3D Machine Vision

3D Cameras

Technical University of Applied Sciences Würzburg-Schweinfurt

3D Camera Techniques

- Depth from Triangulation
  - Passive Stereo Vision
  - Active Stereo Vision
- Time-of-Flight
  - ToF Cameras
  - 2D/3D Laser Scanners, LiDAR (Light Detection and Ranging)
- Quantifying Depth Measures

Examples RGB-D Cameras

1. Intel Realsense 435i
2. Microsoft Kinect 2 / Kinect Azure

3D Camera Techniques

Constraints of 3D Cameras

Depth images can only represent surfaces of objects!

- It is only possible to measure structures in those directions from which the optical system also collects rays.
- Only opaque surfaces can be reconstructed without errors.
- The intensity of all structures on the surfaces larger than the blur circle is preserved. Therefore, these structures are visible with the same contrast.

3D Camera Techniques

Quantifying Depth Measures

Characteristic Values

- depth value Z: absolute measured value of the Z coordinate.
- depth range $\Delta Z = Z_{max} - Z_{min}$: limited range in which a depth measurement with the given depth resolution is possible.
- depth resolution σ_Z: statistical error of the depth measurement, corresponds to the minimum determinable depth difference. This does not have to be constant, but can depend on the depth and e.g. decrease with distance.
- dynamic range of a depth measurement method $\Delta Z / \sigma_Z$.
- distance $D = \sqrt{X^2 + Y^2 + Z^2}$: Distance of a point from the center of projection.

Show some sketch!

Measuring the World

Legacy of Gauss for 3D reconstruction

Carl Friedrich Gauss. Head of the survey of the Kingdom of Hanover from 1821 to the 1840s. Implementation of triangulation with over 3000 points.
Original records of the survey.

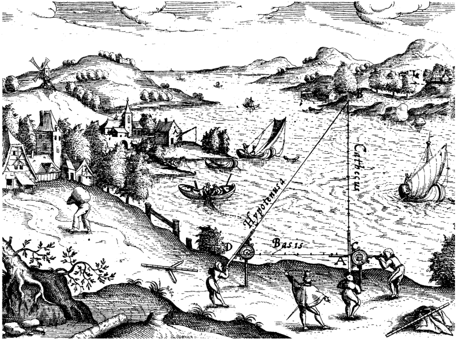
Methods that have endured to this day

- least squares method
- Gaussian distribution
- Gaussian elimination method
- Gauss-Seidel method
- Gauss-Krueger projection
- etc.

The *prince of mathematicians* was also practical

Depth from triangulation

measurement of a point in the triangle



Sketch of a land survey from the 16th century.

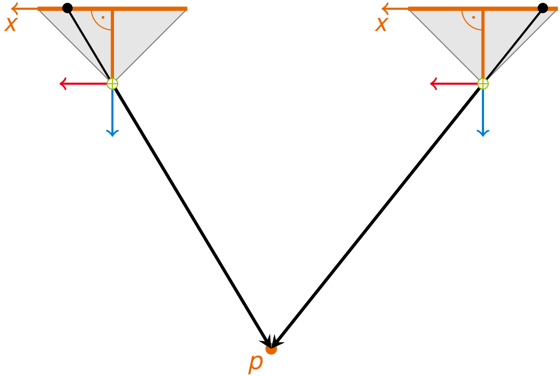
Advantage

- Angles can be measured in the field without contact and more accurately than distances, especially if they are very long.
- From the measurement of one side and two angles in a triangle, all other side lengths and the third angle can be calculated.

Calculate the triangulation!

Depth from triangulation

Passive stereo vision - principle



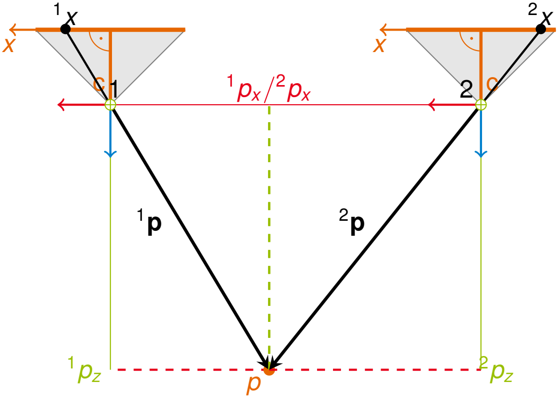
prerequisites

- passive lighting, usually daylight
- parallel shifted image planes
- high-contrast features in the scene (textured surfaces).

