



Chapter 8

Direct Approaches to Visual SLAM

Multiple View Geometry
Summer 2015

Direct Methods

Realtime Dense
Geometry

Dense RGB-D
Tracking

Loop Closure and
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Dense Tracking and
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Large Scale Direct
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Classical Approaches to Multiple View Reconstruction

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In the past chapters we have studied **classical approaches to multiple view reconstruction**. These methods tackle the problem of structure and motion estimation (or visual SLAM) in several steps:

- ① A set of **feature points** is extracted from the images – ideally points such as **corners** which can be reliably identified in subsequent images as well.
- ② One determines a **correspondence of these points across the various images**. This can be done either through local tracking (using optical flow approaches) or by random sampling of possible partners based on a feature descriptor (SIFT, SURF, etc.) associated with each point.
- ③ The **camera motion is estimated** based on a set of corresponding points. In many approaches this is done by a series of algorithms such as the **eight-point algorithm** or the **five-point algorithm** followed by **bundle adjustment**.
- ④ For a given camera motion one can then compute a **dense reconstruction** using photometric stereo approaches.

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Shortcomings of Classical Approaches

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Such classical approaches are **indirect** in the sense that they do not compute structure and motion directly from the images but rather from a sparse set of precomputed feature points. Despite a number of successes, they have several drawbacks:

- From the point of view of statistical inference, they are **suboptimal**: In the selection of feature points much potentially valuable information contained in the colors of each image is discarded.
- They invariably **lack robustness**: Errors in the point correspondence may have devastating effects on the estimated camera motion. Since one often selects very few point pairs only (8 points for the eight-point algorithm, 5 points for the five-point algorithm), any incorrect correspondence will lead to an incorrect motion estimate.
- They do not address the **highly coupled problems of motion estimation and dense structure estimation**. They merely do so for a sparse set of points. As a consequence, improvements in the estimated dense geometry will not be used to improve the camera motion estimates.

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Toward Direct Approaches to Multiview Reconstruction

In the last few years, researchers have been promoting direct approaches to multi-view reconstruction. Rather than extracting a sparse set of feature points to determine the camera motion, direct methods aim at estimating camera motion and dense or semi-dense scene geometry directly from the input images. This has several advantages:

- Direct methods tend to be more robust to noise and other nuisances because they exploit all available input information.
- Direct methods provide a semi-dense geometric reconstruction of the scene which goes well beyond the sparse point cloud generated by the eight-point algorithm or bundle adjustment. Depending on the application, a separate dense reconstruction step may no longer be necessary.
- Direct methods are typically faster because the feature-point extraction and correspondence finding is omitted: They can provide fairly accurate camera motion and scene structure in real-time on a CPU.

Feature-Based versus Direct Methods

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Feature-Based

Input Images



Direct

Input Images



Extract & Match Features
(SIFT / SURF / ...)

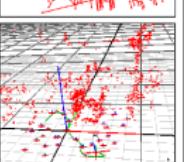


abstract image to feature observations

Track:
min. **reprojection** error
(point distances)



 **Map:**
est. feature-parameters
(3D points / normals)

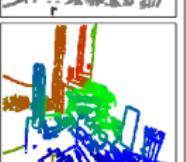


keep full images (no abstraction)

Track:
min. **photometric** error
(intensity differences)



 **Map:**
est. per-pixel depth
(semi-dense depth map)



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Direct Methods for Multi-view Reconstruction

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In the following, we will briefly review several recent works on direct methods for multiple-view reconstruction:

- the method of [Stühmer, Gumhold, Cremers, DAGM 2010](#) which computes dense geometry from a handheld camera in real-time. For given camera motions, the dense reconstruction problem is computed directly from the images.
- the methods of [Steinbrücker, Sturm, Cremers, 2011](#) and [Kerl, Sturm, Cremers, 2013](#) which directly compute the camera motion of an RGB-D camera without feature extraction.
- the method of [Newcombe, Lovegrove, Davison, ICCV 2011](#) which directly determines dense geometry and camera motion from the images.
- the method of [Engel, Sturm, Cremers ICCV 2013](#) and [Engel, Schöps, Cremers ECCV 2014](#) which directly computes camera motion and semi-dense geometry for a handheld (monocular) camera.



