Scanning and Printing Objects in 3D

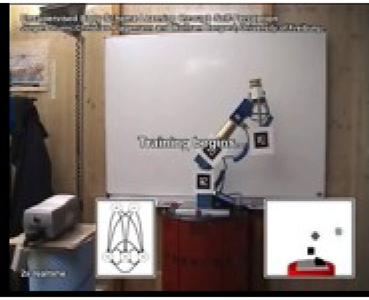
Dr. Jürgen Sturm
metaio GmbH

(formerly Technical University of Munich)

My Research Areas

- Visual navigation for mobile robots

RoboCup



Kinematic Learning

Articulated Objects

Quadrotors

- Camera tracking and 3D reconstruction

RGB-D SLAM

Visual Odometry

Large-Scale Reconstruction

3D Printing

My Research Areas

Camera-based Navigation of a Low-Cost Quadrotor

[IROS ’12, RSS ’13, UAV-g ‘13, RAS ’14]

TUM TeachInf Best Lecture Award 2012 and 2013

EdX Course AUTONAVx with 20k participants

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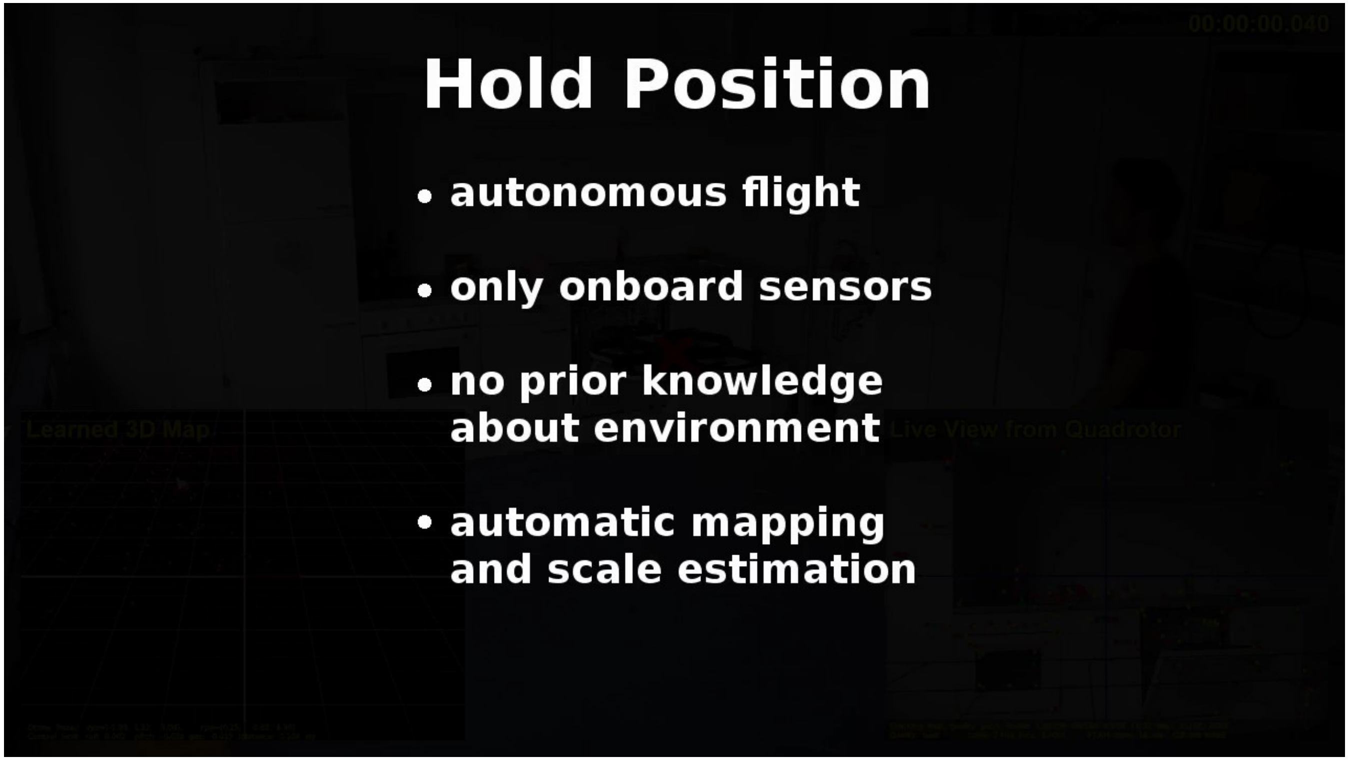
Camera-based Navigation of a Low-Cost Quadrotor



[IROS ’12, RSS ’13, UAV-g ‘13, RAS ’14]

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My Research Areas

EdX Course „Autonomous Navigation for Flying Robots“

[IROS ’12, RSS ’13, UAV-g ‘13, RAS ’14]

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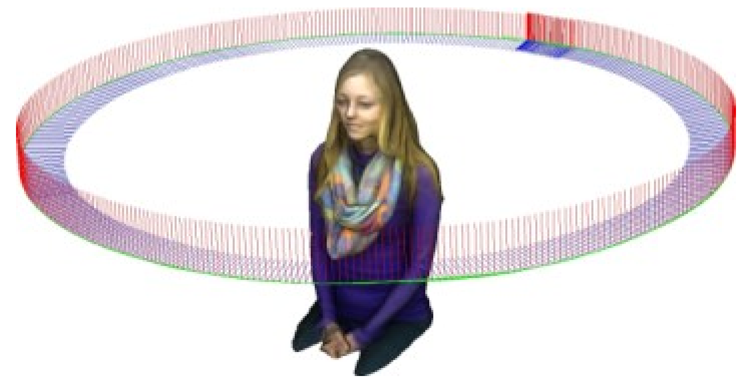
Motivation

Wouldn‘t it be cool to have a 3D photo booth?



Questions:

- How to scan a person in 3D?
- How to prepare the model for 3D printing?

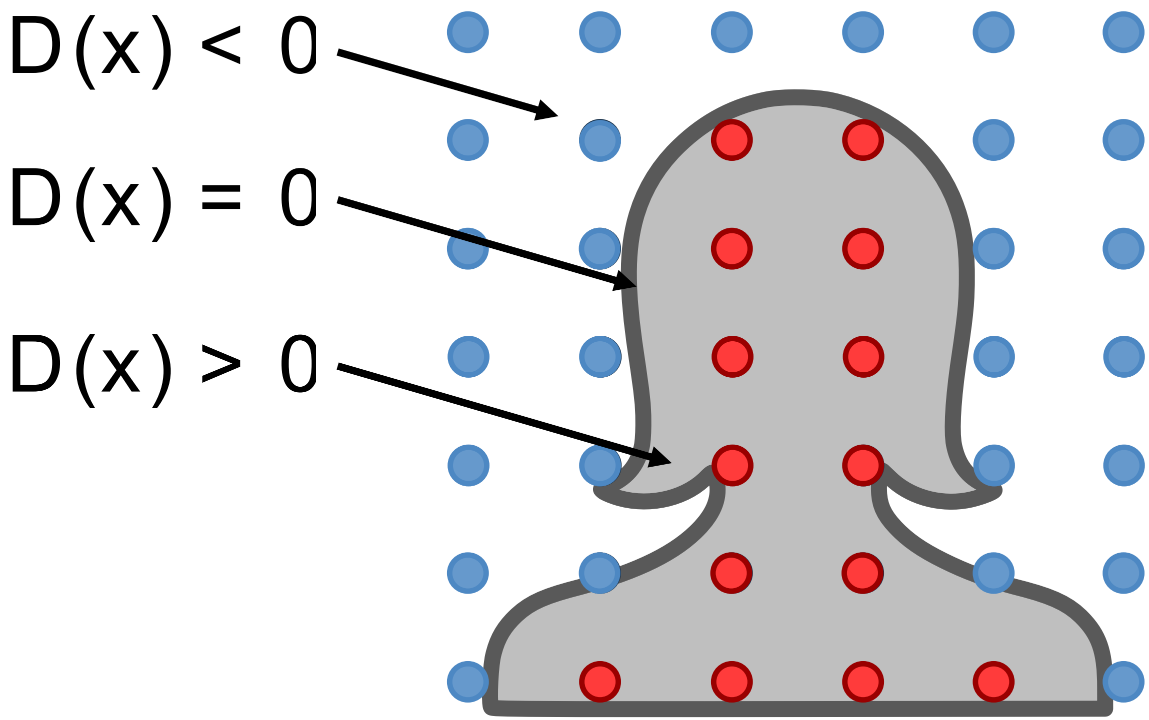
Problem Description

- Setup:
  Static RGB-D camera, person sitting on a swivel chair

- Given: A sequence of color and depth images
- Wanted: Accurate, watertight 3D model

Signed Distance Function (SDF)

[Curless and Levoy, '96]



— Negative signed distance (=outside)

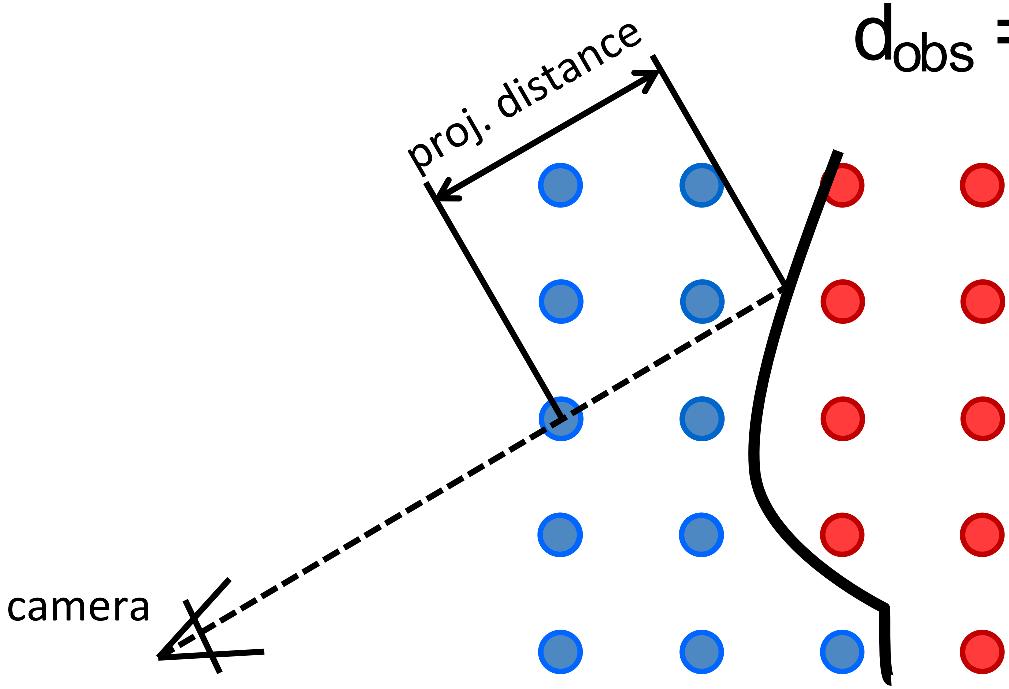
— Positive signed distance (=inside)

Signed Distance Function (SDF)

[Curless and Levoy, '96]

- Compute SDF from a depth image
- Measure distance of each voxel to the observed surface
- Can be done in parallel for all voxels (→ GPU)

