3D Pose Estimation and Mapping with Time-of-Flight Cameras

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Objectives

3D Pose Estimation and Mapping

Based on ToF camera data

No additional sensors

Pose estimation on-the-fly during exploration

Only few approaches can be found [Ohno,06],[Sheh,06],[Prusak,07]

SwissRanger SR-3k

Pixel array resolution:	176 x 144 pixels
Field of view:	47.5° x 39.5°
Non-ambiguity range:	7.5 m (20 MHz)
Frame rate:	variable (typical 25 fps)

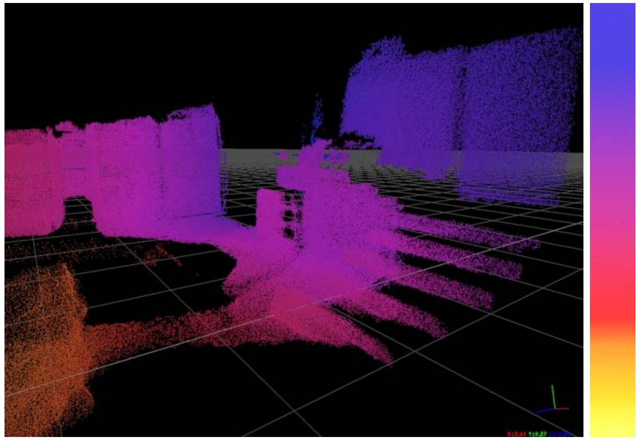

Fig.: Swissranger SR-3k [Mesa,08]

Outline

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- 3D Sensing with ToF Cameras
- 3D Environment Mapping
- Experiments and Results
- Conclusion / Future Work

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ToF Camera Error Model

Non-Systematic Errors [Lange,00]

Photocharge Conversion Noise: noise added in the process of converting optical information in an analogous signal

Quantization Noise

Electronic Shot Noise (Quantum Noise): Poisson-distributed nature of the arrival process of photons and the generation process of electron-hole pairs

$$\Delta r = \frac{c}{4 \pi f_m} \frac{\sqrt{b_l + b_b}}{\sqrt{2} a} , \qquad (1)$$

Indoor applications: $\Delta r \propto d$,

Outdoor applications: $\Delta r \propto d^2$,

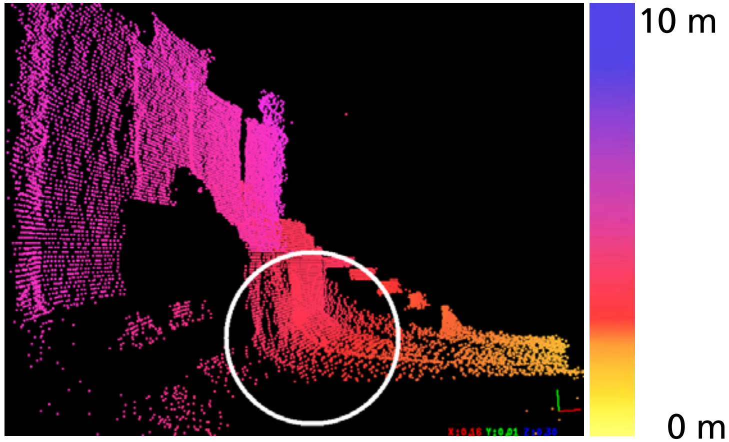
where
Δr: standard dev. of range measurment
c: speed of light
b_l: intensity (LED illumination)
b_b: intensity (background)
f_m: modulation frequency
a: amplitude
d: distance

ToF Camera Error Model

Non-Systematic Errors (cont'd)

Interreflection (multiple ways reflection)

