# Scanning and Printing Objects in 3D

**Jürgen Sturm**

Metaio
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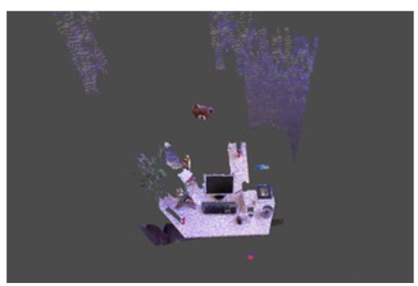
# My Research Areas

- Visual navigation for mobile robots


RGB-D SLAM


Visual Odometry


Large-Scale Reconstruction


3D Printing

# My Research Areas

**Camera-based Navigation of a Low-Cost Quadrocopter**

[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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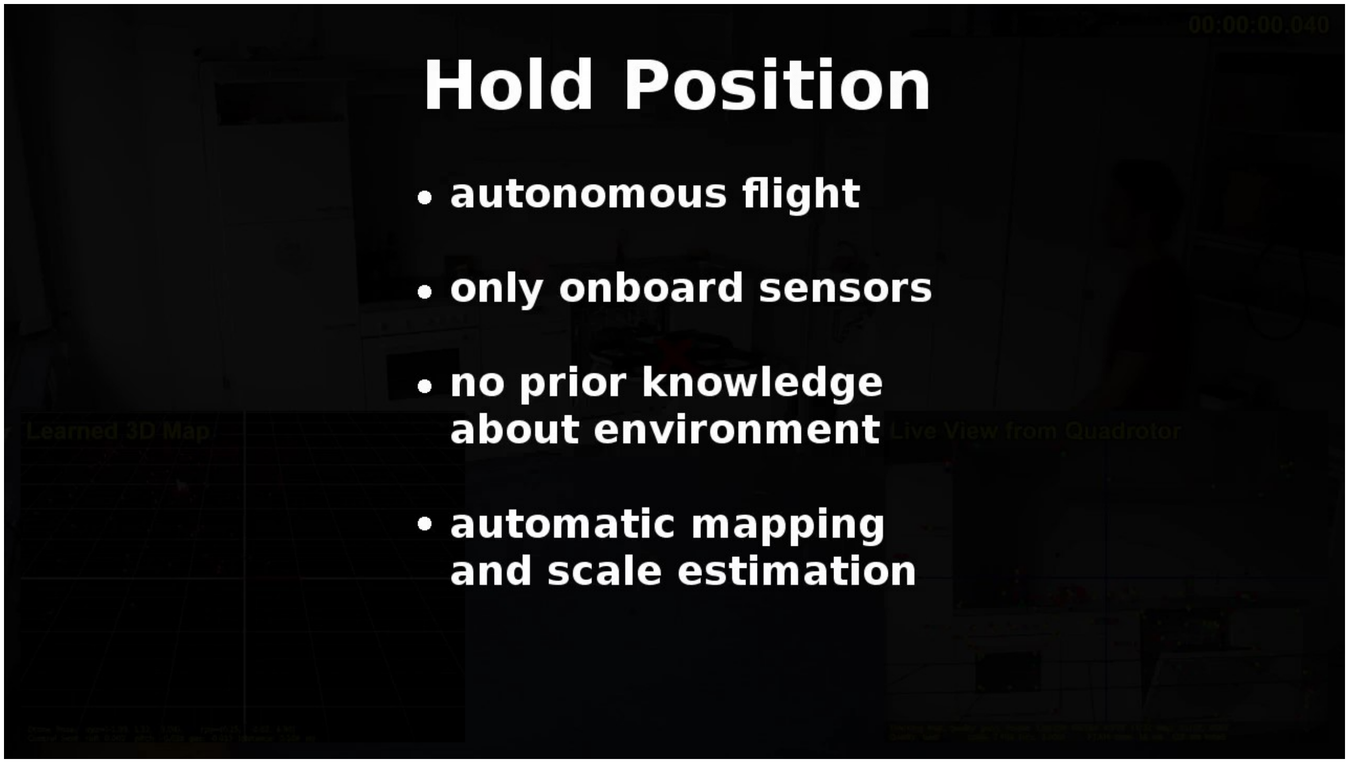
**Camera-based Navigation of a Low-Cost Quadrocopter**




[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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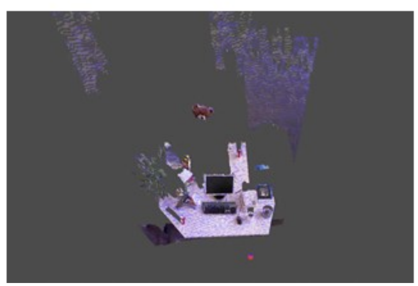

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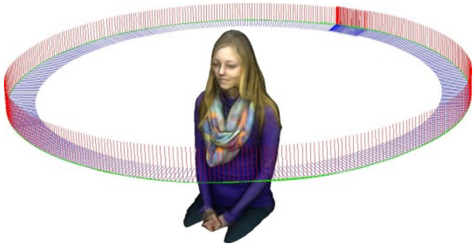
# Motivation

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?



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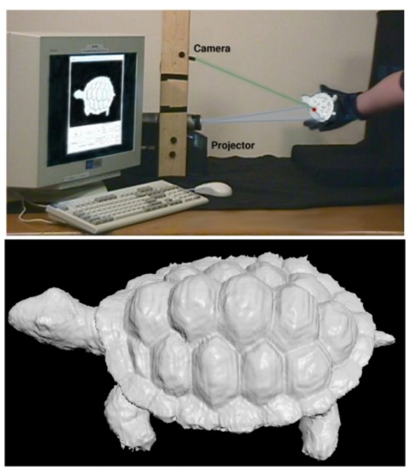
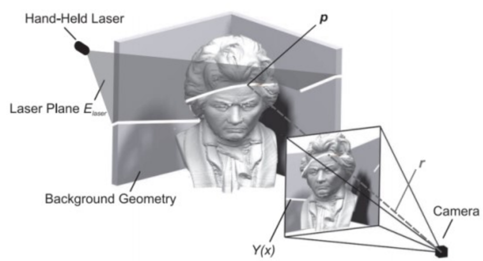
# Related Work

- Structured light [Rusinkiewicz ’02, Winkelbach ‘06]
- Multi-view stereo [e.g., survey of Seitz ‘06]
- KinectFusion [Newcombe ‘11]




[Rusinkiewicz et al., ’02]




[Winkelbach ’06]

[Seitz ’06]

[Newcombe ’11]

# Related Work

- Structured light [Rusinkiewicz ’02, Winkelbach ‘06]
- Multi-view stereo [e.g., survey of Seitz ‘06]
- KinectFusion [Newcombe ‘11]

**Our contributions:**

- Novel method for direct camera tracking (no ICP)
- Simple procedure to scan the upper body of a person
- Ensure printability (close holes, watertight models)
- Minimize printing costs (hollow out), add stand

