Robust 3d Mapping with ToF Cameras

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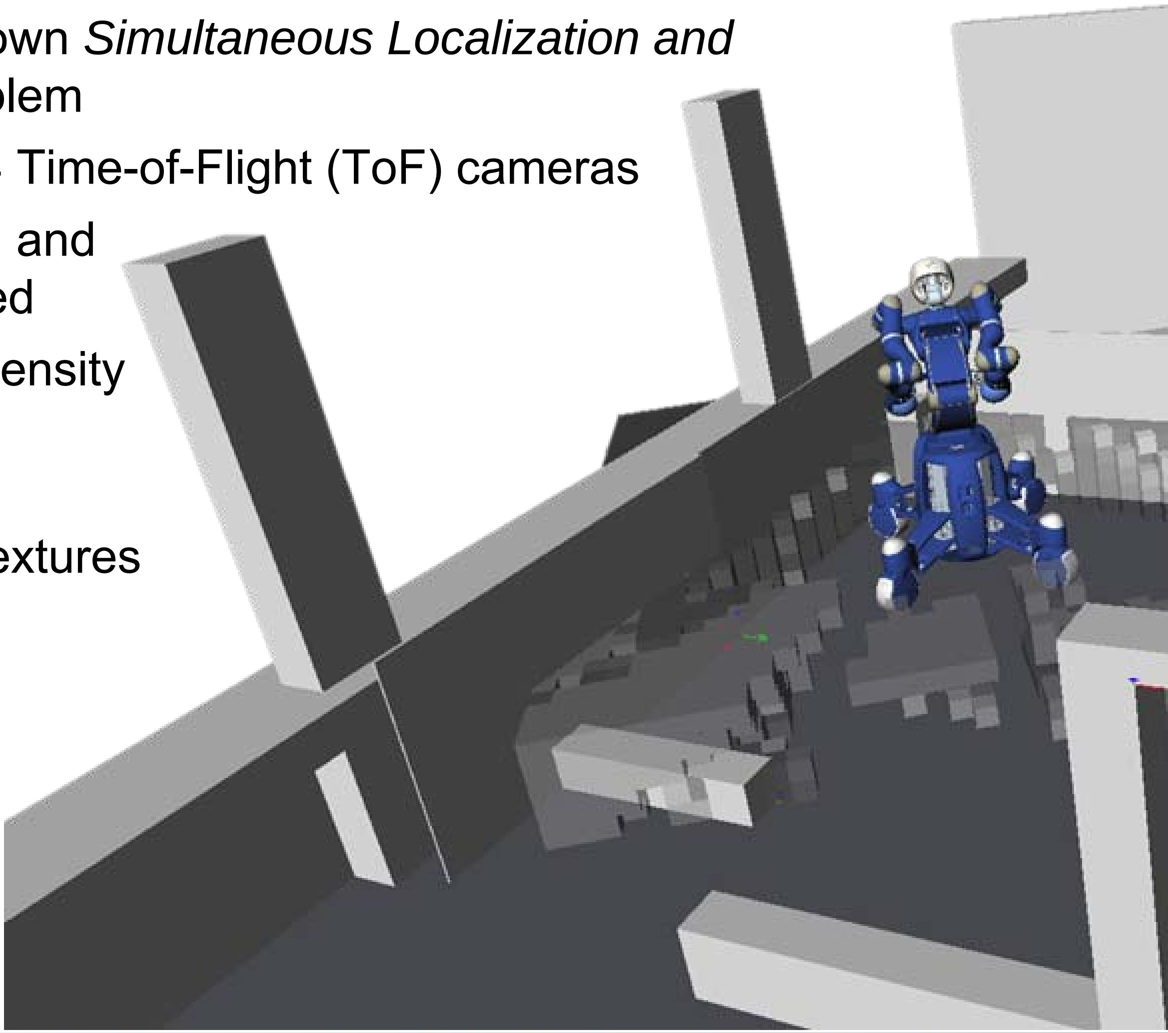
3d Mapping Motivation

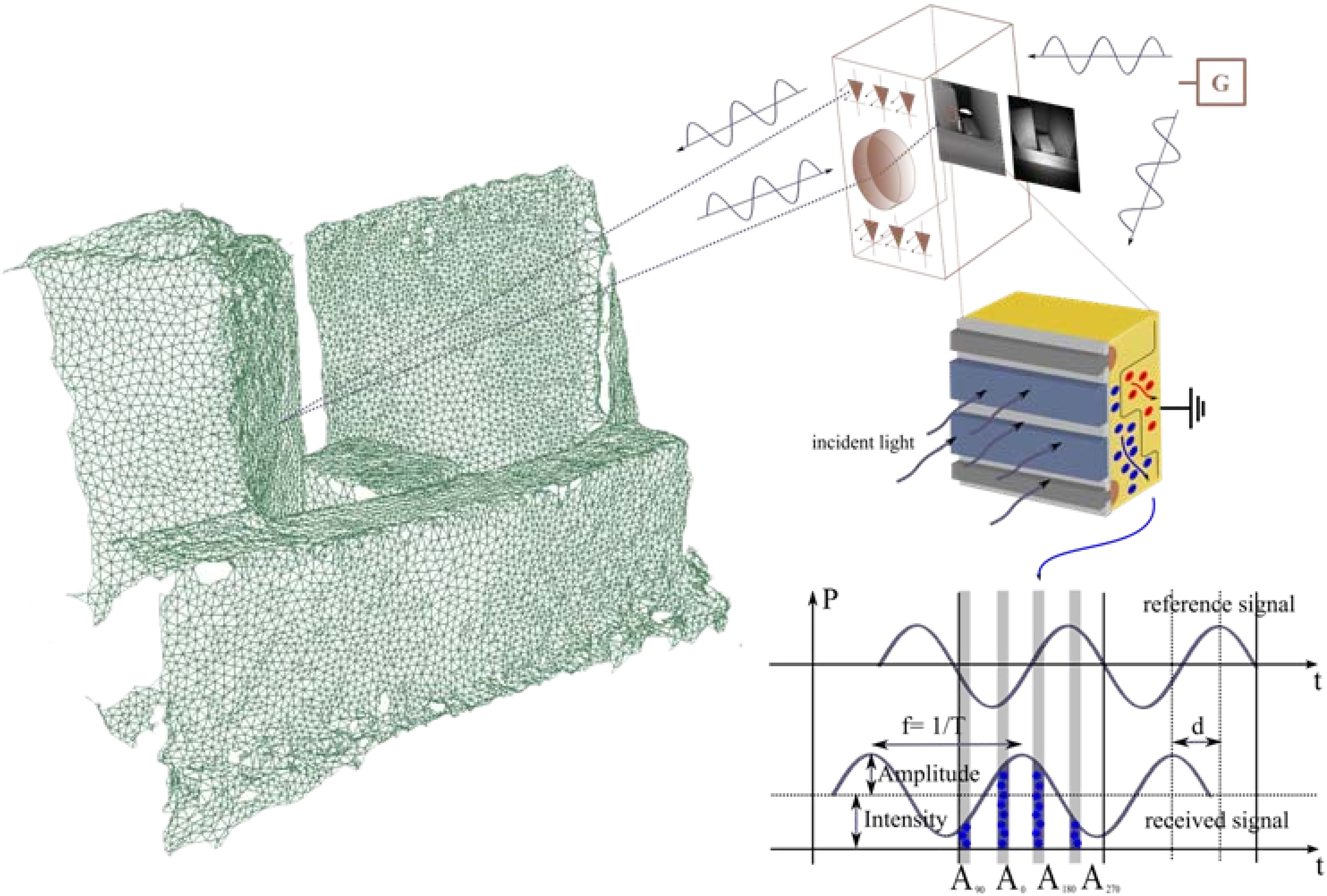
- Subset of the well-known *Simultaneous Localization and Mapping* (SLAM) problem
- Mobile platform with 4 Time-of-Flight (ToF) cameras
  - Compact design and reasonably priced
  - Distance and intensity images in video frame rate
  - Irrespective of textures and illumination
  - Erroneous data



