U9.2. 3D Vision. ToF Systems

SJK002 Computer Vision

Master in Intelligent Systems

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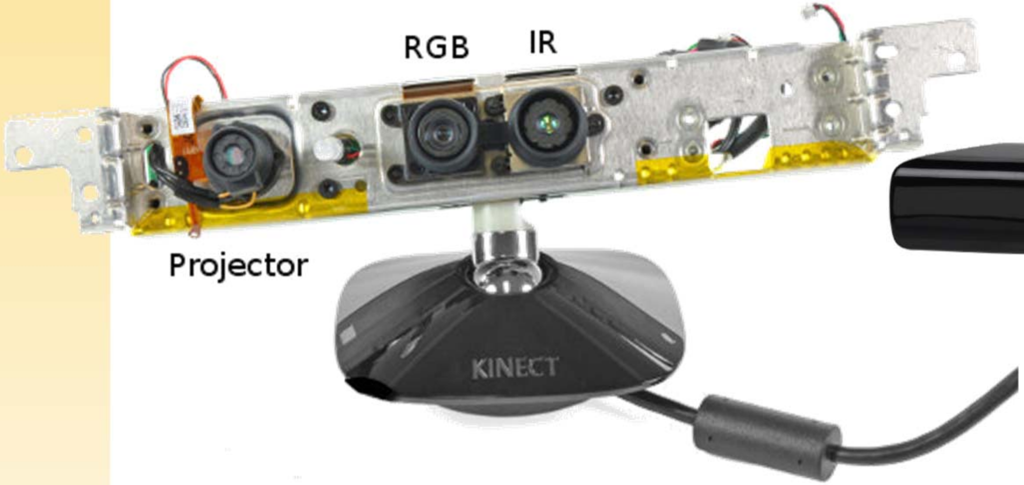
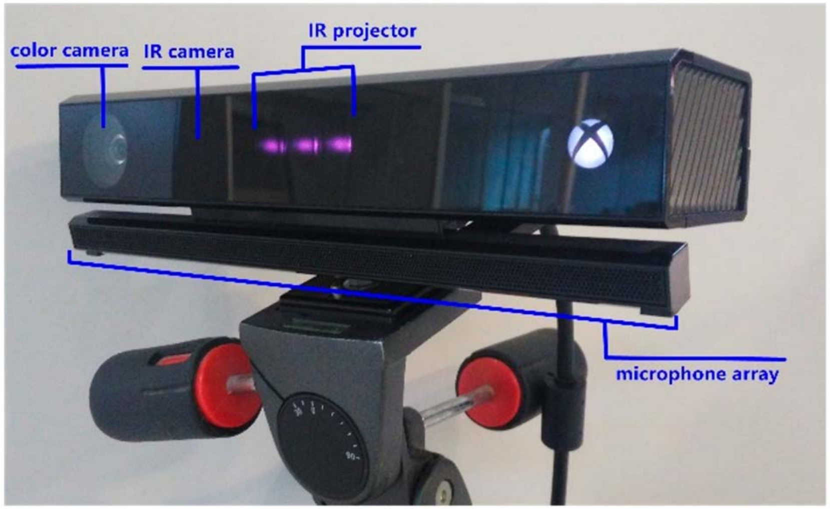
- LIDAR: Light Detection and Ranging

