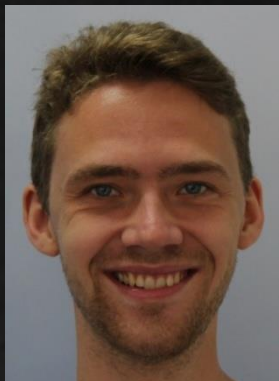


Beyond Features: Dense and Direct Methods for Visual SLAM and Geometric Reconstruction

Daniel Cremers

Computer Science & Mathematics

TU Munich



Jakob Engel, Martin Oswald, Christian Kerl, Frank Steinbrücker, Jan Stühmer & Jürgen Sturm

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:

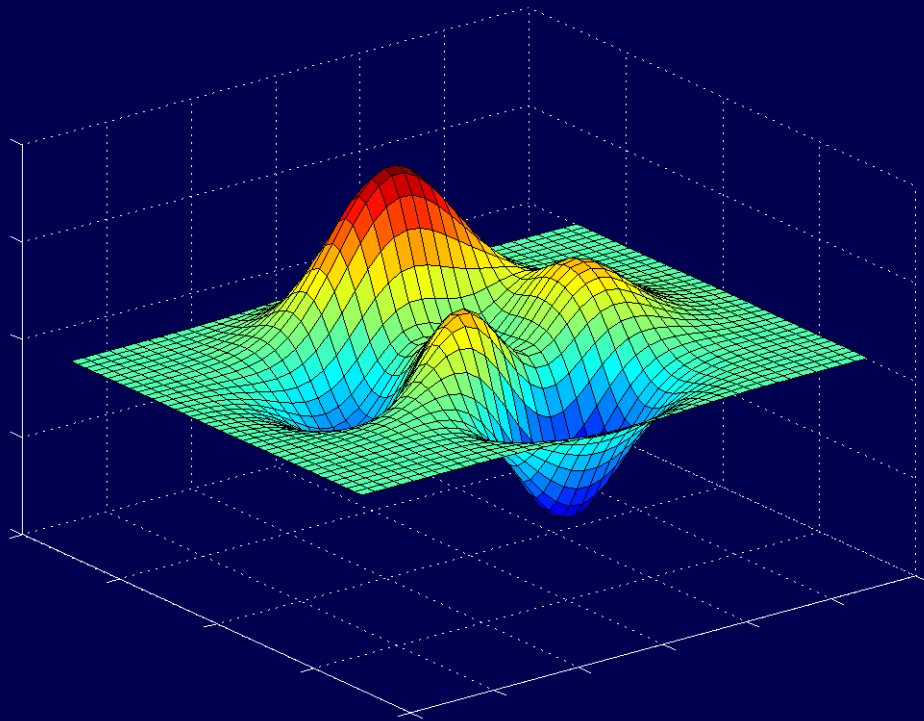
Non-convex energies

*Faugeras, Keriven '96, Duan et al. '04, Yezzi, Sapiro '03,
Seitz et al. '06, Hernandez et al. '07, Labatut et al. '07, ...*

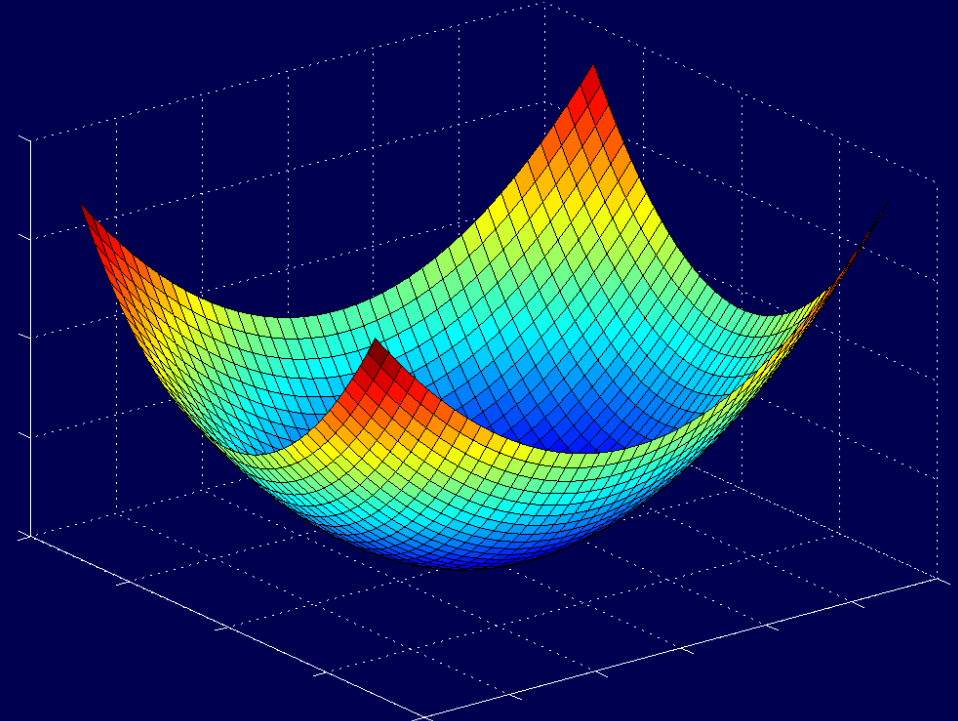
Optical flow estimation:

*Horn, Schunck '81, Nagel, Enkelmann '86, Black, Anandan '93,
Alvarez et al. '99, Brox et al. '04, Baker et al. '07, Zach et al. '07,
Sun et al. '08, Wedel et al. '09, ...*

