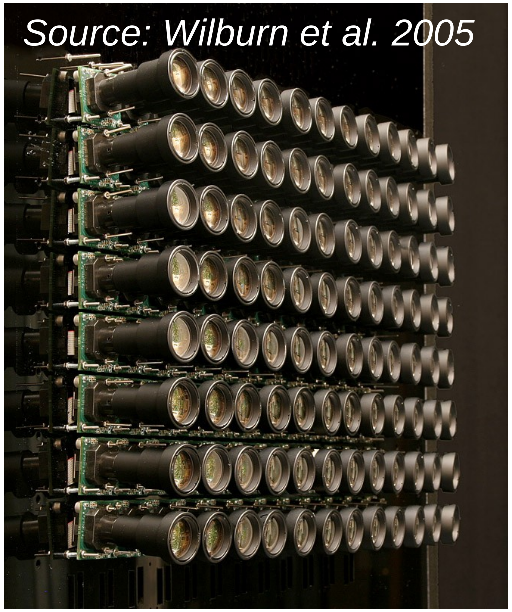
Synchronized Data Capture and Calibration of a Large-Field-of-View Moving Multi-Camera Light Field Rig

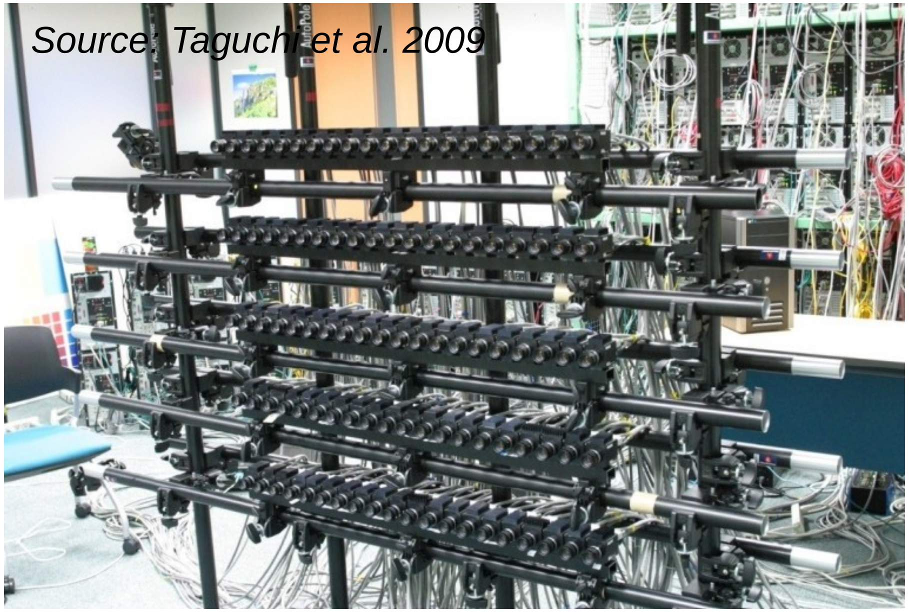
Sandro Esquivel, Yuan Gao, Tim Michels,
Luca Palmieri, Reinhard Koch

Workshop 3DTV-CON 2016
July 6, 2016

Multimedia Information Processing Group
Department of Computer Science
Christian-Albrechts-Universität Kiel

Introduction





- Large-scale camera arrays used for light field capturing of static and dynamic scenes with large range
- Challenges: calibration, synchronization, data storage/transfer

Wilburn, Joshi, Vaish, Talvala, Antunez, Barth, Adams, Horowitz & Levoy: *High Performance Imaging Using Large Camera Arrays*. SIGGRAPH 2005.

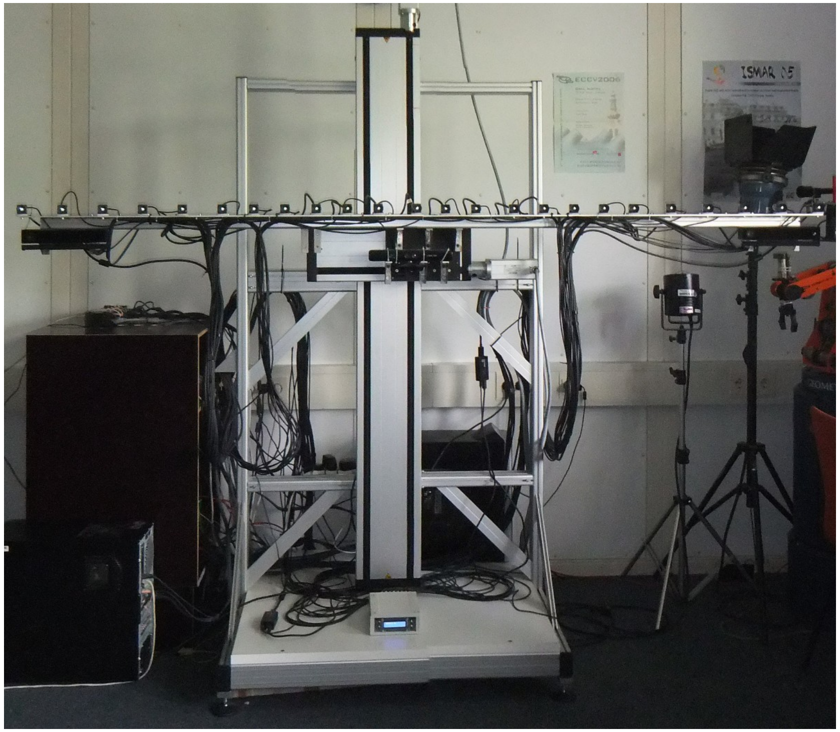
Tanimoto: *FTV Creating Ray-based Image Engineering*. ICIP 2005.

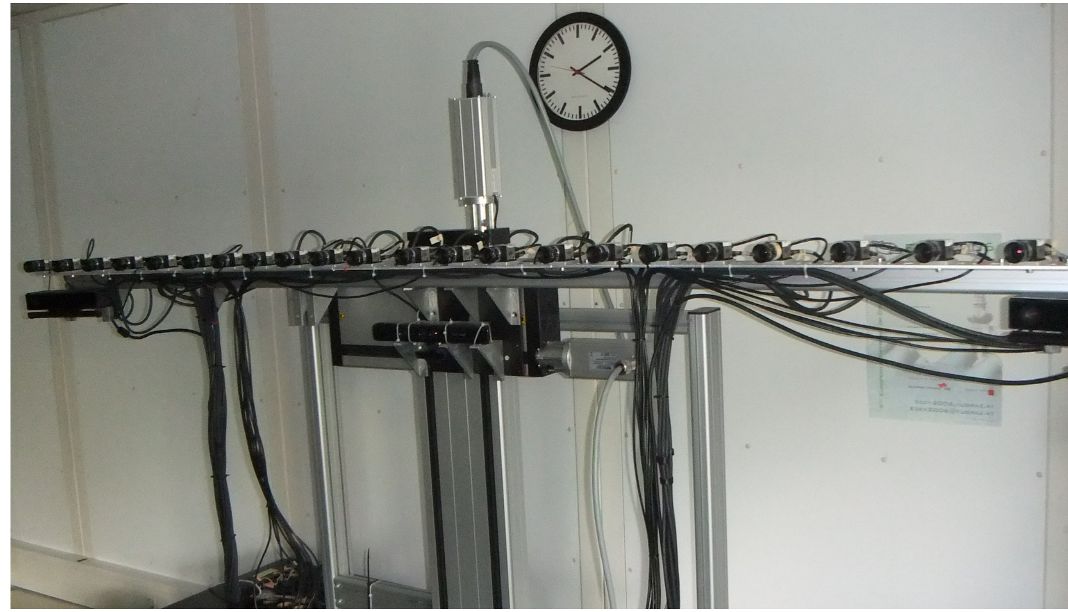
Taguchi, Takahashi & Naemura: *Design and Implementation of a Real-Time Video-Based Rendering System Using a Network Camera Array*. IEICE Trans. Inf. & Syst. (7) 2009.

Outline

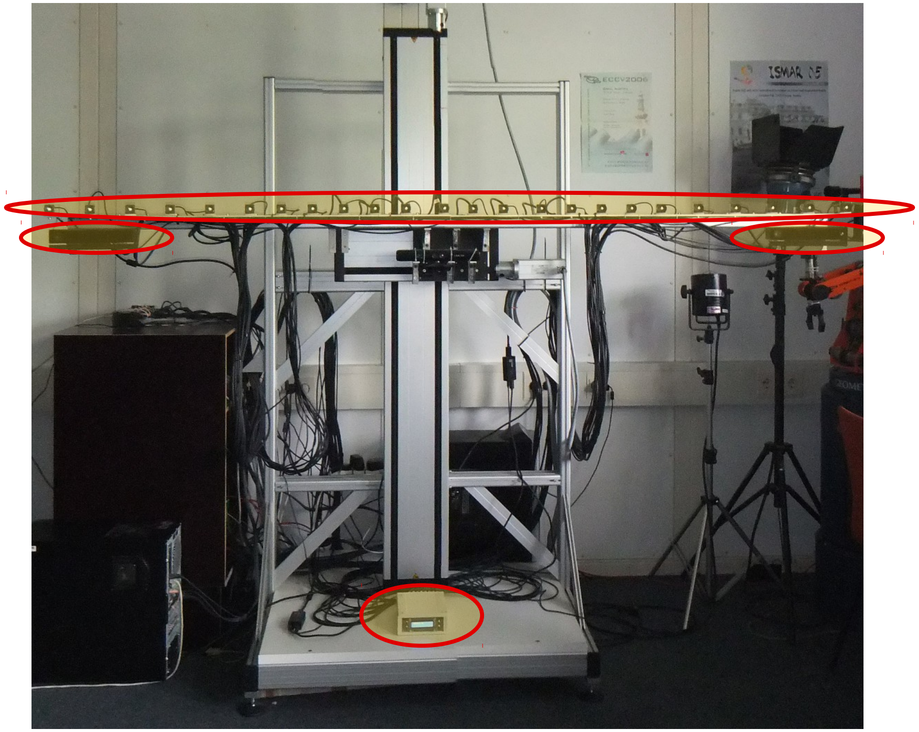
- System overview
- Camera system calibration
  - Intrinsic and extrinsic calibration
  - Depth camera calibration
  - Color correction
  - Results
- Synchronized data capture
- Data storage and transfer
- Applications
- Summary