Outline

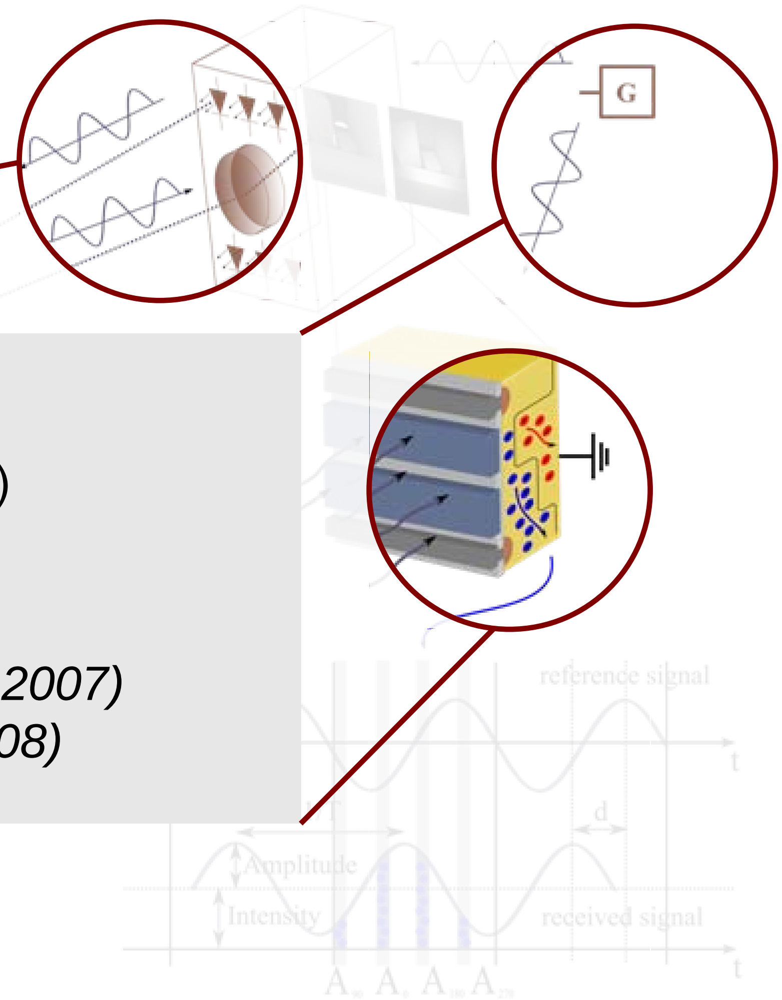
- ToF camera principle and error model
- 3d mapping process
  - Calibration
  - Filtering
  - ICP with frustum culling
  - Error relaxation
- Experimental results
- Contributions

ToF Camera Measurement Principle



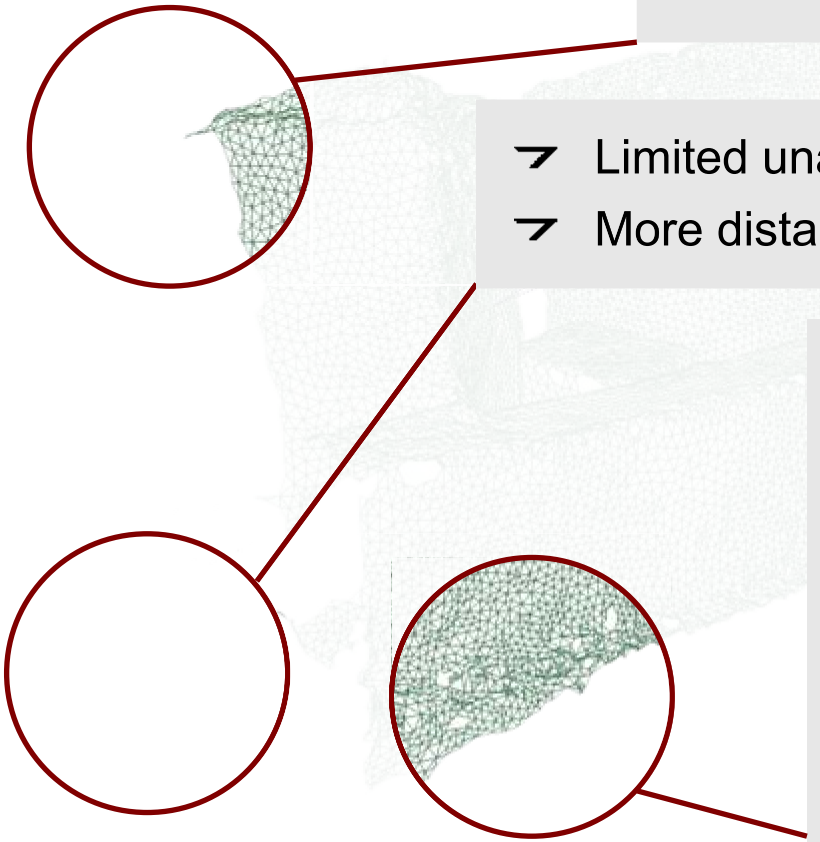
Systematic ToF Camera Errors

- Distance-related error
- Fixed-Pattern-Phase-Noise (FPPN)
- Amplitude-related error
- Tackled by depth calibration
  (cf. Fuchs and May, DAGM Dyn3d 2007)
  (cf. Fuchs and Hirzinger, CVPR 2008)



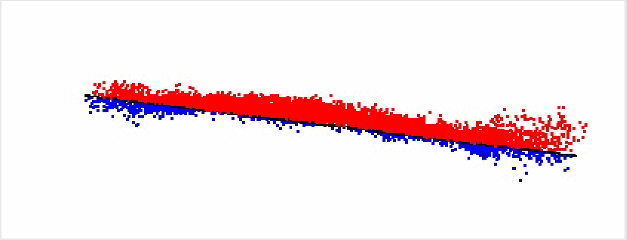
Flying Pixels, Ambiguity and Noise

- Flying pixels at shape transitions, especially at jump edges



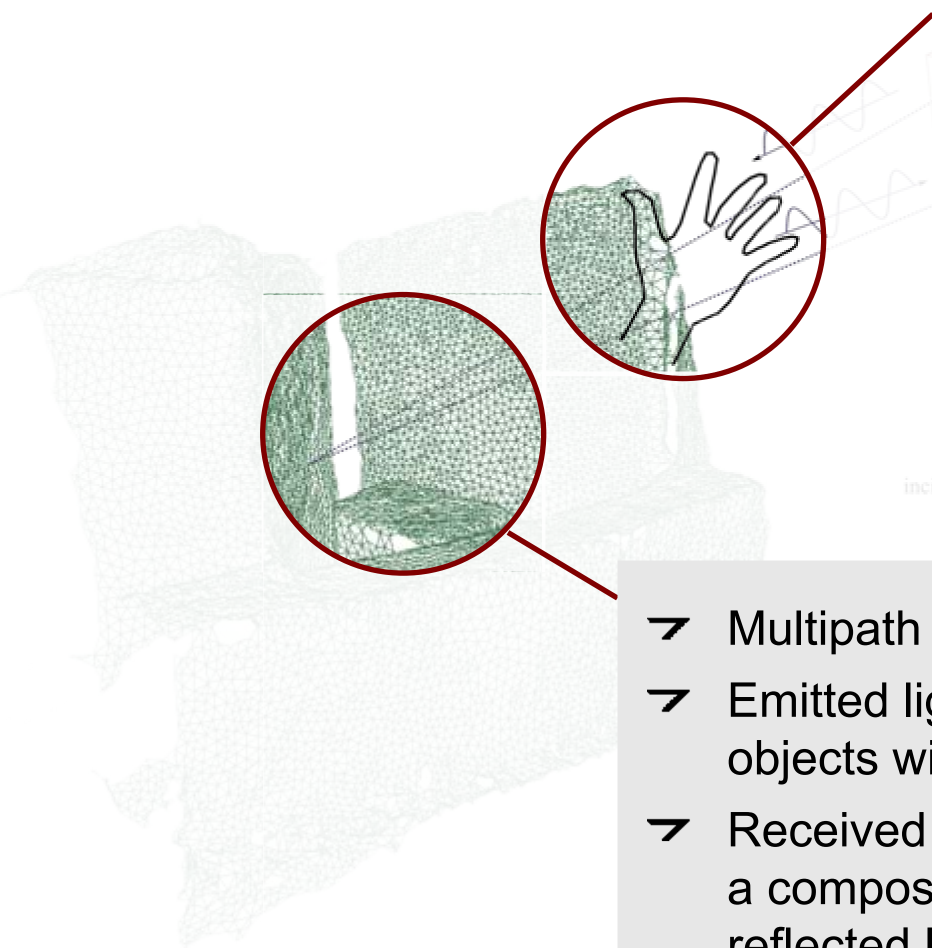
- Limited unambiguousness range, e.g. 7500 mm
- More distant objects appear *X modulo 7500 mm*

- Various noise sources (dark current, photocharge conversion noise, quantization noise etc.)