Optimization and Convexity



Non-convex energy



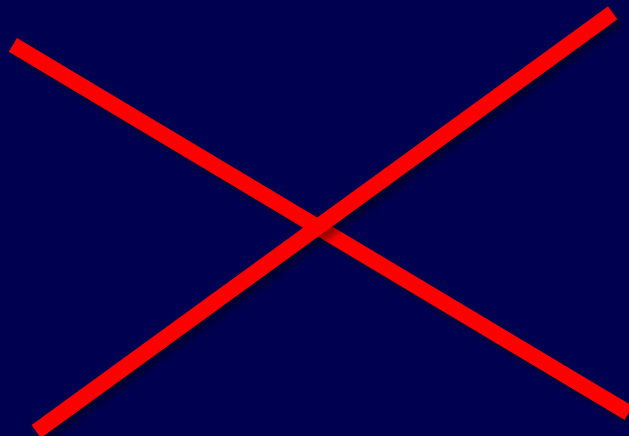
Convex energy



Classical Keypoint Approach



Input
Images





TUM Computer Vision Group



Prof. Dr. Daniel
Cremers



Sabine Wagner



Prof. Dr. Michael
Möller



Dr. Emanuele Rodolà



Dr. Rudolph Triebel



Robert Maier



Thomas Möllenhoff



Mohamed Souiai



Mathieu Aubry



Julia Diebold



Jakob Engel



Vladimir Golkov



Philip Häusser



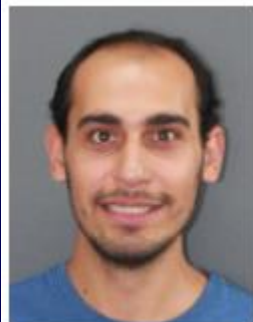
Evgeny Strelakovski



Dr. Jörg Stückler



Jan Stühmer



Caner Hazirbas



Youngwook Kee



Christian Kerl



Maria Klodt



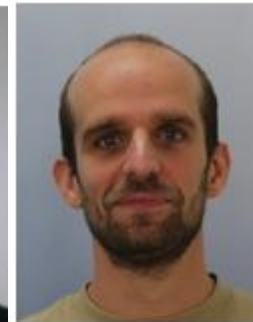
Quirin Lohr



Vladyslav Usenko



Matthias Vestner



Thomas Windheuser



Overview



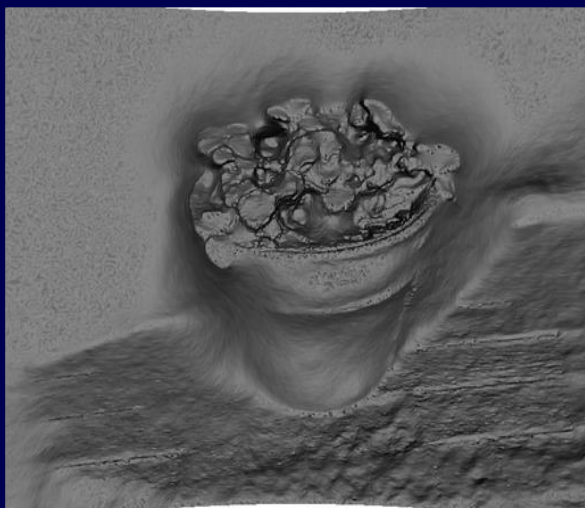
Multiview reconstruction



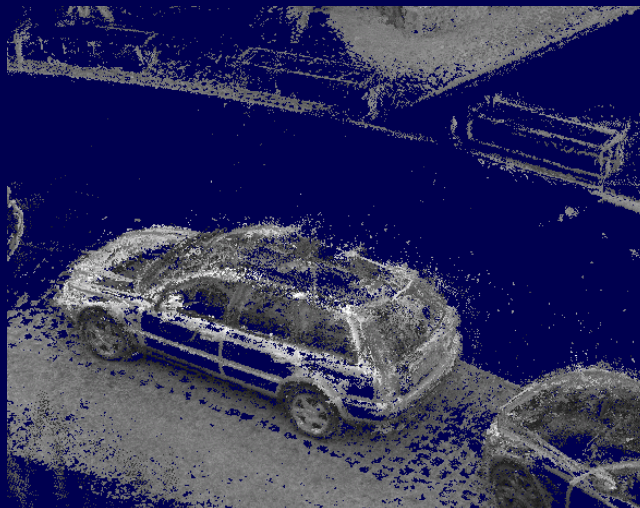
Super-res.textures



Free-viewpoint TV



Realtime dense geometry



Large-Scale Direct SLAM



RGB-D modeling



Overview



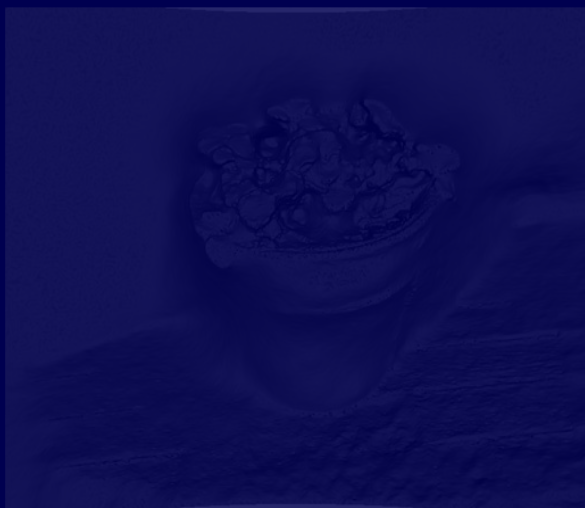
Multiview reconstruction



Super-res. textures



Free-viewpoint TV



Realtime dense geometry



Large-Scale Direct SLAM

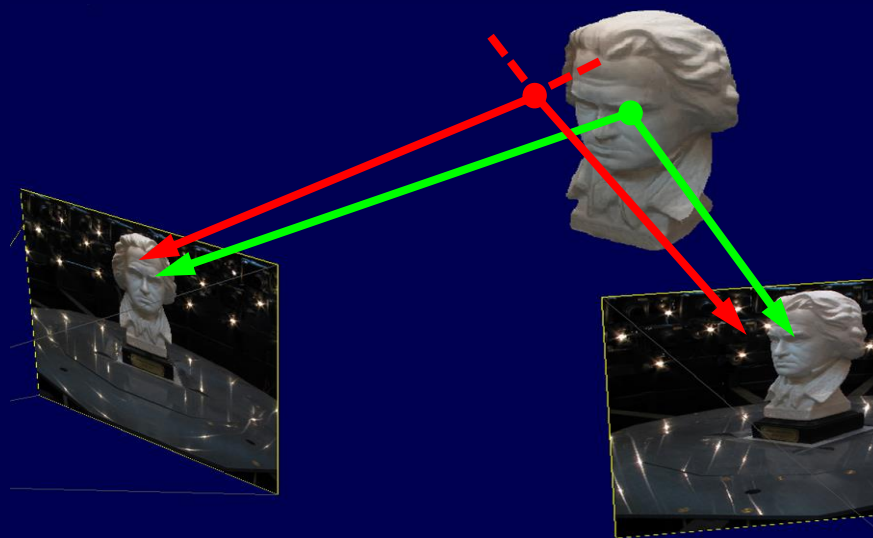


RGB-D modeling

Solutions via Energy Minimization

Photoconsistency function:

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



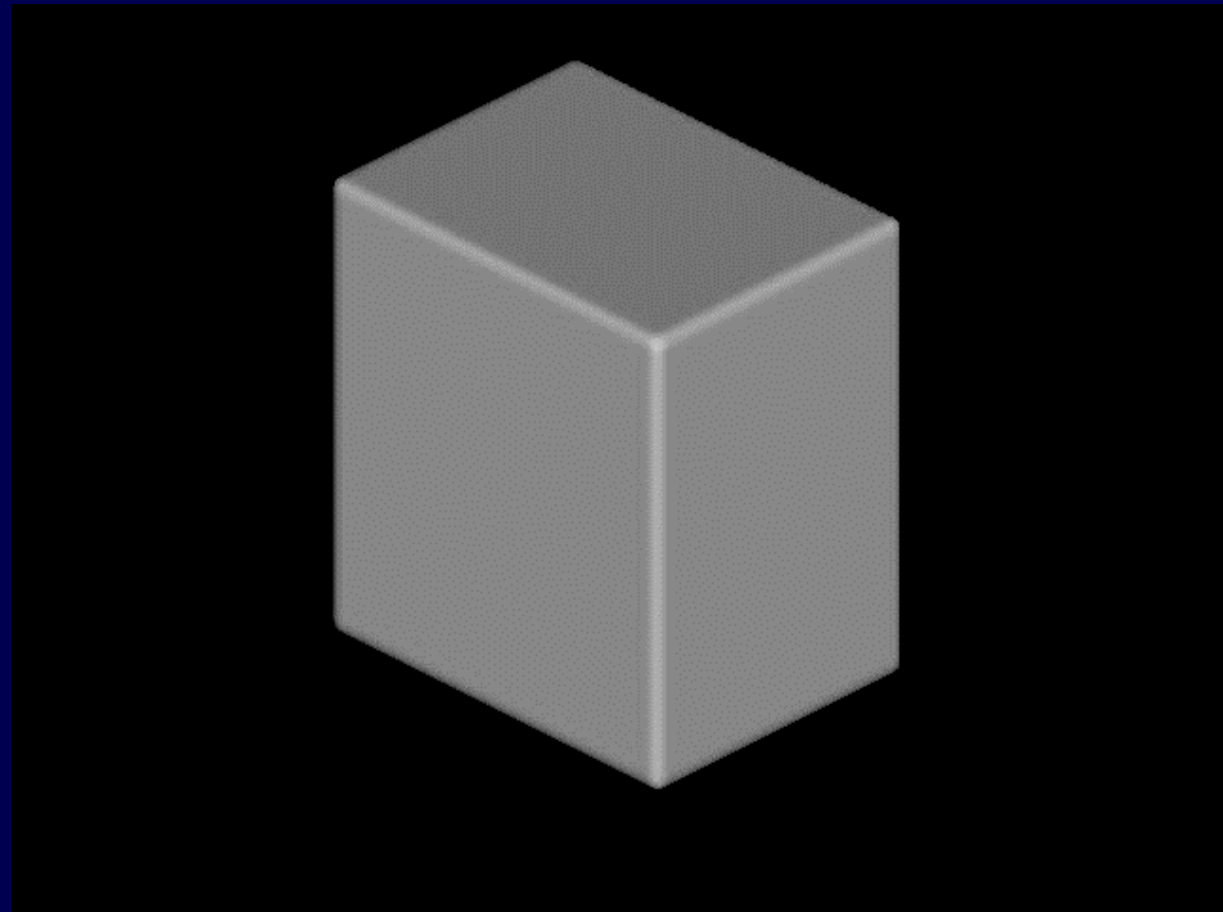
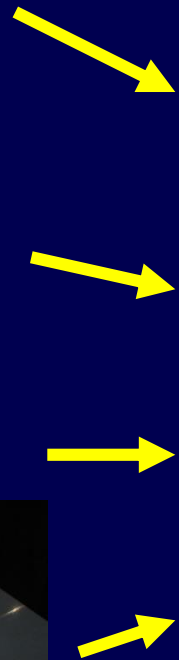
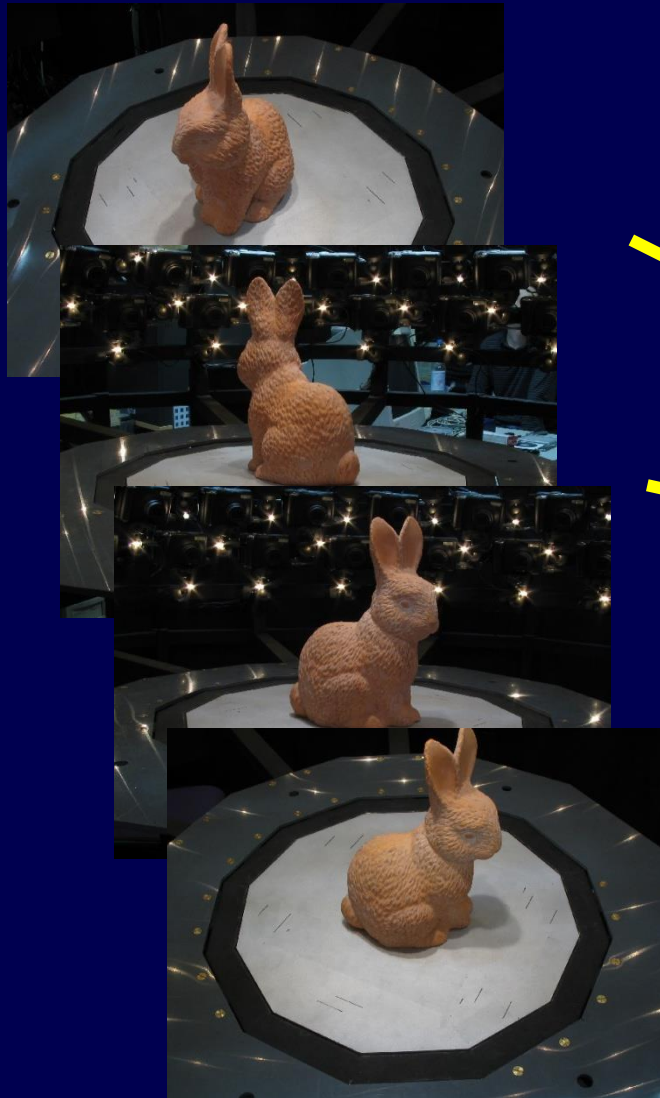
Determine a surface S of optimal photoconsistency by minimizing

$$E(S) = \int_S \rho \, dA$$

Kolev, Klodt, Brox, Cremers, Int. J. of Computer Vision '09:

