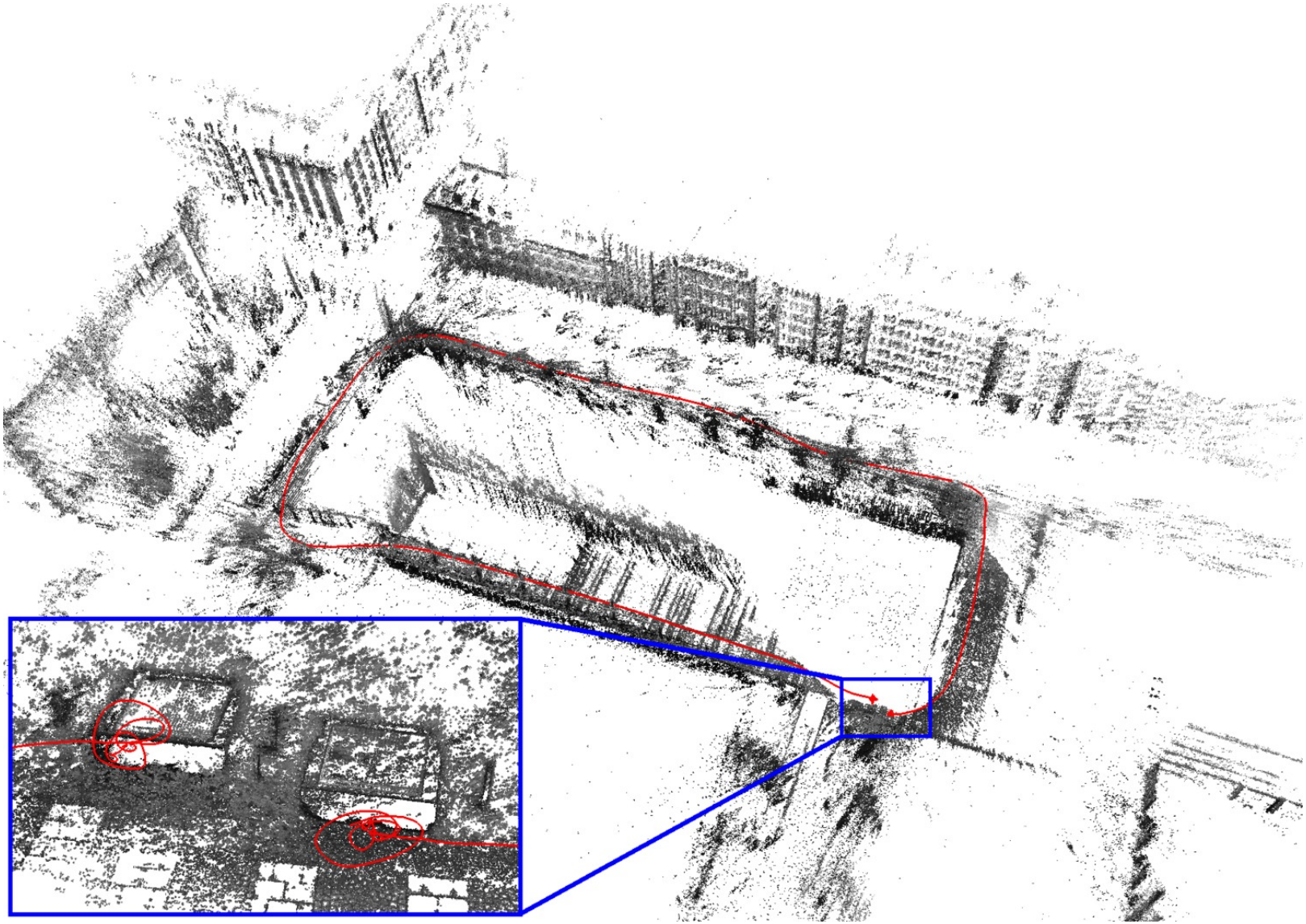
[Engel et al., ECCV 2014]

Semi-Dense Point Cloud and Depth Maps Estimated by DSO



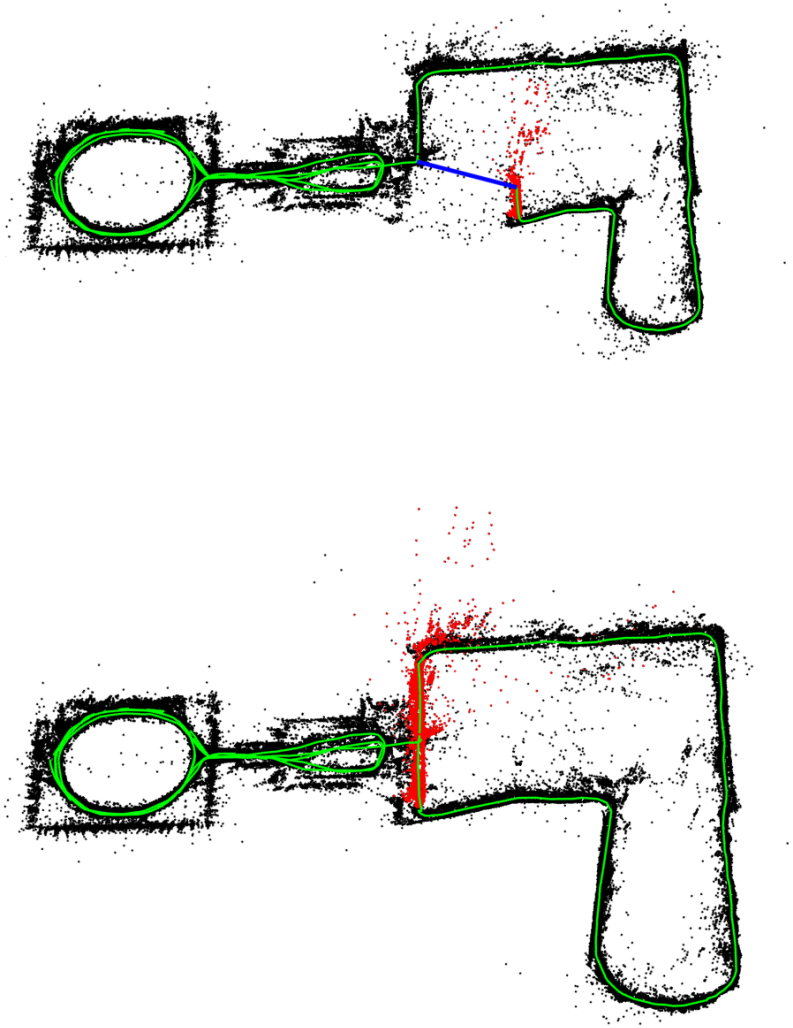
[Engel et al., IEEE TPAMI 2017]