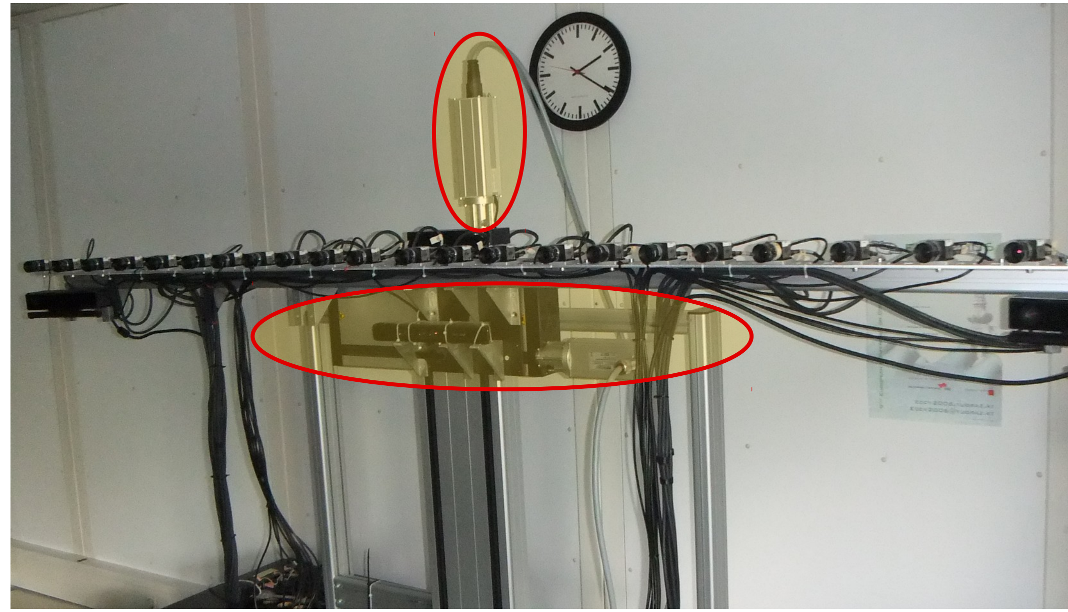
System Overview





- Specifications:
  - Large viewing volume (ca. 5 × 2.5 × 5 m)
  - Capture dynamic scenes with moderate frame rate (up to 15 fps)
  - Use color and depth cameras for *Depth Image-Based Modeling and Rendering*





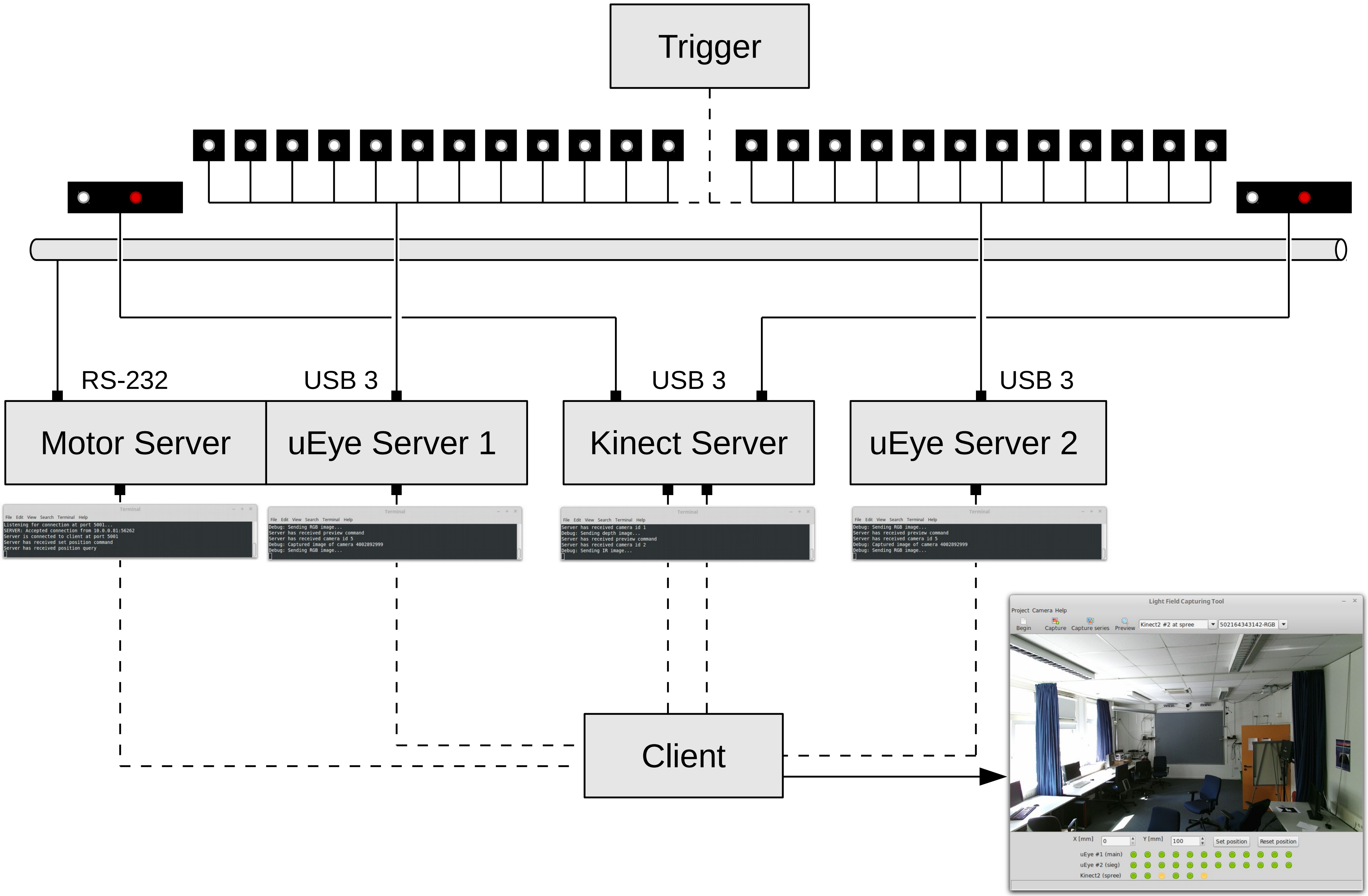
- 24× IDS USB 3 uEye CP RGB cameras at 2 hosts (12 per host)
- 2× Microsoft Kinect v2 RGB-D cameras at 1 host
- 1× isel iMC-S8 microstep controller for 2 linear axes
- 1× hardware trigger for synchronized uEye camera capture

- 24× IDS USB 3 uEye CP RGB cameras at 2 hosts (12 per host)
  - RGB: 1280 × 1024 px, 31° × 25° FOV
  - Lens: Pentax TV Lens 12 mm 1:1.4
- 2× Microsoft Kinect v2 RGB-D cameras at 1 host
  - RGB: 1920 × 1080 px, 84° × 54° FOV
  - Depth: 512 × 424 px, 70° × 60° FOV, 0.5 – 4.5 m range → 9 m
- 1× isel iMC-S8 microstep controller for 2 linear axes
  - resolution: 6.25 µm / step (x-axis), 3.125 µm / step (y-axis)
  - motion range is ca. 2 m vertical and 25 cm horizontal
- 1× hardware trigger for synchronized uEye camera capture

System Overview

- Linear camera setup along movable beam ($\Delta t \approx 11$ cm)
- Rotated inwards (max. $\Delta\alpha \approx 30°$) converging at 4.5 – 5 m distance

System Overview



Camera Images

uEye camera images (top left to bottom right)

Camera Images

Left Kinect color image

Right Kinect color image

Left Kinect depth and IR image

Right Kinect depth and IR image

Outline

- System overview
- Camera system calibration
  - Intrinsic and extrinsic calibration
  - Depth camera calibration
  - Color correction
  - Results
- Synchronized data capture
- Data storage and transfer
- Applications
- Summary

- Find intrinsic parameters for each color camera [Zha00; YEBM02]
- Find extrinsic parameters for all cameras in the rig [Zha00; YEBM02]
- Find motor axis direction vectors via hand-eye calibration [XMNT04]
- Undistort and rectify camera images to facilitate further image processing

✖ Alternative approach: Non-metric calibration [VWJL04]

Zhang: *A Flexible New Technique for Camera Calibration*. PAMI 2000.

Yang, Everett, Buehler & McMillan: *A Real-Time Distributed Light Field Camera*. Eurographics Workshop on Rendering 2002.

