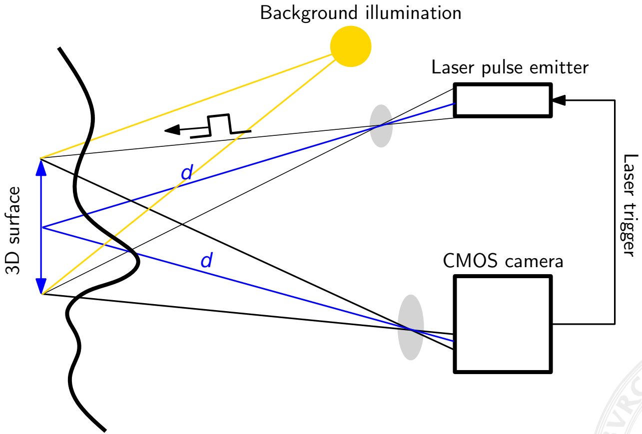
3D Sensors

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

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

ToF Imaging

Pulse Light Modulation – Components



ToF Imaging

Pulse Light Modulation – Components

- Emitter: Emits short (30 to 60 [ns]) laser pulses in NIR spectrum (850 [nm] to 910 [nm])
- Optics: Optimizes efficiency; controls beam angle (via cylindrical lens); homogeneous distribution of laser beam (via diffusing panel)
- CMOS Image sensor: Captures image with a very short electronic "shutter" (30 to 120 [ns])

ToF Imaging

Pulse Light Modulation – Basic principle

- Use light pulse(s) of short duration, generated by a laser

ToF Imaging

Pulse Light Modulation – Basic principle

- Use light pulse(s) of short duration, generated by a laser
- Distance is measured directly from the time delay

ToF Imaging

Pulse Light Modulation – Basic principle

- Use light pulse(s) of short duration, generated by a laser
- Distance is measured directly from the time delay
- Emitted laser energy is low

ToF Imaging

Pulse Light Modulation – Basic principle

- Use light pulse(s) of short duration, generated by a laser
- Distance is measured directly from the time delay
- Emitted laser energy is low
- No phase ambiguity (as with continuous wave modulation)

ToF Imaging

Pulse Light Modulation – Basic principle

- Use light pulse(s) of short duration, generated by a laser
- Distance is measured directly from the time delay
- Emitted laser energy is low
- No phase ambiguity (as with continuous wave modulation)
- Typically used in outdoor applications (e.g., driving)

ToF Imaging

Pulse Light Modulation – Basic principle

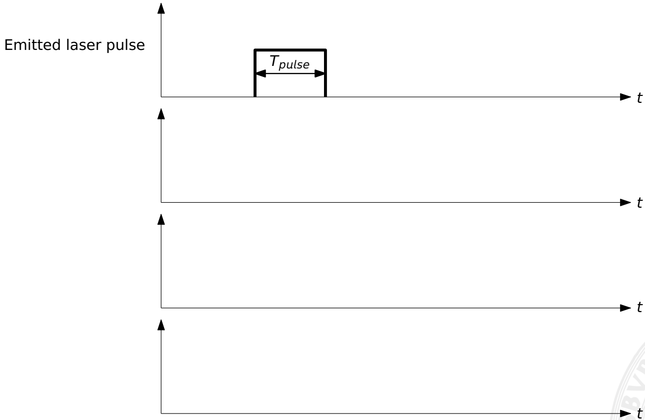
Pulse modulation can be achieved by

- integrating photoelectrons from the reflected light
- starting a "fast" counter at the detection of the reflection
  - Requires fast photo-detector
  - E.g., 1 [mm] accuracy requires pulse timing of ≈ 6.6 [ps]

ToF Imaging

Pulse Light Modulation – Double Short-Time Integration (DSTI)

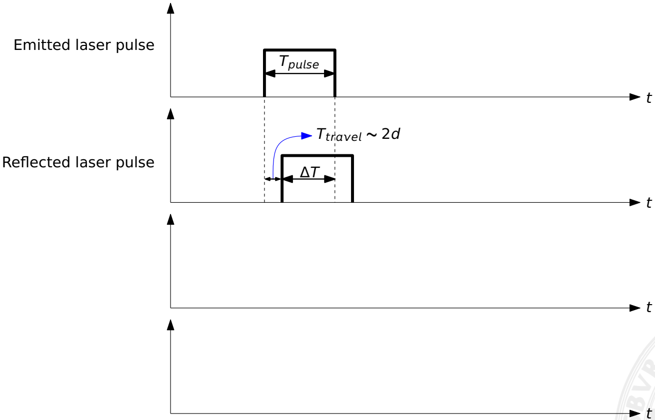
One measurement cycle:



ToF Imaging

Pulse Light Modulation – Double Short-Time Integration (DSTI)

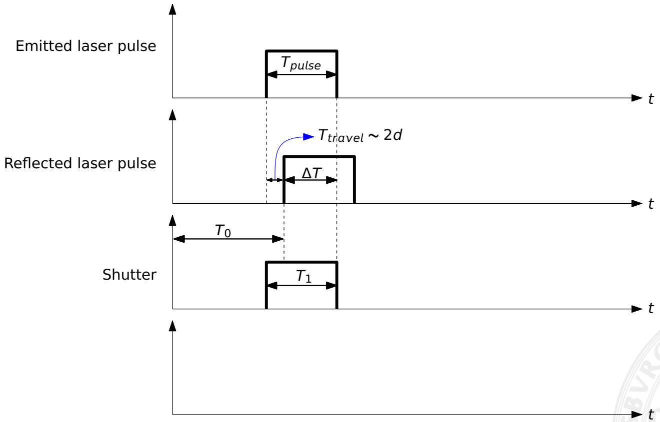
One measurement cycle:



ToF Imaging

Pulse Light Modulation – Double Short-Time Integration (DSTI)

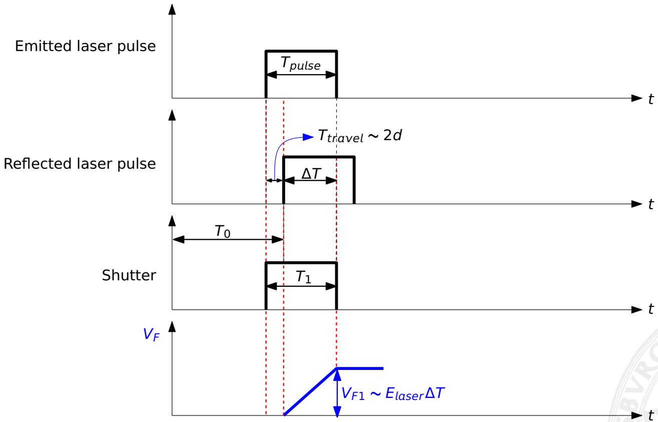
One measurement cycle:



ToF Imaging

Pulse Light Modulation – Double Short-Time Integration (DSTI)

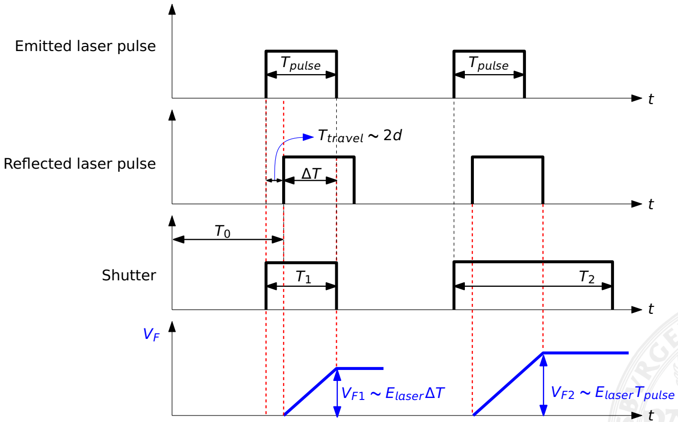
One measurement cycle:



ToF Imaging

Pulse Light Modulation – Double Short-Time Integration (DSTI)

One measurement cycle:



ToF Imaging

Pulse Light Modulation – Double Short-Time Integration (DSTI)

The output voltage (V_F) is

- $\propto$ the number of photons reaching the detector
- dependent on
  - laser power
  - surface reflectance
  - background illumination

ToF Imaging

Pulse Light Modulation – Double Short-Time Integration (DSTI)

The output voltage (V_F) is

- $\propto$ the number of photons reaching the detector
- dependent on
  - laser power
  - surface reflectance
  - background illumination

We have seen that, ...