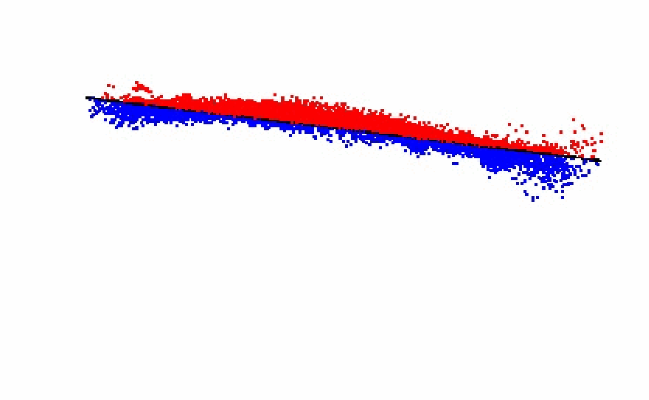


noisy measurements on a calibration plane

Multipath Interference and Light Scattering

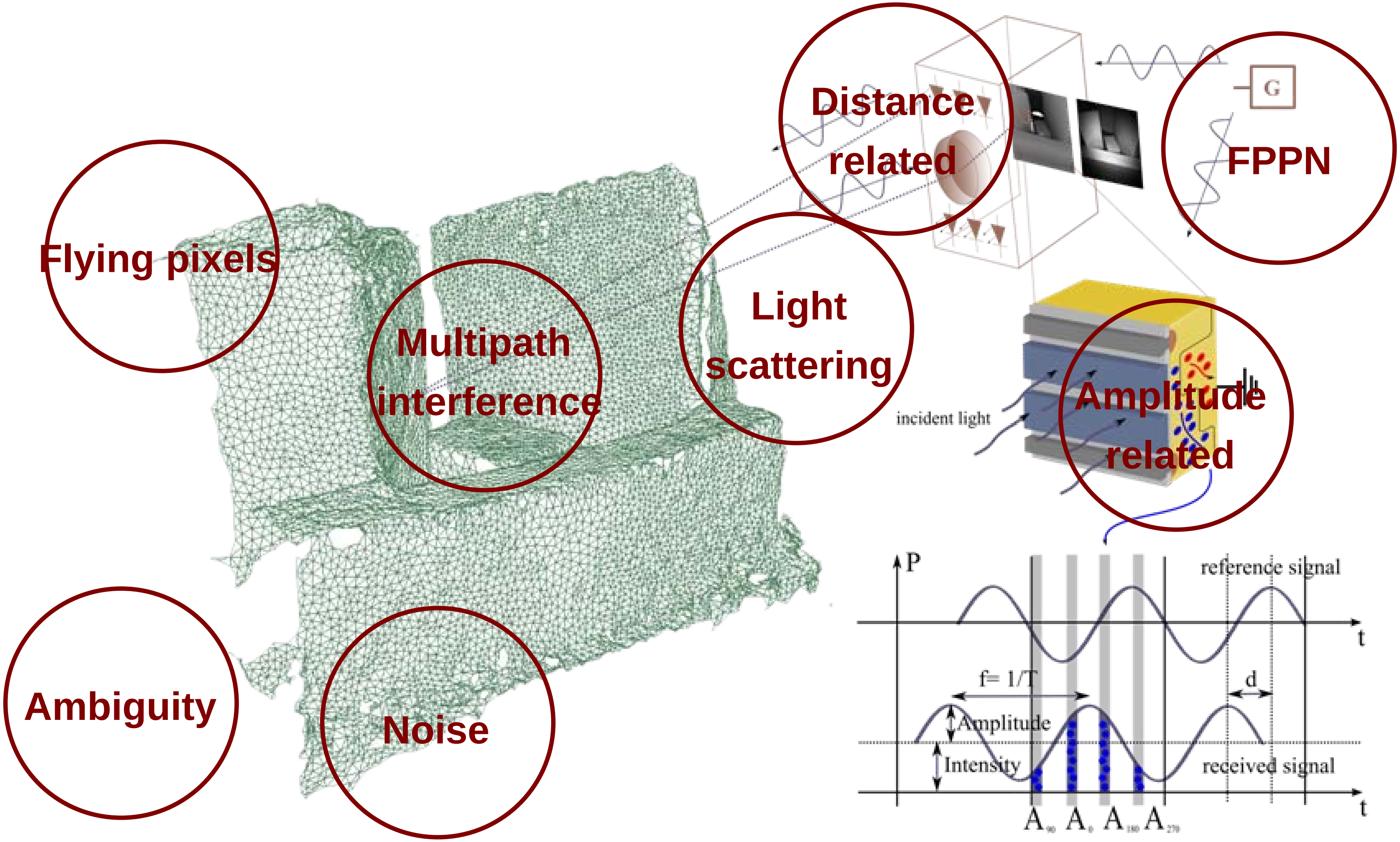


- Light scattering

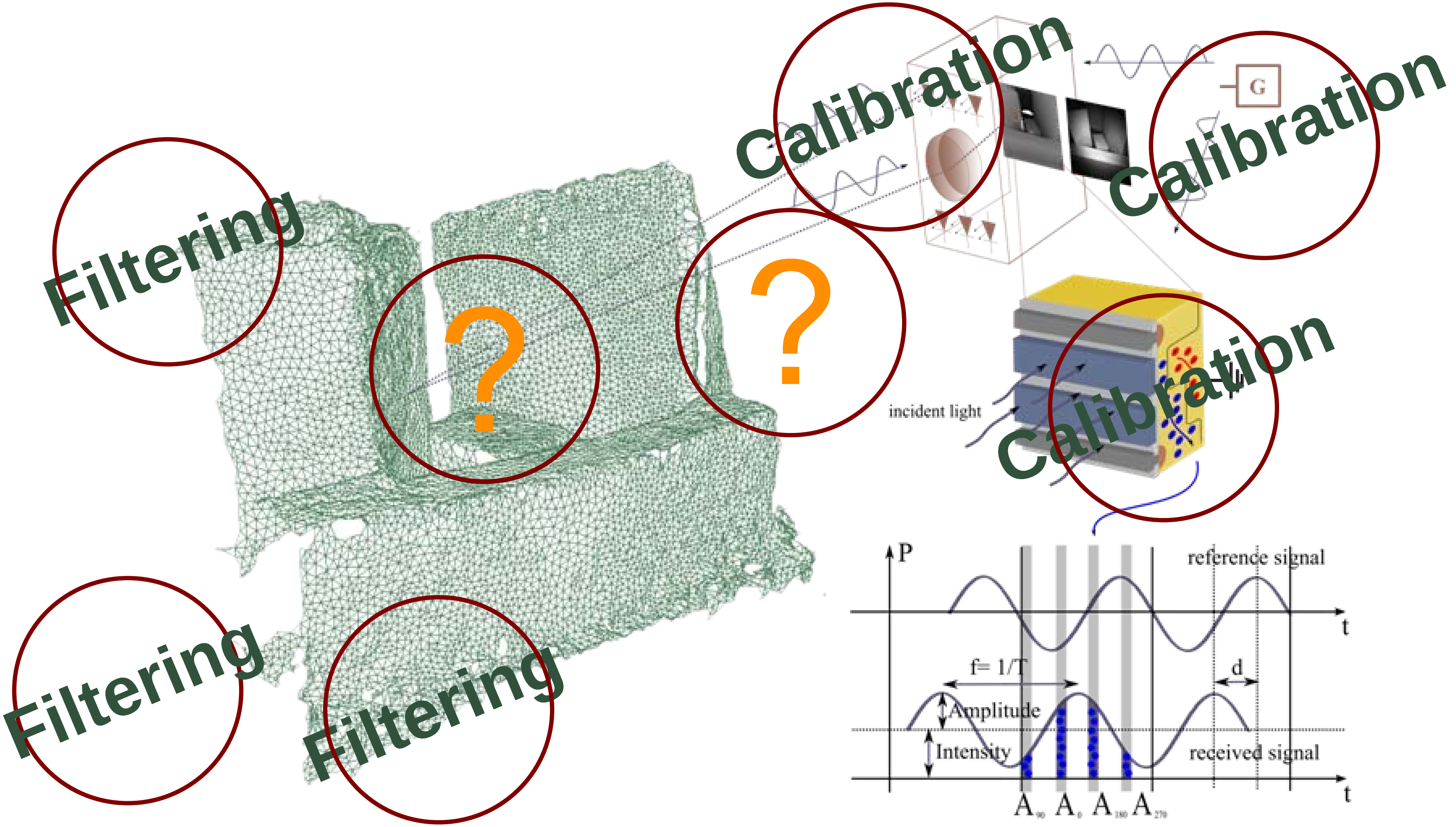


- Multipath interference
- Emitted light is also reflected by the objects within the scene
- Received signal is distorted, because it is a composition of directly and multiple reflected light

Specific ToF Camera Measurement Errors



ToF Camera Errors – Isolation and Minimization



3d Mapping Process - Overview

Preparation

Calibration

1. Intrinsic and depth calibration of ToF camera

Frame-wise

Undistorting

Filtering

Registration

2. Framewise image processing
   1. Undistortion of the incoming data
   2. Filtering of noisy data and jumping edges
   3. Registration of the consecutive point clouds and generation of a global map

Post-processing

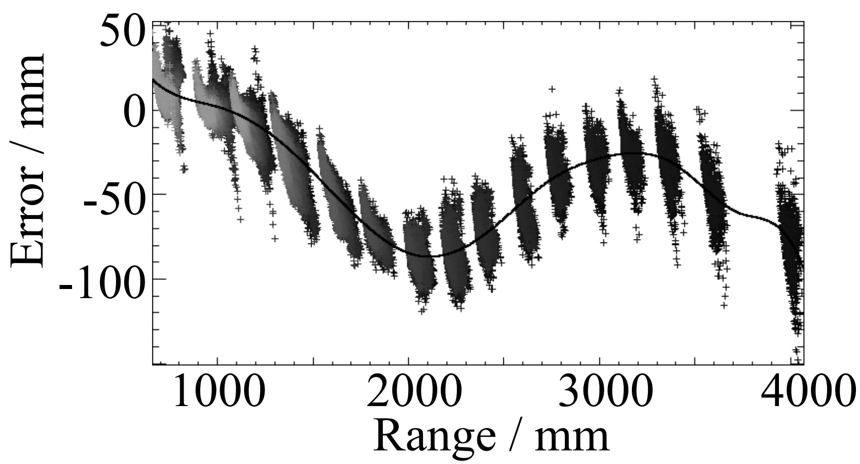
Global Error Relaxation