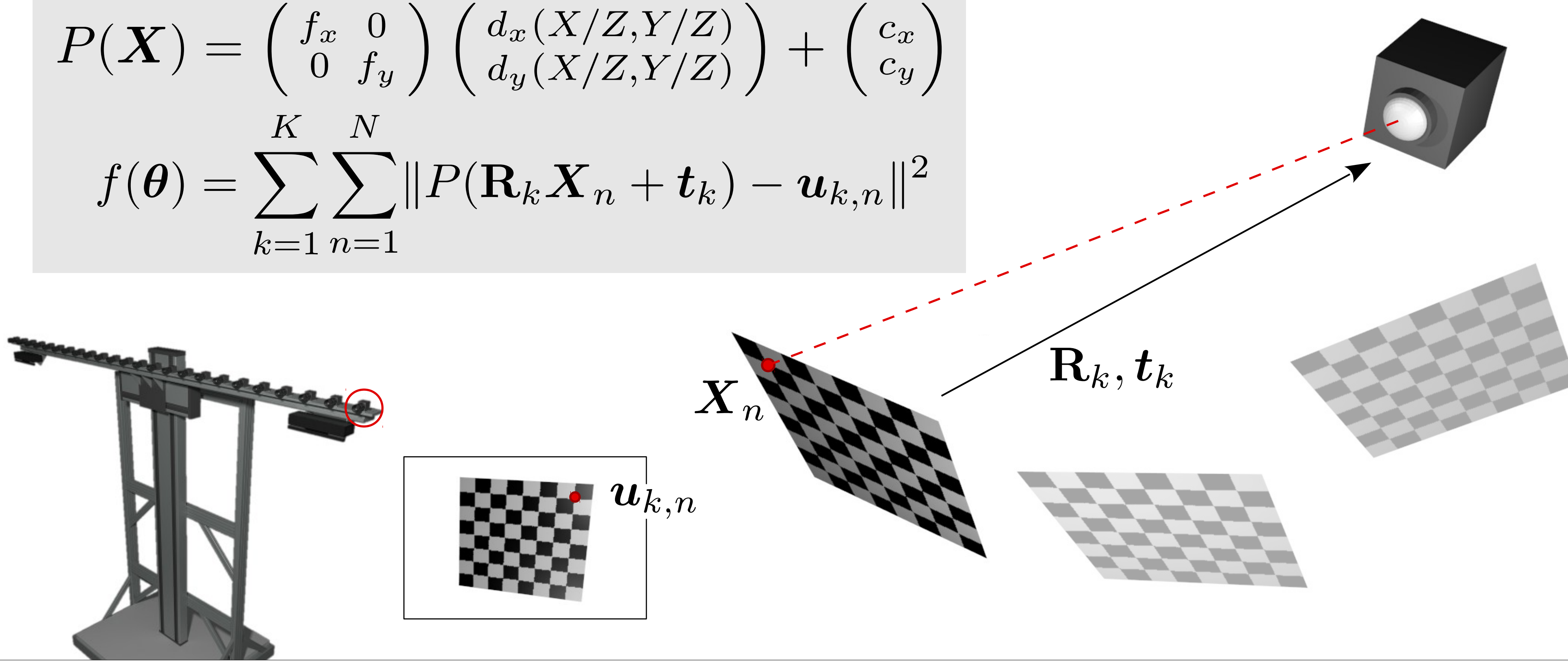
Xu, Maeno, Nagahara & Taniguchi: *Camera Array Calibration for Light Field Acquisition*. Frontiers of Computer Science 9 (5) 2015.

Vaish, Wilburn, Joshi & Levoy: *Using Plane + Parallax for Calibrating Dense Camera Arrays*. CVPR 2004.

- Find intrinsic parameters for each camera via reprojection error minimization from checkerboard images [Zha00]
- Intrinsics model projection and distortion function P

$$P(\boldsymbol{X}) = \begin{pmatrix} f_x & 0 \\ 0 & f_y \end{pmatrix} \begin{pmatrix} d_x(X/Z, Y/Z) \\ d_y(X/Z, Y/Z) \end{pmatrix} + \begin{pmatrix} c_x \\ c_y \end{pmatrix}$$

$$f(\boldsymbol{\theta}) = \sum_{k=1}^{K} \sum_{n=1}^{N} \| P(\mathbf{R}_k \boldsymbol{X}_n + \boldsymbol{t}_k) - \boldsymbol{u}_{k,n} \|^2$$



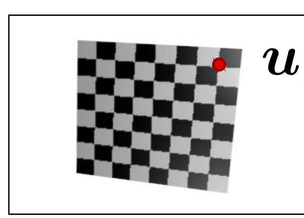
Zhang: *A Flexible New Technique for Camera Calibration*. PAMI 2000.

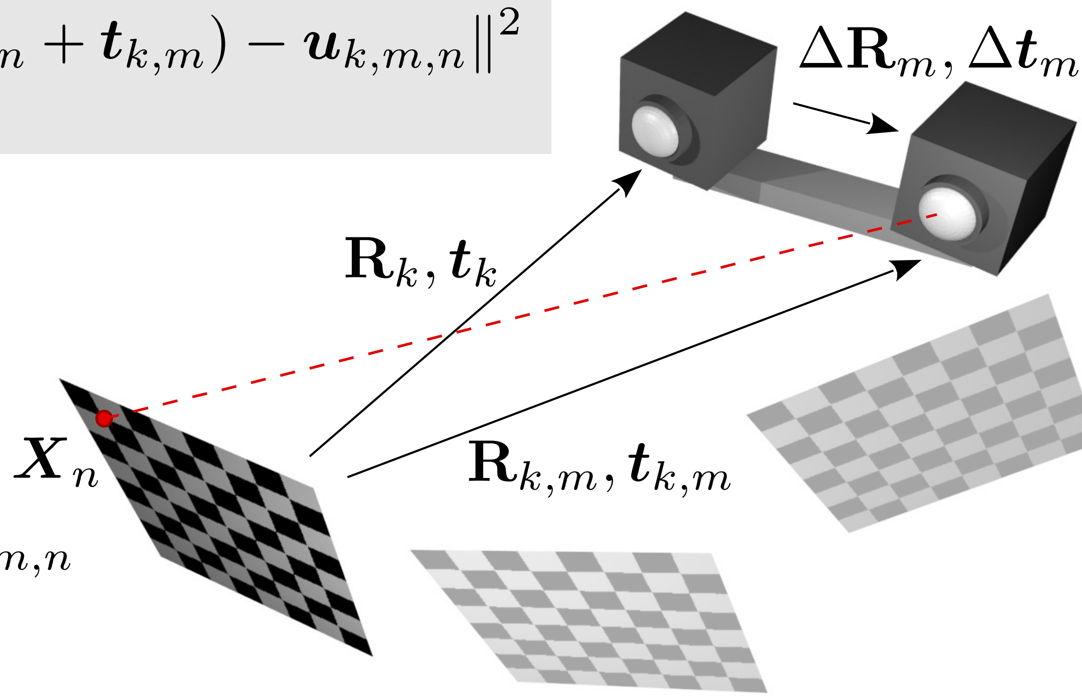
Extrinsic Calibration

- Find extrinsic parameters for M cameras from synchronously captured checkerboard images [Zha00]
- Extrinsics = local pose $\Delta\mathbf{R}_m$, Δt_m in array w. r. t. reference camera

$$f(\boldsymbol{\theta}) = \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N} \| P_m(\mathbf{R}_{k,m}\boldsymbol{X}_n + \boldsymbol{t}_{k,m}) - \boldsymbol{u}_{k,m,n} \|^2$$

$$\begin{aligned} \mathbf{R}_{k,m} &= \Delta\mathbf{R}_m \mathbf{R}_k \\ \boldsymbol{t}_{k,m} &= \Delta\mathbf{R}_m \boldsymbol{t}_k + \Delta\boldsymbol{t}_m \end{aligned}$$



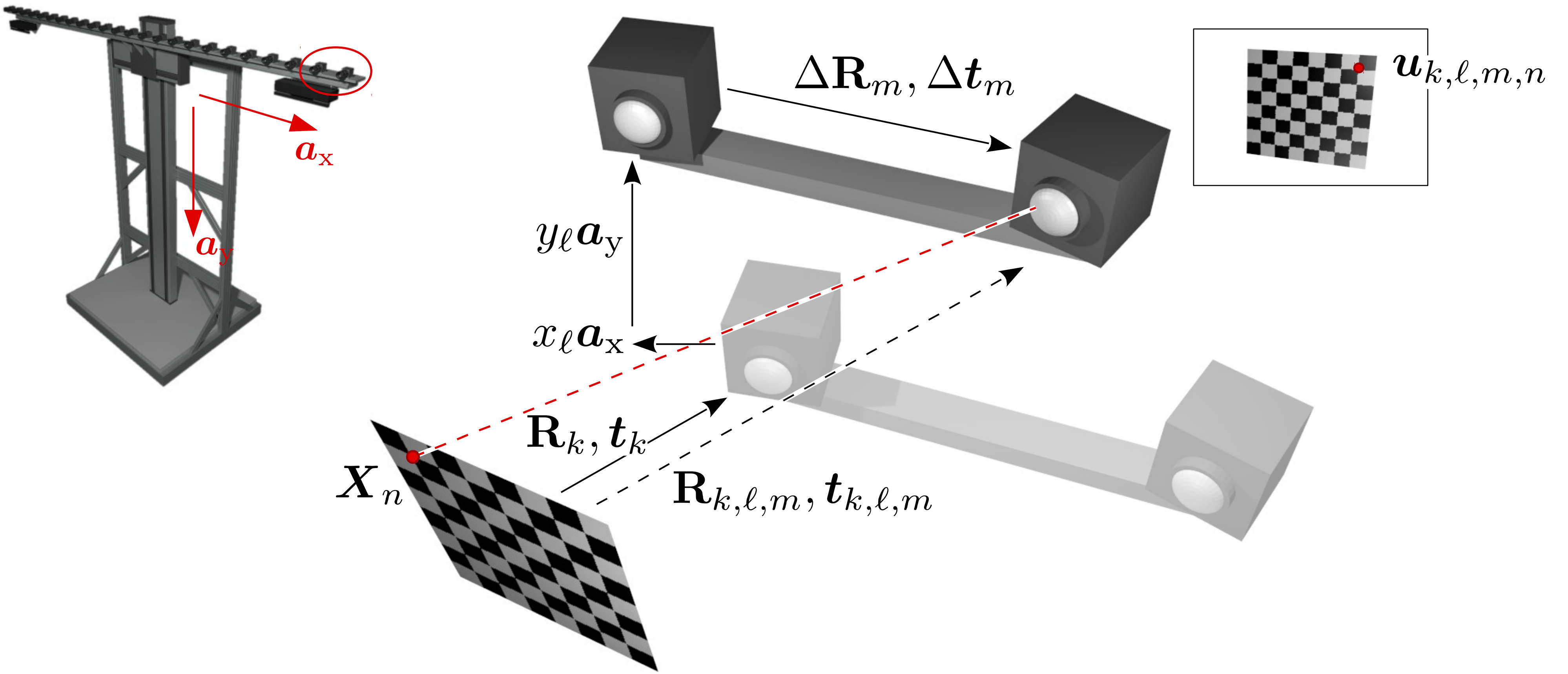


Zhang: *A Flexible New Technique for Camera Calibration*. PAMI 2000.

