Folien zur Vorlesung am 15.4.2025

3D Computer Vision

3D TIME-OF-FLIGHT KAMERAS

Devices and methods

[Microsoft]

Structured light

[PMDTec]

Time-of-Flight

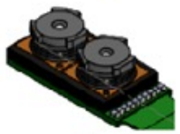
[SICK]

Active triangulation

Passive triangulation

[PTGrey]

Devices and methods

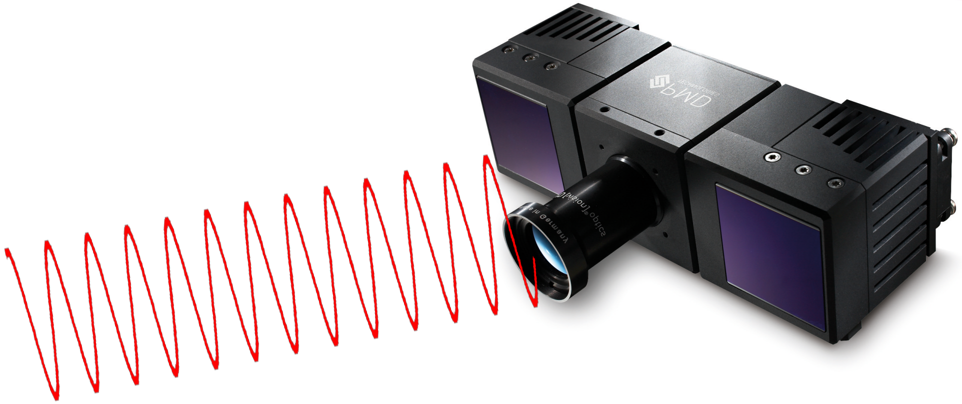
YOLE Développement	Stereo vision	Structured light	Time of Flight
Image resolution	Several Mpix	Max. 1–3 Mpix	Max. VGA
Hardware	Simple cameras Complex system	Demanding illumination Complex system	Simple illumination Complex sensors
Computation power	High	Medium	Low
Limitations	May require illumination in low light	Best indoors Need power	Best indoors Low resolution
Picture (example)	 *Courtesy of ams*	 *Courtesy of Apple*	 *Courtesy of PMD Tech*
Best suited for	Robotic navigation	3D mapping	Short-range gesture capture
Maturity	High	Medium	Low
Players	SONY, ams, STEREOLABS, SAMSUNG, OmniVision	Himax, mantis vision, ams, ST, NAMUGA, intel	Infineon, pmd, SONY, ST, epc, LIPS

[Depth-sensing technologies in **mobile** devices](#) (Source: Yole Développement's Report "3D Imaging & Sensing, 2018 edition, 2018")

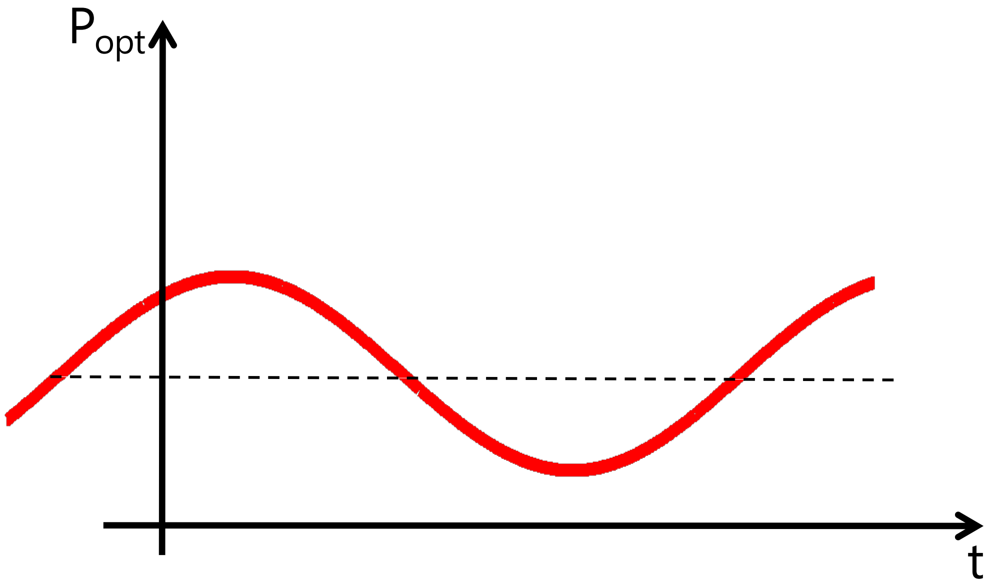
Measurement

[PMDTec]

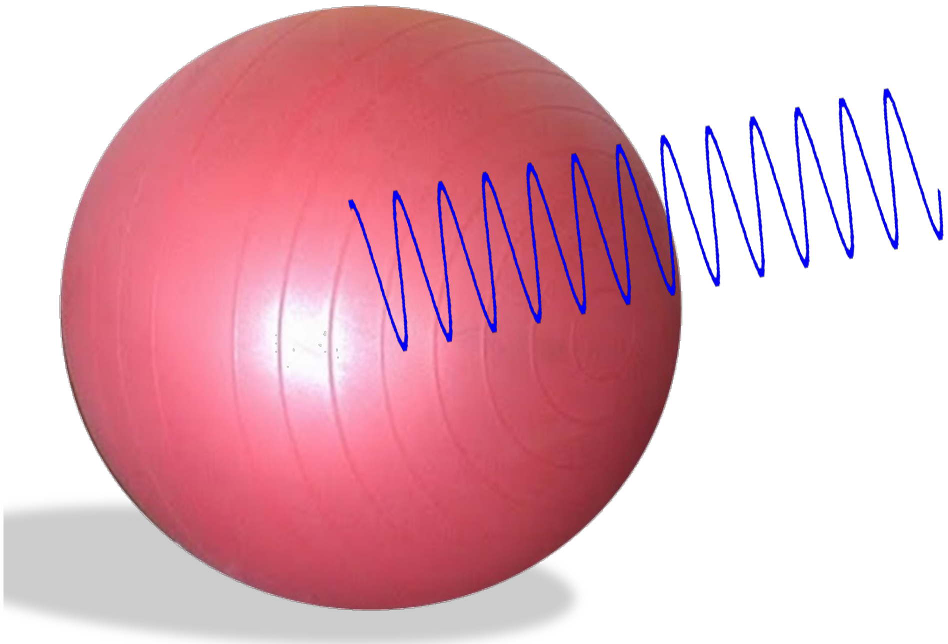
Measurement



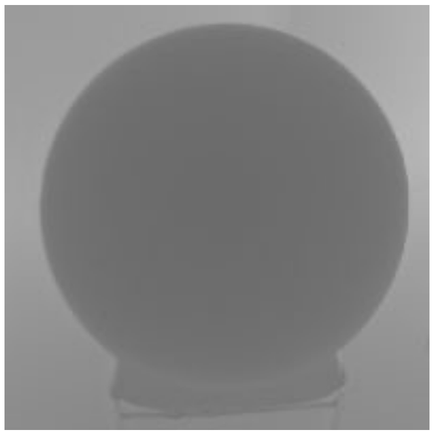
[PMDTec]