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Realtime Dense Geometry from a Handheld Camera

Let $g_i \in SE(3)$ be the rigid body motion from the first camera to the i -th camera, and let $I_i : \Omega \rightarrow \mathbb{R}$ be the i -th image. A **dense depth map** $h : \Omega \rightarrow \mathbb{R}$ can be computed by solving the optimization problem:

$$\min_h \sum_{i=2}^n \int_{\Omega} |I_1(x) - I_i(\pi g_i(hx))| dx + \lambda \int_{\Omega} |\nabla h| dx,$$

where x is represented in homogeneous coordinates and hx is the corresponding 3D point.

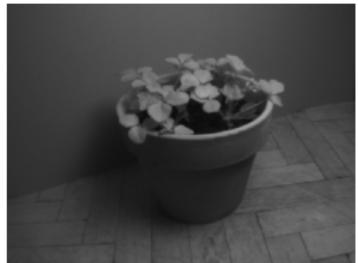
Like in optical flow estimation, the unknown depth map should be such that for all pixels $x \in \Omega$, the transformation into the other images I_i should give rise to the same color as in the reference image I_1 .

This cost function can be minimized at framerate by **coarse-to-fine linearization** solved in parallel on a GPU.

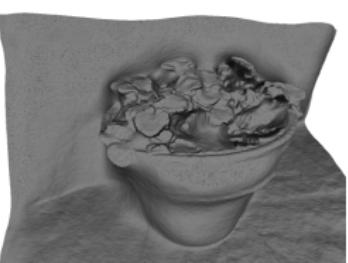
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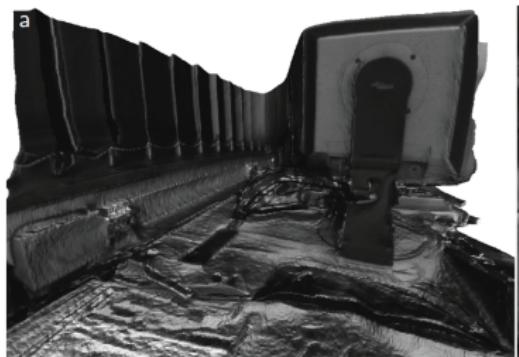
Input image



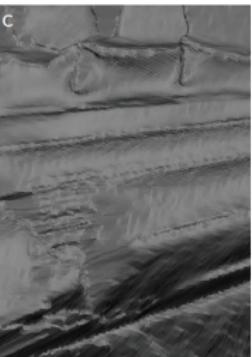
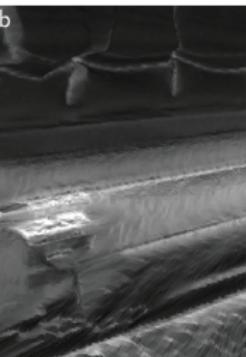
Reconstruction



Textured geometry



Textured reconstructions



Untextured



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Stuehmer, Gumhold, Cremers, DAGM 2010.



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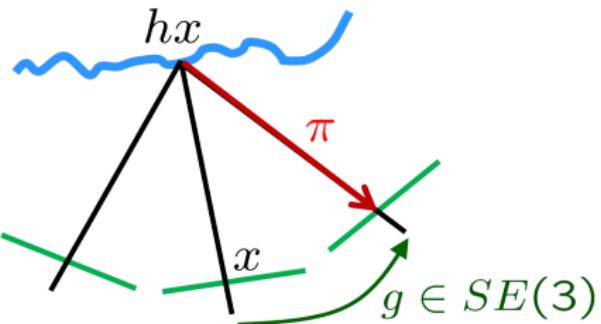
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Dense RGB-D Tracking