Motion Drift in DSO



[Engel et al., IEEE TPAMI 2017]

Loop Detection and Closing in ORB-SLAM



[Mur-Artal et al., IEEE 2015]

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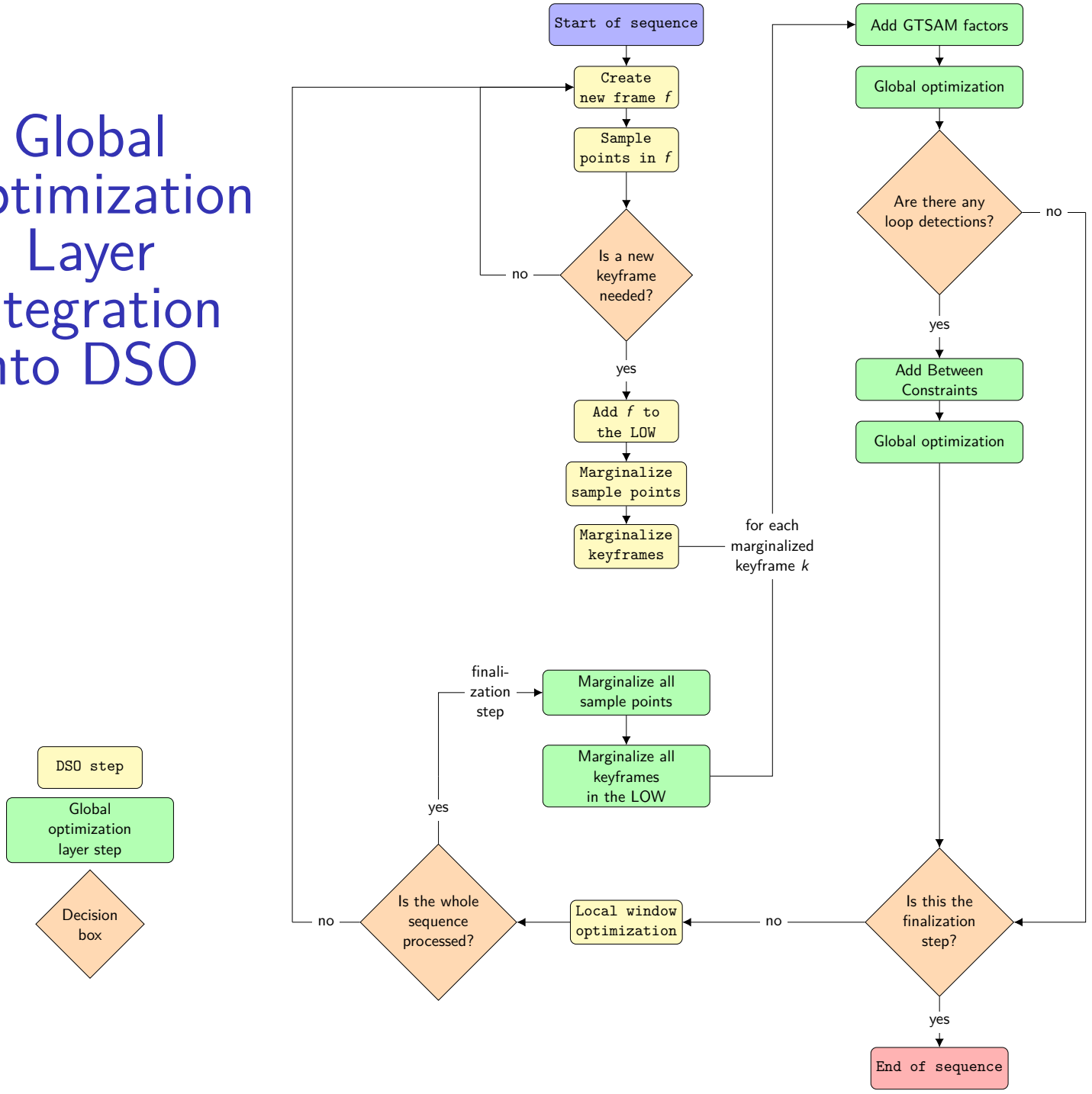
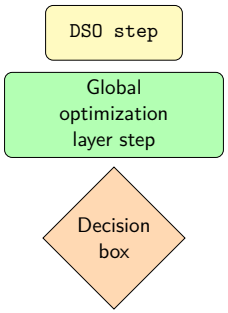
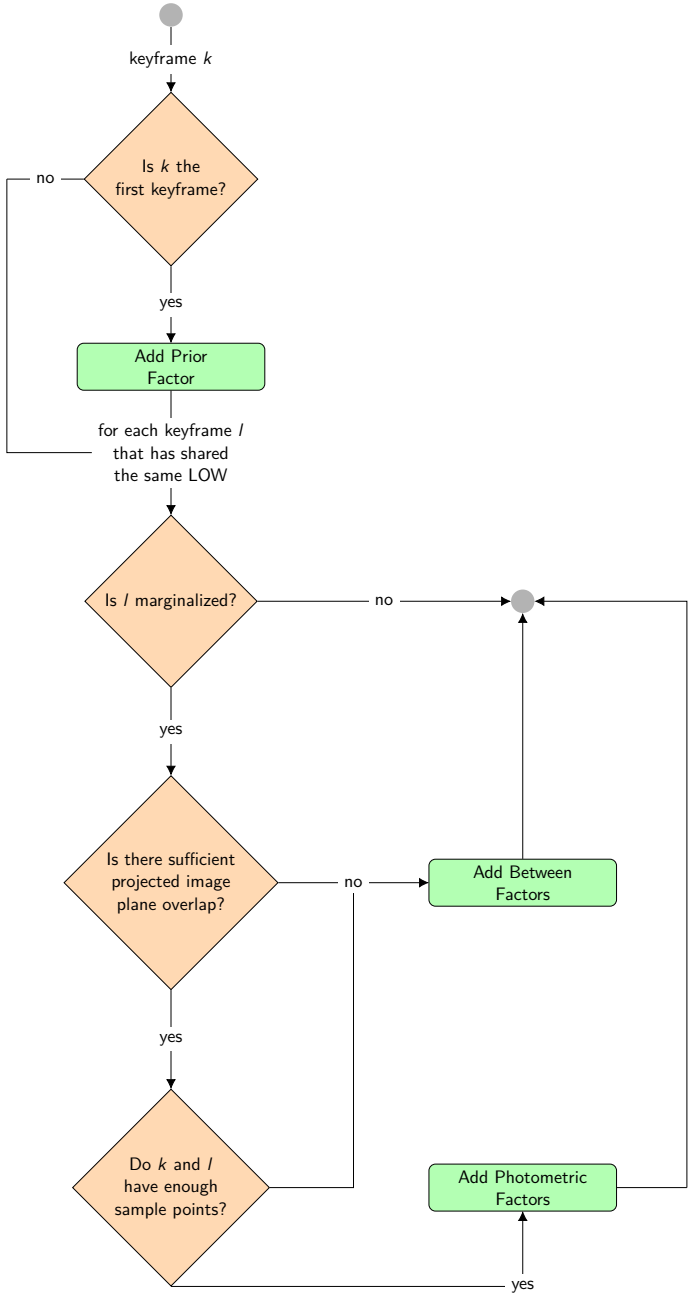
Global Optimization Layer Integration into DSO