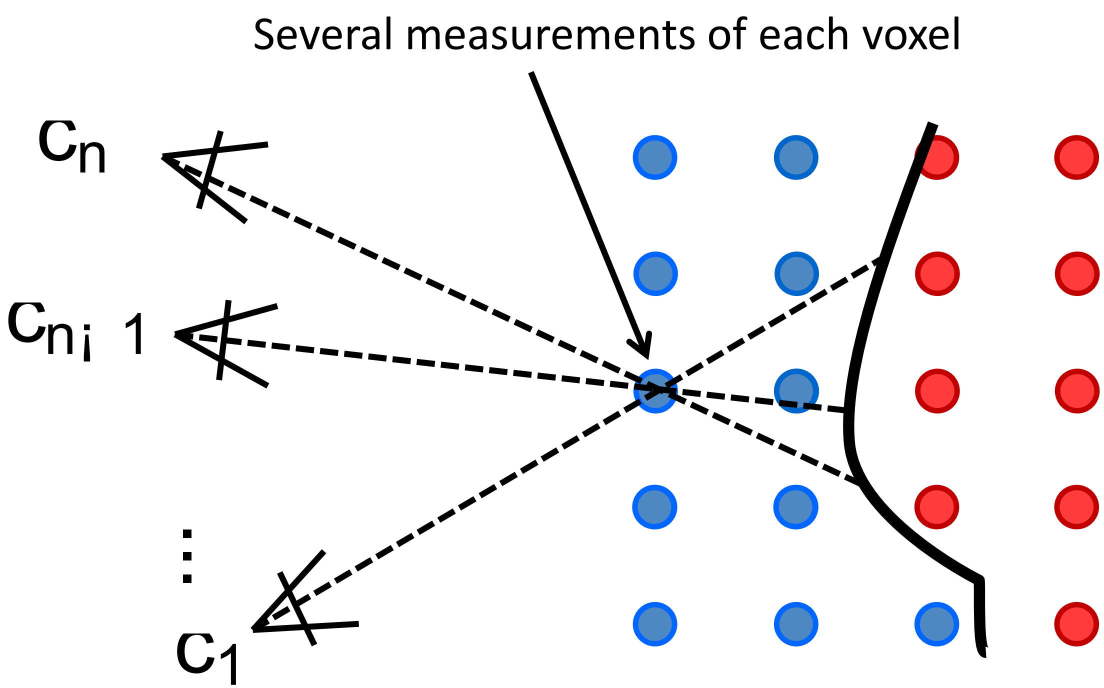
$$d_{obs} = z - I_Z(\pi(x, y, z))$$



Signed Distance Function (SDF)

[Curless and Levoy, '96]

- Calculate weighted average over all measurements
- Assume known camera poses (for now)



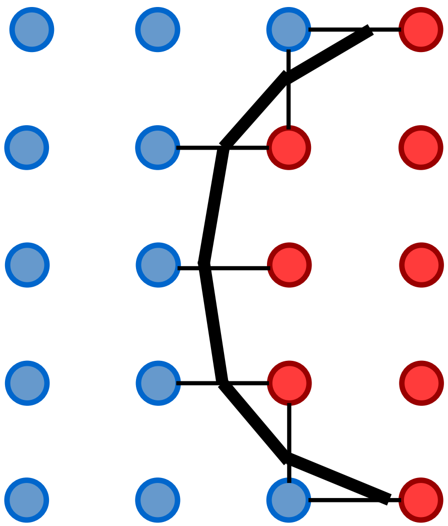
$$D \text{ Ã } \frac{WD + wd}{W + w}$$

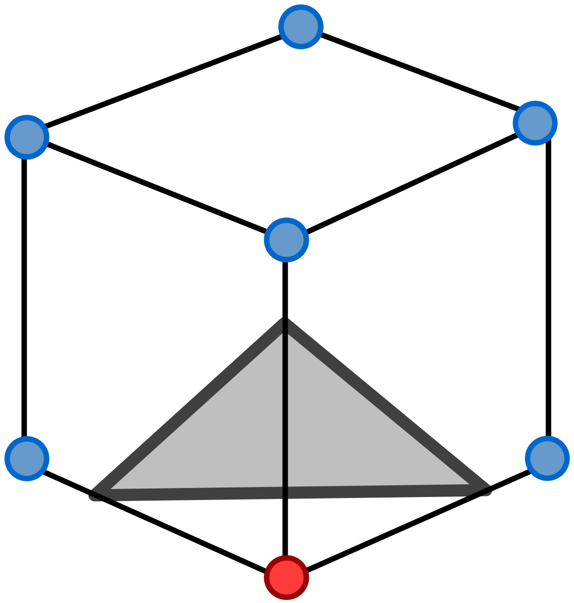
$$C \text{ Ã } \frac{WC + wc}{W + w}$$

$$W \text{ Ã } W + w$$

Mesh Extraction using Marching Cubes

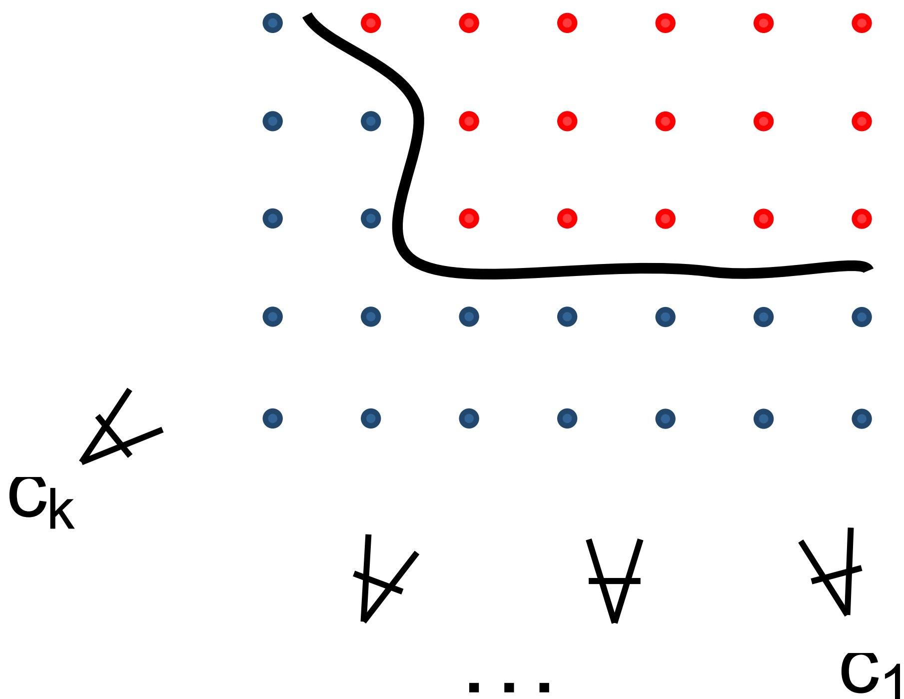
- Find zero-crossings in the signed distance function by interpolation





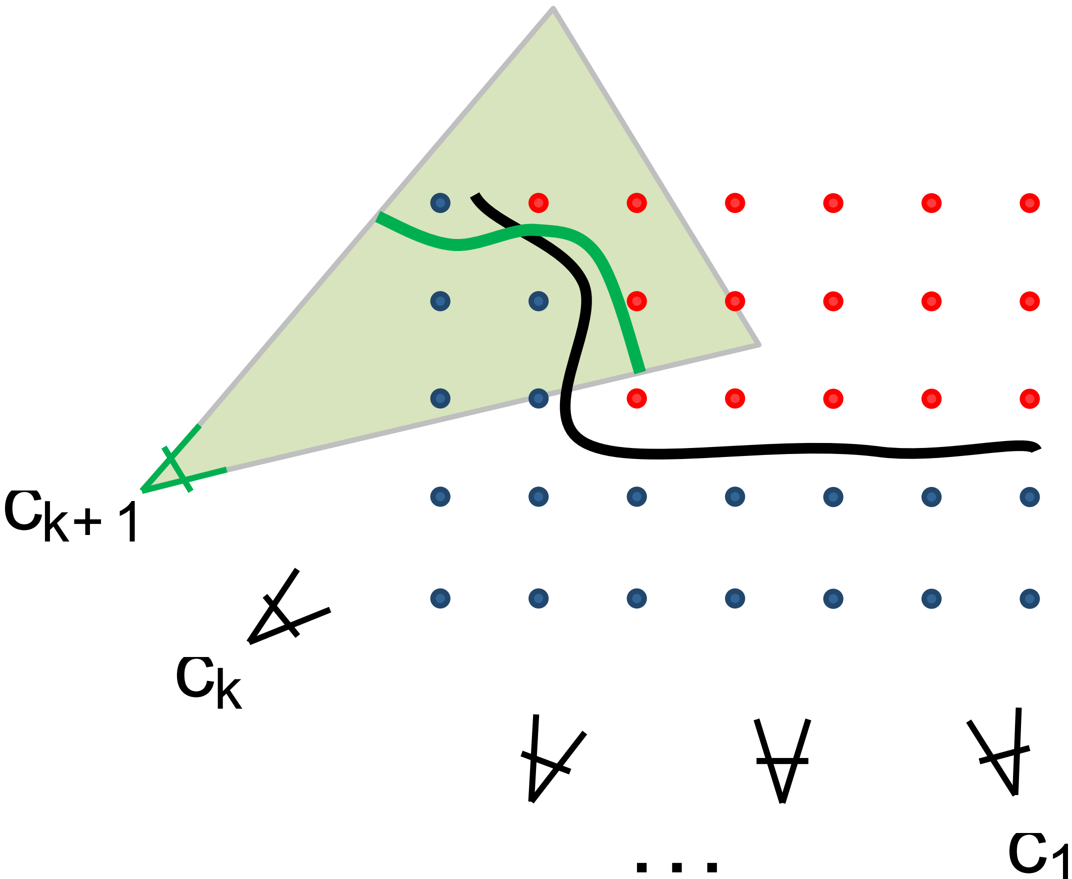
Estimating the Camera Pose

- SDF built from the first k frames



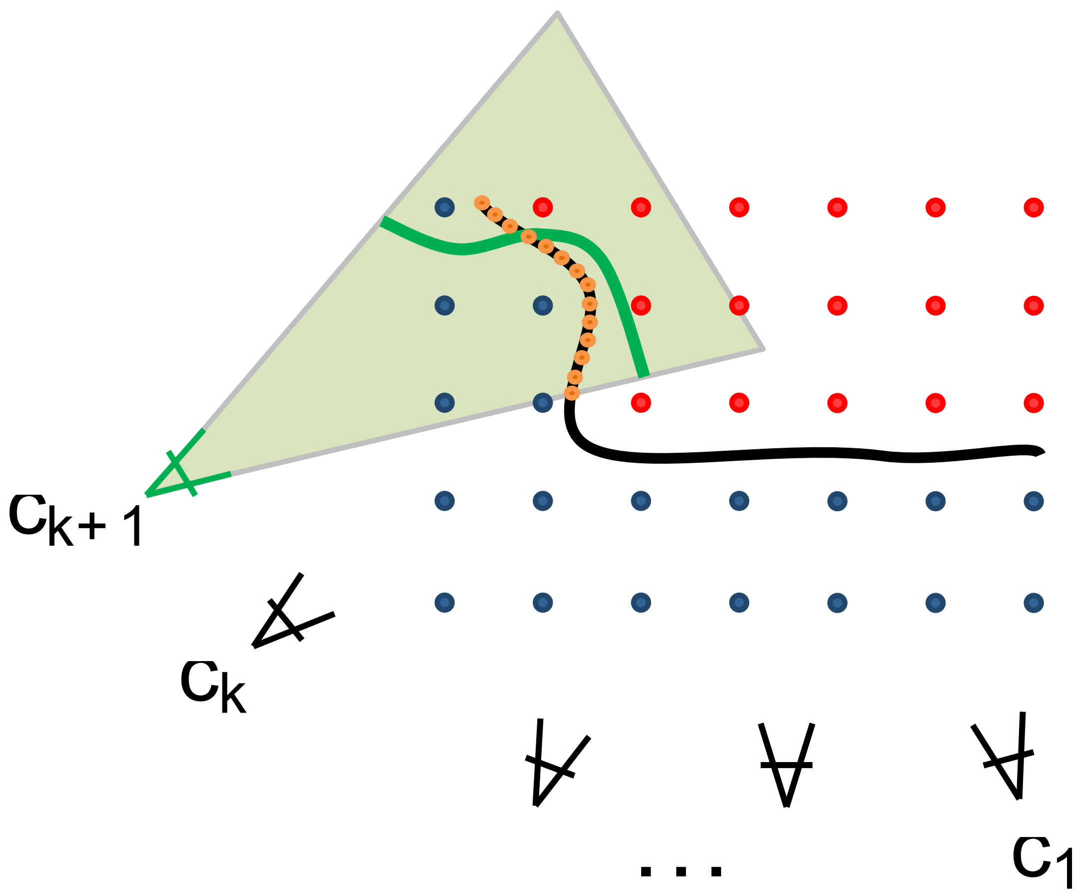
Estimating the Camera Pose

- We seek the next camera pose (k+1)