The approach of Stühmer et al. (2010) relies on a sparse feature-point based camera tracker (PTAM) and computes dense geometry directly on the images. Steinbrücker, Sturm, Cremers (2011) propose a complementary approach to directly compute the camera motion from RGB-D images. The idea is to compute the rigid body motion g_ξ which optimally aligns two subsequent color images I_1 and I_2 :

$$\min_{\xi \in \mathfrak{se}(3)} \int_{\Omega} |I_1(x) - I_2(\pi g_\xi(hx))|^2 dx$$





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The above non-convex problem can be approximated as a convex problem by linearizing the residuum around an initial guess ξ_0 :

$$E(\xi) \approx \int_{\Omega} \left| I_1(x) - I_2(\pi g_{\xi_0}(hx)) - \nabla I_2^\top \left(\frac{d\pi}{dg_\xi} \right) \left(\frac{dg_\xi}{d\xi} \right) \xi \right|^2 dx$$

This is a convex quadratic cost function which gives rise to a linear optimality condition:

$$\frac{dE(\xi)}{d\xi} = A\xi + b = 0$$

To account for larger motions of the camera, this problem is solved in a coarse-to-fine manner. The linearization of the residuum is identical with a Gauss-Newton approach. It corresponds to an approximation of the Hessian by a positive definite matrix.

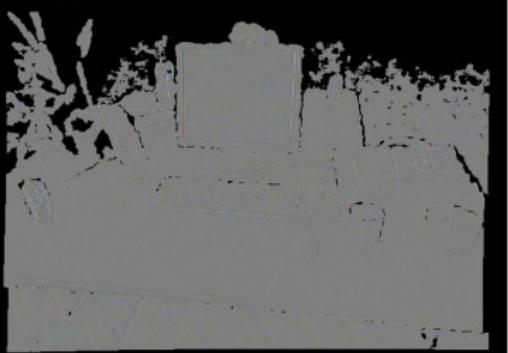
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Registered



Difference



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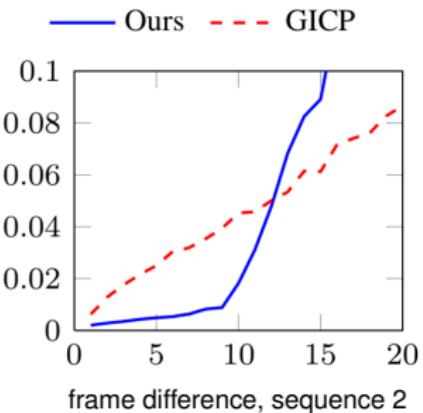
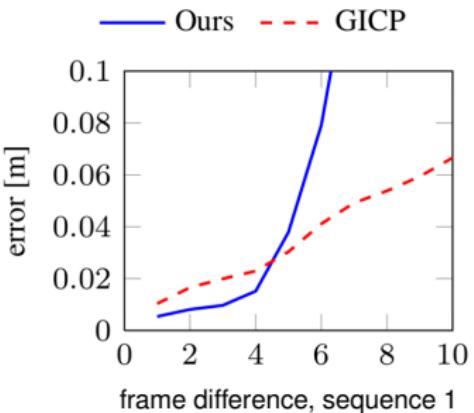
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In the small-baseline setting, this image aligning approach provides more accurate camera motion than the commonly used generalized Iterated Closest Points (GICP) approach.



Steinbrücker, Sturm, Cremers 2011

A related direct tracking approach was proposed for stereo reconstruction in **Comport, Malis, Rives, ICRA 2007**. A generalization which makes use of **non-quadratic penalizers** was proposed in **Kerl, Sturm, Cremers, ICRA 2013**.



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A Benchmark for RGB-D Tracking

Accurately tracking the camera is among the most central challenges in computer vision. Quantitative performance of algorithms can be validated on benchmarks.