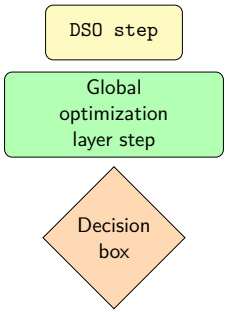


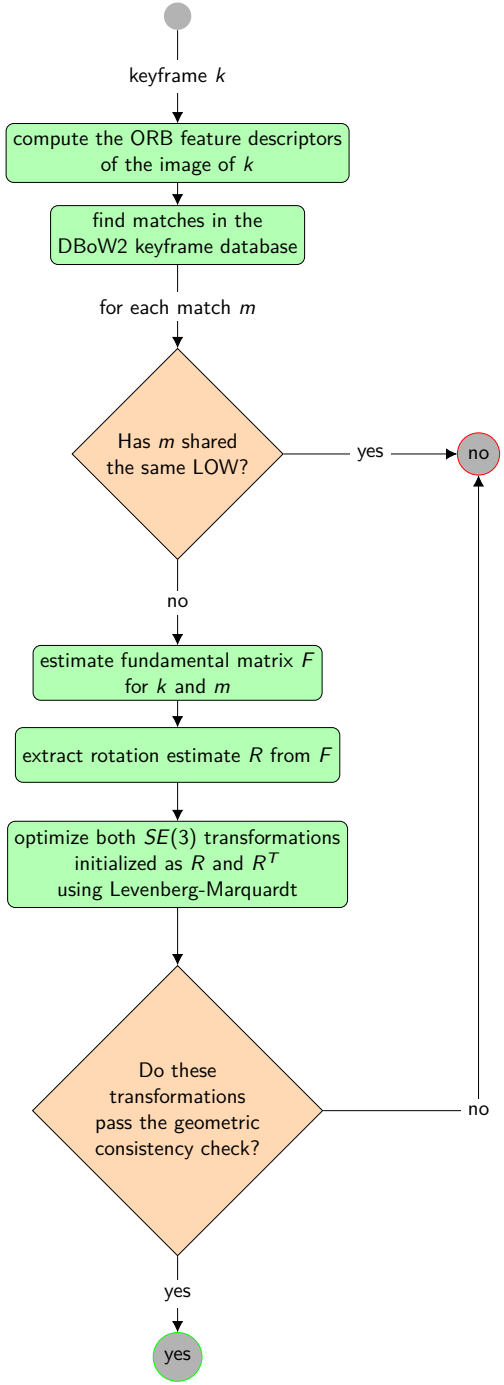
Add GTSAM Factors



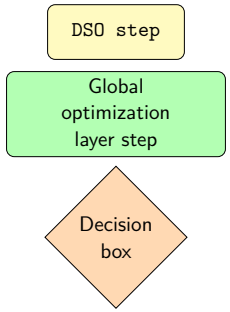


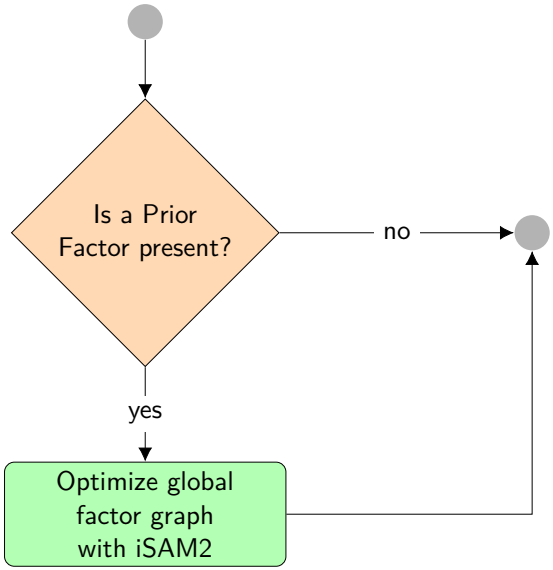
Are There Any Loop Detections?





Global Optimization





Roadmap

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Point Reprojection

$$\Pi : \mathbb{R}^4 \to \mathbb{R}^2 \,, \quad \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix} \mapsto \begin{pmatrix} x/z \\ y/z \end{pmatrix}$$

$$\Pi^{-1} : \mathbb{R}^2 \times \mathbb{R} \to \mathbb{R}^4 \,, \quad (\begin{pmatrix} u \\ v \end{pmatrix}, d_p) \mapsto \begin{pmatrix} u/d_p \\ v/d_p \\ 1/d_p \\ 1 \end{pmatrix}$$

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$$K = \begin{pmatrix} f_x & 0 & c_x & 0 \\ 0 & f_y & c_y & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

