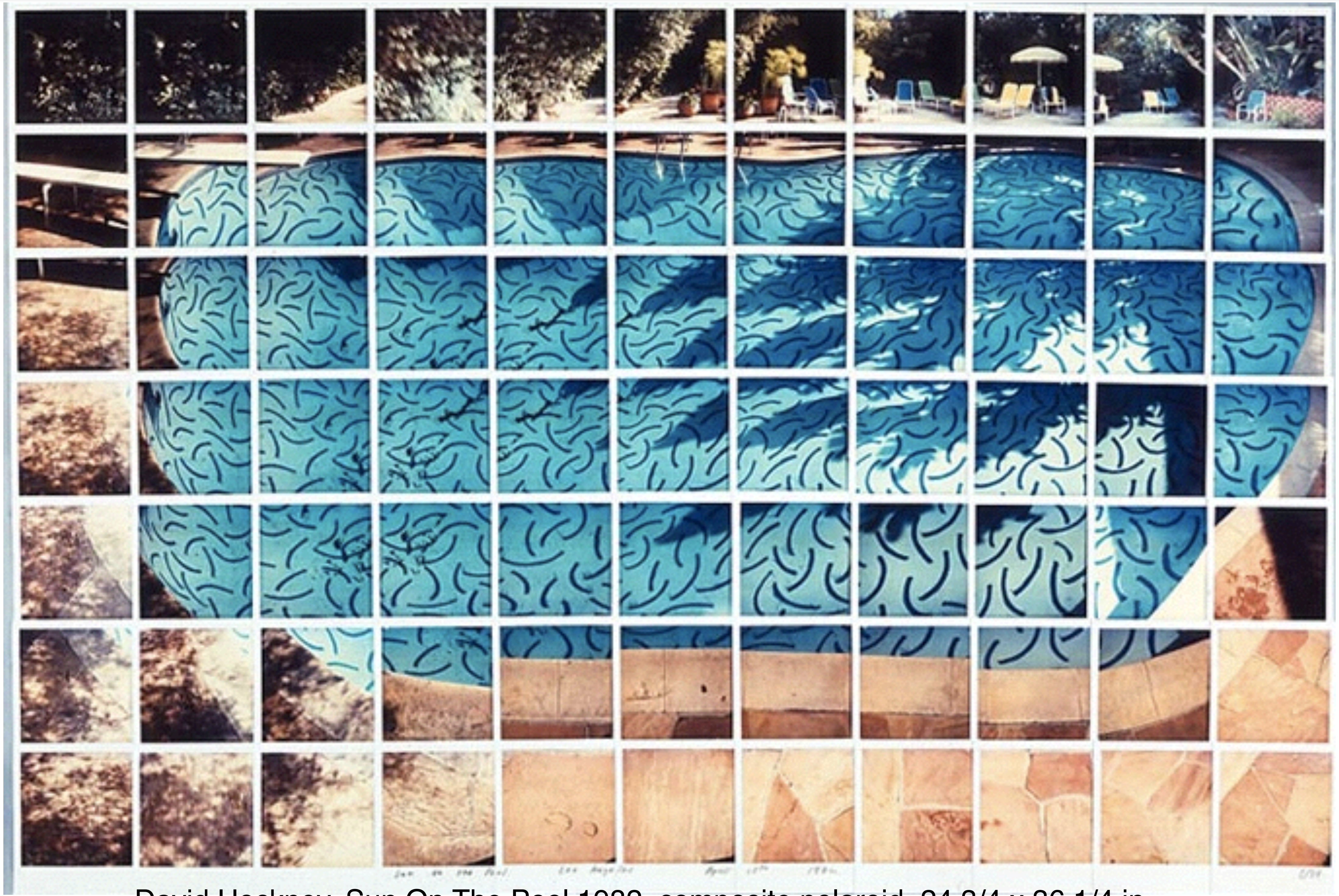
International Time-of-Flight Workshop, 10.03.2014

Algorithmic Enhancement and Validation of Time-of-Flight Imaging

Christoph Garbe, Jens-Malte Gottfried, Daniel Kondermann, Frank Lenzen, Stephan Meister, Rahul Nair and Henrik Schäfer

Image Processing and Modeling
Interdisciplinary Center for Scientific Computing
University of Heidelberg

Combining local and global models



David Hockney, Sun On The Pool 1982, composite polaroid, 24 3/4 x 36 1/4 in

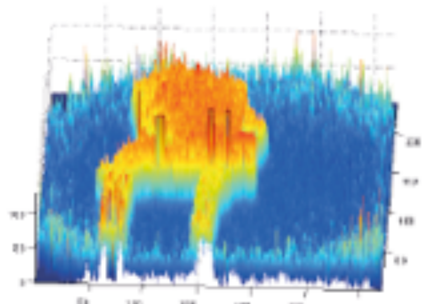
Project Overview

Data Acquisition

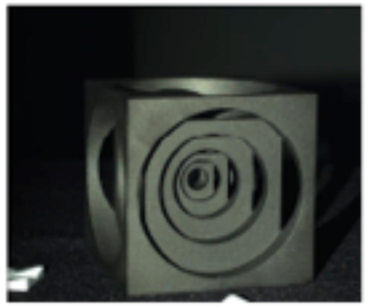
- Time of Flight (ToF)
- Microsoft Kinect
- Plenoptic Camera

- Calibration
- Preprocessing

- Synthetic (Rendered)


Noisy Depth Data

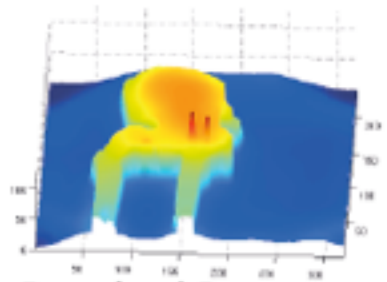

Recorded Gestures


Real Scene

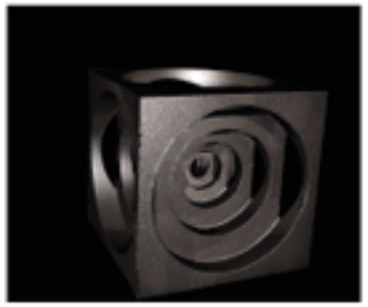
Theme 1: Enhancement

Theme 2: Analysis

Theme 3: Evaluation


Denoised Data


Feature Extraction


Synthetic Scene

Applications

- Accurate 3D Measurements
- Gesture Recognition
- Validation of Realistic Scene Rendering

Theme 3: Evaluation

Data Acquisition

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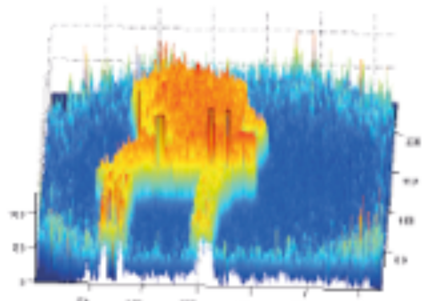

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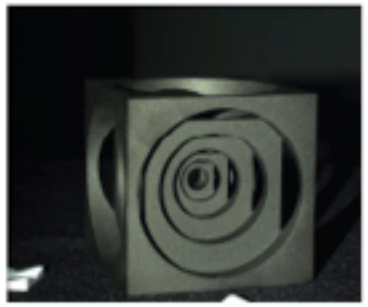

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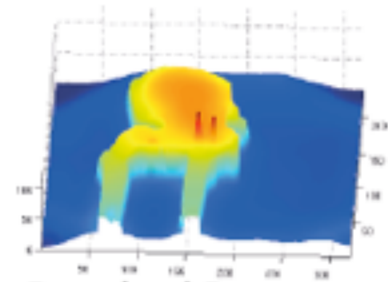

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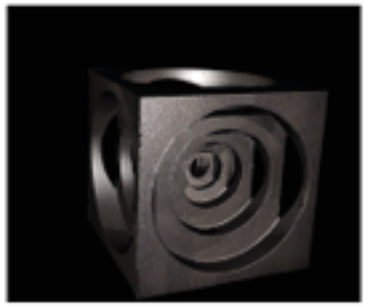

Synthetic Scene

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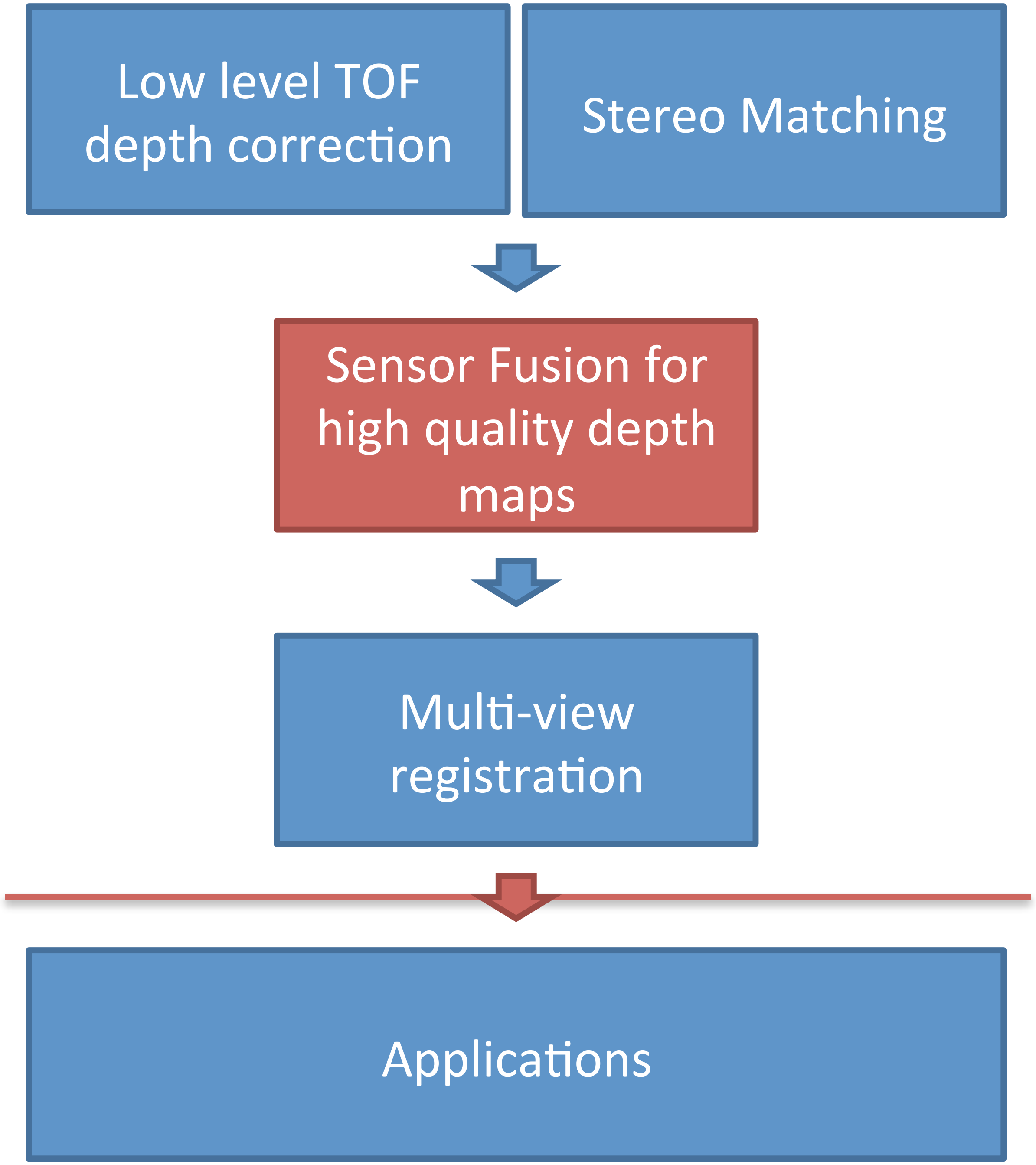
Time of Flight (ToF) Sensor

