Tutorial on 3D Surface Reconstruction in Laparoscopic Surgery

Foundations of Time-of-Flight Cameras and their Application to Surface Reconstruction

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Overview

- Time-of-Flight Cameras: The Photonic Mixing Device (PMD) Principle
- PMD Characteristics and Calibration
- 2D/3D Sensor Fusion
- Endoscopic Application
- Summary

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Time of Flight Cameras

- At a glance: Cameras …
  - … are camera-like distance sensors
  - … deliver range maps plus intensity values instantaneously (up to 40 FPS)
  - … have moderate resolution (max. 204^2 px)
- Basic Technological Approaches for ToF-Cameras
  - Photonic Mixing: Electrical, on-chip mixing in smart pixels
  - Optical Shuttering: Optical mixing
- Current Sensors

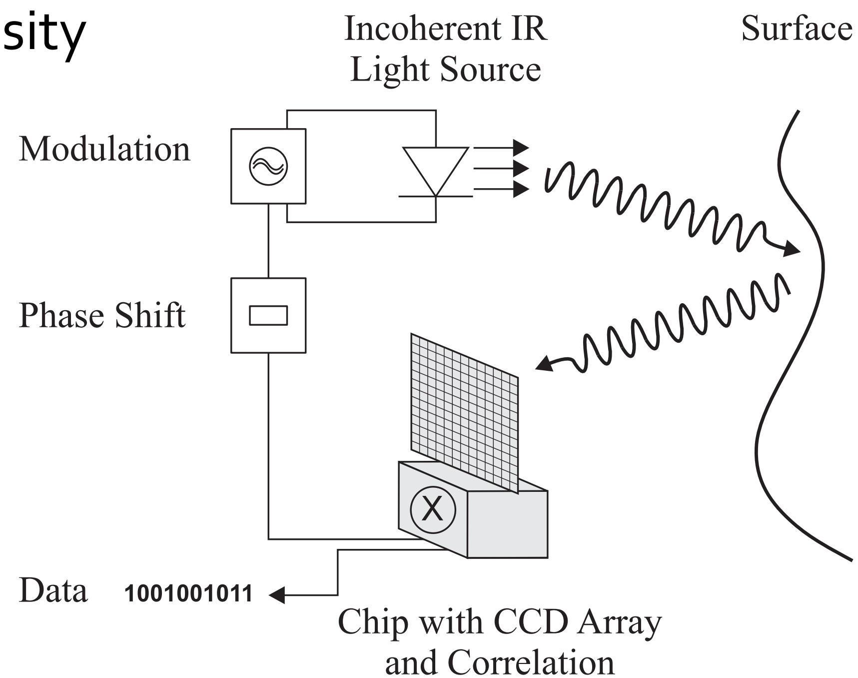
CamCube®
PMD Technologies

SwissRanger 4000®
Mesa Imaging

ZCam®
3DVSystems

Intensity Modulation Approach

- Photonic Mixing Device (PMD):
  - Active time-of-flight approach
  - Intensity modulation of incoherent light (NIR)
  - Correlation of reference signal and optical signal
- "Smart pixel" realizes a photo mixing detector to sample the correlation function with Standard CMOS-technology
- Suppression of background intensity



Intensity Modulation Approach

- Correlation Function $c(\tau)$
  - Reference signal: $g(t+\tau)$ (τ internal phase-shift)
  - Optical signal: $s(t)$
  - Correlation:

$$c(\tau) = s \otimes g = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} s(t) \cdot g(t+\tau)\, dt$$

  - Sinusoidal signal: Trigonometric calculus yields

$$g(t) = \cos(\omega t), \qquad \omega \text{ modulation frequency}$$

$$s(t) = k + a \cdot \cos(\omega t + \phi), \qquad \phi \text{ phase delay (distance)}$$

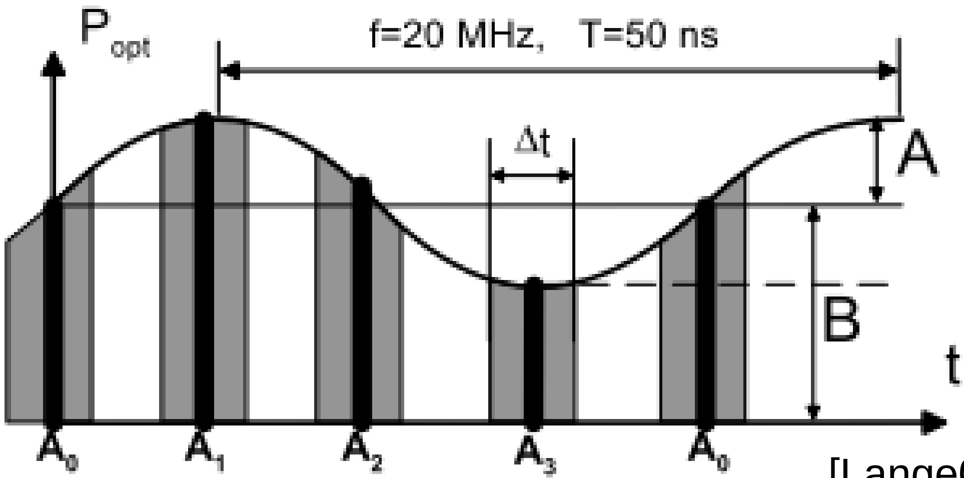
$$c(\tau) = \frac{a}{2} \cos(\omega\tau + \phi)$$