- Superposition of measurements
- Hollows and corners appear rounded off

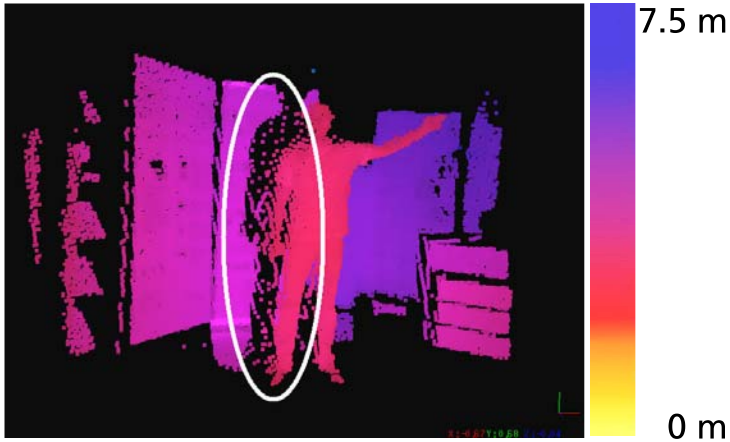


Light Scattering

- Near bright objects superpose measurements from the background

Jump edges

- Multimodal measurements
- Appears as smooth transitions between shapes



ToF Camera Error Model

Systematic Errors

Circular Distance Error

- NIR-LED signal is nonharmonic sinusoidal

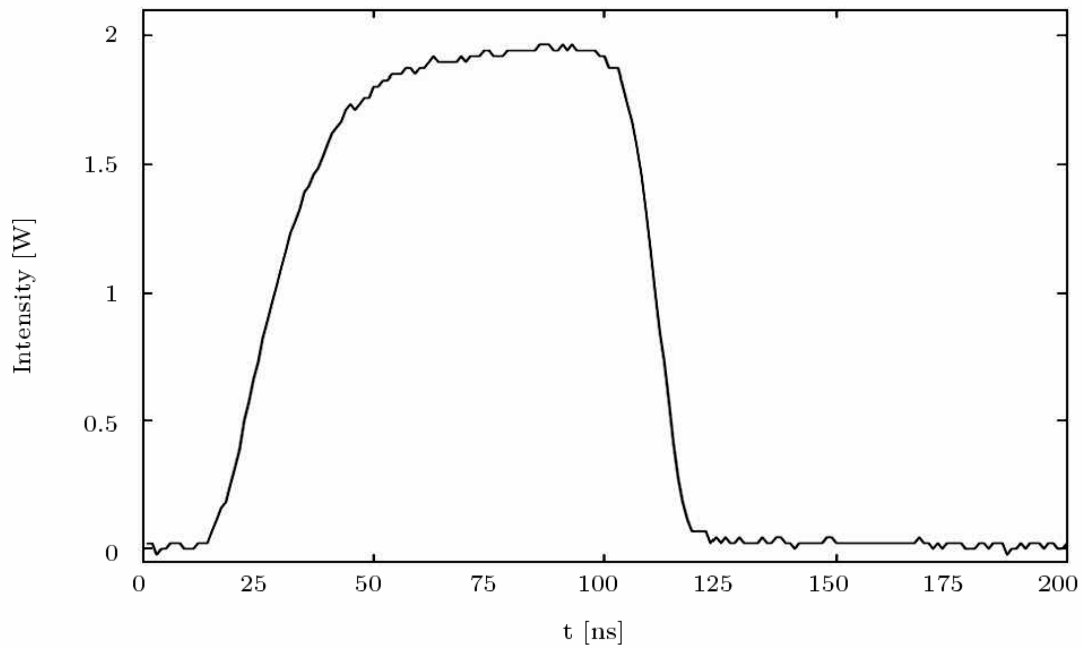
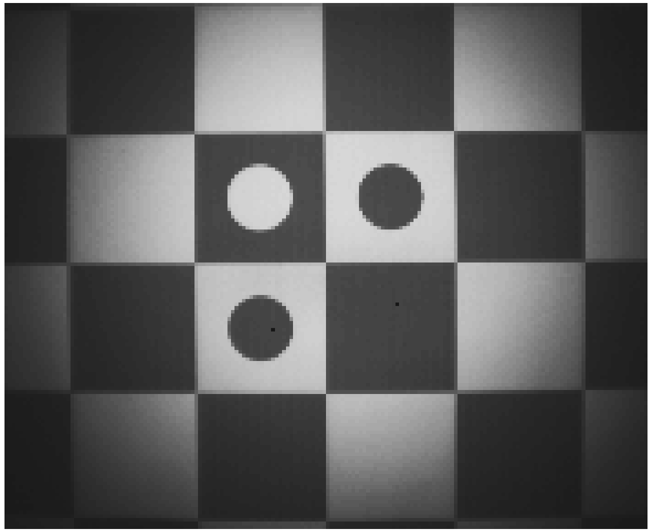


Fig.: Real LED signal, Source: [Lange,00]

ToF Camera Error Model

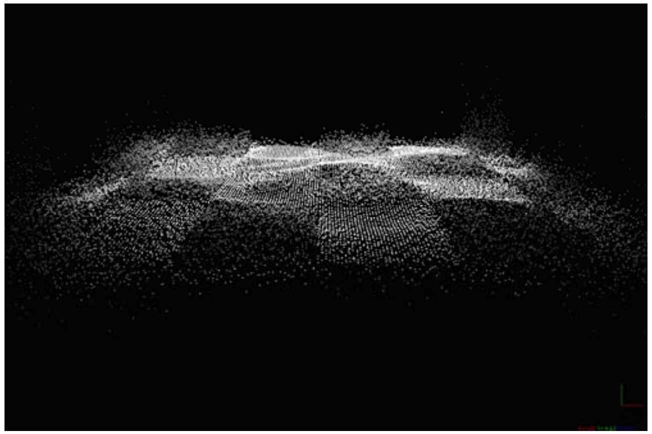


Systematic Errors

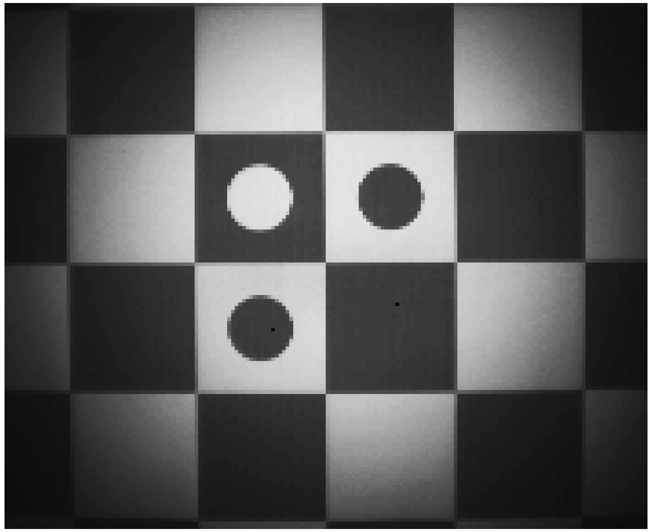
Amplitude Related Error

- Objects in the same distance with different infrared reflectivity provide different range measurements