Sturm, Engelhard, Endres, Burgard, Cremers, IROS 2012

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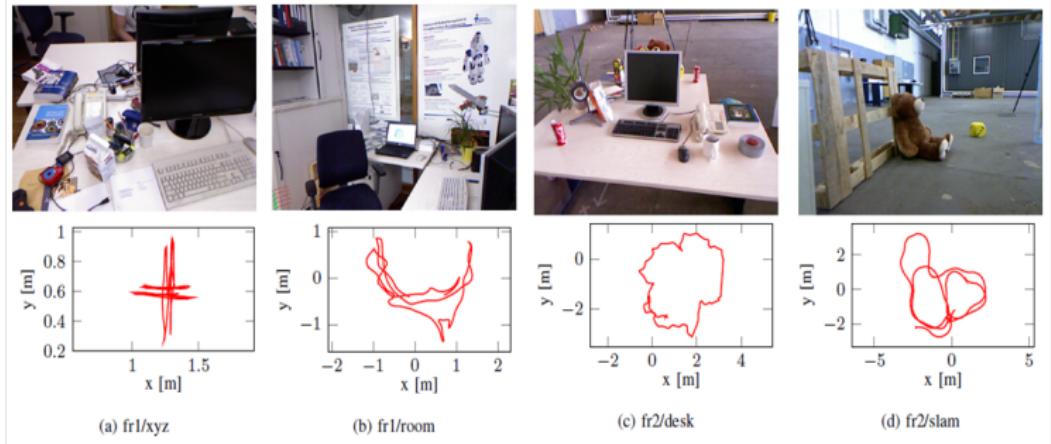
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Sturm, Engelhard, Endres, Burgard, Cremers, IROS 2012



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Combining Photometric and Geometric Consistency

Kerl, Sturm, Cremers, IROS 2013 propose an extension of the RGB-D camera tracker which combines **color consistency** and **geometric consistency** of subsequent RGB-D images.

Assuming that the vector $r_i = (r_{ci}, r_{zi}) \in \mathbb{R}^2$ containing the color and geometric discrepancy for pixel i follows a **bivariate t-distribution**, the maximum likelihood pose estimate can be computed as:

$$\min_{\xi \in \mathbb{R}^6} \sum_i w_i r_i^\top \Sigma^{-1} r_i,$$

with weights w_i based on the student t-distribution:

$$w_i = \frac{\nu + 1}{\nu + r_i^\top \Sigma^{-1} r_i}.$$

This nonlinear weighted least squares problem can be solved in an iteratively reweighted least squares manner by alternating a **Gauss-Newton style optimization** with a **re-estimation of the weights w_i and the matrix Σ** .

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Loop Closure and Global Consistency

When tracking a camera over a longer period of time, errors tend to accumulate. While a single room may still be mapped more or less accurately, mapping a larger environment will lead to increasing distortions: Corridors and walls will no longer be straight but slightly curved.

A remedy is to introduce loop closure, a technique popularized in laser-based SLAM systems. The key idea is to estimate the relative camera motion $\hat{\xi}_{ij}$ for any camera pair i and j in a certain neighborhood. Subsequently, one can determine a globally consistent camera trajectory $\xi = \{\xi_i\}_{i=1..T}$ by solving the nonlinear least squares problem

$$\min_{\xi} \sum_{i \sim j} \left(\hat{\xi}_{ij} - \xi_i \circ \xi_j^{-1} \right)^T \Sigma_{ij} \left(\hat{\xi}_{ij} - \xi_i \circ \xi_j^{-1} \right),$$

where Σ_{ij} denotes the uncertainty of measurement $\hat{\xi}_{ij}$. This problem can be solved using, for example, a Levenberg-Marquardt algorithm.