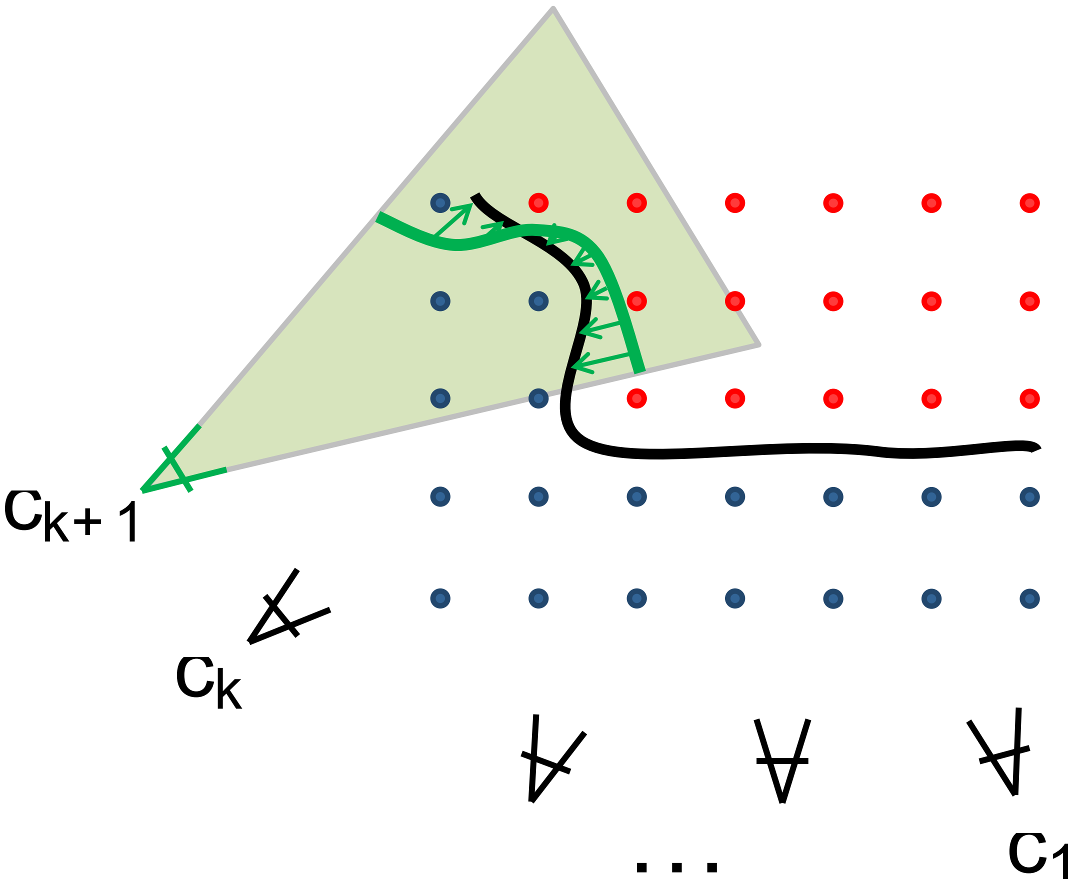
Estimating the Camera Pose

- KinectFusion generates a synthetic depth image from SDF and aligns it using ICP



Estimating the Camera Pose

- Our approach: Use SDF directly during minimization



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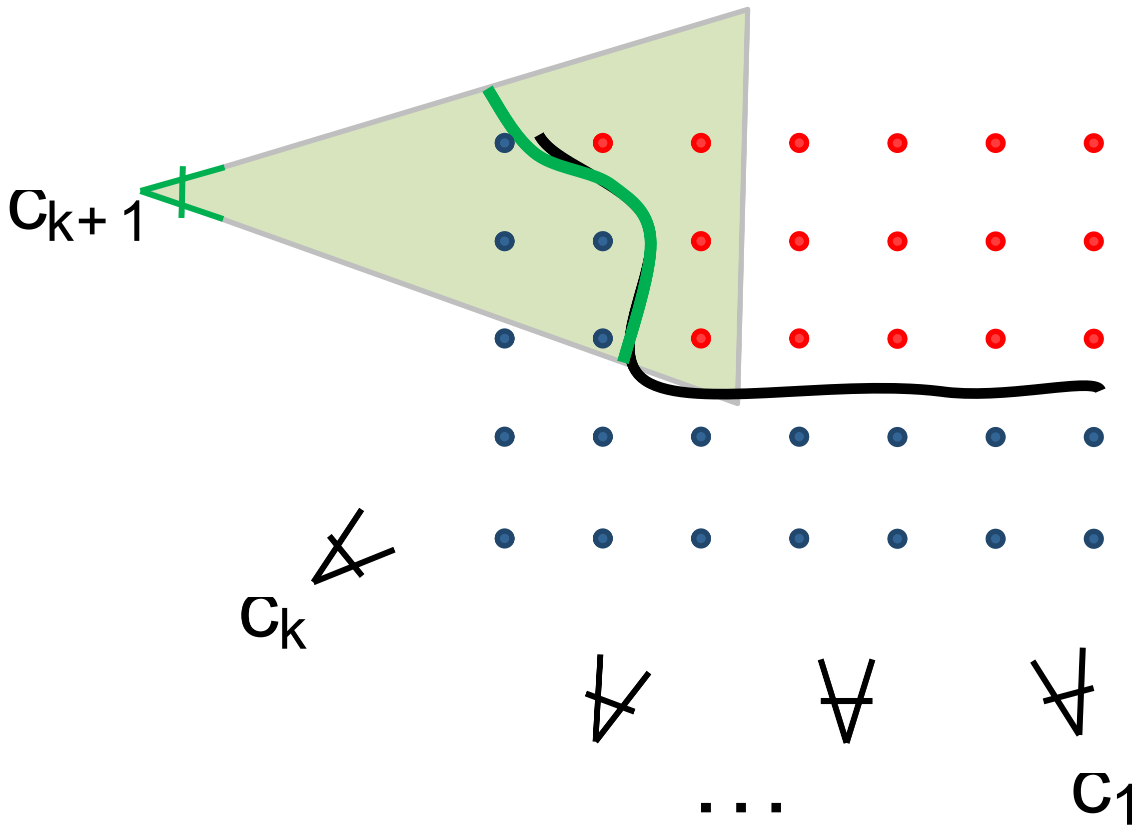

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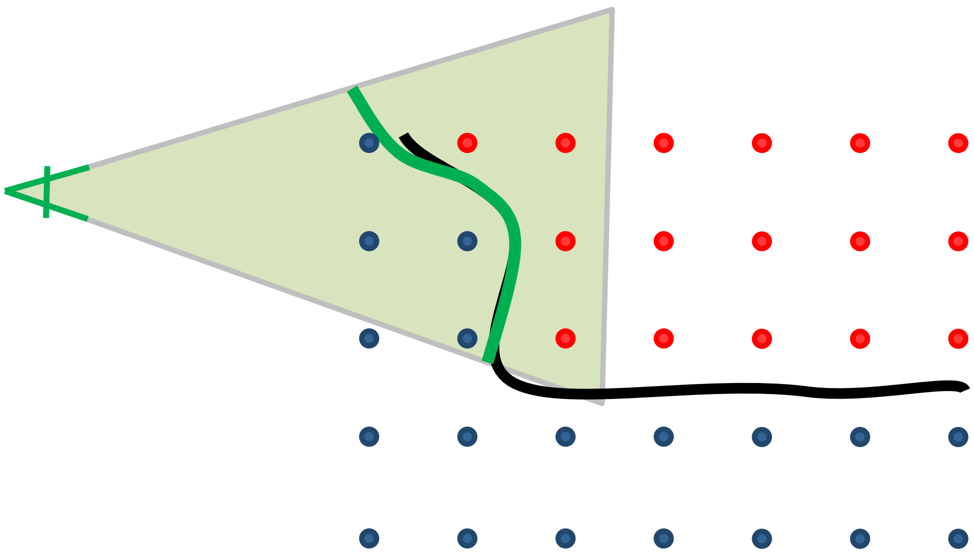


$$\arg\min_{R,\mathbf{t}} \sum_{ij} D(R\mathbf{x}_{ij} + \mathbf{t})^2$$

Evaluation on Benchmark

[Bylow, Sturm, Kerl, Kahl, Cremers; RSS 2013]

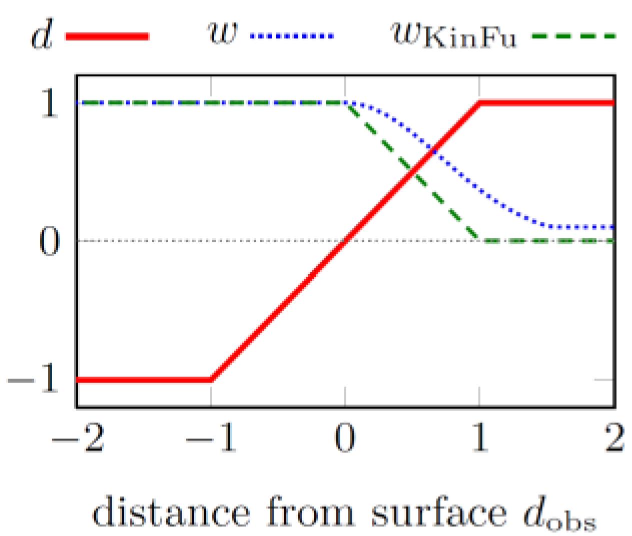
- Thorough evaluation on TUM RGB-D benchmark
- Comparison with KinFu and RGB-D SLAM
- Significantly more accurate and robust than IC

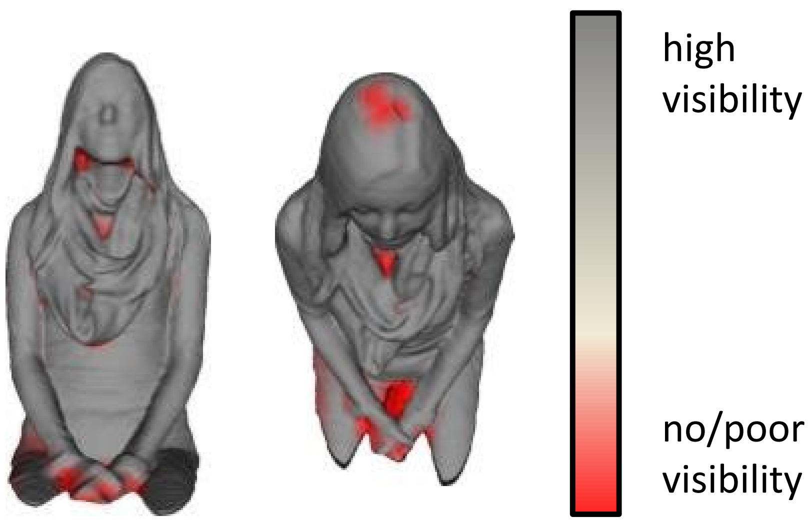
Algorithm	Resolution	Teddy (RMSE)	Desk (RMSE)	Plant (RMSE)
KinFu	256	0.156 m	0.057m	0.598 m
KinFu	512	0.337 m	0.068 m	0.281 m
Our	256	0.086 m	0.038 m	0.047 m
Our	512	0.080 m	0.035 m	0.043 m

