Robotics III: Sensors and Perception in Robotics
Chapter 03: External Sensors

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External (Exteroceptive) Sensors

External sensors

Proximity sensors

- Capacitive Sensors
- Optical Sensors
- Acoustic Sensors

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Depth sensors

- Time-of-Flight based
- Triangulation based

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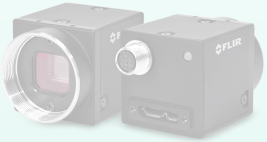
Visual sensors

- Photodiodes
- CCD/CMOS
- Stereo



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Position sensors

- GPS
- Natural/artificial Landmarks

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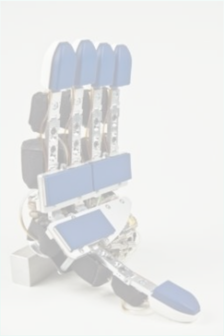
Tactile sensors

- Touch & Slip Sensors
- Force/Torque Sensors



Proximity Sensors

- Detect objects/obstacles within a specific distance range
- Provide binary signal based on a threshold
- Proximity sensors are non-contact devices
- Application:
  - Obstacle avoidance
  - Parking systems

- Advantage of proximity sensors
  - No damage to the object
  - Better durability (permanence)

- Types of proximity sensors:
  - Capacitive
  - Optical
  - Acoustic
  - Others…

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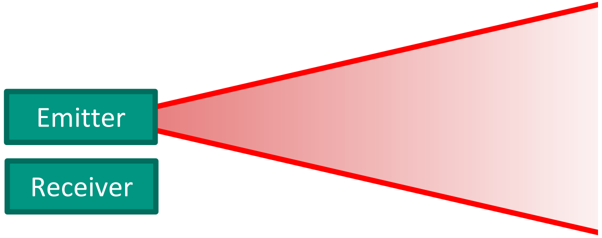
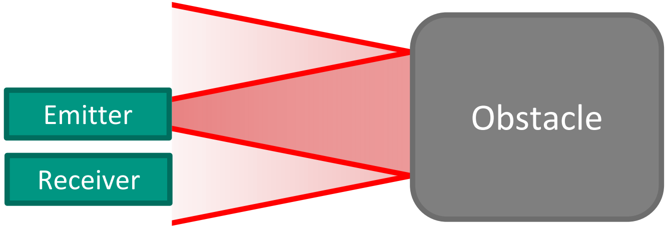
Optical Proximity Sensors

- Rely on light reflection
- Light barrier: Binary output information



Receiver does not detect IR-Light

- Advantages:
  - Larger operating distance than capacitive proximity sensors
  - Non-contact
  - Adjustable threshold value



Receiver detects reflected IR-Light

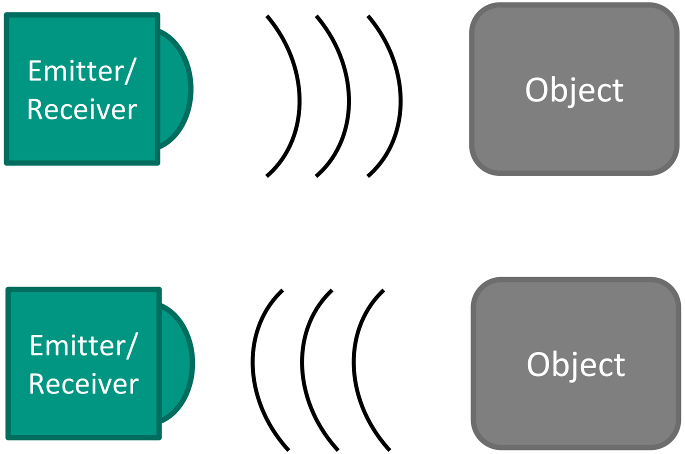
Optical Proximity Sensors

- Reflective light sensor:
  - Red-Light-LED
  - Time of Flight (ToF) measurement / Triangulation with background suppression
  - Standard in automation, very cost-effective, but also in smart phones

- Laser reflex light sensor:
  - Distance: $7 - 200mm$
  - Smallest Object Diameter: $1 - 2mm$
  - Measuring Rates: $1000 - 5000Hz$

Acoustic Proximity Sensors

- Acoustic principle for ultrasound
- The transmitter emits a wave in the ultrasonic region of the acoustical spectrum, typically $20 - 200\ kHz$ (higher than audible range of human hearing)
- Distance can be calculated using the **Time-of-Flight**, i.e., time difference between the sent and received signal



- Advantage:
  - Emission and detection with the same converter
  - Time of Flight -> distance approximation possible
  - Useful over distances out to several meters for detecting most solid (also transparent) objects and liquid.
- Problem:
  - Noise

External (Exteroceptive) Sensors

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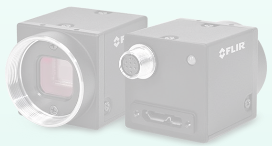

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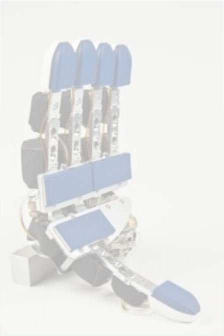
- Touch & Slip Sensors
- Force/Torque Sensors