- Low amplitude = high degree of noise



ToF Camera Error Model



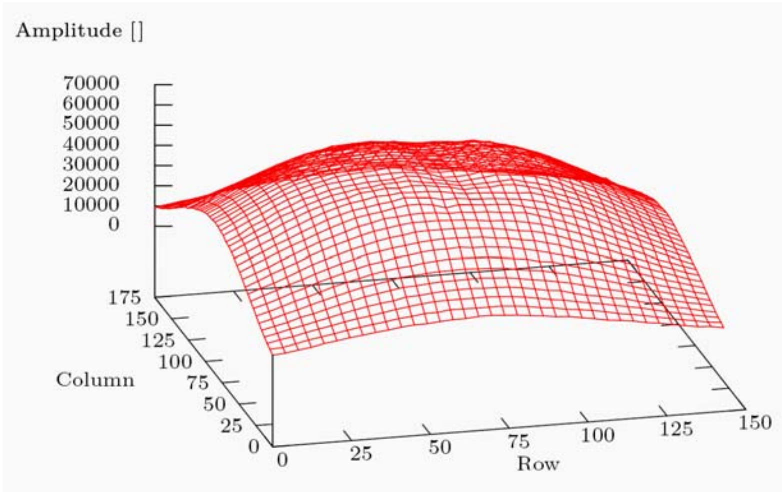
Systematic Errors

Inhomogeneous Scene Illumination

- Illumination decreases in the pheripherial area (entails amplitude related errors and varying SNR)
- (Issue for feature extraction)

Fixed Pattern Noise

- Related to latencies and different material properties in each CMOS gate (constant pixel offset)
- Signal propagation delay



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3D Environment Mapping

Main issues

Accuracy / Precision of range measurements

- Filtering
- Calibration

Large amount of data (provided with up to 30+ fps)

- Reduction of data (Scanline Approximation, SIFT, KLT)

Accumulation of errors during registration process

- Distrubution of error after loop-closure

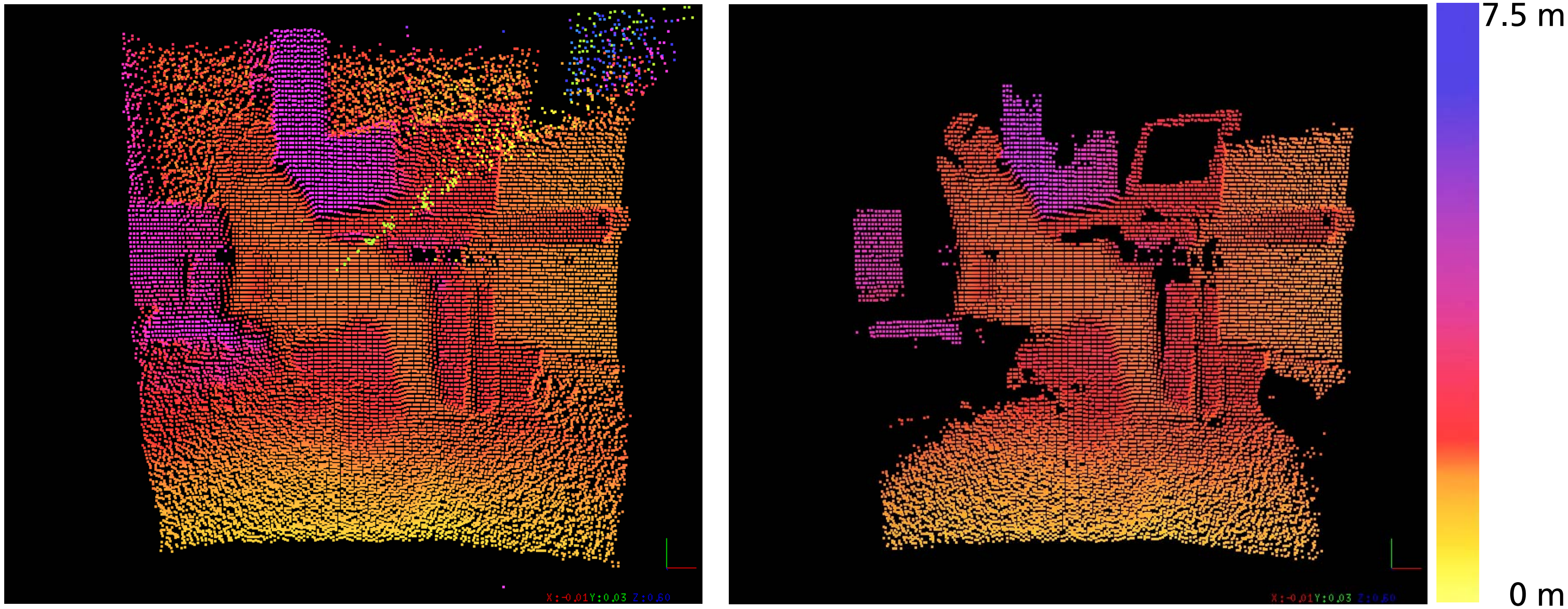
Evaluation

- Comparison of calculated pose with ground truth data (KUKA robot arm)
- Isometry of map
- First-to-last registration error