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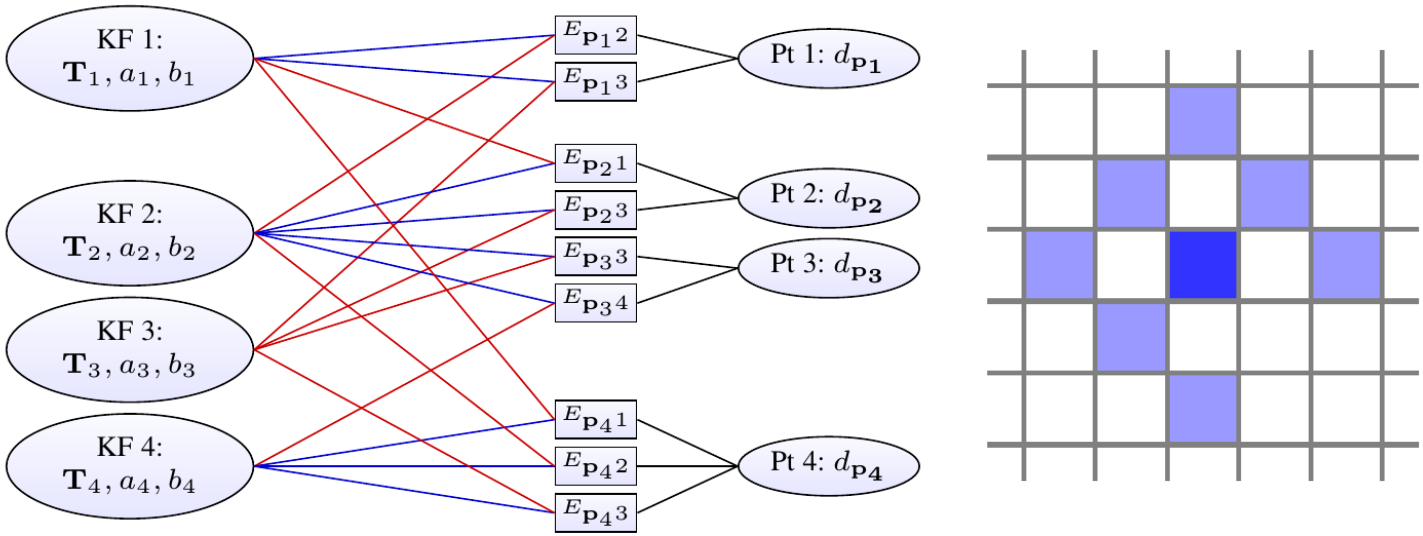
$$K = \begin{pmatrix} f_x & 0 & c_x & 0 \\ 0 & f_y & c_y & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathbf{p}' = \Pi \left(K \; T_i^j \; K^{-1} \; \Pi^{-1} \left(\mathbf{p}, d_p \right) \right)$$

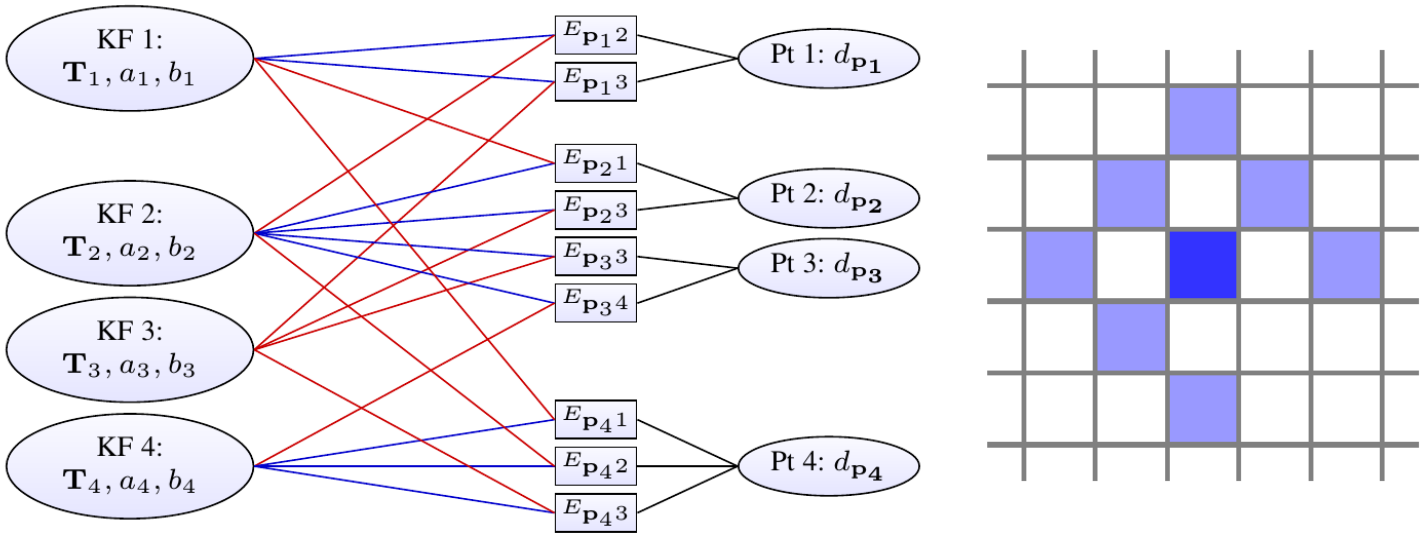
Photometric Error Formulation in DSO



[Engel et al., IEEE TPAMI 2017]

$$E_{\mathbf{p}ij} = \sum_{\mathbf{q} \in N_{\mathbf{p}}} \left\| (I_j[\mathbf{q}'] - b_j) - \frac{t_j e^{a_j}}{t_i e^{a_i}} (I_i[\mathbf{q}] - b_i) \right\|_\gamma$$

Photometric Error Formulation in DSO



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$$E_w = \sum_{i \in F} \sum_{\mathbf{p} \in P_i} \sum_{j \in obs(\mathbf{p}, i)} E_{\mathbf{p}ij}$$

Global Photometric Error Formulation

Photometric Factor

$$E_{PhF}(i,j) = \sum_{\mathbf{p} \in pr(i,j)} \sum_{\mathbf{q} \in N_{\mathbf{p}}} w_{\delta} \left((I_j[\mathbf{q}'] - b_j) - \frac{t_j e^{a_j}}{t_i e^{a_i}} (I_i[\mathbf{q}] - b_i) \right)$$

Global Photometric Error Formulation

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Global Photometric Energy

$$E_{global} = \sum_{(i,j) \in K} E_{PhF}(i,j)$$

Gauss-Newton Optimization

Non-Linear Objective Function

$$h : (G^n)_{n \in F} \to \mathbb{R}^m \ , \ (g^n)_{n \in F} \mapsto R$$

$$x^* = arg \min_x \| h(x) \|_2^2$$

Gauss-Newton Optimization

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Objective Function Linearization

$$h(a \oplus \xi) \approx h(a) + H_a \, \xi$$

$$\xi^* = arg \min_\xi \| h(a) + H_a \, \xi \|_2^2$$

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Normal Equations

$$H_a^T \ H_a \ \xi = -H_a^T \ h(a)$$

Roadmap

Runtime Evaluation

Routine	Runtime
Addition of GTSAM Factors	637 μs
Loop Detection	29 *ms*
Global Optimization without Between Constraints	335 *ms*
Global Optimization with at least one Between Constraint	2,3 *s*
Global Optimization just after the addition of a Between Constraint	7,3 *s*

Evaluation Metrics

Absolute Trajectory Error

$$ATE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\|trans(Q_i^{-1}SP_i)\|^2}$$