- reflected pulses are shifted by T_{travel}
- the shutter is synchronized with emitted pulses

ToF Imaging

Pulse Light Modulation – Double Short-Time Integration (DSTI)

Two (different) shutter times are used:

1. T_1 (same length as pulse time T_{pulse})
2. T_2 (longer than pulse time T_{pulse})

ToF Imaging

Pulse Light Modulation – Double Short-Time Integration (DSTI)

How can we compute ΔT and eventually the distance d?

- We know that

$$V_{F1} \propto E_{laser} \Delta T$$

and

$$V_{F2} \propto E_{laser} T_{pulse}$$

ToF Imaging

Pulse Light Modulation – Double Short-Time Integration (DSTI)

How can we compute ΔT and eventually the distance d?

- We know that

$$V_{F1} \propto E_{laser} \Delta T$$

  and

$$V_{F2} \propto E_{laser} T_{pulse}$$

- We also know that $\Delta T = T_{pulse} - T_{travel}$ and thus

$$\Delta T = \frac{V_{F1}}{V_{F2}} T_{pulse}$$

ToF Imaging

Pulse Light Modulation – Double Short-Time Integration (DSTI)

Finally, the distance d can be computed as

$$d = \frac{c}{2} T_{travel} = \frac{c}{2}(T_{pulse} - \Delta T) = \frac{c}{2} T_{pulse} \left(1 - \frac{V_{F1}}{V_{F2}}\right)$$

ToF Imaging

Pulse Light Modulation – Maximum and minimum depth

Let's assume that the shutter opens (and thus the integration window becomes active) as the laser pulse starts.

From

$$d = \frac{c}{2}(T_{pulse} - \Delta T)$$

we see that the *maximum range* is

ToF Imaging

Pulse Light Modulation – Maximum and minimum depth

Let's assume that the shutter opens (and thus the integration window becomes active) as the laser pulse starts.

From

$$d = \frac{c}{2}(T_{pulse} - \Delta T)$$

we see that the *maximum range* is

$$d_{max} = \frac{c}{2} T_{pulse} \quad \text{i.e., when } T_{pulse} = T_{travel}$$

Example: For a 30 [ns] pulse, we get

$$d_{max} = \frac{3 \times 10^8 \ [m/s]}{2} \cdot (30 \times 10^{-9} \ [s]) = 4.5 \ [m]$$

ToF Imaging

Pulse Light Modulation – Maximum and minimum depth

How can we adjust max/min. depth?

1. Increase duration of T_{pulse}

ToF Imaging

Pulse Light Modulation – Maximum and minimum depth

How can we adjust max/min. depth?

1. Increase duration of T_{pulse}
2. Delay between pulse and opening of shutter (leading to $d_{min} > 0$)

ToF Imaging

Pulse Light Modulation – Maximum and minimum depth

How can we adjust max/min. depth?

1. Increase duration of T_{pulse}
2. Delay between pulse and opening of shutter (leading to $d_{min} > 0$)

In case of (2), we get

$$d_{max} = \frac{c}{2}(T_{delay} + T_{pulse})$$

Thus, we generate a *blind zone*

$$d_{min} = \frac{c}{2} T_{delay}$$

ToF Imaging

Pulse Light Modulation – Practical considerations

Strategy: Repeat measurement-cycle n times and accumulate resulting voltages!

- $\Rightarrow$ increases SNR (and range accuracy) by $\sqrt{n}$

ToF Imaging

Pulse Light Modulation – Practical considerations

Strategy: Repeat measurement-cycle n times and accumulate resulting voltages!

- $\Rightarrow$ increases SNR (and range accuracy) by $\sqrt{n}$

Explanation: Say we have n i.i.d. measurements $x_1, \ldots, x_n$ (output of photodiode) with mean μ and variance σ^2. We know that

$$V(\overline{x}) = V\left(\frac{x_1 + \cdots + x_n}{n}\right) = \frac{\sigma^2}{n}$$

Hence, the stochastic error reduces by $\frac{1}{\sqrt{n}}$.

Slide credits / Literature

Most of the material presented in this lecture is either taken from the textbook of Dal Mutto et al., online at

http://freia.dei.unipd.it/nuovo/Papers/ToF-Kinect-book.pdf

and the PhD thesis of O. Elkhalili here.