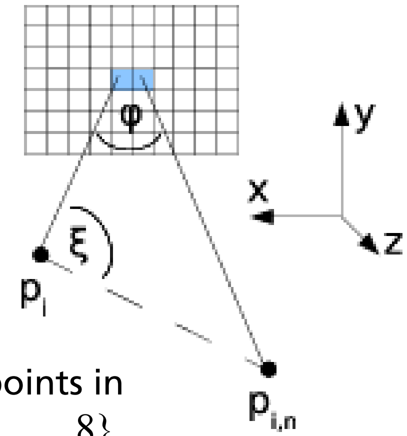
3D Environment Mapping

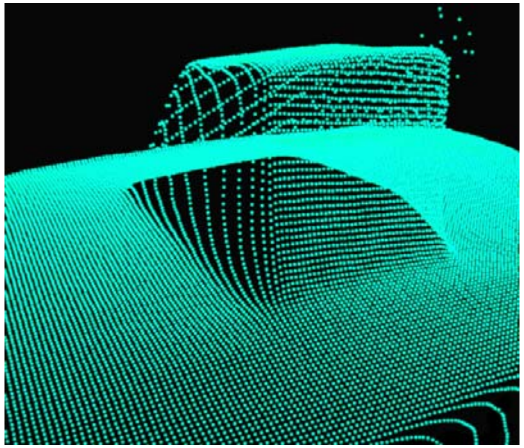
Filtering

Amplitude-Range Ratio (assuming: $\Delta r \propto d$)



3D Environment Mapping



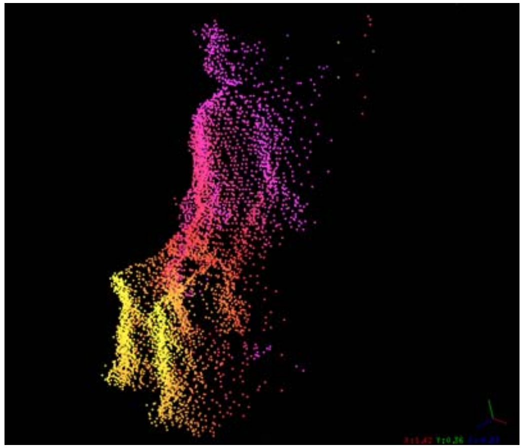


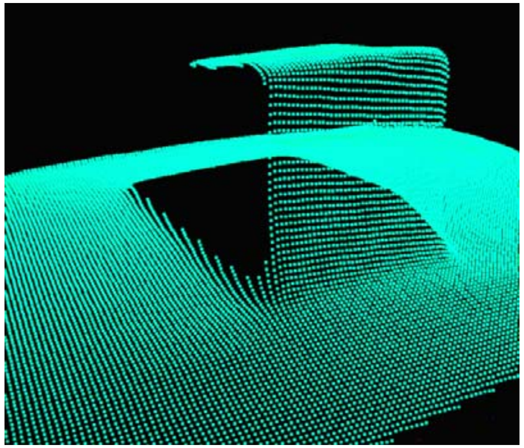
Filtering

Jump edge filtering

Let $P = \{\mathbf{p}_i \mid \mathbf{p}_i \in \mathbb{R}^3, i = 1, \ldots, N_p\}$ be a set of 3D points in the camera coordinate system and $P_n = \{\mathbf{p}_{i,n} \mid n = 1, \ldots, 8\}$ the set of neighbor points of $\mathbf{p}_i$, jump edges J can be selected with

$$\xi_i = \max \arcsin \left[\frac{\| \mathbf{p}_{i,n} \|}{\| \mathbf{p}_{i,n} - \mathbf{p}_i \|} \sin \varphi \right], \qquad (2)$$





$$J = \{\mathbf{p}_i \mid \xi_i > \xi_{th}\}, \qquad (3)$$

where

φ : apex angle of two neighboring pixel

ξ_{th} : threshold

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3D Environment Mapping

Challenges

- Small apex angle (3D data might have low structure)
- High degree of measurement errors

Pose Estimation

- ICP (Iterative Closest Point) matching [Besl,92]
- ICP matching on edges (scanline approx.) [Sappa,01]
- SIFT (Scale Invariant Feature Transformation) [Lowe,04]
- KLT (Kanade-Lucas-Tomasi) tracking [Lucas&Kanade,81] [Tomasi&Kanade,91]
- Extension for ICP
    - Trimmed ICP [Prusak,07]
    - Discard border assignments [Prusak,07]
    - Weighting based on amplitude data