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Absolute Trajectory Error

$$ATE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\|trans(Q_i^{-1}SP_i)\|^2}$$

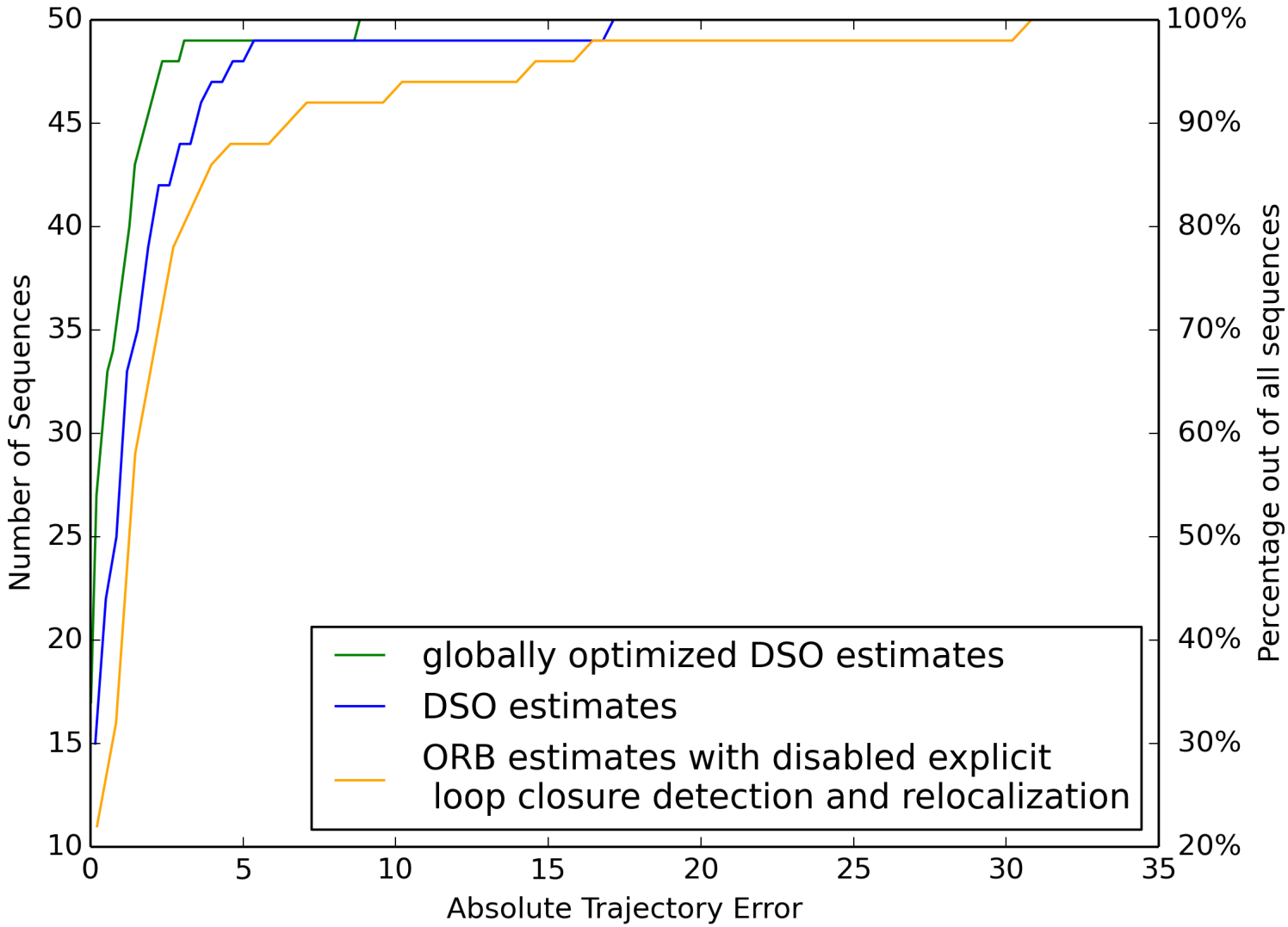
Relative Pose Error

$$E_i = (Q_i^{-1}Q_{i+\Delta})^{-1}(P_i^{-1}P_{i+\Delta})$$

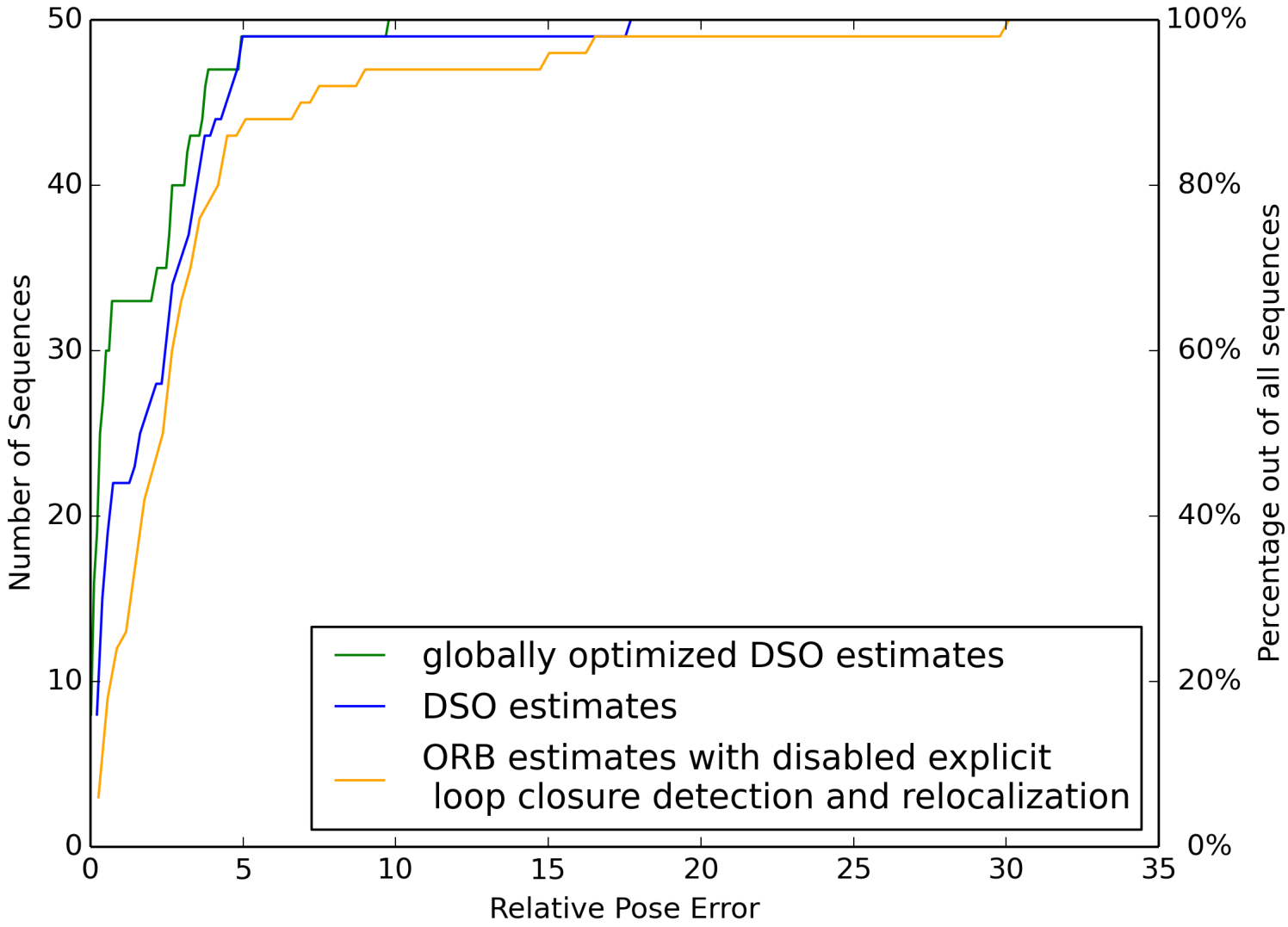
$$RMSE_\Delta = \sqrt{\frac{1}{n-\Delta}\sum_{i=1}^{n-\Delta}\|trans(E_i)\|^2}$$

