3D Sensors

(Source: https://www.google.com/selfdrivingcar/)

Slide credit to Radu Horaud, http://perception.inrialpes.fr

3D Sensors

Overview

Basic principle: Measure depth based

1. on illuminating the scene with a controlled light source, *and*
2. then measuring the backscattered light.

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1. on illuminating the scene with a controlled light source, *and*
2. then measuring the backscattered light.

Two classes of sensors:

1. *Time of Flight (ToF) sensors*: Measure *depth* by estimating the time delay from light emission to light detection.
2. *Projected-light sensors*: Combine the projection of a light pattern with a standard 2D camera and measure depth via triangulation.

3D Sensors

Examples – Types of ToF sensors

1. Point-wise ToF sensors: mounted on a two-dimensional pan-tilt scanning mechanism, also referred to as Light Detection and Ranging (LIDAR).
2. Matricial ToF sensors: estimate depth in a "single shot" using a matrix of ToF sensors (in practice, they use CMOS or CCD image sensors coupled with a lens system).

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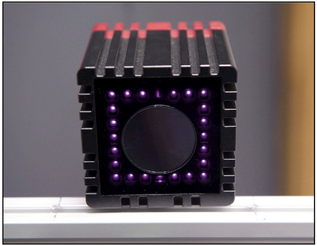
Examples – Matricial ToF sensors



SR4000 (Swiss Ranger)

(Source: http://www.hizook.com, http://www.mesa-imaging.ch)

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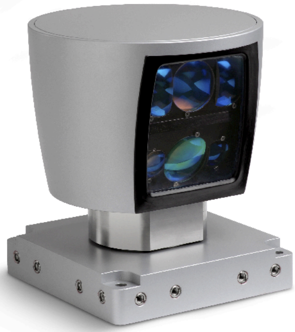
Examples – Point-wise ToF sensors



Velodyne HDL-64E & HDL-32E

(Source: http://velodynelidar.com/lidar/lidar.aspx)

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Examples – Point-wise ToF sensors (Velodyne usage)


BAIDU self-driving car, NAVYA driverless shuttle
(Source: http://velodynelidar.com)

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Examples – 3D Flash LIDAR cameras (direct ToF)

TigerEye 3D

(Source: http://www.advancedscientificconcepts.com/products/tigereye.html

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Examples – Projected light sensors

Microsoft Kinect

(Source: https://de.wikipedia.org/wiki/Kinect)

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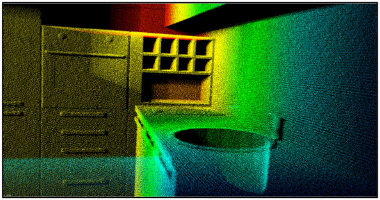
Examples – Projected light sensors

Asus Xtion Pro Live

(Source: `http://vr-zone.com`)

Time-of-Flight (ToF)

Principles



Simulated ToF image, using “Blensor” http://blensor.org

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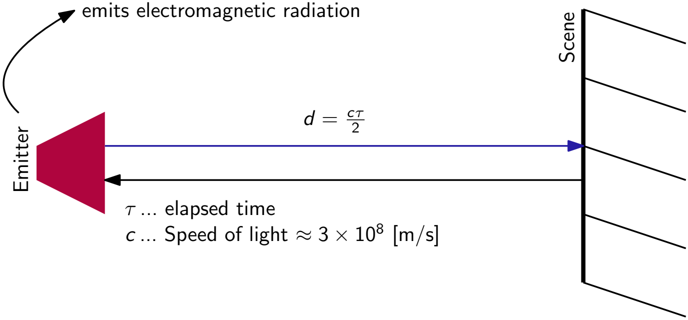
ToF principles



What is the challenge?

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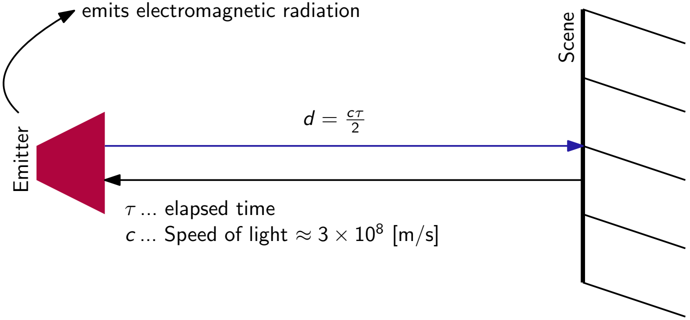
ToF principles



What is the challenge?