Problem reduces to
line by line correspondence search!

Depth from triangulation

Passive stereo vision - principle



A point p on an object is viewed by two cameras C_1 and C_2 in stereo configuration. The position of the cameras to each other differs only by the baseline b along the X-axis.

Recap
OptiTrack lab
2. semester!

Depth from triangulation

Passive stereo vision - principle

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We calculate the coordinates ${}^{1}\mathbf{p}$ and ${}^{2}\mathbf{p}$ of the point p with respect to the first C_1 and second C_2 camera, if we assume the coordinates of the projections ${}^{1}x$ and ${}^{2}x$ and thus the disparity $d = {}^{1}x - {}^{2}x > 0$ (parallax) have been measured correctly and the displacement ${}^{2}t_x = b$ of the cameras with respect to camera 2, as well as the camera constant c of the cameras are known. The following relationships are necessary for this:

$$
\begin{aligned}
{}^{1}p_z &= {}^{2}p_z = Z\,, && (1)\\
b = {}^{2}t_x &= {}^{2}p_x - {}^{1}p_x\,, && (2)\\
\frac{{}^{1}x}{c} &= -\frac{{}^{1}p_x}{{}^{1}p_z}\,, && (3)\\
\frac{{}^{2}x}{c} &= -\frac{{}^{2}p_x}{{}^{2}p_z}\,. && (4)
\end{aligned}
$$

Depth from triangulation

Passive stereo vision - principle

The signs of the coordinates must be taken into account:

$$ {}^1p_x < 0\,, \quad {}^2p_x > 0\,, \quad {}^1x > 0\,, \quad {}^2x < 0\,. \tag{5} $$

We solve the equations (3) and (4) for ${}^2p_x$ and ${}^1p_x$:

$$ {}^1p_x = -{}^1p_z \frac{{}^1x}{c}\,, \quad {}^2p_x = -{}^2p_z \frac{{}^2x}{c}\,. \tag{6} $$

According to equation (1) the z-coordinates are identical: ${}^1p_z =^2 p_z = Z$. If we now put ${}^2p_x$ and ${}^1p_x$ into equation (2), we get the formula for the depth of the point p:

$$ b = -{}^2p_z \frac{{}^2x}{c} - \left(-{}^1p_z\right) \frac{{}^1x}{c} = \frac{Z}{c}({}^1x -^2 x) \quad \to Z = \frac{c \cdot b}{({}^1x -^2 x)} = \frac{c \cdot b}{d}\,. \tag{7} $$

Depth from triangulation

Passive stereo vision - principle

The x-coordinates result accordingly to:

$$^{1}p_x = -\frac{c \cdot b}{(^{1}x - {}^{2}x)} \frac{^{1}x}{c} = -b\frac{^{1}x}{d}\,, \quad {}^{2}p_x = \frac{b \cdot {}^{2}x}{(^{2}x - {}^{1}x)} = -b\frac{^{2}x}{d}\,. \tag{8}$$

Summary for virtual camera image

$$Z = c\frac{b}{d}\,, \tag{9}$$

$$X = x\frac{b}{d}\,, \tag{10}$$

$$Y = y\frac{b}{d}\,. \tag{11}$$

What can be deduced from the ratio b/d?

Depth from triangulation

Passive stereo vision - Exercise

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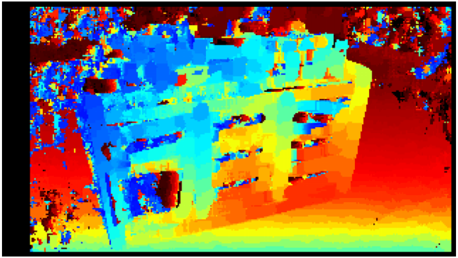
1. From equation (9), calculate the
   1.1 depth resolution $\frac{\partial Z(Z)}{\partial d}$ and
   1.2 the sensitivity of the disparity $\frac{\partial d(Z)}{\partial Z}$

   as a function of absolute depth Z.
2. Calculate the distance as a function of x, y, c, b and d:
3. Calculate the change in parallax in px/m (pixels per meter) for a stereo system with a baseline of $200mm$, a focal length of $f = 100mm$, and a pixel width of $10\mu m$ for distances $10m$ and $100m$ considering the approximation for far-field images: $c \approx f$.
4. The relationship between camera constant c, disparity d and angle γ is given as follows: $\tan\gamma = \frac{c}{d}$. For a camera constant of $c = 3mm$ and a pixel size of $10\mu m$, changing the disparity by $\pm 1px = \pm 10\mu m$ by the disparity $d = 1mm = 100px$ results in the following angular deviations $\Delta\gamma$:

Passive Stereo Vision

Example

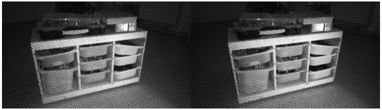


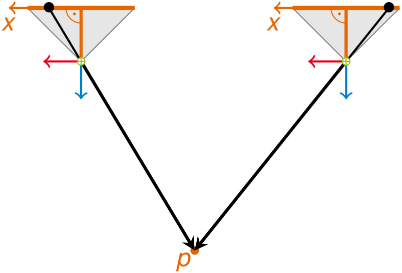
Source: www.intelrealsense.com

Structured Light - 1st Principle

Functionality with structured light

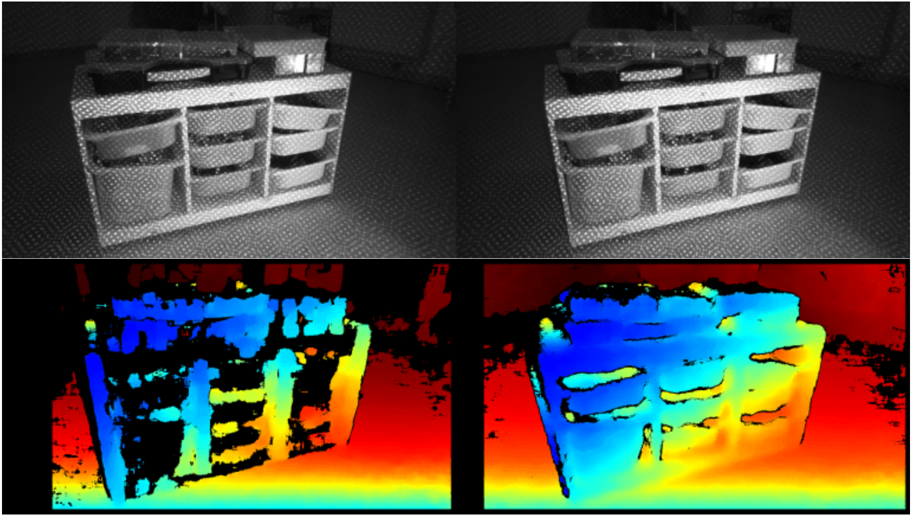
- projector projects a texture with high contrast on the scene.
- From the correspondence search the 3D image is reconstructed.
- prerequisite for error-free reconstructions is sufficiently strong projection of patterns.





Active 3D Cameras

Structured Light - 1st Principle Example

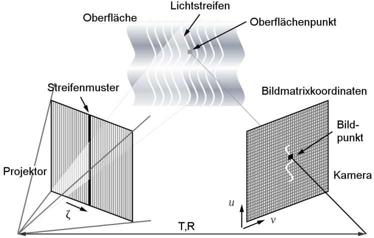


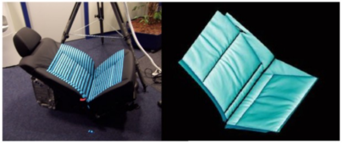
Active 3D Cameras

Structured Light - 2nd Principle

Functionality with structured light

- projector projects a sequence of light patterns of different structures and wavelengths onto a scene, e.g. stripe patterns. These encode individual points of high contrast.
- The 3D profile is reconstructed from the image of the distortion of the light pattern.
- Prerequisite for error-free reconstructions is a fully calibrated projector-camera system.





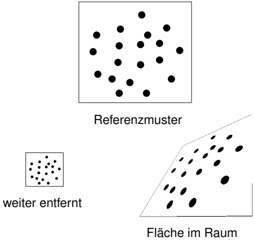
Source: www.wikipedia.org

Active 3D Cameras

Example Kinect 1 - 2nd Principle

Operating principle of the KINECT-1 sensor

- infrared laser projector projects a dot pattern onto the scene.
- Infrared camera (CMOS) with a resolution 1600x1200 pixels captures the image of the distortion of the dot pattern.
- color camera (CMOS) with a resolution of 640x480 pixels records the irradiance of visible light
- distorted dot pattern and irradiances are combined to a true color 3D profile with a frame rate of 30 Hz in real time