- active modulated illumination
- 200 x 200 pixels
- 8 images per shot at 4 different phase shifts
- suppression of background illumination
- phase shift ϕ (distance) and intensity image A (amplitude)

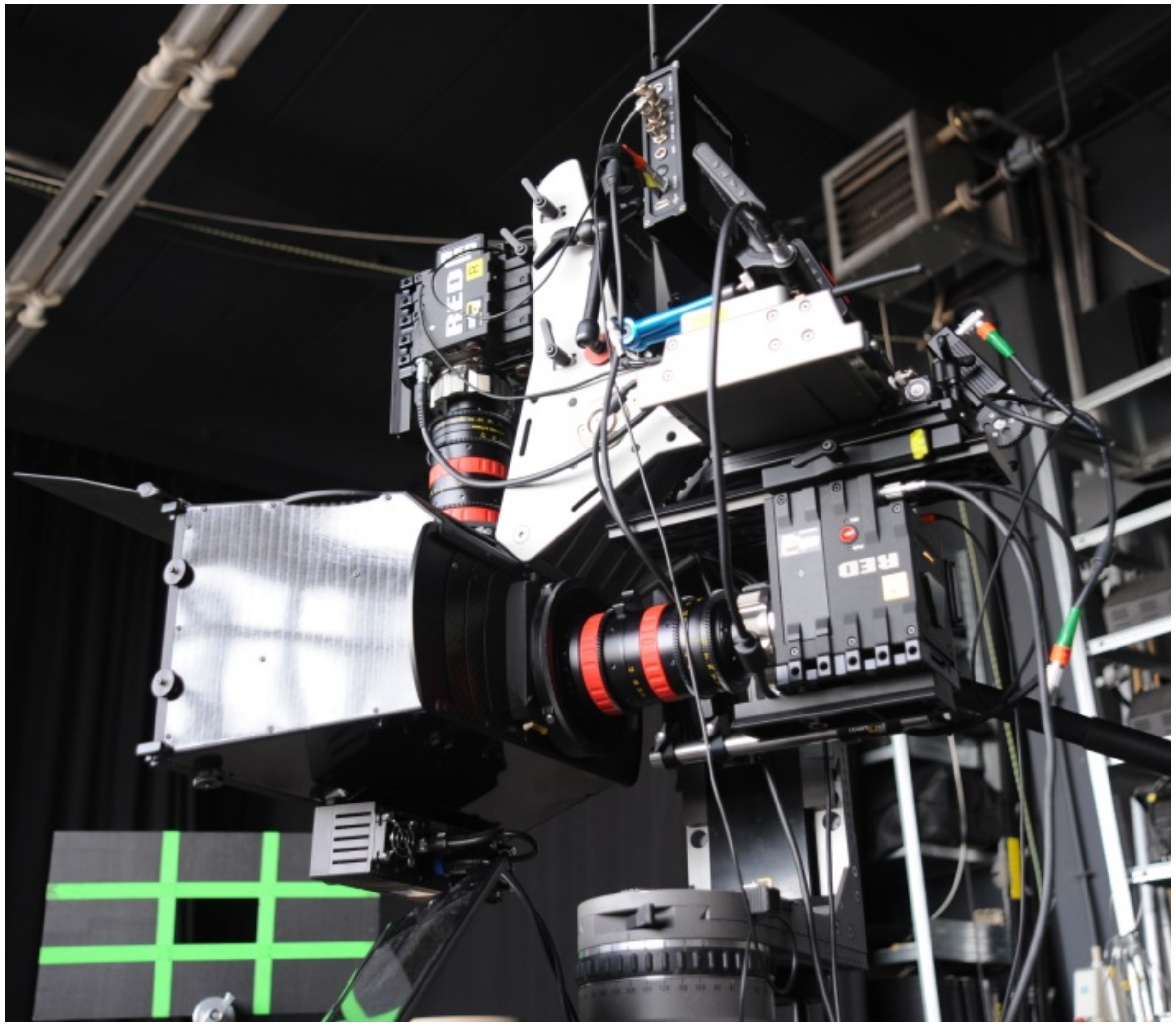
Combining Stereo and ToF

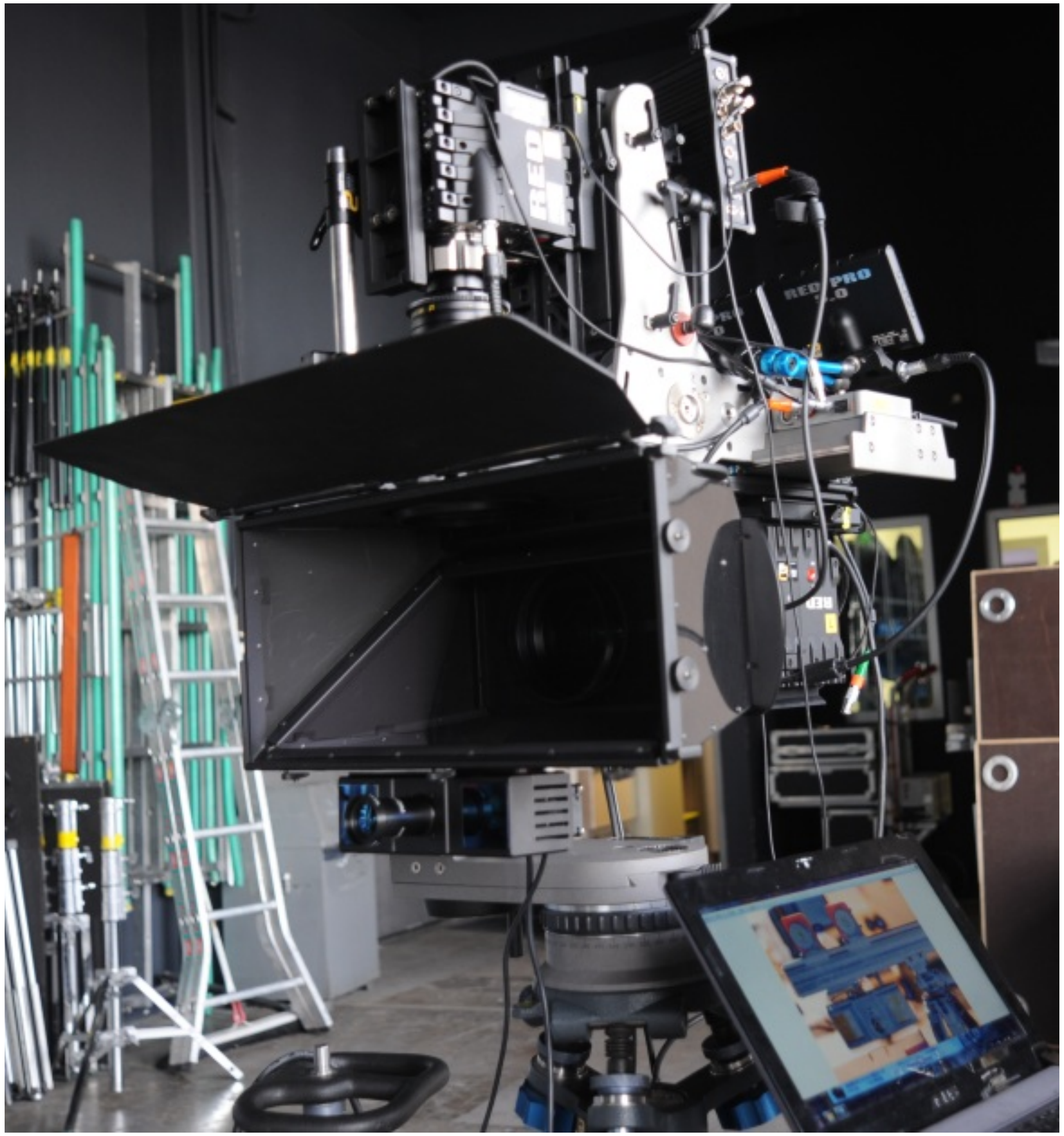
- Gray-value Cameras @1.3 K
- TOF Camera with 200 x 200 pixels.