It takes $\approx$ 3.3 [ps] to cover a 1 [mm] path. For such a resolution, we would need a clock, capable of measuring 3.3 [ps] time steps!

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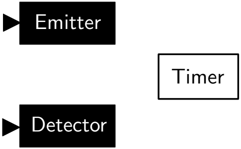
ToF principles

Working principle: measure the absolute time that a light pulse needs to travel from a target object to a detector.

Pulsed modulation: measure the ToF directly

3D Surface

Source: `http://graphics.stanford.edu`



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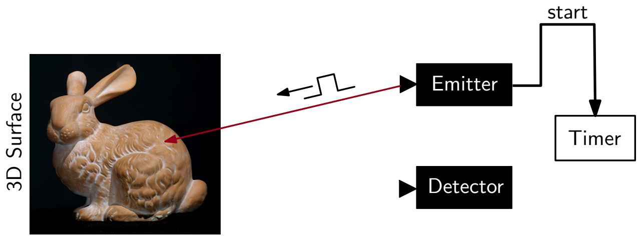

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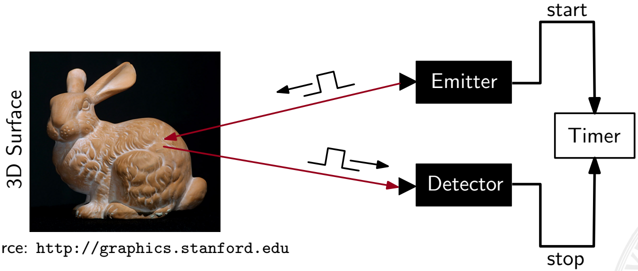

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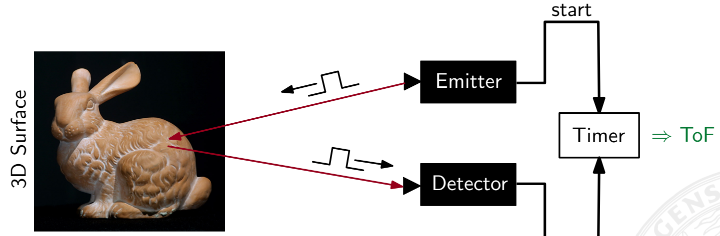

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ToF principles (Pulsed-modulation)

Advantages:

- High energy light pulses

  $\Rightarrow$ less influence of background illumination
- Illumination and observation directions are collinear

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Disadvantages:

- Arrival time must be measured very precisely
- Needs very short light pulses with fast rise/fall times
- High optical power
- Typically, these ToF sensors use lasers or laser diodes

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ToF principles (CW-modulation)

Today, we focus on continuous wave (CW) modulation:

- uses continuous light waves
- detected wave after reflection has *shifted phase*
- *phase shift is proportional to distance* from reflected surface

3D Surface

e.g., 20 Mhz

Emitter

Detector

3D Sensors

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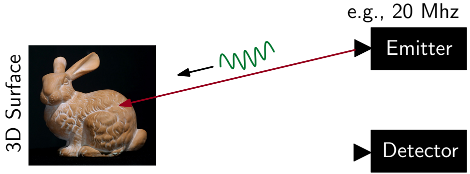

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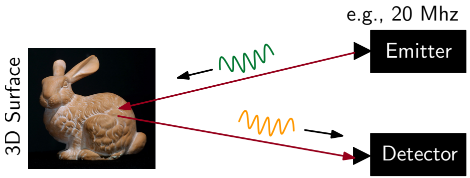

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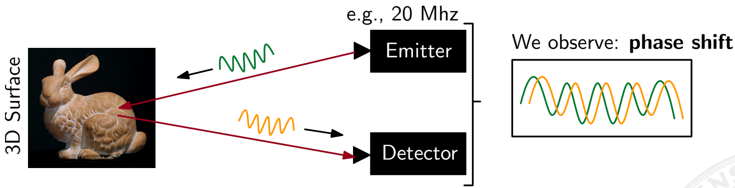

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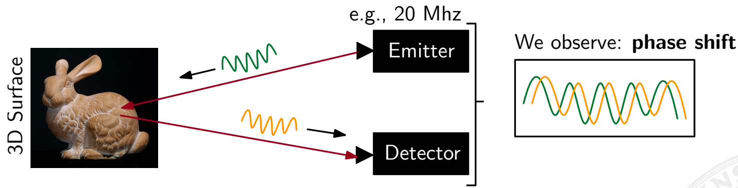

A way to recover the phase shift is by cross-correlation between the emitted and received signal!