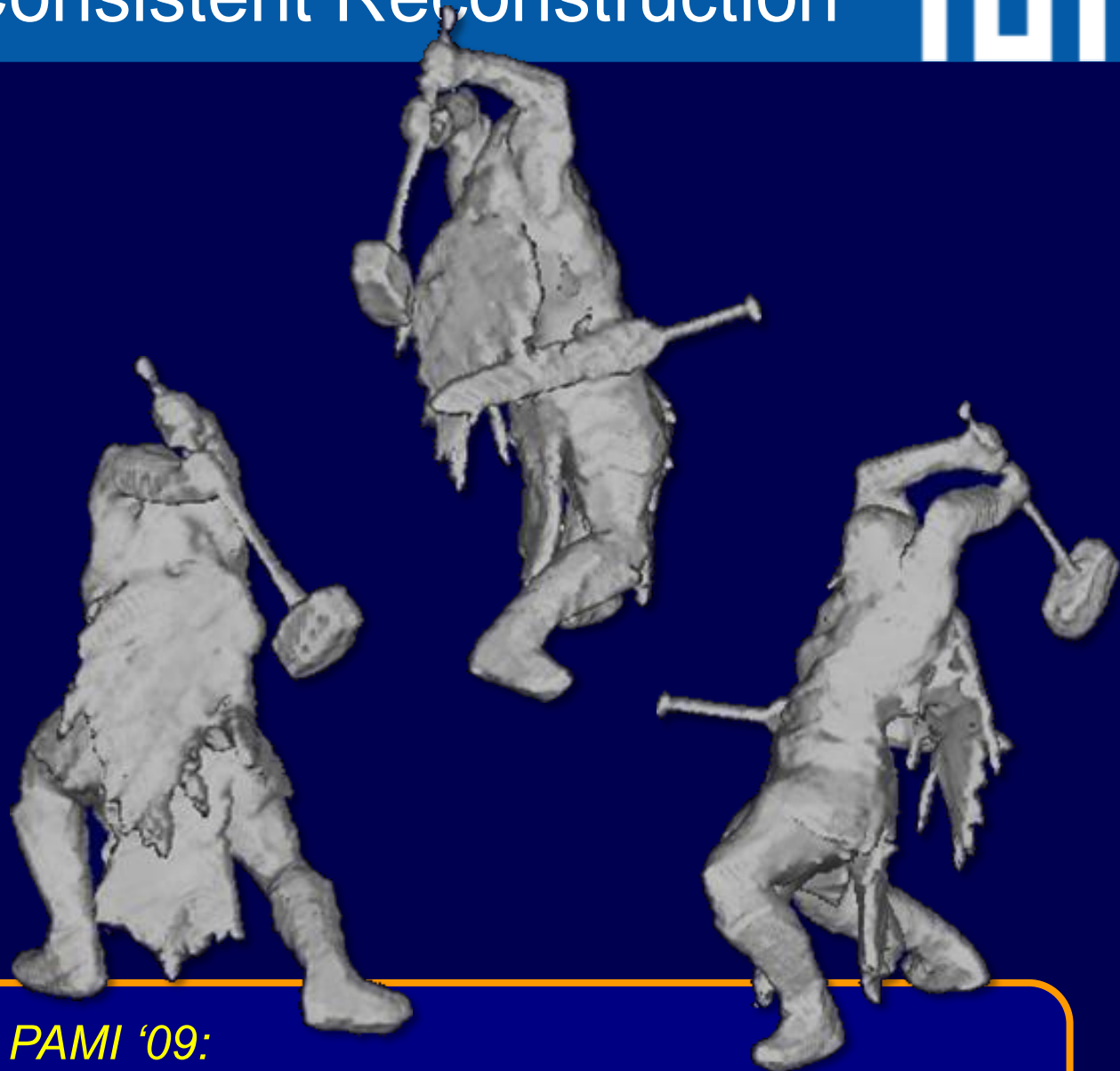
Theorem: Globally optimal surfaces can be computed via convex relaxation.

Evolution to Global Optimum



Kolev, Klodt, Brox, Cremers, IJCV 2009

Silhouette-Consistent Reconstruction



Kolev, Cremers, ECCV '08, PAMI '09:

Theorem: Provably silhouette-consistent reconstructions can be computed by convex optimization over convex domains.