Intensity Modulation Approach

- Distance computation
  - Sampling $c(\tau)$ for 4 different internal phase shifts yields four phase images $A_i = c(i \cdot \frac{\pi}{2})$
  - Demodulation gets phase delay

$$\phi = \arctan\left(\frac{A_3 - A_1}{A_0 - A_2}\right), \quad a = \frac{\sqrt{(A_3 - A_1)^2 + (A_0 - A_2)^2}}{2}$$

  - Applying speed of light gets distance $d = \frac{c}{4\pi\omega}\phi, \quad c \approx 3 \cdot 10^8 \frac{m}{s}$



[Lange00]

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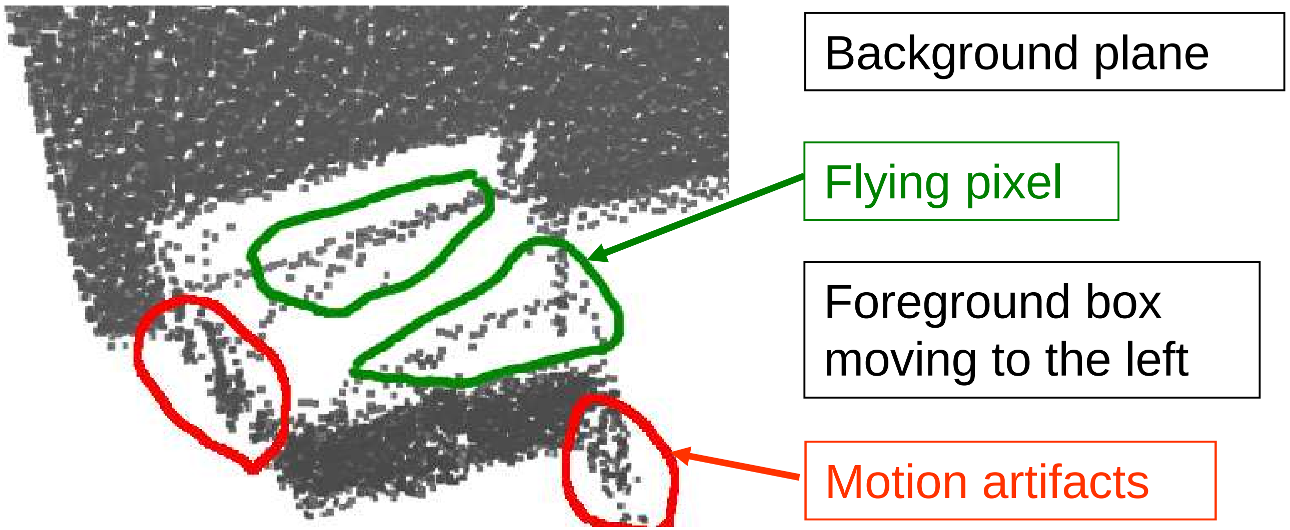
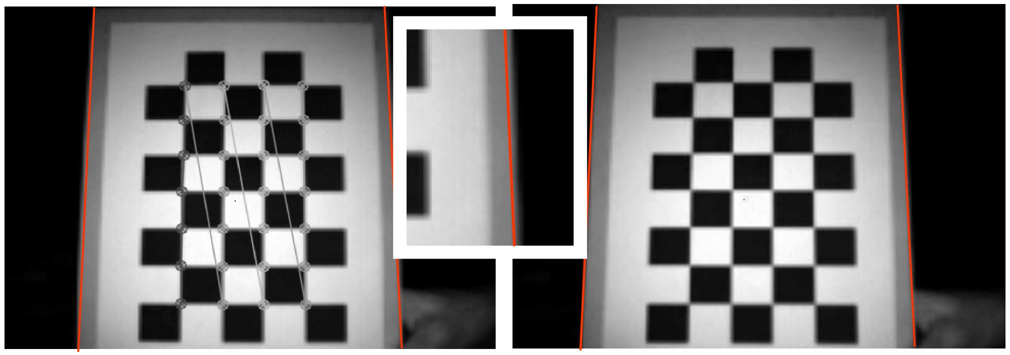
Sensor Characteristics & Challenges

- Low Resolution compared to 2D sensors ⇨ "Flying Pixels"
- Systematic Error (wiggling): No ideal sine-signal
  ⇨ demodulation yields wrong distance
- Intensity-related Error: Low incident active light
  - yields increased noise level and
  - non-zero mean shift in distance measurement
- Motion artifacts due to multi-exposure approach