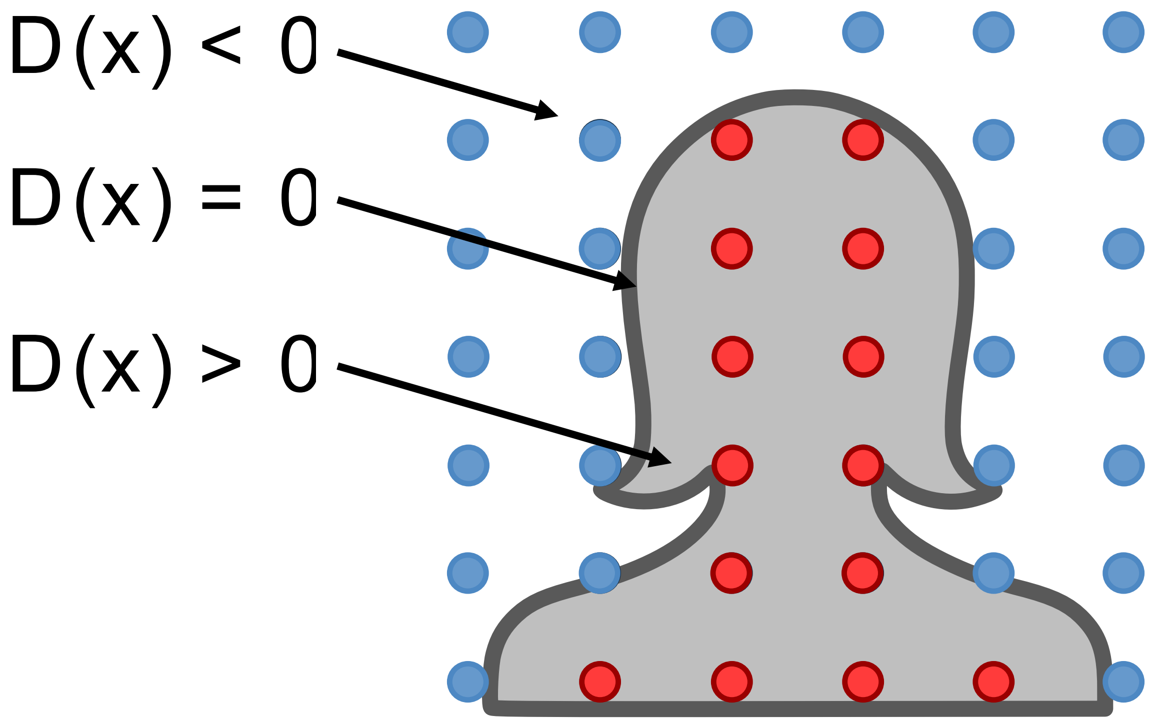
# Problem Description

- **Setup:** Static camera, rotating person


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

# Signed Distance Function (SDF)

## [Curless and Levoy, ’96]



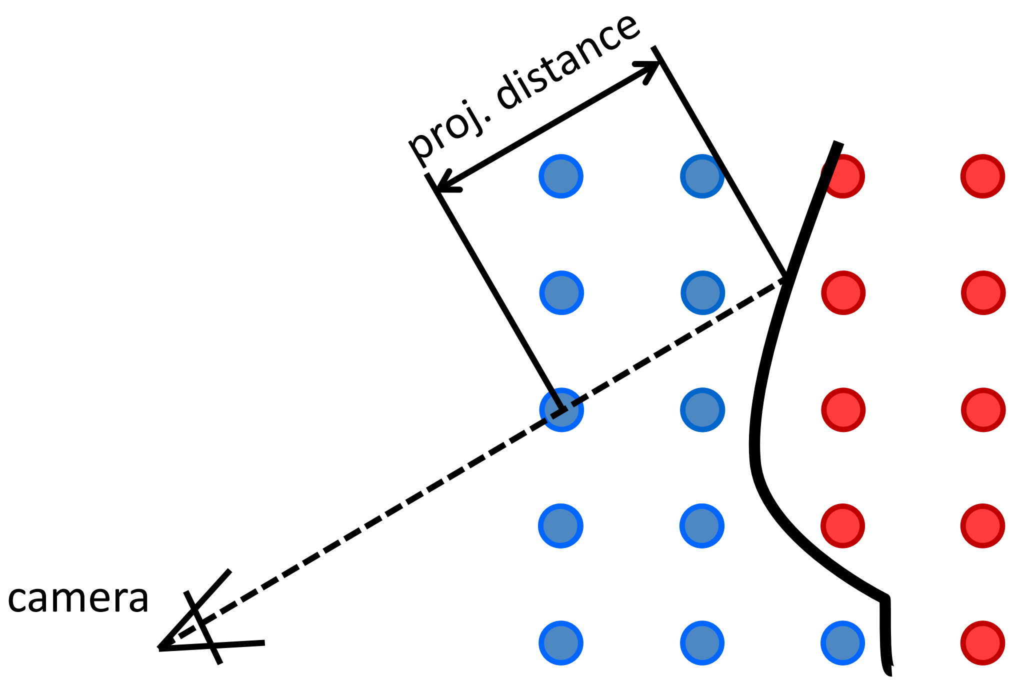

— Negative signed distance (=outside)

— Positive signed distance (=inside)

# Signed Distance Function (SDF)

## [Curless and Levoy, '96]

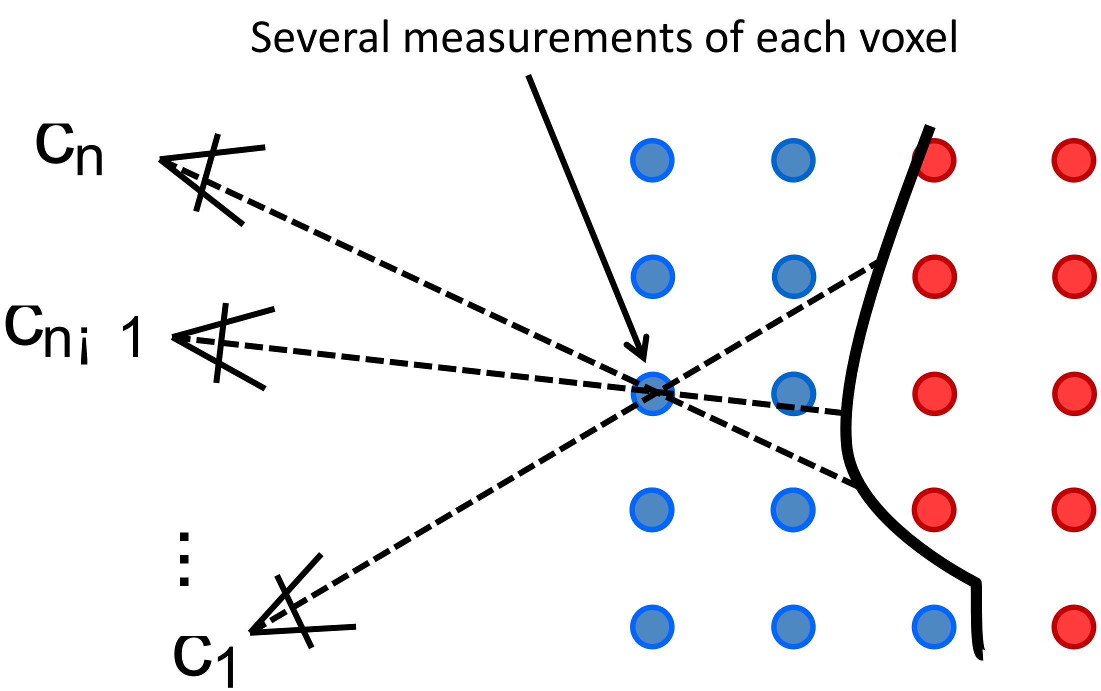
- Compute SDF from a depth image
- Measure distance of each voxel to the observed surface $d_{obs} = z - I_Z(\pi(x, y, z))$