Overview



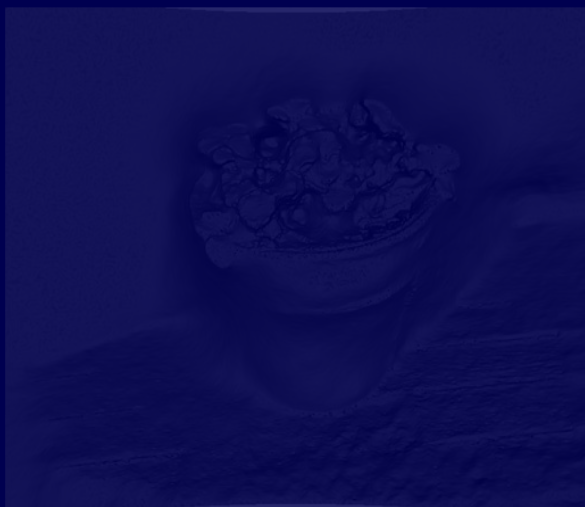
Multiview reconstruction



Super-res.textures



Free-viewpoint TV



Realtime dense geometry



Large-Scale Direct SLAM



RGB-D modeling

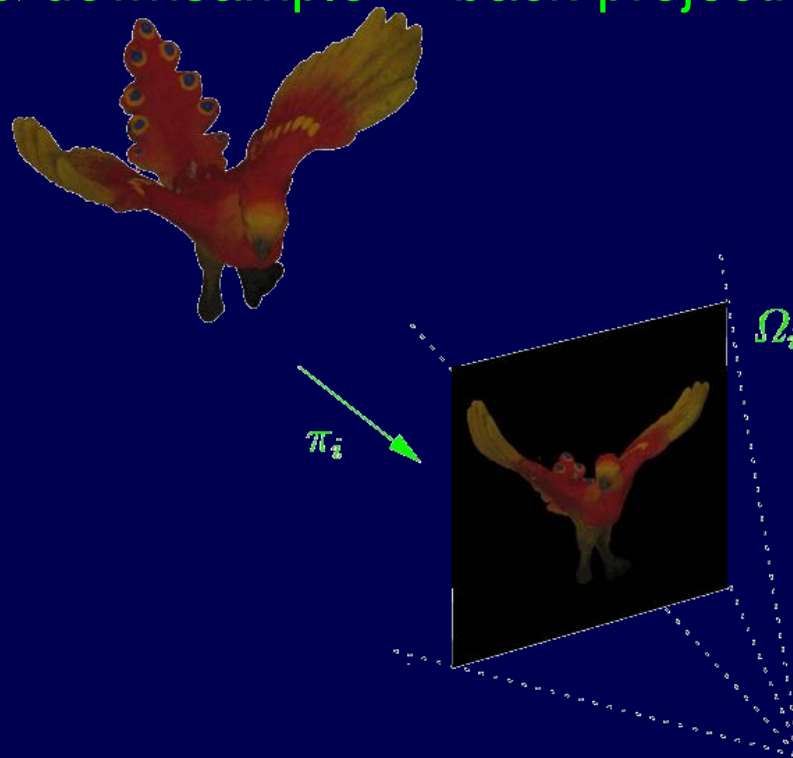
Super-Resolution Texture Map

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

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

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*



Overview



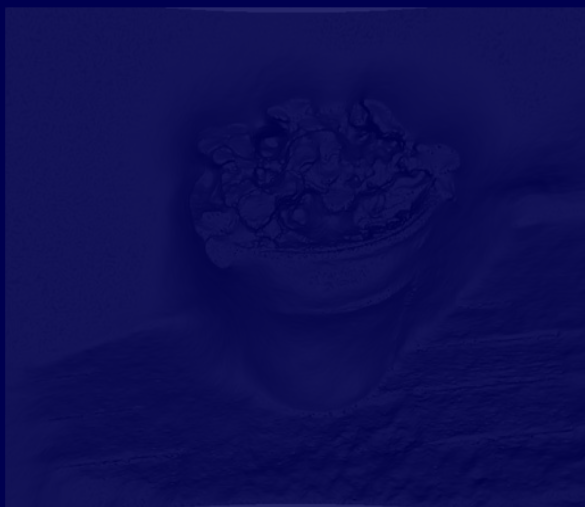
Multiview reconstruction



Super-res.textures



Free-viewpoint TV



Realtime dense geometry

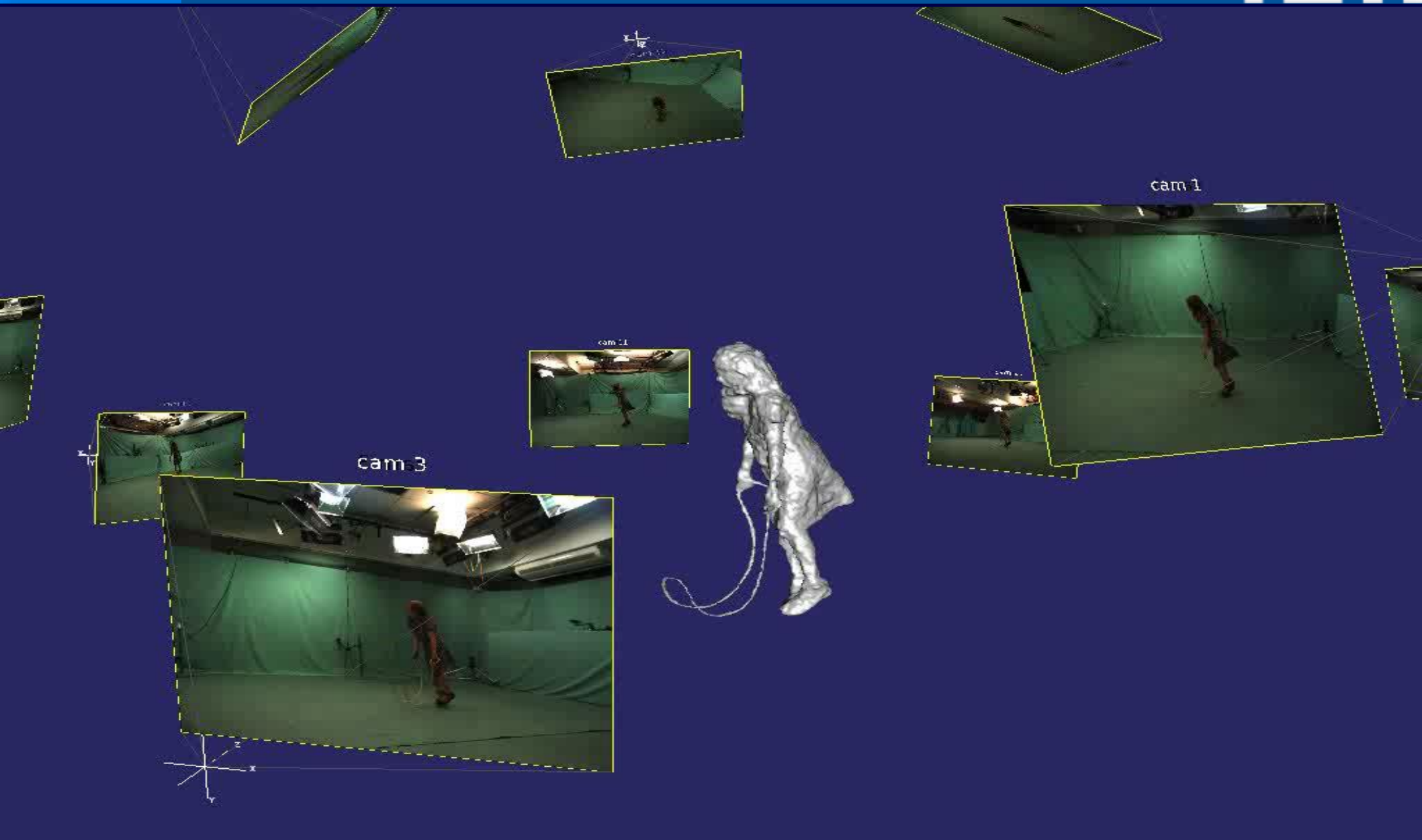


Large-Scale Direct SLAM



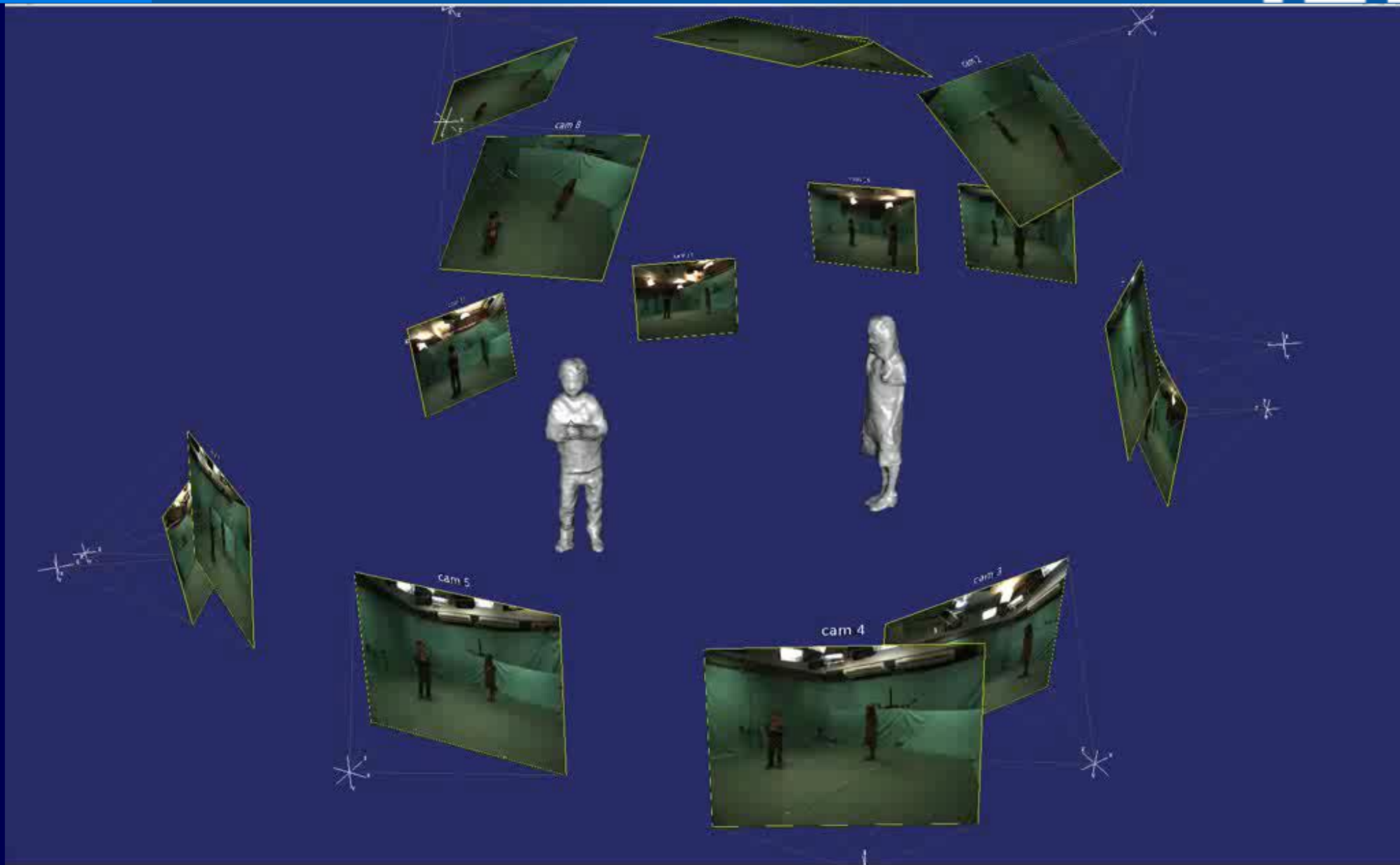
RGB-D modeling

Reconstructing Dynamic Scenes



Oswald, Stühmer, Cremers, ECCV '14

Action Reconstruction



Oswald, Cremers, ICCV '13 4DMoD Workshop



Action Reconstruction





Multiview Reconstruction



Can we do realtime dense reconstruction from a handheld camera?



Overview



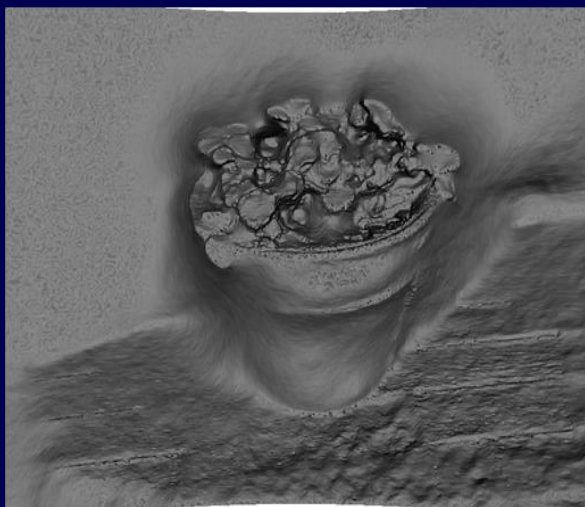
Multiview reconstruction



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

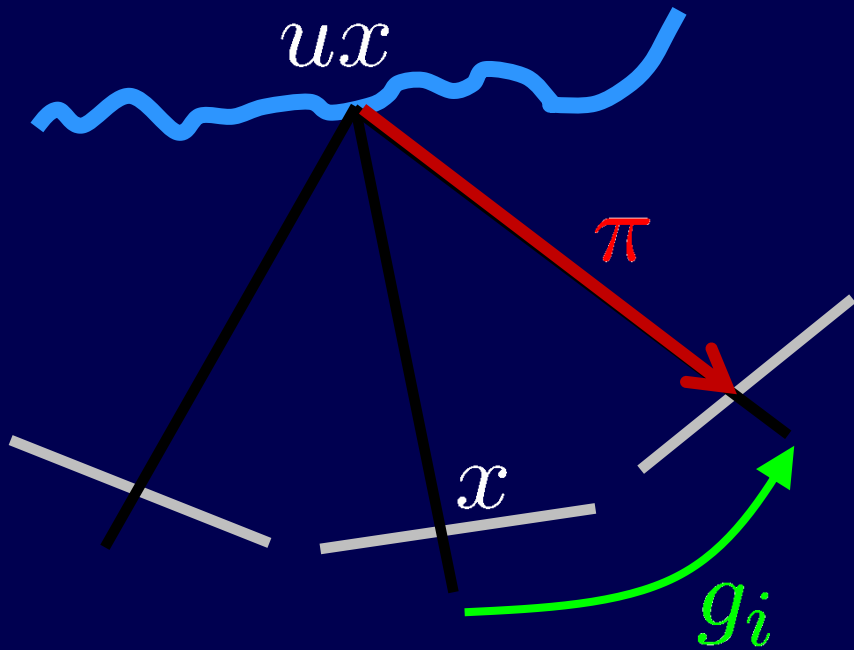


Optical flow field*

* 60 fps at 640 x 480 resolution

Wedel, Pock, Bischof, Cremers, ICCV '09

...to Realtime Dense Reconstruction



Brightness constancy:

$$I_0(x) \stackrel{!}{=} I_i(\pi(g_i(u \cdot x)))$$

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

~~+~~

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

Stuehmer, Gumhold, Cremers, DAGM '10



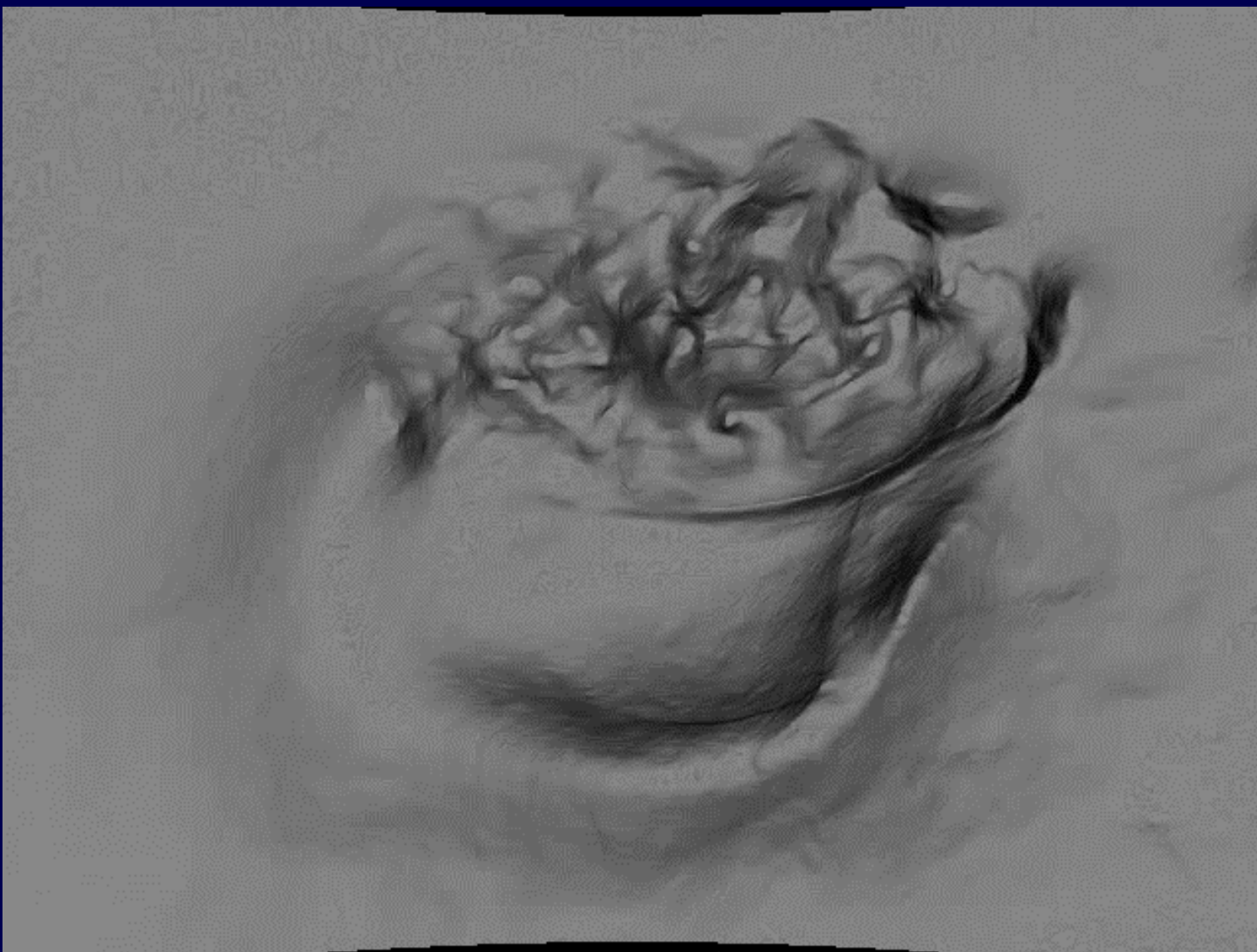
Realtime Dense Reconstruction



Stuehmer, Gumhold, Cremers, DAGM '10



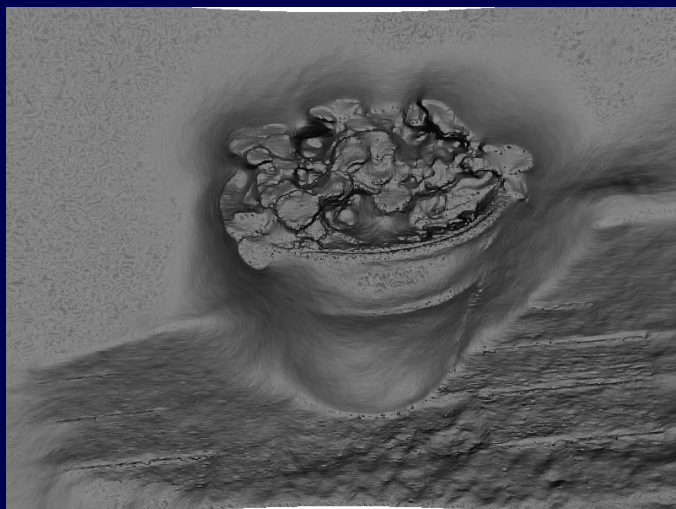
Realtime Dense Reconstruction



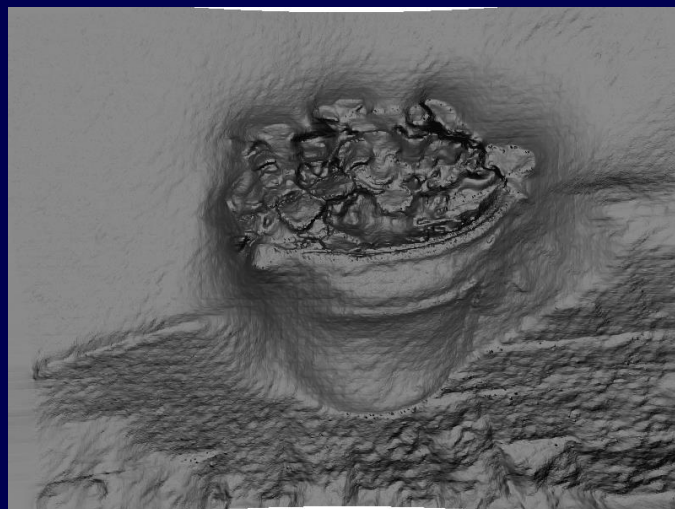
Stuehmer, Gumhold, Cremers, DAGM '10



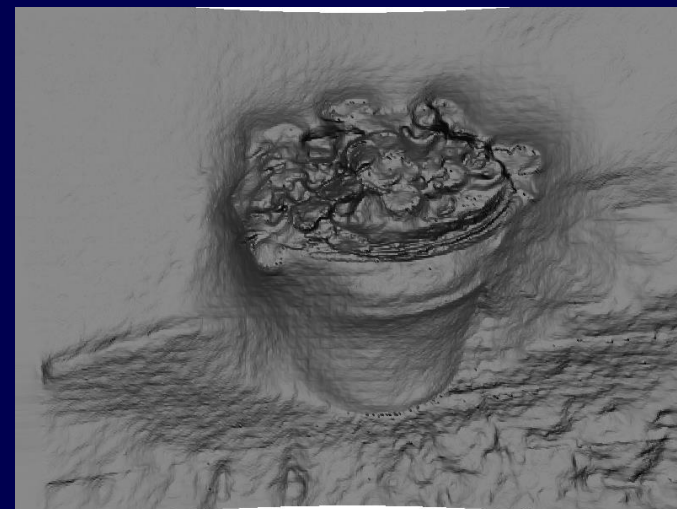
Realtime Dense Reconstruction



1.8 fps



11.3 fps



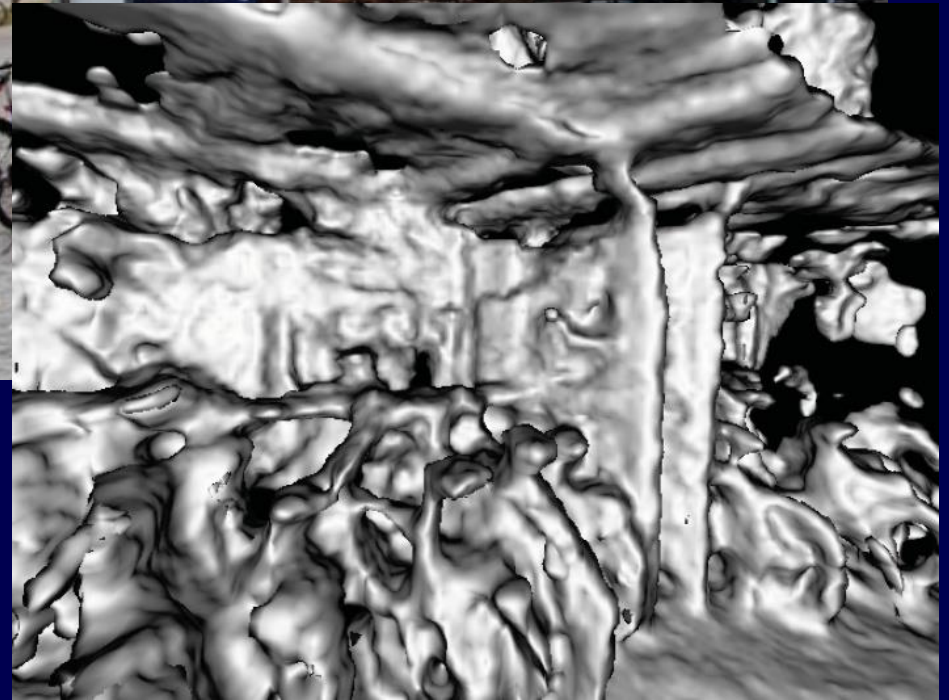
24 fps

Stuehmer, Gumhold, Cremers, DAGM '10

Realtime Dense Reconstruction



Newcombe et al., ICCV '11



Wendel et al., CVPR '12



Overview



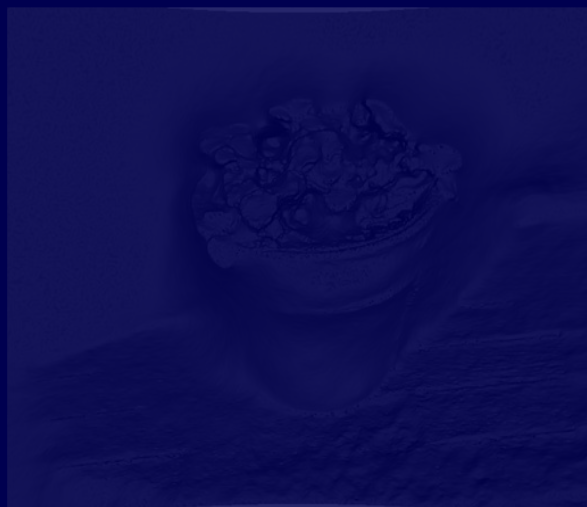
Multiview reconstruction



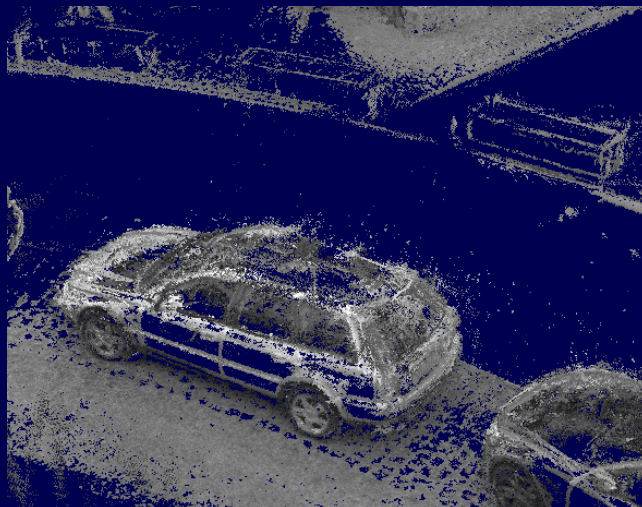
Super-res.textures



Free-viewpoint TV



Realtime dense geometry

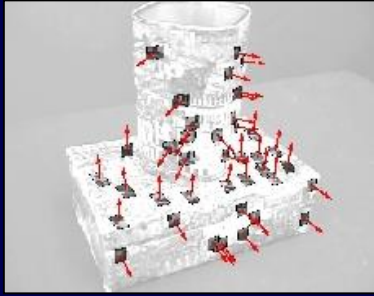


Large-Scale Direct SLAM



RGB-D modeling

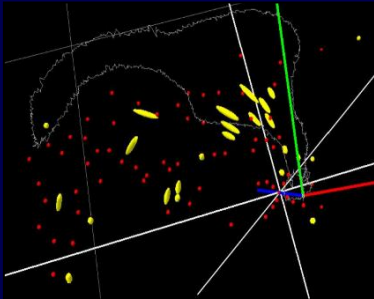
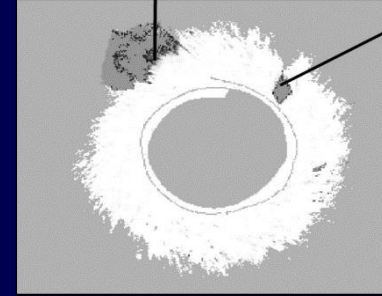
Real-time Visual SLAM



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

Visual Odometry.