Full Metric Calibration

- Find motion direction vectors for motor axes [XMNT15]
- Global optimization of all camera system parameters using rigid coupling constraints
  - Use central camera as reference for rig
  - Capture checkerboard at K positions from L motor positions each
  - Refine extrinsics $\Delta\mathbf{R}_m$, Δt_m for M cameras and axis vectors a_x, a_y
  - Observations are 2d image points $u_{k,\ell,m,n}$ of N checkerboard points X_n and L motor axis offsets x_ℓ, y_ℓ
  - Error function is joint reprojection error
  - Predict all checkerboard poses from reference poses $\mathbf{R}_k$, t_k

Xu, Maeno, Nagahara & Taniguchi: *Camera Array Calibration for Light Field Acquisition*. Frontiers of Computer Science 9 (5) 2015.

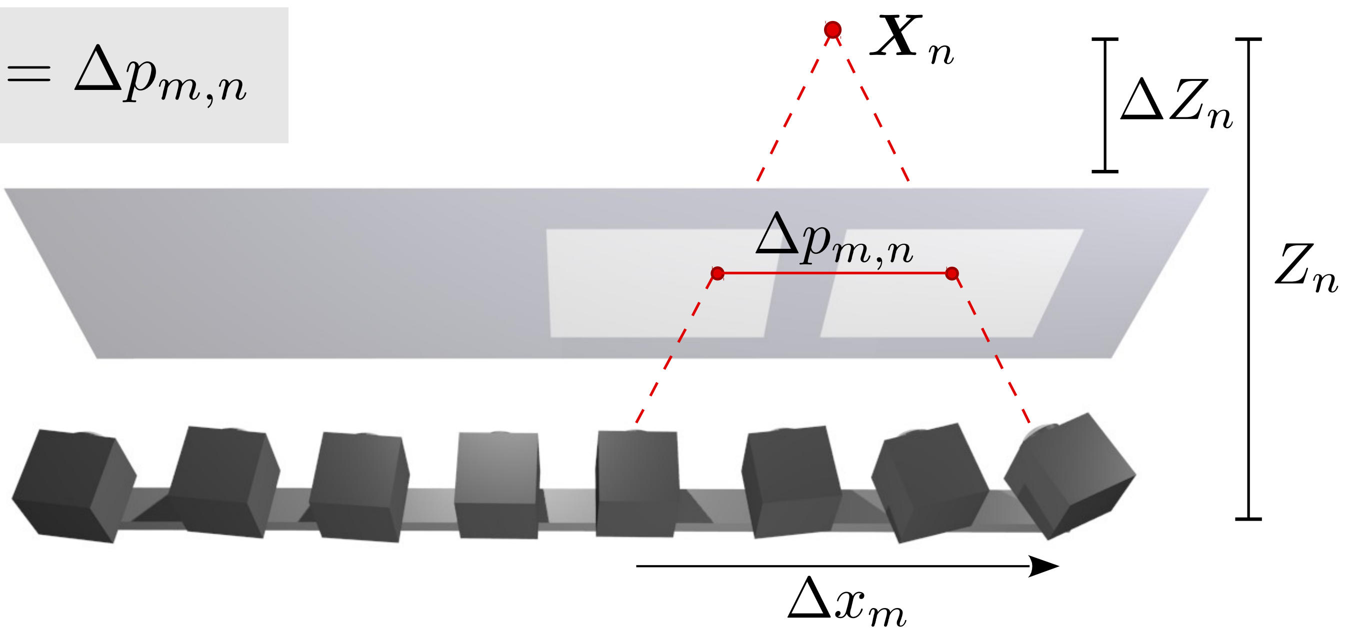


$$f(\boldsymbol{\theta}) = \sum_{k=1}^{K} \sum_{\ell=1}^{L} \sum_{m=1}^{M} \sum_{n=1}^{N} \| P_m(\mathbf{R}_{k,\ell,m} \boldsymbol{X}_n + \boldsymbol{t}_{k,\ell,m}) - \boldsymbol{u}_{k,\ell,m,n} \|^2$$

$$\mathbf{R}_{k,\ell,m} = \Delta\mathbf{R}_m \mathbf{R}_k, \ \boldsymbol{t}_{k,\ell,m} = \Delta\mathbf{R}_m(\boldsymbol{t}_k + x_\ell \boldsymbol{a}_\mathrm{x} + y_\ell \boldsymbol{a}_\mathrm{y}) + \Delta\boldsymbol{t}_m$$

- “Plane + Parallax” approach for planar camera setup:
  - Map camera images to parallel reference plane via homography estimation (compensates rotation, intrinsics, and vertical offset)
  - Estimate relative position from parallax between corresponding points
- Calibration of projection P up to unknown perspective 3d warp

$$\frac{\Delta Z_n}{Z_n} \Delta x_m = \Delta p_{m,n}$$



Vaish et al.: *Using Plane + Parallax for Calibrating Dense Camera Arrays*. CVPR 2004.

Non-Metric Calibration

- ✚ Linear approach, no initial solution needed
- ✚ Robust for narrow FOV and distant scenes
- ✚ Useful for tasks like synthetic aperture imaging
- ✖ Projection centers must be coplanar
- ✖ Mapping from 3d points to 2d image points is incomplete
- ✖ Fusion with depth maps is difficult

Vaish et al.: *Using Plane + Parallax for Calibrating Dense Camera Arrays*. CVPR 2004.

Outline

- System overview
- Camera system calibration
  - Intrinsic and extrinsic calibration
  - Depth camera calibration
  - Color correction
  - Results
- Synchronized data capture
- Data storage and transfer
- Applications
- Summary

- Find intrinsic/extrinsic parameters for each ToF sensor [SBK08; PP15]
- Find parameters for depth correction [SBK08; ZWYD08; LMLG15]
- Improve calibration parameters provided by manufacturer
- Find relative pose between 3d point clouds from each device [KND15]

Schiller, Beder & Koch: *Calibration of a PMD-Camera Using a Planar Calibration Pattern together with a Multi-Camera Setup*. ISPRS 2008.

Pagliari & Pinto: *Calibration of Kinect for Xbox One and Comparison between the Two Generations of Microsoft Sensors*. MDPI Sensors (15) 2015.

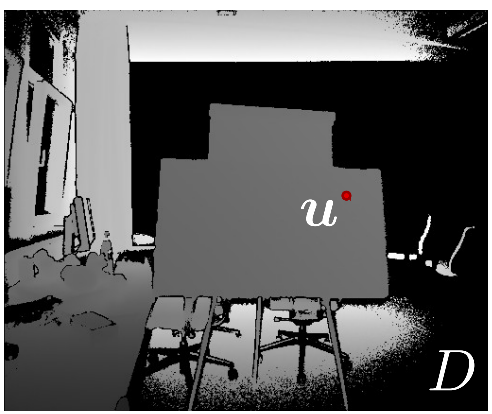
Lachat, Macher, Landes & Grussenmeyer: *Assessment and Calibration of a RGB-D Camera Towards a Potential Use for Close-Range 3D Modeling*. Remote Sensing 6 (10) 2015.

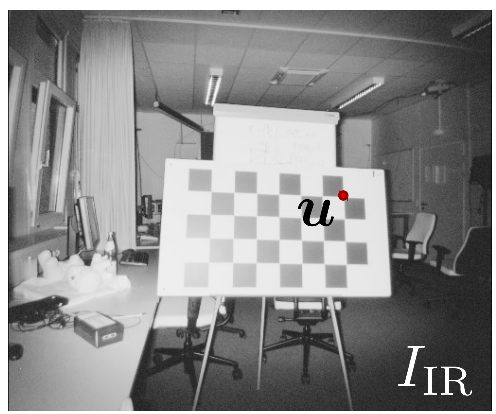
Kowalski, Naruniec & Daniluk: *LiveScan3D: A Fast and Inexpensive 3D Data Acquisition System for Multiple Kinect v2 Sensors*. 3DV 2015.

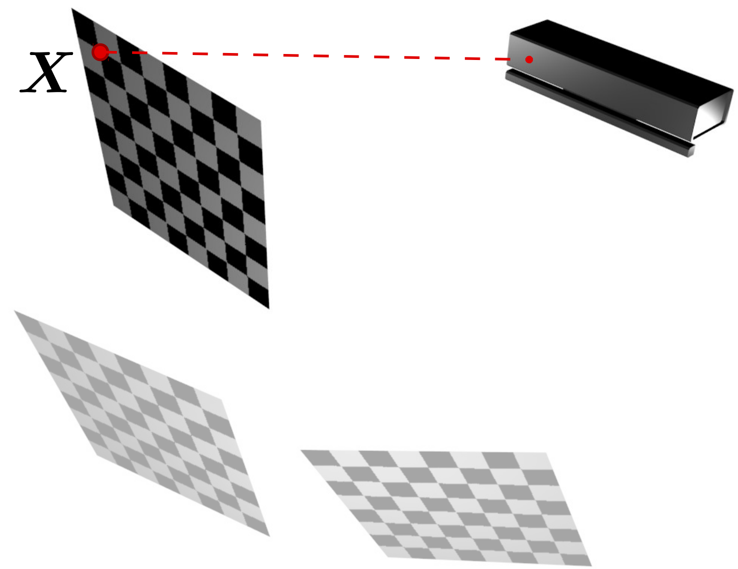
Zhu et al.: *Fusion of ToF Depth and Stereo for High Accuracy Depth Map*. CVPR 2008.