# Signed Distance Function (SDF)

### [Curless and Levoy, ’96]

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



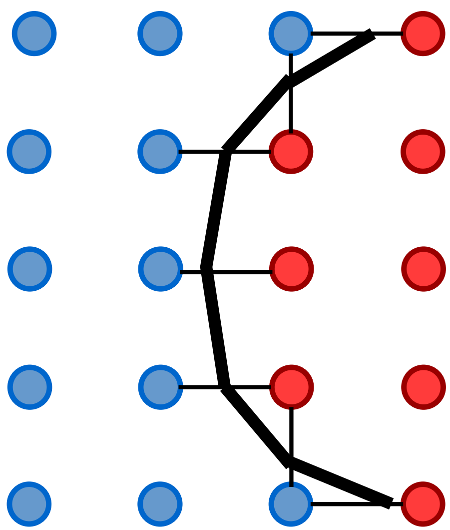

$$D \leftarrow \frac{WD + wd}{W + w}$$

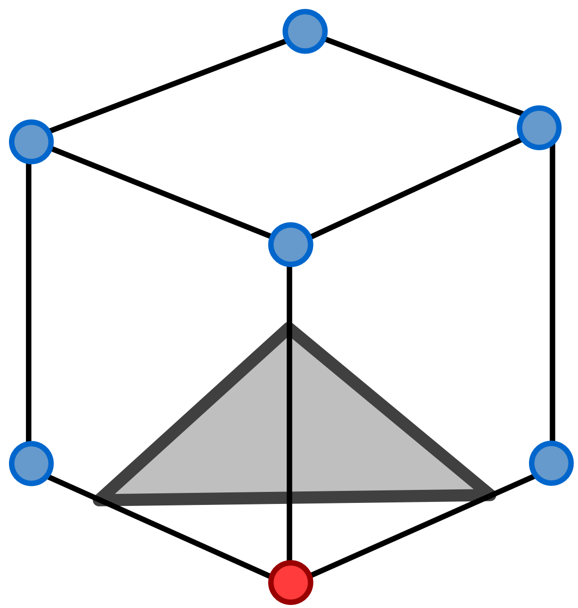
$$C \leftarrow \frac{WC + wc}{W + w}$$

$$W \leftarrow W + w$$

# Mesh Extraction

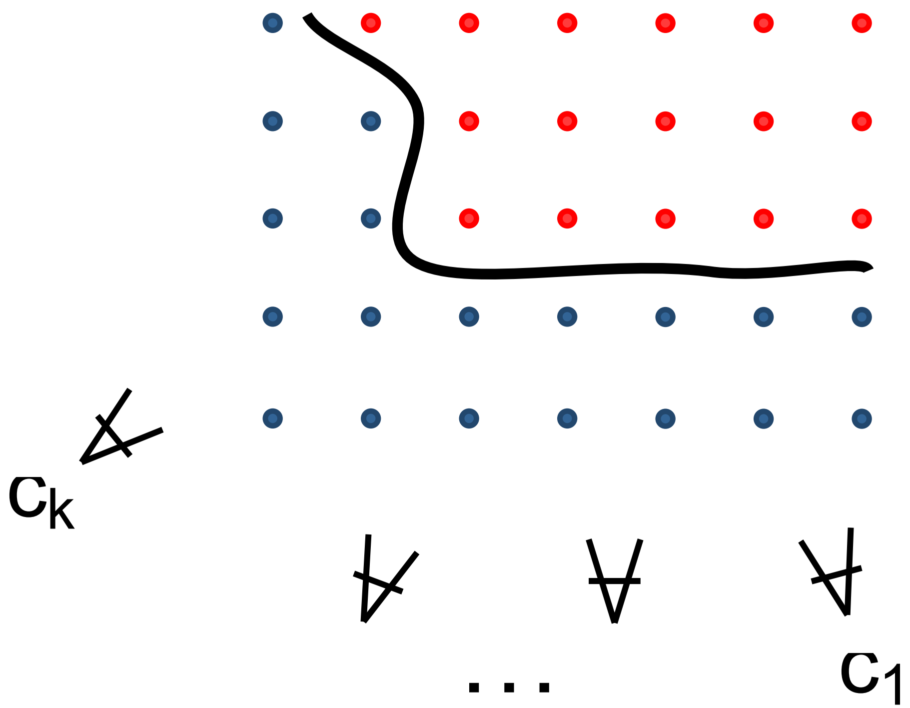
- **Marching cubes:** Find zero-crossings in the signed distance function by interpolation





# Estimating the Camera Pose

- SDF built from the first k frames



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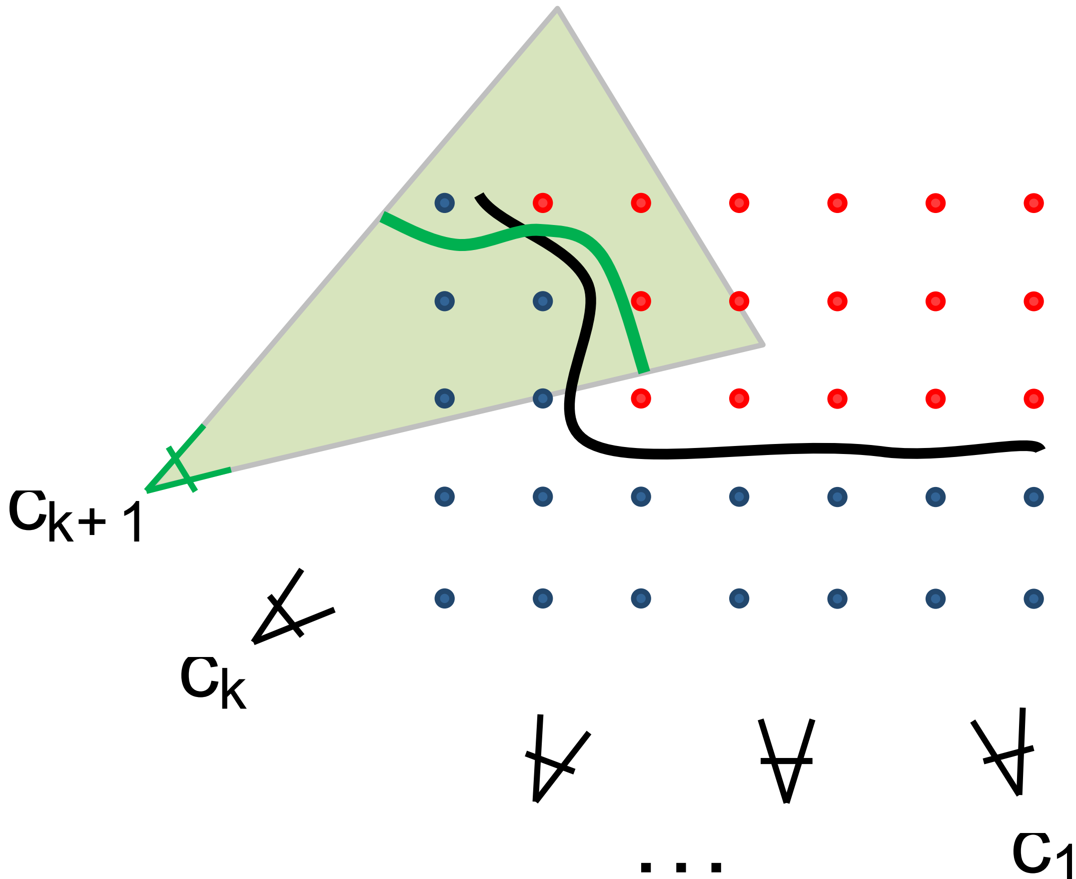
# Estimating the Camera Pose