Calibration

- Classical intrinsic and extrinsic calibration based on intensity images using e.g. OpenCV
- Depth-Calibration requires reference (depth) data
  - Track-line, robot (costs!)
  - Standard image based techniques for extrinsic parameters (plane estimation)
- Purely image based techniques works only for “high res”, i.e. ≥ 120x160 px

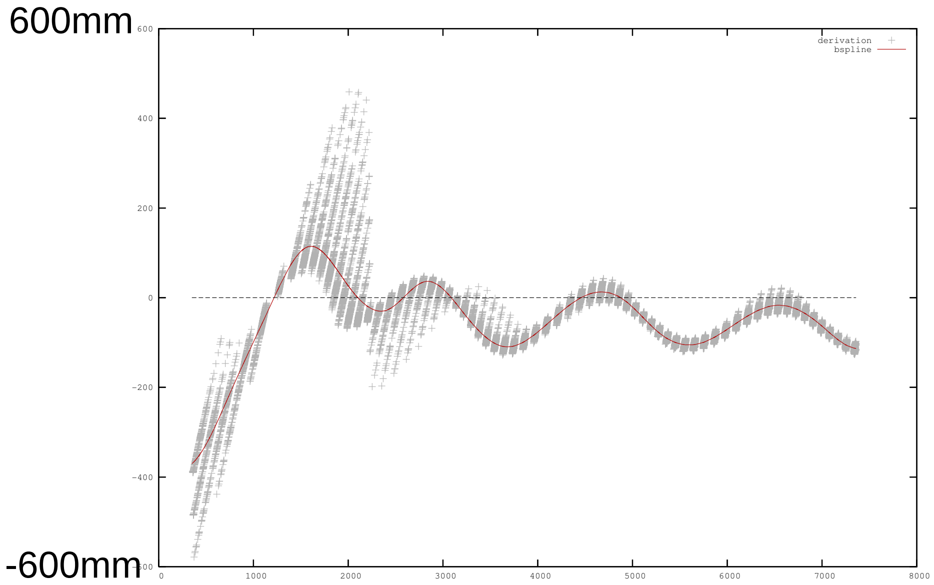


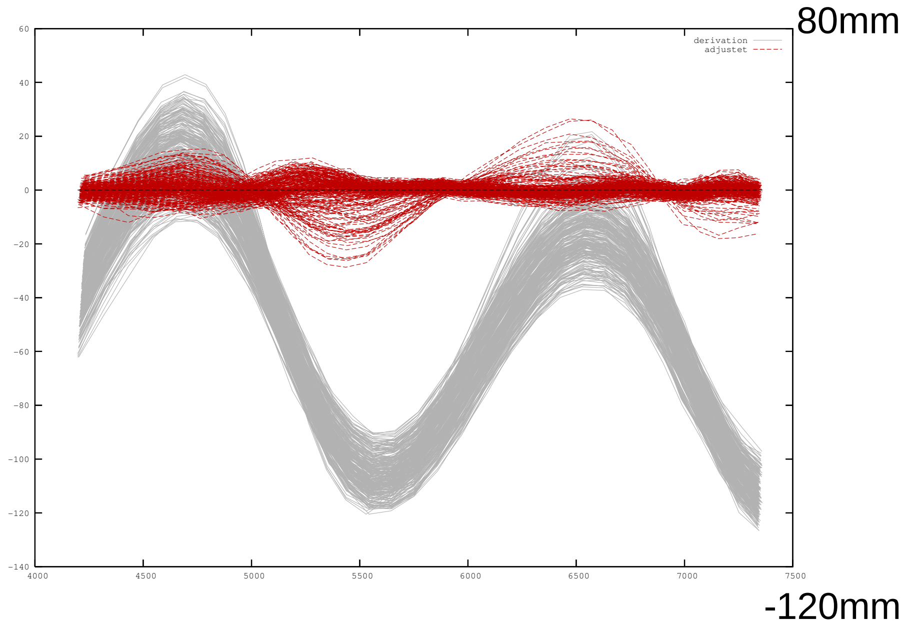
Distorted PMD-Image　　Undistorted PMD-Image

- Alternative: Calibration based on several sensors

Systematic Error (Wiggling)

- Observation:
  - Periodical distance error with varying periodicity and amplitude
- Correction functions used
  - Lookup tables , e.g. [Kahlmann06]
  - B-splines, e.g. [Lindner06]