- Find intrinsic parameters from checkerboard in IR images [Zha00]
- Refine depth on 3d plane via *Analysis by Synthesis* [SBK08; PP15]
- Improve via joint calibration with color cameras

$$\boldsymbol{X} = D(\boldsymbol{u})\, P_{\mathrm{IR}}^{-1}(\boldsymbol{u})$$



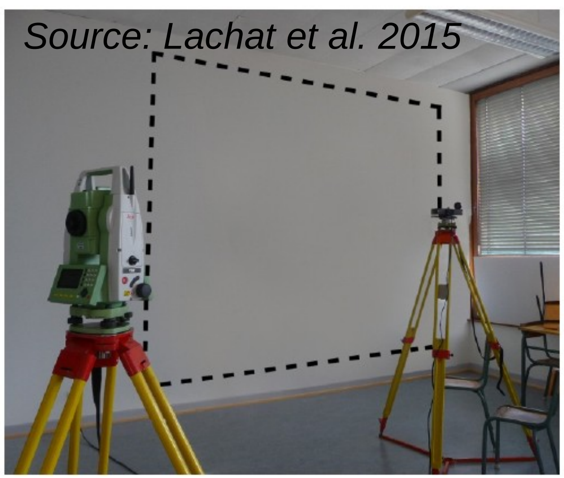




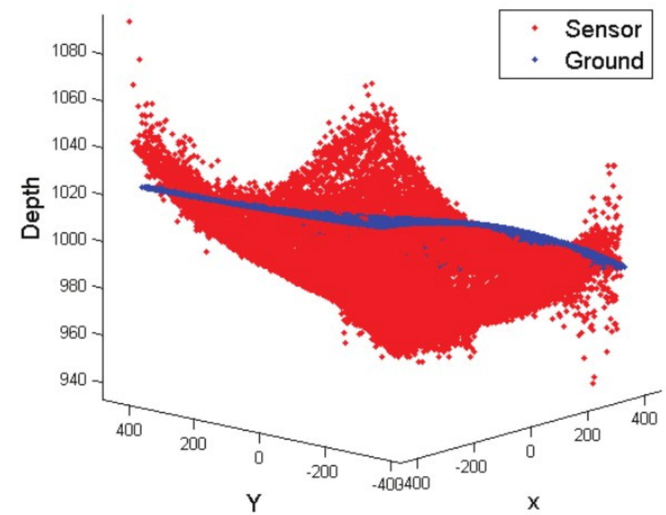
Schiller, Beder & Koch: *Calibration of a PMD-Camera Using a Planar Calibration Pattern together with a Multi-Camera Setup*. ISPRS 2008.

Pagliari & Pinto: *Calibration of Kinect for Xbox One and Comparison between the Two Generations of Microsoft Sensors*. MDPI Sensors (15) 2015.

- Correct systematic and intensity-related distance error using 3d reference points [LMLG15; ZWYD08]
  - provide 3d points from color camera or 3d laser distance measures
  - model depth correction with lookup tables, polynomials or B-splines
  - refine via joint calibration with color cameras


Source: Lachat et al. 2015


Source: Zhu et al. 2008

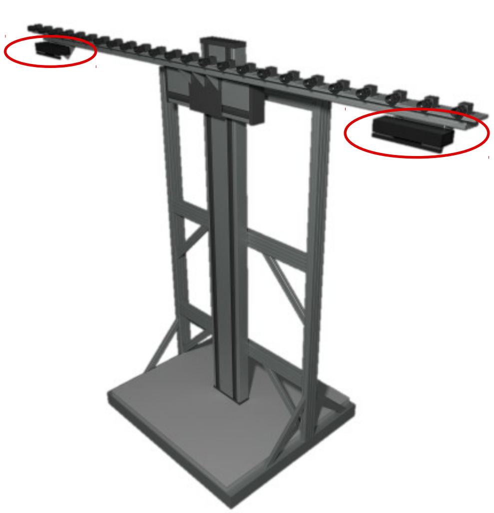
Source: Zhu et al. 2008


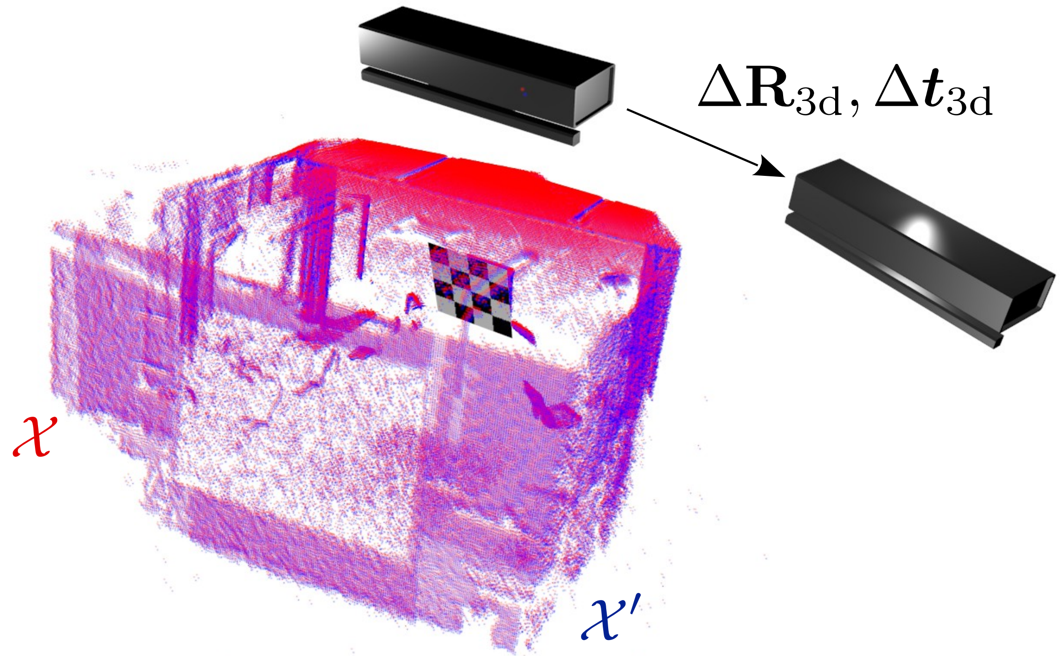
Lachat, Macher, Landes & Grussenmeyer: *Assessment and Calibration of a RGB-D Camera Towards a Potential Use for Close-Range 3D Modeling*. Remote Sensing 6 (10) 2015.

Zhu et al.: *Fusion of ToF Depth and Stereo for High Accuracy Depth Map*. CVPR 2008.

- Find relative pose between depth cameras from registration of 3d point clouds using *Iterative Closest Point* [KND15]

$$\min_{\Delta\boldsymbol{\theta}} \sum_{\boldsymbol{X} \in \mathcal{X}} \min_{\boldsymbol{X}' \in \mathcal{X}'} \|\Delta\mathbf{R}_{3\mathrm{d}}\boldsymbol{X} + \Delta\boldsymbol{t}_{3\mathrm{d}} - \boldsymbol{X}'\|^2$$





Kowalski, Naruniec & Daniluk: *LiveScan3D: A Fast and Inexpensive 3D Data Acquisition System for Multiple Kinect v2 Sensors*. 3DV 2015.

Outline

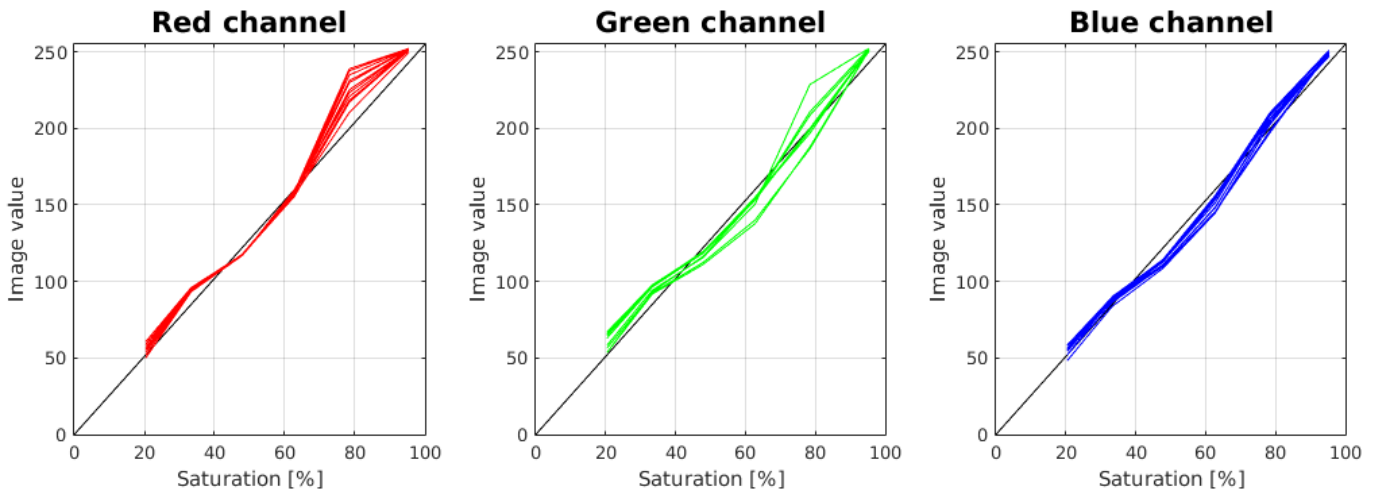
- System overview
- Camera system calibration
  - Intrinsic and extrinsic calibration
  - Depth camera calibration
  - Color correction
  - Results
- Synchronized data capture
- Data storage and transfer
- Applications and results
- Summary