The scaled-up version

- 11 sequences with a production rig @ 4k & 30 fps from Screen Plane



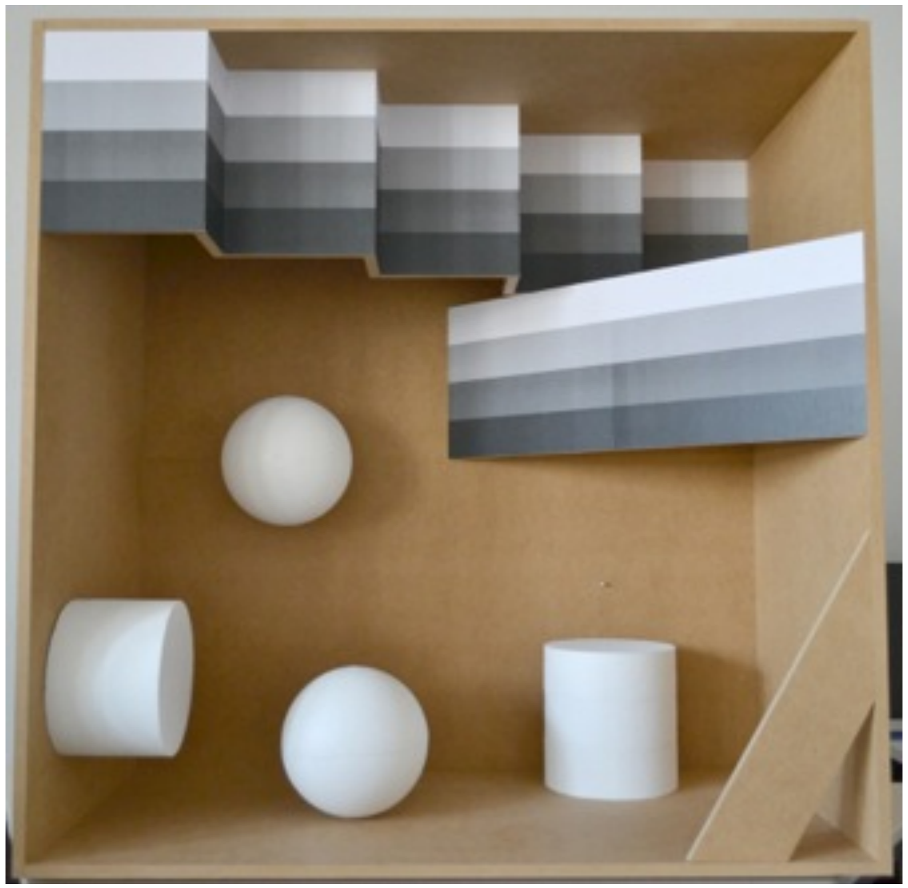


Ground Truth (Real Scene)

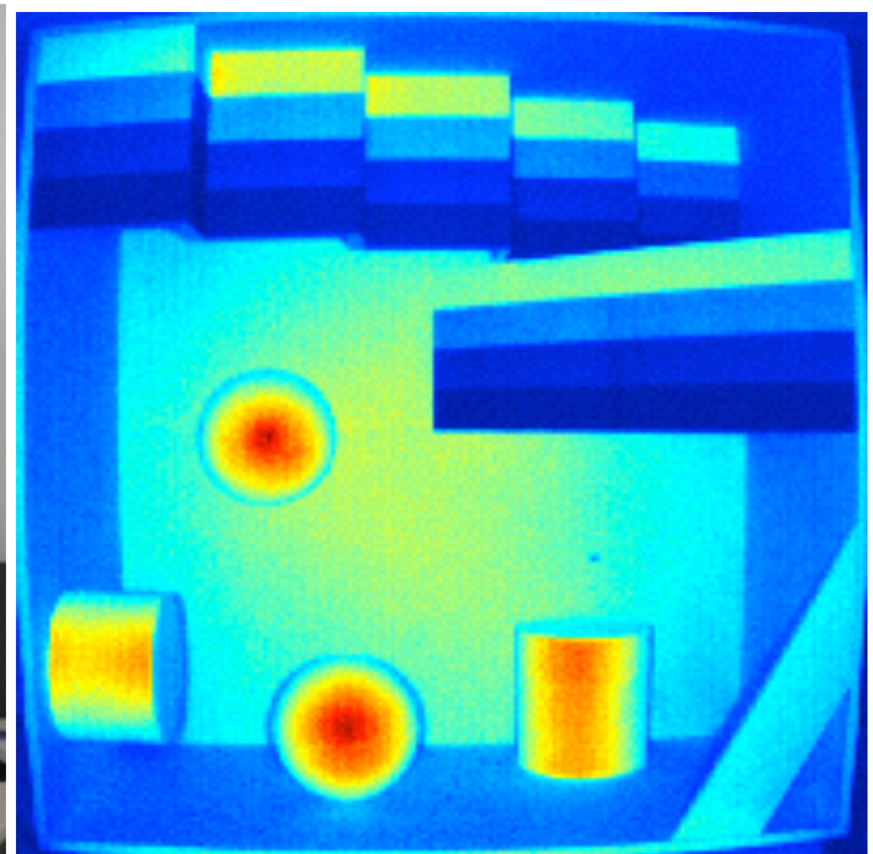
Approach

- Created test dataset with object of known geometry (HCI Box)
  - Precision measurement of depicted object (< 1mm)
  - Supply 3D polygon mesh in commonly used data formats
  - Recorded sequences with calibrated camera and known camera pose
- More at: http://hci.iwr.uni-heidelberg.de/Benchmarks/document/hcibox/