$$RPE = \frac{1}{n}\sum_{\Delta=1}^{n} RMSE_\Delta$$

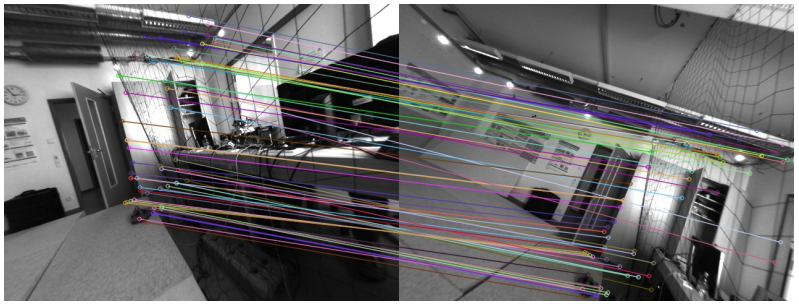
ATE Cumulative Distribution Function

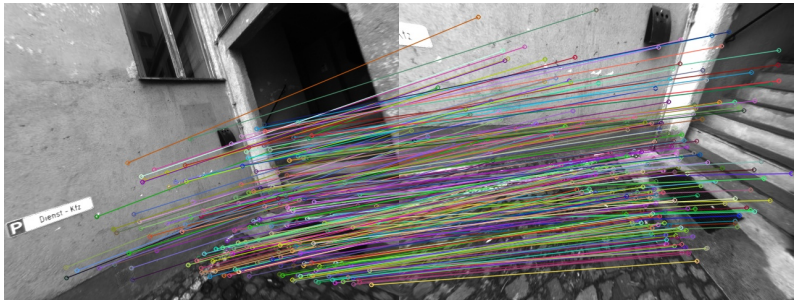


RPE Cumulative Distribution Function



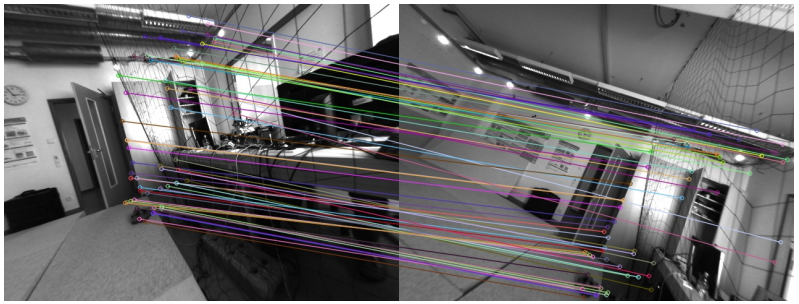
Loop Detection Recall and Precision

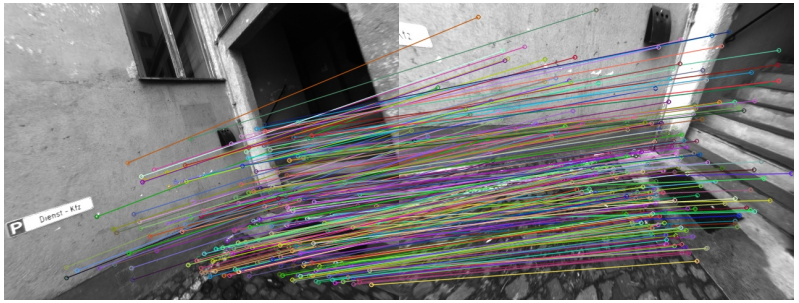




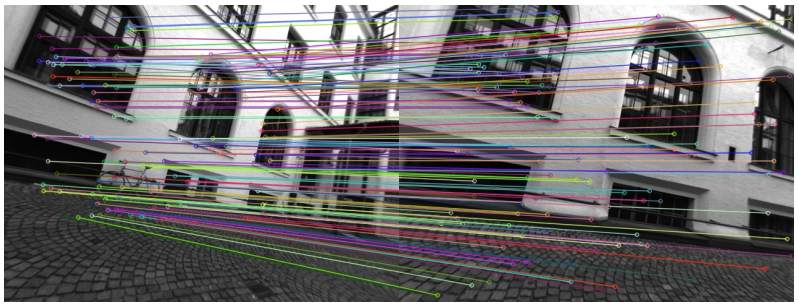
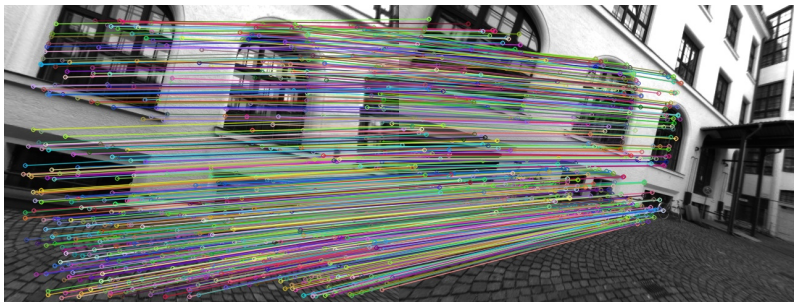