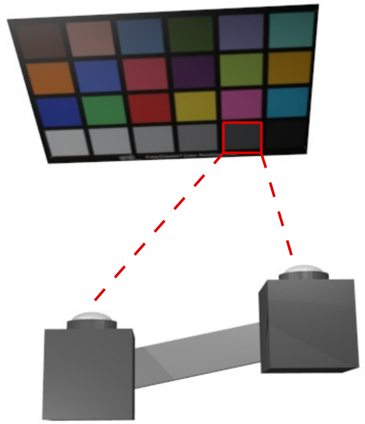
- Color varies between cameras even with same (default) settings
- Leads to artifacts in view interpolation/color image fusion

Color chart images from different uEye cameras

Color Correction

- Color varies between cameras even with same (default) settings
- Leads to artifacts in view interpolation/color image fusion
- Automatic color correction with color calibration chart images [Jos04]
  - Capture RGB responses for grayscale patches
  - Set camera gains/offsets to match responses to lines iteratively
  - Refine resulting responses with lookup tables

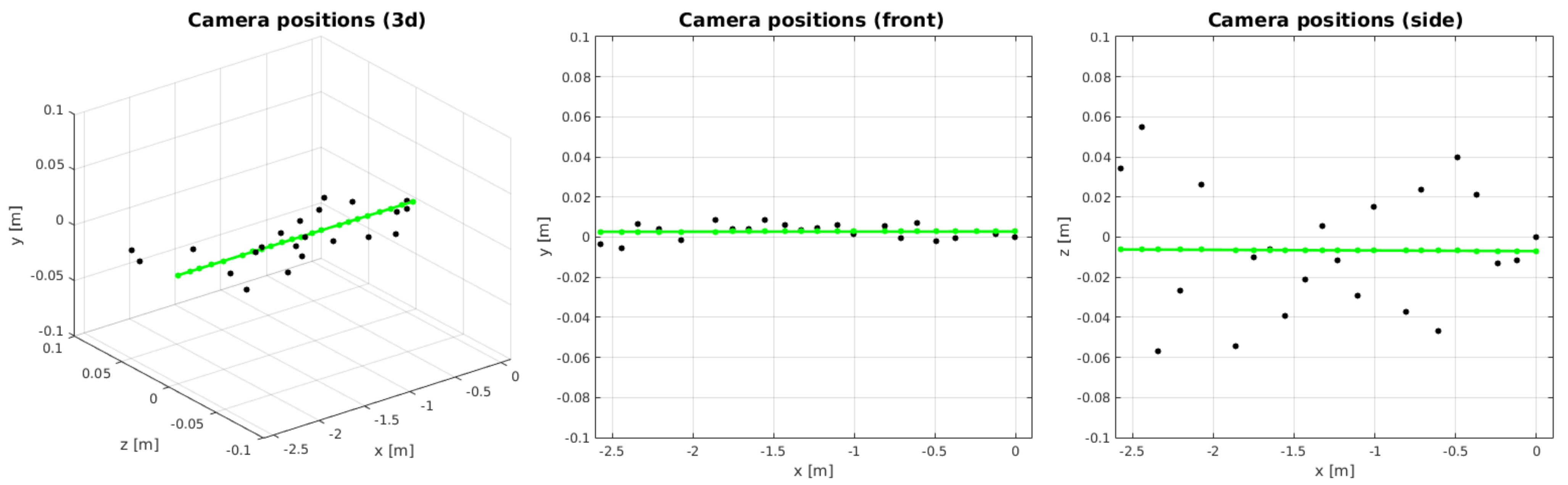




Joshi: *Color Calibration for Large Arrays of Inexpensive Image Sensors*. M.Sc. Thesis 2004.

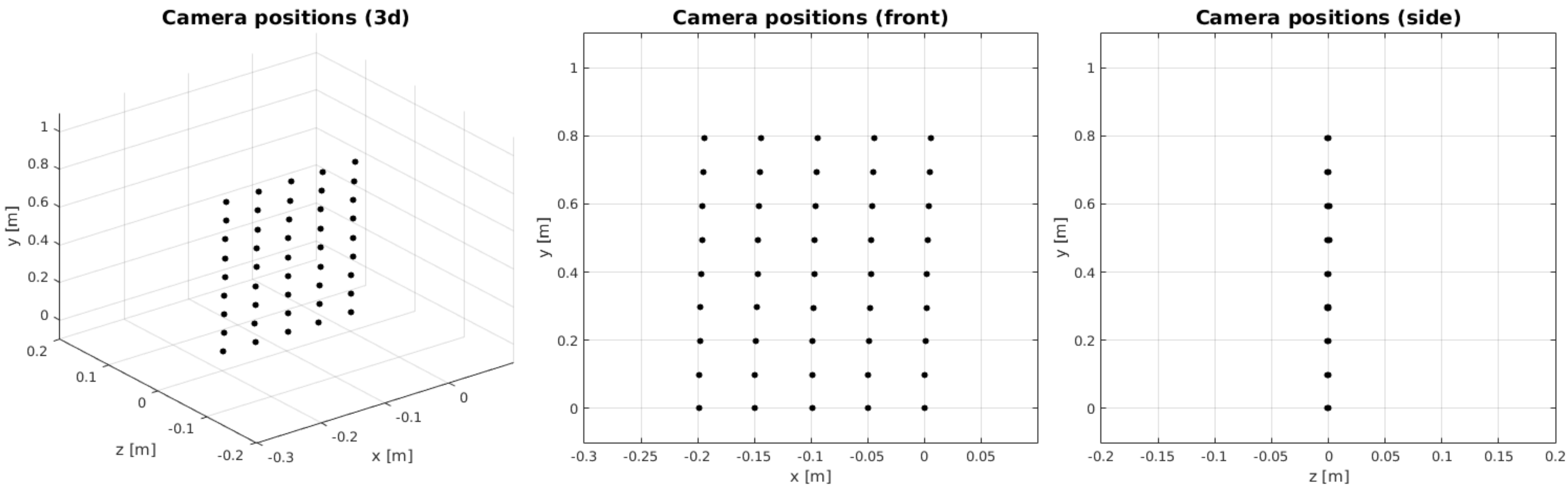
Outline

- System overview
- Camera system calibration
  - Intrinsic and extrinsic calibration
  - Depth camera calibration
  - Color correction
  - Results
- Synchronized data capture
- Data storage and transfer
- Applications and results
- Summary



- Extrinsic calibration of 22 uEye cameras from 26 × 22 images
- Results show non-collinearity of projection centers
- Average deviation from line: $\sigma_y = 3.9$ mm, $\sigma_z = 31.4$ mm
- Average reprojection error: $\sigma_u = 0.13$ px