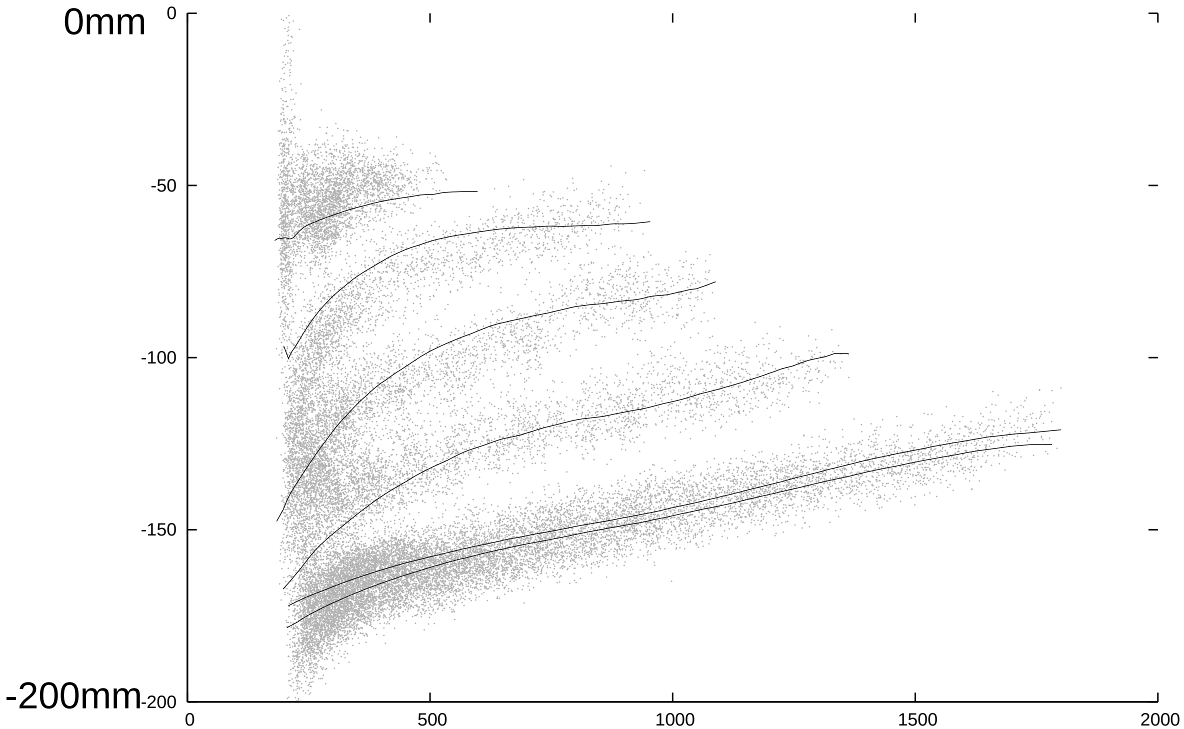




Depth error with fitted B-spline

Illumination-Based Error

- Observation: Nonlinear dependency from illumination
- Approaches to considering this error:
  - Combined depth & illumination calibration using bi-variate B-splines
    ⇨requires a large amount of reference data [Lindner08]
  - Separation of depth and intensity error ⇨ less amount of reference data



Deviation between measured and real distance over intensity with fitted B-splines

Illumination-Based Error (Cont'd)

- Approach: Separate systematic and intensity error correction
- Problem: Intensity relative error partially corrected by systematic correction → Intensity dependent correction need to correct wiggling offset
- Next ToF-cam generation may solve the problem electronically

		100%	80%	60%	40%	20%	0%
	Wiggling	0.1073	0.8905	1.6932	2.4432	2.7929	2.7218
1.0 m	Coupled	0.1973	0.1918	0.2714	0.2838	0.3498	0.7179
	Decoupled	0.1325	0.1239	0.1470	0.2032	0.3627	0.7572
	Wiggling	0.1088	0.7991	1.4507	1.6025	2.0964	2.5058
1.4 m	Coupled	0.3619	0.3220	0.3809	0.3715	0.6800	1.4711
	Decoupled	0.1095	0.1974	0.3848	0.4257	0.8659	1.7188
	Wiggling	0.2170	0.5018	0.7423	1.12713	2.1967	3.5027
1.8 m	Coupled	0.6699	0.5972	0.6131	0.7908	1.5728	3.4599
	Decoupled	0.2483	0.3338	0.4809	0.9292	1.8140	3.3225
	Wiggling	0.2438	0.6284	1.1121	1.7288	2.9523	5.0360
2.2 m	Coupled	0.9506	0.9824	0.8875	1.2031	2.0513	3.3471
	Decoupled	0.2257	0.5347	0.9104	1.5165	2.8597	4.9302

Remaining distance error after wiggling correction (Ø 1.62cm),
coupled (Ø 0.97cm) and decoupled (Ø 0.98 cm) intensity correction [Lindner10]