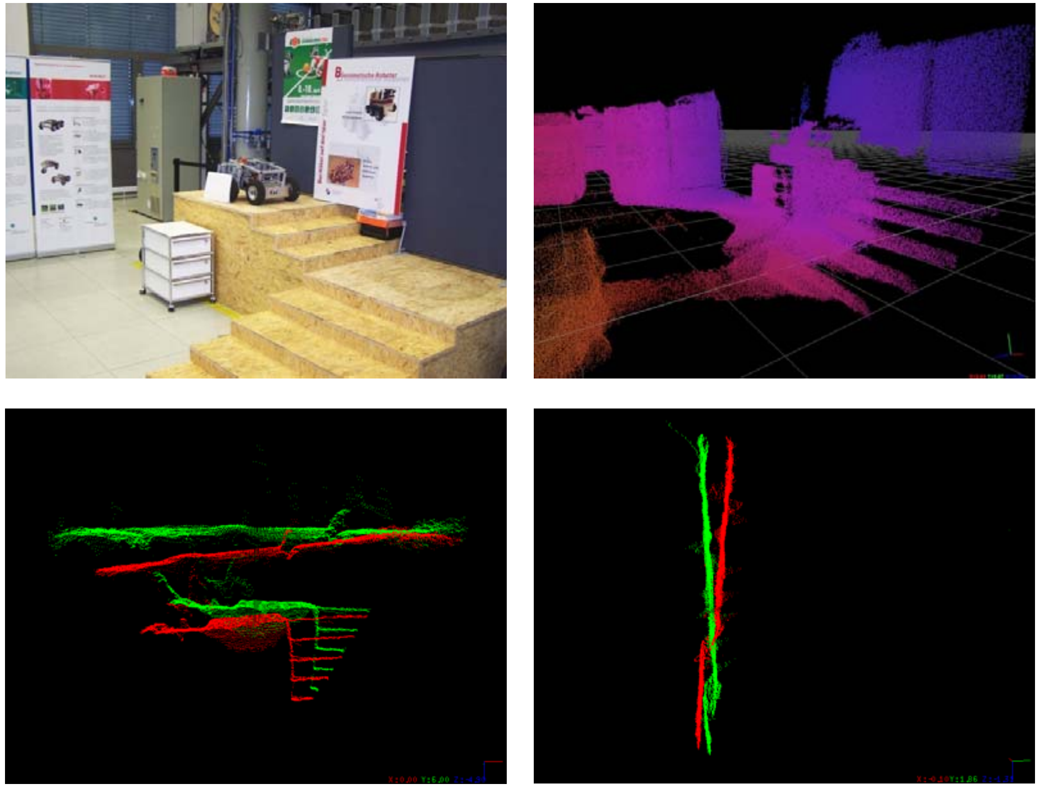
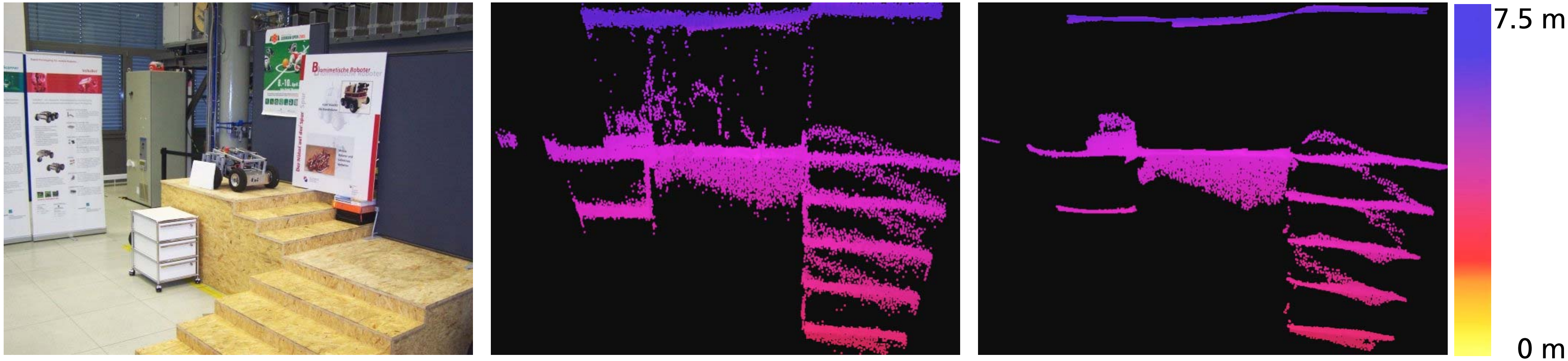


Fig.: Scene / Model matching

3D Environment Mapping

Refinement

- Error distribution (First-to-last registration)
- PCA analysis (surface detection)



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Experiments and Results – Introduction Calibration Issues

Three possible approaches for ToF camera calibration

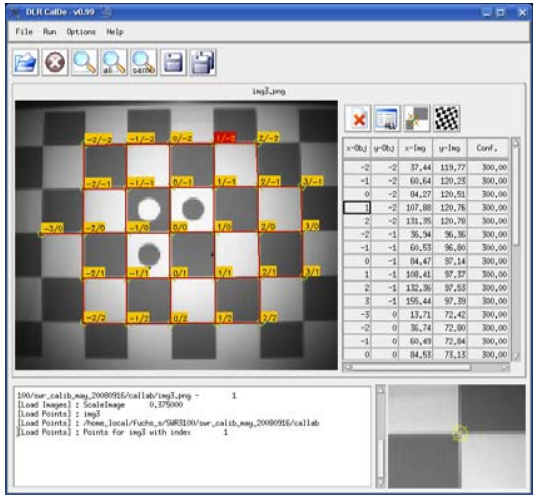
High Precision Measurement Rack	Robot serving as External Postioning System [Fuchs,07],[Fuchs,08]	No External Positioning System
• Very accurate for the whole working range of the ToF camera • Very laborious	• Limited to working range of robot • Efficient and sufficient for robotic applications	• Whole working range of the camera feasible, but limited by the Dimensions of the calibration pattern and the resolution of the camera