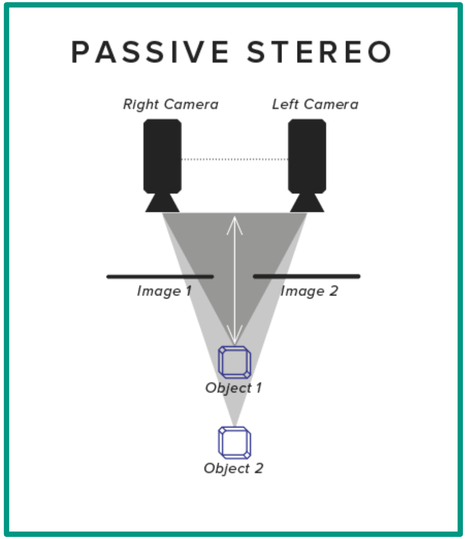
Distance Sensors

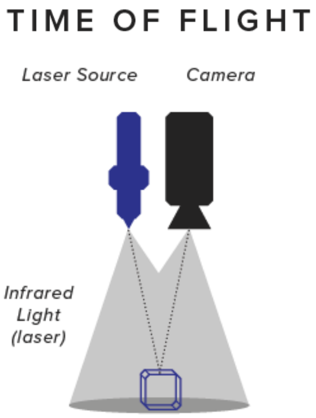
- Measurement of the distance between the sensor and the object
- Advantages:
  - Larger range than proximity sensors
  - Exact distance information (not only binary information)
  - Suitable for the detection of geometric environmental information (environment modeling)
- Types:
  - Passive Systems
    - Stereo camera systems
  - Active Systems
    - Laser scanner
    - Time of Flight (ToF) camera
    - Laser stripe
    - Pattern projection

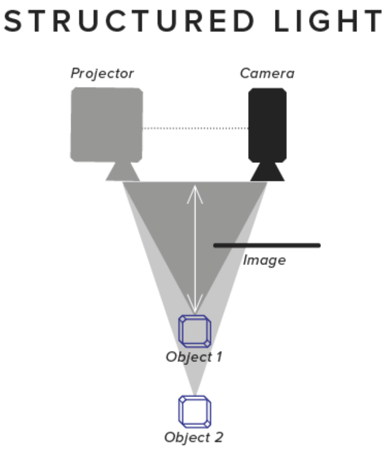
Difference:

- The passive methods ***do not need*** their own light source, but they use the ***ambient*** light for gathering the distance information
- The active methods need a ***light source*** of their own for illuminating the target.

Depth Sensors: Overview



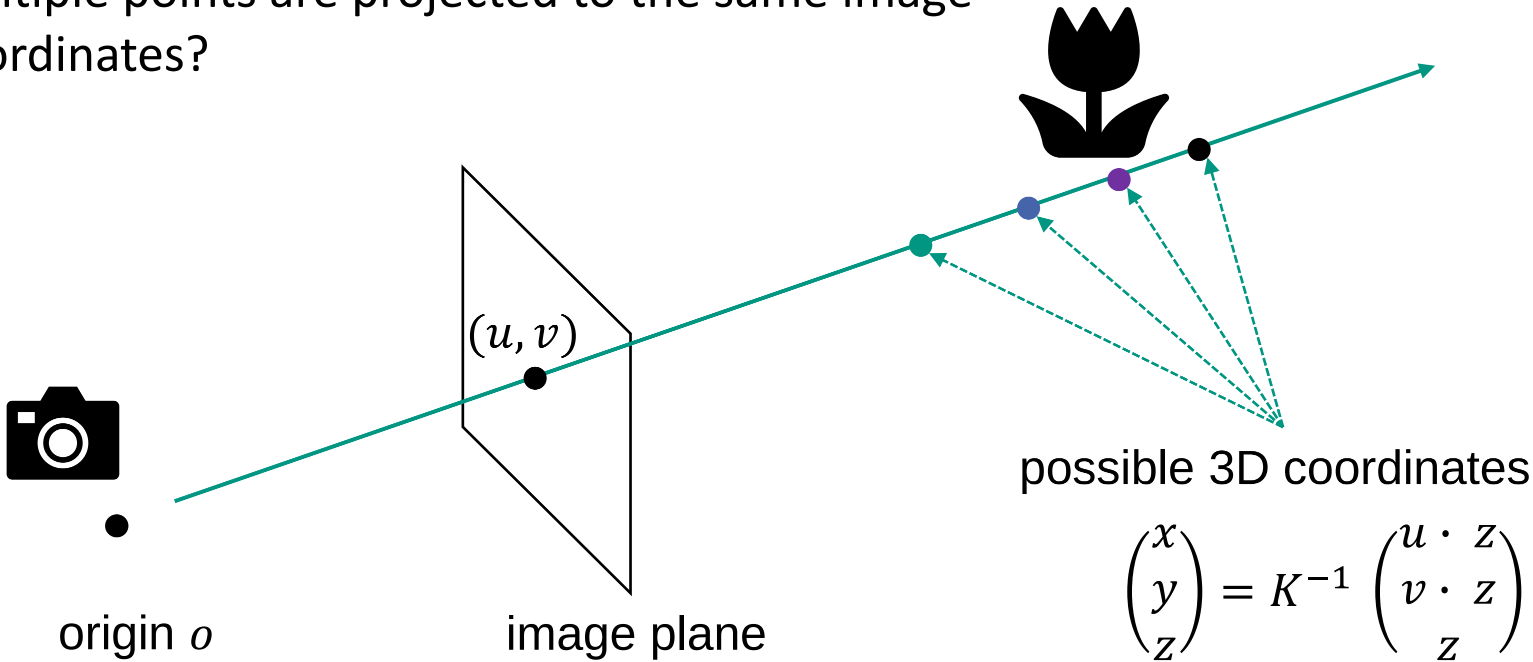




https://medium.com/@DAQRI/depth-cameras-for-mobile-ar-from-iphones-to-wearables-and-beyond-ea29758ec280

Motivation: Can We Compute a 3D Coordinate?