Nistér, Naroditsky, Bergen; CVPR '04.



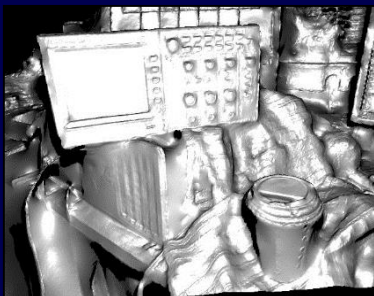
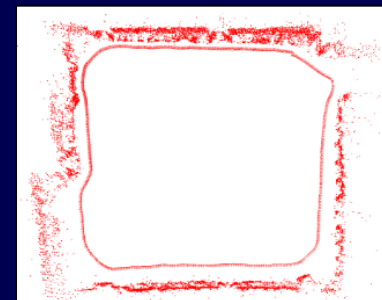
Scalable monocular SLAM.
Eade, Drummond; CVPR '06.

Parallel Tracking and Mapping for Small
AR Workspaces. *Klein, Murray; ISMAR '07.*



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.

REMODE: Probabilistic, Monocular Dense Reconstruction
in Real Time. *Pizzoli, Forster, Scaramuzza; ICRA '14.*






Real-time Visual SLAM



Keypoint-Based

Direct (LSD-SLAM)

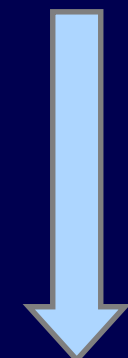
Input Images



Input Images



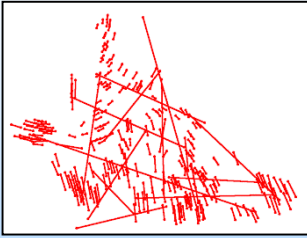
Extract & Match Features
(SIFT / SURF / BRIEF / ...)

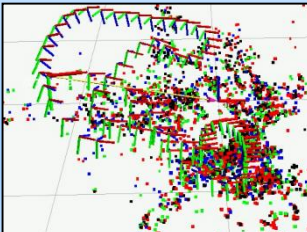
abstract images to feature observations

keep full image


Track:
min. reprojection error
(point distances)



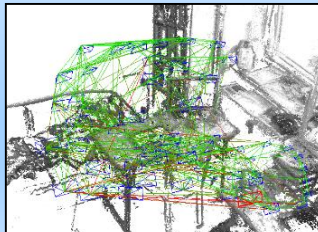
Map:
est. feature-parameters
(3D points / normals)



Track:
min. photometric error
(intensity difference)



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



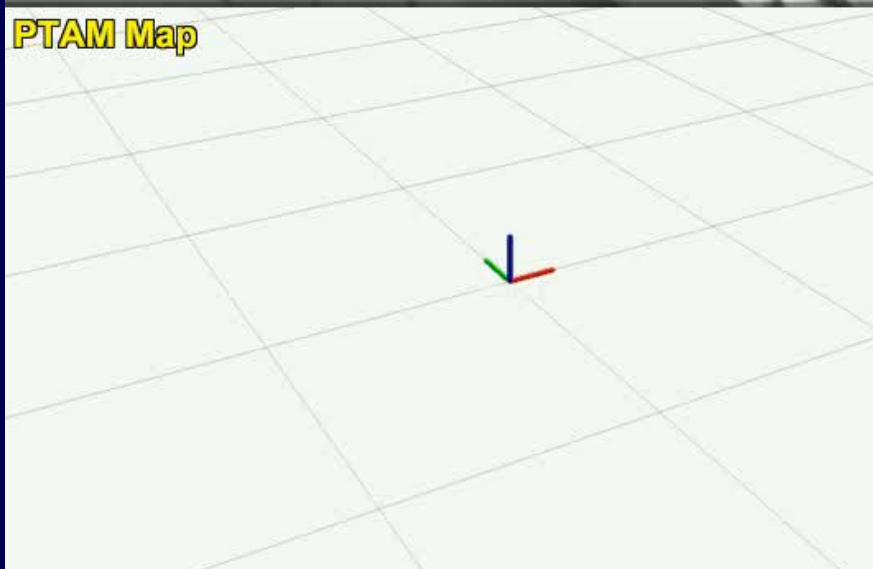
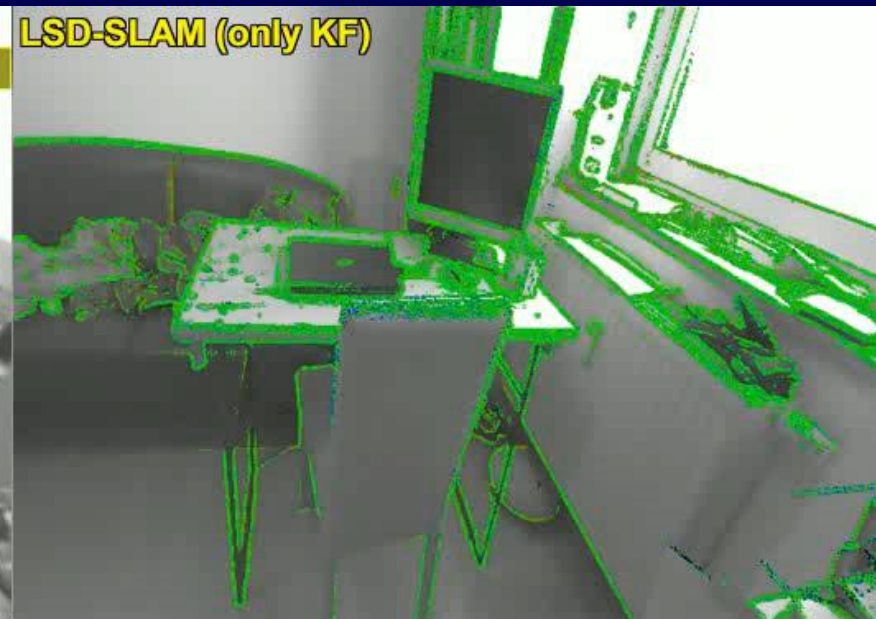