	Percentage
Recall	84%
Precision	93%

Loop Detection Recall and Precision

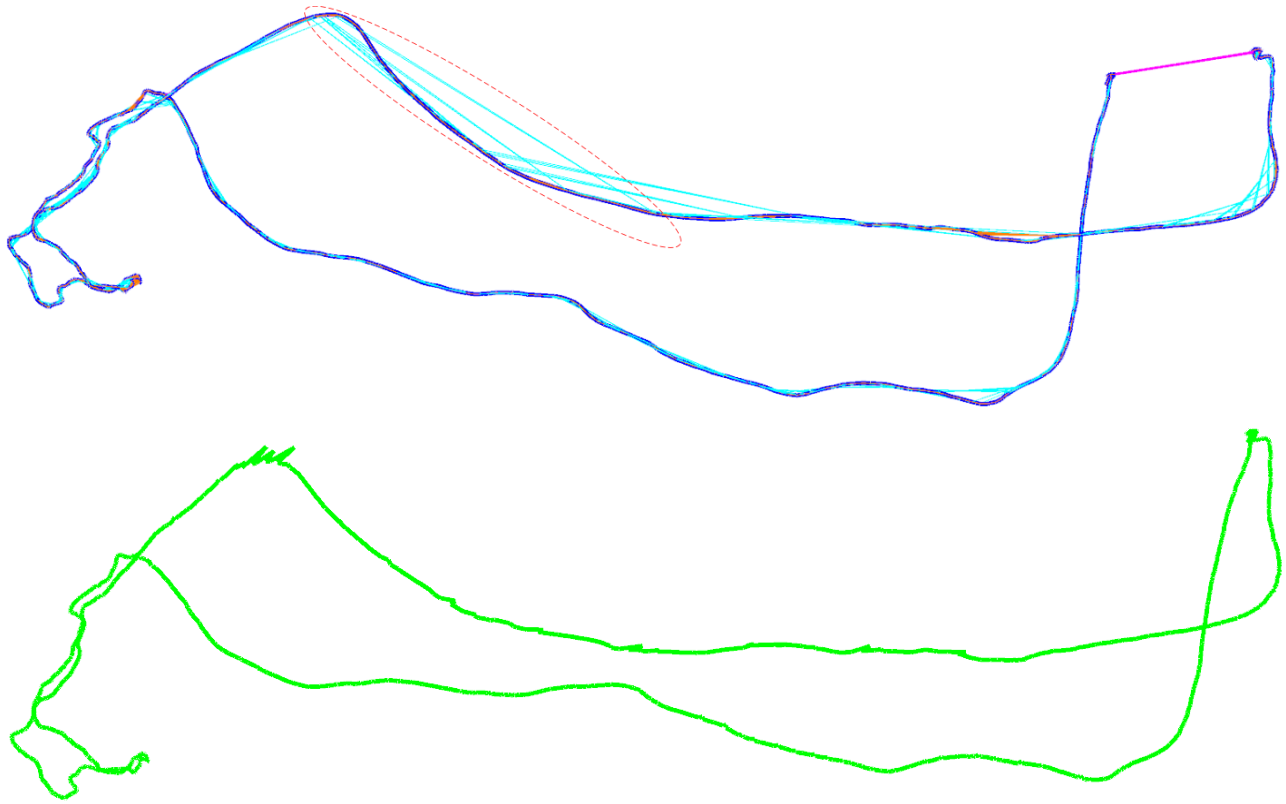





False Loop Detections at Repetitive Structures

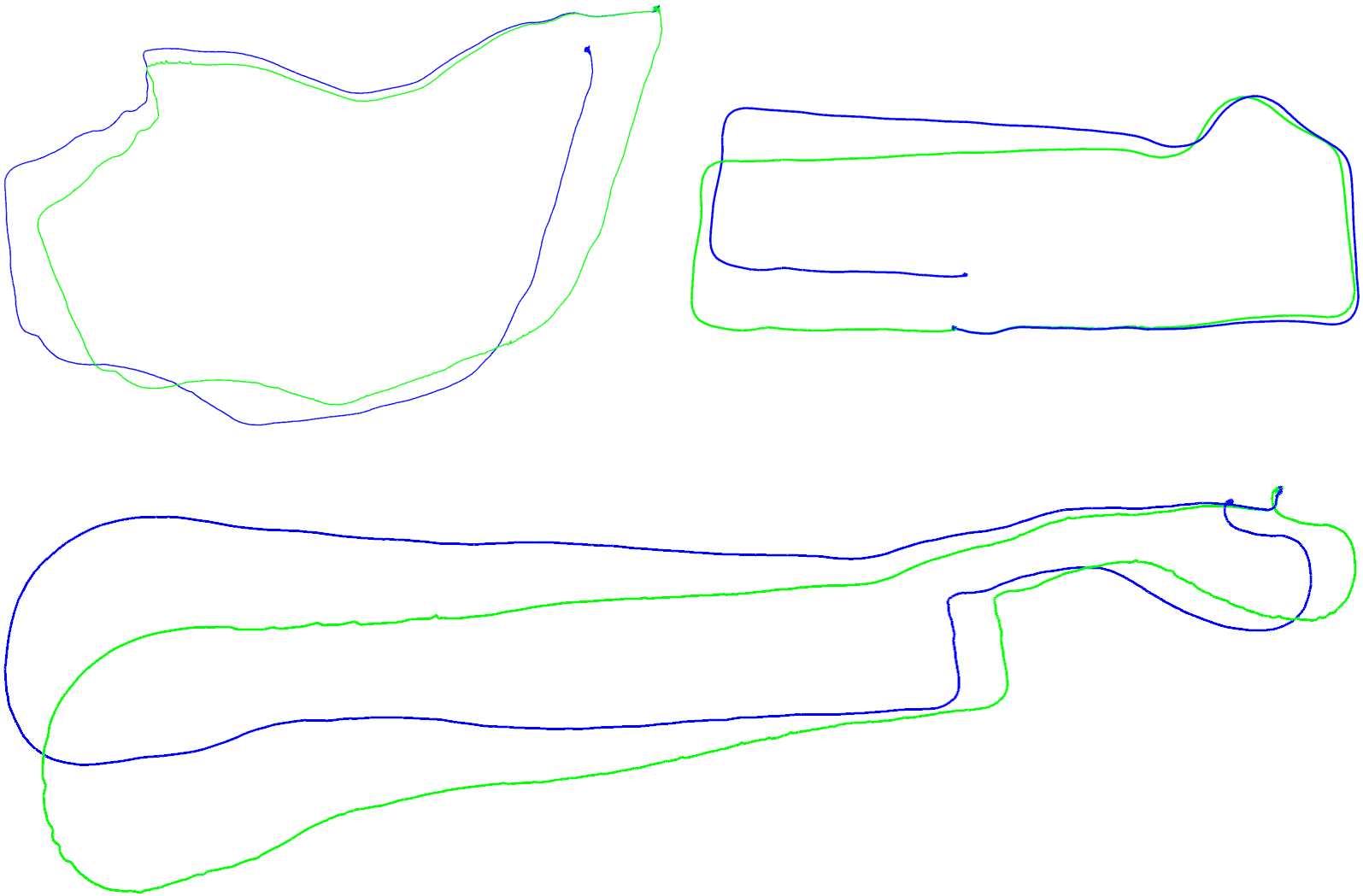
GTSAM Factors and Global Optimization



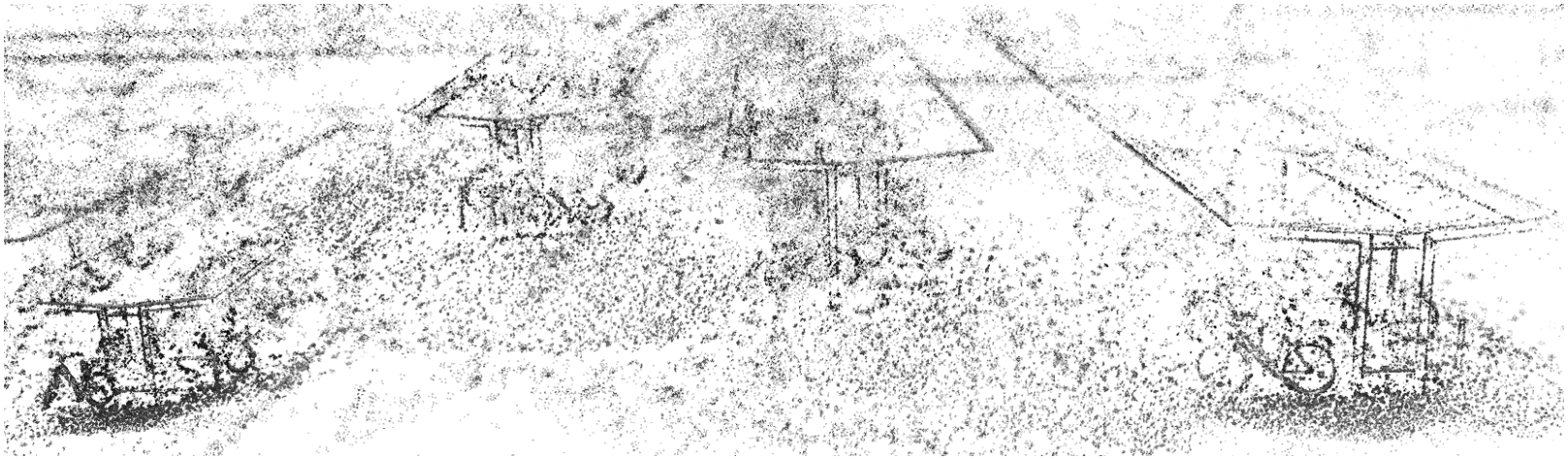
- Original trajectory estimate
- Globally optimized trajectory estimate
- Photometric Factor
- Between Factor
- Between Constraint

Global Optimization of Trajectory Estimates

Global Optimization of Trajectory Estimates



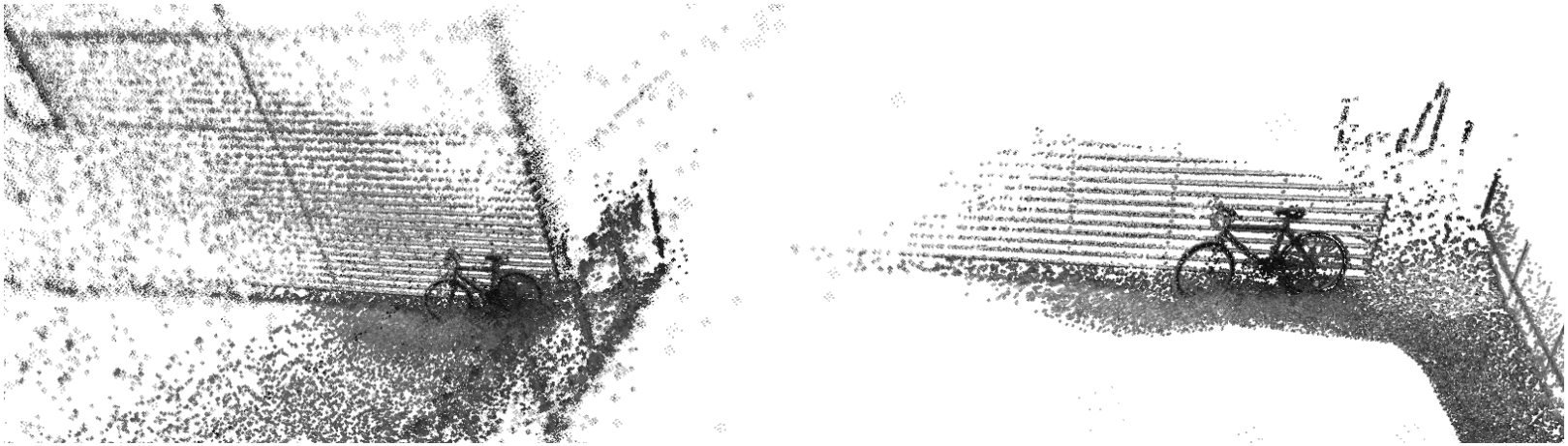
Pointclouds Before and After Global Optimization



DSO

Our approach

Pointclouds Before and After Global Optimization



DSO

Our approach

Roadmap

Summary of Contributions

- Custom Photometric Factors for the implementation of our direct global energy formulation
- Loop detection and closing mechanism for global consistency
- Global factor graph optimization

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- Custom Photometric Factors for the implementation of our direct global energy formulation
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Evaluation results

- High accuracy and robustness of our loop detection mechanism
- Low absolute trajectory and relative pose error in comparison with DSO and ORB-SLAM
- Substantial motion drift reduction in the optimized trajectory

Future Work

- Global optimization of both keyframe camera poses and sample point depths
- Purely photometric optimization as a final step
- Development into a full SLAM system
- $Sim(3)$ transformations for scale drift reduction
- Parallelization for reduction of the overall computational time

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