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.

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.

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.

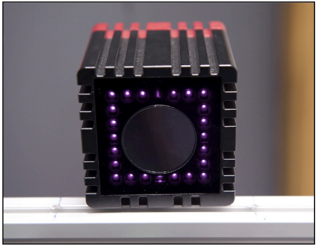
3D Sensors

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).

3D Sensors

Examples – Matricial ToF sensors

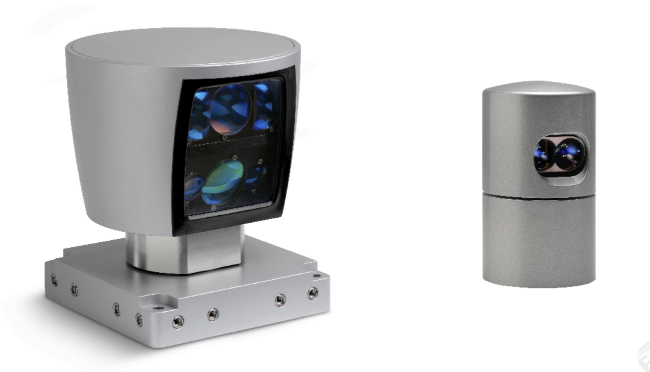


SR4000 (Swiss Ranger)

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

3D Sensors

Examples – Point-wise ToF sensors



Velodyne HDL-64E & HDL-32E
(Source: http://velodynelidar.com/lidar/lidar.aspx)

3D Sensors

Examples – Point-wise ToF sensors (Velodyne usage)

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

3D Sensors

Examples – 3D Flash LIDAR cameras (direct ToF)

TigerEye 3D

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

3D Sensors

Examples – Projected light sensors

Microsoft Kinect

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

3D Sensors

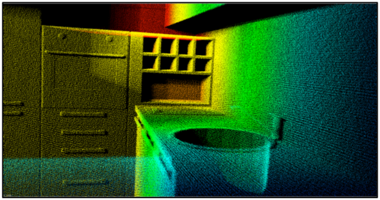
Examples – Projected light sensors

Asus Xtion Pro Live

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

Time-of-Flight (ToF)

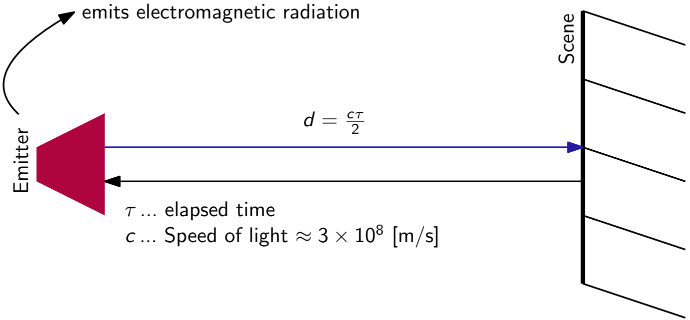
Principles



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

3D Sensors

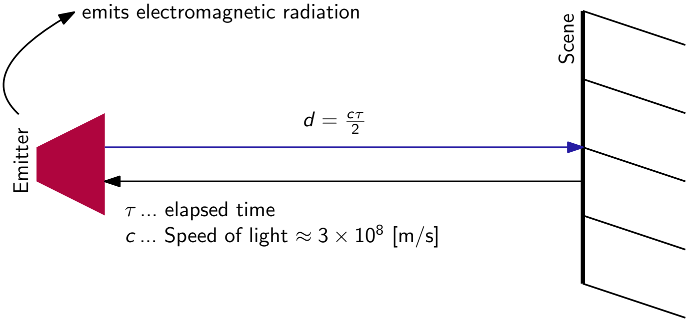
ToF principles



What is the challenge?

3D Sensors

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!