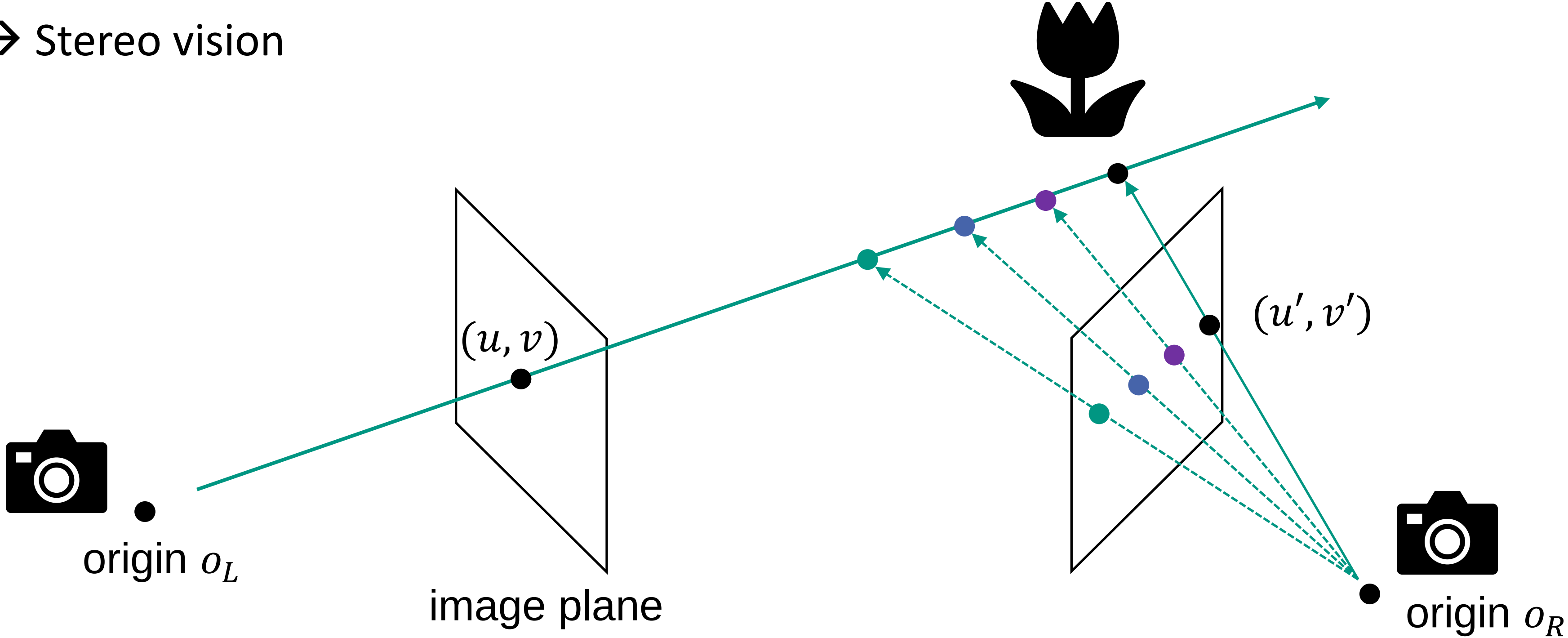
- How can we resolve the ambiguity since multiple points are projected to the same image coordinates?



$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = K^{-1} \begin{pmatrix} u \cdot z \\ v \cdot z \\ z \end{pmatrix}$$