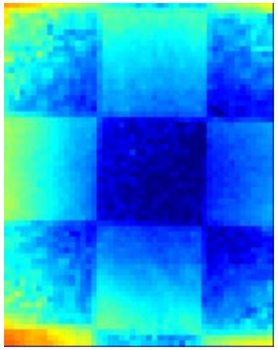
Refinement

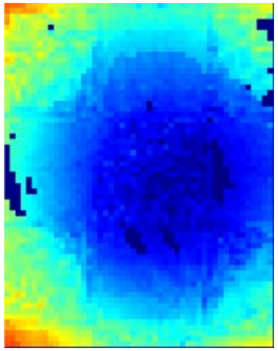
3. Post-processing
   1. Loop-closure and error estimation between first and last frame
   2. Global error relaxation by GraphSLAM
   3. Refinement

ToF Camera Calibration

- Pinhole camera calibration procedure
  (cf. Strobl and Hirzinger, ICRA 2008)
- Estimation of ToF camera specific parameters
  (cf. Fuchs and May, DAGM Dyn3D 2007)
  (cf. Fuchs and Hirzinger, CVPR 2008)
- Undistortion and correction of the incoming images

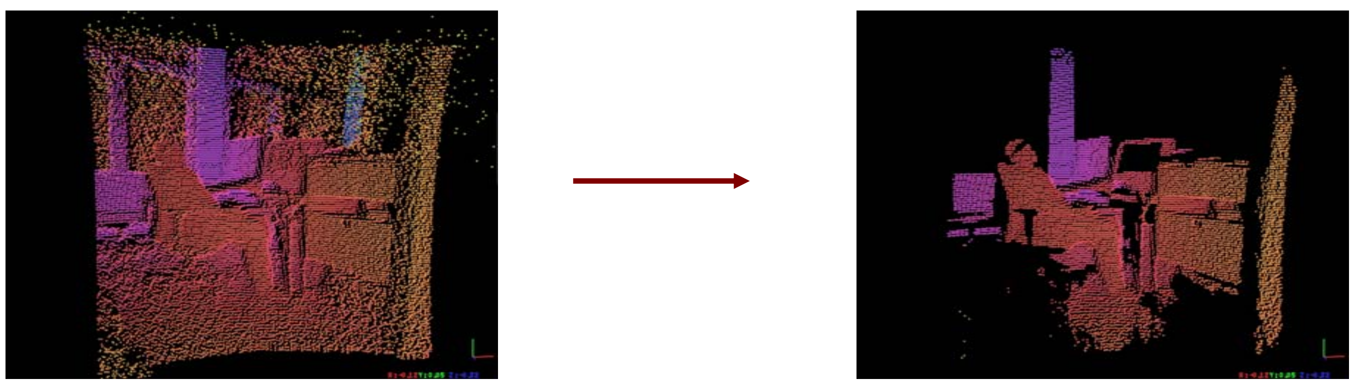






Filtering Noisy Data and Ambiguities

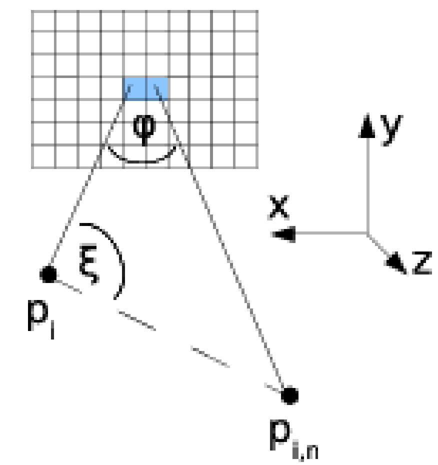
- Amplitude filtering
- Distant dependent threshold
- Filters low amplitudes from
  - Objects with low infrared reflectivity
  - Objects in larger distances to the camera



Filtering Jump Edges

Preparation
Calibration
Frame-wise
Undistorting
Filtering
Registration
Post-processing
Global Error Relaxation
Refinement