Motion Compensation

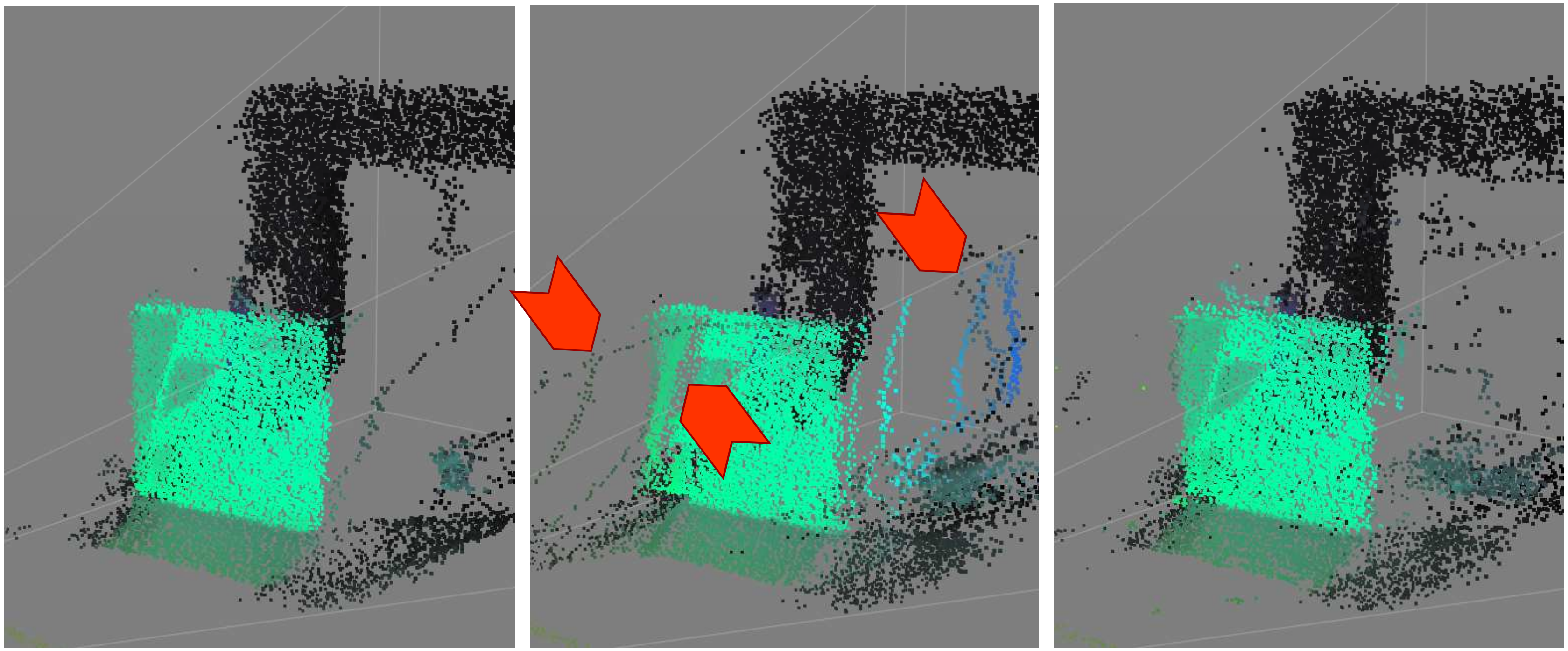
- Observation: Subsequent phase images yield motion artifacts
- Approach: Align phase images A_i using optical flow [Lindner09]
- Problems to be solved:
  - PMD pixels have inhomogeneous gain behavior
  - Mixing & inhomogeneous illumination → non-comparable intensities

Correction for mixing

Correction for radial falloff

Motion Compensation

- Results:
  - Robust and accurate correction for motion artifacts
  - Performance: 10-20 FPS on a current graphics hardware



Reference w/o motion comp. with motion comp.

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2D/3D Sensor Fusion

- Goal: Combine ToF-camera with standard RGB-camera
  - Compensate for low ToF-resolution
  - Add additional colour information
- General fusion approaches
  - Binocular, i.e. two separate cameras → two optical centers
  - Monocular, e.g. using a beam-splitter to separate NIR and VIS

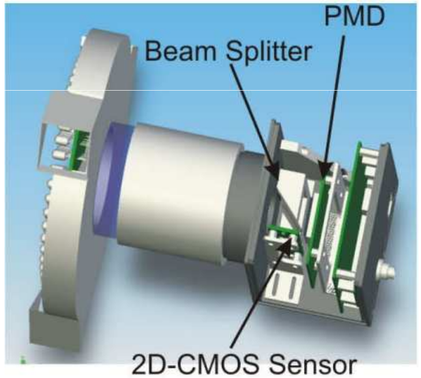
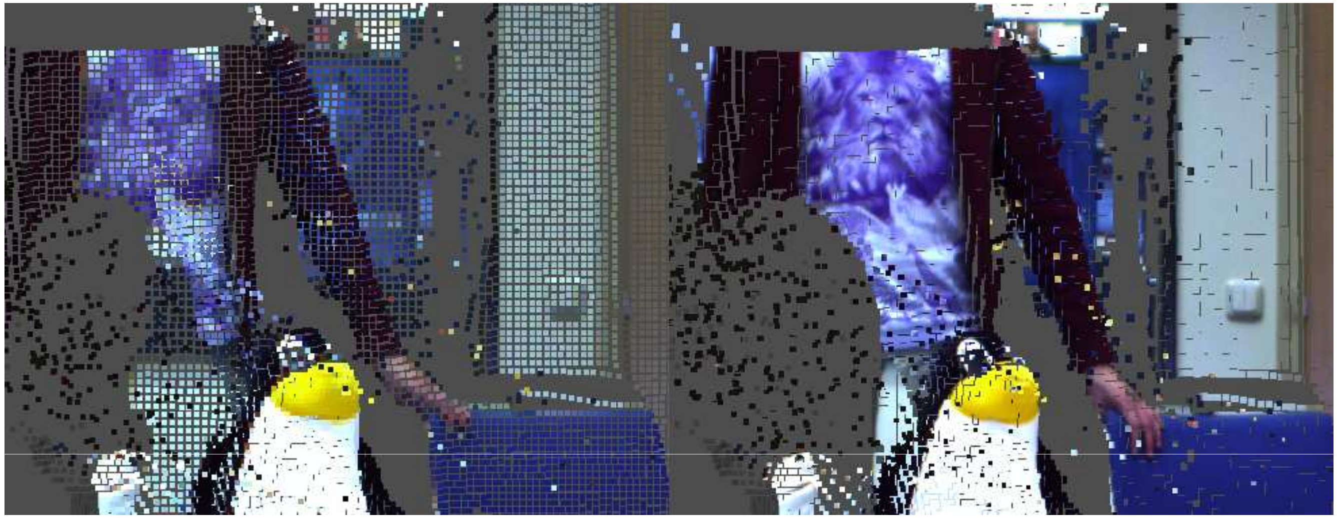