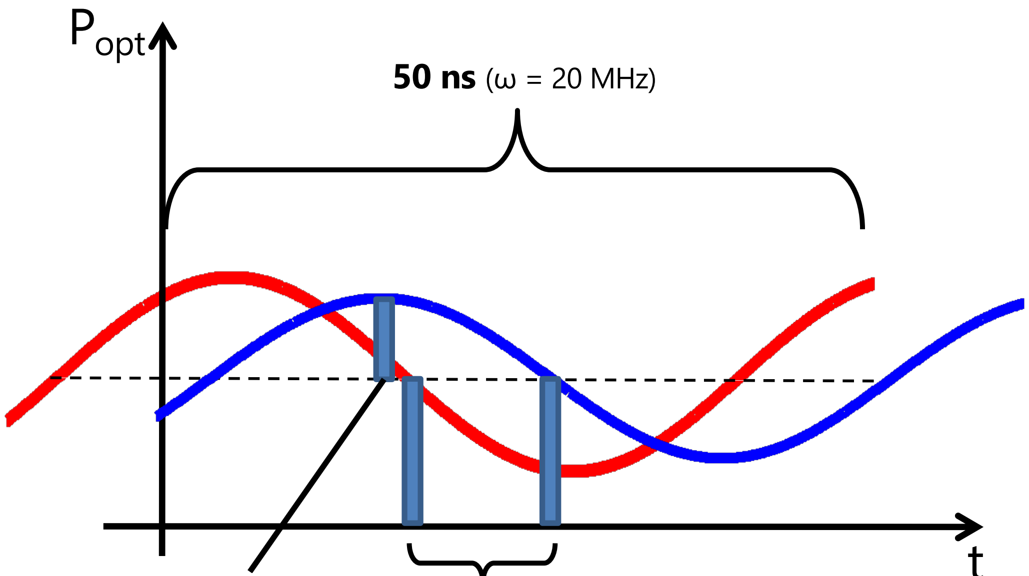


Measurement

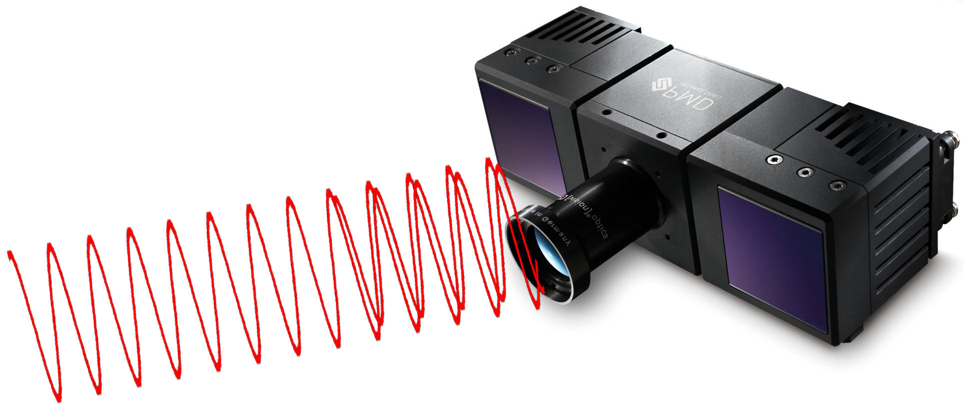


[PMDTec]

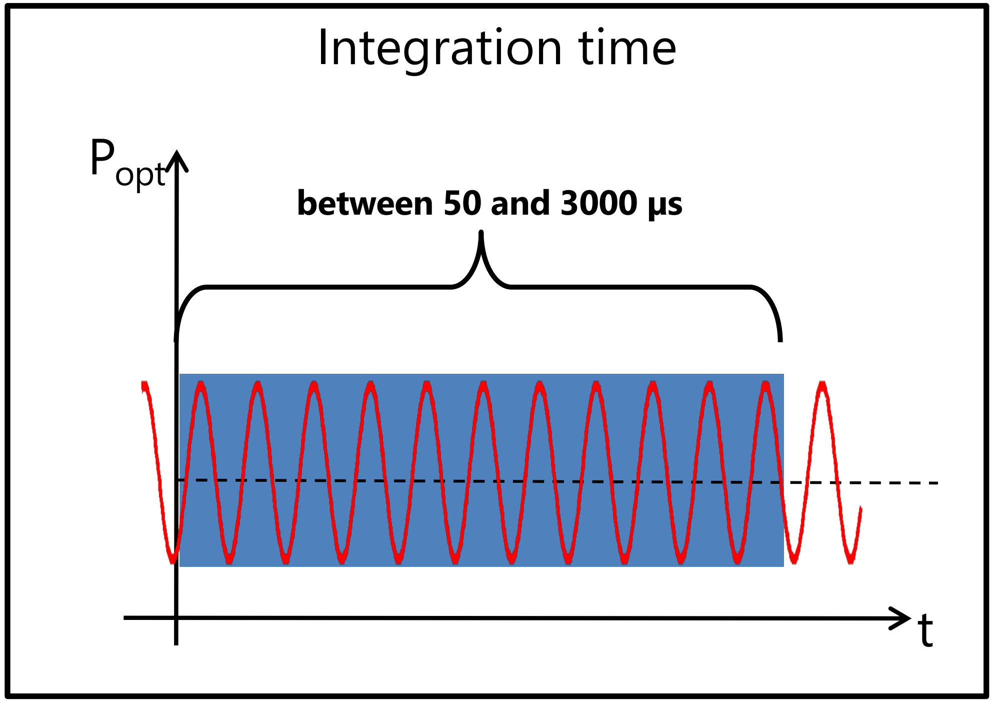




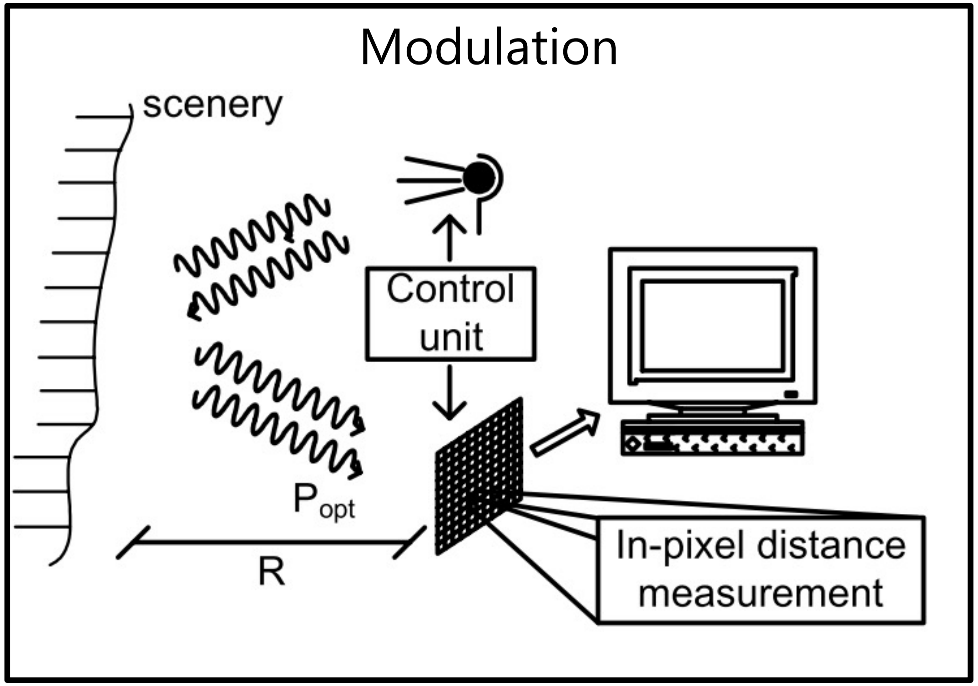
Measurement



[PMDTec]



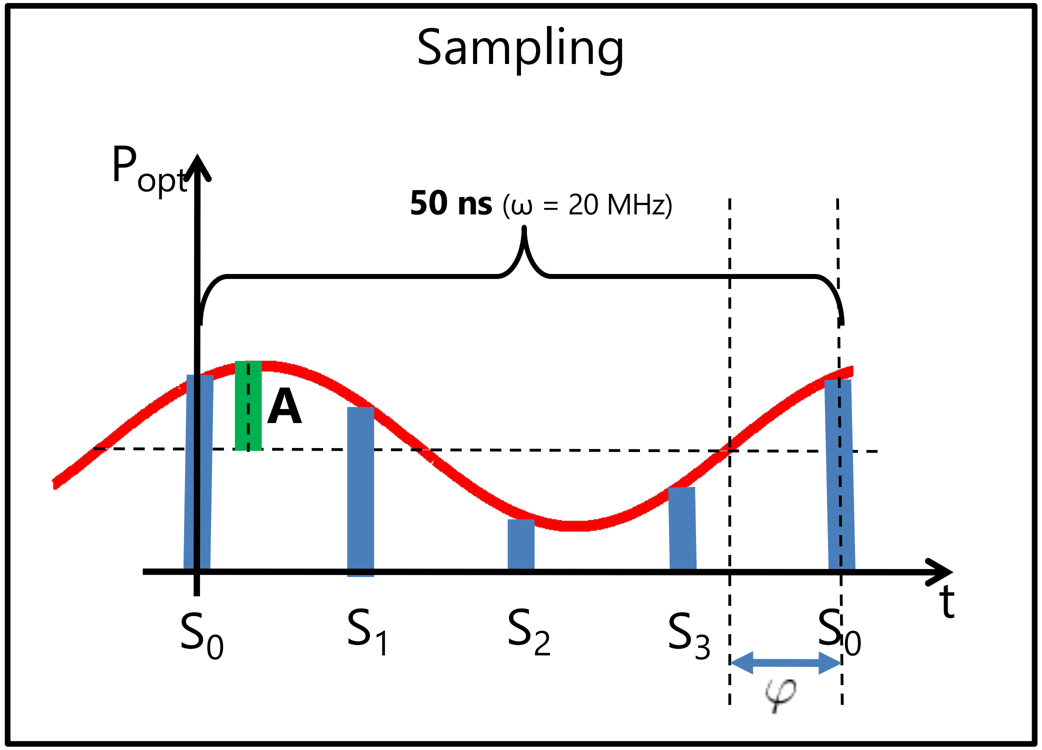
Measurement – Technical details



[Büttgen2005]

[PMDTec]

Measurement – Mathematical details



[PMDTec]