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



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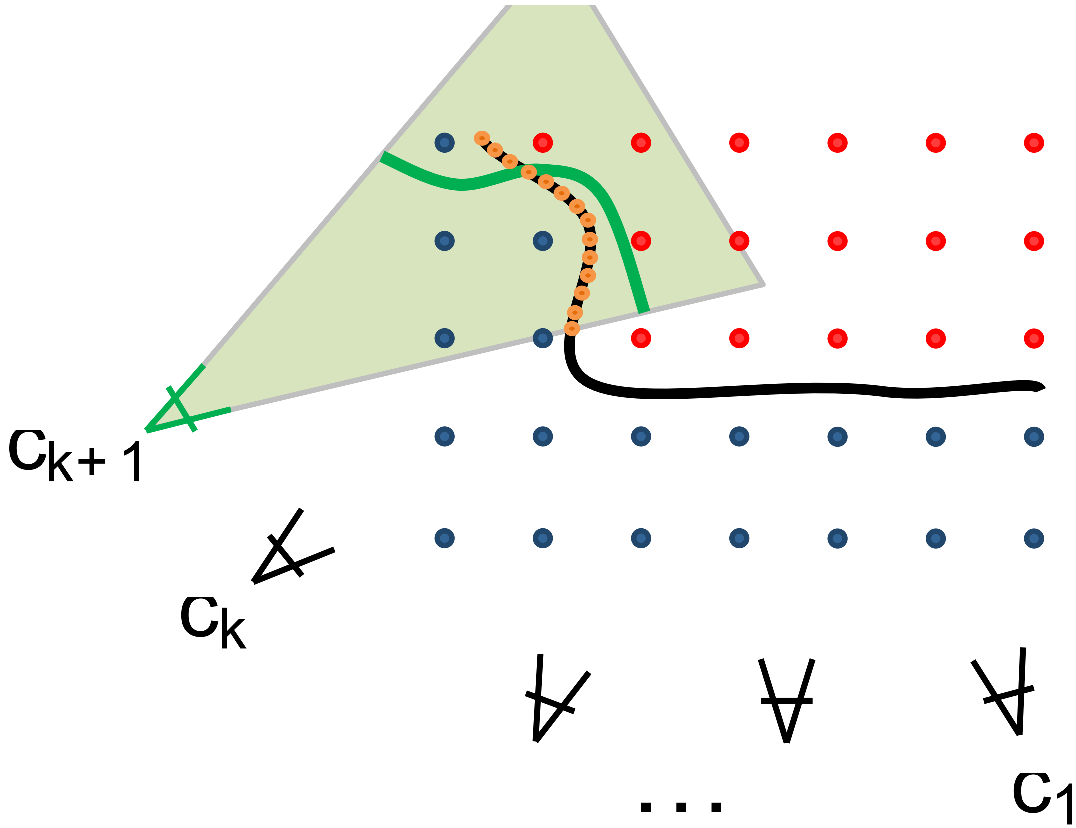
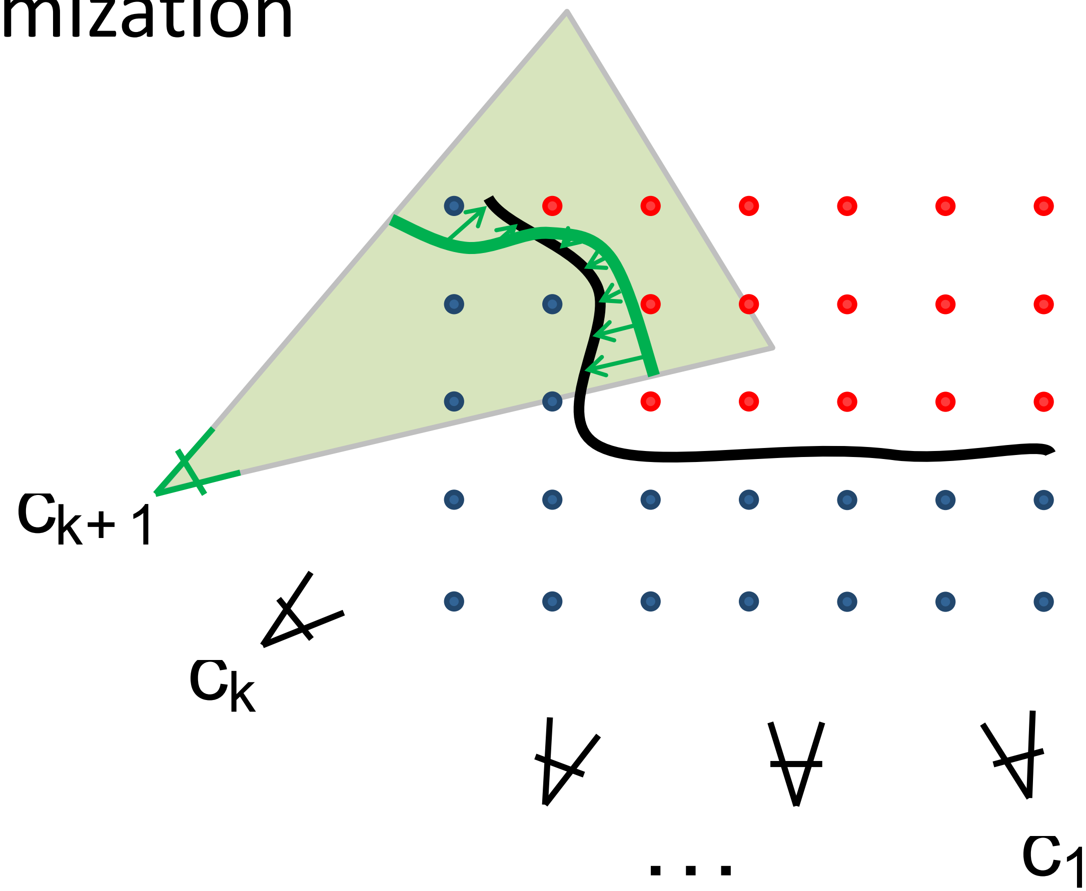
# Estimating the Camera Pose

- 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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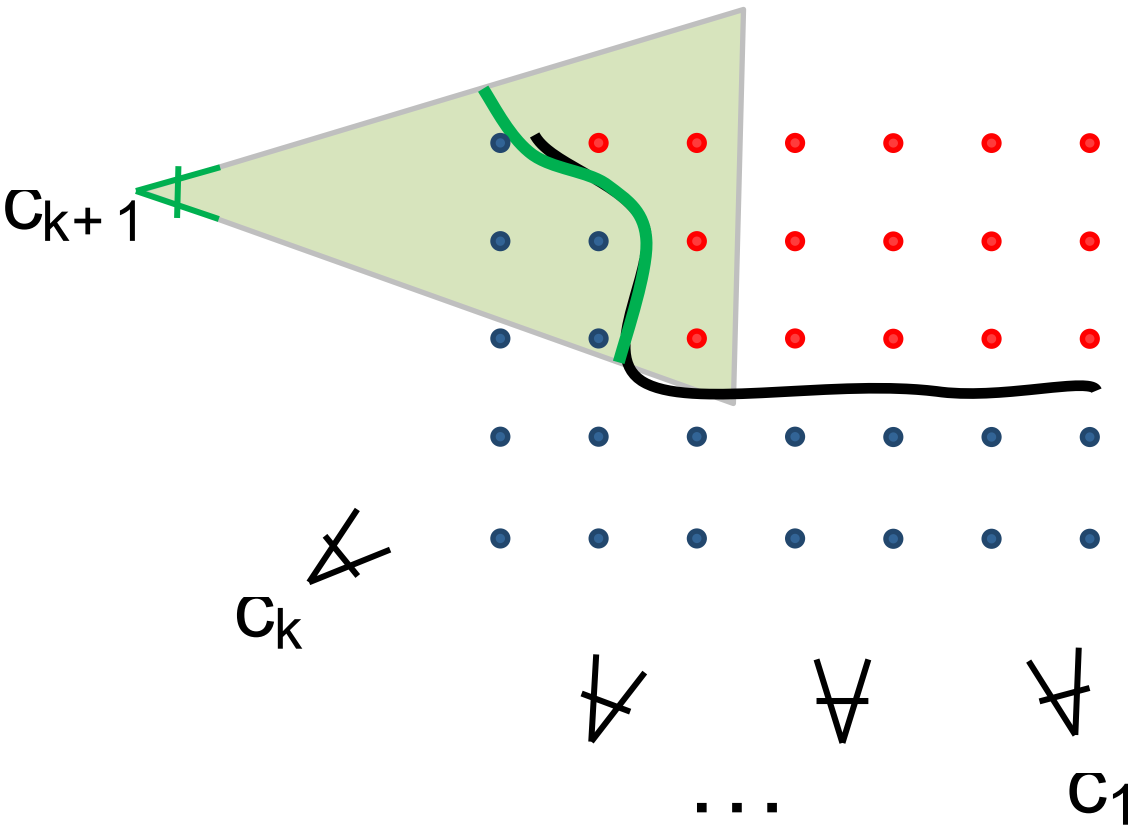