Triangulation

- Solve ambiguity with a second camera
- → Stereo vision



Passive Methods – Stereo Vision

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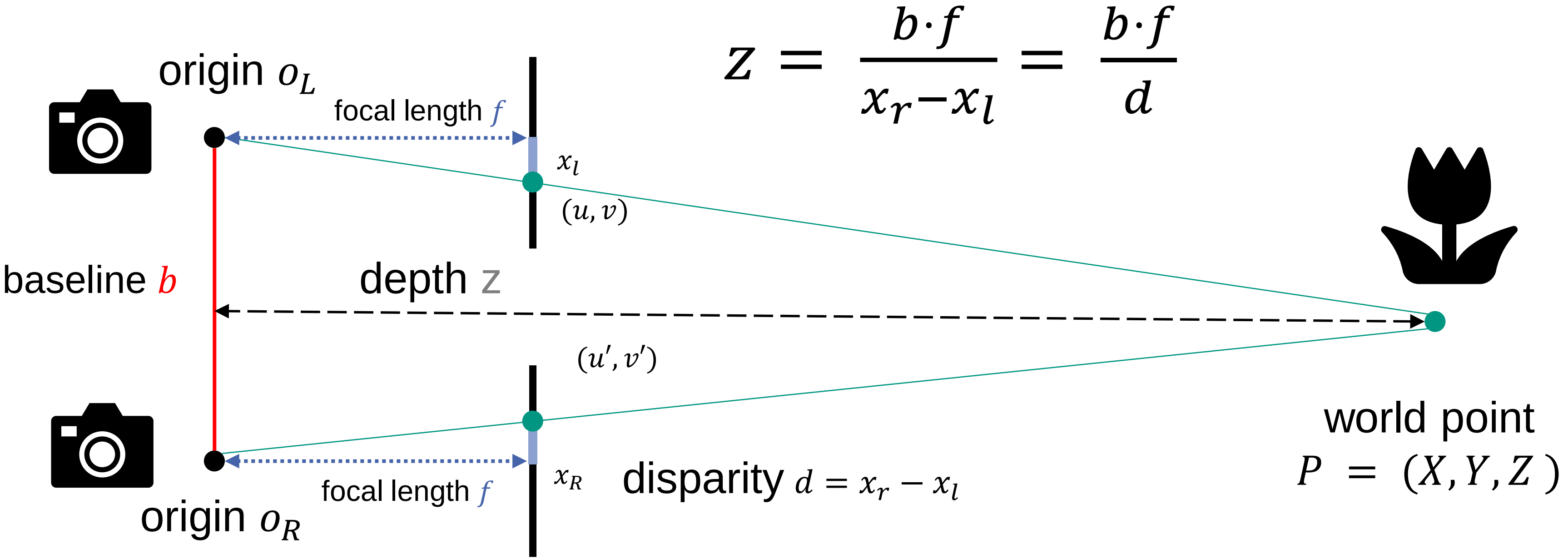
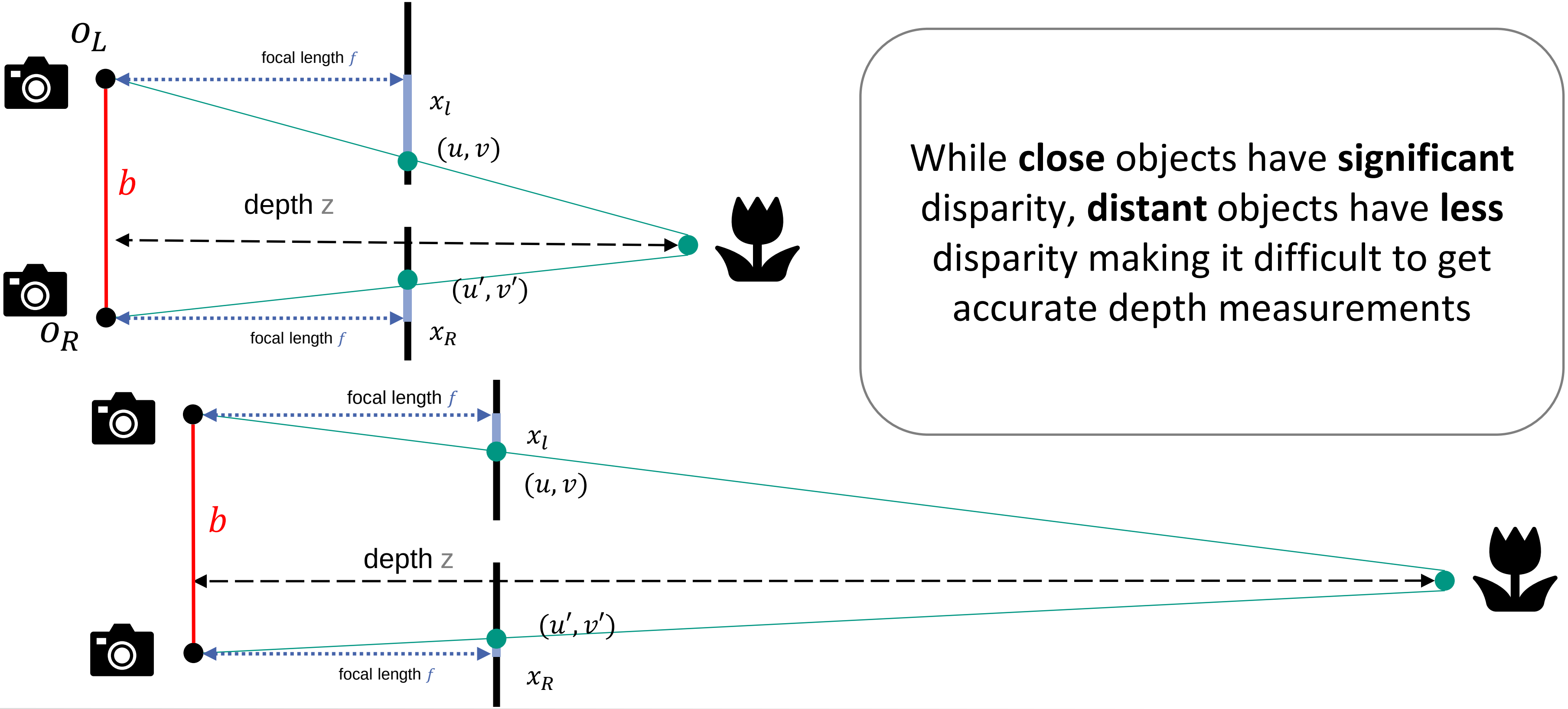
- „Passive Triangulation“ (Triangulation with ambient light)
  - Example: Human eye and stereo camera systems
  - Depth reconstruction using images from different perspectives
- Operating mode: Object at position P with different coordinates in image plane ➔ Triangulation of corresponding pixels.
  - Theorem of intersecting lines