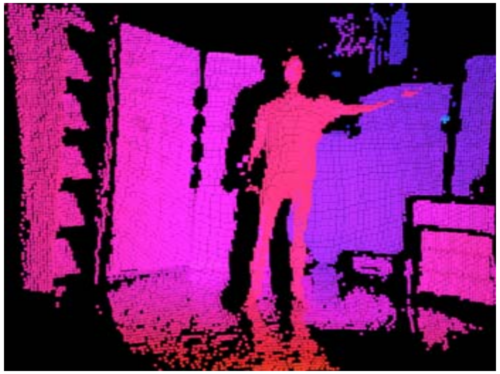
- Computing „Neighborhood angle“ as a threshold for rejecting measurements *(cf. Fuchs and May, DAGM Dyn3D 2007)*



„Neighborhood angle“

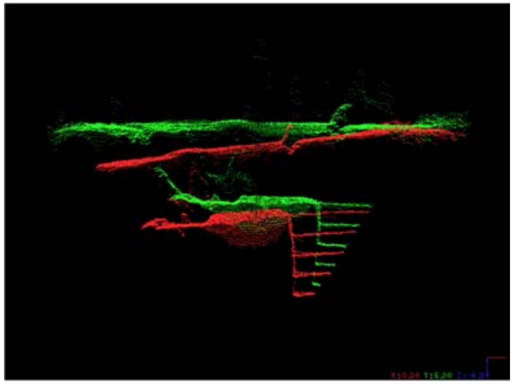
$$\xi_i = \max \arcsin \frac{\|\mathbf{p}_{i,n}\|}{\|\mathbf{p}_{i,n} - \mathbf{p}_i\|} \sin \varphi$$

→



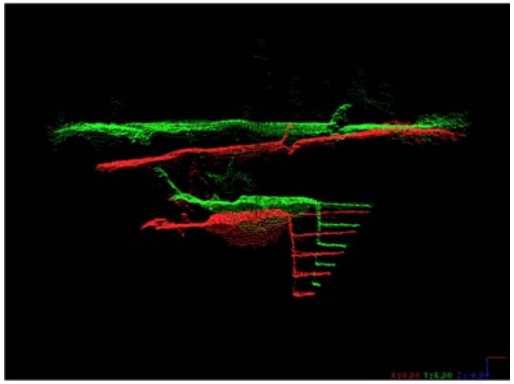
Registration

- Consecutive point clouds are registered by ICP algorithm
- Accumulation of ego motion
- Actual point clouds can be localized with respect to the first measurement
- Standard („Vanilla“) ICP assumes full coverage of scene and model
- Due to camera movement:
  → non-overlapping areas induce wrong point assignments

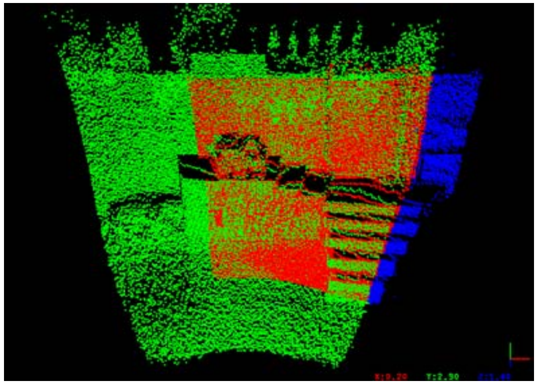


Registration – Frustum Culling

- Non-parametric and fast test
- Uses the intersection of both frustums
- Embedded in the iteration process
  - A priori pose estimation in each iteration is used for computation of frustum intersection
  - Discard point outliers



Two point clouds of the stairs



Only the red points lay within the frustum intersection

Experiments

- Demonstrating
  - robustness,
  - achievable accuracy and
  - impact of error sources

- Accuracy of 3d mapping by comparing
  - estimated ego motion or
  - created 3d map

  with an appropriate ground truth

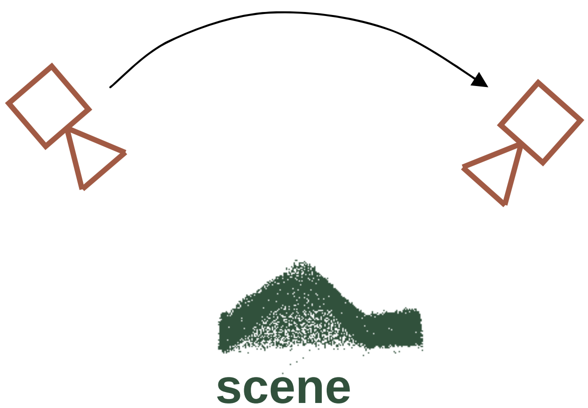
- Ground truth is given by
  - Odometry of an industrial robot
  - Manually measured significant scene features

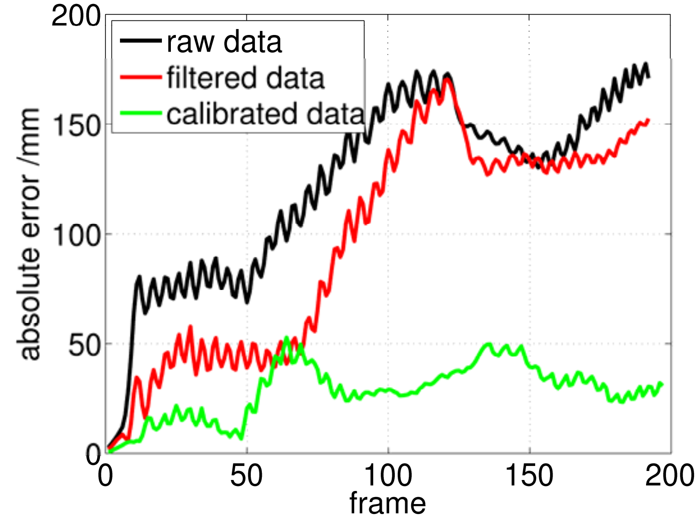
Swissranger SR 3100

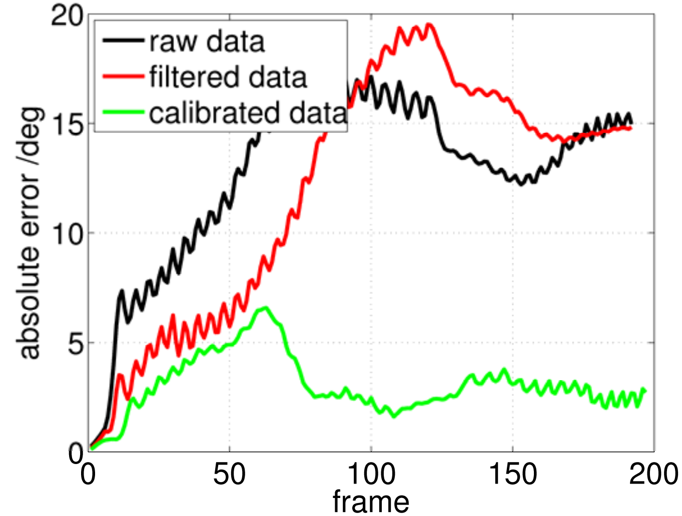
- CMOS/CCD
- 176x144 pixel
- Aperture: 40° / 47°

Results – Impact of Filtering and Calibration I

- Simple trajectory:
  rotation at x-axis of camera by 90 °
- Path length: 950 mm
- Translational error is reduced
  by > 50 % from 150 mm to 25 mm
- Rotational error is reduced
  by > 50 % from 15 ° to 3 °