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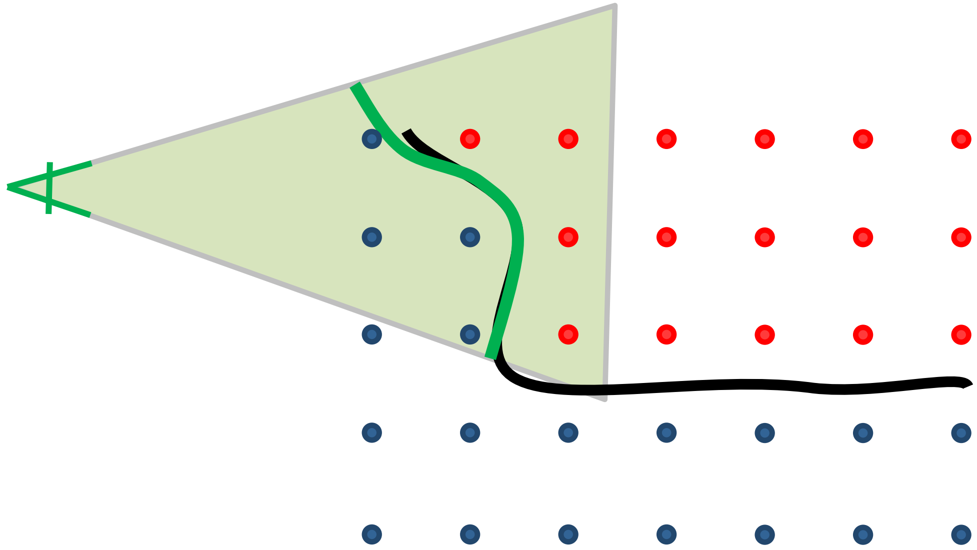

$$\arg\min_{R,\mathbf{t}} \sum_{ij} D(R\mathbf{x}_{ij} + \mathbf{t})^2$$



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# Evaluation on Benchmark

## [Bylow et al., RSS 2013]

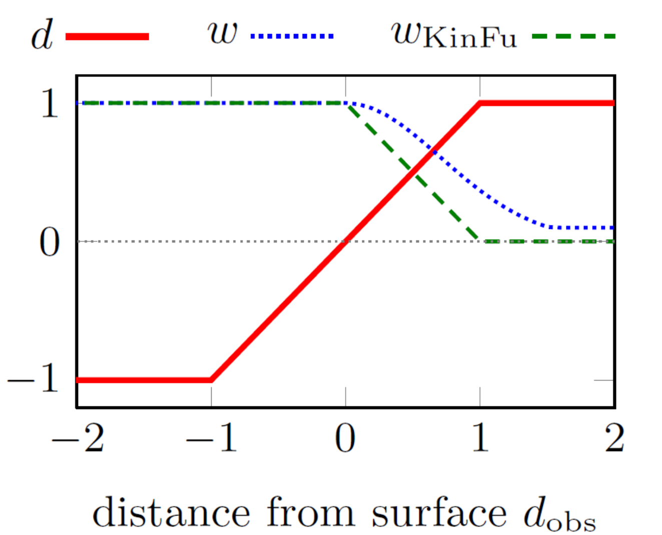
- Thorough evaluation on TUM RGB-D benchmark
- Comparison with KinFu and RGB-D SLAM
- Significantly more accurate and robust than ICP

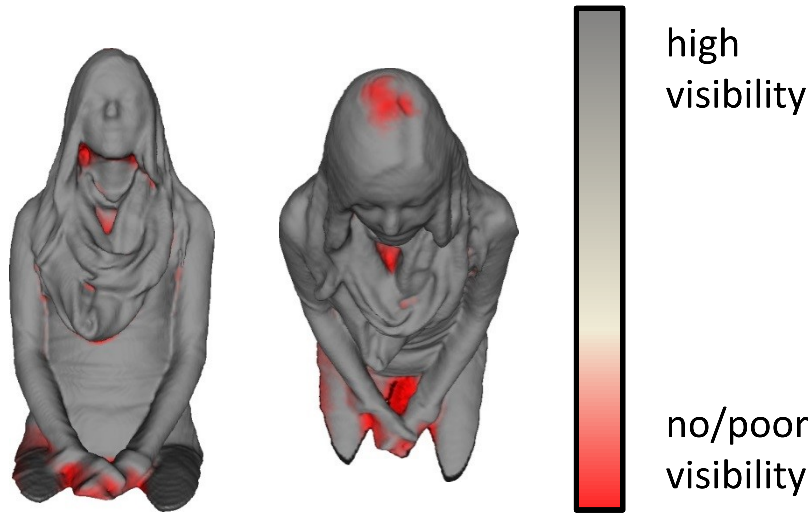
| Algorithm | Resolution | Teddy (RMSE) | Desk (RMSE) | Plant (RMSE) |
|---|---|---|---|---|
| KinFu | 256 | 0.156 m | 0.057m | 0.598 m |
| KinFu | 512 | 0.337 m | 0.068 m | 0.281 m |
| Our | 256 | 0.086 m | 0.038 m | 0.047 m |
| Our | 512 | **0.080 m** | **0.035 m** | **0.043 m** |

# Automatically Close Holes

## [Sturm et al., GCPR ’13]

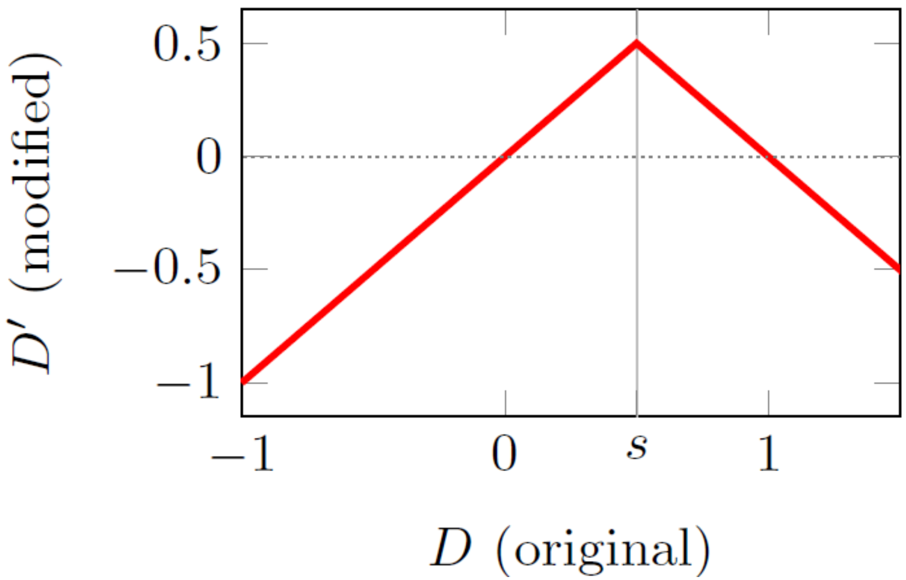
- Certain voxels are never observed in near range
- Regions with no data result in holes
- **Idea:** Truncate weights to positive values



# Hollowing Out
## [Sturm et al., GCPR ’13]

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




before

after

# Video (real-time)
## [Sturm et al., GCPR ’13]



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# Examples of Printed Figures