Automatically Close Holes

[Sturm, Bylow, Kahl, Cremers; GCPR 2013]

- Certain voxels are never observed in near range
- Regions with no data result in holes
- Idea: Truncate weights to positive values

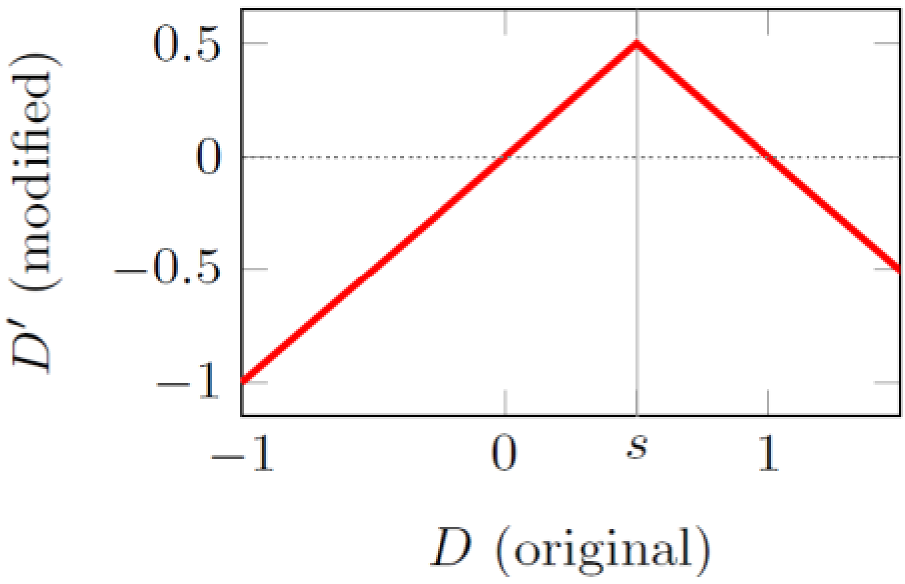




Hollowing Out

[Sturm, Bylow, Kahl, Cremers; GCPR 2013]

- Printing cost is mostly dominated by volume
- Idea: Make the model hollow



Video (real-time)

[Sturm, Bylow, Kahl, Cremers; GCPR 2013]

Examples of Printed Figures
[Sturm, Bylow, Kahl, Cremers; GCPR 2013]

More Examples

[Sturm, Bylow, Kahl, Cremers; GCPR 2013]

- Need a present?
- Live Demo after the talk

FabliTec 3D Scanner

- 3D scanning software “FabliTec 3D Scanner”
- TUM spin-off, founded in 2013
- Targeting private users
- Sale and user support
- Prerequisites
  - Windows 7/8
  - Graphics card from Nvidia
  - Xbox Kinect camera
- Partners
  - German RepRap GmbH
  - Conrad Electronic
  - Volumental (formerly Kinect-at-home)
- Download free demo version from

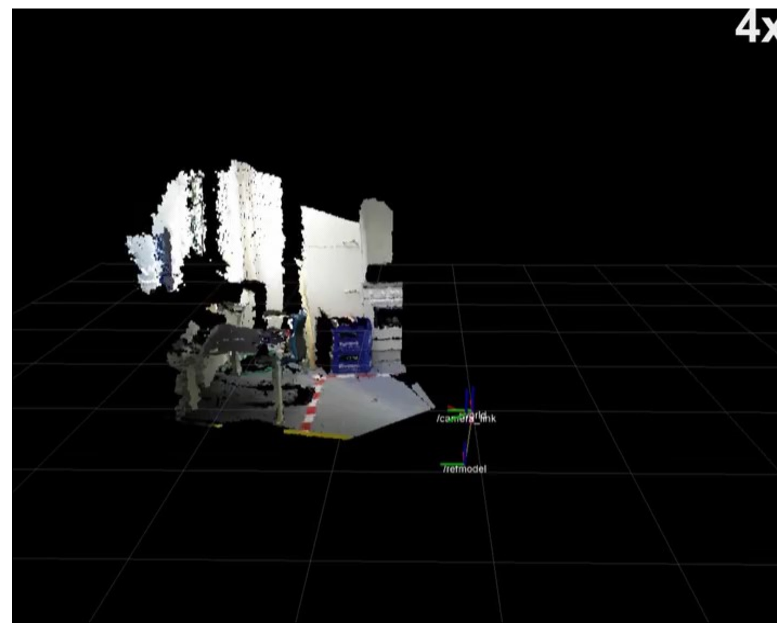
http://www.fablitec.com

3D Reconstruction from a Quadrocopter

[Bylow et al., RSS 2013; Sturm et al., UAV-g 2013]

- AscTec Pelican quadrocopter
- Real-time 3D reconstruction, position tracking and control (external processing on GPU)

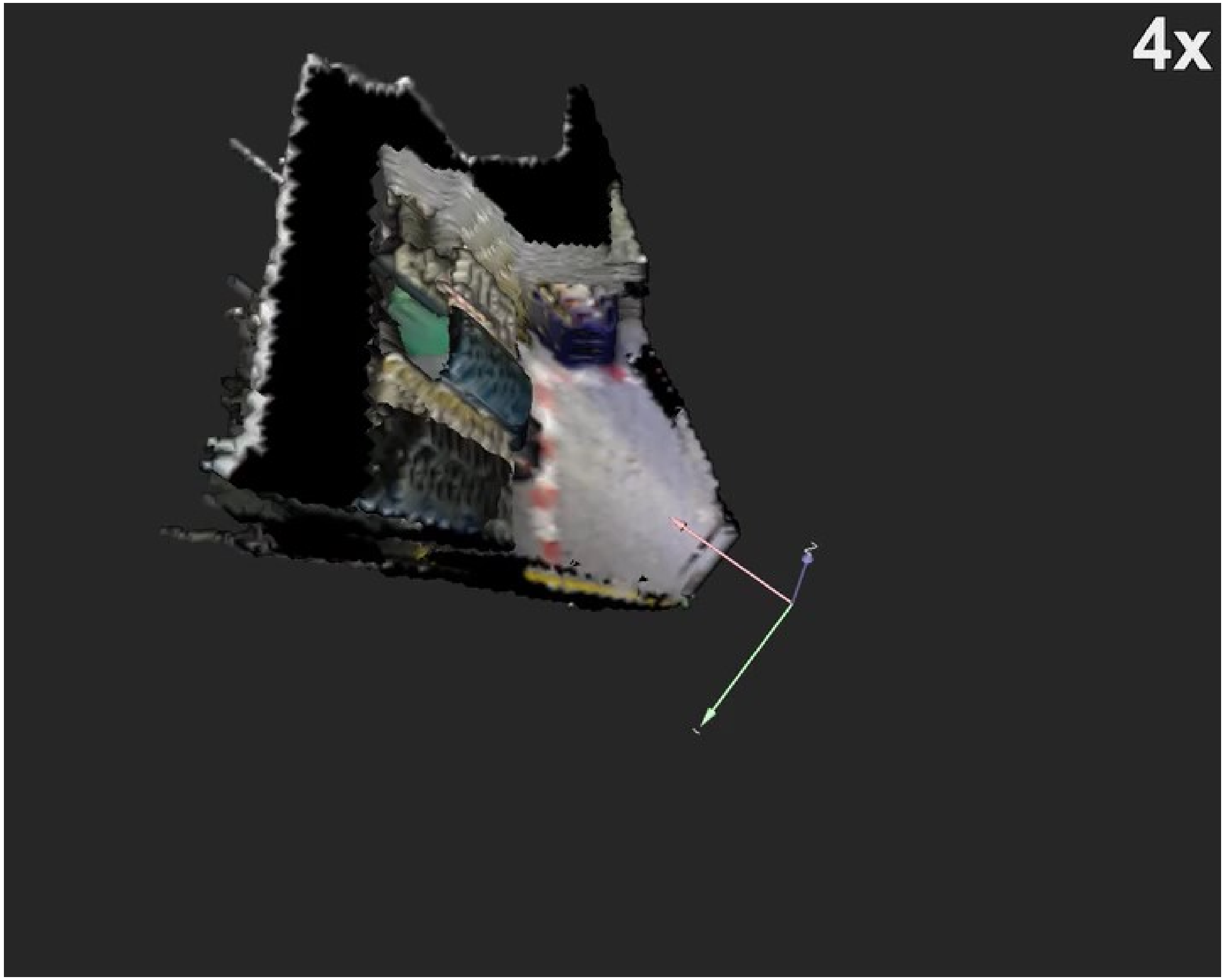
external view



estimated pose

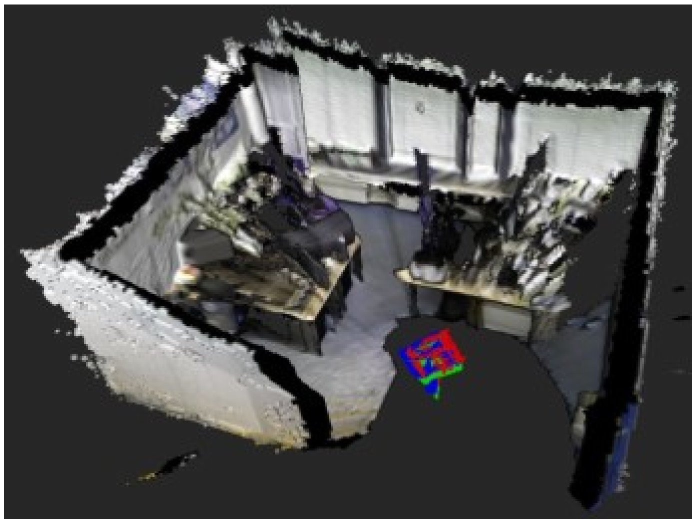
Resulting 3D Model

[Bylow et al., RSS 2013; Sturm et al., UAV-g 2013]



More Examples

[Sturm, Bylow, Kerl, Kahl, Cremers; UAV-g 2013]

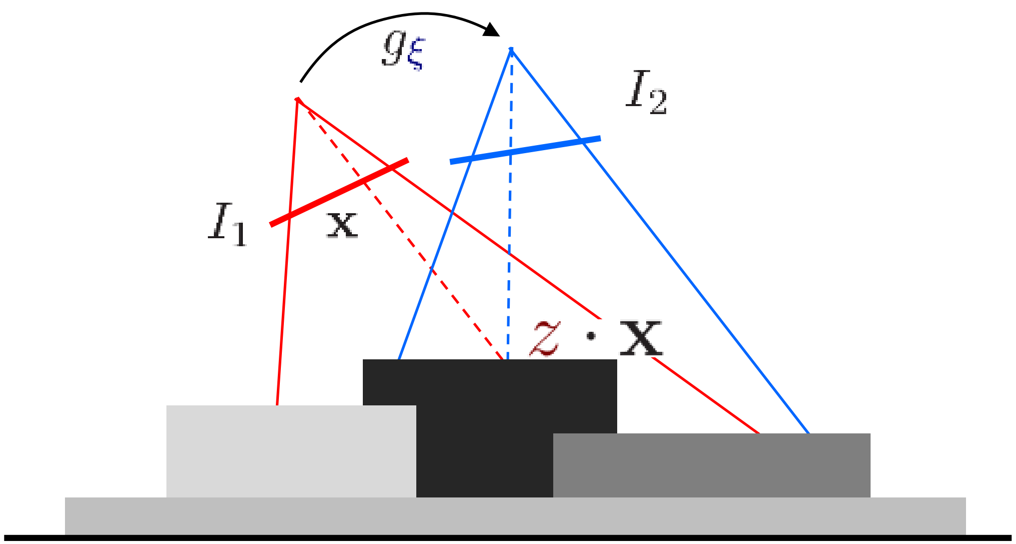


- Nice 3D models, but:
  - Large memory and computational requirements are suboptimal for use on quadrocopter
  - Significant drift in larger environments
- How can we improve on this?