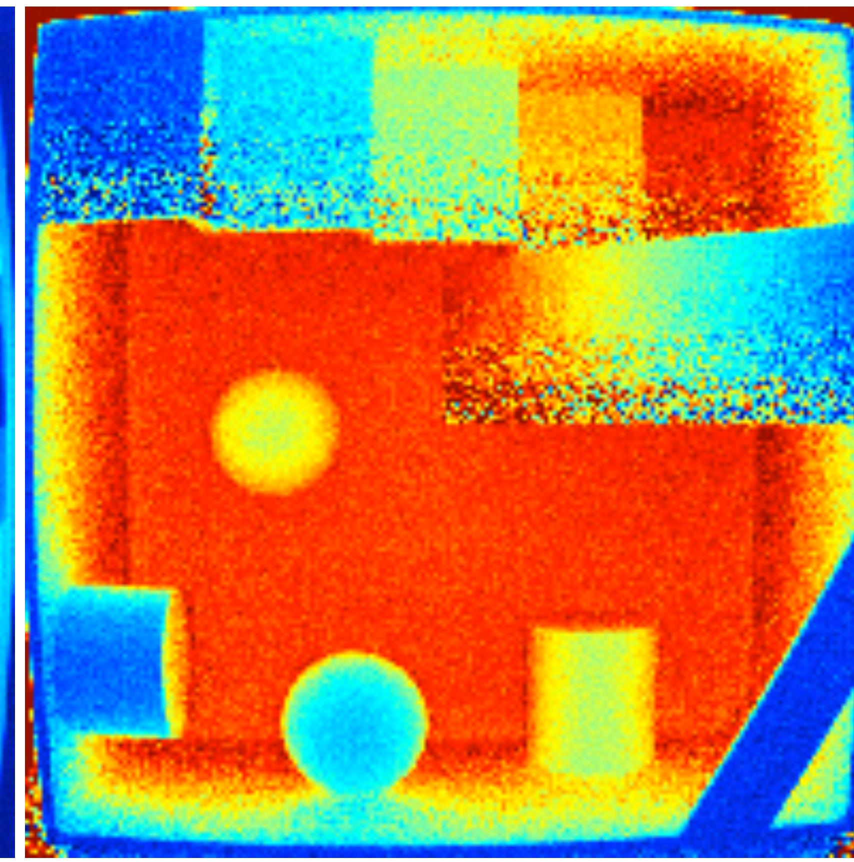
Ground Truth Data



RGB

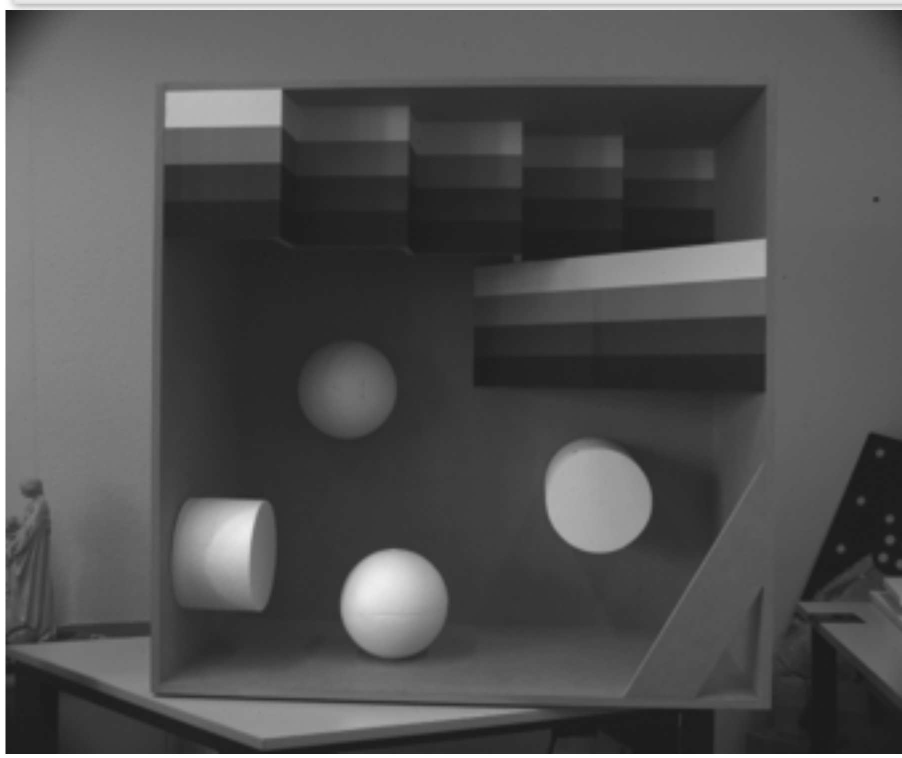


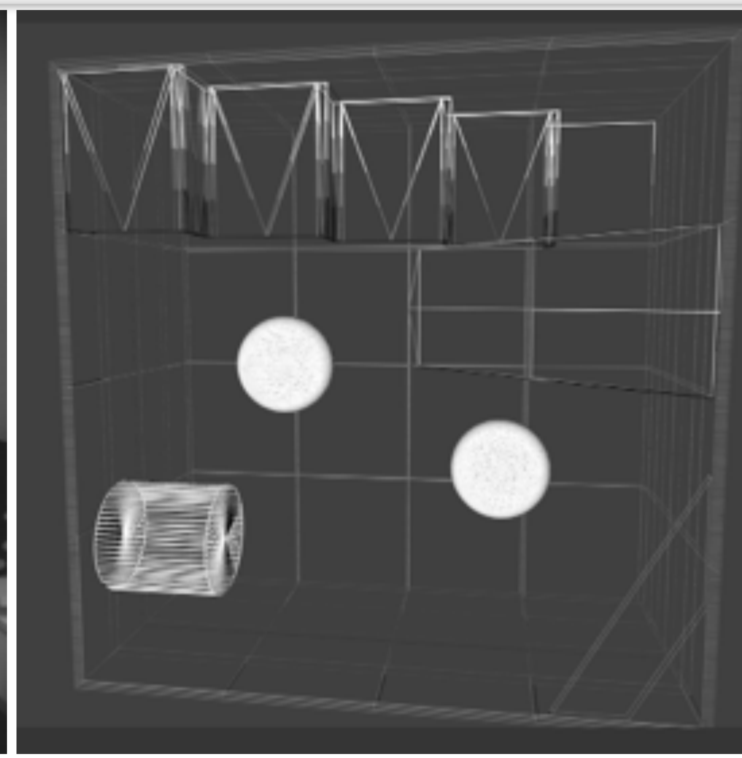
Amplitude

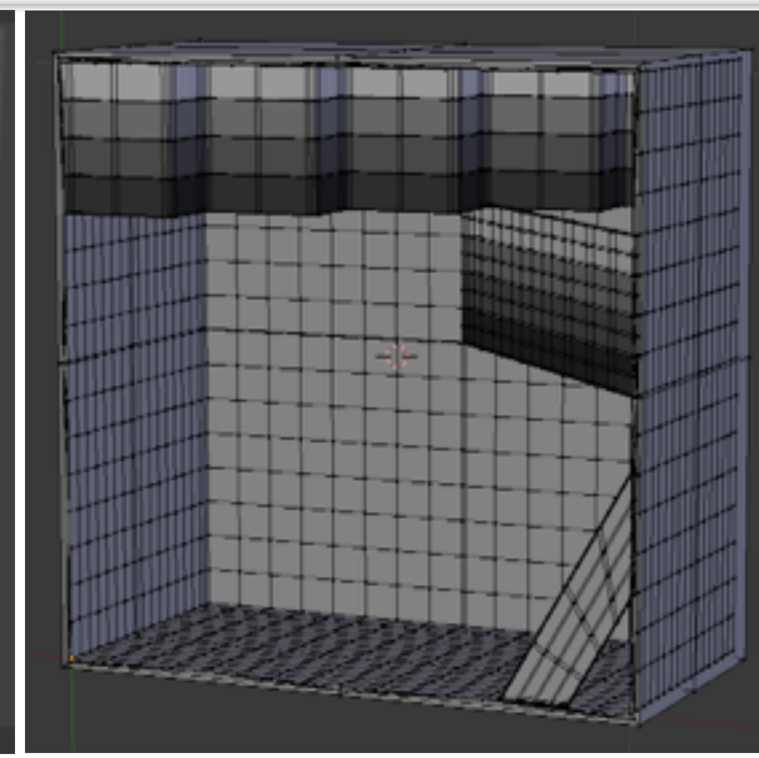


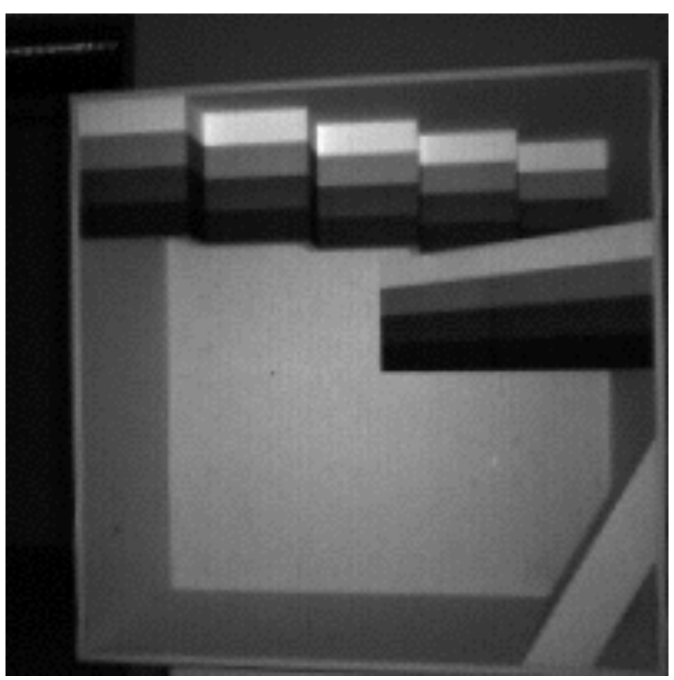
Depth

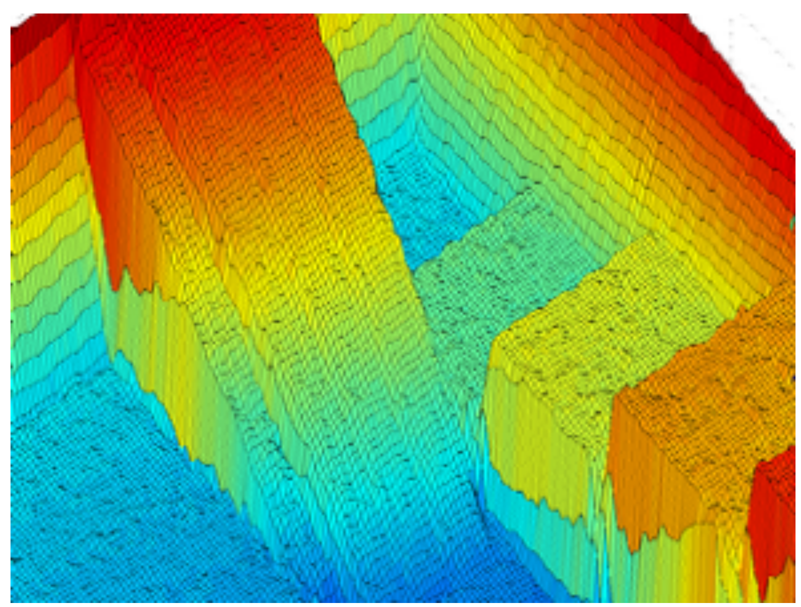
The HCI-Box

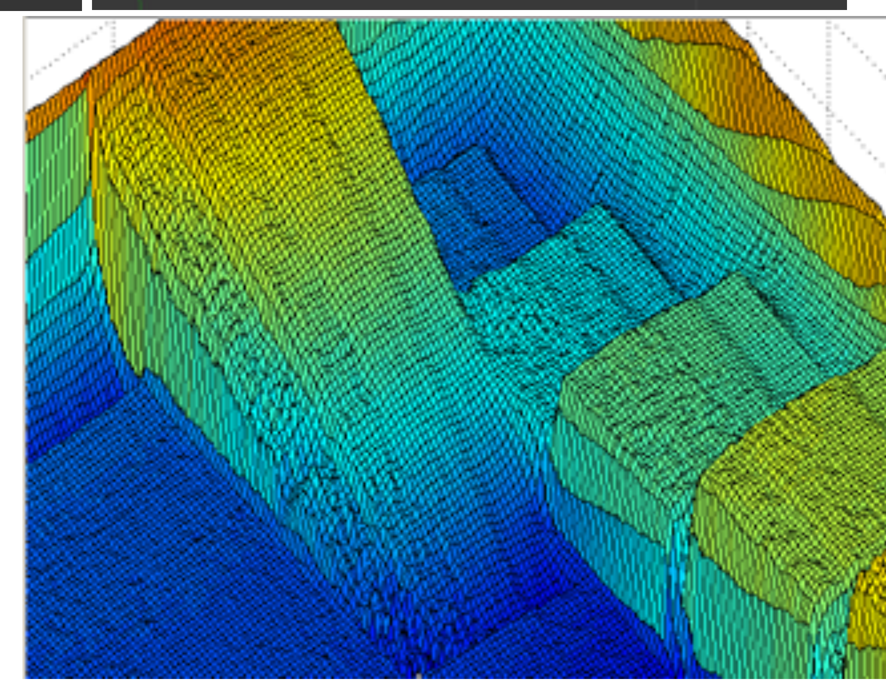












Ground Truth (Synthetic Scene)

Approach

- Physically correct simulation of ToF output
  - simulate correct light propagation using path tracing methods
  - consider multipath and material dependent effects
  - correct simulation of motion artifacts by handling of subframes
- Details at http://hci.iwr.uni-heidelberg.de/Benchmarks/document/tof_bidirpathtracer/

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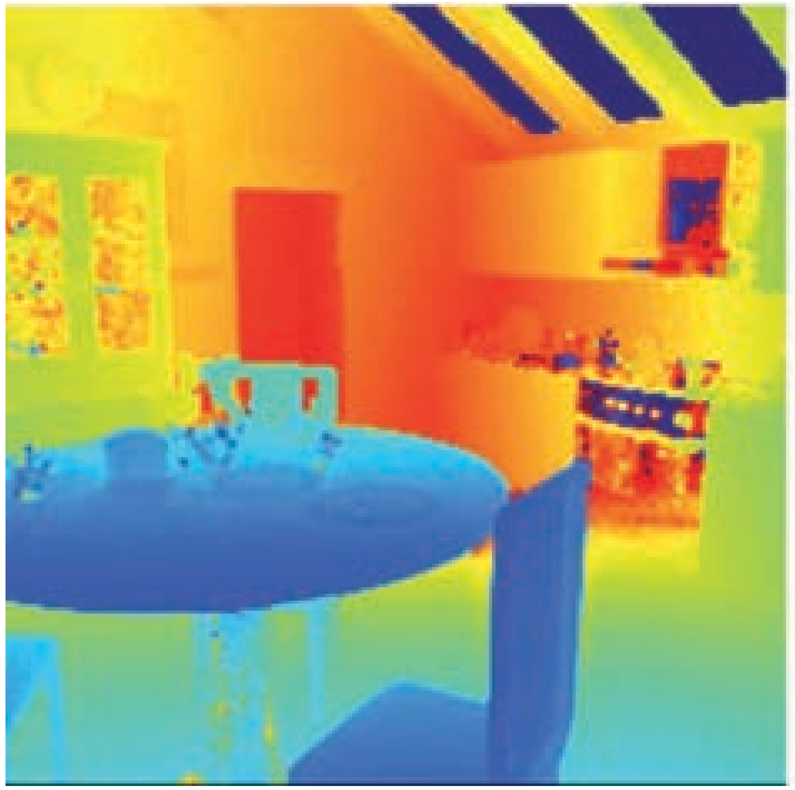