LSD SLAM: Large-Scale Direct SLAM



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

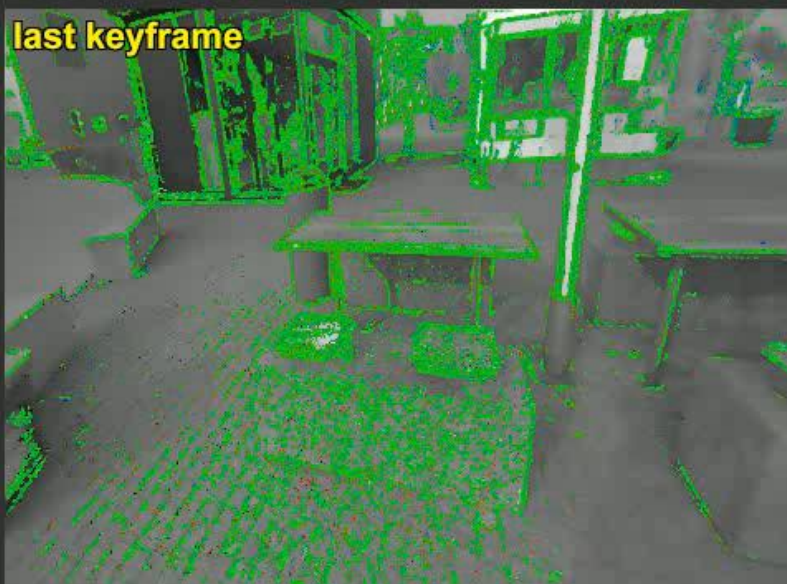


00:00:00.0

camera image



last keyframe



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



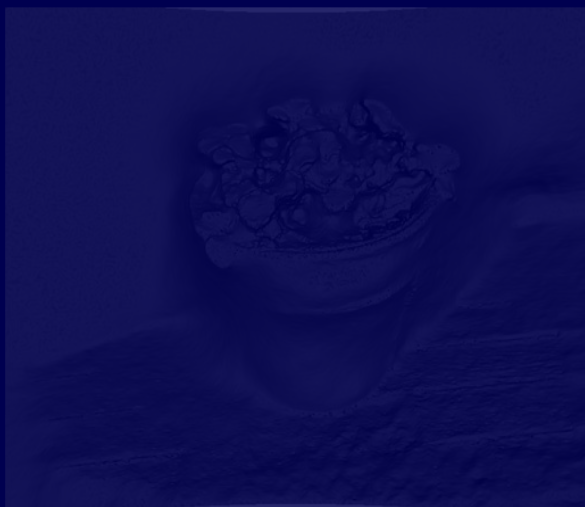
Multiview reconstruction



Super-res.textures



Free-viewpoint TV



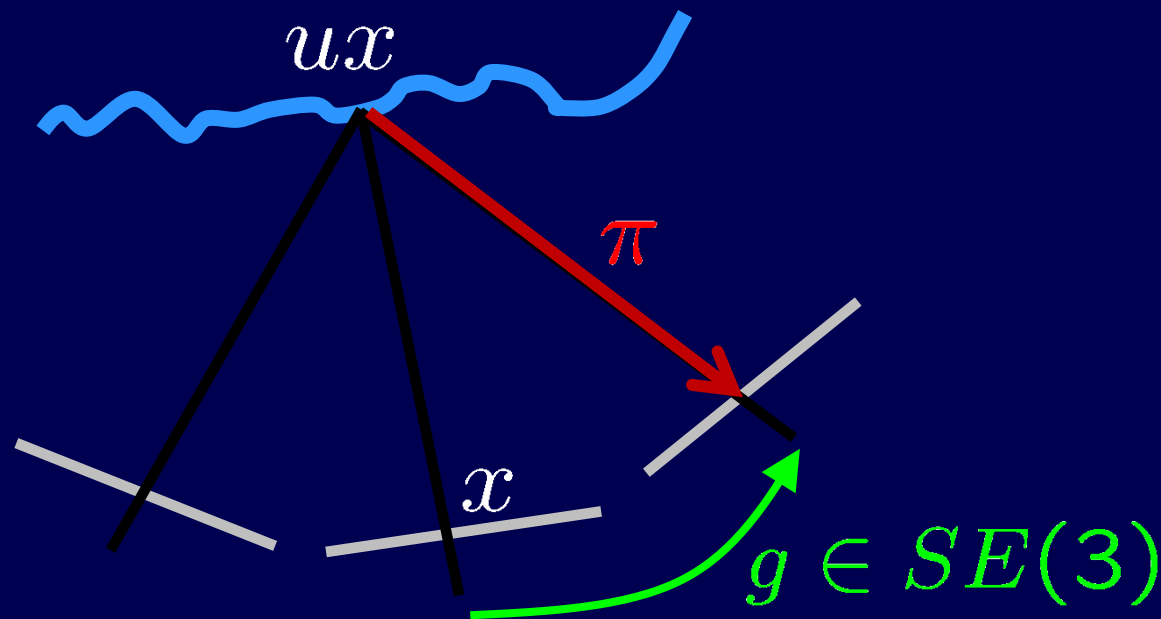
Realtime dense geometry



Large-Scale Direct SLAM



RGB-D modeling



Lie algebra representation of rigid body motion:

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

Photo-consistency:

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

Steinbruecker, Sturm, Cremers '11, Kerl et al. ICRA '13

Photo-consistency:

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

Taylor expansion:

$$E(\xi) \approx \int_{\Omega} \left| I_0(x) - I_i - \nabla I^{\top} \begin{pmatrix} \frac{d\pi}{dg_{\xi}} \end{pmatrix} \begin{pmatrix} \frac{dg_{\xi}}{d\xi} \end{pmatrix} \xi \right|^2 dx$$

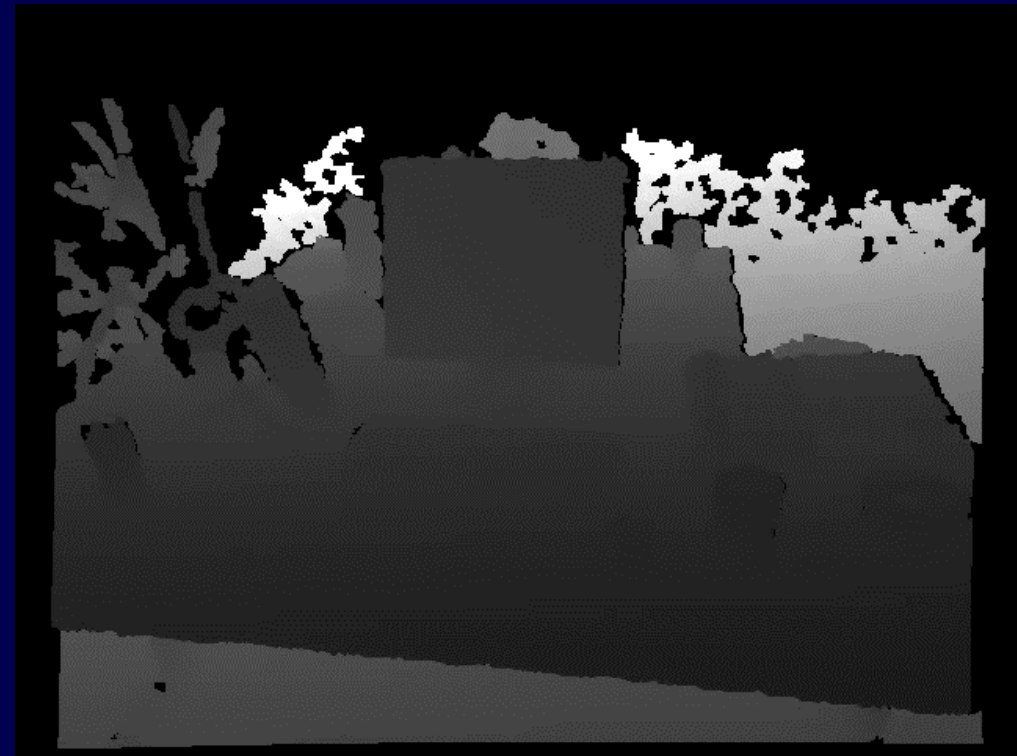
Optimal solution:

$$\frac{dE(\xi)}{d\xi} = A\xi + b = 0 \quad \longrightarrow \quad \xi = -A^{-1}b$$

Solve in coarse-to fine manner.

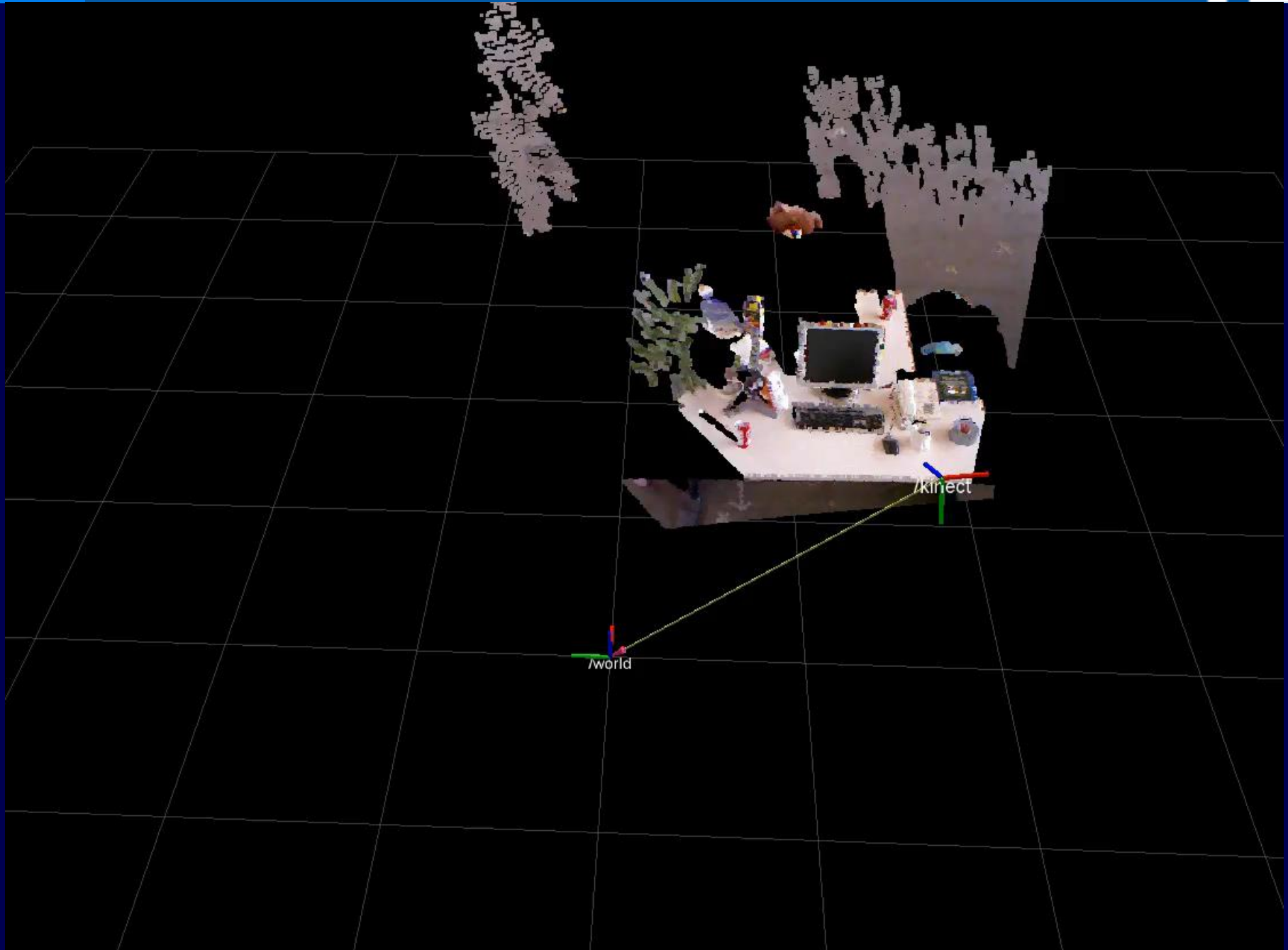
Steinbruecker, Sturm, Cremers '11, Kerl et al. ICRA '13

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**



Computer Vision Group
Department of Computer Science
Technical University of Munich