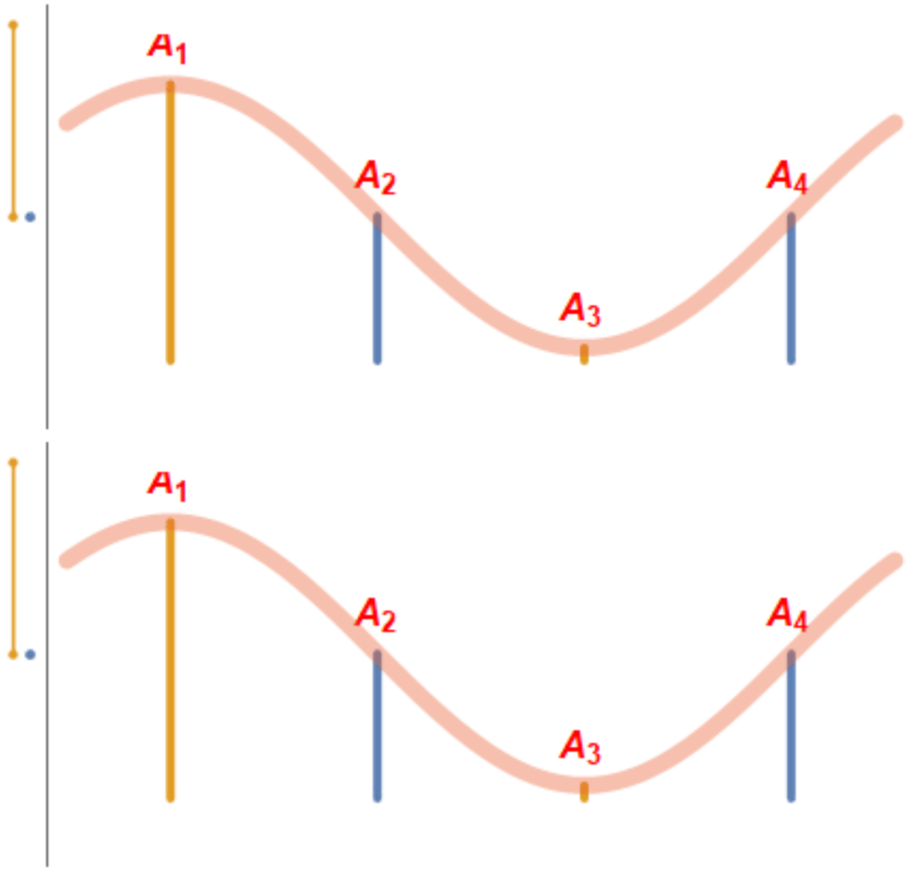
$$Phase\ \varphi = \arctan\left(\frac{S_3 - S_1}{S_0 - S_2}\right)$$

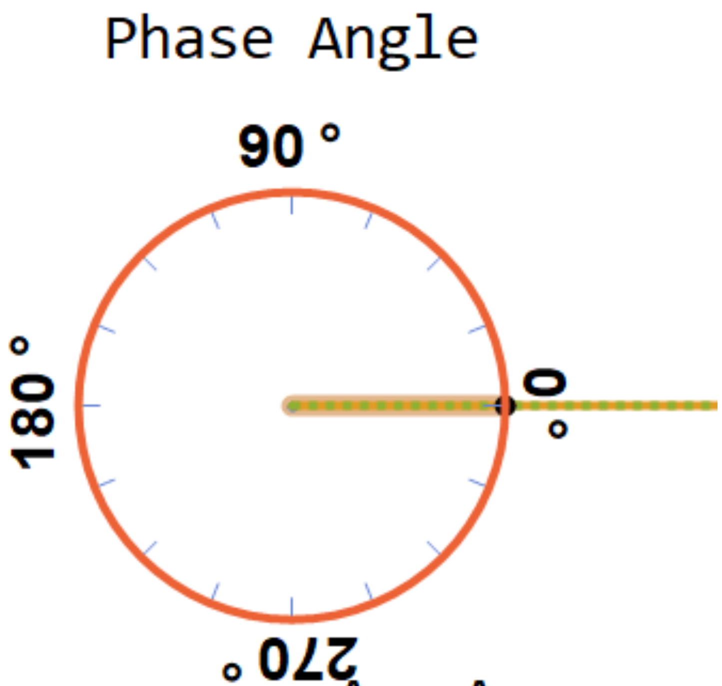
$$Distance\ D = \frac{c\varphi}{4\pi\omega}$$

$$Amplitude\ A = \frac{\sqrt{(S_3 - S_1)^2 + (S_0 - S_2)^2}}{2}$$

$$Intensity\ I = \frac{S_0 + S_1 + S_2 + S_3}{4}$$

Measurement – Mathematical details





$$\varphi = \mathrm{ArcTan}\left[\frac{A_1 - A_3}{A_2 - A_4}\right]$$

Image source: [Recommended reading on allaboutcircuits.com]

Measurement – Alternative modulation

Pulse-based

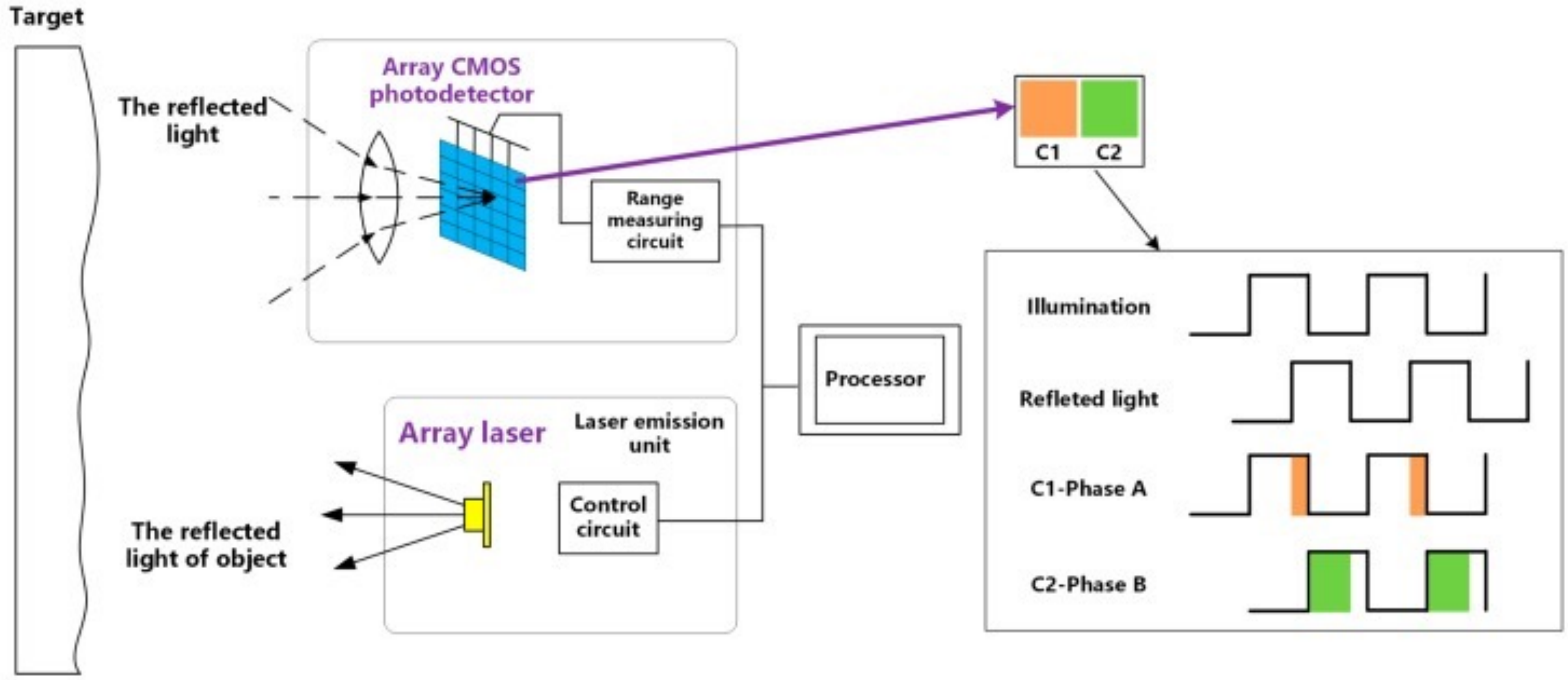


Image source: [Zhai2019]