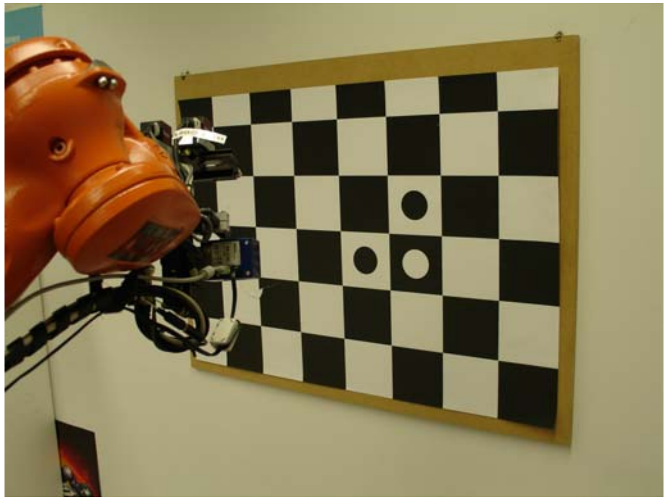
Experiments and Results – Photogrammetric and Depth Calibration

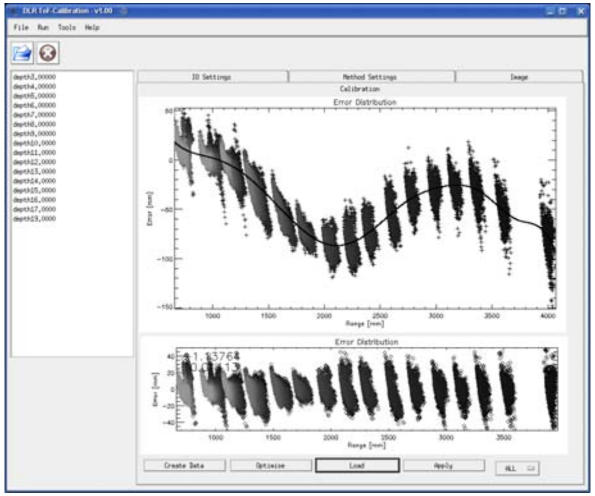
- Intrinsic parameter estimation applying a chequer board calibration pattern (DLR CalDe, Callab)

- Either using a robot as external positioning system
- Or estimating the calibration pattern pose from the image data (corners and known grid size)