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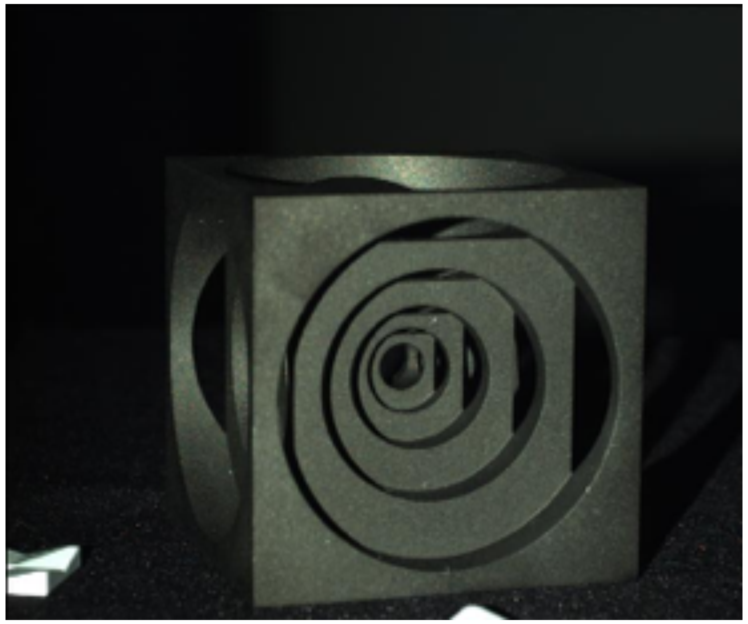
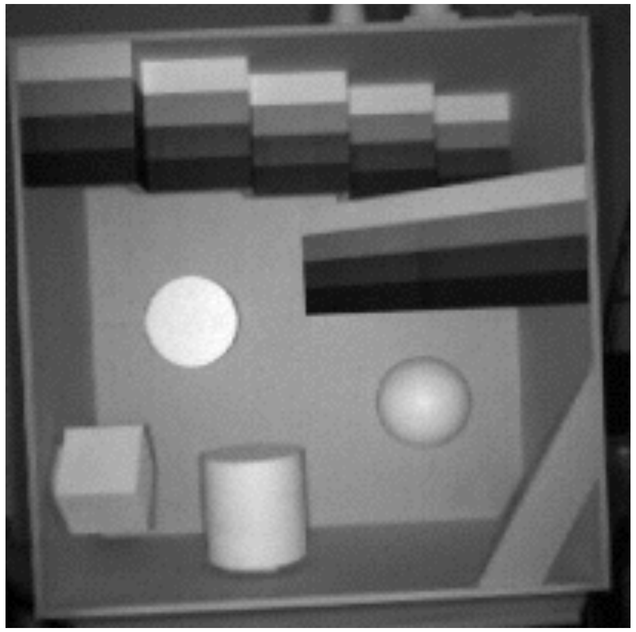
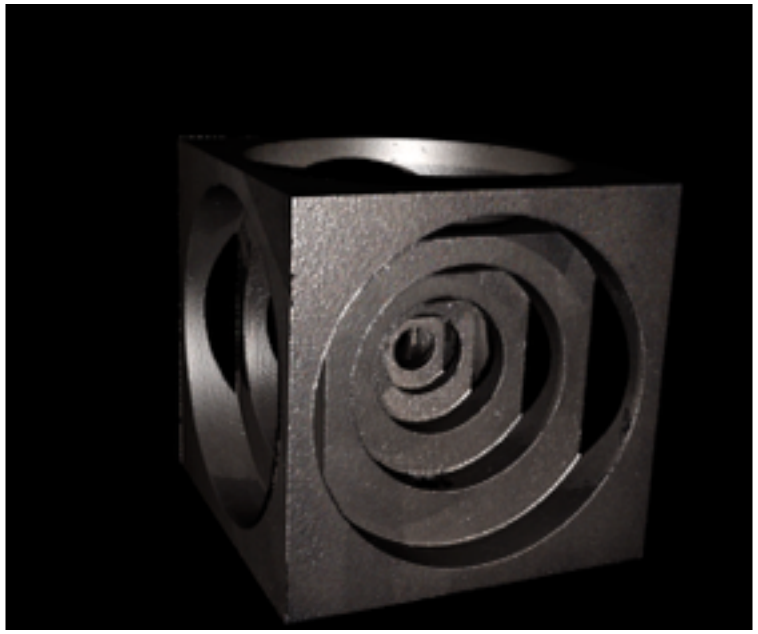
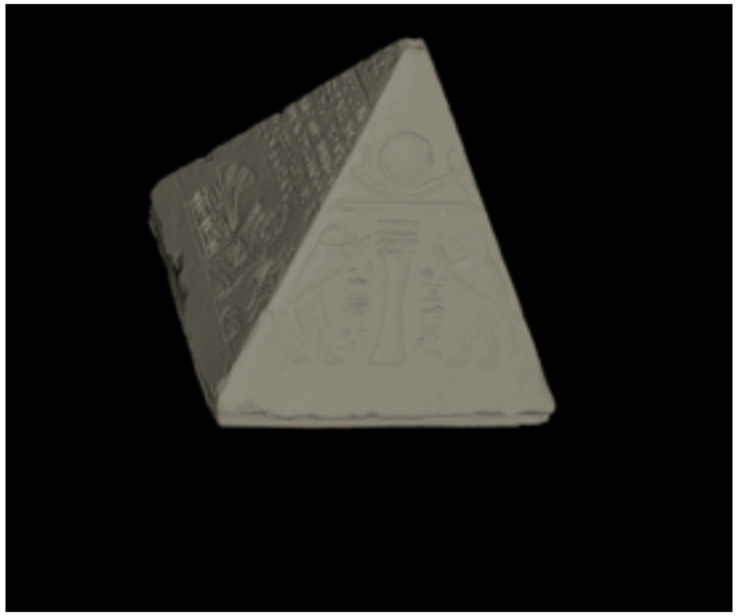
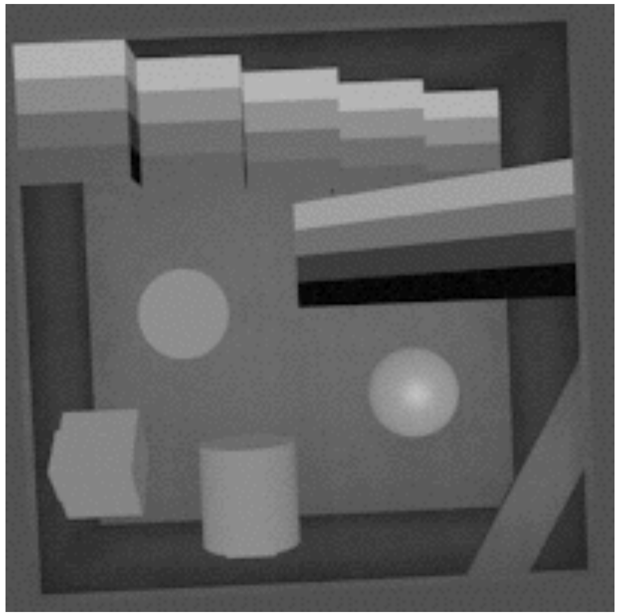
Real vs Synthetic

Real





Synthetic

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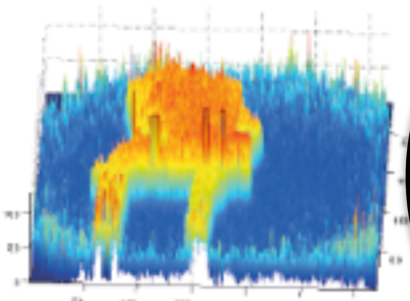

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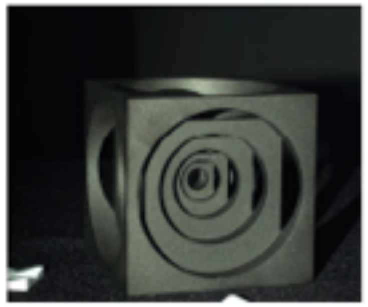

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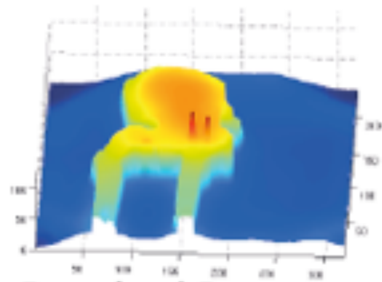

Denoised Data

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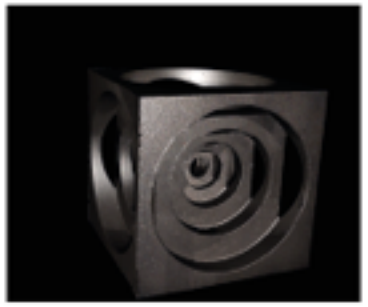

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Denoising ToF Data

- Goal: remove noise contained in ToF data
- Advantage: accurate depth measurement at low SNR
  - objects with low reflectivity
  - higher depth ranges

Denoising strategies

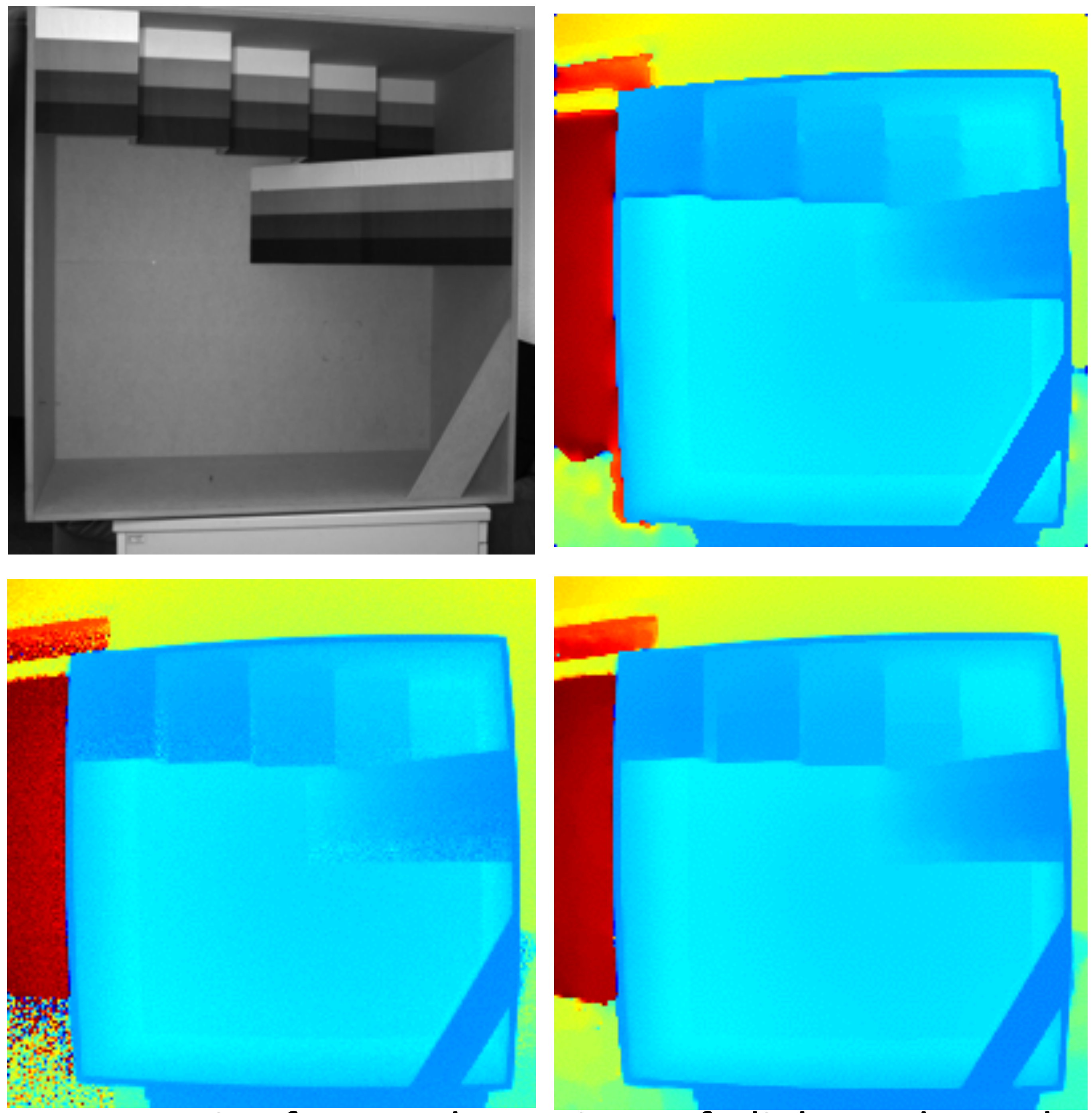
- We investigated several denoising strategies for ToF at different stages, e.g.
  - Earliest stage : denoise four raw images by bilateral filtering
  - Intermediate data: Denoising complex-valued data
  - Latest stage: denoise depth map with anisotropic second order total variation (TV)