Dense Visual Odometry

[Steinbrücker, Sturm, Cremers, ICCV LDRMC 2011; Kerl, Sturm, Cremers, ICRA 2013]

- Can we compute the camera motion directly?
- Idea



- Photo-consistency constraint $I_1(\mathbf{x}) = I_2\left(\pi(g_\xi(z \cdot \mathbf{x})\right)$
- Geometry-consistency constraint $Z_2(\mathbf{x}') = \mathbf{p}'_z$

How to deal with noise?

[Steinbrücker, Sturm, Cremers; ICCV LDRMC 2011]

- Photo-consistency constraint will not perfectly hold
  - Sensor noise
  - Pose error
  - Reflections, specular surfaces
  - Dynamic objects (e.g., walking people)
- Residuals will be non-zero

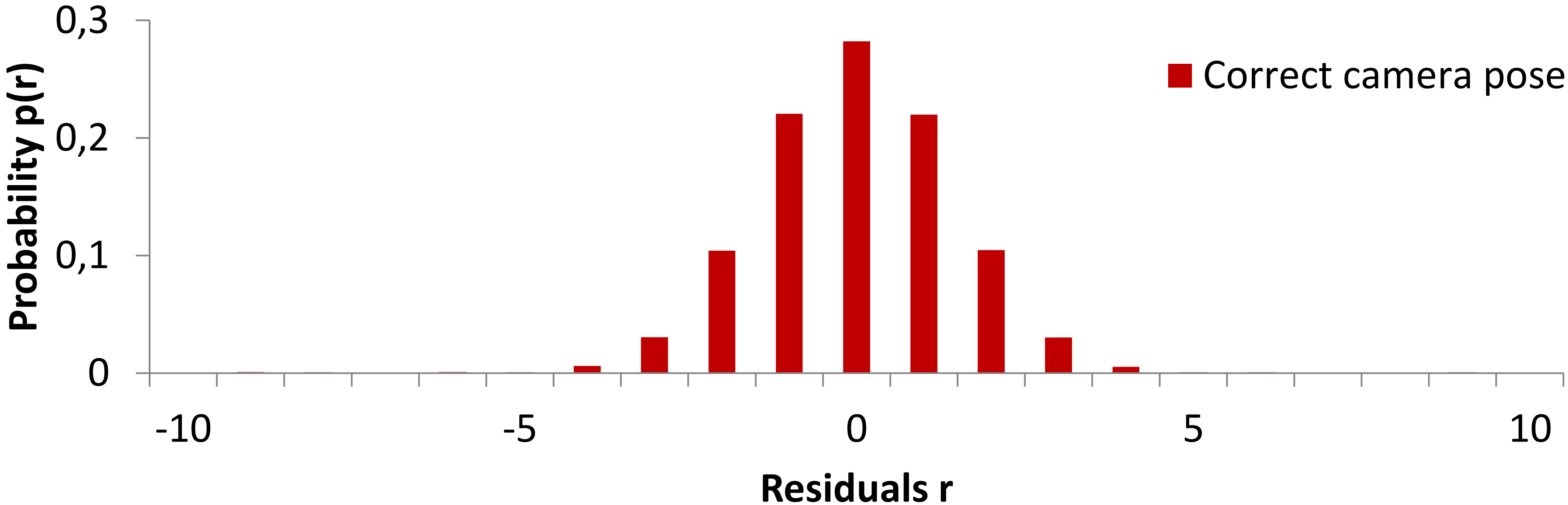
$$r = I_1(\mathbf{x}) - I_2\left(\pi(g_\xi(z \cdot \mathbf{x}))\right) \qquad \left(\mathbf{r} = \begin{pmatrix} I_2(\mathbf{x}') - I_1(\mathbf{x}) \\ Z_2(\mathbf{x}') - \mathbf{p}'_z \end{pmatrix}\right)$$

- How does the residual distribution $p(r)$ look like?

How to deal with noise?

[Steinbrücker, Sturm, Cremers; ICCV LDRMC 2011]

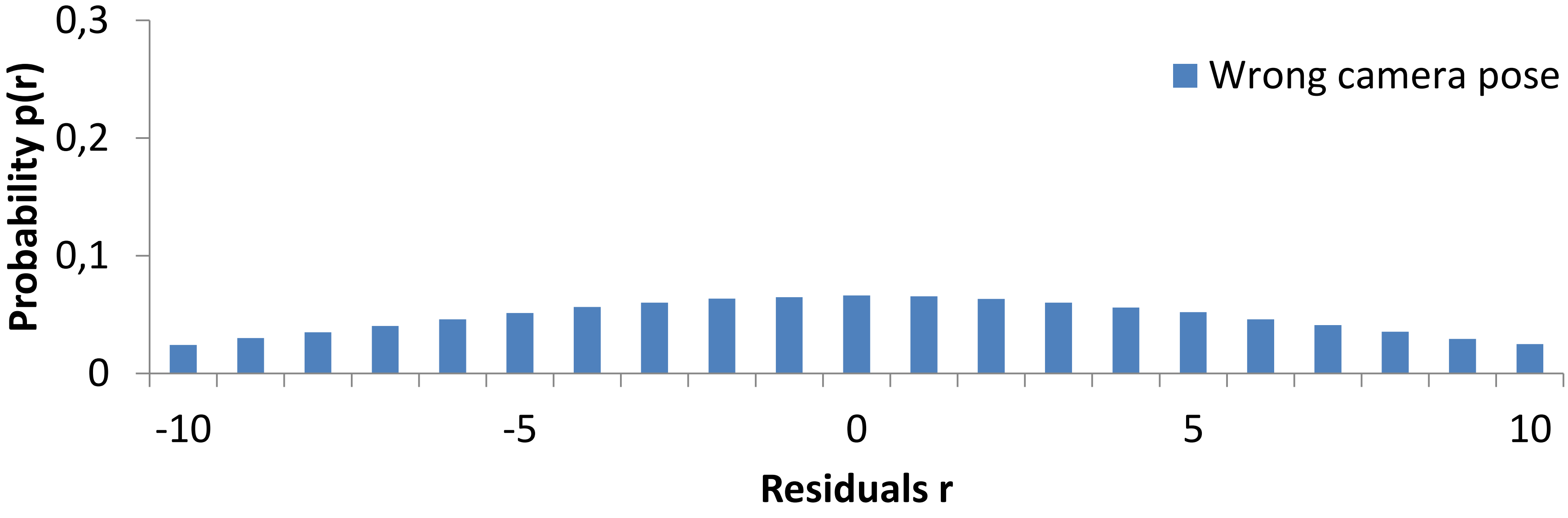
- Zero-mean, peaked distribution
- Example: Correct camera pose



How to deal with noise?

[Steinbrücker, Sturm, Cremers; ICCV LDRMC 2011]

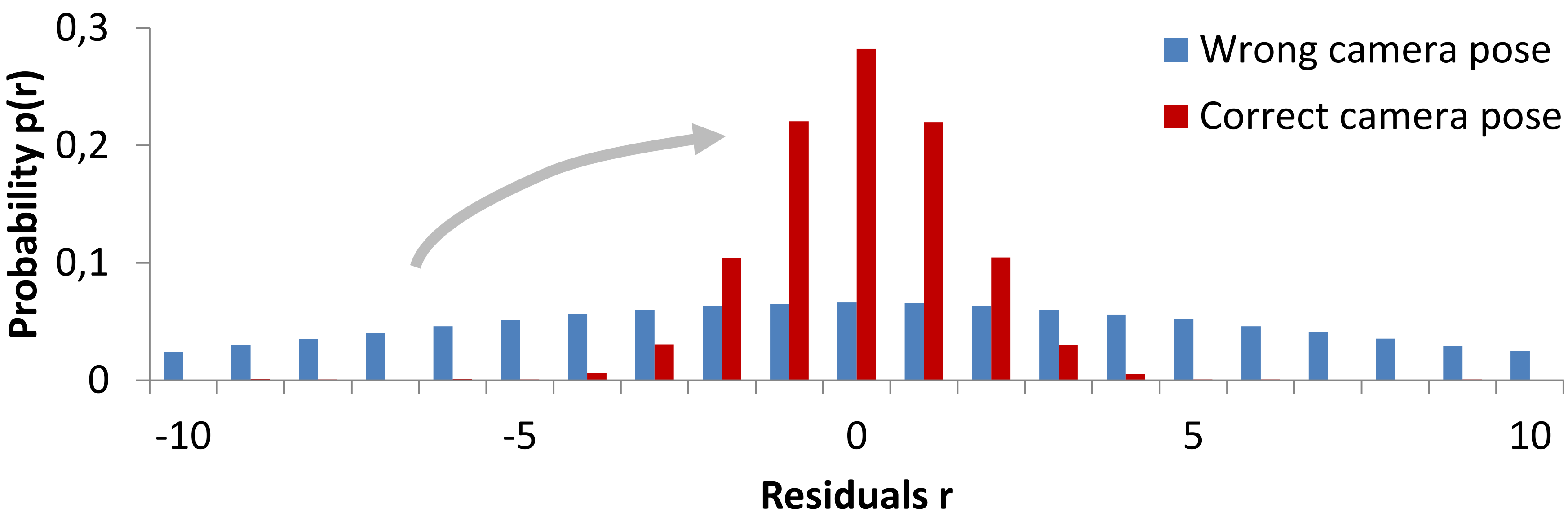
- Zero-mean, peaked distribution
- Example: Wrong camera pose



Residual Distribution

[Steinbrücker, Sturm, Cremers; ICCV LDRMC 2011]

- Our goal: Find the camera pose that maximizes the observation likelihood



Dense Alignment

[Steinbrücker, Sturm, Cremers; ICCV LDRMC 2011]

- Our goal: Find the camera pose that maximizes the observation likelihood

$$\boldsymbol{\xi}^* = \arg\max_{\boldsymbol{\xi}} \prod_i p(r_i(\boldsymbol{\xi}))$$

compute over all pixels

- Assume pixel-wise residuals are conditionally independent
- How can we solve this optimization problem?