Stereo-Vision: Triangulation



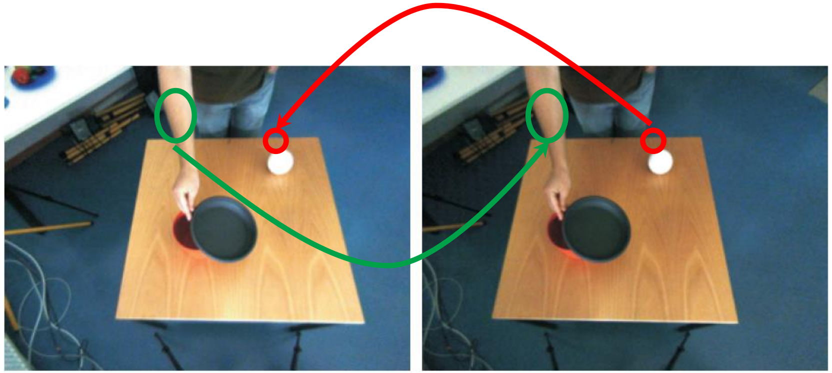
- Compute depth z with triangulation

Stereo-Vision: Disparity



While **close** objects have **significant** disparity, **distant** objects have **less** disparity making it difficult to get accurate depth measurements

Passive Methods – Stereo Vision



Advantages

- Adjustable focal lengths/baseline
- No special illumination is required

Disadvantages

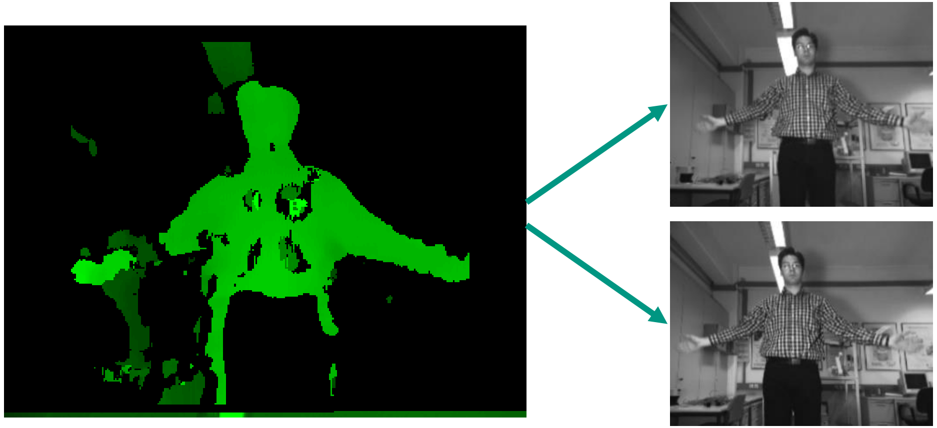
- At least two **calibrated** cameras required
- Correspondence problem on homogeneous surfaces

- Stereo vision is only good for close to mid-range distances (2-5 meters, depending on the baseline). For longer distances we use other clues to figure out distance!

Passive Methods – Stereo Vision

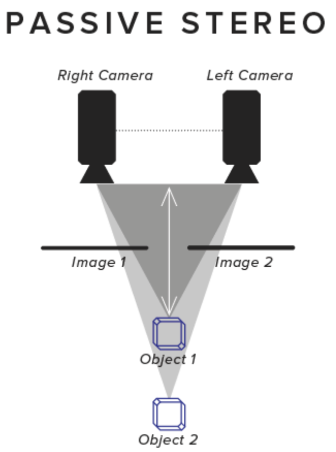
- **Correspondence problem:** What point pairs in the image plane correspond to the same scene element?

- Differences in:
  - Brightness
  - Color
  - Image region

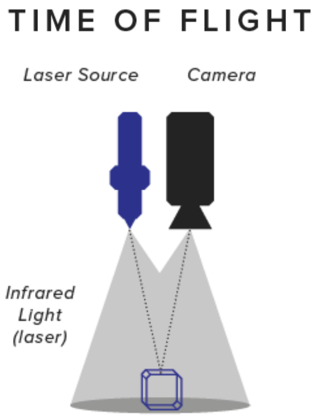


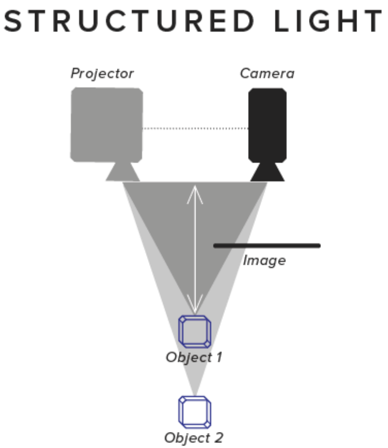
- **Epipolar line construction** can facilitate the search for corresponding features
  - Reduces search space to the intersections of epipolar lines

Depth Sensors: Overview



Active Methods





https://medium.com/@DAQRI/depth-cameras-for-mobile-ar-from-iphones-to-wearables-and-beyond-ea29758ec280