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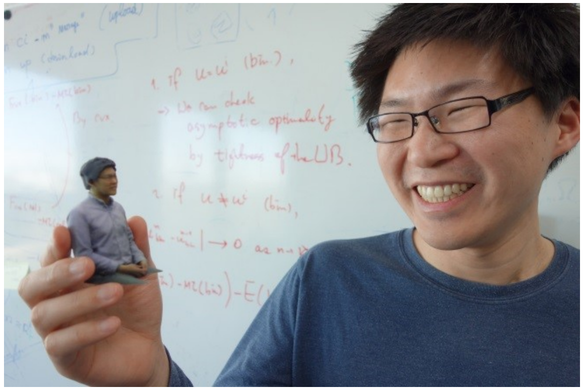
# More Examples



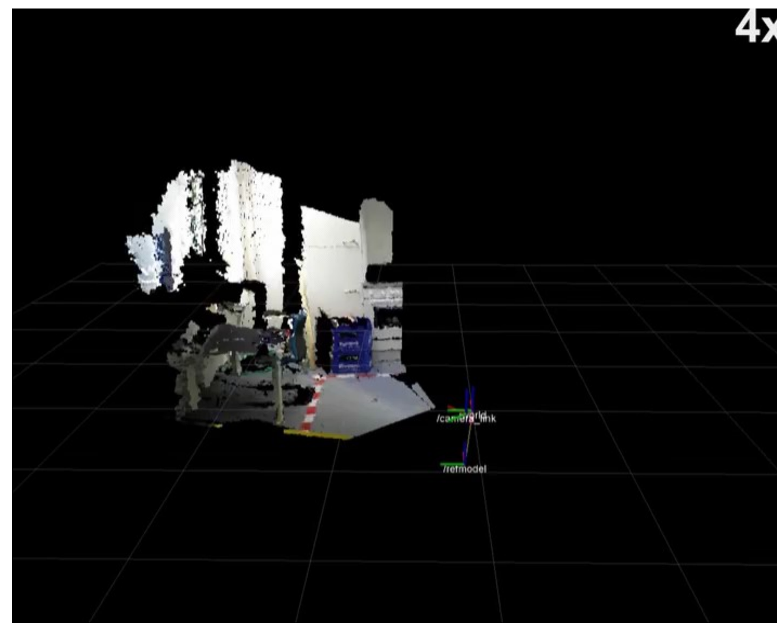

- Need a present?
- **Live Demo after the talk**

# 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 / GPU)


external view




estimated pose



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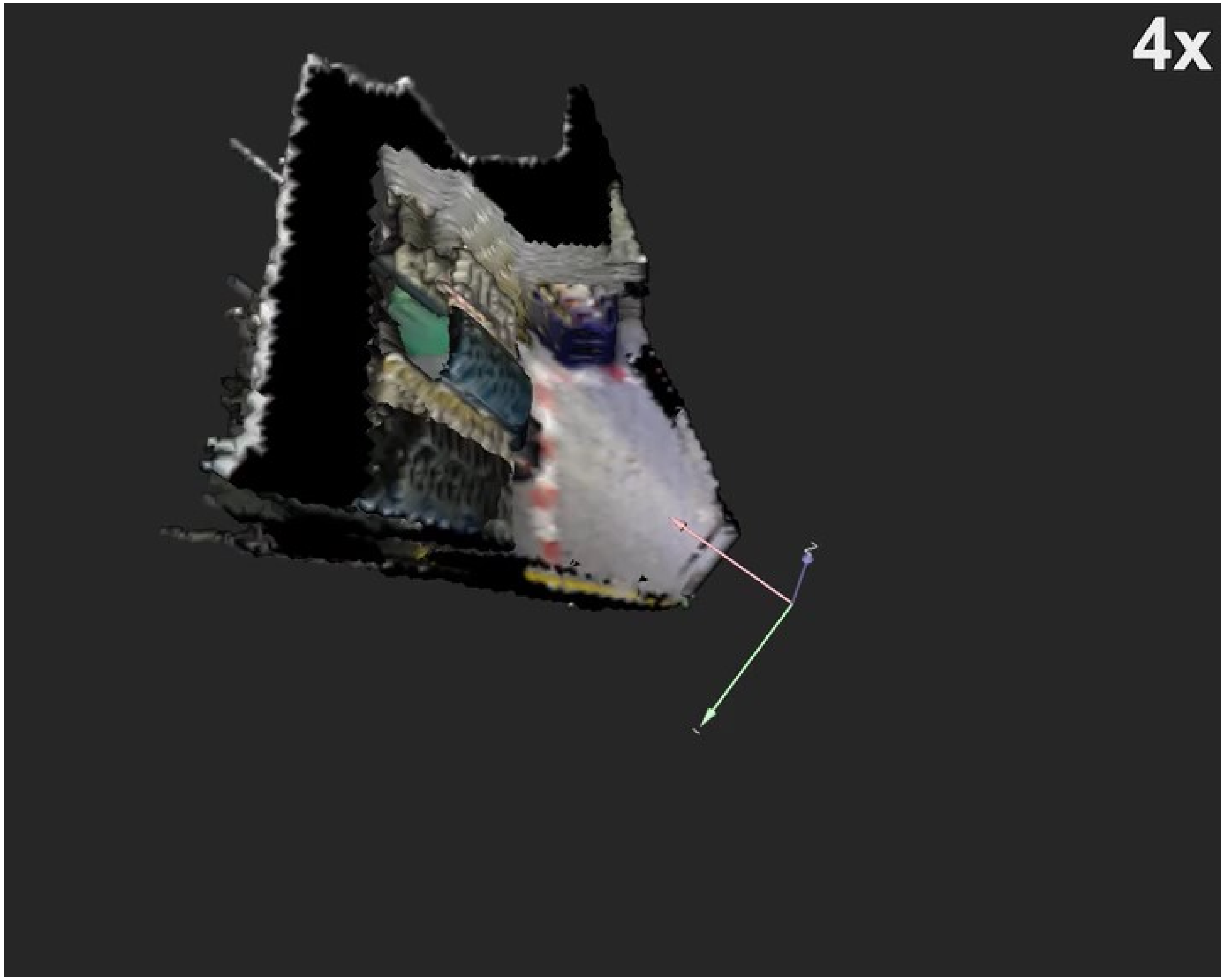
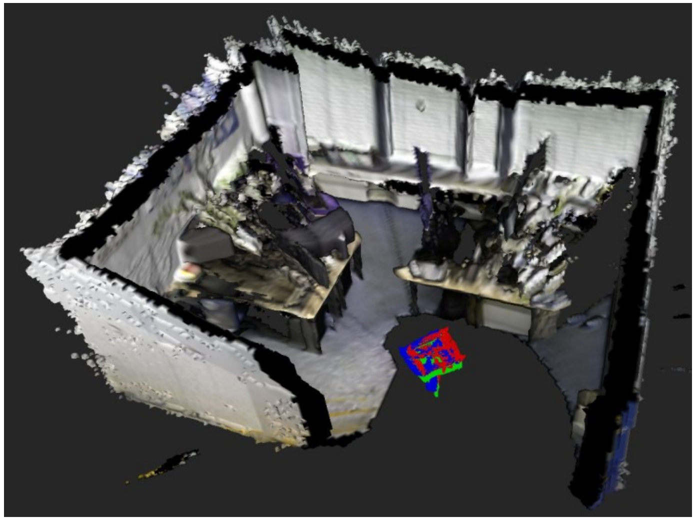
# Resulting 3D Model