Error sources

- Infrared ambient light influences measurement quality
- Only one sensor can be operated at a time (otherwise ambiguities due to multiple patterns)

Source: http://gilotopia.blogspot.com

http://kinecthacks.net

Active Cameras

Time-of-Flight Camera

Functionality of a PMD sensor

- Pulsed or modulated infrared light.
- Time or phase shift between emitted and received light waves encodes distance

Pulsed infrared light

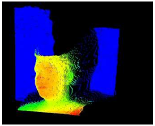
$$d = \frac{c\tau}{n},$$

$$\text{distance} = \frac{\text{speed of light} \times \text{runtime}}{\text{Refractive index}}.$$

Light passes $1cm$ in $33ps$. I.e., very precise time measurements necessary.

ToF Camera

Distance



Intensity

Active Cameras

Time-of-Flight Camera

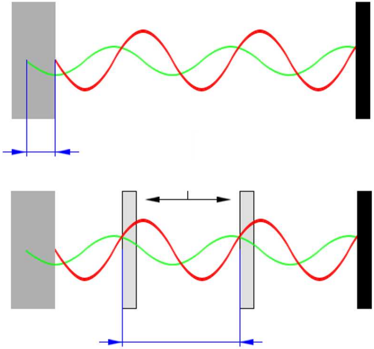
Modulated infrared light

$$\frac{2\tau}{T} = \frac{\phi}{2\pi}\,,$$

$$\frac{\text{runtime}}{\text{time period}} = \frac{\text{phase shift}}{2\pi}\,.$$

$$d = \frac{\phi}{4\pi} \cdot \frac{cT}{n}\,.$$

$$d_{max} = \frac{cT}{2n}\,,\ (\phi = 2\pi)\,.$$



modulated light wave, reflected light wave
phase shift, sensor, objekt

Active Cameras

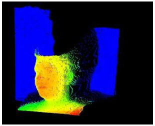
Time-of-Flight Camera

Sources of error

- ambiguities with periodic carrier signal
- Intensity dependence of depth measurement
- Ambient light influences measurement quality
- motion artifacts
- temperature drift
- noise

ToF Camera

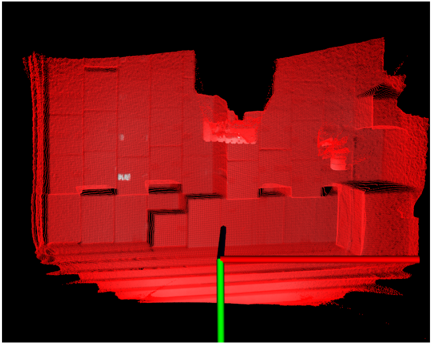
Distance



Intensity

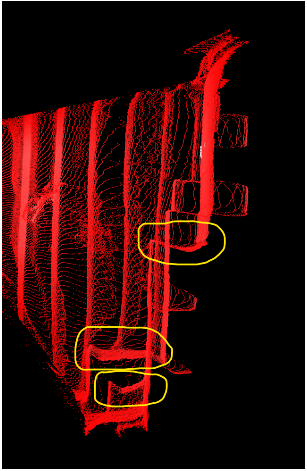
ToF Camera

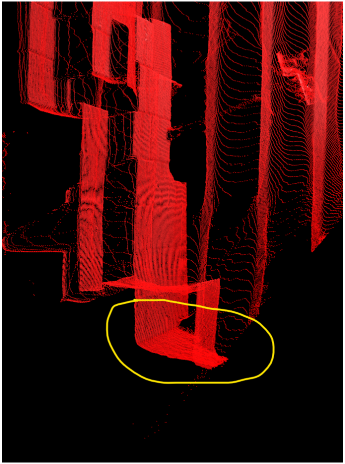
Example Errors Multipath Reflections



ToF Camera

Example Errors Multipath Reflections





LiDAR (Light Detection and Ranging)

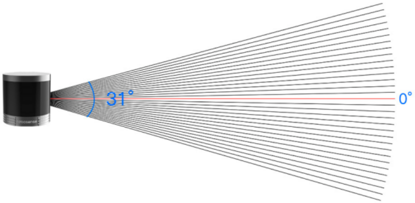
Measuring principle of mechanical LiDAR

- depth from runtime
- scanning or rotating laser pulses → fields of view from more than 180° to 360° all-around view