Image from [Ghobadi10]

- Calibration
  - In general: Multi-camera 2D/3D fusion approaches are more robust
  - Tool download under: www.mip.informatik.uni-kiel.de

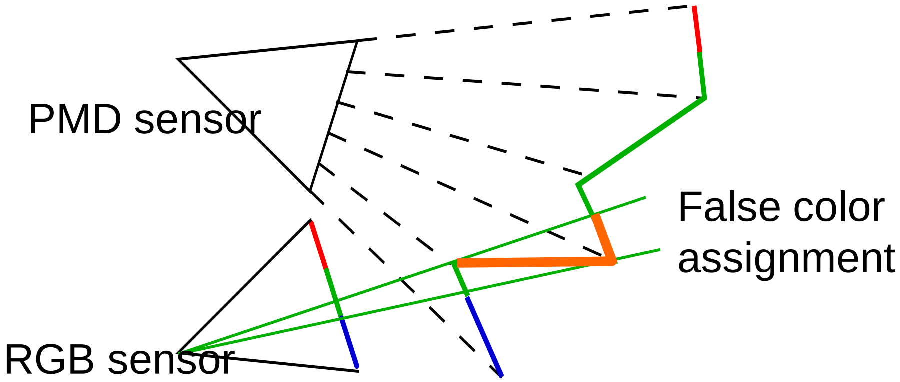
2D/3D Sensor Fusion: Some General Issues

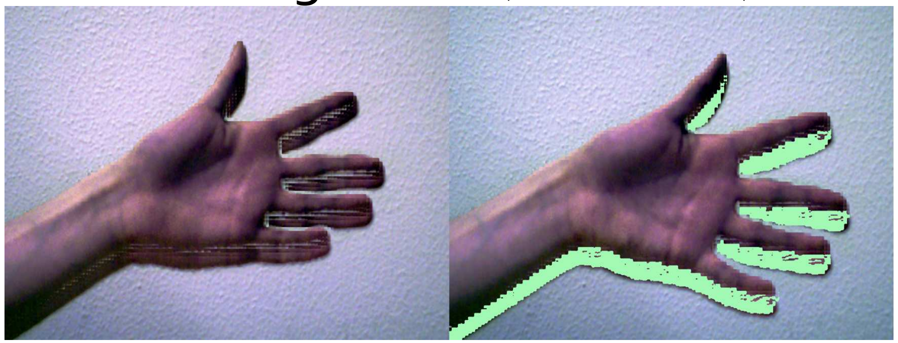
- Fusing Low Resolution ToF with High Resolution RGB Sensor



Left: Per-pixel colour assignment; Right: Texture projection

- Binocular approach leads to false colour assignment (near field)





False color assignment below hand

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3D ToF Endoscopy: System Setup

- Main Advantage of ToF-Cameras: Compact devise without any baseline requirement
- General technical concept
  - Coupling of the ToF-illumination with the endoscope's light transport system
  - Monocular approach: Beam splitter allows for 2D/3D data acquisition
- First Prototype [Penne09]
  - Single fiber-coupled high-power laser diode replaces the illumination unit
  - Low resolution PMD-chip (48x64) only (no additional 2D camera)