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



# More Examples

## [Bylow et al., RSS 2013; Sturm et al., 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?



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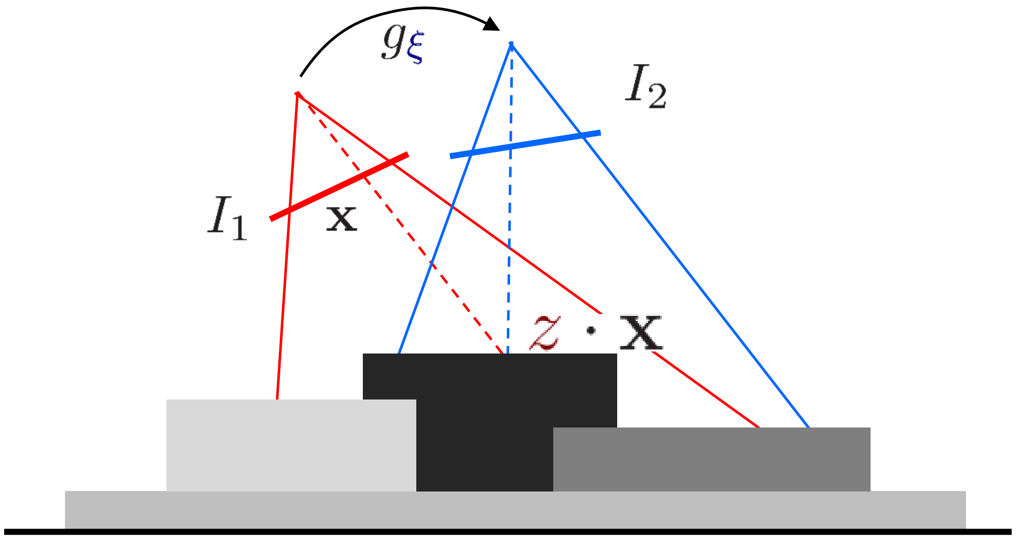
# Dense Visual Odometry

## [Steinbrücker et al., ICCV 2011; Kerl et al., ICRA 2013]

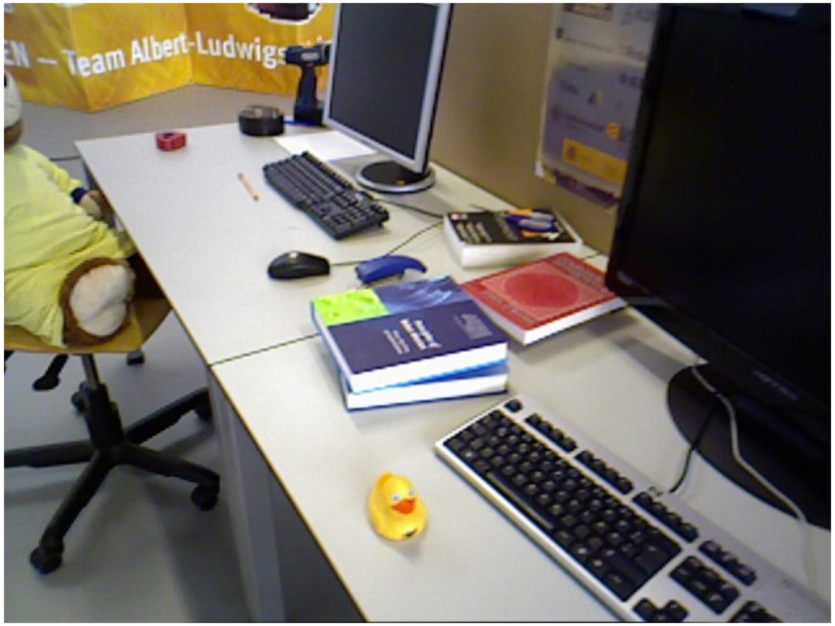
- Can we compute the camera motion directly?
- Idea



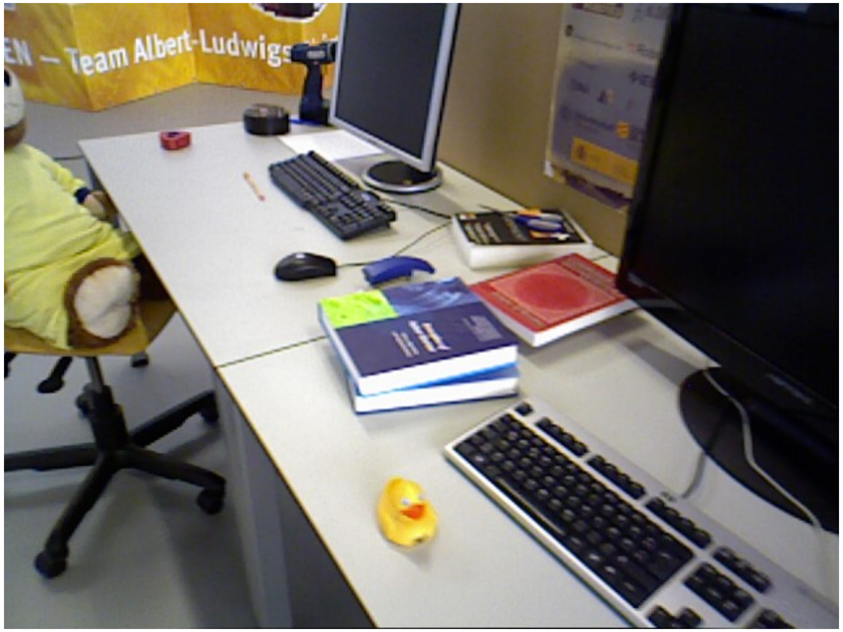

- Photo-consistency constraint

$$I_1(\mathbf{x}) = I_2\left(\pi(g_\xi(z \cdot \mathbf{x}))\right) \text{ for all pixels } \mathbf{x}$$

# Example: Input Images
## [Steinbrücker et al., ICCV 2011; Kerl et al., ICRA 2013]



$I_1$



$I_2$



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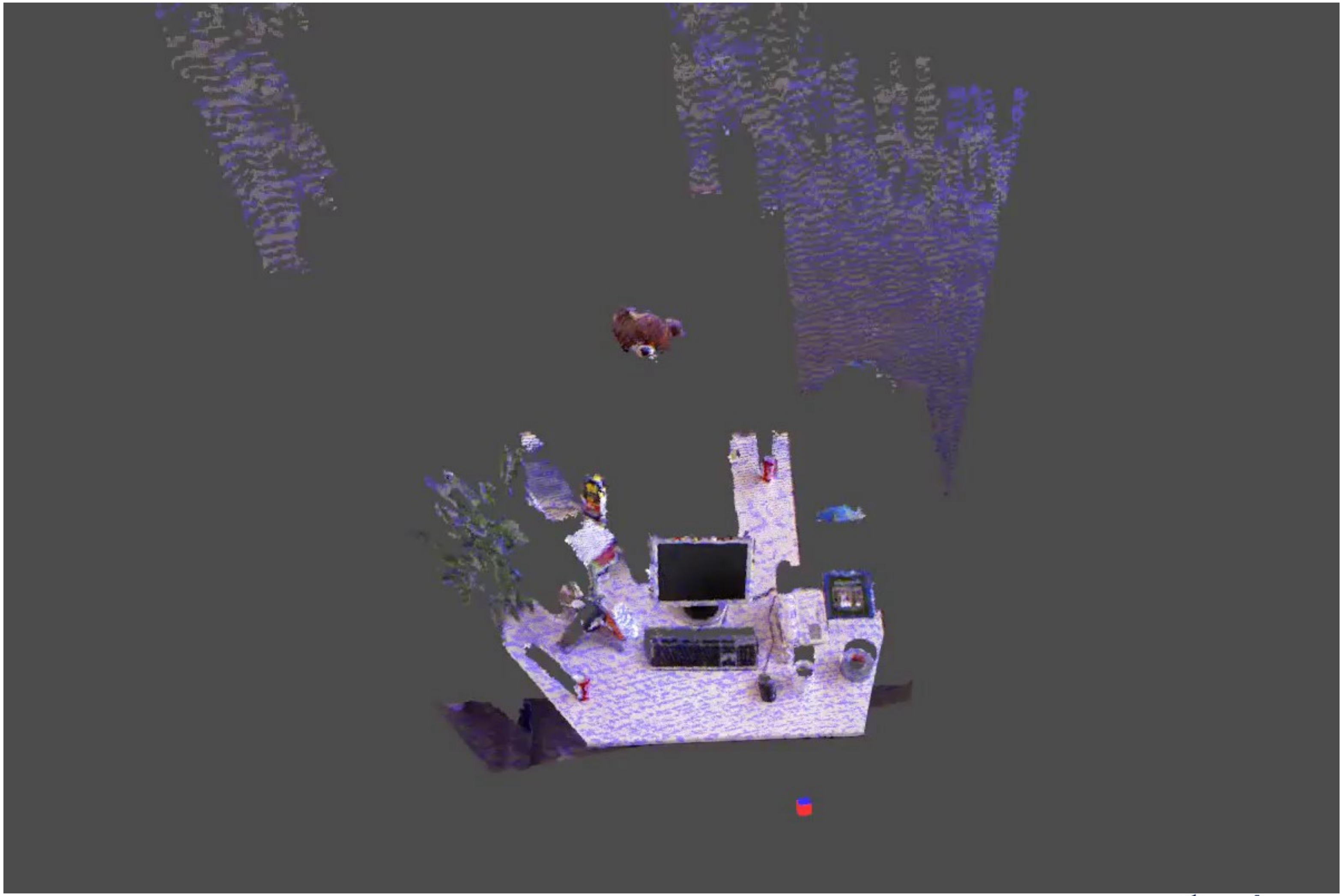
# Example: Residuals
## [Steinbrücker et al., ICCV 2011; Kerl et al., ICRA 2013]