ToF – Hardware architecture

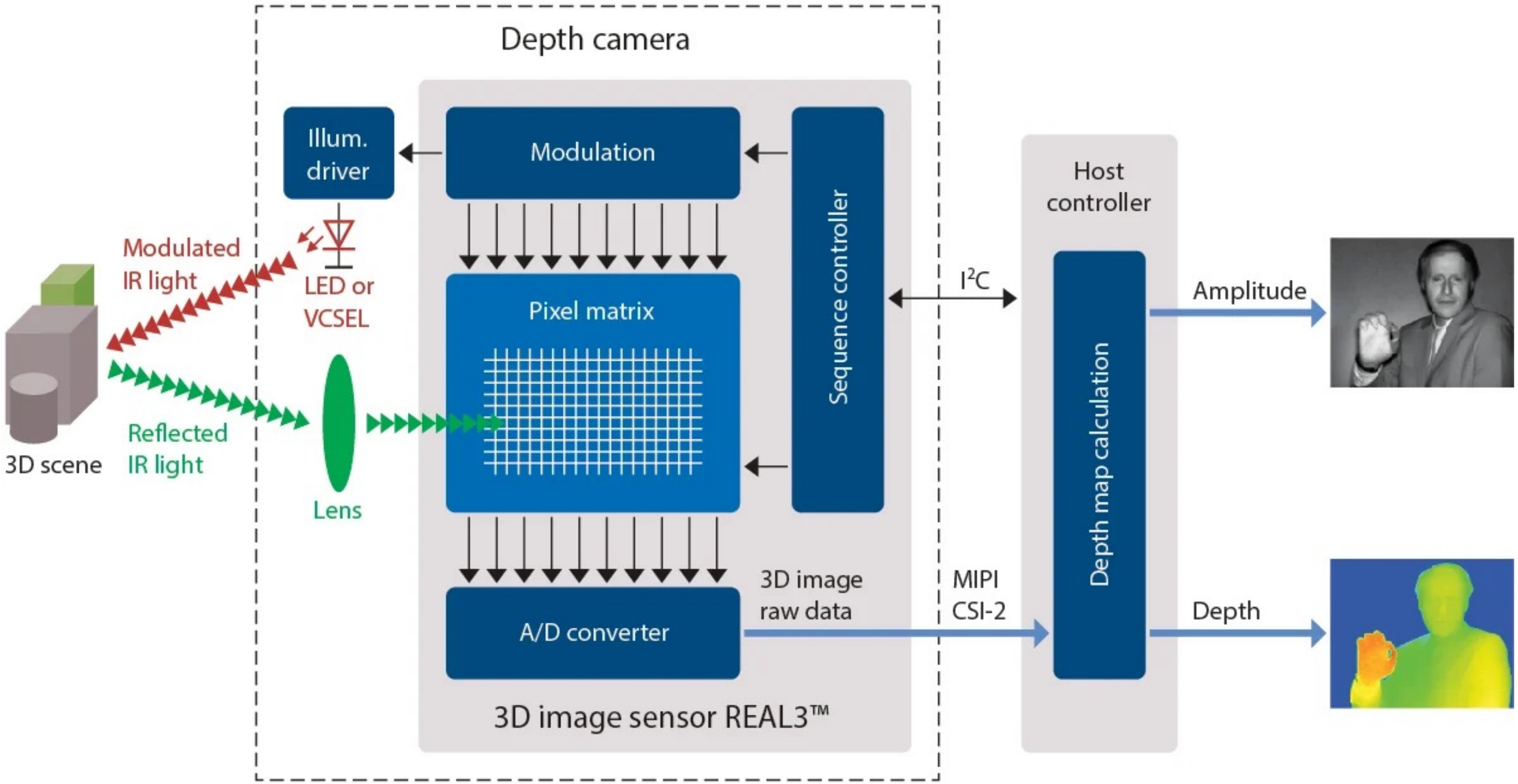


Image source: [Recommended reading on allaboutcircuits.com]

ToF - Hardware

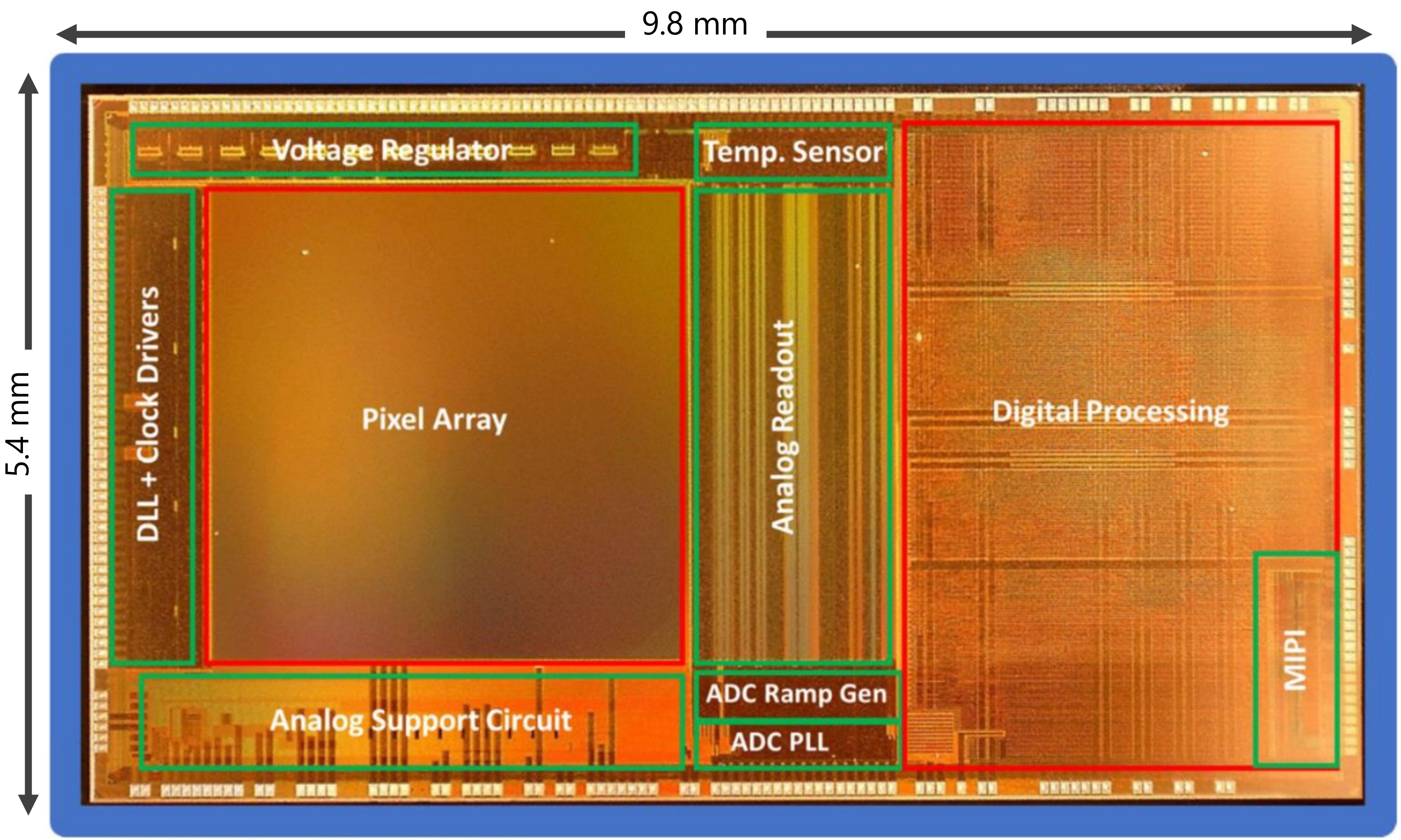
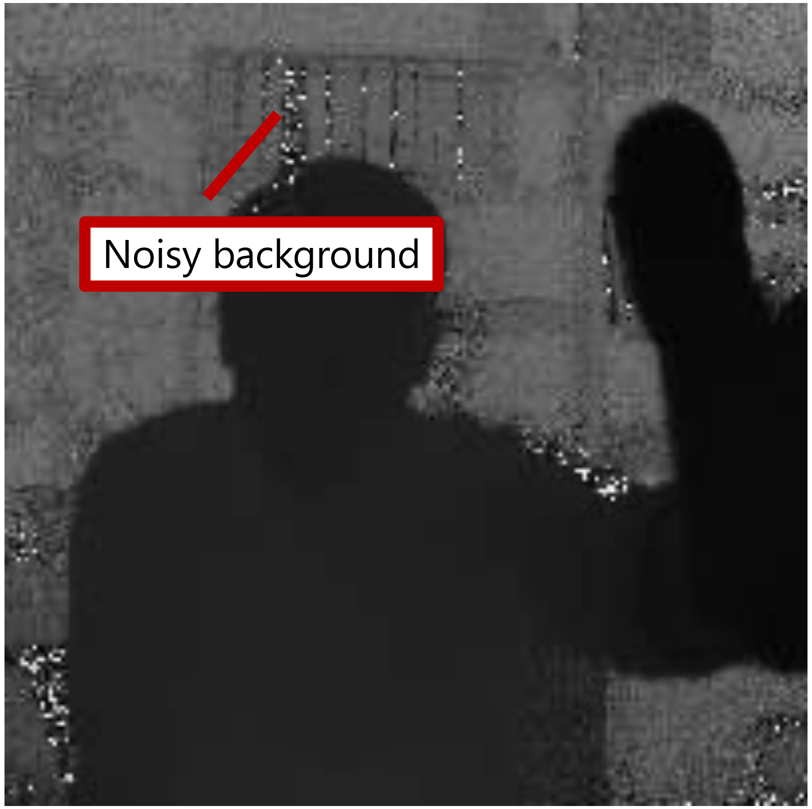