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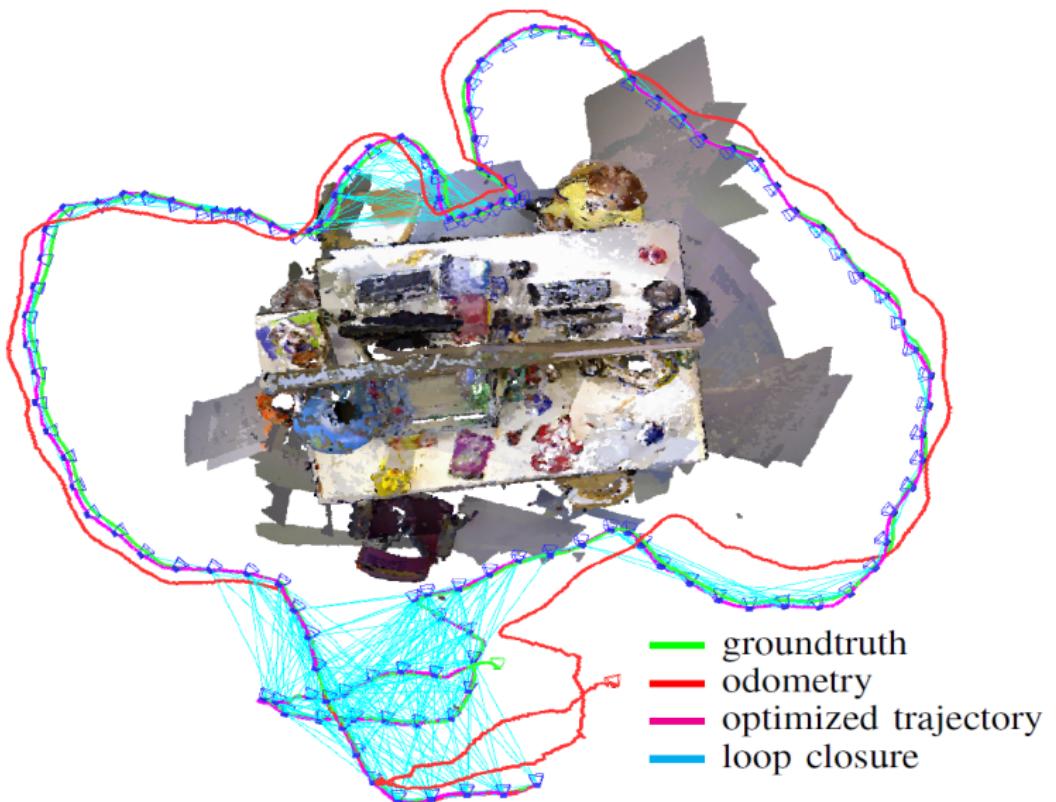
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Kerl, Sturm, Cremers, IROS 2013

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Dense Tracking and Mapping

Newcombe, Lovegrove & Davison (ICCV 2011) propose an algorithm which computes both the geometry of the scene and the camera motion from a direct and dense algorithm.

They compute the inverse depth $u = 1/h$ by minimizing a cost function of the form

$$\min_u \sum_{i=2}^n \int_{\Omega} \left| I_i(x) - I_i \left(\pi g_i \left(\frac{x}{u} \right) \right) \right| dx + \lambda \int_{\Omega} \rho(x) |\nabla u| dx,$$

for fixed camera motions g_i . The function ρ introduces an edge-dependent weighting assigning small weights in locations where the input images exhibit strong gradients:

$$\rho(x) = \exp(-|\nabla I_\sigma(x)|^\alpha).$$

The camera tracking is then performed with respect to the textured reconstruction in a manner similar to Steinbrücker et al. (2011). The method is initialized using feature point based stereo.

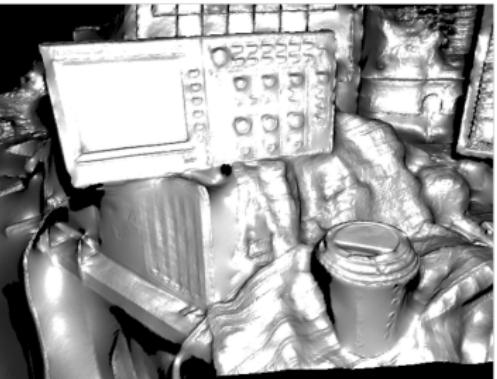
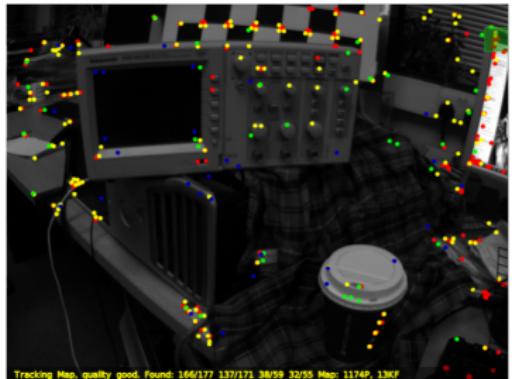
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A method for real-time direct monocular SLAM is proposed in Engel, Sturm, Cremers, ICCV 2013 and Engel, Schöps, Cremers, ECCV 2014. It combines several contributions which make it well-suited for robust large-scale monocular SLAM:

- Rather than tracking and putting into correspondence a sparse set of feature points, the method estimates a **semi-dense depth map** which associates an inverse depth with each pixel that exhibits sufficient gray value variation.
- To account for noise and uncertainty each inverse depth value is associated with an **uncertainty** which is **propagated and updated over time** like in a Kalman filter.
- Since monocular SLAM is invariably defined up to scale only, we explicitly facilitate scaling of the reconstruction by modeling the camera motion using the **Lie group of 3D similarity transformations $Sim(3)$** .
- Global consistency is assured by **loop closing on $Sim(3)$** .



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Tracking by Direct $\text{sim}(3)$ Image Alignment

Since reconstructions from a monocular camera are only defined up to scale, **Engel, Schöps, Cremers, ECCV 2014** account for rescaling of the environment by representing the camera motion as an element in the **Lie group of 3D similarity transformations $\text{Sim}(3)$** which is defined as:

$$\text{Sim}(3) = \left\{ \begin{pmatrix} sR & T \\ 0 & 1 \end{pmatrix} \text{ with } R \in SO(3), T \in \mathbb{R}^3, s \in \mathbb{R}_+ \right\}.$$

One can minimize a **nonlinear least squares problem**

$$\min_{\xi \in \text{Sim}(3)} \sum_i w_i r_i^2(\xi),$$

where r_i denotes the color residuum across different images and w_i a weighting as suggested in Kerl et al. IROS 2013.

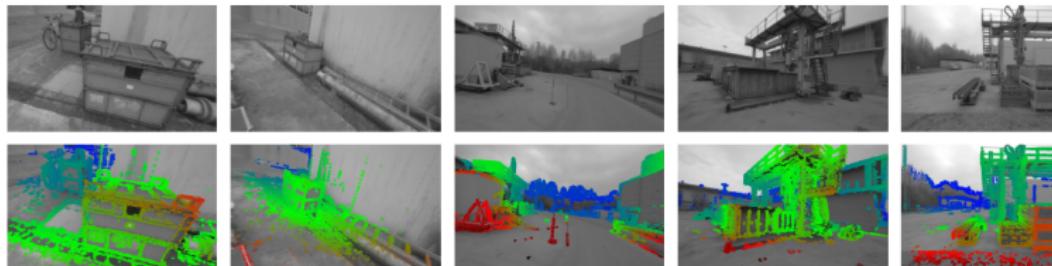
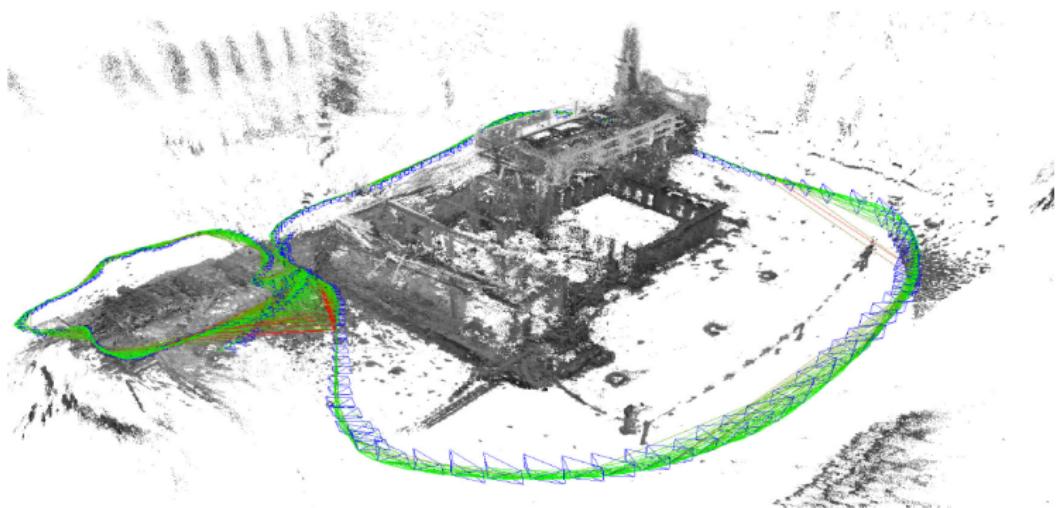
The above cost function can then be optimized by a **weighted Gauss-Newton algorithm on the Lie group $\text{Sim}(3)$** :