Active Methods – for Distance Measurement

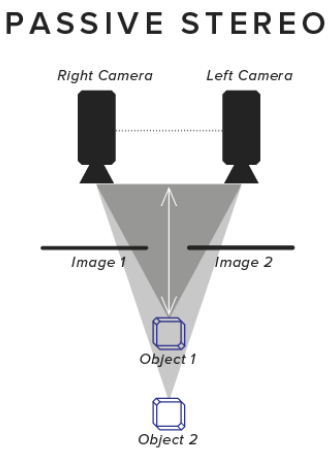
- Use an active energy source to create an artificial texture on the surface to be measured.
  - Stable against external disturbances
  - Measurement by deflection of emitted energy
    ➔ 2D or 3D Distance measurement

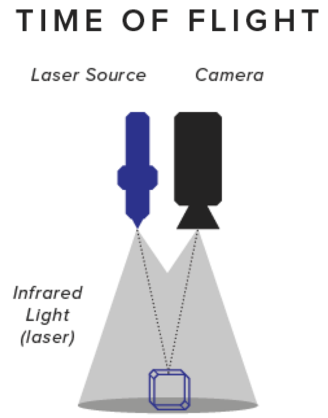
- Generates dense depth image: $\boldsymbol{P}_{ij} = (x_{ij}, y_{ij}, z_{ij}),\ 1 \leq i \leq m, 1 \leq j \leq n$
- With equidistant quantization in X- and Y-directions

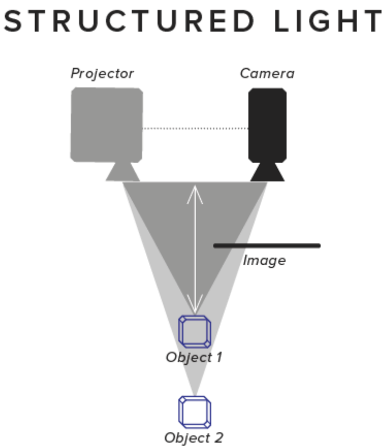
$$Im_{ij} = (z_{ij}), \qquad 1 \leq i \leq m, 1 \leq j \leq n$$

- **Measurement Principles**
  - Time-of-Flight
  - Structured Light

Depth Sensors: Overview







https://medium.com/@DAQRI/depth-cameras-for-mobile-ar-from-iphones-to-wearables-and-beyond-ea29758ec280

Time-of-Flight (I)

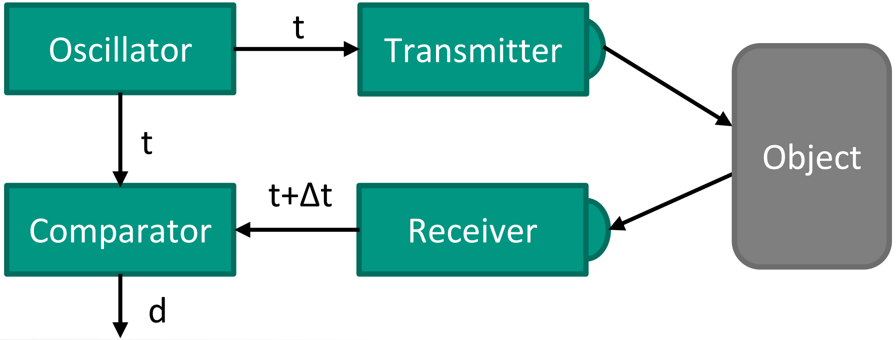
- Time-of-flight (TOF) range sensors measure the round-trip time required for a laser pulse of emitted energy to travel to a reflecting object, then echo back to a receiver.
- Distance (d) from sensor to target surface by: $d = \frac{1}{2} c \cdot t$

  c: signal speed

  t: Time of Flight (elapsed time) is measureable

  t is the time for a round-trip -> distance is given by $d = \frac{1}{2} c\, t$

- Measurement of t
  - Directly
  - From phase shift of the signal after its modulation



Time-of-Flight (II)

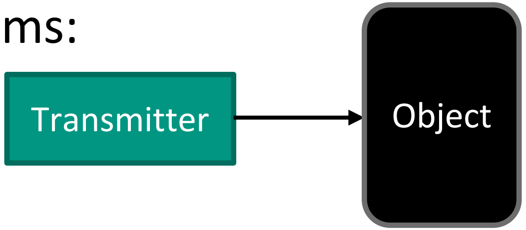
- Although the implementation differs, time-of-flight measurement can be accomplished with
  - Radio waves (radar)
  - Sound or ultrasonic waves (sonar)
  - Light waves (laser radar - lidar)

- The same measuring principle is used for all signal types.

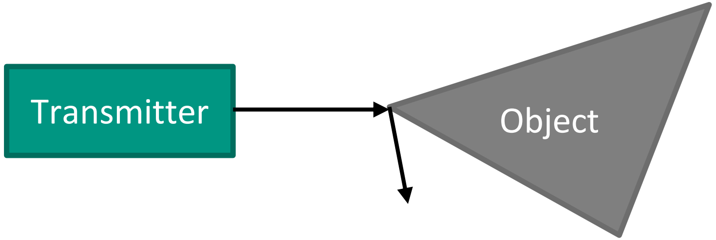
- Potential ***error sources*** for ToF systems are
  - Variations in the propagation speed:
    - Example: In acoustic based systems, the speed of sound is influenced by temperature changes, and to a lesser extent by humidity.
  - Uncertainties in determining the exact time of arrival of the reflected pulse
  - Inaccuracies in the timing circuit used to measure the round-trip time of flight
  - Interaction of the incident wave with the target surface.

