Beyond Features: Dense and Direct Methods for Visual SLAM and Geometric Reconstruction

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3D Reconstruction from Images

infinite-dimensional optimization
Image segmentation:

Geman, Geman ’84, Blake, Zisserman ‘87, Kass et al. ’88, Mumford, Shah ’89, Caselles et al. ‘95, Kichenassamy et al. ‘95, Paragios, Deriche ’99, Chan, Vese ‘01, Tsai et al. ‘01, …

Multiview stereo reconstruction:

Faugeras, Keriven ’98, Duan et al. ‘04, Yezzi, Soatto ’03, Seitz et al. ‘06, Hernandez et al. ‘07, Labatut et al. ’07, …

Optical flow estimation:

Optimization and Convexity

Non-convex energy

Convex energy
Classical Keypoint Approach

Input Images

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

Input Images

Track: min. reprojection error (point distances)

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

Abstract images to feature observations
Beyond Features: Direct & Dense 3D Reconstruction
Overview

- Multiview reconstruction
- Super-res. textures
- Free-viewpoint TV

- Realtime dense geometry
- Large-Scale Direct SLAM
- RGB-D modeling
Overview

Multiview reconstruction

Super-res. textures

Free-viewpoint TV

Realtime dense geometry

Large-Scale Direct SLAM

RGB-D modeling
Photoconsistency function:

\[ \rho : \mathbb{R}^3 \rightarrow [0, 1] \]

Determine a surface \( S \) of optimal photoconsistency by minimizing

\[
E(S) = \int_S \rho \, dA
\]

**Theorem:** Globally optimal surfaces can be computed via convex relaxation.

*Kolev, Klodt, Brox, Cremers, Int. J. of Computer Vision ’09*
Evolution to Global Optimum

Kolev, Klodt, Brox, Cremers, IJCV 2009
Kolev, Cremers, ECCV ‘08, PAMI ‘09:
Theorem: Provably silhouette-consistent reconstructions can be computed by convex optimization over convex domains.
Overview

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Given all images $\mathcal{I}_i : \Omega_i \rightarrow \mathbb{R}^3$, determine the surface color $T : S \rightarrow \mathbb{R}^3$

\[
\min_T \sum_{i=1}^{n} \int_{\Omega_i} \left( b \ast (T \circ \beta_i) - \mathcal{I}_i \right)^2 dx + \lambda \int_S \| \nabla_s T \| ds
\]

blur & downsample  back-projection

Goldlücke, Cremers, ICCV ’09, DAGM ’09
Super-Resolution Texture Map

Goldlücke, Cremers, ICCV ’09, DAGM ’09

* Best Paper Award
Super-Resolution Texture Map

Closeup of input image

Super-resolution texture

Goldlücke, Cremers, ICCV ’09, DAGM ’09*

* Best Paper Award

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Beyond Features: Direct & Dense 3D Reconstruction

Oswald, Stühmer, Cremers, ECCV ‘14
Action Reconstruction
Can we do realtime dense reconstruction from a handheld camera?
Overview

Multiview reconstruction

Super-res. textures

Free-viewpoint TV

Realtime dense geometry

Large-Scale Direct SLAM

RGB-D modeling
From Optical Flow…

Input video

Optical flow field

Wedel, Pock, Bischof, Cremers, ICCV ‘09
From Optical Flow…

Input video

Optical flow field*

* 60 fps at 640 x 480 resolution

Wedel, Pock, Bischof, Cremers, ICCV ‘09
...to Realtime Dense Reconstruction

Brightness constancy:

\[ I_0(x) \approx I_i \left( \pi \left( g_i(u \cdot x) \right) \right) \]

\[
\min_{u,v} \sum_i \int_{\Omega} \left| I_0(x) - I_i \left( \pi \left( g_i(u \cdot x) \right) \right) \right| \, dx + \int_{\Omega} |\nabla u(x)| \, dx
\]

\[
+ \frac{1}{\theta} \int_{\Omega} (u - v)^2 \, dx + \int_{\Omega} |\nabla v(x)| \, dx
\]

Stuehmer, Gumhold, Cremers, DAGM ’10
Realtime Dense Reconstruction

Stuehmer, Gumhold, Cremers, DAGM ’10
Realtime Dense Reconstruction

Stuehmer, Gumhold, Cremers, DAGM ’10
Realtime Dense Reconstruction

Stuehmer, Gumhold, Cremers, DAGM ’10
Realtime Dense Reconstruction

Newcombe et al., ICCV ’11  Wendel et al., CVPR ’12
Overview

Multiview reconstruction

Super-res. textures

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Large-Scale Direct SLAM

RGB-D modeling
Real-time Visual SLAM

Structure from Motion Causally Integrated Over Time. 
*Chiuso, Favaro, Jin, Soatto*; PAMI ’02.