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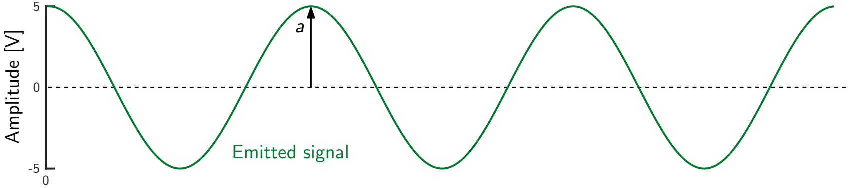
ToF principles (CW-modulation)



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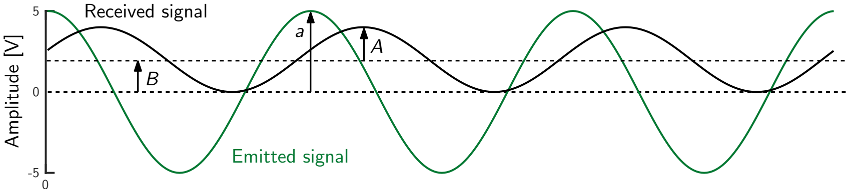

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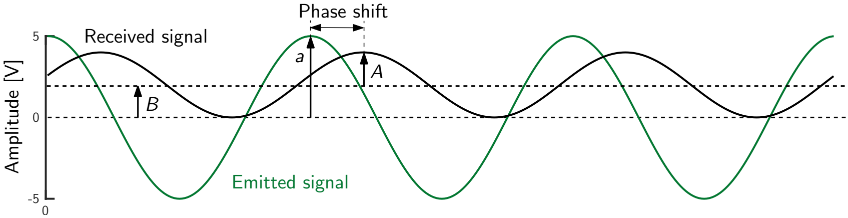

In this illustration, $A = 2$, $a = 5$ and bias $B = 2$.

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ToF principles (CW-modulation)

Phase shift recovery through cross-correlation: We know that the relationship between distance d, light speed c and ToF τ is

$$d = \frac{1}{2}c\tau$$

3D Sensors

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Assuming a constant bias B and a cosine signal with modulation frequency f and amplitude a, the emitted $s(t)$ and received $r(t)$ signals are given as

$$s(t) = a_1 + a_2 \cos(2\pi ft) \quad \text{and} \quad r(t) = A\cos(2\pi ft - 2\pi f\tau) + B$$

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B is an offset, due to ambient illumination!

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Using cross-correlation between the emitted and received signal, we can recover the phase.

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Let's look at the following integral first:

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The solution to this integral is (the correlation function)

$$C(x,\tau) = \frac{a_2 A}{2} \cos(\underbrace{2\pi f\tau}_{\phi} + \underbrace{2\pi fx}_{\psi}) + a_1 B$$

Equivalently,

$$C(\psi,\phi) = \frac{a_2 A}{2} \cos(\psi+\phi) + a_1 B$$

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ToF principles (4-bucket algorithm)

We can now evaluate $C(\psi, \phi)$ at four selected phases (aka 4-bucket algorithm), i.e.,

$$
\begin{aligned}
C_0 &= C(0, \phi) \\
C_1 &= C(\pi/2, \phi) \\
C_2 &= C(\pi, \phi) \\
C_3 &= C(3\pi/2, \phi)
\end{aligned}
$$

to recover the three unknowns A, B and τ.

Using standard trigonometric relationships, we obtain

$$\phi = 2\pi f \tau = \tan^{-1}\left(\frac{C_3 - C_1}{C_0 - C_2}\right)$$

$$A = \frac{1}{2a_2}\sqrt{(C_3 - C_1)^2 + (C_0 - C_2)^2}$$

$$B = \frac{1}{4a_1}\sum_{i=0}^{3} C_i$$

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ToF principles (phase wrapping)

Can you think of any problems related to that approach?