Kinect

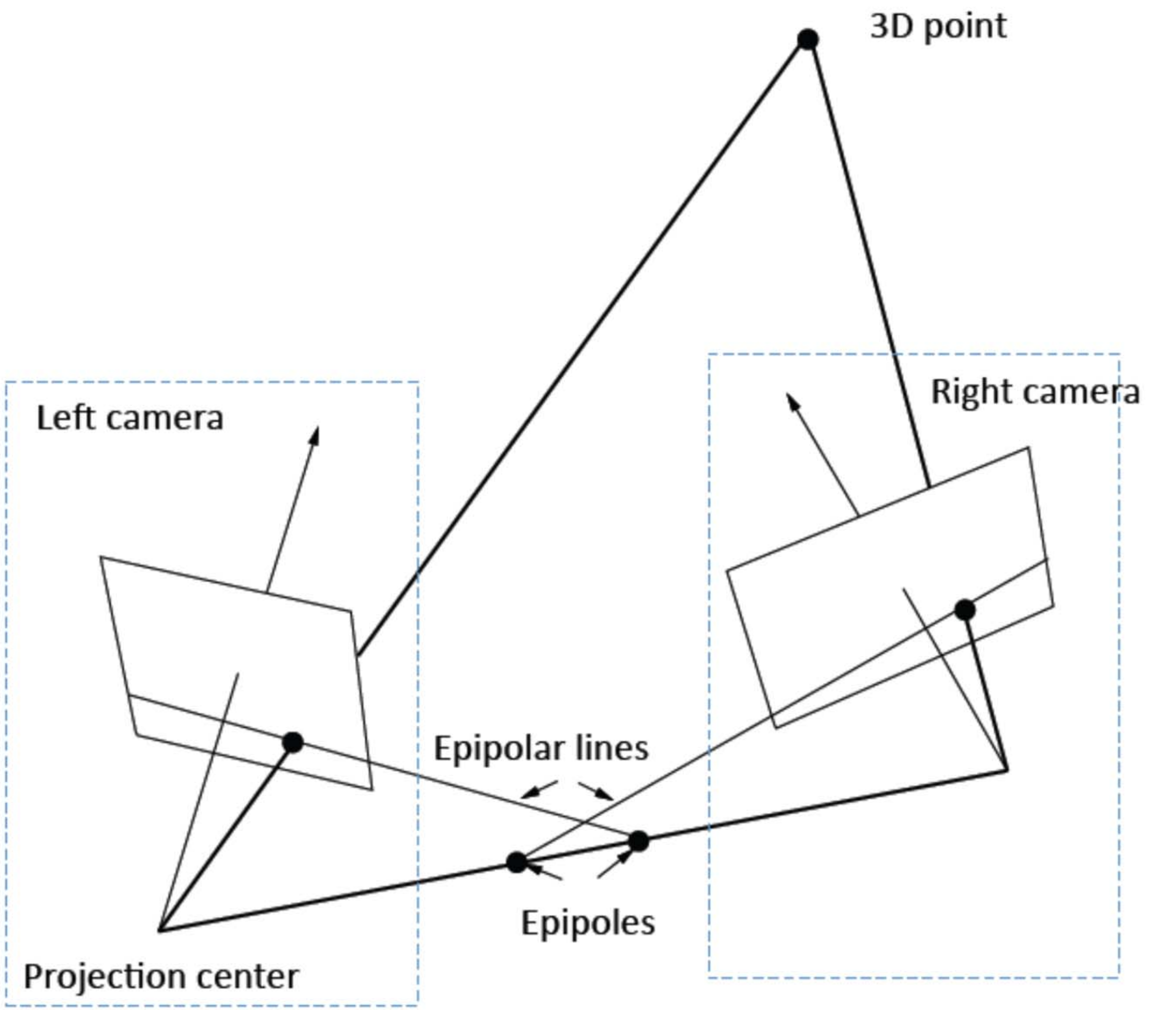


Kinect v1

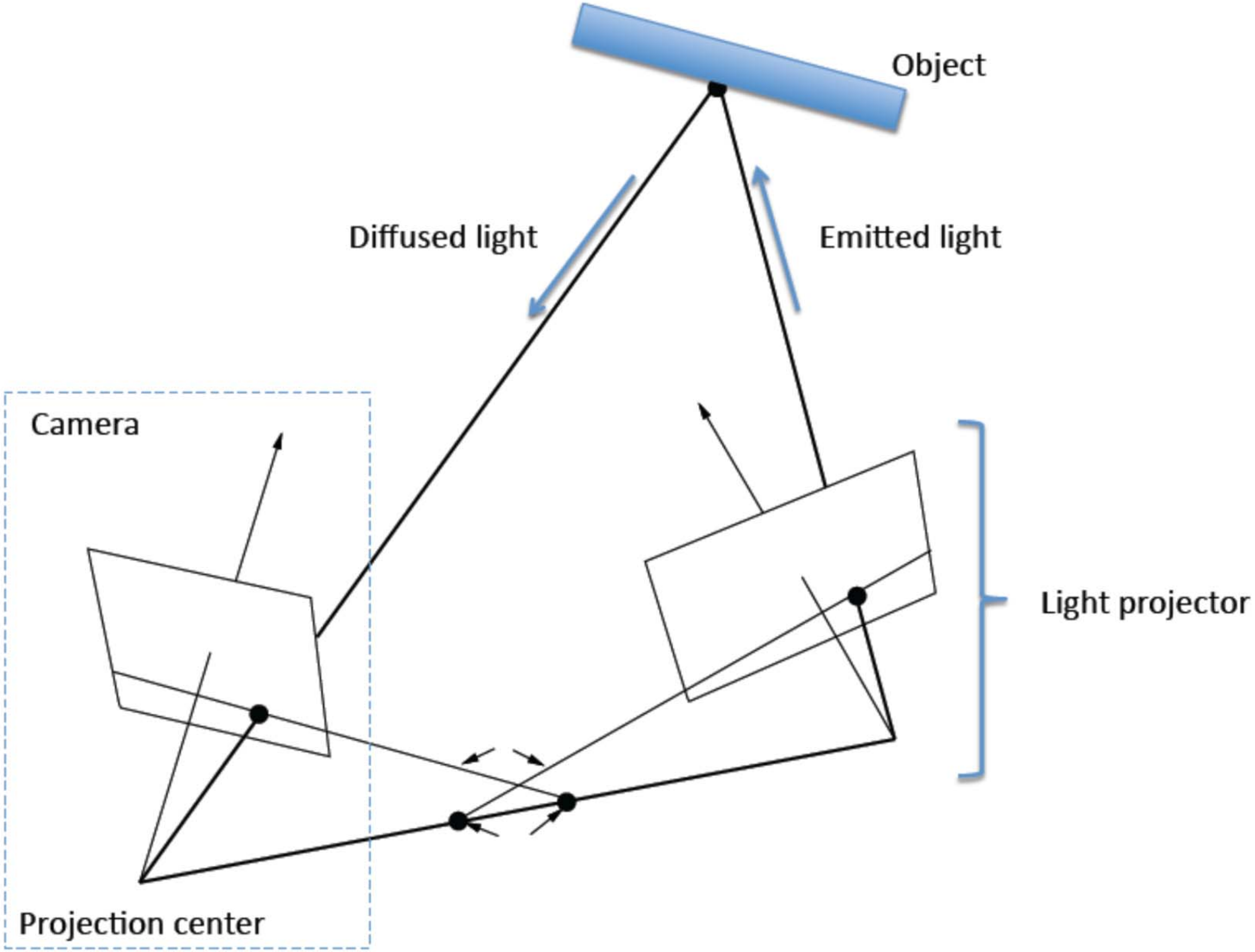


Kinect v2

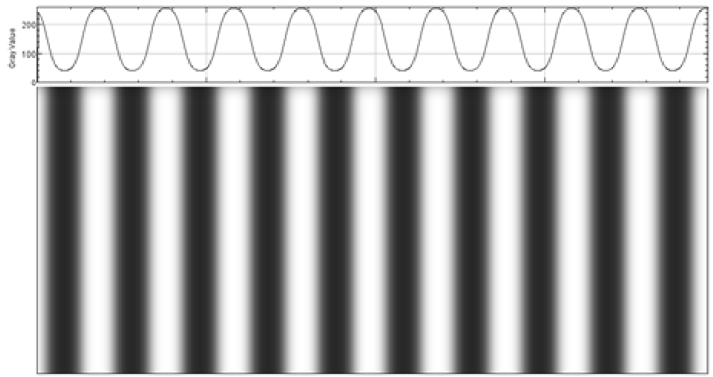
Structured light



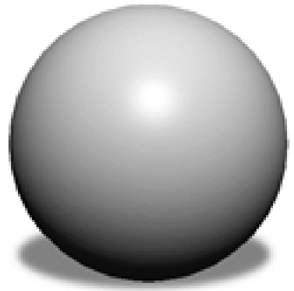