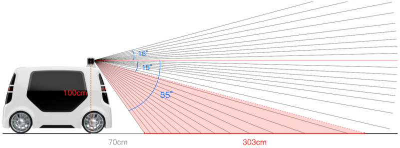
Disadvantages

- Suffers from wear and tear
- Inaccuracy due to mechanical movement
- Size limits field of application
- Mechanics increase production costs

Solid-state LiDAR are better: Mirrors are moved electromagnetically



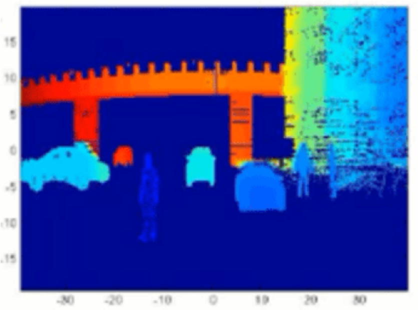
Robosense Helios 1615



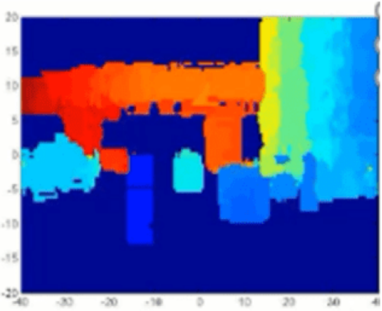
Robosense Helios 5515

3D Scanner

Example Velodyne



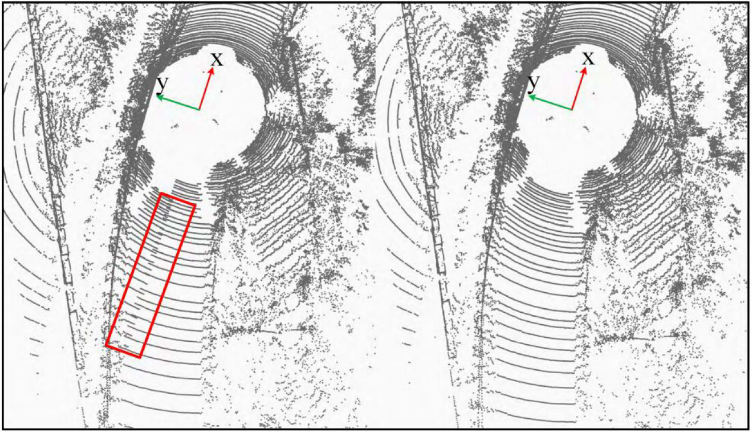
Lidar



High Resolution Radar

3D Scanner

Errors because of Egomotion



Links: Beispiel einer verzerrten Punktwolke; **Rechts:** Korrigierte Punktwolke

3D Camera Techniques

Characterization of a depth measurement

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measurement errors

- systematic, reproducible errors: can be reduced or compensated for by calibration and control of the system state (e.g. temperature control, self-motion compensation)
  - depth distortion: Systematic deviation from the true depth. May vary with the depth itself.
  - amplitude-related errors: Systematic dependence on the position of the surface normal and the strength of the reflected light.
  - integration-time-related errors: Systematic dependence on the duration of the measurement or the integration time of several measurements.
  - temperature-related errors: Dependency of the depth resolution on the temperature.

3D Camera Techniques

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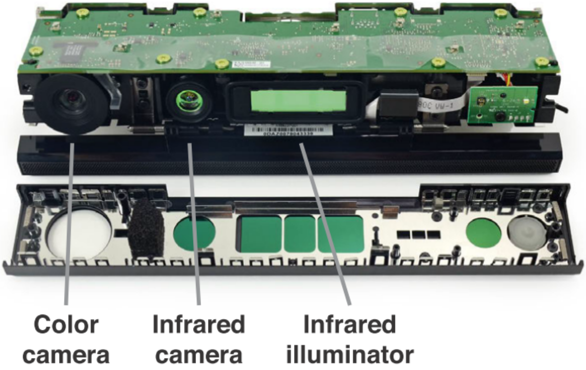
Characterization of a depth measurement

measurement errors

- unsystematic, random errors: can be characterized, e.g., by mean and variance
  - occlusions: Lighting and cameras are slightly offset from each other. This results in occlusions. $\rightarrow$ Distances in the overlapping visible range of the cameras cannot be measured at depth discontinuities.
  - interference: Overexposure due to e.g. too much stray light from the sun or artificial lighting in the visible or also infrared range.
  - multiple reflections: if partial surfaces collide at large angles (strongly concave surfaces), several different light beams from the same active camera can arrive at one pixel of the image surface and falsify time-of-flight measurements.
  - object and camera movements: The assumption of all time-of-flight and triangulation methods is a static scene during the measurement acquisition. If this condition is not met due to a fast moving camera or fast moving objects in the scene, measurement errors will occur.