3D Sensors

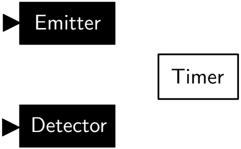
ToF principles

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`

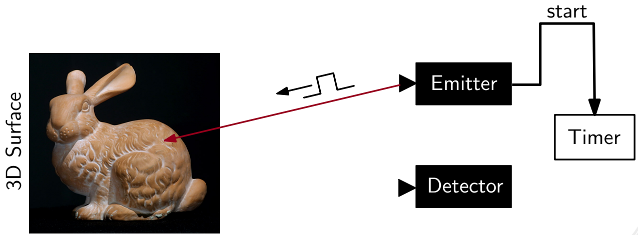


3D Sensors

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



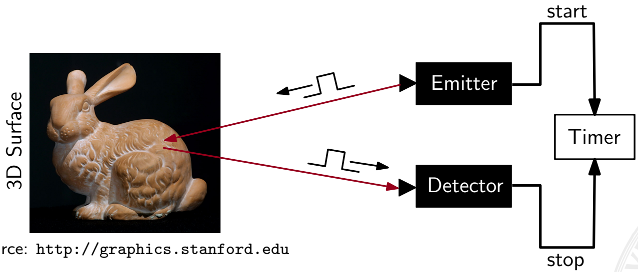
Source: `http://graphics.stanford.edu`

3D Sensors

ToF principles

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

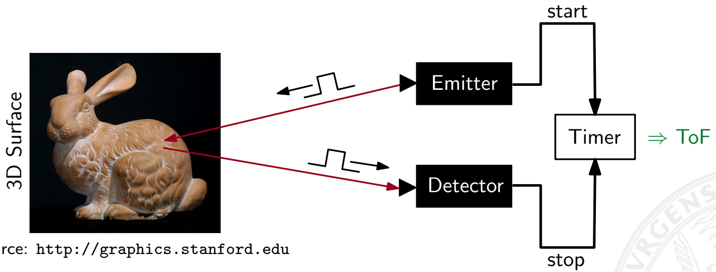
Pulsed modulation: measure the ToF directly



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

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



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

3D Sensors

ToF principles (Pulsed-modulation)

Advantages:

- High energy light pulses
  $\Rightarrow$ less influence of background illumination
- Illumination and observation directions are collinear

3D Sensors

ToF principles (Pulsed-modulation)

Advantages:

- High energy light pulses

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

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

3D Sensors

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

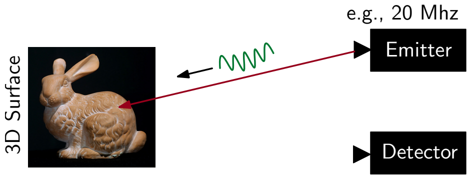
Detector

3D Sensors

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

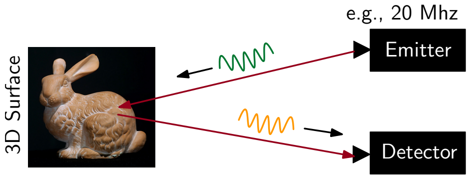


3D Sensors

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

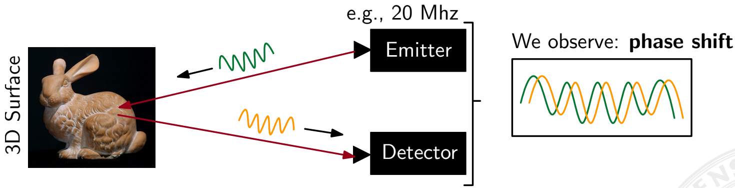


3D Sensors

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

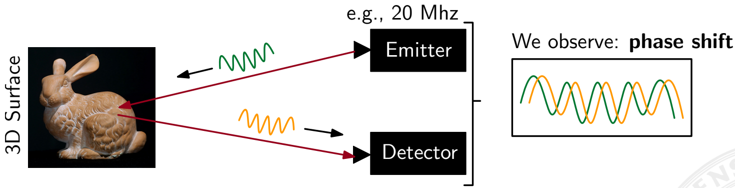


3D Sensors

ToF principles (CW-modulation)

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

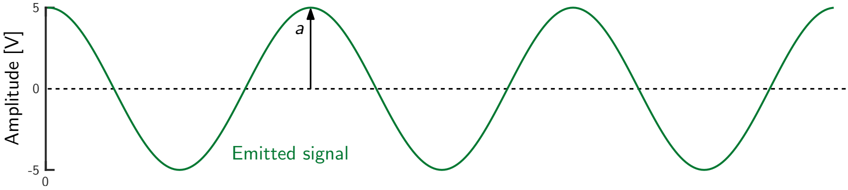
- uses continuous light waves
- detected wave after reflection has *shifted phase*
- *phase shift is proportional to distance* from reflected surface



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

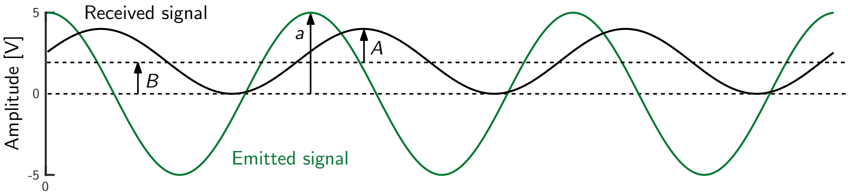
3D Sensors

ToF principles (CW-modulation)



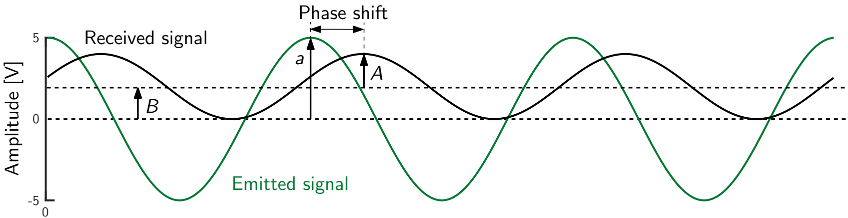
3D Sensors

ToF principles (CW-modulation)



3D Sensors

ToF principles (CW-modulation)



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

3D Sensors

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

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

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

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

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

3D Sensors

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

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

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

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

B is an offset, due to ambient illumination!