Structured light



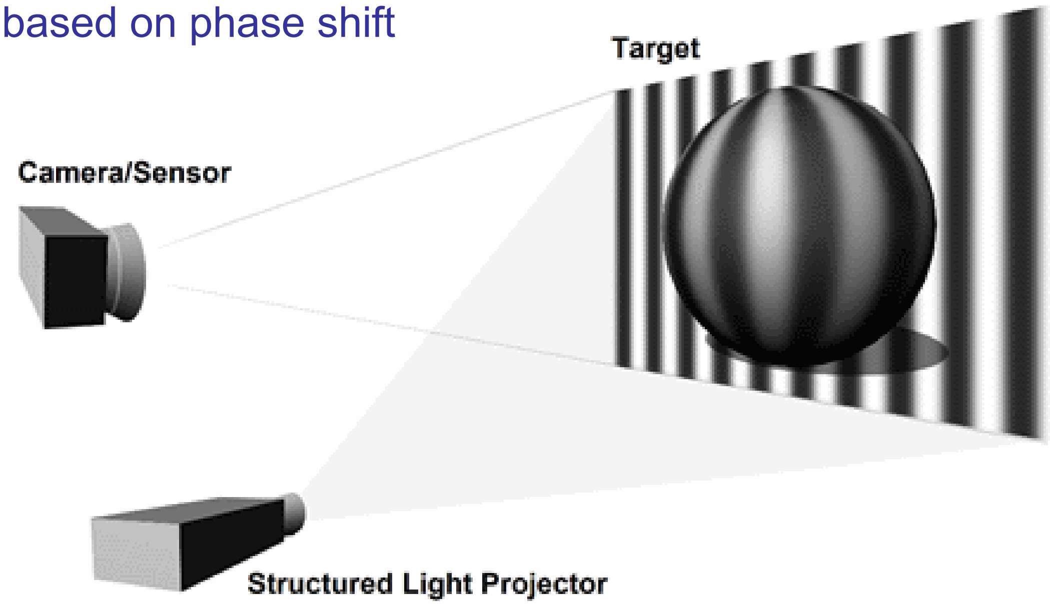
Structured light



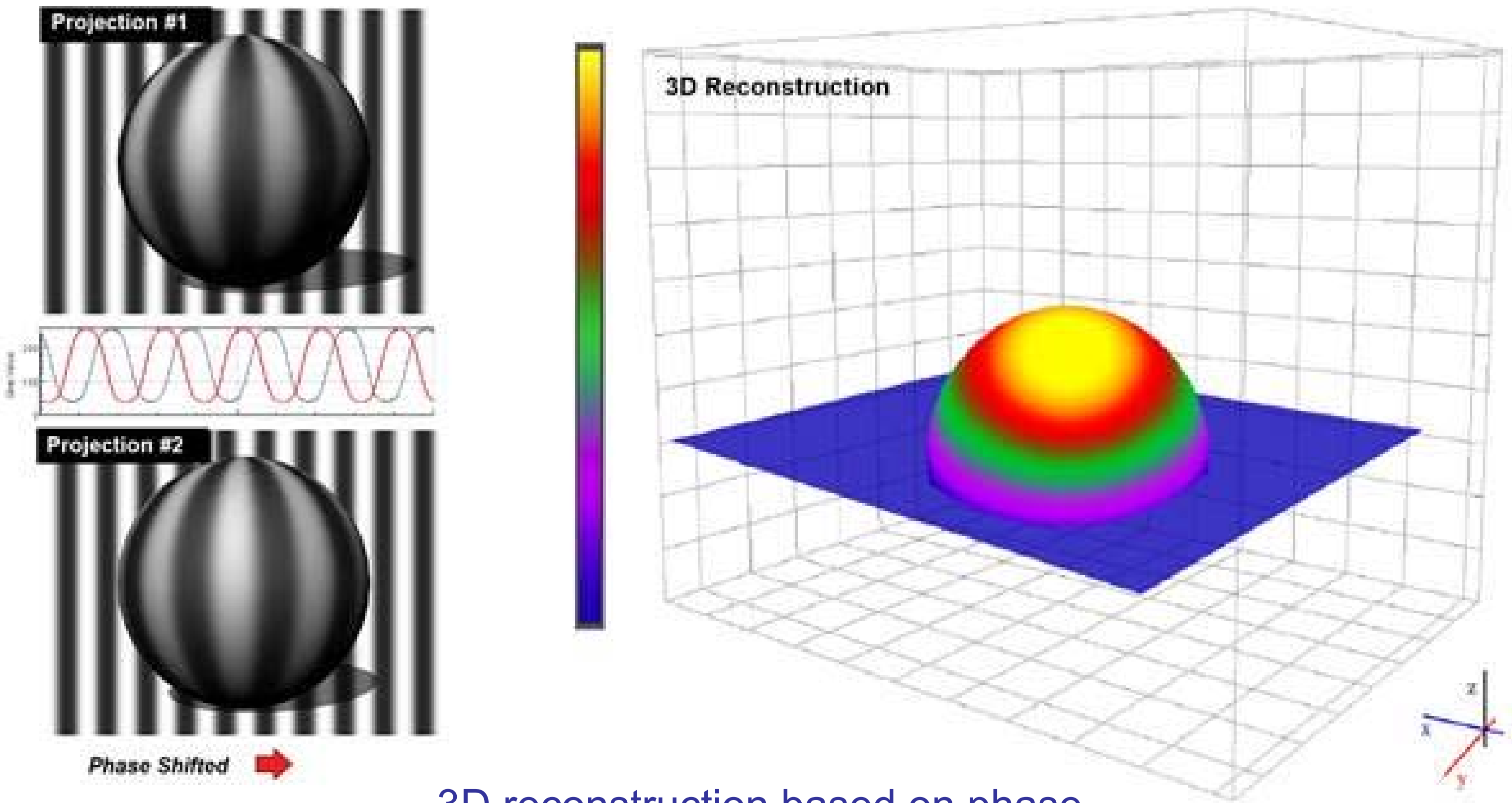
Wave pattern image for structured light based on phase shift