Figure 5.8.7: Die Photograph (from chip front side)

Azure Kinect Image sensor [Bamji2018]

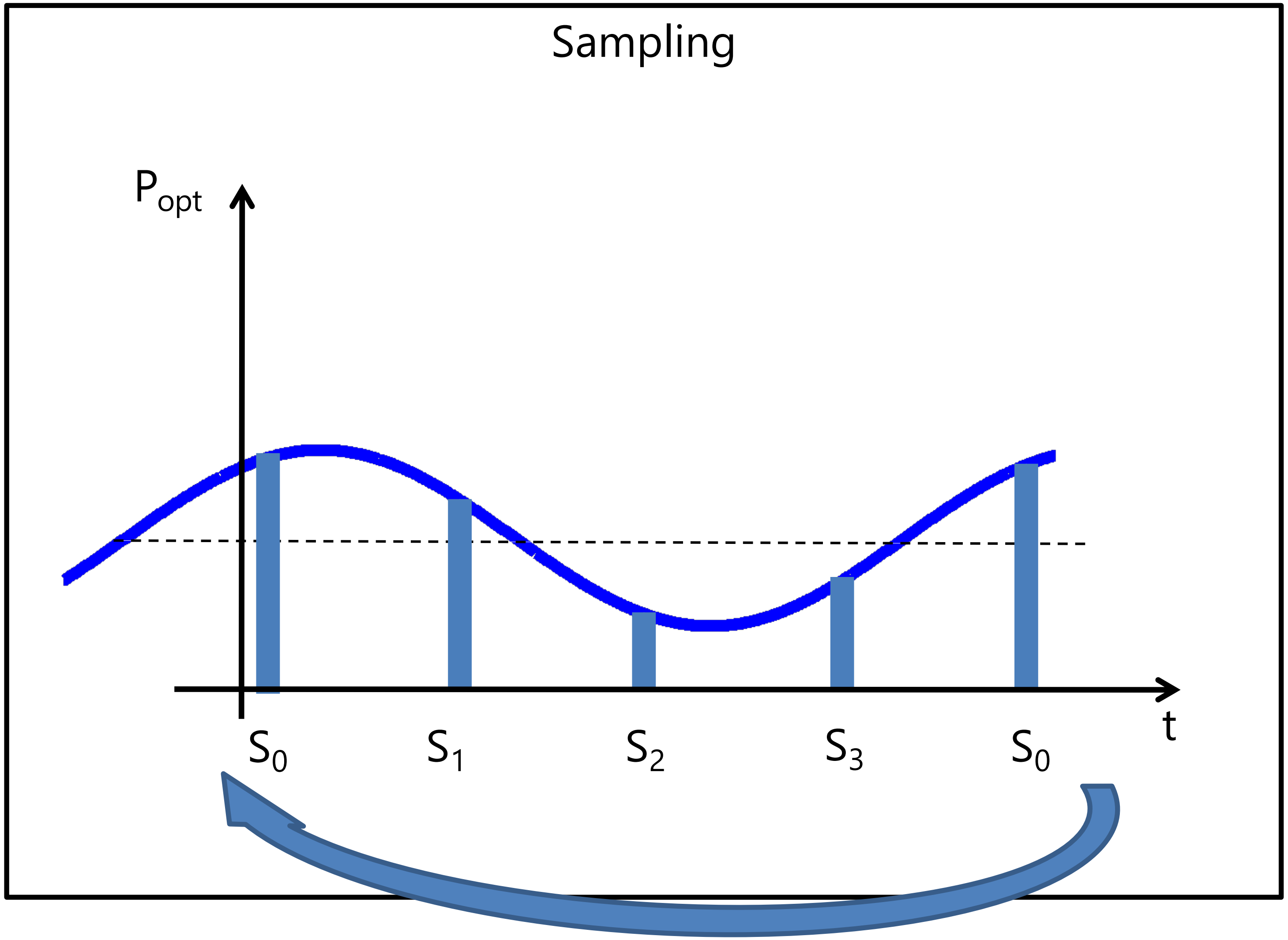
Problems – integration time



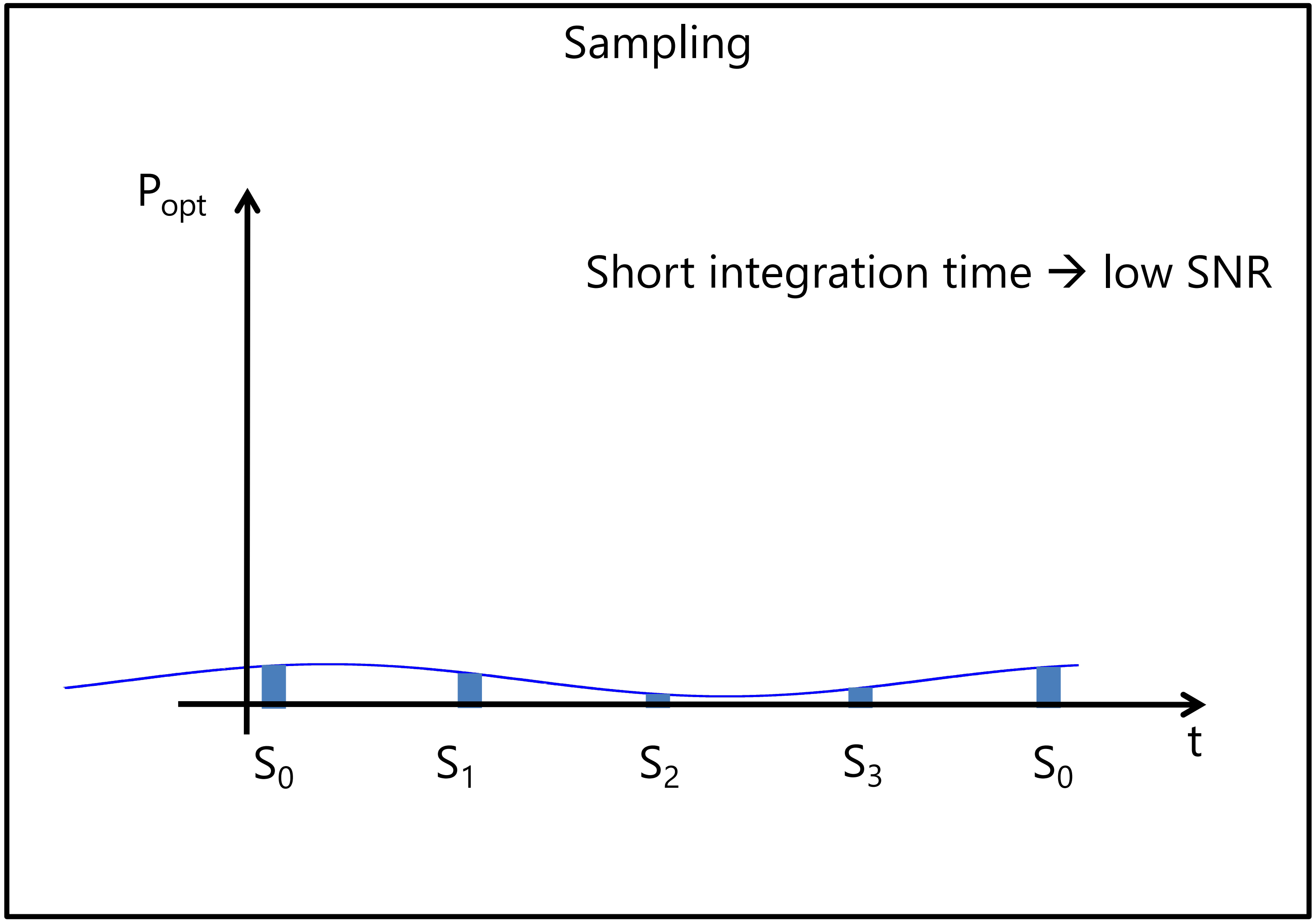
Short integration time (50 µs)

Long integration time (1250 µs)