Time-of-Flight (III)

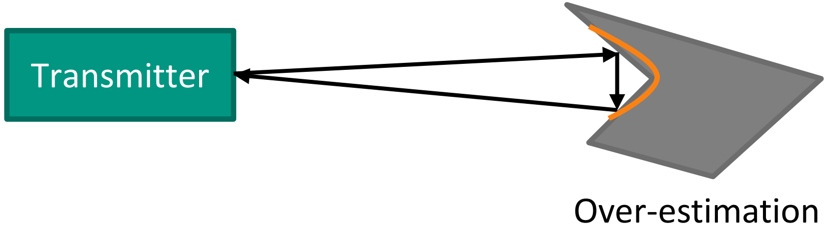
- Typical (signal type dependent) problems:
  - Absorption of the beam



  - Scattering



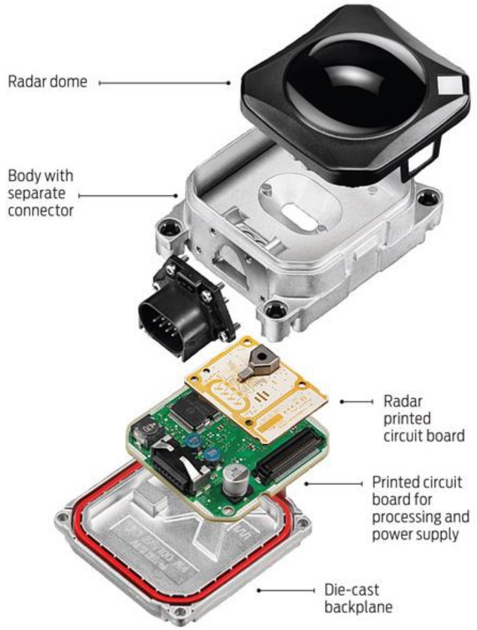
  - Multiple reflection



Time-of-Flight: Radar

- Radar is an active sensor and usually uses electromagnetic energy in the range 1-12.5 GHz
  - this corresponds to wavelengths of 30-2 cm (microwave energy)
  - unaffected by fog, rain, dust, haze and smoke

- **Purpose:** detection, location, distance measurement
- **Transmitter:** strongly bundled waves in the mm, cm & dm ranges as short pulses (high transmission power, clear reflection)
- **Receiver:** registers reflections between the pulses
- Diameter of a radio wave bundle is inversely proportional to the antenna size.
  - Large antenna is required for fine resolution
  - Radio waves spread with light speed
  - Accurate time measurement over short distance – only with complex electronics



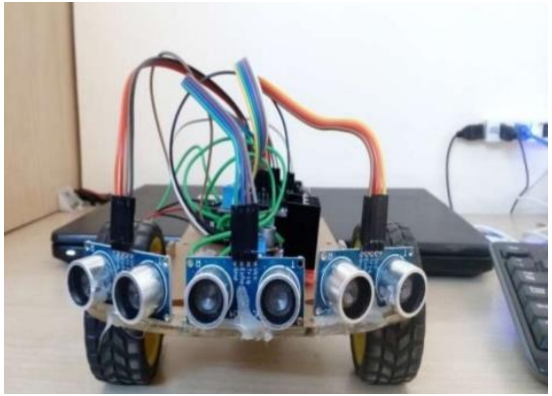
Automotive radar ©Bosch

Time-of-Flight: Ultrasound (I)

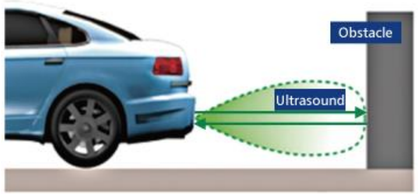
- Referred to as ultrasound sensors or sonar sensors
- The operation principle of sonar sensors includes
  1. **Emission of a short ultrasonic acoustic signal** (duration ~ 1 ms, frequency 50-250 kHz, higher than human hearing limit)
  2. Measurement of the time until reflected impulse received
- Ultrasonic sensors emit a *chirp* (e.g. 1.2 milliseconds), where a chirp is a short powerful pulse of a range of frequencies
- As the speed of sound in air is known, the distance to the object can be computed from the elapsed time between emission and echo
- An **ultrasonic sensor array** helps to detect position of obstacles
- In robotics: collision avoidance for mobile robots, autonomous cars, …

Time-of-Flight: Ultrasound (II)

- **Examples**



Mobile Robot



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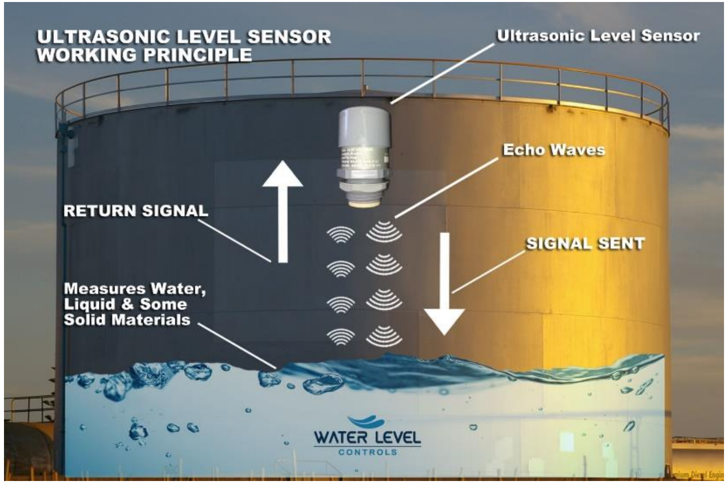