Dense Alignment

[Steinbrücker, Sturm, Cremers; ICCV LDRMC 2011]

- Take negative logarithm

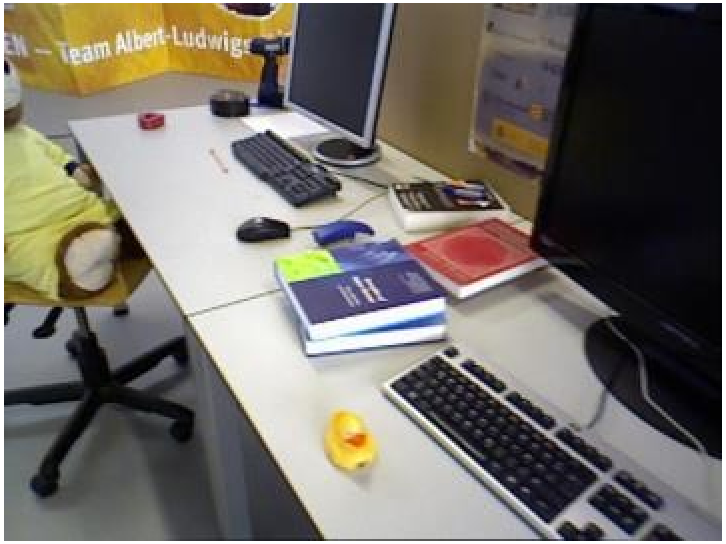
$$\boldsymbol{\xi}^* = \arg\min_{\boldsymbol{\xi}} \sum_i -\log p(r_i(\boldsymbol{\xi}))$$

- Set derivative to zero

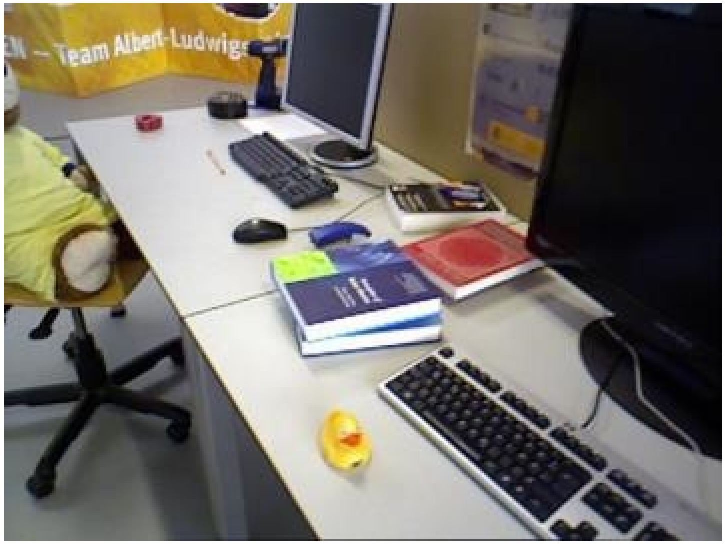
$$\sum_i \frac{\partial \log p(r_i(\boldsymbol{\xi}))}{\partial \boldsymbol{\xi}} = \sum_i \frac{\partial \log p(r_i)}{\partial r_i} \frac{\partial r_i(\boldsymbol{\xi})}{\partial \boldsymbol{\xi}} \stackrel{!}{=} 0$$

- $r_i(\boldsymbol{\xi})$ is non-linear in $\boldsymbol{\xi}$
- Solve using Gauss-Newton method (linearize, solve, repeat)

Example
[Kerl, Sturm, Cremers; ICRA 2013]



I_1



I_2

Example

[Kerl, Sturm, Cremers; ICRA 2013]

Residuals before registration

$(I_2(\mathbf{x}') - I_1(x))^2 \quad \boldsymbol{\xi} = \mathbf{0}$

Residuals after registration

$(I_2(\mathbf{x}') - I_1(x))^2 \quad \boldsymbol{\xi} = \boldsymbol{\xi}^*$

Coarse-to-Fine

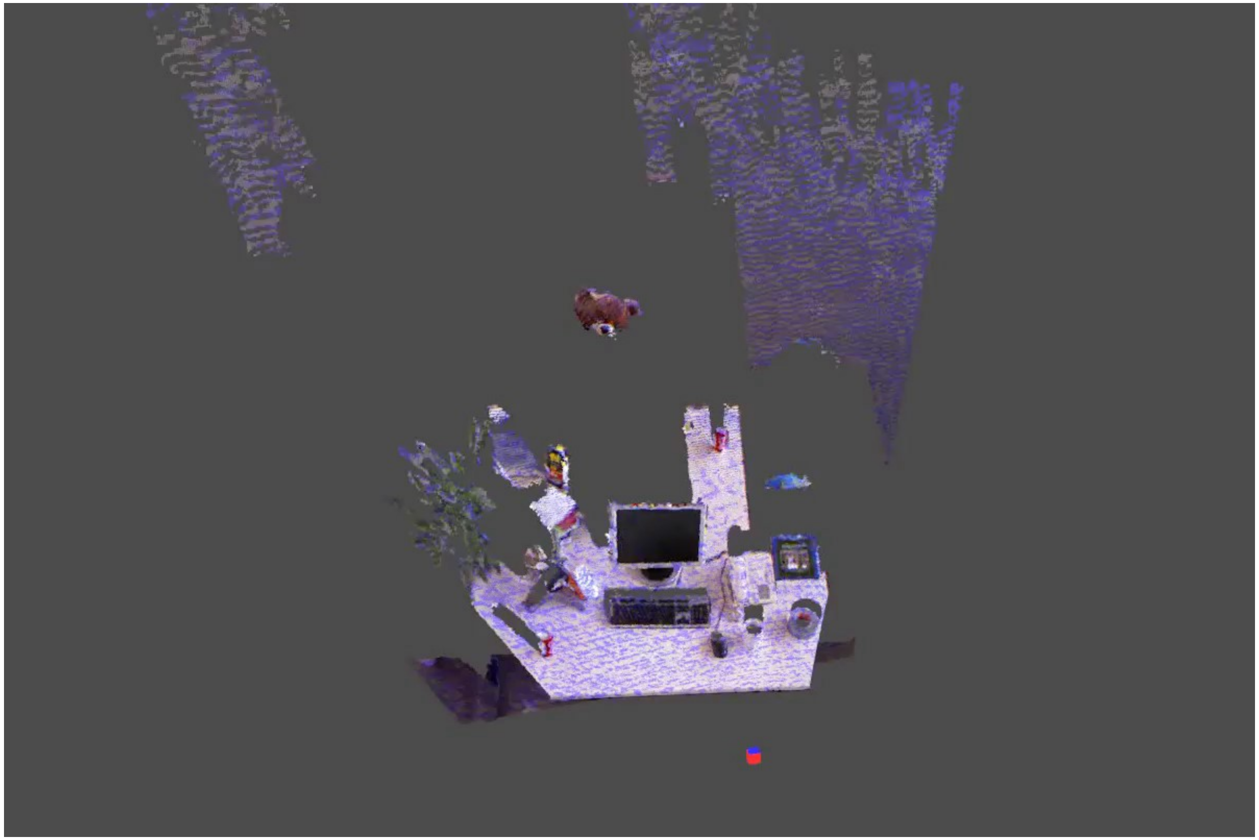
[Steinbrücker, Sturm, Cremers; ICCV LDRMC 2011]

- Linearization only holds for small motions
- Coarse-to-fine scheme
- Image pyramids

Dense Visual Odometry: Results

[Steinbrücker, Sturm, Cremers, ICCV LDRMC 2011; Kerl, Sturm, Cremers, ICRA 2013]

- Runs in real-time on single CPU core (SSE optimized)
- Available as open-source
- Average drift: ~3cm/s

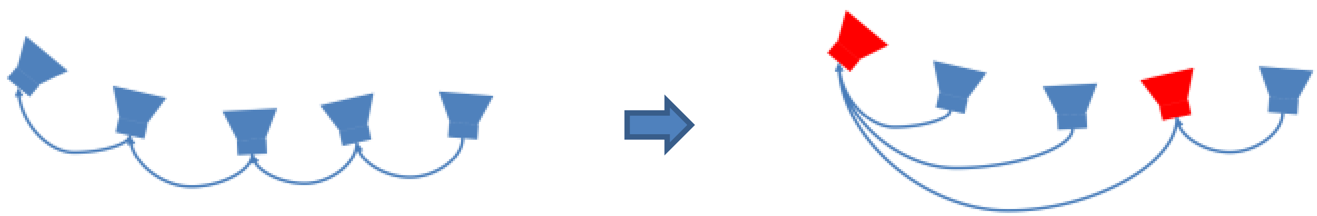


Dense Visual Odometry: Results

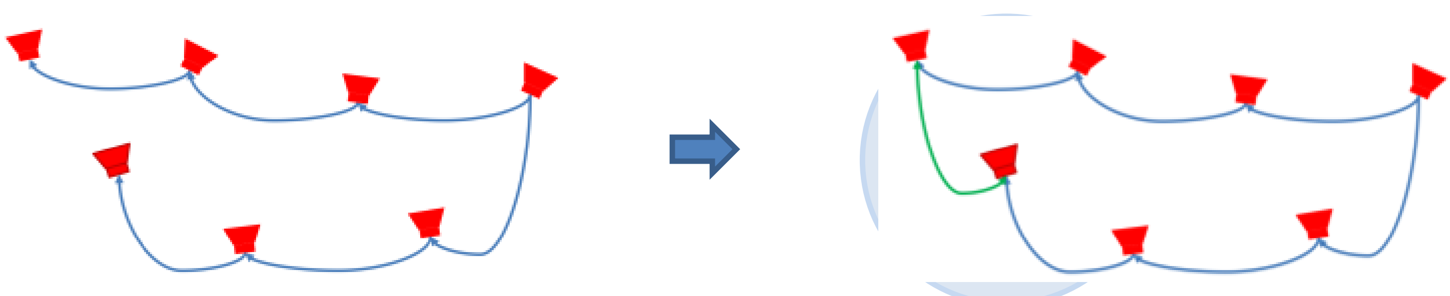
[Kerl, Sturm, Cremers; IROS 2013]

- Problem: Considerable drift accumulation (1.8m/min)
- How can we further reduce this drift?

- Local drift: Track w.r.t. key frames



- Global drift: Detect loop closures and optimize pose graph



Dense Visual Odometry: Results

[Kerl, Sturm, Cremers; IROS 2013]

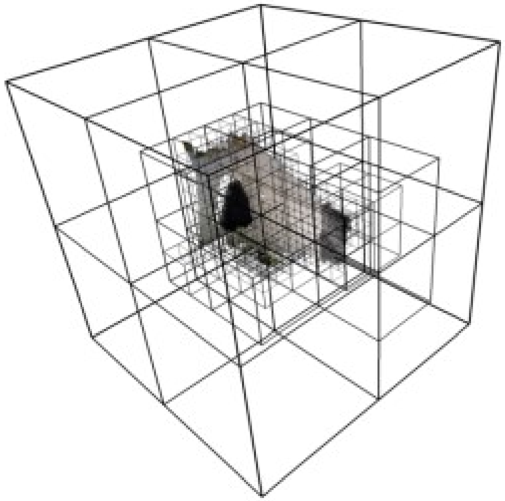
- Keyframes are added dynamically (based on entropy evaluation)
- Localize w.r.t to current keyframe (first CPU core/thread)
- Detect loop closures and optimize pose graph (second CPU core/thread)

Large-Scale 3D Reconstruction
[Steinbrücker, Kerl, Sturm, Cremers; ICCV 2013]

- We have: Optimized pose graph
- We want: High-resolution 3D map

- Problem: High-resolution voxel grids consume much memory (grows cubically)
  - 512^3 voxels, 24 byte per voxel → 3.2 GB
  - 1024^3 voxels, 24 byte per voxel → 24 GB
  - …