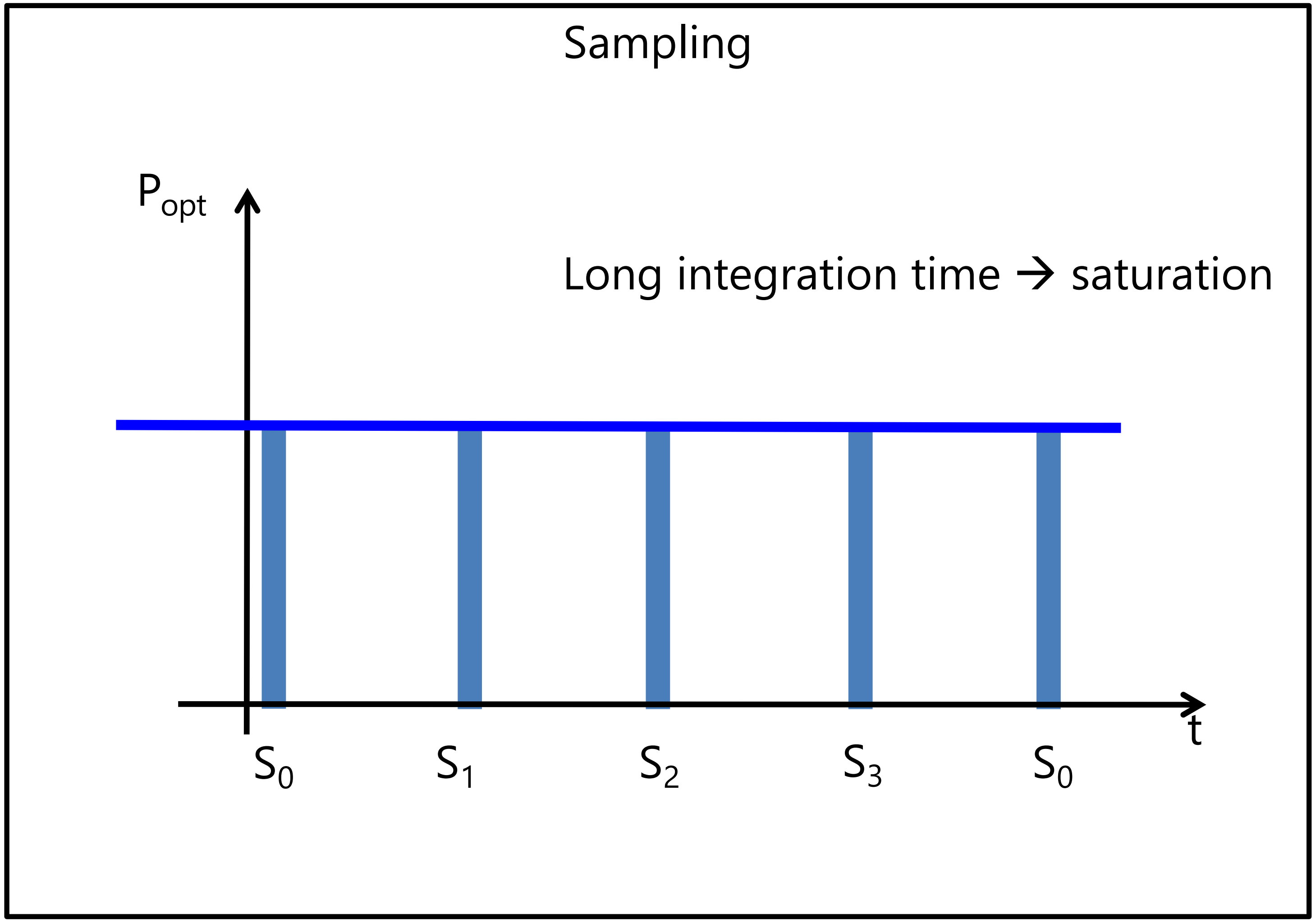
Problems – integration time



Problems – integration time

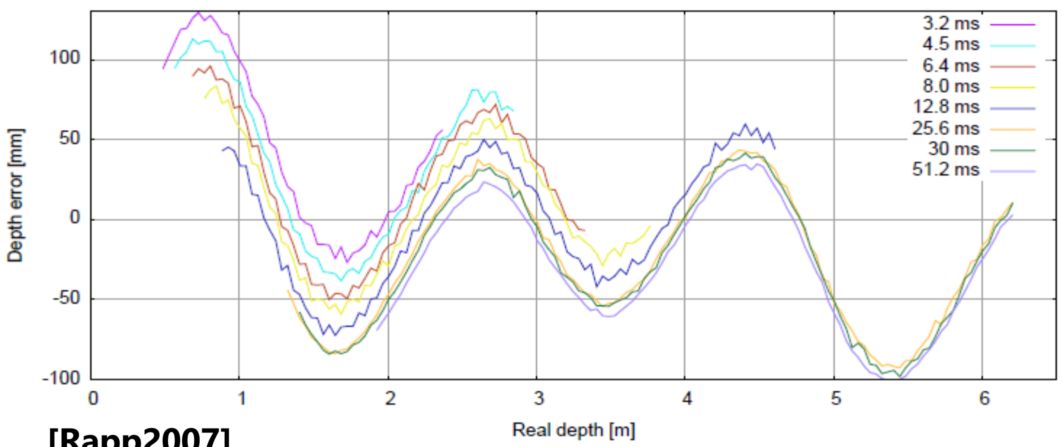


Problems – integration time



Problems – modulation

- Wrong assumption: The reference signal is a sine wave.
- In practice: light signals cannot be modulated perfectly by electronic circuits.
- This results in the so called „wiggling error".

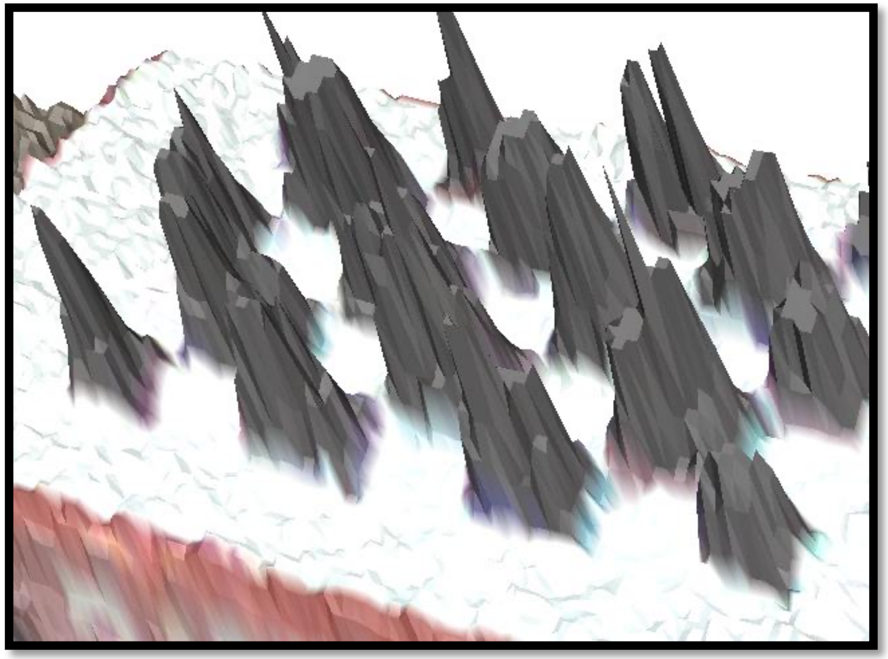


[Rapp2007]

Solutions:
Light guide [MESA, SICK]
Demodulation [Rapp2007, Frank2009, Lindner2008,…]
Calibration [Lindner2010, Schiller2011, Radmer2008, Müllenhaupt2010,…]

Problems – reflection

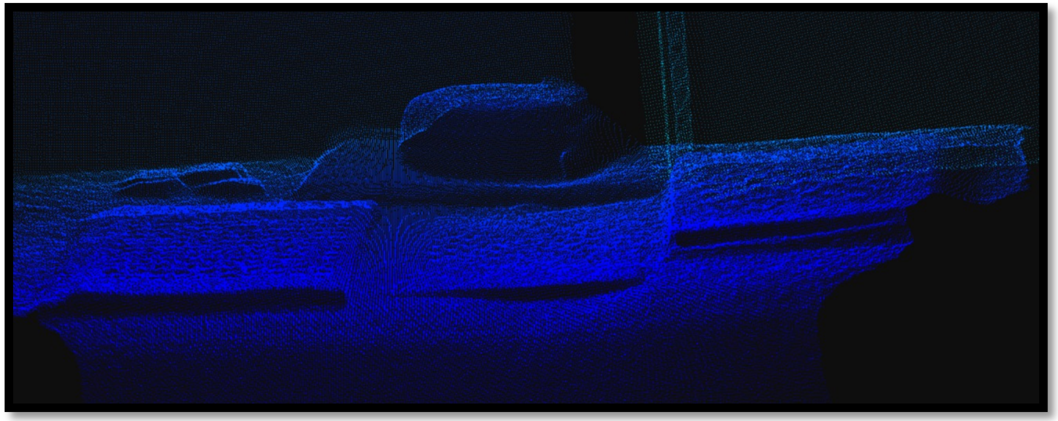
- Wrong assumption: The reflection properties of all captured objects are the same.
- In practice: various surfaces
- This results in depth differences on textured surfaces.
  - Old image (PMD, 2012)