Calibration Results

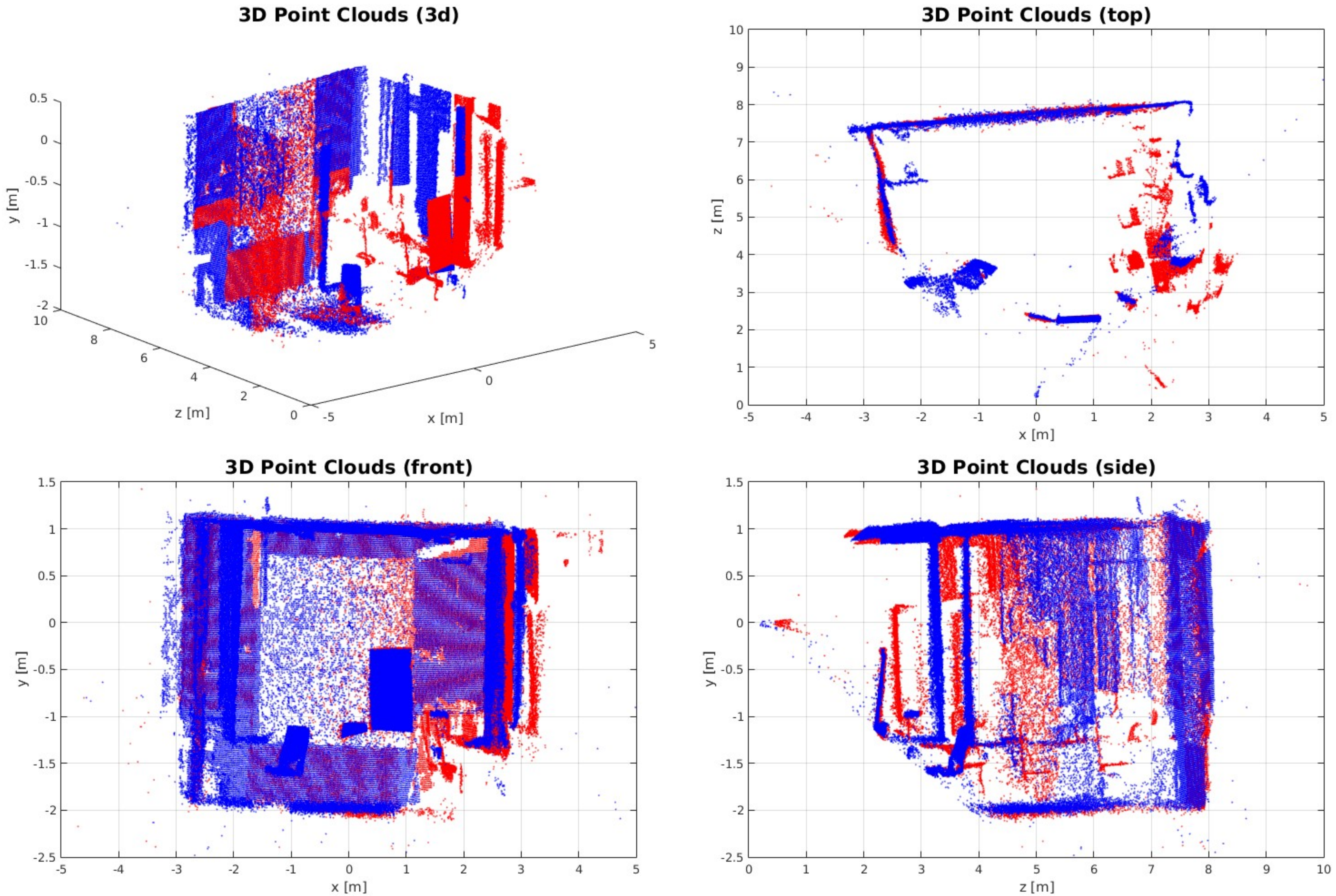


- Hand-eye calibration using 5 × 9 motor positions for 22 cameras
- Results: a_x = (0.9997, 0.0003, 0.0230), $\alpha(a_x, e_x)$ = 1.32°
  a_y = (-0.0045, 0.9999, -0.0075), $\alpha(a_y, e_y)$ = 0.51°
- Average deviation from plane: σ_d = 2.1 mm → 0.47 mm
- Average reprojection error: σ_u = 0.49 px → 0.21 px

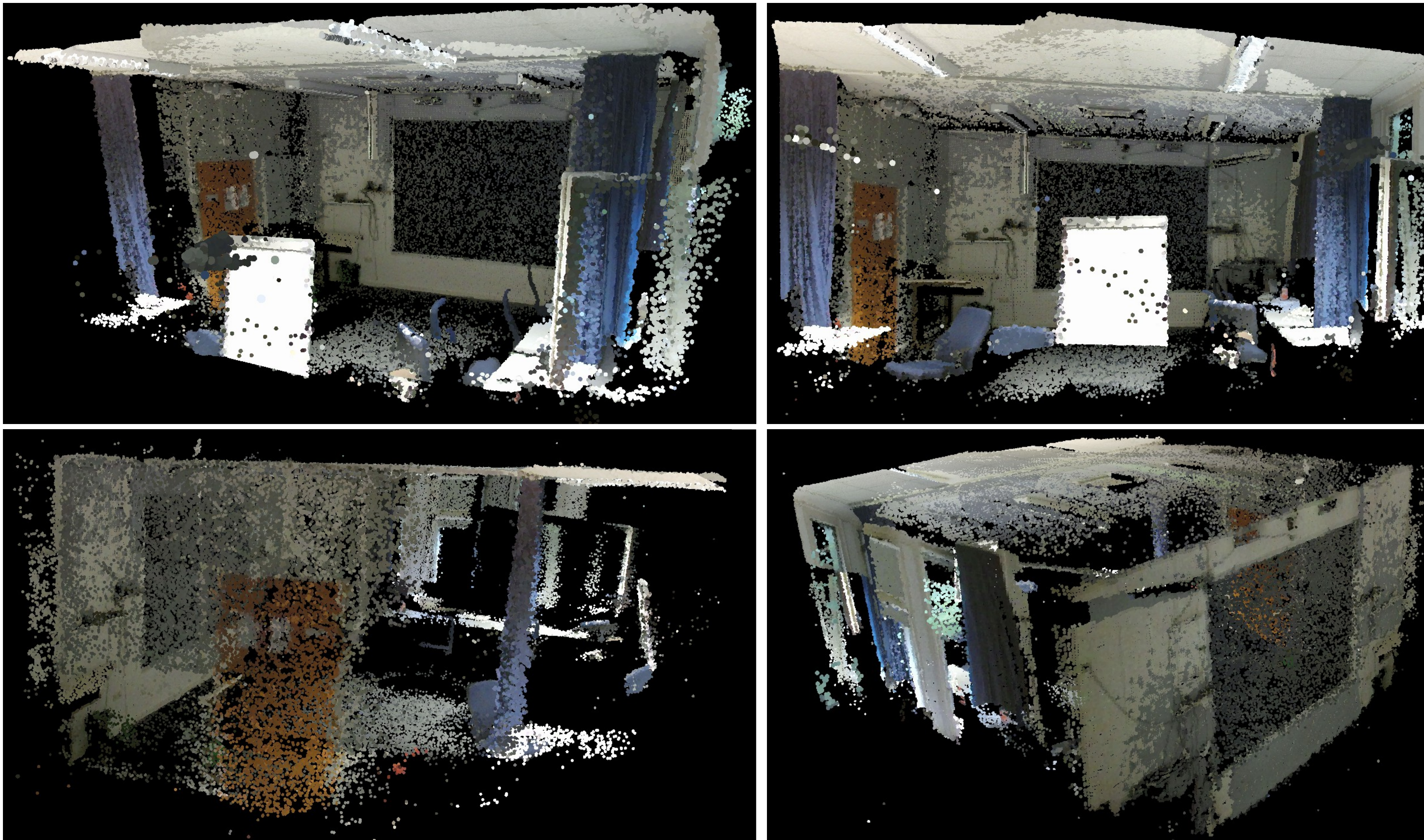
Calibration Results

M I P Multimedia Information Processing

- Results for depth map fusion of left/right Kinect2 sensor



- Results for colored 3d points of left/right Kinect2 sensor



Outline

- System overview
- Camera system calibration
  - Intrinsic and extrinsic calibration
  - Depth camera calibration
  - Color correction
  - Results
- **Synchronized data capture**
- Data storage and transfer
- Applications
- Summary

Synchronized Data Capture

- Synchronize uEye cameras
  - use hardware trigger
- Synchronize Kinect2 cameras internally
  - trigger with signals, use timestamps for finetuning
- Synchronize Kinect2 cameras and uEye cameras
  - skip frames (for continuous capture), use timestamps for alignment
- Issues with multiple Kinect2 sensors
  - use multiple USB 3 boards or multiple server hosts
  - take care of inter-device interference [SLK15; KND15]

Sarbolandi, Lefloch & Kolb: *Kinect Range Sensing: Structured-Light versus Time-of-Flight Kinect*. Journal of Computer Vision and Image Understanding, 2015.

- System overview
- Camera system calibration
  - Intrinsic and extrinsic calibration
  - Depth camera calibration
  - Color correction
  - Results
- Synchronized data capture
- **Data storage and transfer**
- Applications
- Summary

Data Storage and Transfer

- Large amounts of uncompressed data
  - 3.93 MB per uEye camera image = 2 × 47.19 MB for 2 × 12 cameras
  - 6.22 MB per Kinect2 color image = 12.44 MB for 2 devices
  - 0.87 MB per Kinect2 depth image = 1.74 MB for 2 devices
- Hosts for uEye cameras process 708 MB/s each at 15 fps
  - feasible with modern SSD devices (800 MB/s)
- However, compression and selective capture needed for real-time light field capturing!

Outline

- System overview
- Camera system calibration
  - Intrinsic and extrinsic calibration
  - Depth camera calibration
  - Color correction
  - Results
- Synchronized data capture
- Data storage and transfer
- Applications
- Summary

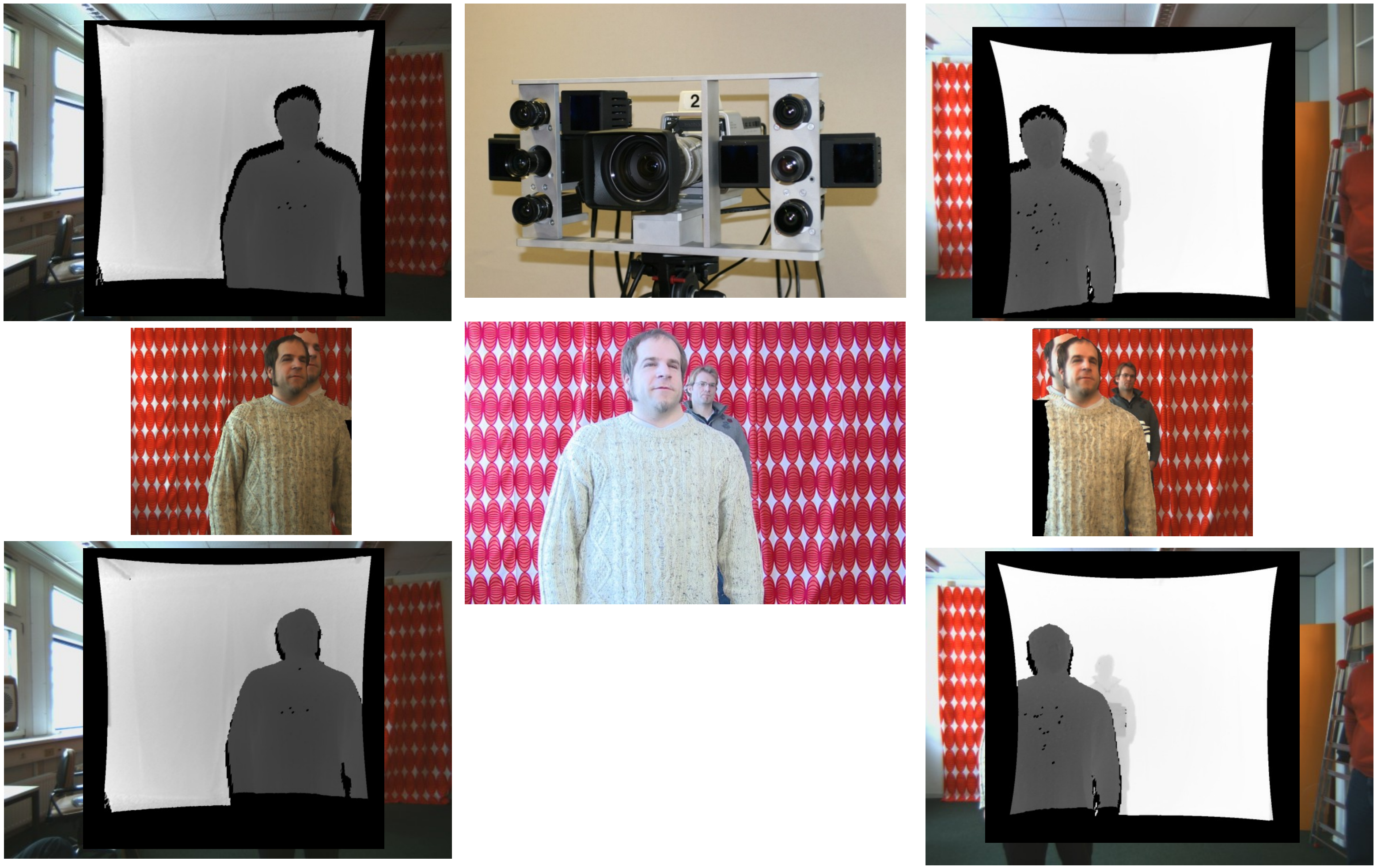
- Live 3D-TV content creation with a portable RGB-D camera rig