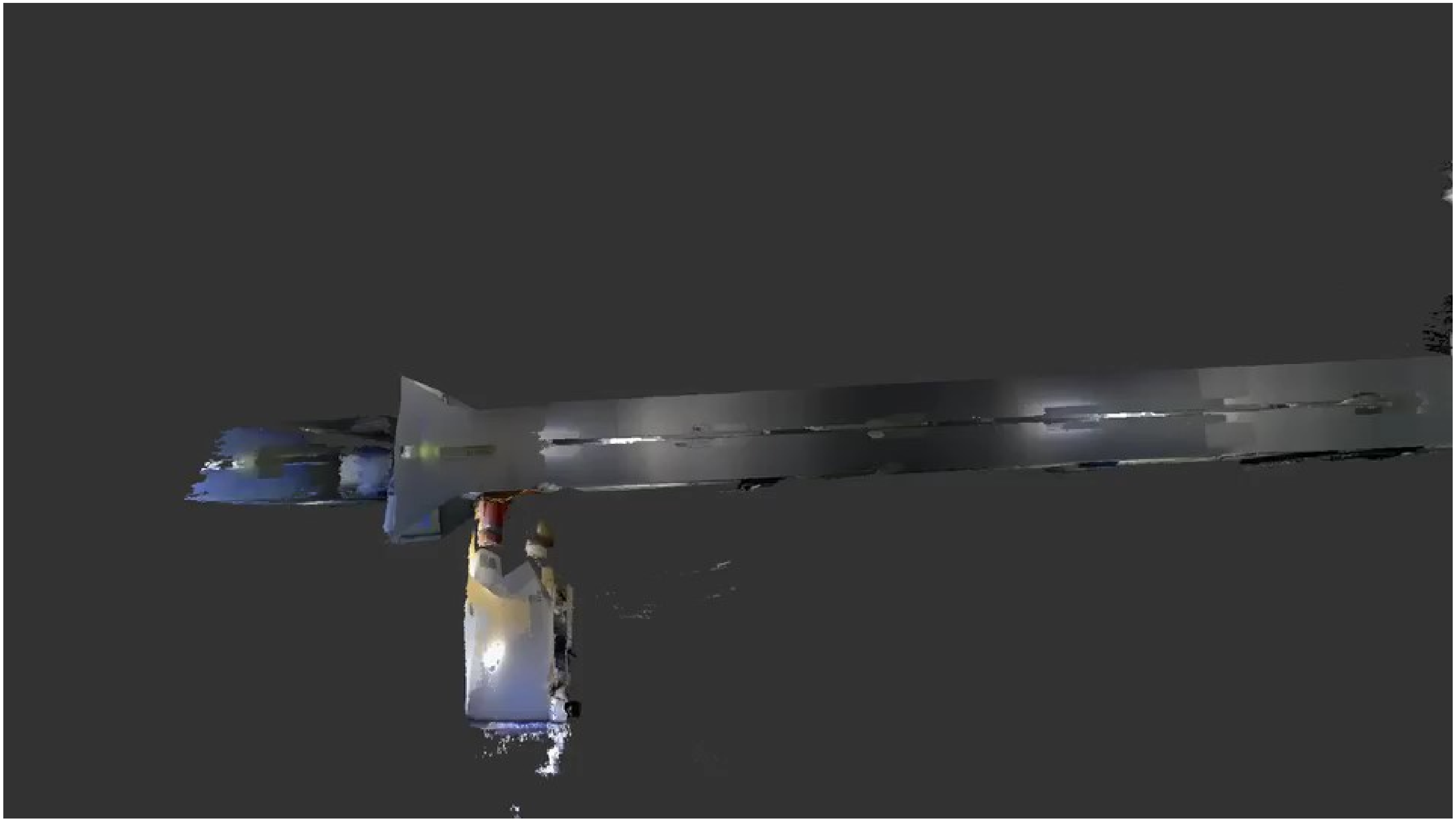
- Idea:
  - Save data in oct-tree data structure
  - Only allocate cells that are close to the surf
  - Store geometry at multiple resolutions
  - Tree can grow dynamically (no fixed size)



Large-Scale 3D Reconstruction

[Steinbrücker, Kerl, Sturm, Cremers; ICCV 2013]

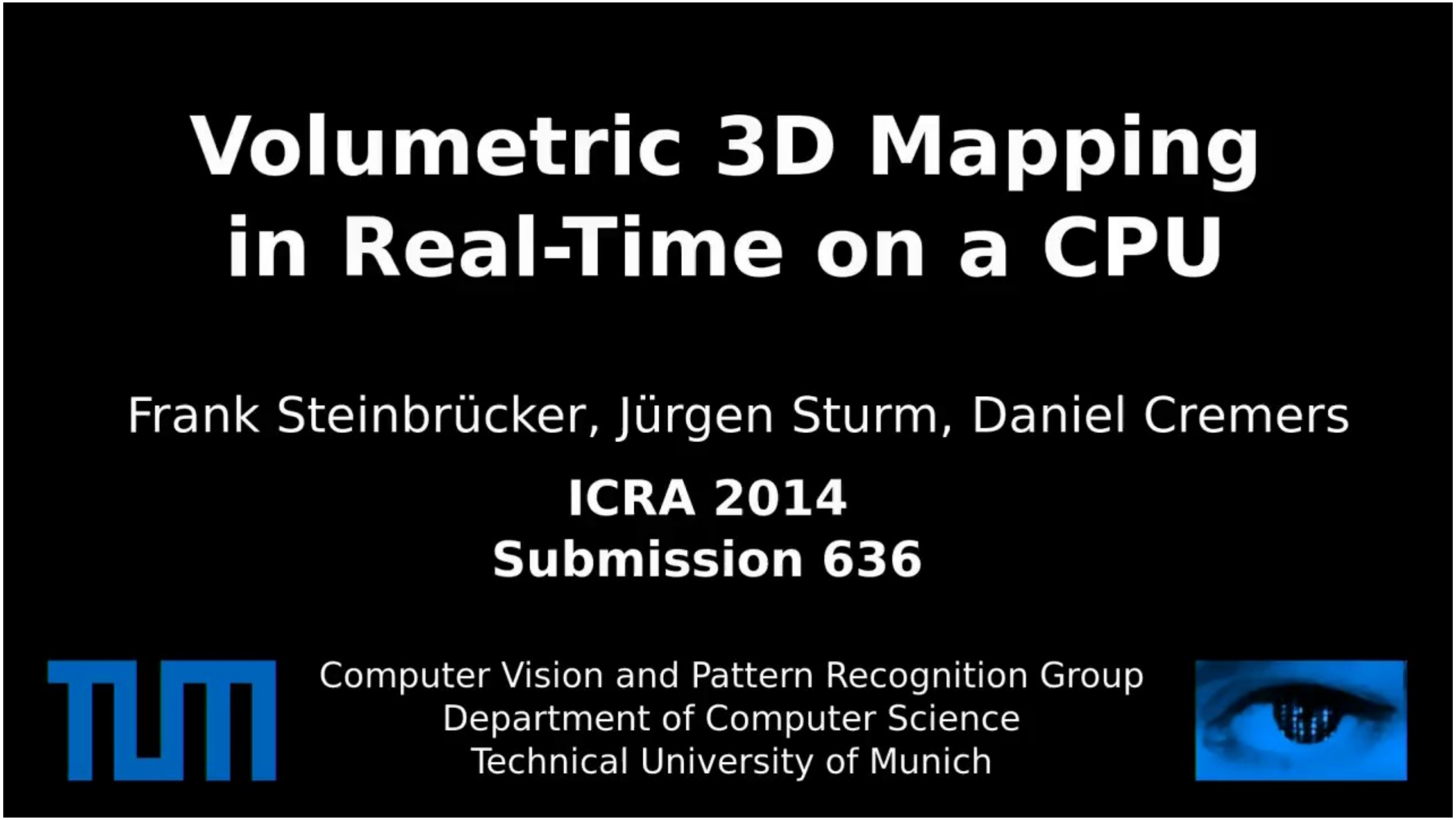
- Runs at 200 fps on a GPU (assuming camera poses are known)



3D Mapping in Real-Time on a CPU

[Steinbrücker, Sturm, Cremers; ICRA 2014]

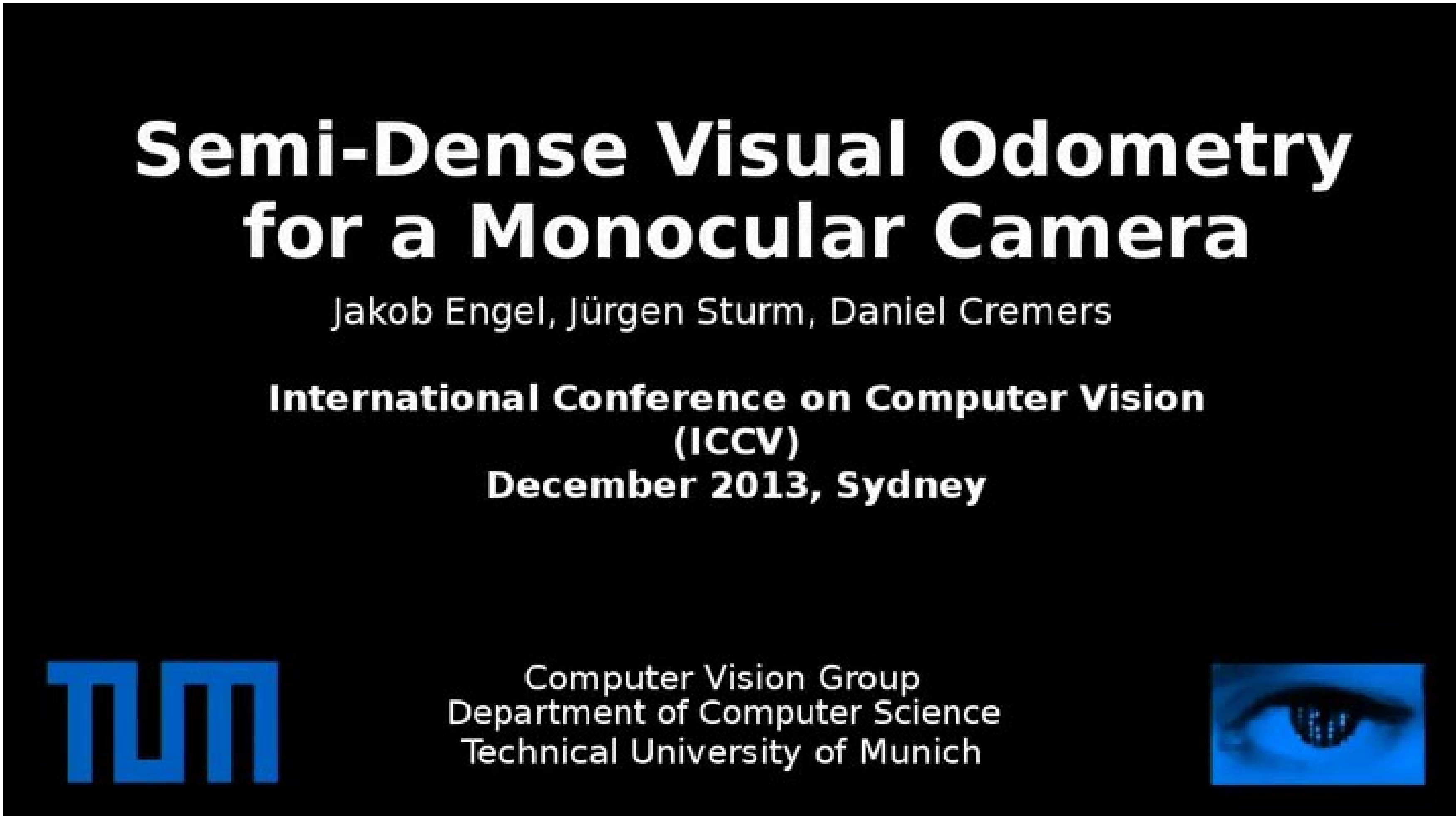
- Runs at 45 fps on CPU, available as open-source!



Same with a Monocular Camera?

[Engel, Sturm, Cremers; ICCV 2013]

- Soon available as open-source!