Target object

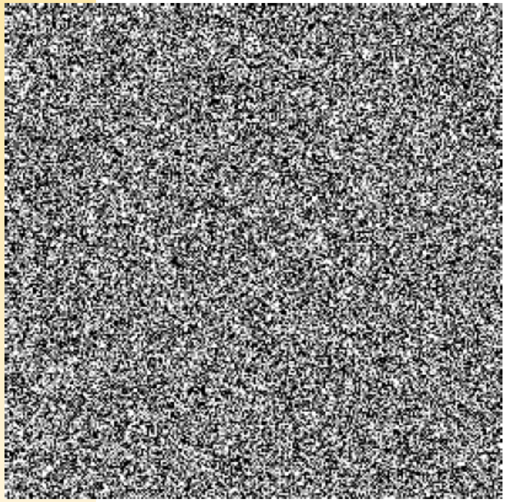


Structured light



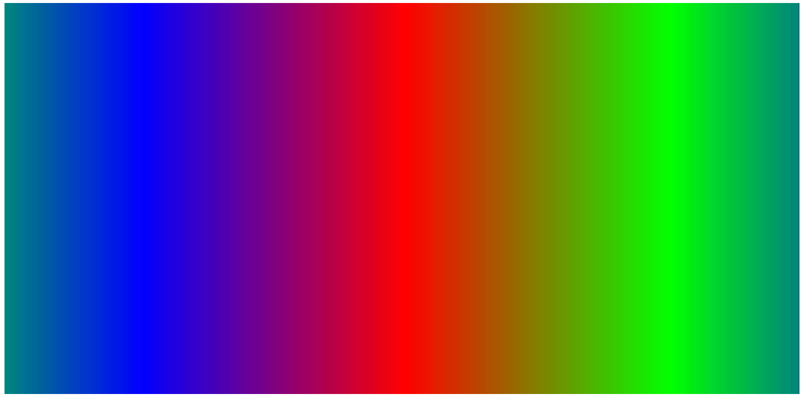
3D reconstruction based on phase shift wave patterns of structured light

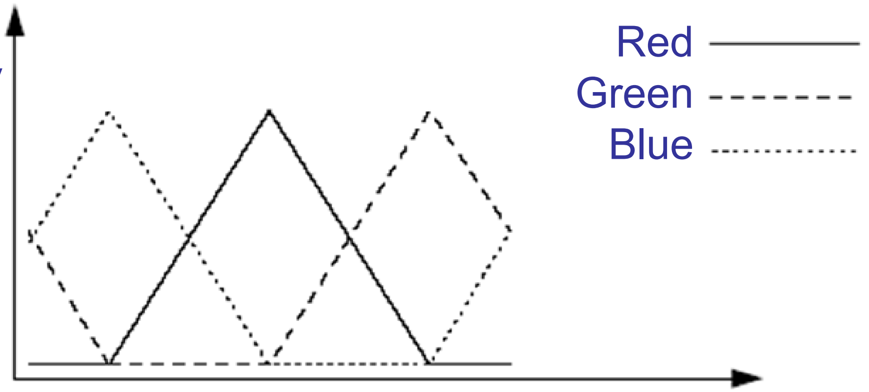
Structured light



Random pattern

Color pattern





One component is always null,
and the pattern intensity is uniform

System calibration

- Calibrate intrinsic parameters of the IR camera.
- Calibrate extrinsic parameters with respect to a single calibration grid.
- Transform the calibration plane in the camera coordinates system.
- Calibrate the projector in the camera reference system.
- Move the calibration plane to several scene positions.
- Rectify the camera-projector system to align the image of the camera with the projector plane.
- Calibration software, for example: https://github.com/jakobwilm/slstudio/

Correspondence

- As a stereo vision system, the problem is to find the correspondence between a point in the image of the camera and the corresponding point in the projector pattern.
- Each pixel of the projector can be signaled to be recognized by:
  - Temporal signal.
  - Spatial signal.
  - Combination of both.
- Use cross correlation: define a window around the target pixel and use correlation techinques between the window image values and the calibration pattern values.