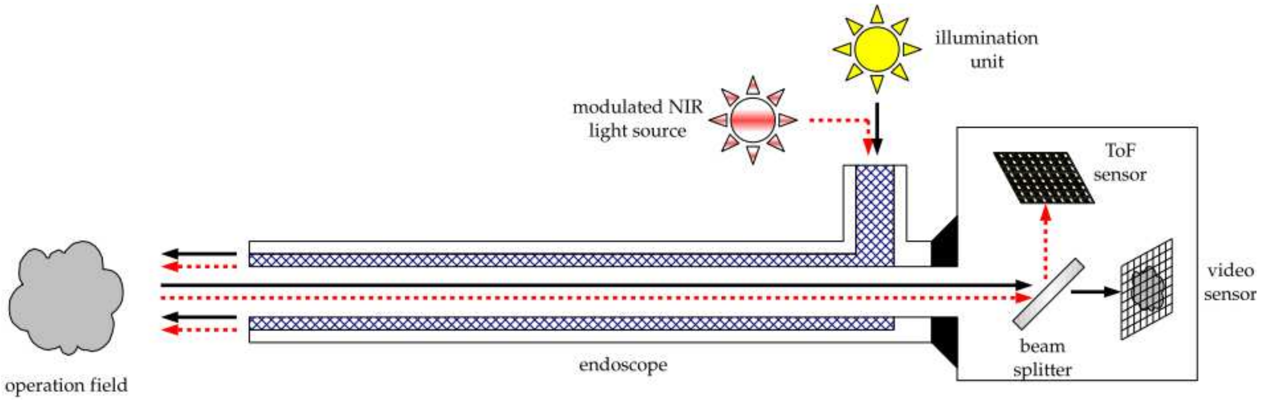


Image from [Winter09]

3D ToF Endoscopy: Data Processing

- General Goal & Challenge:
  - Calibration: Standard ToF-calibration plus correction for endoscope length
  - High-speed processing of ToF data (204^2 px * 20FPS = 800k points per sec)
  - Incremental surface reconstruction requires new algorithms
- Classical Surface Reconstruction:
  - Successive steps for acquisition, pre-processing, mesh generation and post-processing

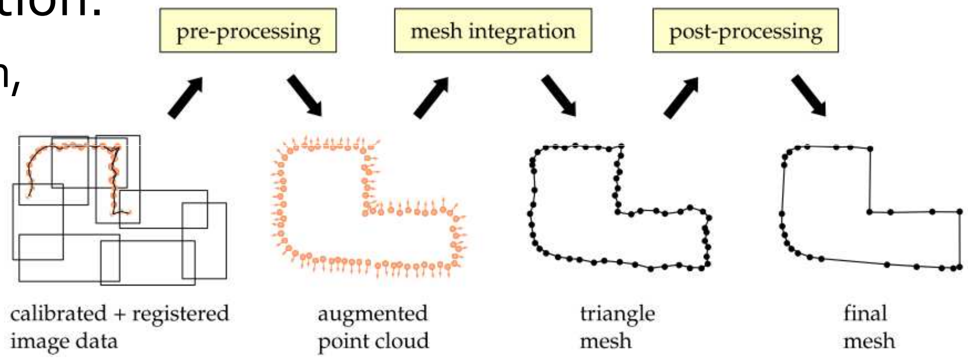


Image from [Winter09]

- Incremental Surface Reconstruction requires
  - Parallel processing of new points and triangle in each step
  - Advancing front approach: Ongoing finalization of geometry → finalized portions can not be altered if new data comes in
  - Ongoing refinement: Revisiting object regions → new points influence the final surface

3D ToF Endoscopy: Ridge-Based Approach [Winter09]

- General idea of the ridge-based approach
  - Each 3D point distributes "volume" in 3-space using a kernel function
  - Superposition of all points give a density-like scalar field (stored in a grid)
  - Final surface is found by following the ridge of the scalar field

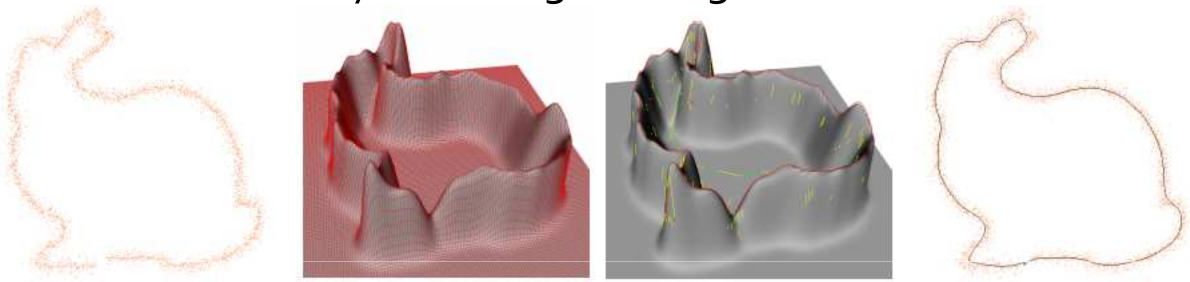


Image from [Winter09]

- Incremental version
  - Ongoing integration of point contributions into the scalar field
  - Reconstruction when some local criterion is met