Lenzen et al, Denoising Strategies for ToF data, Time-of-Flight and Depth Imaging: Sensors, Algorithms, and Applications, Springer, 2013, DOI: 10.1007/978-3-642-44964-2_2

Denoising strategies

Scene

Bilateral + Median on raw data



Raw Depth

Higher order TV on depth data

Lenzen et al, Denoising Strategies for ToF data, Time-of-Flight and Depth Imaging: Sensors, Algorithms, and Applications, Springer, 2013, DOI: 10.1007/978-3-642-44964-2_2

Favoured denoising approach

1. Stage: edge detection
   – multimodal edge detection
   – suppress artefacts of ToF device
2. Stage: adaptive, anisotropic denoising
   – no smoothing across object boundaries
   – smooth image gradients

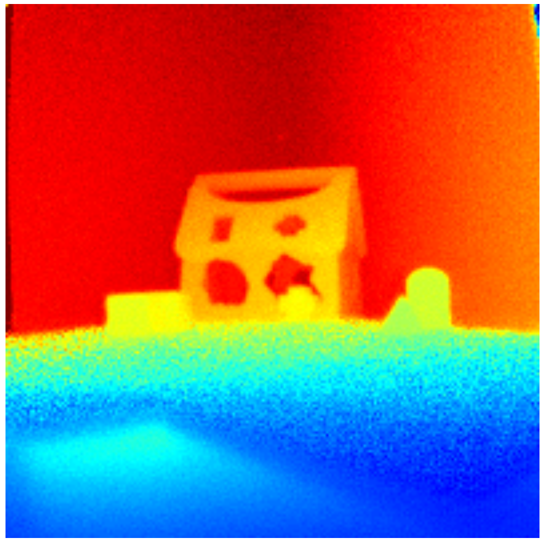
Favoured denoising approach

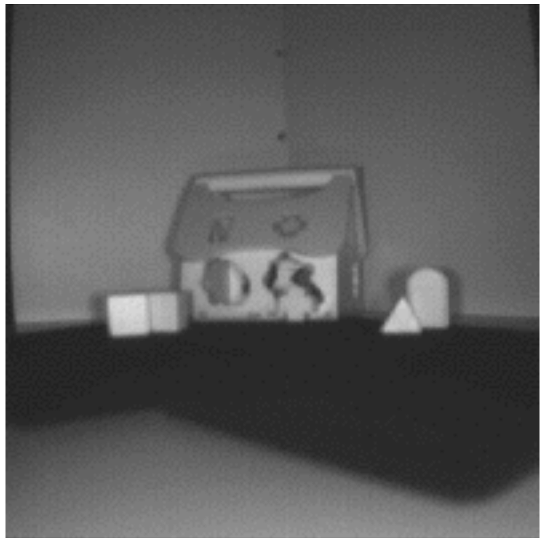
1. Stage: Edge Detection

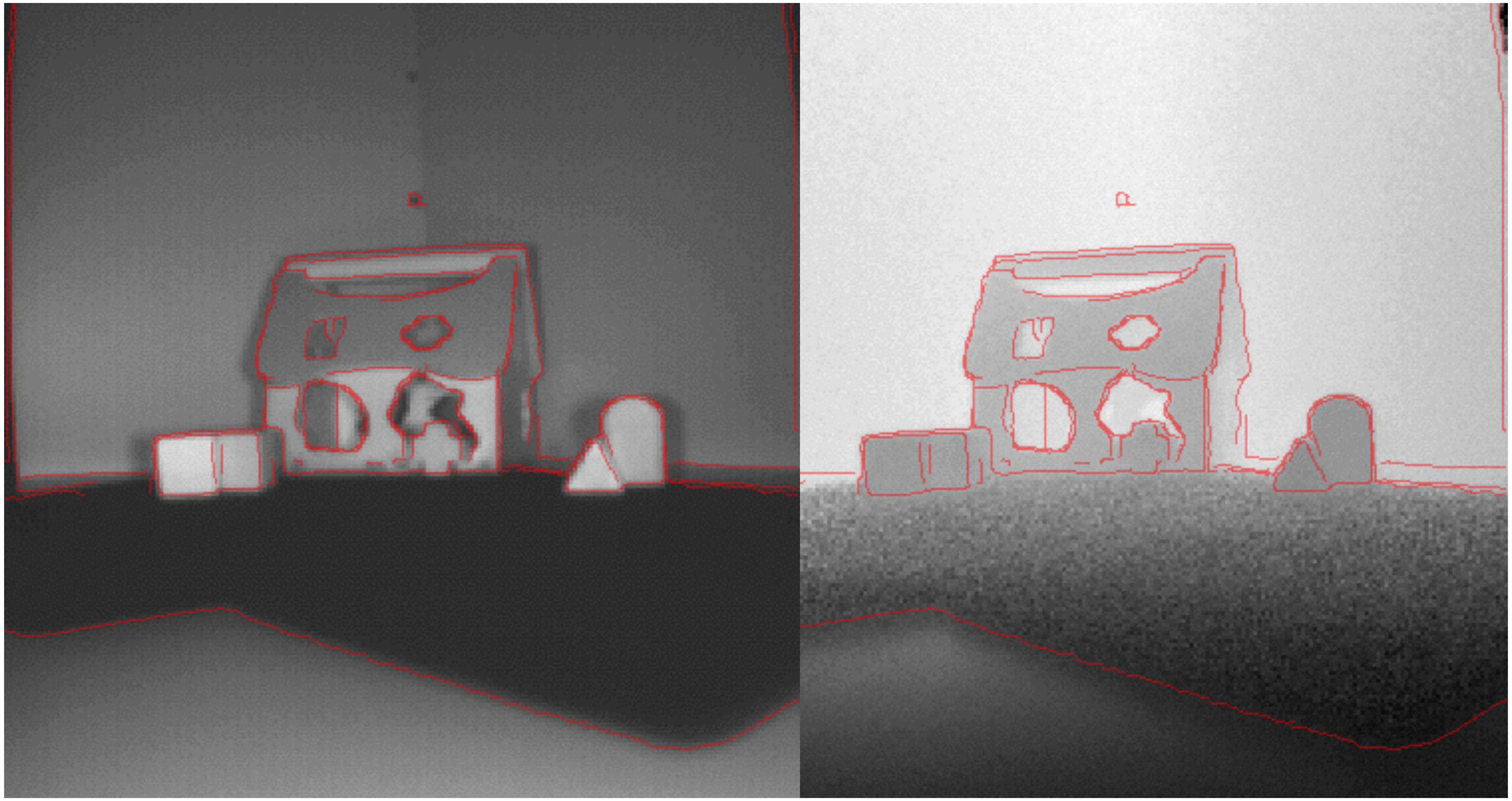
- Find edges in depth and intensity data
- Remove texture edges
- Identify shadow casting depth edges along with shadows (intensity edges)
- Remove the later while keeping the former
- Determine edge normals