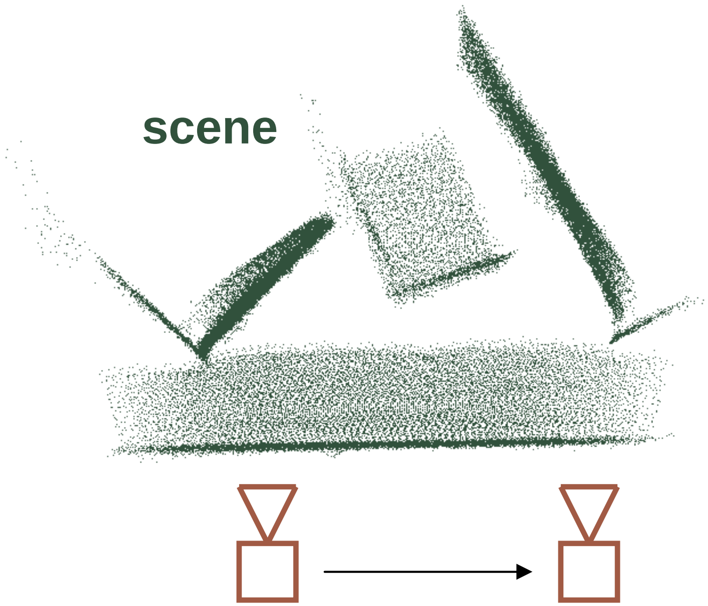


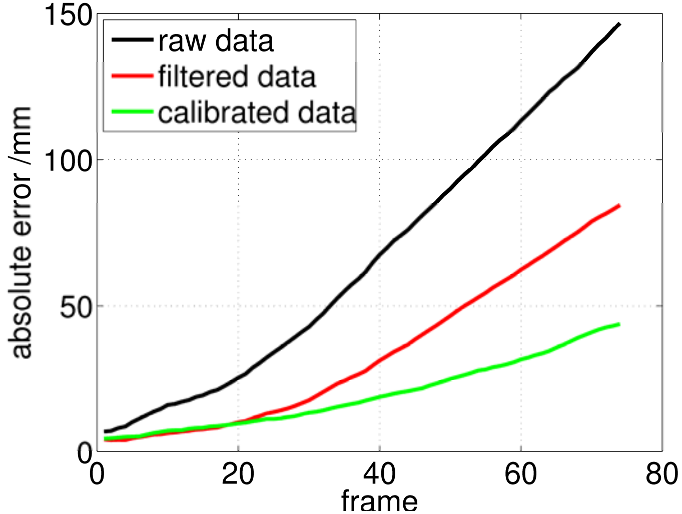


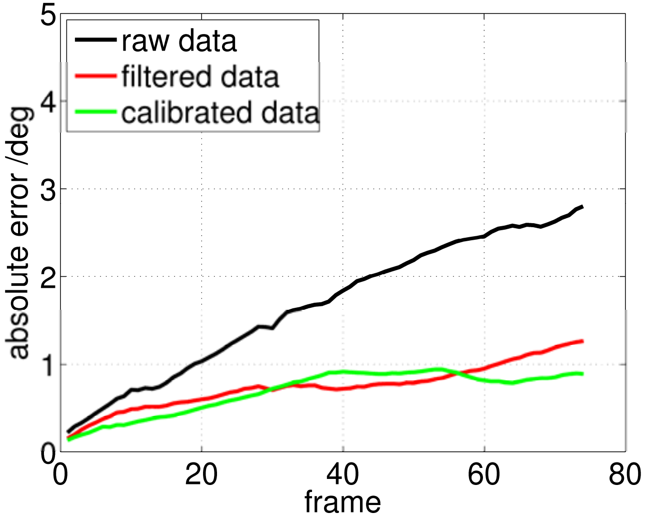


Results – Impact of Filtering and Calibration II

- Simple trajectory: 400 mm in x-direction
- Translational error is reduced
  by > 50 % from 150 mm to 40 mm
- Rotational error is reduced
  by > 50 % from 3 ° to 1 °

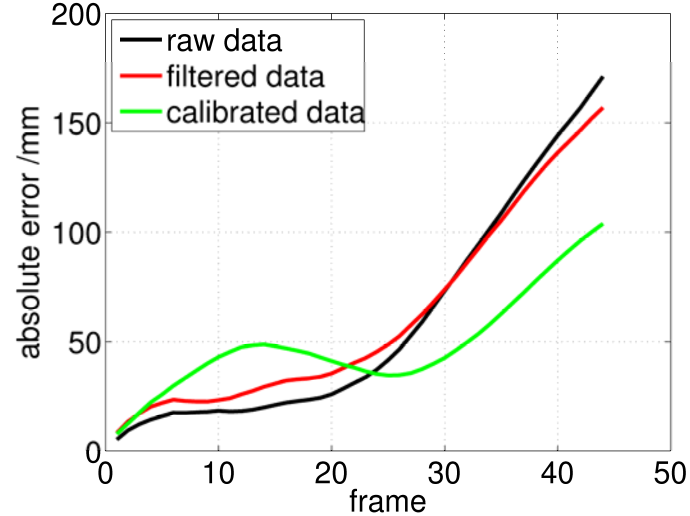


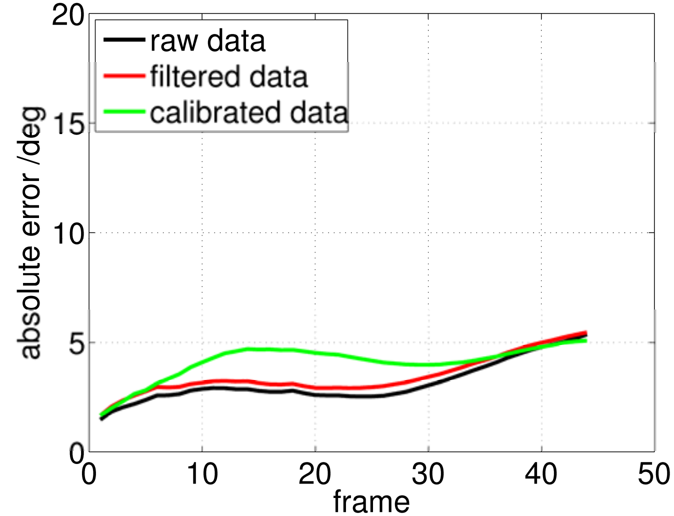


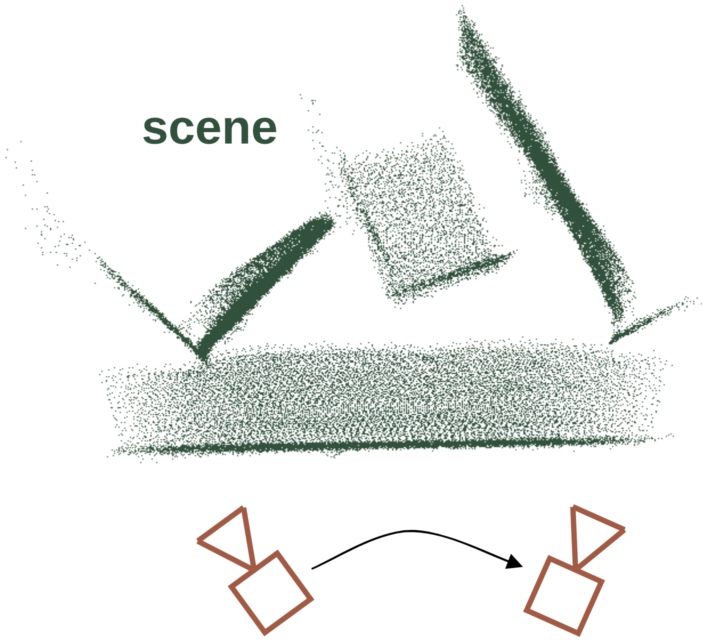


Results – Impact of Filtering and Calibration III

- Simple trajectory: Rotation at z-axis of robot-tcp by 50 degrees
- Translational error is reduced, but is nearly 100 % of the covered distance
- Errors are significantly larger compared with previous experiments