Visual Odometry.
*Nistér, Naroditsky, Bergen*; CVPR ’04.

Scalable monocular SLAM.
*Eade, Drummond*; CVPR ’06.


MonoSLAM: Real-time single camera SLAM. 
*Davison, Reid, Molton, Stasse*; PAMI ’07.

Scale Drift-Aware Large Scale Monocular SLAM. 
*Strasdat, Montiel, Davison*; RSS ’10.

DTAM: Dense Tracking and Mapping in Real-Time. 
*Newcombe, Lovegrove, Davison*; ICCV ’11.

Real-time Visual SLAM

Keypoint-Based

- Input Images
- Extract & Match Features (SIFT / SURF / BRIEF /...)
- abstract images to feature observations
- Track: min. reprojection error (point distances)
- Map: est. feature-parameters (3D points / normals)

Direct (LSD-SLAM)

- Input Images
- keep full image
- Track: min. photometric error (intensity difference)
- Map: est. per-pixel depth (semi-dense depth map)
LSD SLAM: Large-Scale Direct SLAM

Engel, Sturm, Cremers, ICCV ‘13, Engel, Schöps, Cremers, ECCV ‘14
Keypoint versus Direct SLAM

Engel, Schöps, Cremers, ECCV 2014
Camera Pose Optim. & Loop Closure

Engel, Sturm, Cremers, ICCV ‘13, Engel, Schöps, Cremers, ECCV ‘14
LSD SLAM: Large-Scale Direct SLAM

Engel, Sturm, Cremers, ICCV ‘13, Engel, Schöps, Cremers, ECCV ‘14
LSD SLAM: Large-Scale Direct SLAM

Engel, Sturm, Cremers, ICCV '13, Engel, Schöps, Cremers, ECCV '14
Large-Scale Direct Monocular SLAM

Engel, Sturm, Cremers, ICCV ‘13, Engel, Schöps, Cremers, ECCV ‘14
Overview

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Realtime Dense Camera Calibration

Lie algebra representation of rigid body motion:

$$g_\xi = \exp\left(\xi\right), \quad \xi \in \mathbb{R}^6$$

Photo-consistency:

$$\min_{\xi \in \mathbb{R}^6} \int_{\Omega} \left| I_0(x) - I_i\left(\pi(g_\xi (u \cdot x))\right)\right|^2 \, dx$$

Steinbruecker, Sturm, Cremers ‘11, Kerl et al. ICRA ‘13
Realtime Dense Camera Calibration

Photo-consistency:

\[ E(\xi) = \int_{\Omega} \left| I_0(x) - I_i(\pi(g_\xi(u \cdot x))) \right|^2 \, dx \]

Taylor expansion:

\[ E(\xi) \approx \int_{\Omega} \left| I_0(x) - I_i - \nabla I^\top \left( \frac{d\pi}{dg_\xi} \right) \left( \frac{dg_\xi}{d\xi} \right) \xi \right|^2 \, dx \]

Optimal solution:

\[ \frac{dE(\xi)}{d\xi} = A\xi + b = 0 \quad \rightarrow \quad \xi = -A^{-1}b \]

Solve in coarse-to-fine manner.

Steinbruecker, Sturm, Cremers ‘11, Kerl et al. ICRA ‘13
Realtime Dense Camera Calibration

http://cvpr.in.tum.de/datasets/rgbd-dataset
Third Person Perspective
CopyMe3D: Scanning and Printing Persons in 3D

Jürgen Sturm, Erik Bylow, Fredrik Kahl, Daniel Cremers

German Conference on Pattern Recognition (GCPR)
September 2013

Download demo @ http://www.fablitec.com
Realtime 3D Modeling

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Beyond Features: Direct & Dense 3D Reconstruction
Reconstruction on the Fly

Bylow, Sturm, Kerl, Kahl, Cremers  RSS ‘13
Steinbrücker, Kerl, Sturm, Cremers ICCV '13
Realtime Large-Scale Reconstruction

Steinbrücker, Kerl, Sturm, Cremers  ICCV ‘13, ICRA ‘14
Summary

- multiview reconstruction
- super-res. textures
- action reconstruction
- realtime dense geometry
- direct semi-dense SLAM
- RGB-D modeling
Realtime 3D Modeling

Download free demo @ http://www.fablitec.com