Favoured denoising approach

Edge Detection



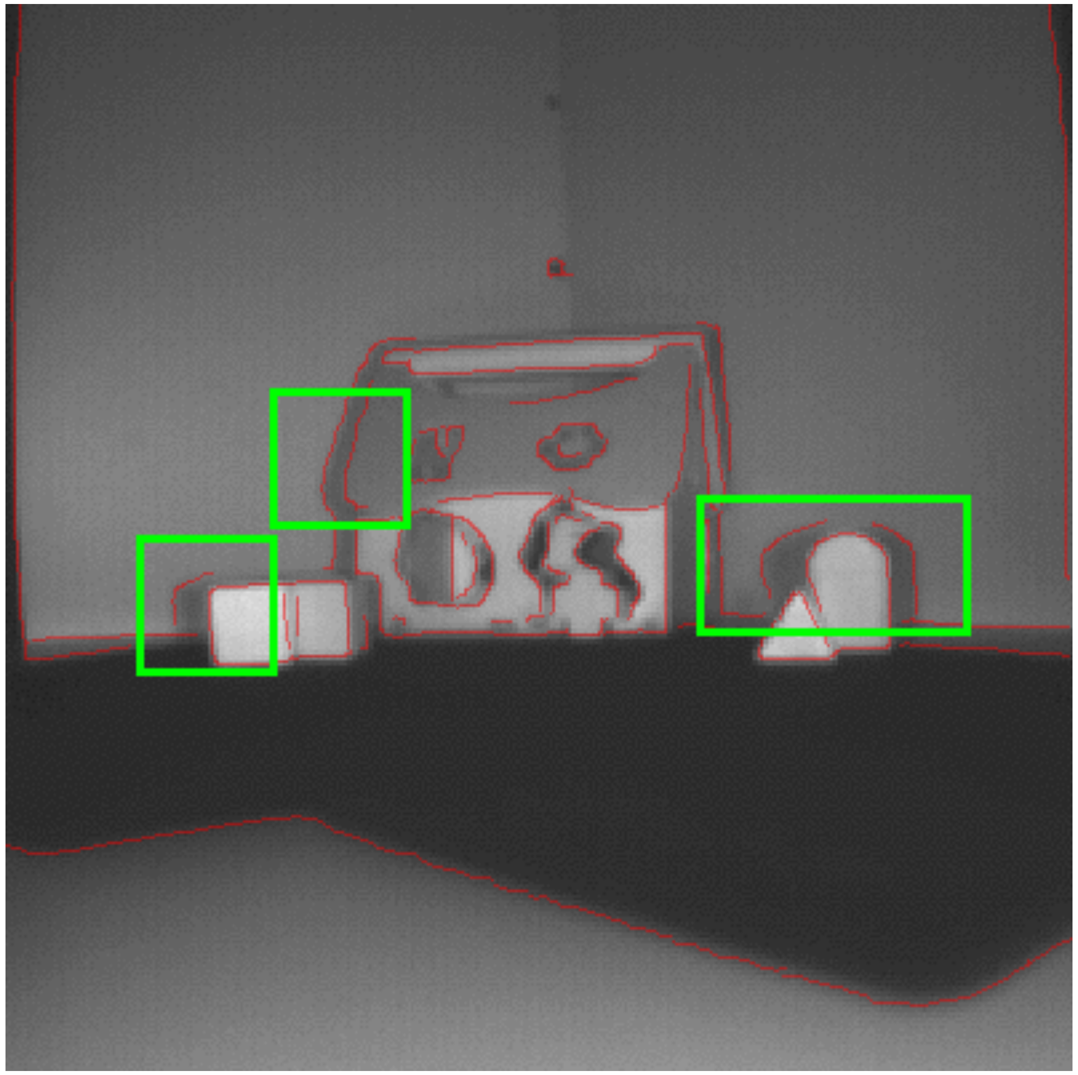


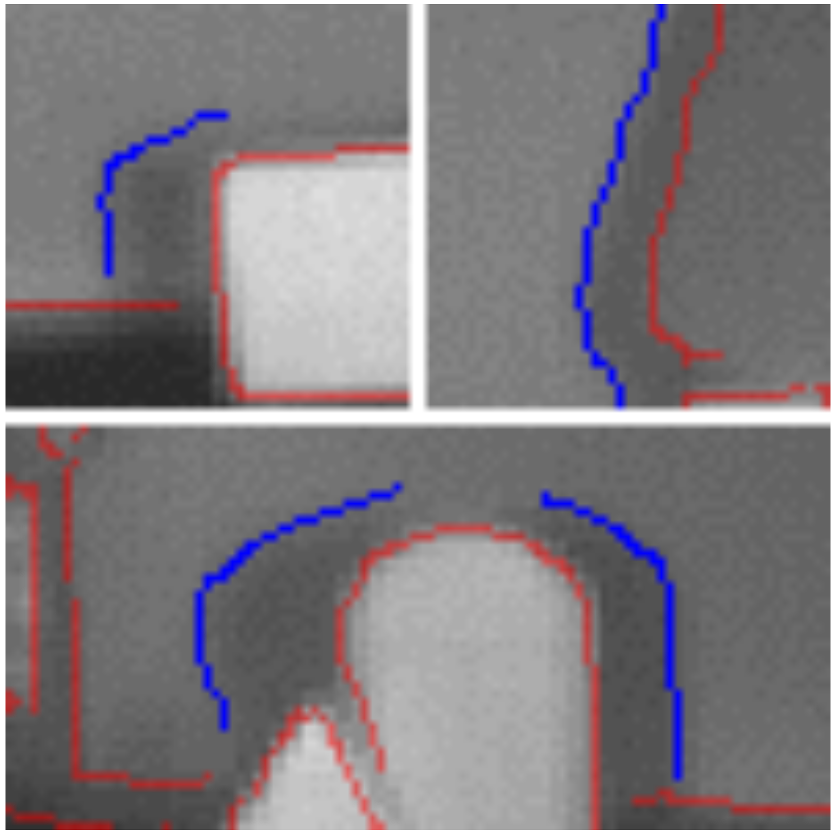


Schäfer, H. and Lenzen, F. and Garbe, C.S., Depth and Intensity Based Edge Detection in Time-of-Flight Images, 3DTV-Conference, IEEE, pp. 111-118. 2013. DOI: 10.1109/3DV.2013.23

Favoured denoising approach

Edge Detection





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Favoured denoising approach

2. Stage: Denoising

- Use anisotropic second order total variation (penalizing L1-norm of image gradient)
- Adapt to the local noise level (amplitude-dependent)
- Reduce smoothing across edges, smooth mainly parallel to edges.
- Second order reduces stair-casing (typical for first order TV)

Lenzen, F. and Schäfer, H. and Garbe, C.S., Denoising Time-Of-Flight Data with Adaptive Total Variation, Advances in Visual Computing, LNCS 6938, pp. 337-346. 2011.
DOI: 10.1007/978-3-642-24028-7_31

The model formulation

variational approach
$$\min_{u\in\mathbb{R}^{n,m}} F(u) := \min_u \sum_{i,j} w_{i,j}(u_{i,j}-d_{i,j})^2 + \phi(u).$$

intensity dependent noise
$$\min_u \sum_{i,j} \frac{A_{i,j}^2}{\sigma_0^2}|u_{i,j}-d_{i,j}|^2 + \phi(u),$$

the regularizer
$$\phi(u) := \sum_{i,j}\left(c_{i,j}\sqrt{\begin{pmatrix} D_x u_{i,j} \\ D_y u_{i,j}\end{pmatrix}^T G_{i,j}\begin{pmatrix} D_x u_{i,j} \\ D_y u_{i,j}\end{pmatrix}} + (1-c_{i,j})\gamma_{i,j}\left\|\begin{pmatrix} D_{xx} u_{i,j} \\ D_{yy} u_{i,j} \\ D_{xy} u_{i,j}\end{pmatrix}\right\|_F\right),$$

edge direction
$$G_{i,j} = \alpha_{i,j}^2 v_{i,j} v_{i,j}^T + \beta_{i,j}^2(\mathrm{Id} - v_{i,j}v_{i,j}^T)$$

Lenzen, F. and Schäfer, H. and Garbe, C.S., Denoising Time-Of-Flight Data with Adaptive Total Variation, Advances in Visual Computing, LNCS 6938, pp. 337-346. 2011.
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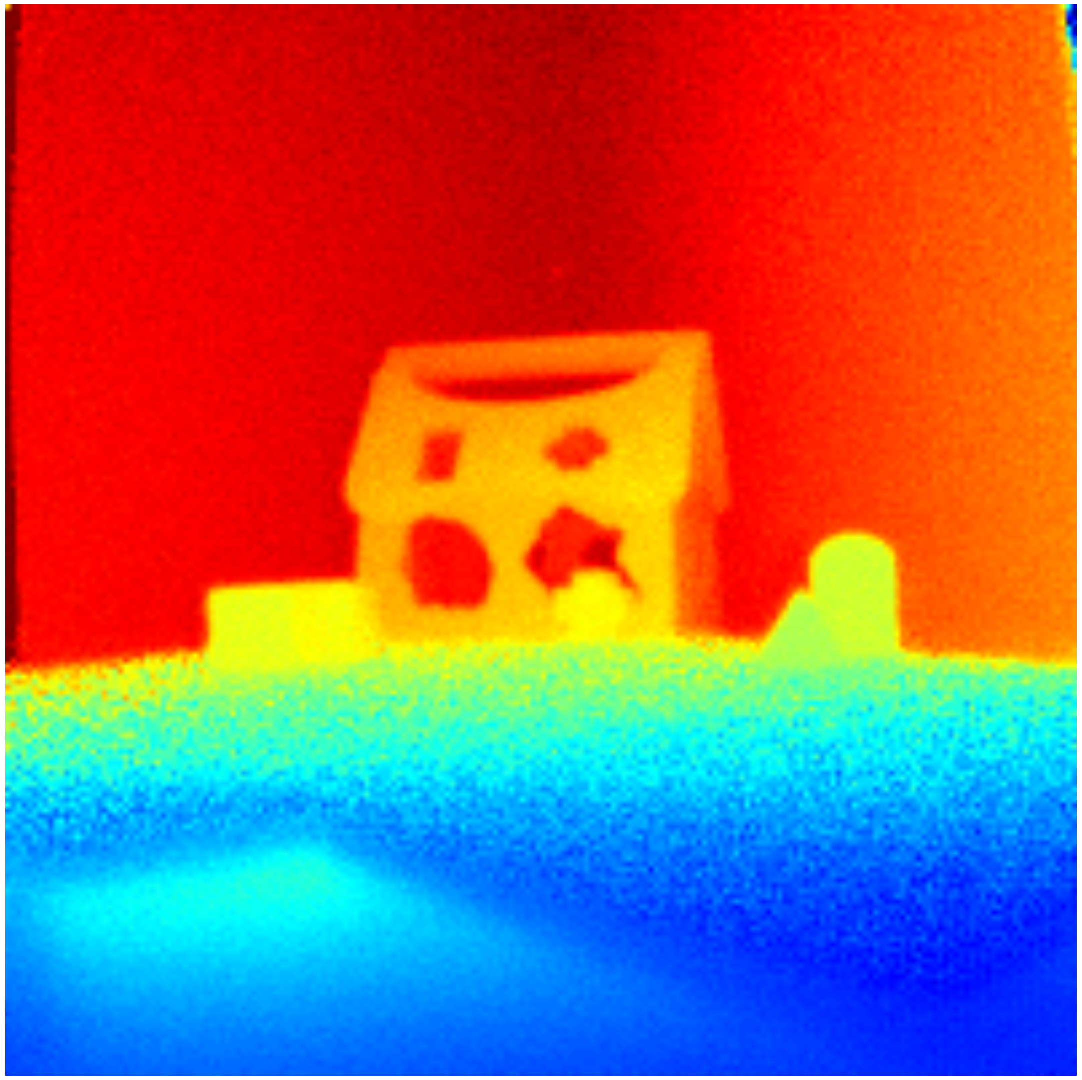