Download demo @ <http://www.fablitec.com>



Realtime 3D Modeling



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



Realtime 3D Modeling



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



Realtime 3D Modeling



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



Realtime 3D Modeling



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



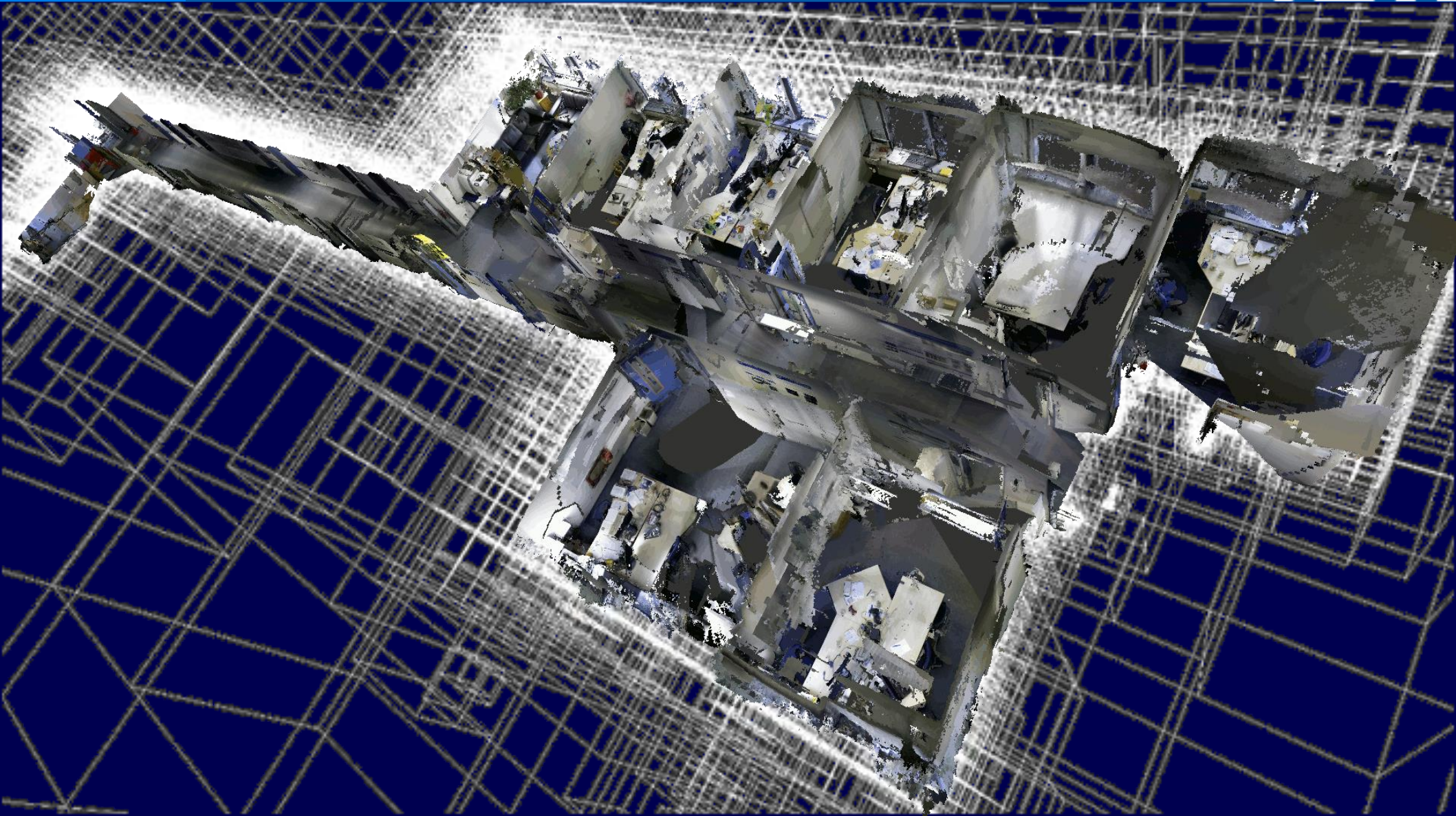
Reconstruction on the Fly



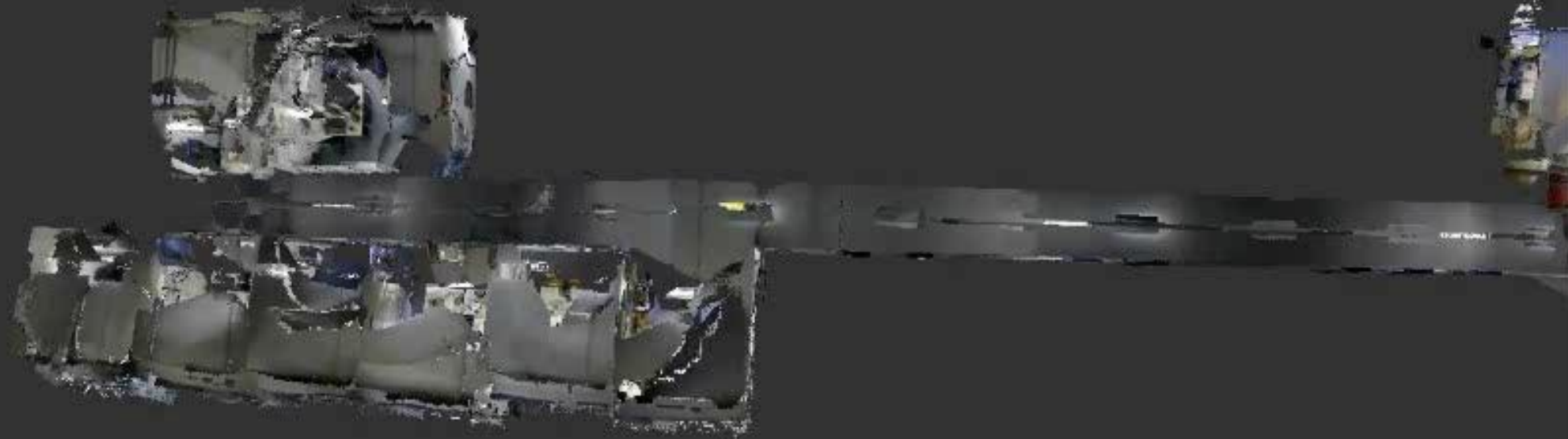
Bylow, Sturm, Kerl, Kahl, Cremers RSS '13



Large Scale: Octrees



Steinbrücker, Kerl, Sturm, Cremers ICCV '13



Large-Scale Reconstruction

Steinbrücker, Kerl, Sturm, Cremers ICCV '13, ICRA '14



Summary



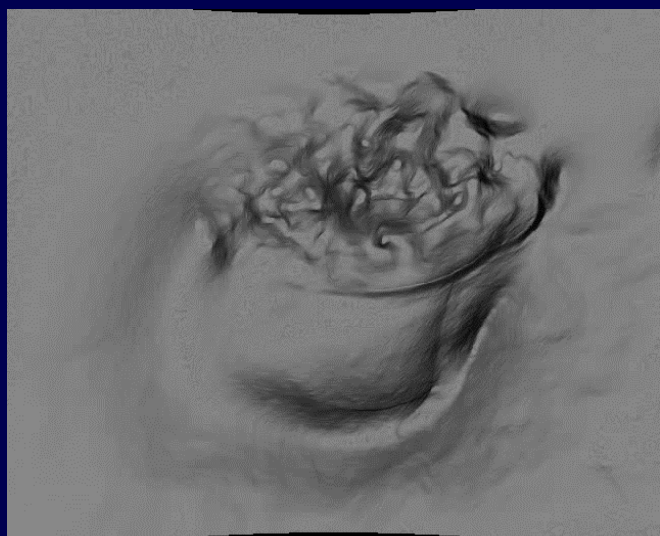
multiview reconstruction



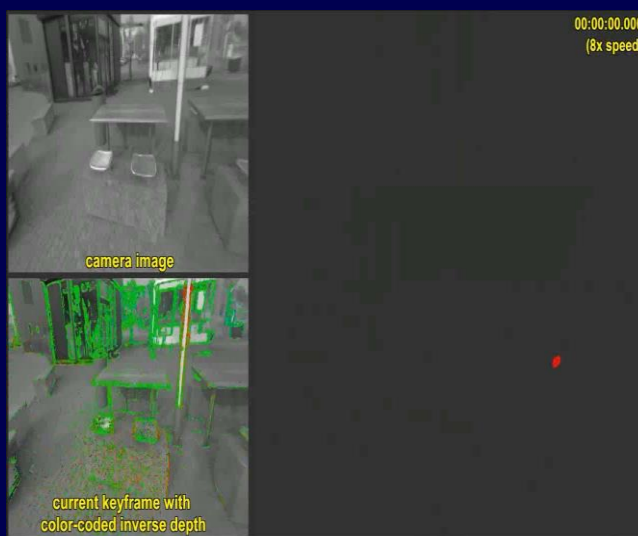
super-res. textures



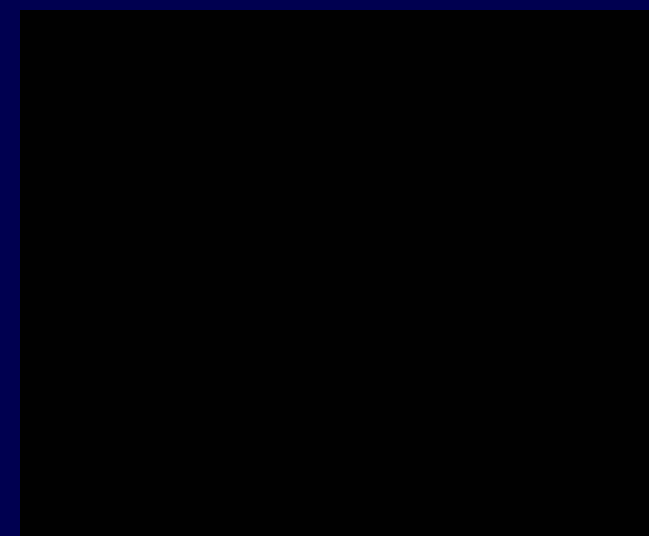
action reconstruction



realtime dense geometry



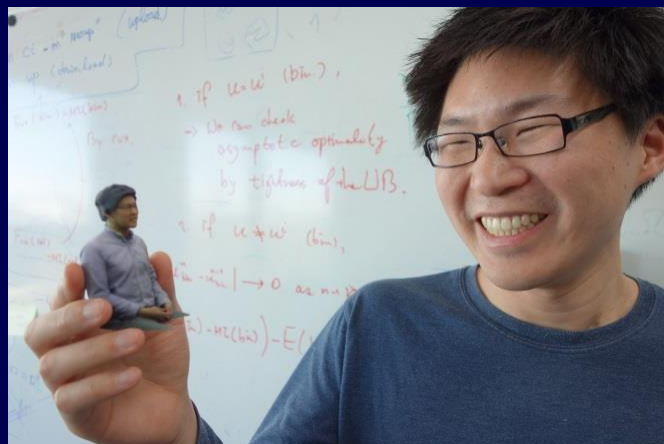
direct semi-dense SLAM



RGB-D modeling



Realtime 3D Modeling



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