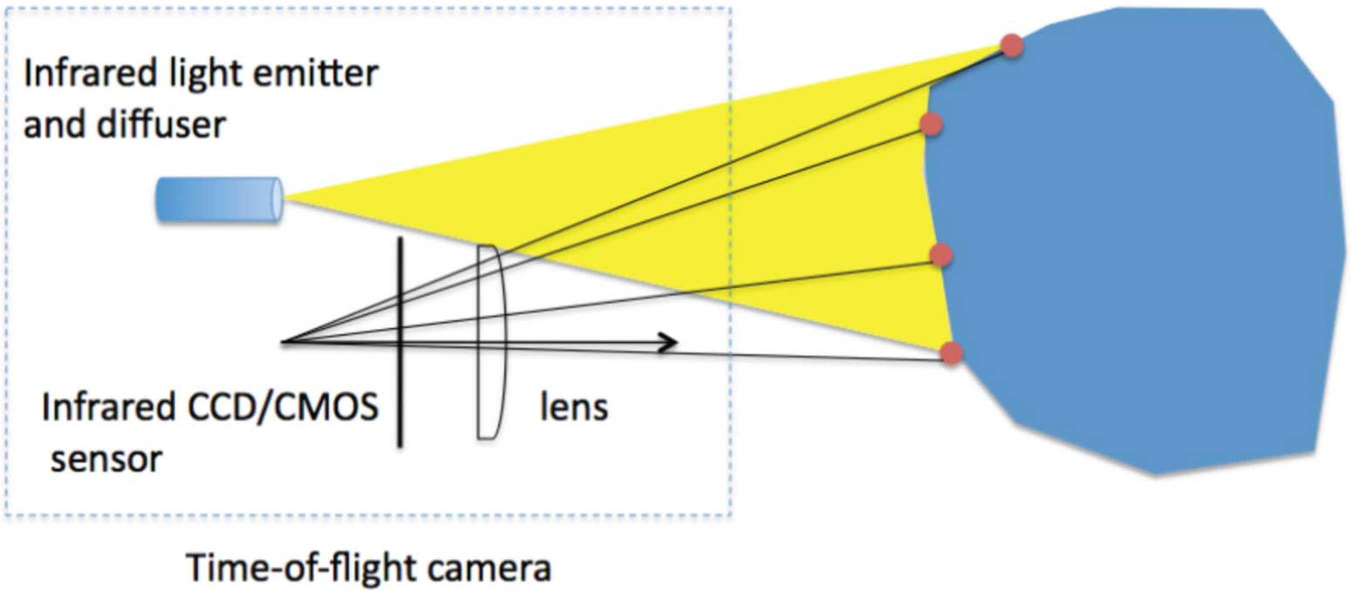
Limitations

- Structured light system calibration needs projector information (pattern, etc.):
  - Kinect does not provide this information.
- As a stereo system, it provides limited range estimation.
- Very sensitive to light saturation:
  - Bad behaviour in outdoor scenarios, with natural illumination.
- Problems with partial occlusion and light scattering (hair, wool fabrics, …).
- Advantage:
  - Good spatial resolution, usually better than ToF.

Time of Flight, ToF

- Principle:
  - Measure the time a light pulse lasts going from the camera light source to an object and back to the sensor.
- Light travels at a speed 300.000 Km/s
- ToF system:
  - Pulsed modulation (PM)
  - Continuous Wave modulation (CW-modulation)

ToF cameras



Infrared light emitter
and diffuser
Infrared CCD/CMOS
sensor
lens
Time-of-flight camera

ToF. CW-modulation

- ToF distance: $d = \frac{1}{2}c\tau$

- In practice τ is measured in an indirect way.

- Continuous Wave modulation (CW-modulation)
  - Measures the phase difference between the emitted and received signal.
  - Different signal shapes: sinusoidal, square, …
  - Base on cross correlation between signals. Signal frequency is known.

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ToF. CW-modulation

- Amplitude modulated frequencies used between 10-100 MHz.
- Relation between signal phase and ToF:

$$\phi = 2\pi f \tau$$

- Phase ϕ is defined up to 2π: *phase warping*.
- Amplitude of the received signal A depends on object reflectivity and sensor sensitivity.
- Amplitude A decreases as $1/d^2$, mainly due to dispersion.
- Ambient illumination is a constant B

ToF. CW-modulation

- Emitted signal:

$$s(t) = a\cos(2\pi f t)$$

- Received signal:

$$r(t) = A\cos(2\pi f(t-\tau)) + B$$

- Cross correlation between emitted and received signals:

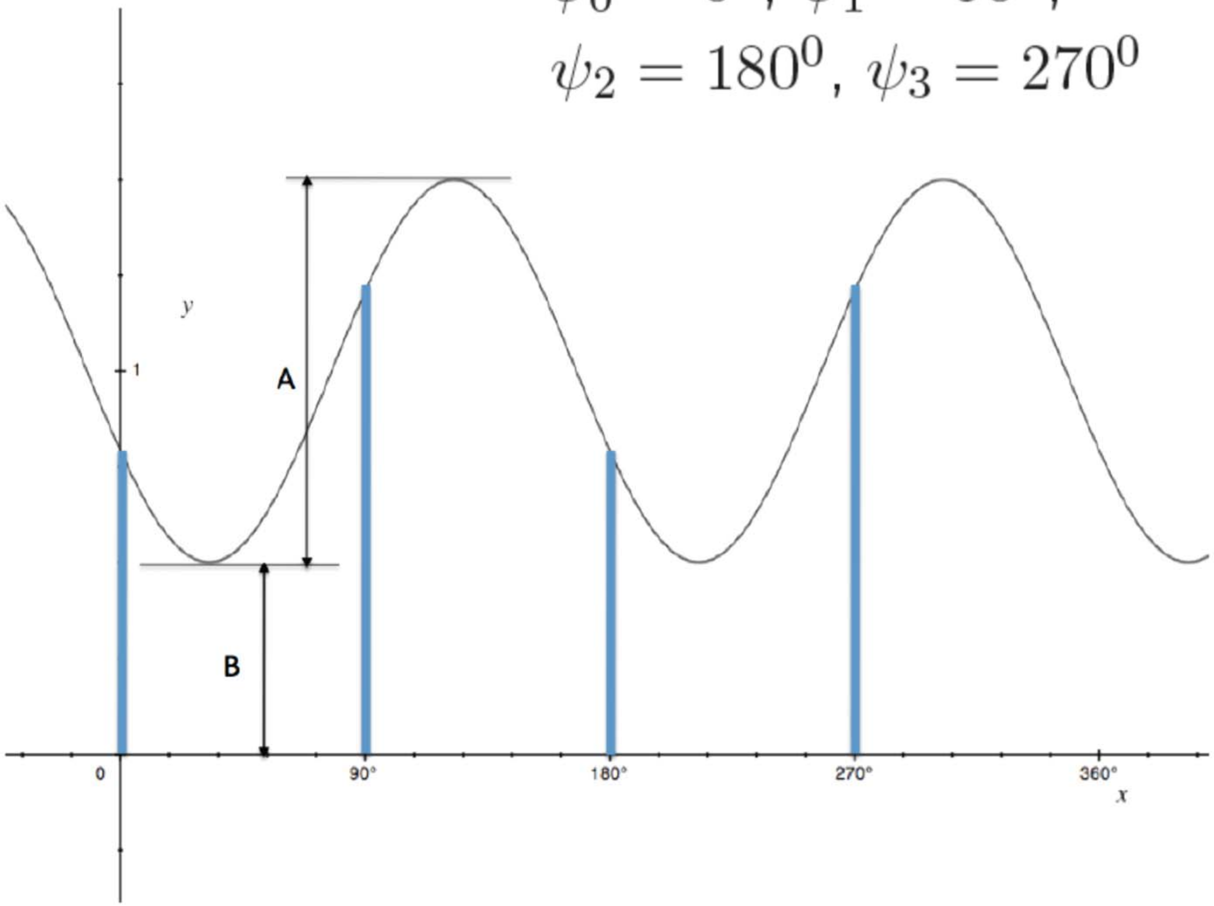
$$C(x) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} r(t)s(t+x)dt$$

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

ToF. CW-modulation

- 4 cubes method:
  - Estimate values of $C(\psi)$ in four phases

$$\psi_0 = 0^0,\ \psi_1 = 90^0,$$
$$\psi_2 = 180^0,\ \psi_3 = 270^0$$



ToF. CW-modulation

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

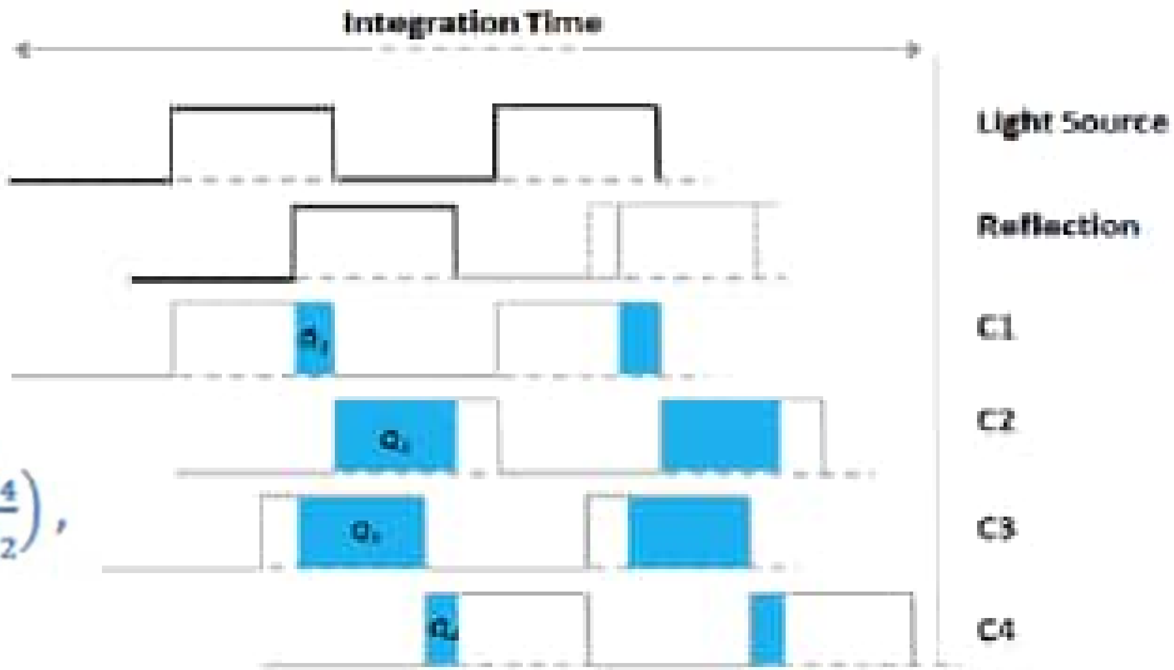
$$\psi_0 = 0^0,\ \psi_1 = 90^0,$$
$$\psi_2 = 180^0,\ \psi_3 = 270^0$$

$$\begin{aligned}
\phi &= 2\pi f\tau = \arctan\left(\frac{C(x_3) - C(x_1)}{C(x_0) - C(x_2)}\right) \\
A &= \frac{1}{2a}\sqrt{(C(x_3) - C(x_1))^2 + (C(x_0) - C(x_2))^2} \\
B &= \frac{1}{4}(C(x_0) + C(x_1) + (C(x_2) + C(x_3))
\end{aligned}$$

ToF. CW-modulation

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

- In practice:



$$\varphi = \arctan\left(\frac{Q_3 - Q_4}{Q_1 - Q_2}\right),$$

$$d = \frac{c}{4\pi f}\varphi.$$

ToF. CW-modulation

- E.g. for a frequency f = 30MHz
  - Unambiguous range from dmin = 0 to dmax = 5 m.