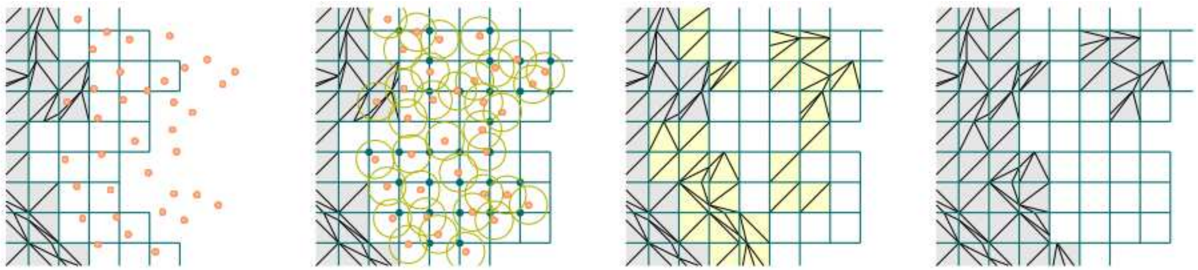
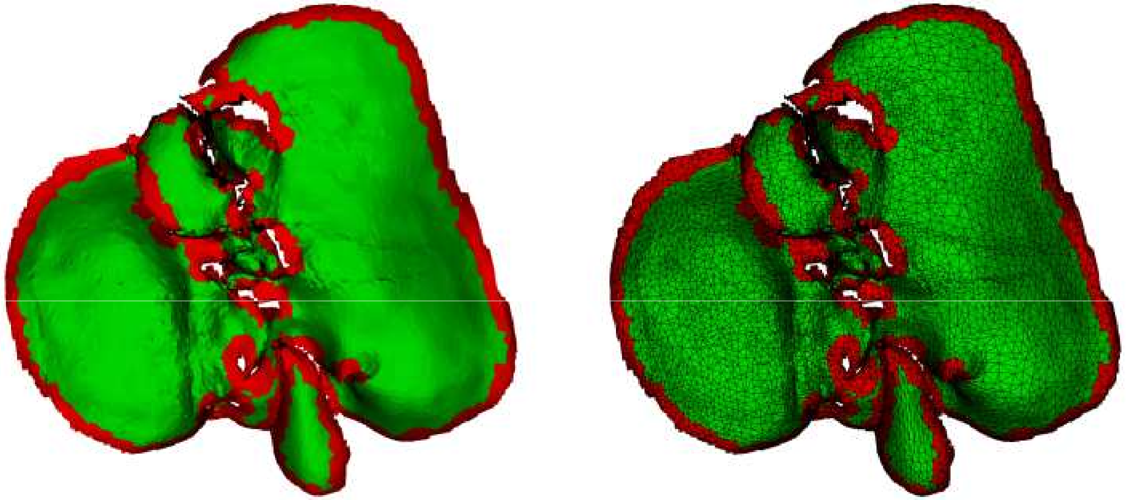


Image from [Winter09]

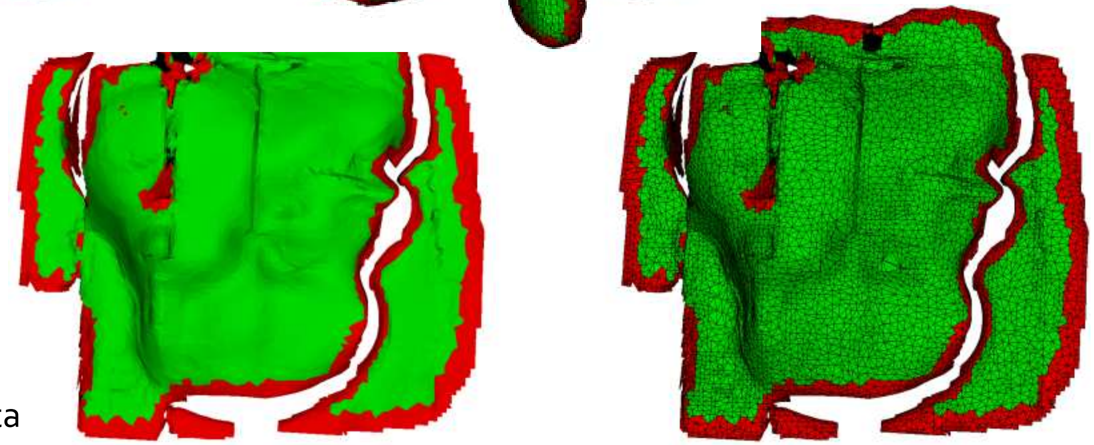
3D ToF Endoscopy: Results [Winter09]

- [Winter09] evaluated his work using an silicon liver
  - Ideal data based on a 3D scan of the model
  - Real ToF-data (48x64 pixel)

Liver model



Ideal range data



Real ToF data

Summary

- Time-of-Flight Technology is very promising for laparoscopic applications
  - Compact sensor principle (no baseline) for real-time range maps
- Advantages and Achievements
  - Active technology → even weakly textured surfaces can be handled
  - Various calibration issues (wiggling, intensity related error, motion artefacts) have already been solved
  - Low resolution & missing colour can be overcome with sensor fusion
- Further Challenges for Laparoscopic Applications
  - Hardware integration is quite tedious
  - Real-time data processing, e.g. using the data redundancy is application dependant

Thank you for your attention

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