Summary

- (Scientific) Take home messages:
  - Dense methods make better use of available data
  - Supersede sparse/feature-based approaches
  - Real-time visual SLAM and 3D reconstruction is there

- Dense visual odometry: simple, fast, efficient
- Dense visual SLAM: eliminates drift
- Dense 3D reconstruction: nice models

- Nice, but..
  But what do we need this for??

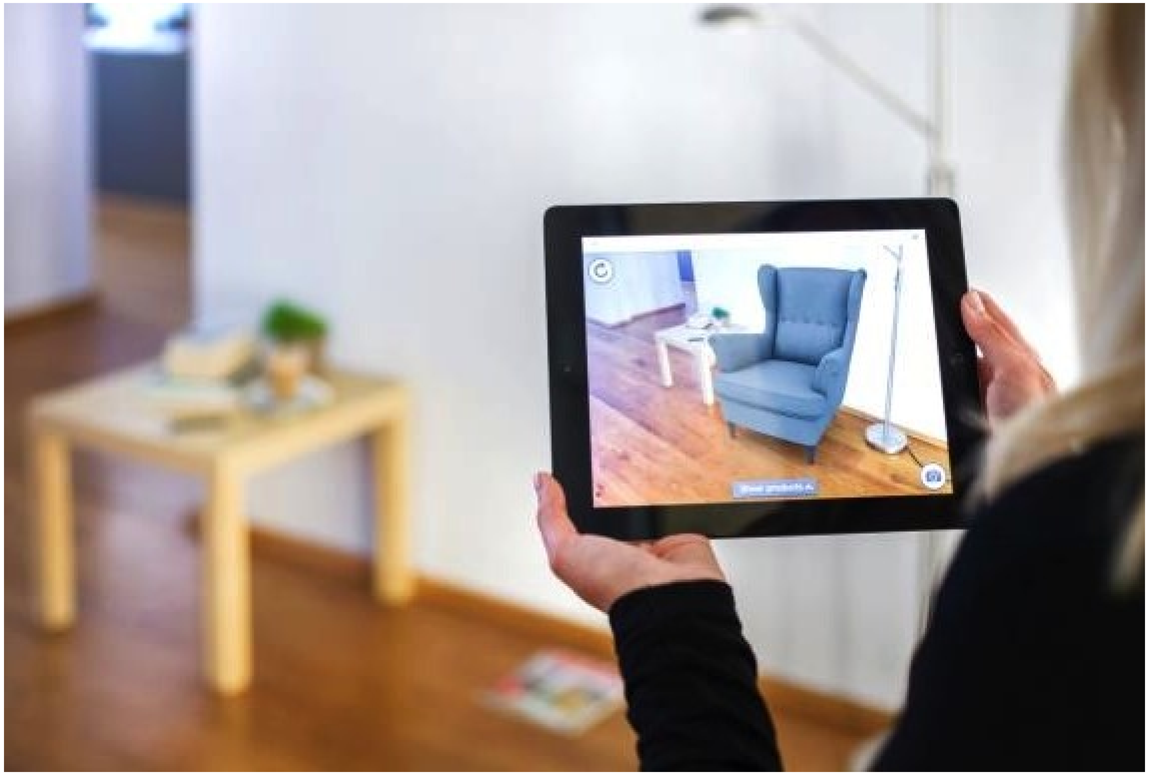
What do we need this for?

- Robotics
  - Laser scanners will eventually get replaced by (depth) cameras
  - Localization, mapping/SLAM, exploration, navigation
- Augmented reality (AR)
  - Games that play in your home
  - Virtual shopping: place furniture
  - User manuals: teach interactively how to repair/maintain a device

Key capabilities:

- Know how the camera is moving (odometry)
- Know where the camera is (absolute position)
- Know how the environment looks like (occlusion modeling, scene understanding)

The 2014 IKEA Catalog App (powered by metaio SDK)



Utilizes next-generation SLAM tracking to place furniture in home, easily and conveniently

Influences and educates purchasing decision while driving massive brand awareness

http://www.youtube.com/watch?v=vDNzTasuYEw

Volkswagen XL1 MARTA (powered by metaio SDK)

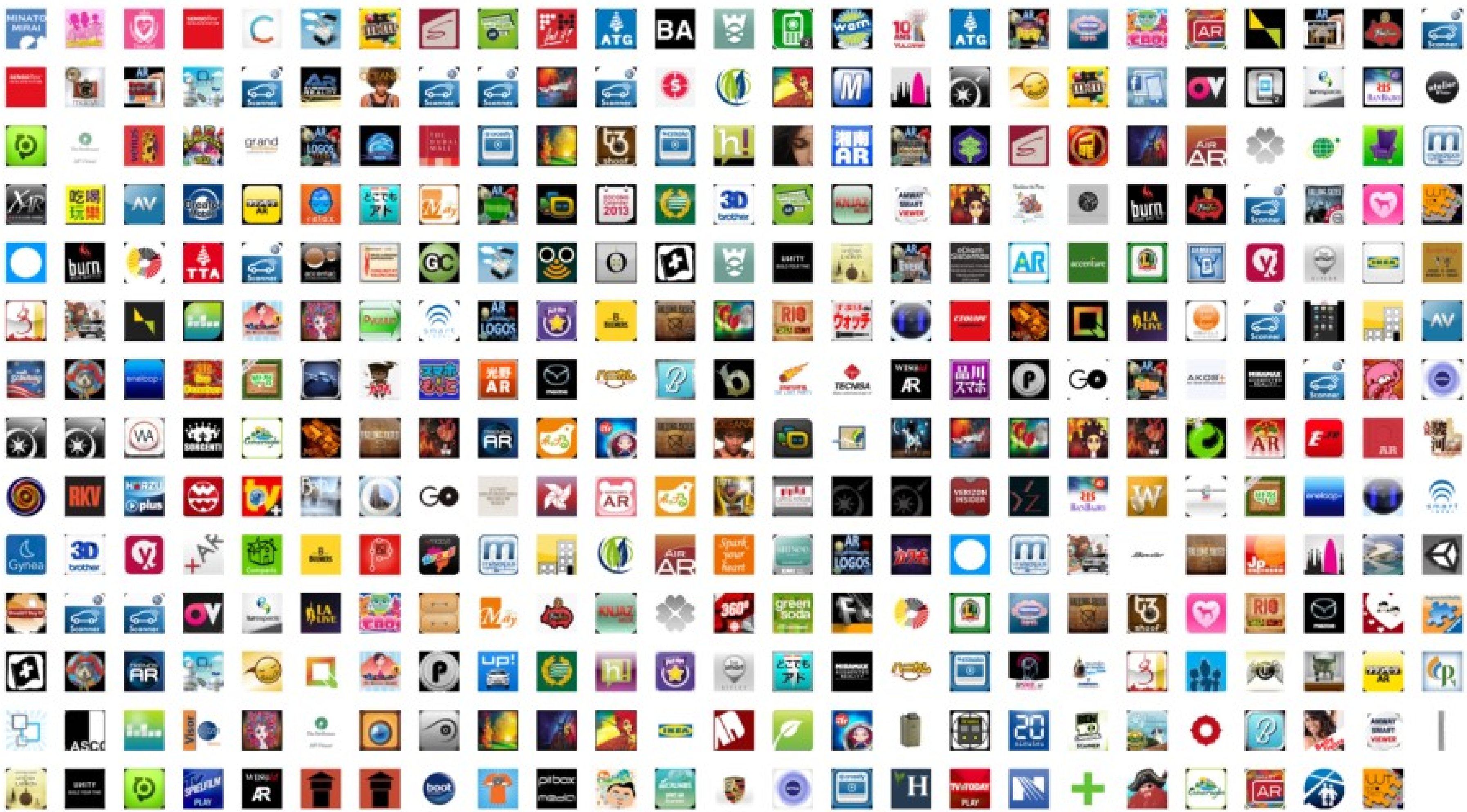
First-ever integrated AR support system for service technicians

Visualizes and overlays animated step-by-step service instructions

Utilizes Metaio's most robust 2D and 3D AR tracking technology.

http://www.youtube.com/watch?v=h2l3VzrkmRY

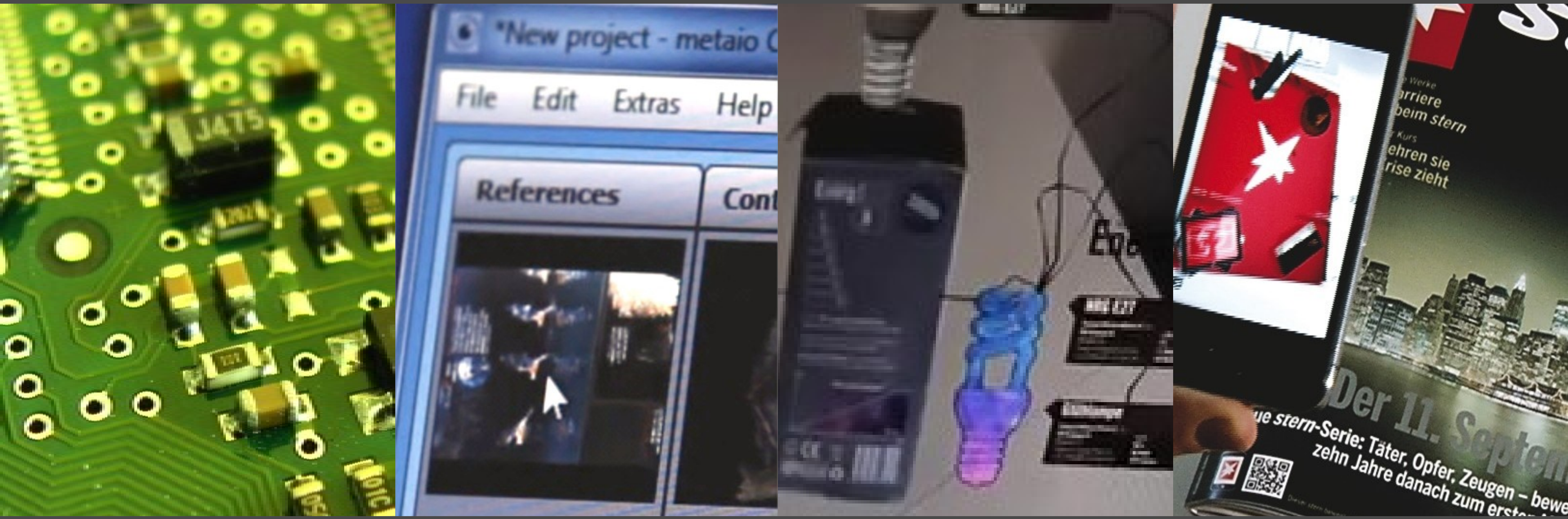
Some of the AR apps based on metaio SDK



metaio – A Brief introduction

- ✓ **ONLY dedicated company** to serve the entire AR value chain
- ✓ **10+ years of professional experience** in AR development
- ✓ **130+ people** working in Germany (HQ) and the USA
- ✓ **1000+ B2B** customers worldwide
- ✓ **100,000+ active developers** across the world
- ✓ **5million+ downloads** of metaio´s AR browser (junaio)

AR Food Chain – Always ON, Always Augmented!



Hardware	Software	Content	Users
(AREngine)	AR Applications	AR Usage	AR Content Access

intel
Imagination
NVIDIA
ARM
Texas Instruments

metaio SDK
metaio Creator
metaio Cloud
metaio Engineer

UCHIDA
CYBERNET
ON-X
the mass media lab
DNP Dai Nippon Printing
j.spot

junaio powered by metaio
junaio certified developer

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http://twitter.com/#!/twitt_AR

http://augmentedblog.wordpress.com/

http://www.youtube.com/user/metaioAR