- For larger distance we must apply “phase unwrapping” techniques.
- Accuracy increases with modulation frequency.
- Several and different ToF frequencies can be combined.
- Needs significant integration times, over several periods, in order to increase SNR:
- Blurring effects because of motion.

ToF. CW-modulation

ToF Camera Module

Features:

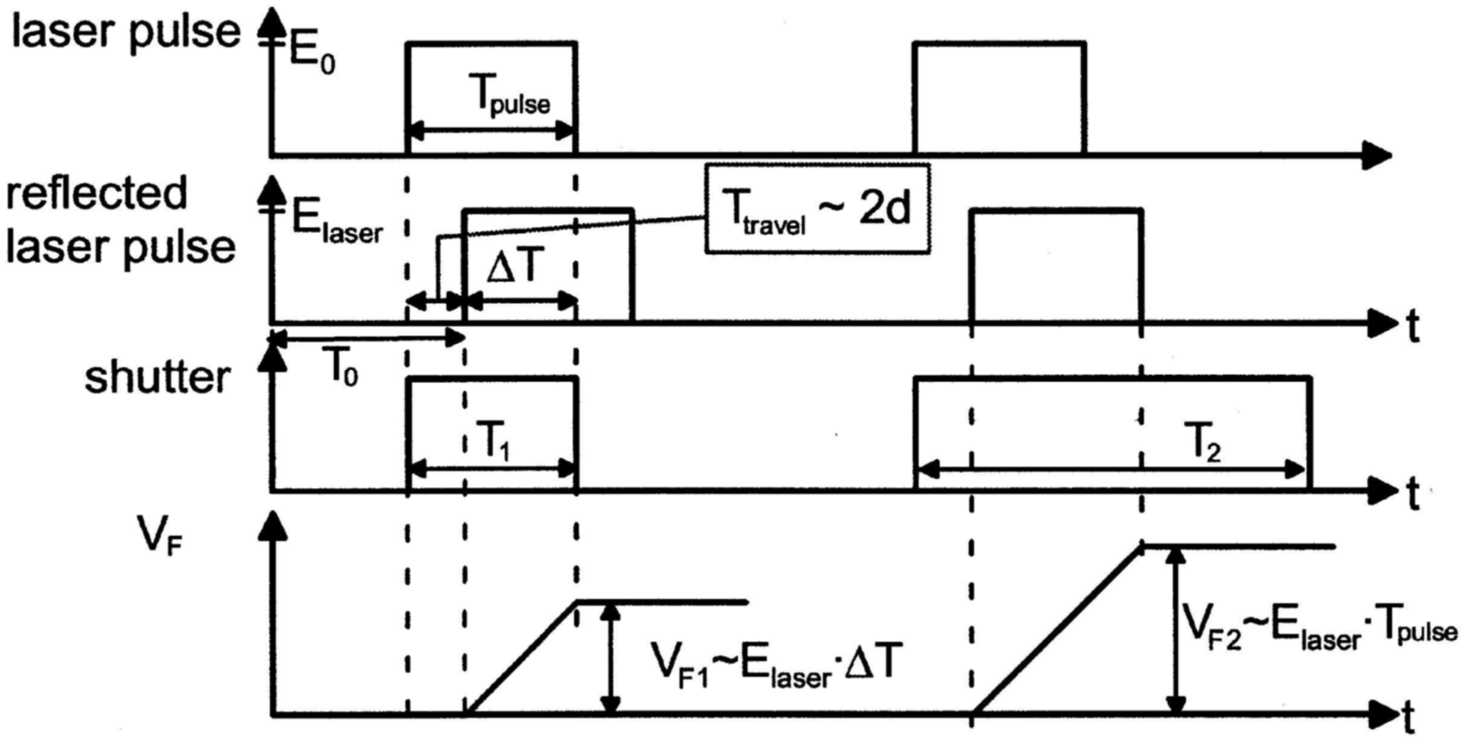
- Based on ADI's ToF Signal Chain Products and Technology
- Can output depth map and (710 version) TOF + RGB Image (can disable)
- FOV 70 X 54
- Depth camera support image size: up to 640*480@30FPS
- RGB camera support image size: up to 1920*1080@30FPS
- USB 2.0 interface
- Support OS: Runs on Android / Runs on Linux / Runs on Windows 7/8/10
- Pico depth sensor SDK, sample code and tools (Open NI SDK Compatible)
- Sample application algorithms available from ADI in Python

https://www.analog.com/en/applications/technology/3d-time-of-flight.html

ToF. Pulsed Modulation

- Laser light pulse of nanoseconds order.
- Distance is estimated by directly measuring the delay between the emitted pulse and received signal.
- Very short pulses of high optical power can be used:
  - Pulse irradiance should be much higher than the background illumination.
- Total emitted energy should be low (class 1).
- Does not suffer from ambiguous range, as in CW.
- Can be used outdoors.