Camera rig with 5 color cameras +
2 ToF depth cameras (left/right)

Schiller, Bartczak, Kellner & Koch: *Increasing Realism and Supporting Content Planning for Dynamic Scenes in a Mixed Reality System Incorporating a ToF Camera*. CVMP 2008.

Applications

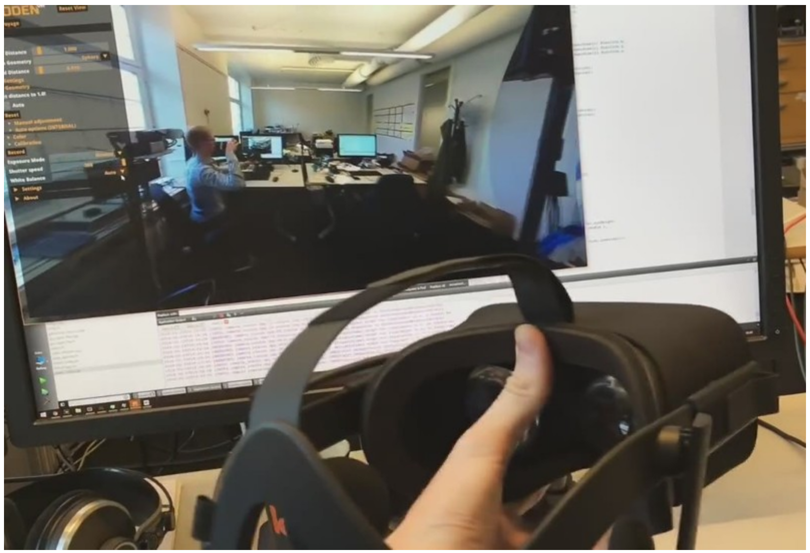
- Live 3D-TV content creation with a portable RGB-D camera rig

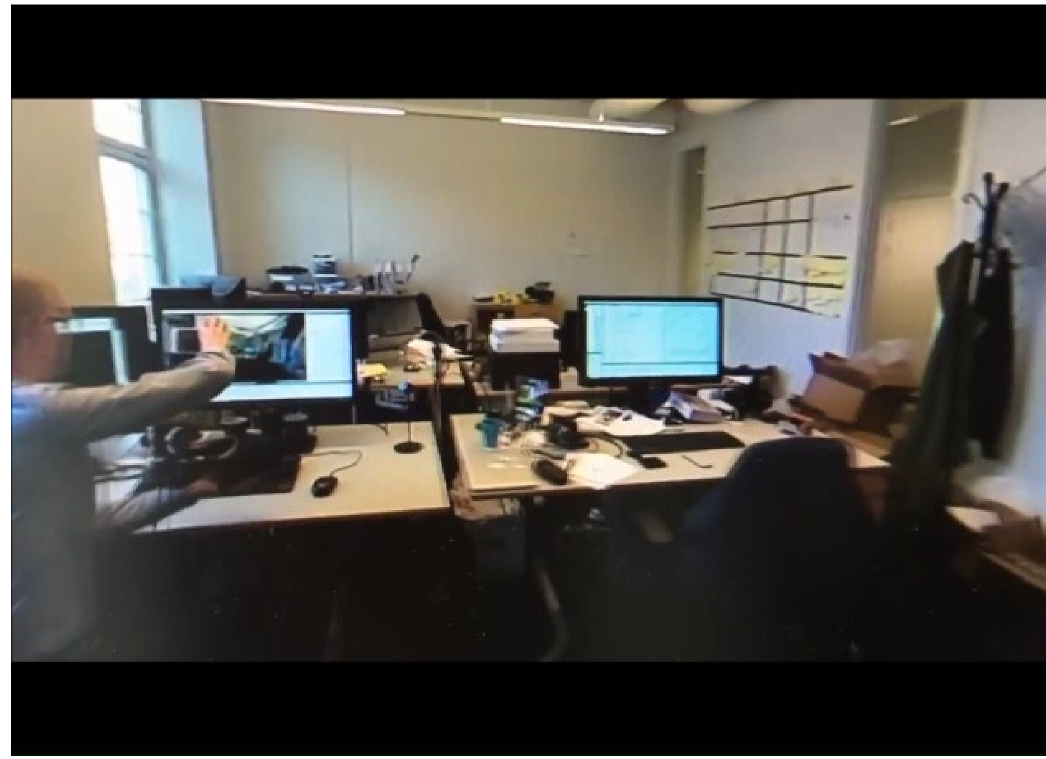


Schiller, Bartczak, Kellner & Koch: *Increasing Realism and Supporting Content Planning for Dynamic Scenes in a Mixed Reality System Incorporating a ToF Camera*. CVMP 2008.

Applications

- Virtual Reality light field viewer using Oculus Rift headset





voysys

Voysys Live VR Lightfield – Quick Tech Demo. May 26, 2016.
https://www.youtube.com/watch?v=BGVFhFMRrUE

Outline

- System overview
- Camera system calibration
  - Intrinsic and extrinsic calibration
  - Depth camera calibration
  - Color correction
  - Results
- Synchronized data capture
- Data storage and transfer
- Applications
- Summary

Summary

- Overview of large-scale RGB-D capturing system at CAU
  - Server/client architecture for remote/distributed control
  - Hardware/software synchronization of data capture
- Intrinsic and extrinsic calibration of capturing system using established methods for multi-camera setups
- Automatic color calibration necessary to reduce inter-camera color/brightness variance
- Calibration of depth cameras necessary to improve 3d measurements

Future Work

M I P Multimedia Information Processing

- Improvement of capturing software
  - Integrate calibration methods
  - Synchronization of Kinect2 cameras still challenging
- Data compression for light field storage (offline)
- Selective capture for real-time light field processing (online)
- Adaptation of existing applications to large-scale setup
  - Video capture for autostereoscopic displays
  - Light field viewer using virtual reality headsets
- Create dense light field datasets for evaluation purposes

References

- Gurbuz et a.: *Color Calibration for Multi-Camera Imaging Systems*. IUCS 2010.
- Joshi: *Color Calibration for Large Arrays of Inexpensive Image Sensors*. M.Sc. 2004.
- Kowalski, Naruniec & Daniluk: *LiveScan3D: A Fast and Inexpensive 3D Data Acquisition System for Multiple Kinect v2 Sensors*. 3DV 2015.
- Lachat et al.: *Assessment and Calibration of a RGB-D Camera Towards a Potential Use for Close-Range 3D Modeling*. Remote Sens. 6 (10) 2015.
- Pagliari & Pinto: *Calibration of Kinect for Xbox One and Comparison between the Two Generations of Microsoft Sensors*. MDPI Sensors (15) 2015.
- Sarbolandi, Lefloch & Kolb: *Kinect Range Sensing*. Comp. Vis. and Image Underst. 2015.
- Schiller, Beder & Koch: *Calibration of a PMD-Camera Using a Planar Calibration Pattern together with a Multi-Camera Setup*. ISPRS 2008.
- Taguchi et al.: *Design and Implementation of a Real-Time Video-Based Rendering System Using a Network Camera Array*. IEICE Trans. Inf. & Syst. (7) 2009.
- Tanimoto: *FTV Creating Ray-based Image Engineering*. ICIP 2005.
- Vaish et al.: *Using Plane + Parallax for Calibrating Dense Camera Arrays*. CVPR 2004.
- Wilburn et al.: *High Performance Imaging Using Large Camera Arrays*. SIGGRAPH 2005.
- Yang et al.: *A Real-Time Distributed Light Field Camera*. Eurographics Workshop 2002.
- Xu et al.: *Camera Array Calibration for Light Field Acquisition*. Front. Comp. 9 (5) 2015.
- Zhang: *A Flexible New Technique for Camera Calibration*. PAMI 2000.
- Zhu et al.: *Fusion of ToF Depth and Stereo for High Accuracy Depth Map*. CVPR 2008.

Acknowledgments

- This work has been supported by:
  - European Training Network on Full Parallax Imaging (ETN-FPI, H2020-MSCA-ITN-2015, ref. no. 676401)
  - Intel Visual Computing Institute (2015–2017)
  - DFG – Deutsche Forschungsgemeinschaft (KO2044/8-1)