Solutions:
Calibration [Lindner2010, Schiller2011, Radmer2008, Müllenhaupt2010,…]

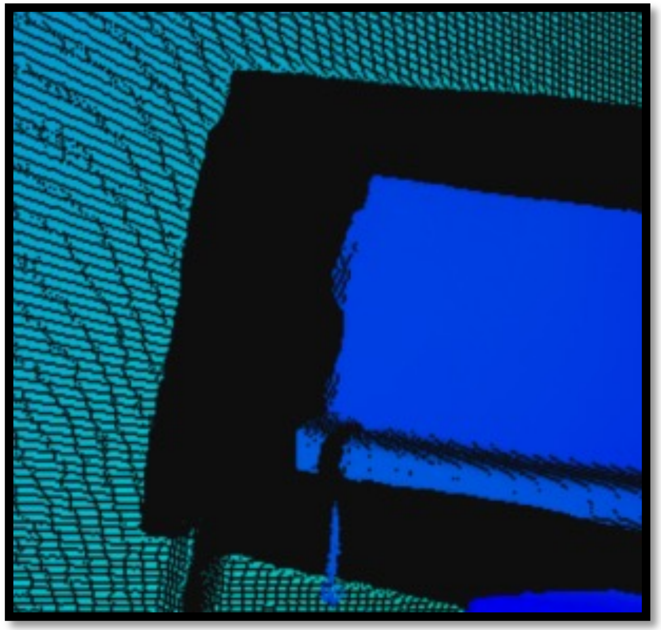
Problems – reflection

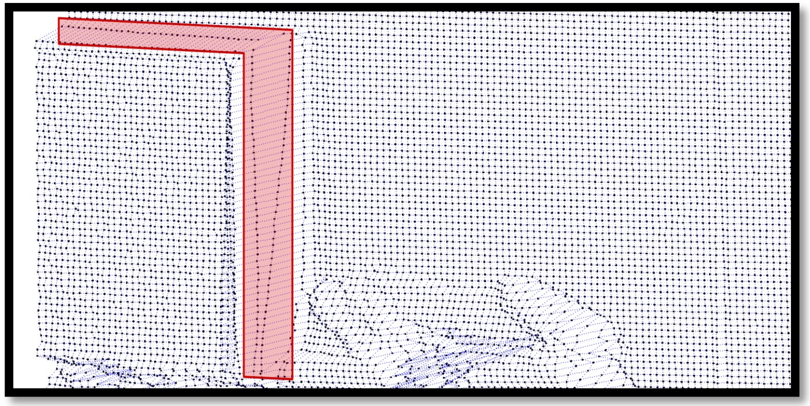
- Wrong assumption: The reflection properties of all captured objects are the same.
- In practice: various surfaces
- This results in depth differences on textured surfaces.
  - Azure Kinect performs much better, but still has the problem.



Problems – depth discontinuities

- Wrong assumption: The distance inside one pixel is constant.
- In practice: depth discontinuities
- This results in „flying pixels"





Solutions:
Additional camera [Huhle2010]
Machine Learning [Reynolds2011]
Azure Kinect

Problems – multipath

- Wrong assumption: The light signal comes back directly
- In practice: multiple light paths
- This results in round corners
- Azure Kinect detects multi-path

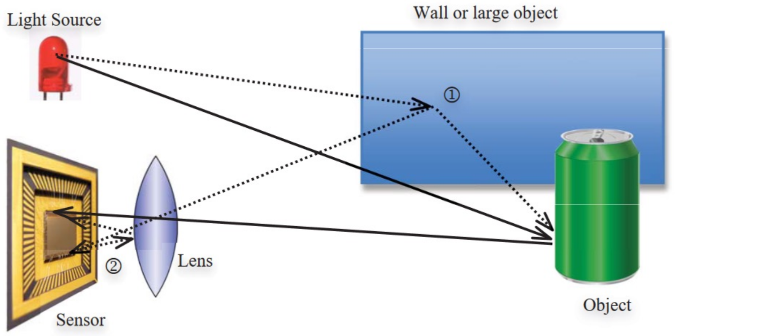
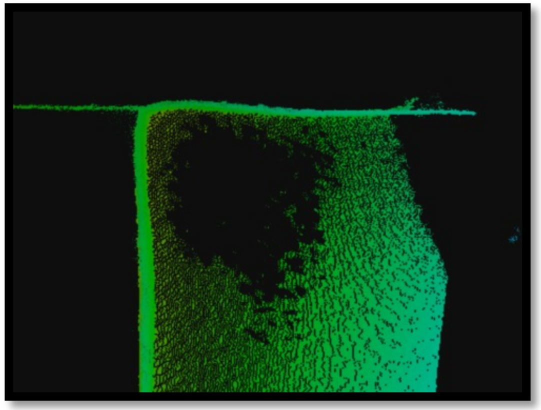
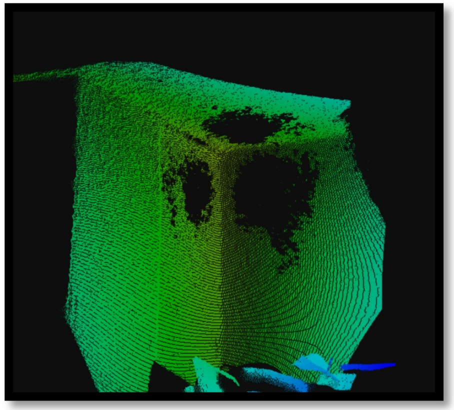


Figure 1 – Illustration of light propagation in a range imaging camera. Solid lines show direct part illumination and detection, broken lines show interfering multi-path. Sources of multi-path include ① scattering within the scene and② scatting within the lens system. (Images from Wikimedia Commons).





Solutions:
Multiple frequencies [Dorrington2011, Azure Kinect]