3D Sensors

ToF principles (CW-modulation)

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

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

Let's look at the following integral first:

$$C(x) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} r(t)s(t+x)dt$$

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

Let's look at the following integral first:

$$C(x) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} r(t)s(t+x)dt$$

The solution to this integral is (the correlation function)

$$C(x) = \frac{aA}{2} \cos(\underbrace{2\pi f \tau}_{\phi} + 2\pi f x) + B$$

3D Sensors

ToF principles (4-bucket algorithm)

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

$$
\begin{aligned}
2\pi f x_0 &= 0^\circ \\
2\pi f x_1 &= 90^\circ \\
2\pi f x_2 &= 180^\circ \\
2\pi f x_3 &= 270^\circ
\end{aligned}
$$

to recover the three unknowns A, B and τ.

Using standard trigonometric relationships, we obtain

$$\phi = 2\pi f \tau = \tan^{-1}\left(\frac{C(x_3) - C(x_1)}{C(x_0) - C(x_2)}\right)$$

$$A = \frac{1}{2a}\sqrt{(C(x_3) - C(x_1))^2 + (C(x_0) - C(x_2))^2}$$

$$B = 0.25 \sum_i C(x_i)$$

3D Sensors

ToF principles (phase wrapping)

Can you think of any problems related to that approach?

3D Sensors

ToF principles (phase wrapping)

Can you think of any problems related to that approach?

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

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

3D Sensors

ToF principles (phase wrapping)

Can you think of any problems related to that approach?

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

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

This *ambiguity* is referred to as phase wrapping!

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

Here, n denotes the number of wrappings.

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

3D Sensors

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)

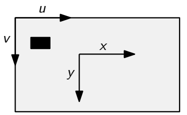
After the demodulation, the signal $C(\psi)$, i.e.,

$$C(\psi) = \frac{aA}{2}\cos(2\pi f\tau + \underbrace{2\pi fx}_{\psi}) + B$$

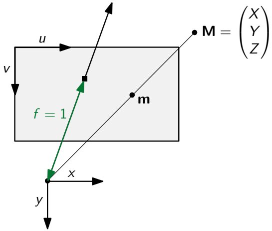
is integrated at four equally-spaced intervals within one modulation period.

3D Sensors

ToF principles – From depth to Euclidean coordinates



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

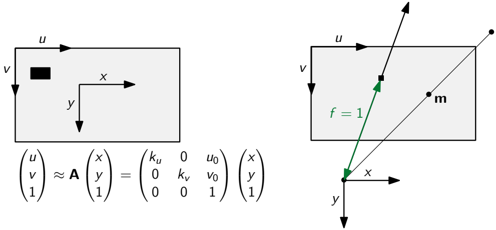


The ToF camera measures the depth d from the 3D point $\mathbf{M}$ to the optical center, hence

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

3D Sensors

ToF principles – From depth to Euclidean coordinates



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

$$\mathbf{M} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

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

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

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

From depth to Euclidean coordinates

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

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

and (x, y) coordinates

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

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

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

3D Sensors

Distortions

We observe distortions due to ...

- Phase warping (already covered)

  $\Rightarrow$ leads to ambiguities in distance measurements!

3D Sensors

Distortions

We observe distortions due to ...

- Phase warping (already covered)

  $\Rightarrow$ leads to ambiguities in distance measurements!

- Non-ideal sinusoid generation & non-instantaneous sampling

  $\Rightarrow$ leads to harmonic distortion in the estimated phase shift!

3D Sensors

Distortions

We observe distortions due to ...

- Phase warping (already covered)

  $\Rightarrow$ leads to ambiguities in distance measurements!
- Non-ideal sinusoid generation & non-instantaneous sampling

  $\Rightarrow$ leads to harmonic distortion in the estimated phase shift!
- Photon-shot noise

  $\Rightarrow$ affects the precision of distance measurements

3D Sensors

Distortions

We observe distortions due to ...

- Phase warping (already covered)

  $\Rightarrow$ leads to ambiguities in distance measurements!
- Non-ideal sinusoid generation & non-instantaneous sampling

  $\Rightarrow$ leads to harmonic distortion in the estimated phase shift!
- Photon-shot noise

  $\Rightarrow$ affects the precision of distance measurements
- Saturation & Motion blur

3D Sensors

Distortions – More details on photon-shot noise

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

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

3D Sensors

Distortions – More details on photon-shot noise

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

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

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

3D Sensors

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

3D Sensors

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

Usually, better components lead to less noise with the exception of photon-shot noise!

3D Sensors

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

Usually, better components lead to less noise with the exception of photon-shot noise!

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

3D Sensors

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.