$$I_1(\mathbf{x}) - I_2\left(w(\mathbf{0}, \mathbf{x})\right)$$

$$I_1(\mathbf{x}) - I_2\left(w(\xi^*, \mathbf{x})\right)$$

# Dense Visual Odometry: Results

**[Steinbrücker et al., ICCV 2011]**





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# Dense SLAM

## [Kerl et al., IROS 2013]

- Dense Visual Odometry
  - Input: Two RGB-D frames
  - Output: Relative pose
  - Runs in real-time on single CPU core
- Use this in pose graph SLAM
  - Select keyframes
  - Detect loop-closures
  - Build and optimize pose graph (using g2o)

# Results: 3D Pose Graph

## [Kerl et al., IROS 2013]




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# High-Quality 3D Reconstruction
## [Steinbrücker et al., 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
  - …



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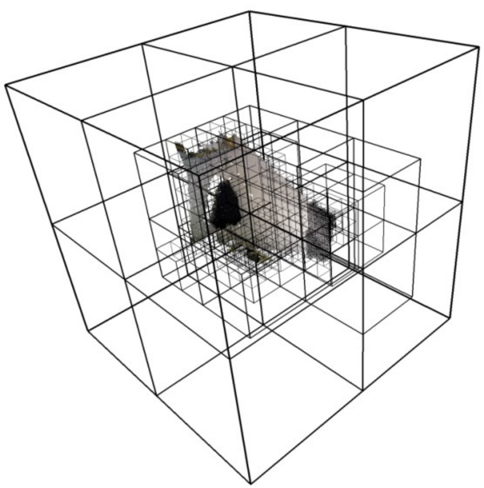
# High-Resolution 3D Reconstruction

**[Steinbrücker et al., ICCV 2013]**

- Save data in oct-tree data structure
- Leaves are only allocated when needed
- Store geometry at multiple resolutions
- Tree can grow dynamically (no fixed size)





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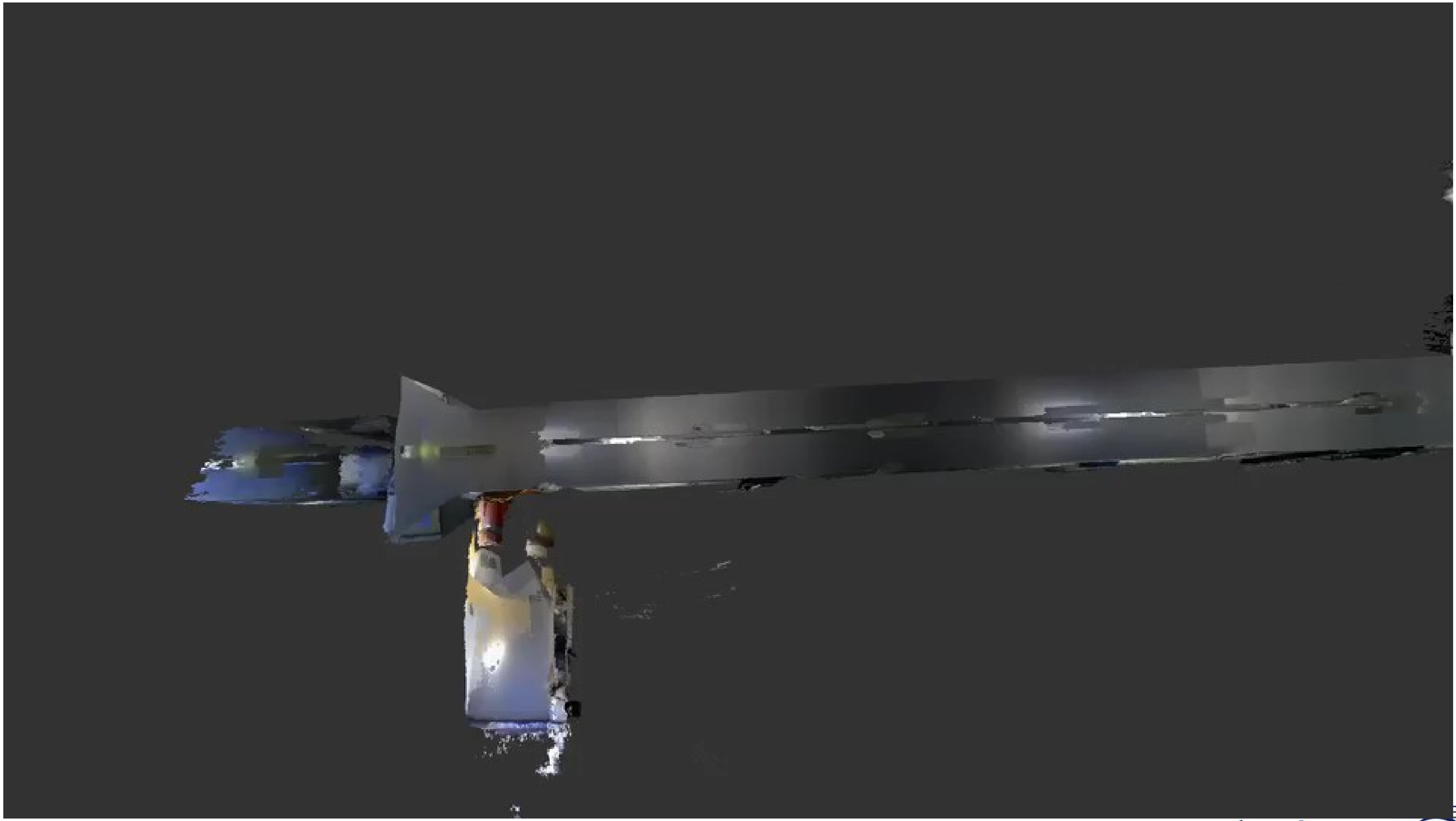
# Large-Scale 3D Reconstruction

## [Steinbrücker et al., ICCV 2013]



# CPU-based 3D Reconstruction

## [Steinbrücker et al., ICRA 2014]

# Can we do the same with a monocular camera? [Engel et al., ICCV 2013]

# Conclusion

- Scan and print persons in 3D
- Dense visual odometry and SLAM
- 3D reconstruction of large-scale environments
- Real-time processing, real-world data
- 3D printing technology enables exciting applications