- Identifiing spline parameters for distance-related measurement error



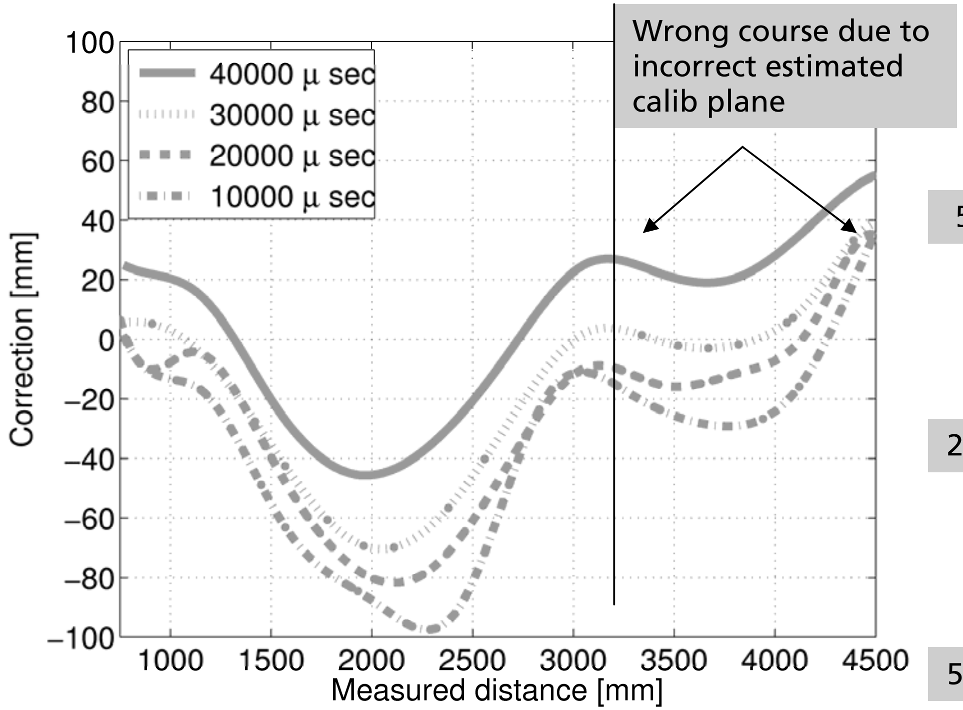


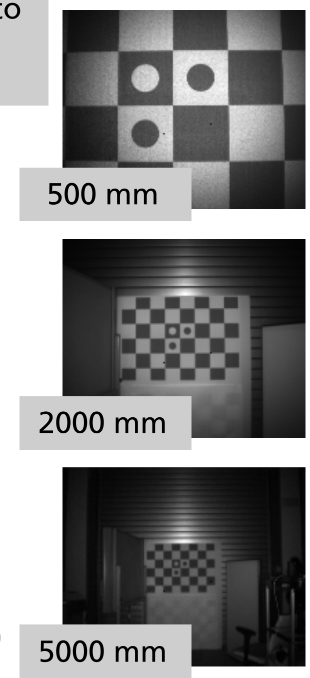


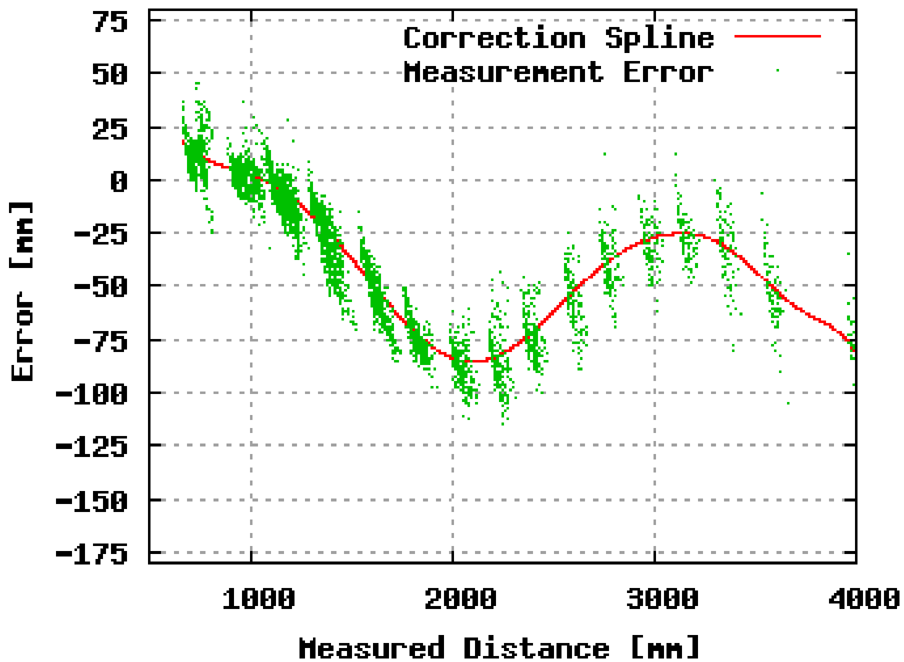
Experiments and Results – Calibration Results for several Integration Times

- Correction spline depends on the camera's integration time
  → The higher the integration time, the closer the measurements

- The calibration becomes imprecise for distances greater than 3500 mm
  → Small resolution and apex-angle cause imprecise calib plane pose estimation
  → The spline does not fit a harmonic sinus







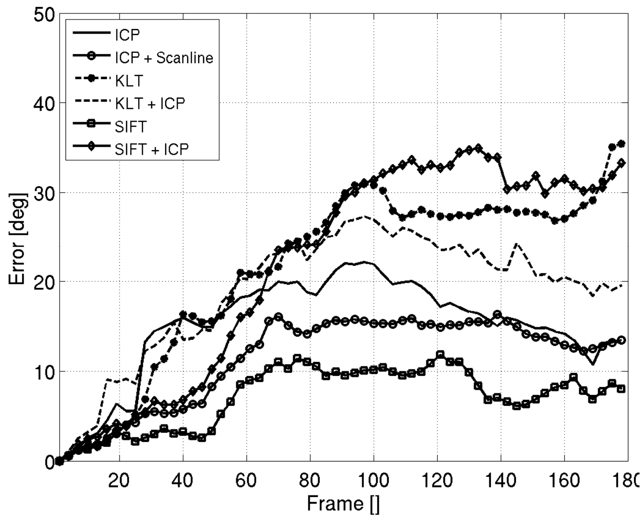
Experiments and Results – Mapping of a Labratory Scene

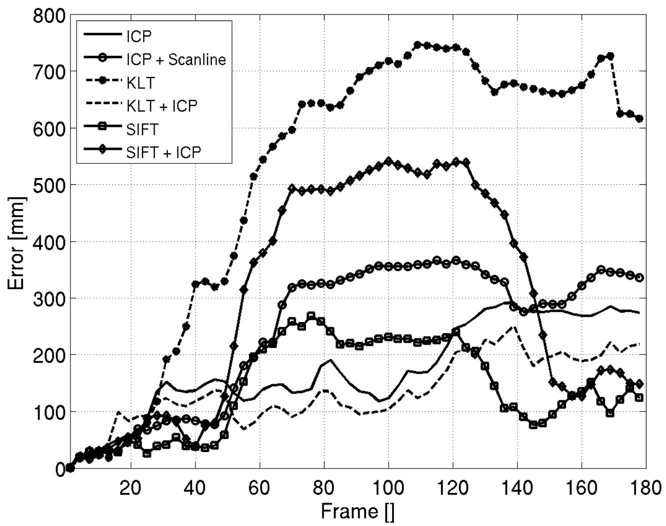
Objective: Evaluation of accuracy of ego-motion estimation

Performance of pose estimation is dependend on scene (e.g. texture, surface/edge ratio)

Small apex angle is the most restricting sensor modality

With some extensions (discarding border assignments, amplitude based weighting)
accuracy of ICP increases: $\Delta t < 150mm$, $\theta < 4°$