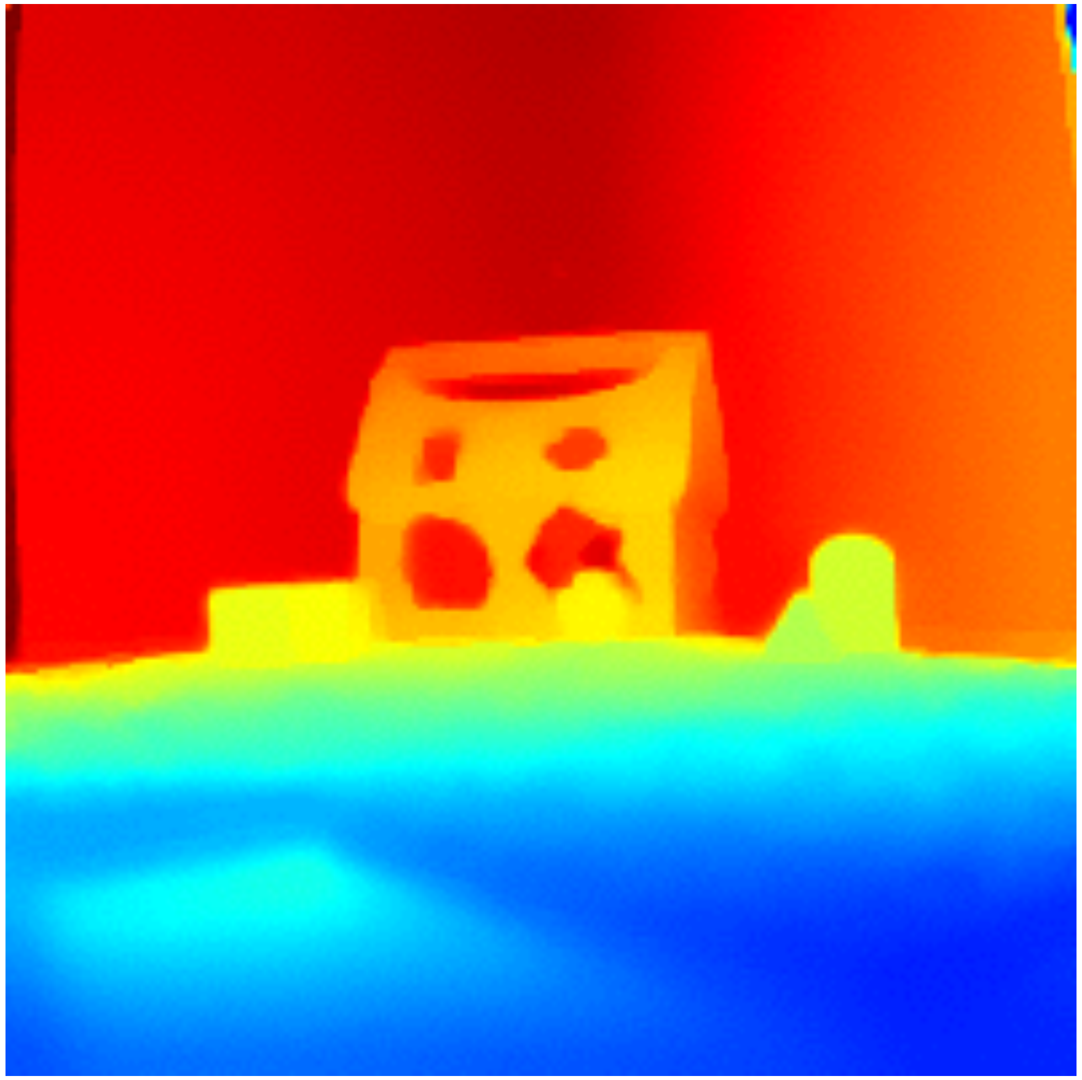

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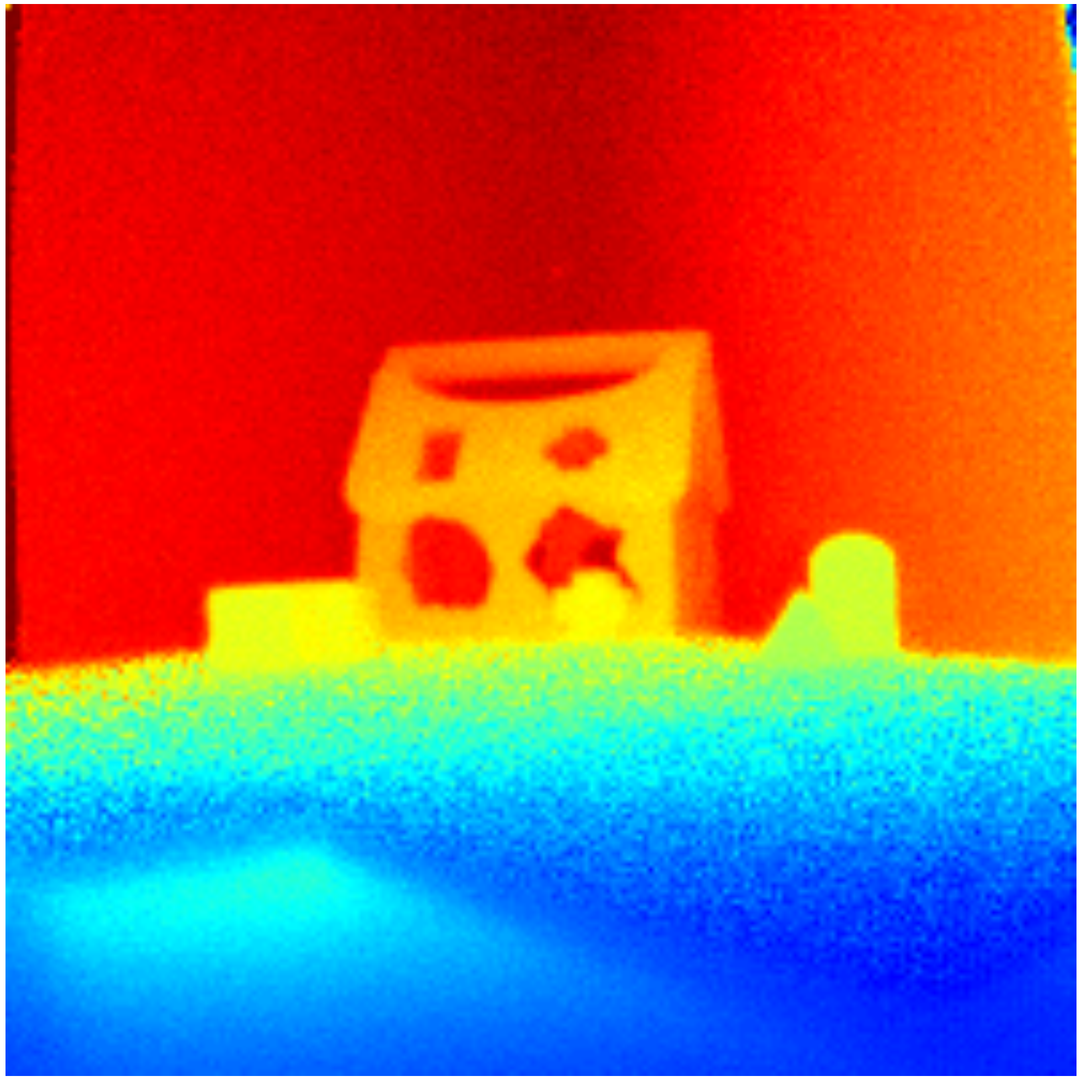

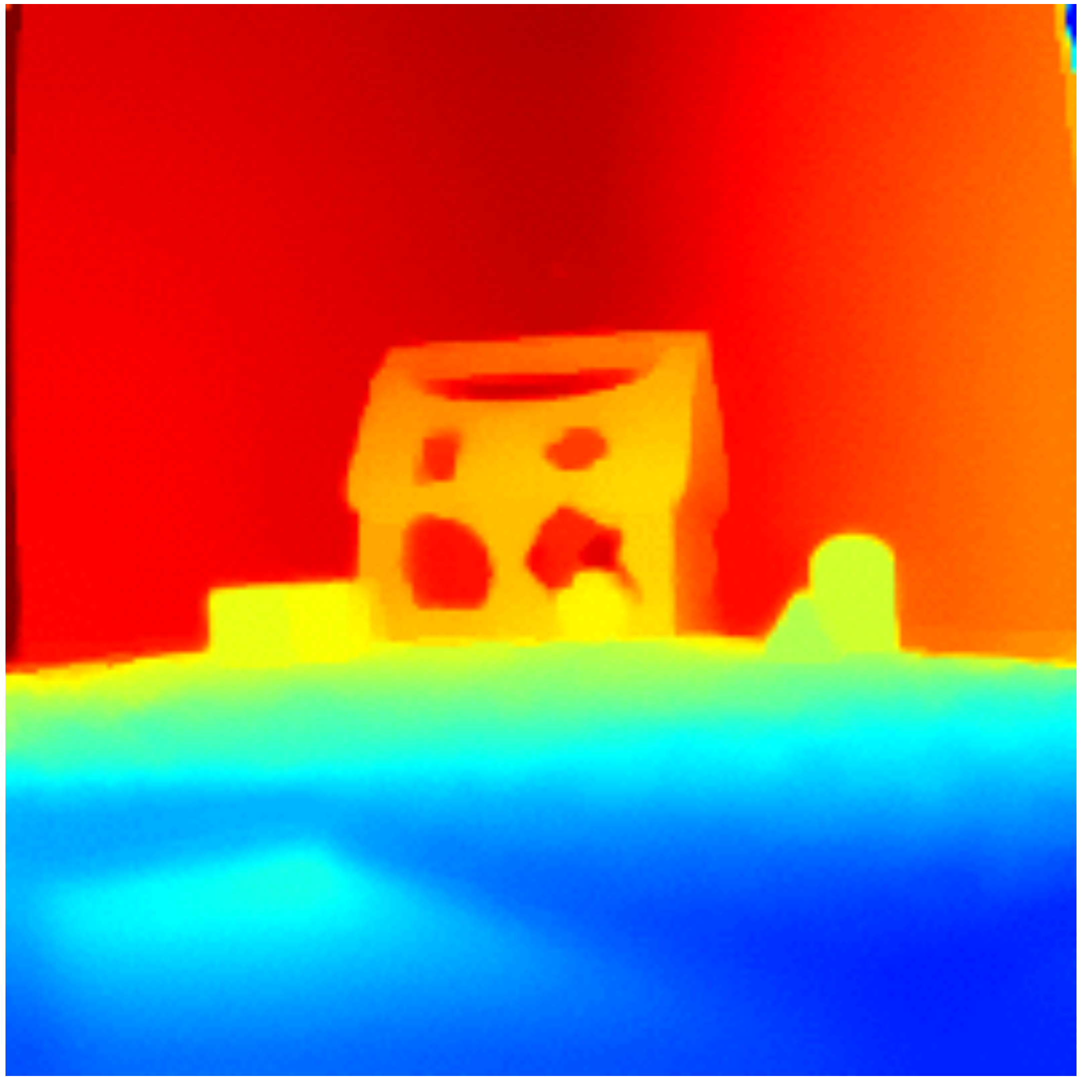

Software package available (C++, GPL license):
see http://hci.iwr.uni-heidelberg.de/Staff/flenzen/?page=tof_denoising for details.
Code available upon request: please send email to frank.Lenzen@iwr.uni-heidelberg.de

Conclusion

- Data sets for validation are available
  - real scenes, combined with stereo
  - synthetically rendered scenes
    - ToF specifics such as multi-path included
- Denoising
  - several denoising strategies have been tested
  - most accurate based on adaptive, anisotropic higher order TV of depth data
  - source code available on request

Funding

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Baden-Württemberg GmbH

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