$$\xi^{(t+1)} = \Delta_\xi \circ \xi^{(t)}, \quad \text{with } \Delta_\xi = (J^\top W J)^{-1} J^\top W r, \quad J = \frac{\partial r}{\partial \xi}$$

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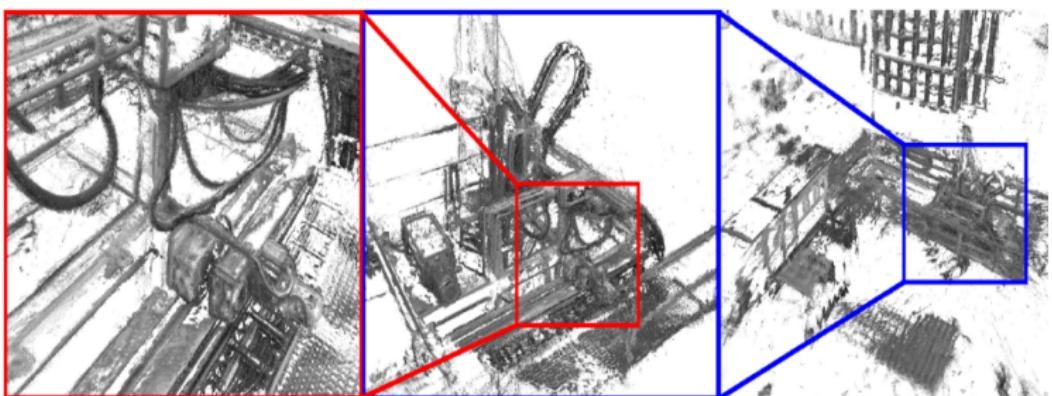
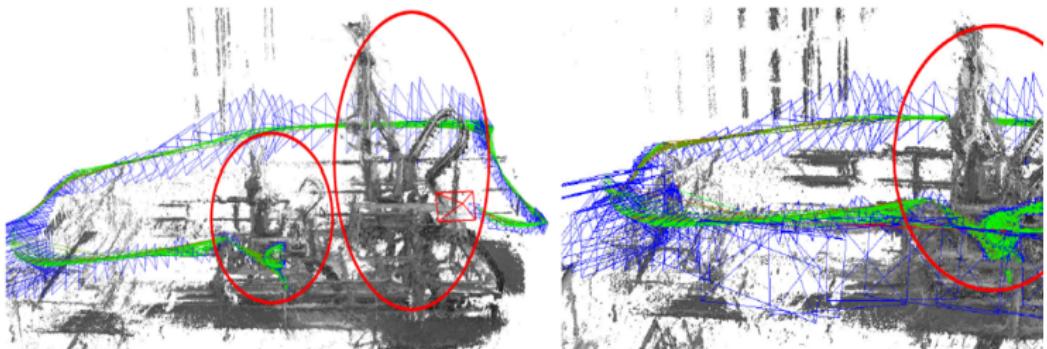
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Engel, Schöps, Cremers, ECCV 2014

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Engel, Schöps, Cremers, ECCV 2014

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