Applications


Automotive


Robotics


Digital Signage


Home Automation


Virtual Reality


Medical


Health


Sport & Fitness


Retail


Military


Television


Video Games

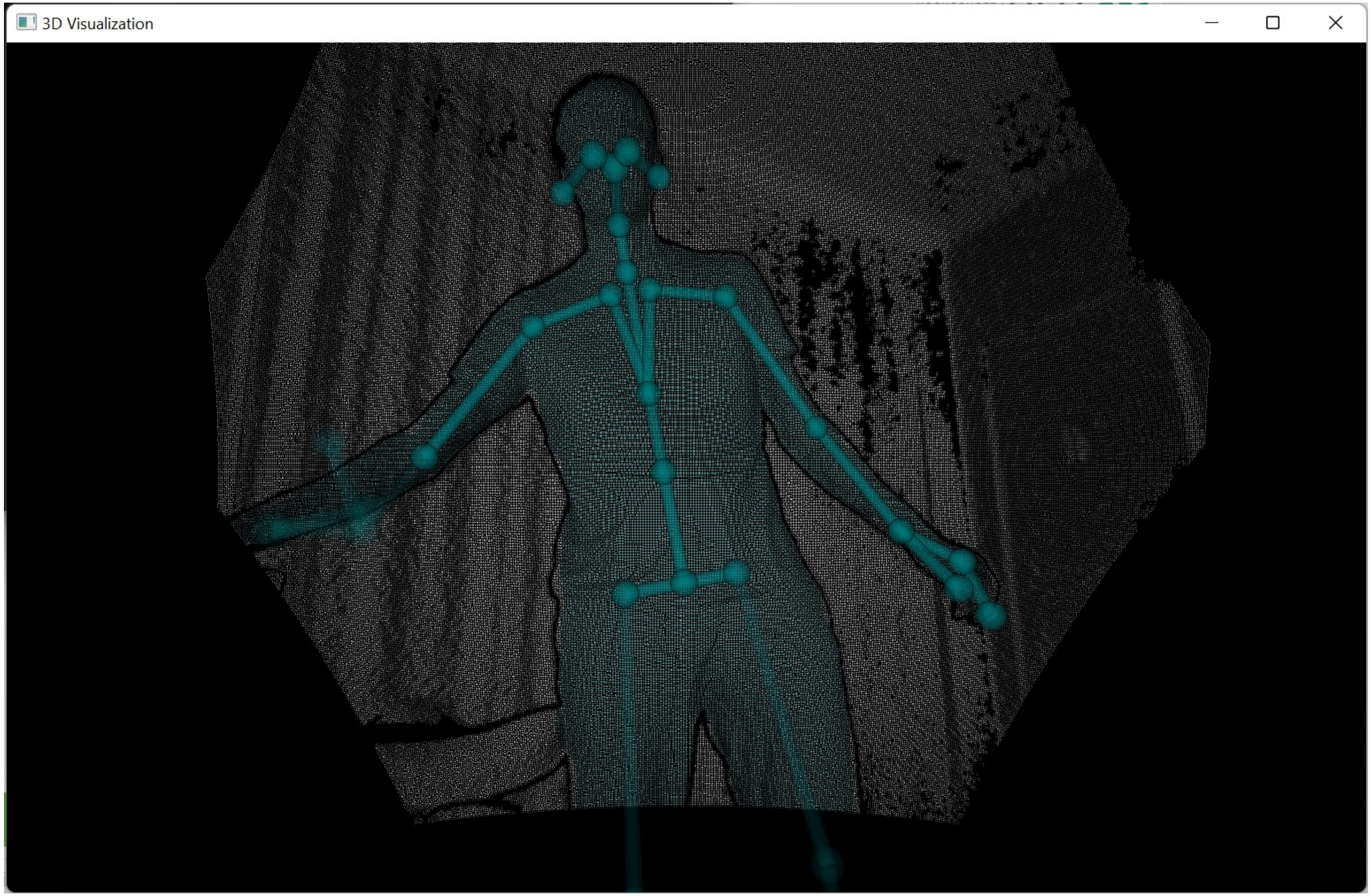

Entertainment


Handheld

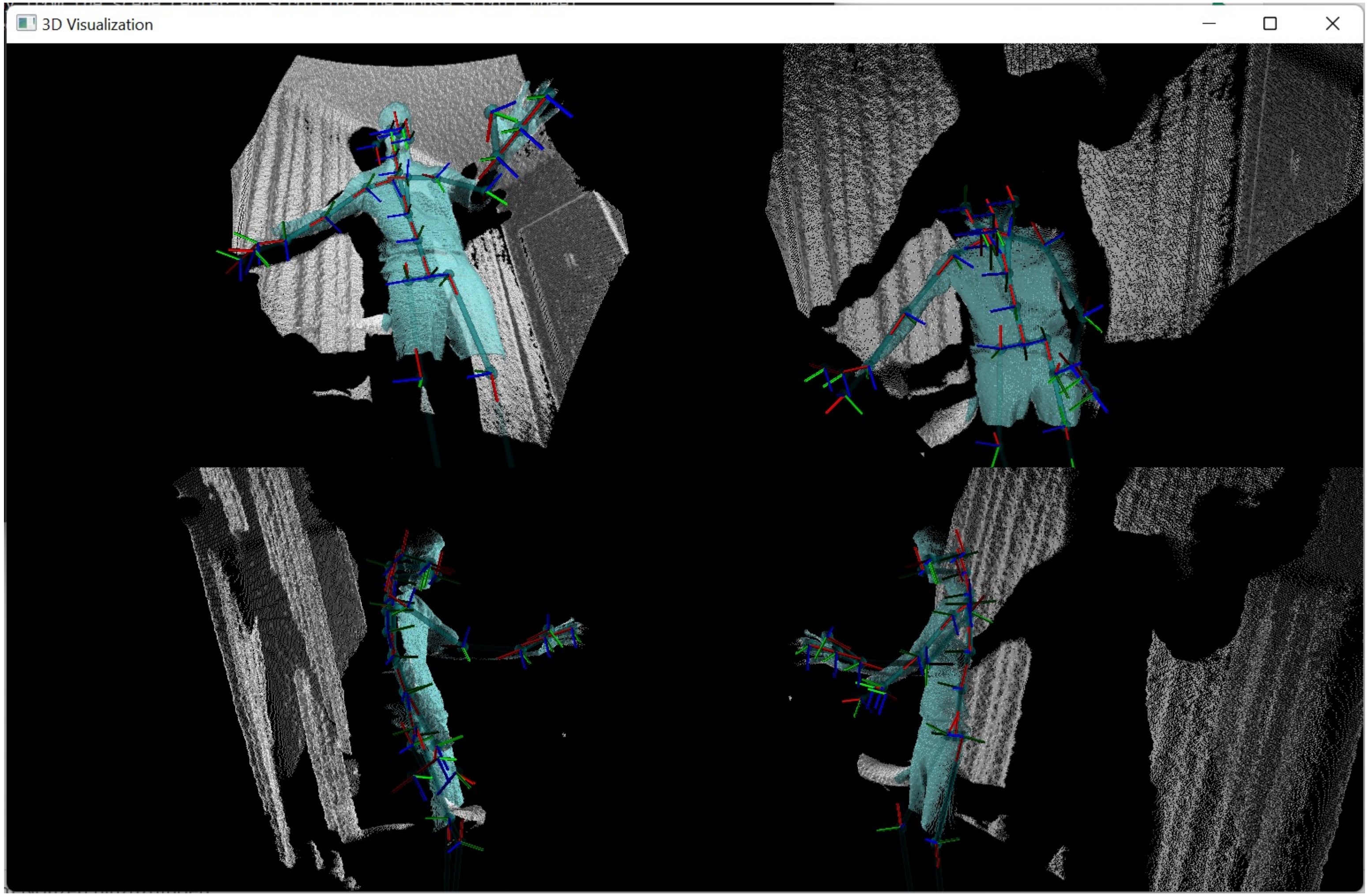

Computers

Image source: [Texas Instruments 2014]

Body and gesture tracking

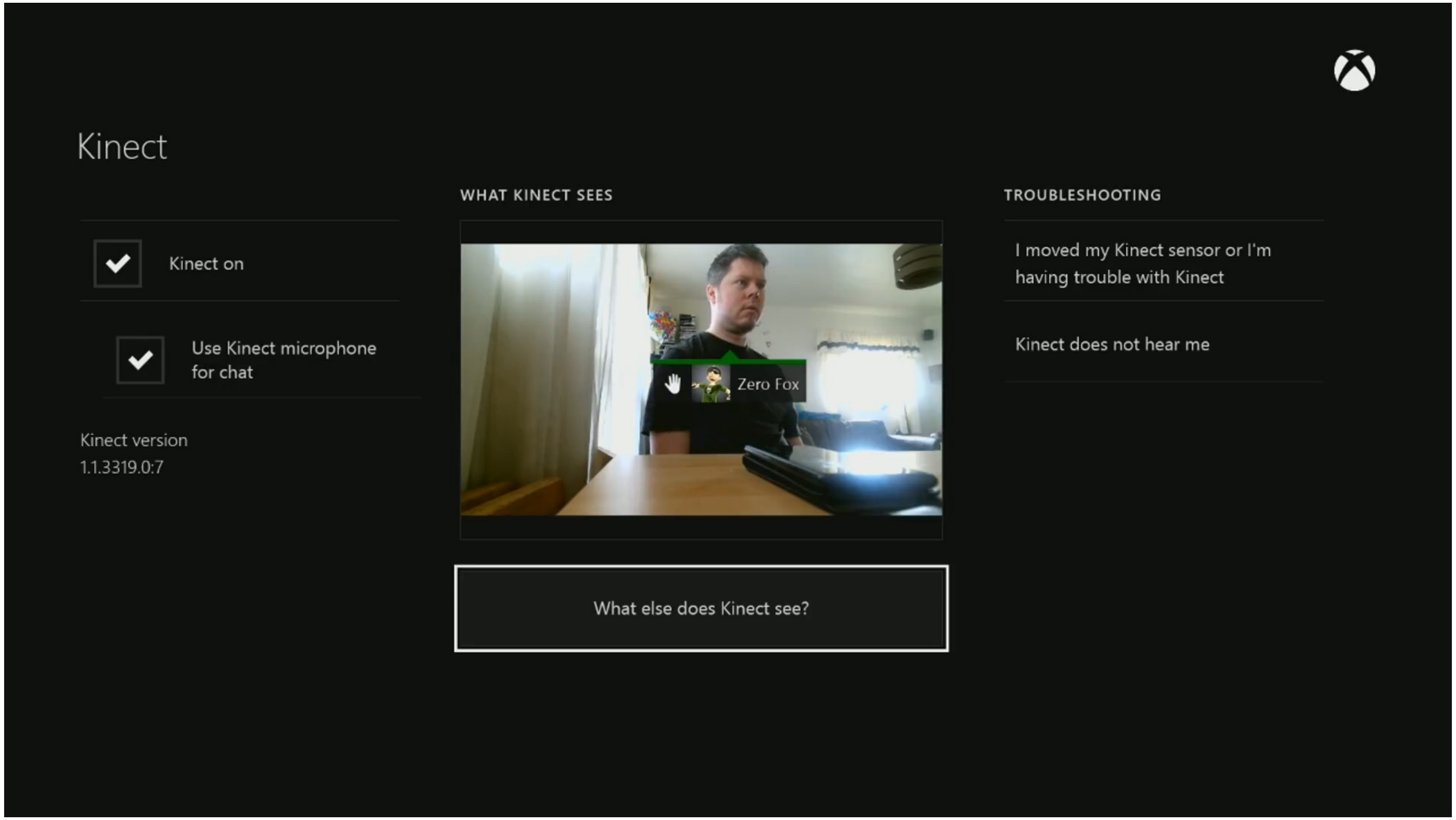


Body and gesture tracking



Ghost sensing

- Just search for „Kinect ghost" on Youtube…



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