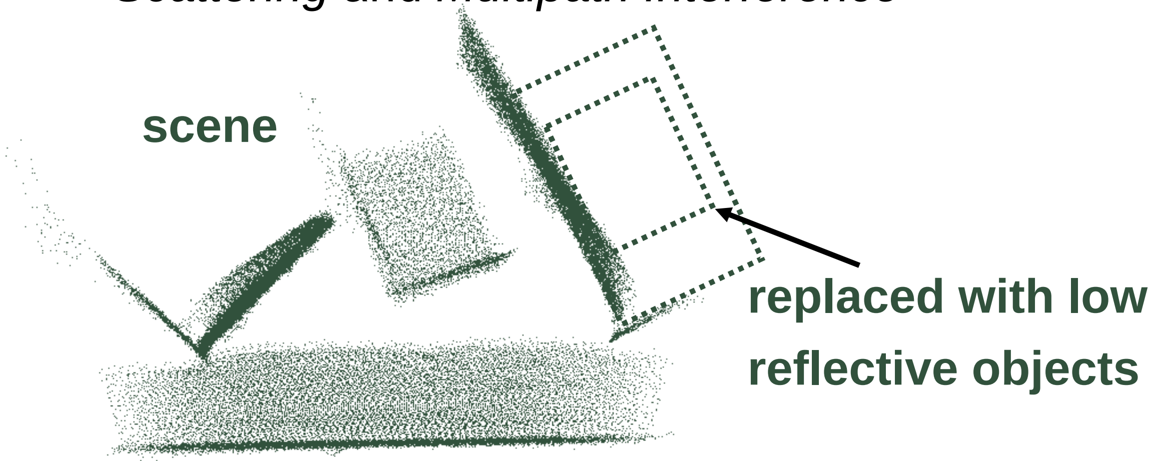


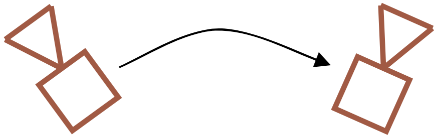


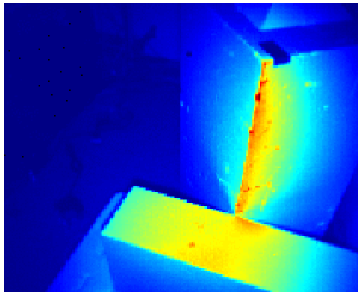


Light Scattering and Multipath Interference

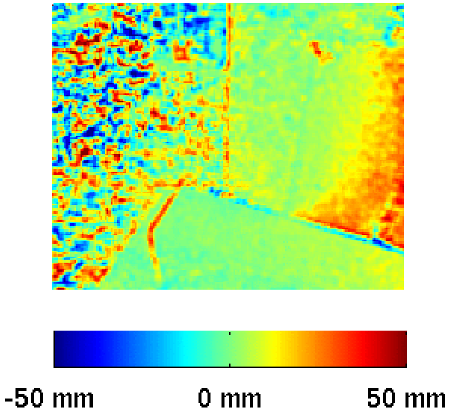
- Again: Rotation at robot-tcp-z by 50 °
- Highly reflective object was replaced
- Comparison of distance images with images from previous experiment
- Difference images display the distortions by *Light Scattering* and *Multipath Interference*







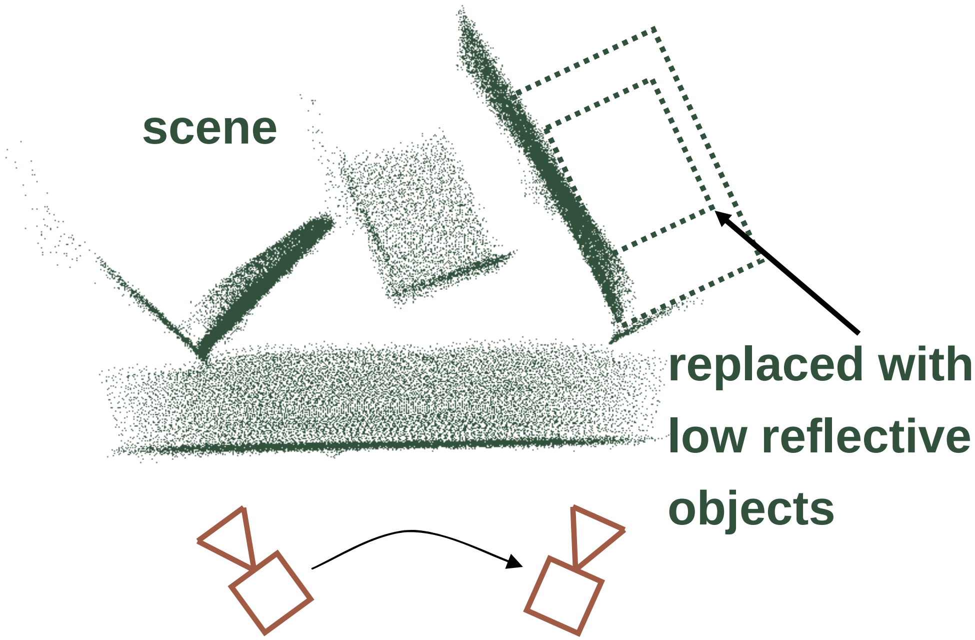
depth image

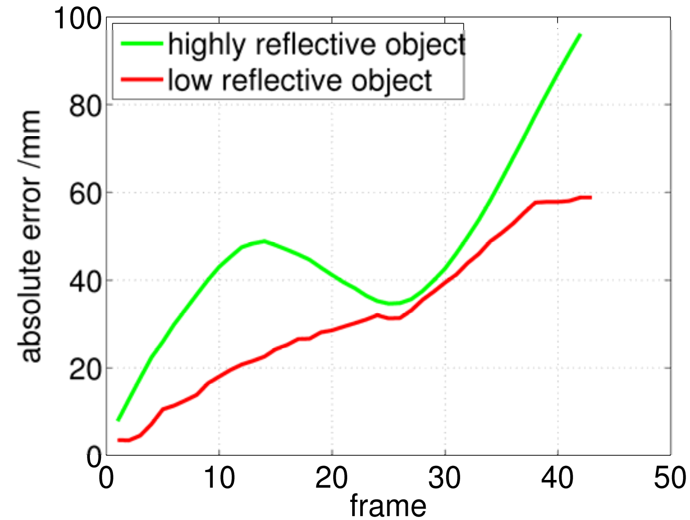


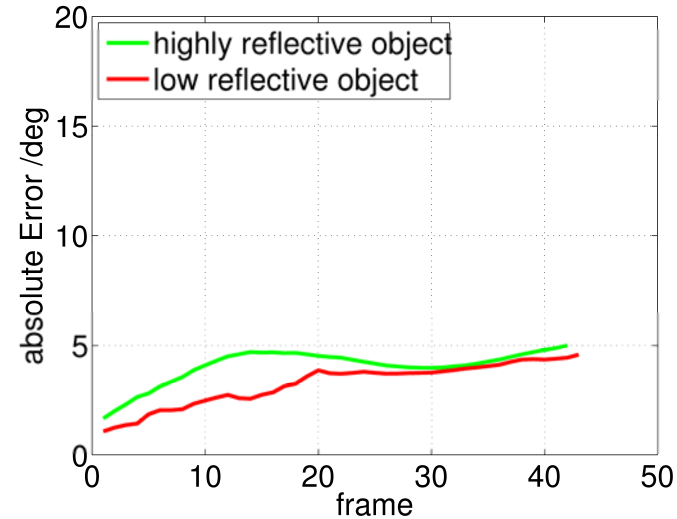
difference image

Light Scattering and Multipath Interference

- Due to the low reflective object: Decrease of translational and rotational error
- Multiple reflections and scattering nearly double the error!