ToF. Pulsed Modulation



Elkhalili et al. (2004). IEEE Transactions on Solid-State Circuits, Vol. 39. No 7, pages 1208-1212

ToF. Pulsed Modulation

$$\Delta T = T_{\text{pulse}} - T_{\text{travel}}$$

During the first integration

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

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

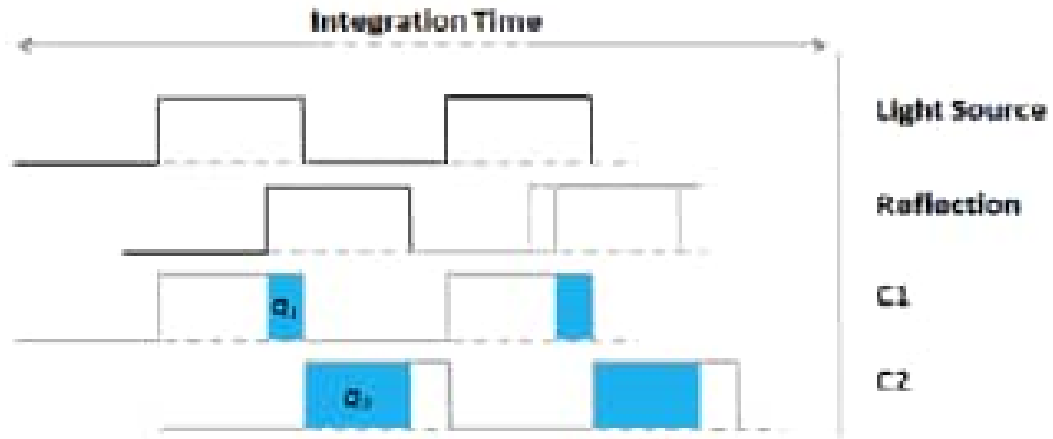
During the second integration, total reflected pulse energy is measured

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

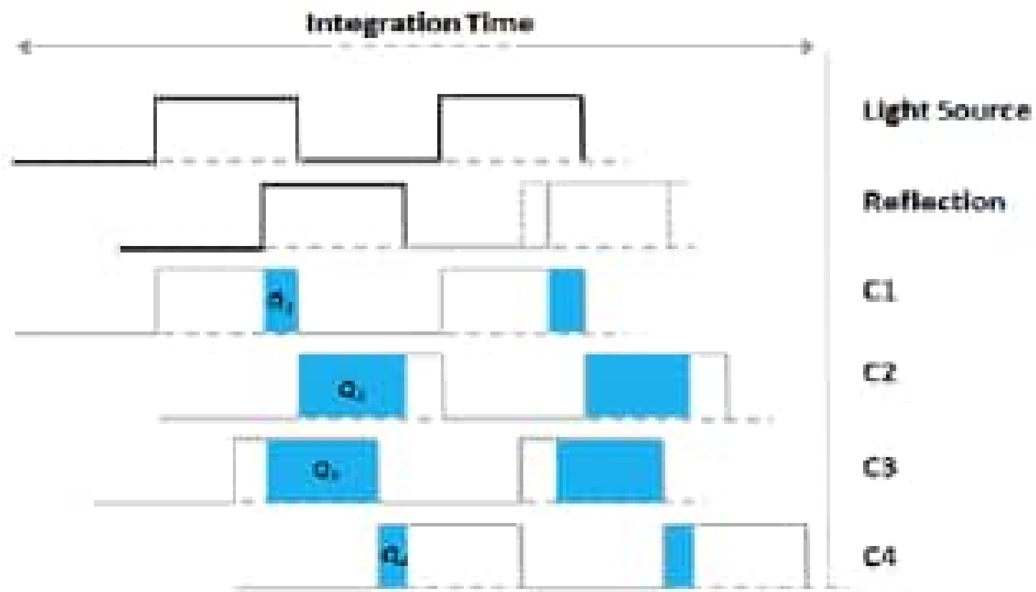
$$d = \frac{c}{2} T_{\text{travel}} = \frac{c}{2}(T_{\text{pulse}} - \Delta T) = \frac{c}{2} T_{\text{pulse}} \left(1 - \frac{V_{F1}}{V_{F2}}\right)$$

ToF. Pulsed Modulation

Pulsed modulation



Continuous Wave modulation CW



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ToF. Pulsed Modulation

- Precision:
  - Based on estimating $\Delta T = T_{\text{pulse}} - T_{\text{travel}}$
  - Note that it is zero if $T_{\text{travel}} = T_{\text{pulse}}$
  - Maximum range $d_{\max} = \frac{c}{2} T_{\text{pulse}}$
- Example: $T_{\text{pulse}} = 30\text{ns}$ maximum distance 4,5 m.
- Maximum range can be extended by:
  - Increment light pulse duration.
  - Introduce a delay between the emitted pulse start and the beginning of integration time (shutter):
    - Produces a minimum distance $d_{\min} > 0$

ToF. Pulsed Modulation

- Example of sensor parameters for a ToF system:

Number of pixels:	4×64
Pixel size:	130×300 μm^2
Laser wavelength:	$850 - 910nm$
Depth accuracy (1 pulse):	$< 5cm$
Depth accuracy (100 pulses):	$< 1cm$

ToF. Pulsed Modulation

Tiger Eye 3D video camera

- 128 x 128 pixels APD (avalanche photo diode); 30Hz
- 1570 nm eye-safe laser
- 3^0 field of view (actual full FOV = 3^0 x 3^0); Range up to 1100 meters
- 9^0 field of view (actual full FOV = 8.6^0 x 8.6^0); Range up to 450 meters
- 45^0 x 22^0 field of view; Range up to 150 meters
- 45^0 field of view; Range up to 60 meters