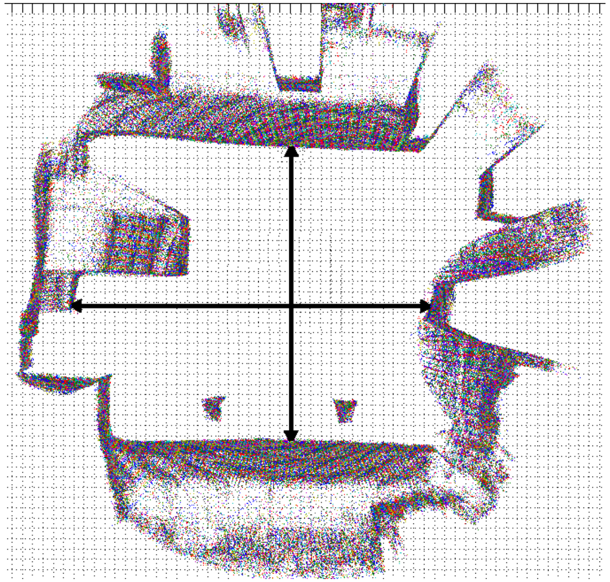
Experiments and Results – Mapping of a Labratory Scene

Objective: Evaluation of accuracy of ego-motion estimation

Scene extends 1800 x 1800 mm of styrofoam objects

SR3000 attached to an Industrial robot and calibrated

360° rotation, 180 depth images, path length 950 mm



	Accuracy in ego-motion estimation	Reconstruction error
Manufacturer's calibration	175 mm and 7°	Horizontal: 165 mm Vertical: 85 mm
Individual improved calibration	150 mm and 4°	Horizontal: 35 mm Vertical: 20 mm

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Experiments and Results – Mapping of a Larger Scene

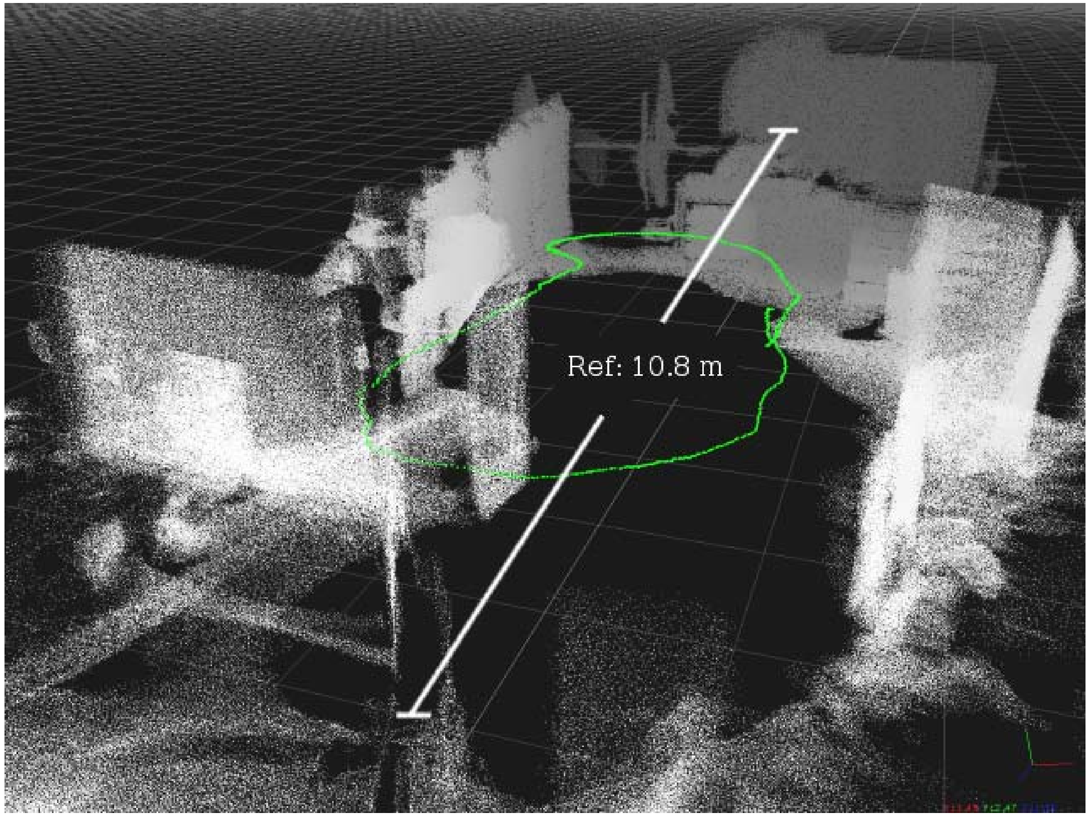
Dealing with great working range and high dynamics regarding the integration time and object's reflectivity

Evaluation of accuracy with extended ICP

Dimension: 19.4 m in the longest distance

Isometry measure: 11.2 m (vs. 10.8 m)

	Pose estimation in 3 DoF (x,z,θ_y)	Pose estimation in 6 DoF
Manufactuer's calibration	270 mm 6°	1230 mm 32°
Individual improved calibration	300 mm 1°	1740 mm 9°



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Conclusion and Summary

- Possibility of 3D mapping with ToF cameras
- Fully 2.5D captures allows for mapping during motion (avoids stop-scan-go behavior)
- Complex error model manageable with calibration and filtering
- Scene-dependent performance of tested pose estimation approaches

Outlook / Future Work

- More systematic evaluation of accuracy in pose estimation (more suitable path/motion)
- Including global scan relaxation approach
- Comparing performance with other ToF cameras (e.g. IFM O3D100)
- Improvement of calibration by using a greater calibration pattern

Video demonstration

see: http://www.iais.fraunhofer.de/3325.html

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