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We can easily compute the depth d from the recovered phase as

$$d = \frac{1}{2}\tau c = \frac{1}{2}c\frac{\phi}{2\pi f} = \frac{c}{2f}\frac{\phi}{2\pi}$$

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This *ambiguity* is referred to as phase wrapping!

$$d = \left(\frac{\phi}{2\pi} + n\right) d_{\text{max}}, \quad \text{with} \quad n = 0, 1, 2, \ldots$$

Here, n denotes the number of wrappings.

Example: for $f = 30$ [Mhz], the unambiguous range is 0-5 [m].

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ToF principles (phase wrapping)

The CCD sensor plays several roles:

1. The incoming photons are converted to electron charges
2. Clocking
3. Signal processing (i.e., demodulation)

After the demodulation, the signal $C(\psi, \phi)$ is integrated at four equally-spaced intervals within one modulation period.

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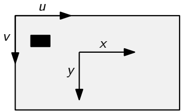
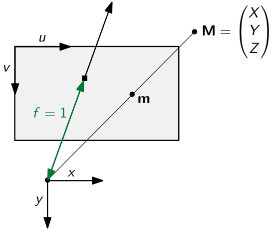
ToF principles – From depth to Euclidean coordinates



$$\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} \approx \mathbf{A} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \begin{pmatrix} k_u & 0 & u_0 \\ 0 & k_v & v_0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}$$



The ToF camera measures the depth d from the 3D point $\mathbf{M}$ to the optical center, hence

$$d = \|\mathbf{M}\|$$

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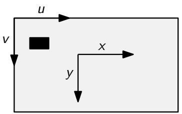
ToF principles – From depth to Euclidean coordinates



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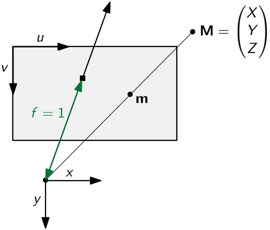

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We also know (from similar triangles) that

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = Z \begin{pmatrix} X/Z \\ Y/Z \\ 1 \end{pmatrix} = Z \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}$$

3D Sensors

From depth to Euclidean coordinates

Now, the point $\mathbf{m}$ has (u, v)-coordinates

$$\mathbf{p} = [u\ v\ 1]^\top$$

and (x, y) coordinates

$$\mathbf{m} = [x\ y\ 1]^\top \quad \text{with} \quad \mathbf{m} = \mathbf{A}^{-1}\mathbf{p} \ .$$

3D Sensors

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Next, we have $Z = \|\mathbf{M}\| \,/\, \|\mathbf{m}\|$ and consequently

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = Z \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \frac{\|\mathbf{M}\|}{\|\mathbf{m}\|} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = \frac{d}{\|\mathbf{A}^{-1}\mathbf{p}\|} \mathbf{A}^{-1} \begin{pmatrix} u \\ v \\ 1 \end{pmatrix}$$

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Distortions

We observe distortions due to ...

- Phase warping (already covered)

  $\Rightarrow$ leads to ambiguities in distance measurements!

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- Photon-shot noise

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- Saturation & Motion blur

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Distortions – More details on photon-shot noise

Interestingly, the noise which affects the distance measurement can be approximated by a Gaussian with variance

$$\sigma_d = \frac{c}{4\pi f \sqrt{2}} \frac{\sqrt{B}}{A}$$

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We observe

- As A gets larger, precision improves
- As B gets larger, precision gets worse
- B depends on background illumination and amplitude A
- An increase in B due to increase in A does not hurt (since $\sqrt{B}$)
- Increase $f \Rightarrow$ better precision, but loss in max. measurable d

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Distortions – Other noise sources

Other noise sources are, e.g.:

- Thermal noise caused by the receiver signal amplifier
- Noise caused by quantization of the received signal

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A typical strategy to counteract noise effects is signal averaging over several periods.

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Distortions – Signal averaging

Typical averaging intervals are between 1 [ms] and 100 [ms]. In case of $f = 30$ [Mhz], e.g., we get a *period* T of

$$T = 33.3 \times 10^{-9} \approx 33 \text{ [ns]}$$

and consequently, for averaging over 1 [ms], we cover 3×10^4 periods, or, for 100 [ms], 3×10^6 periods.

The averaging interval length is called the integration time.