Time of Flight Kamera

Kinect 2 – Setup



Time of Flight Kamera

Kinect 2 – Specifications

TABLE I. KINECT V2 SPECIFICATIONS

		PrimeSense Carmine 1.08	Kinect v2
Infrared/depth camera	**Resolution**	320×240 px	512×424 px
	Field of view (h×v)	$57.5^\circ \times 45.0^\circ$	$70.6^\circ \times 60.0^\circ$
	Angular resolution	0.18°/px	0.14°/px
	Operating range	0.8–3.5 m	0.5–4.5 m
Color camera	**Resolution**	640×480 px	1920×1080 px
	Field of view (h×v)	$57.5^\circ \times 45.0^\circ$	$84.1^\circ \times 53.8^\circ$
Frame rate		30 Hz	30 Hz
Minimum latency			20 ms
Shutter type			Global shutter
Dimensions (w×d×h) [mm]		$180 \times 35 \times 25$	$249 \times 66 \times 67$
Mass (without cables)		160 g	970 g
Connection type		USB 2.0	USB 3.0
Voltage		5 V DC	12 V DC
Power usage		2.25 W	$\sim$15 W
Price		200 USD	200 USD

Time of Flight Kamera

Kinect 2 – Test Measures

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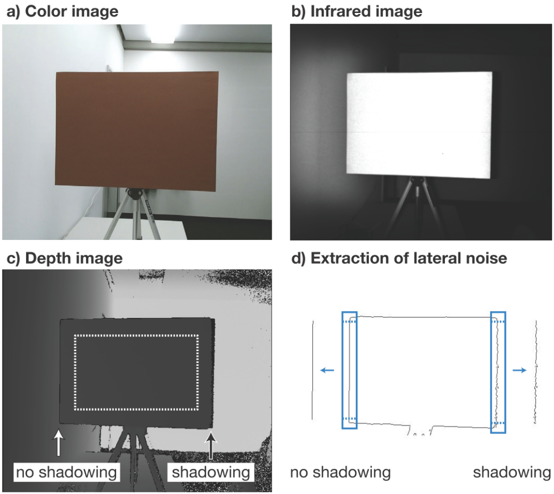

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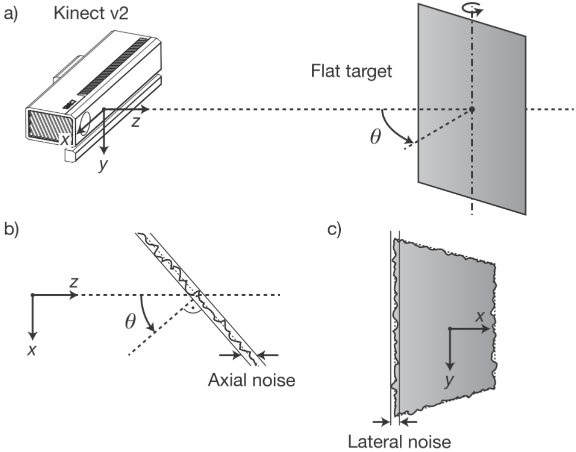
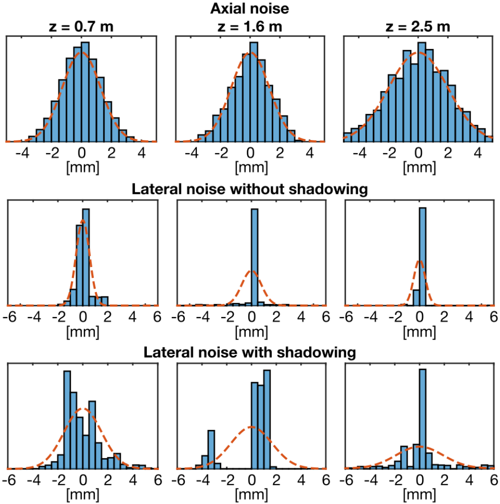
Kinect 2 – Lateral & Axial Noise



Kinect 2 – Statistics from 10000 Measurements



Time of Flight Kamera

Kinect 2 – Systematic Offsets