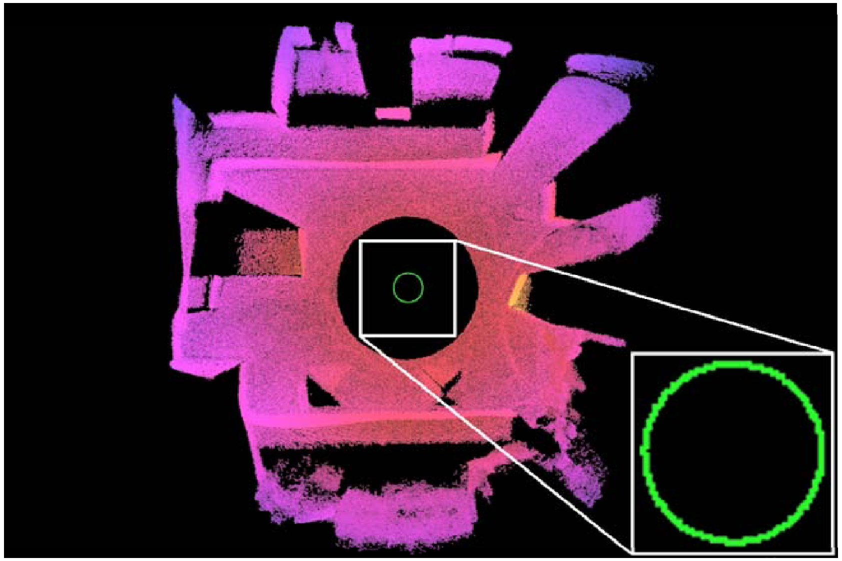






Experimental Results – Evaluation Setup

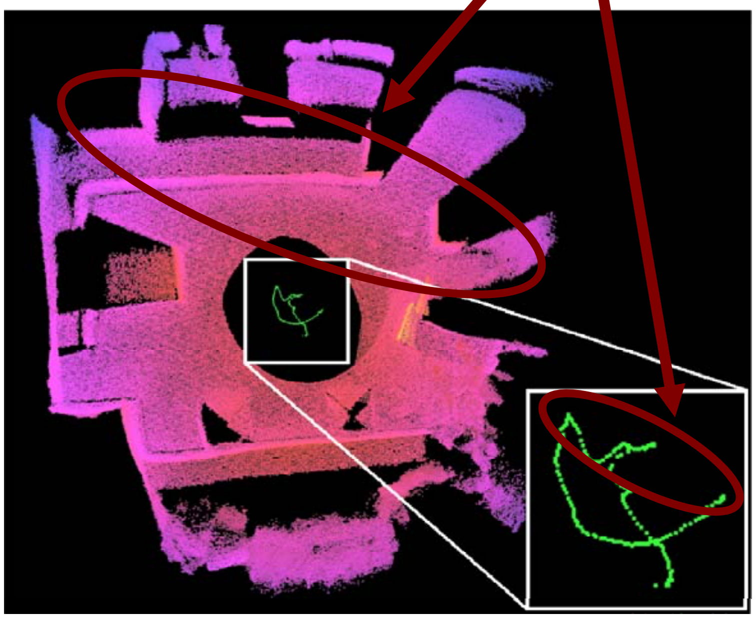
- Styrofoam objects assembled in square measuring 1.8 m
- Circumferentially captured the scene with 180 images
- Circular trajectory with a diameter of 300 mm
  (path length 950 mm)



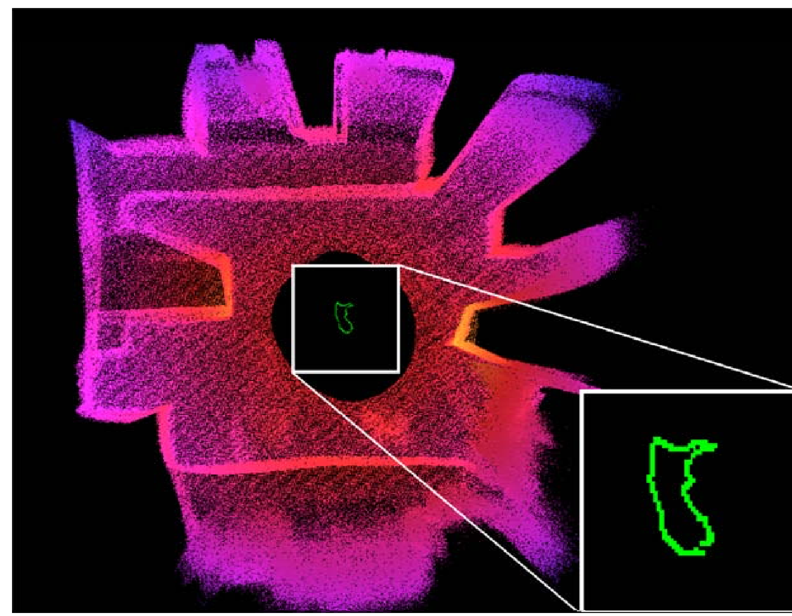
Experimental Results – Laboratory Scene

- Error before loop cloosure: 150 mm / 6°
- Isometry: Deviations of 35 mm and 20 mm

Especially first part of trajectory is affected by multipath reflections



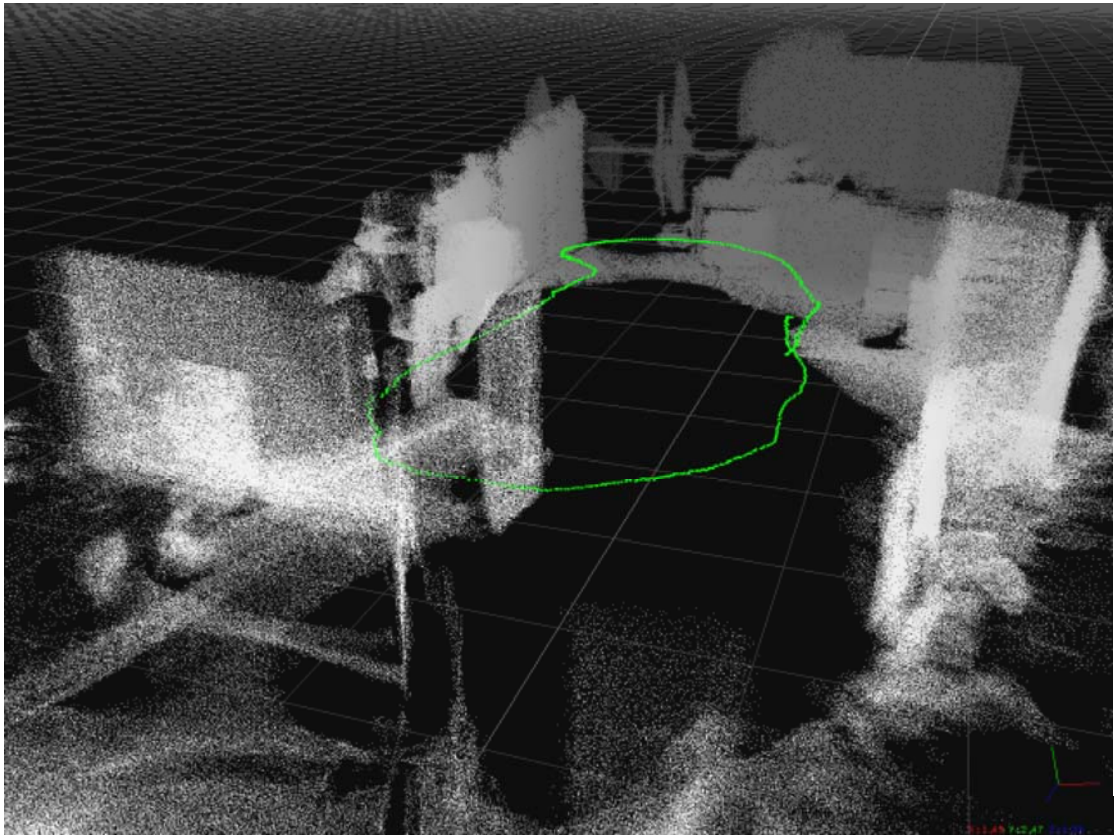
raw map



globally relaxed error

Experimental Results – Larger Environment

- Ambiguities
- Longest distance
  ≈ 19 m
- Spurious, noisy measurements
- Path length ≈ 10 m
- Error in Ego motion estimation:
  1.7 m / 9 °
- Error in isometry:
  0.4 m



Experimental Results – Larger Environment

Contributions

- Robust 3d mapping with ToF cameras
- Promising results in spite of erroneous data, due to
  - Calibration
  - Filtering
  - ICP Optimization
- Identified remaining crucial influences
- Provide the data for further investigations
  Site: http://www.robotic.de/242/

Thank you for your attention!