© https://waterlevelcontrols.com/ultrasonic-level-sensor-transmitter/

Time-of-Flight: Ultrasound (III)

- **Limitations** of sonar sensors:
  - Relatively narrow cone
    - Example: for a **360° coverage**, a typical mobile robot sensor configuration needs to use **24 sensors**, each one mapping a cone of about 15°
  - Uncertainty of beam spreading
  - Specular **reflections** (mirror like) give rise to erroneous readings
    - The sonar beam hits a smooth surface at a shallow angle and so reflects away from the sensor
    - Sensor deliver information only if an object further away reflects the beam - but distance is incorrect
  - Arrays of sonar sensors can lead to **crosstalk**
    - One sensor detects the reflected beam of another sensor
  - The **speed of sound depends on** air temperature and pressure
    - A temperature change of 16 degree can cause a 30cm error at 10m!

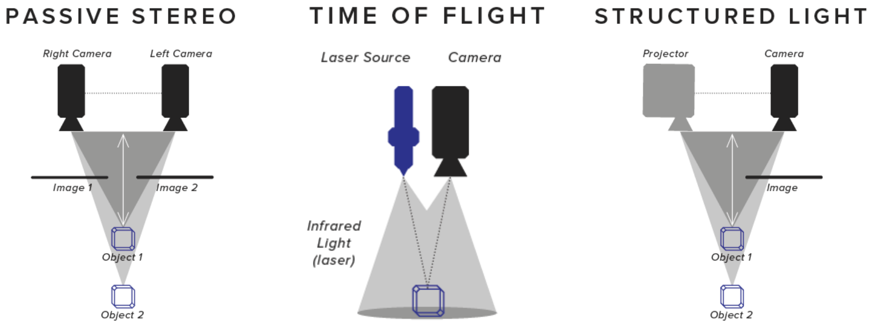
Recap: Proximity and Distance Sensors

Proximity Sensors

- Provide binary signal (there is an object or there is no object) within a certain distance range
- Usually detect light reflection on the surface of an object

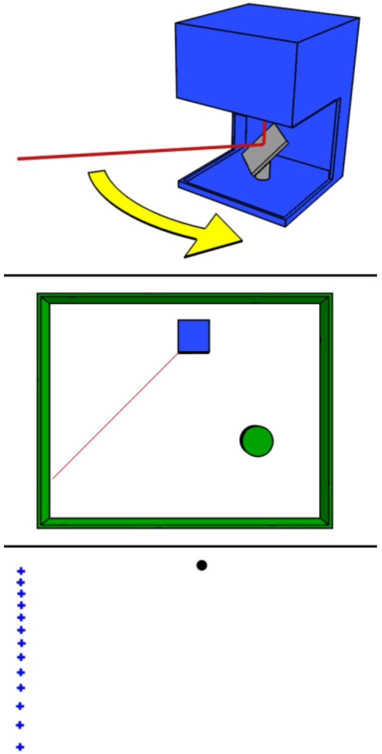
Distance Sensors

- Measure the **actual distance** to an object
- Different measurement principles:
  - Stereo Vision
  - Time of Flight
  - Structured Light



Time-of-Flight: LiDAR

- Laser range finders are commonly used to measure the distance to objects
  - Known as laser radars (or **LiDARs** = **Li**ght **D**etection **a**nd **R**anging sensors)
- Illumination of target with laser (UV, visible or IR) and measurement of reflection
- Deflecting mirrors can be used to obtain scene representation



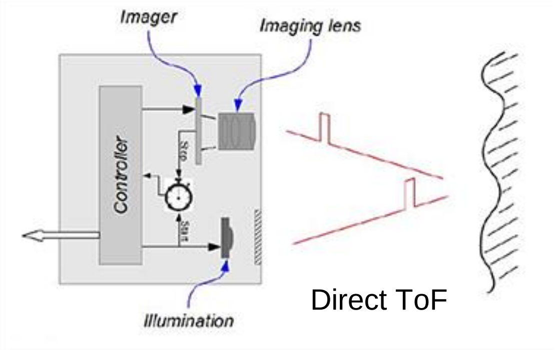
https://en. LIDAR-scanned-SICK-LMS-animationwikipedia.org/wiki/Lidar#/media/File:.gif

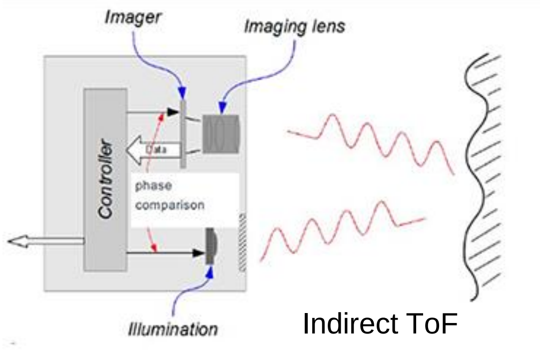
LiDAR: Operating Principles (I)

- Two prevalent measurement principles
  - Direct ToF
  - Indirect ToF

- **Direct ToF:**
  - send out short pulses of light that last just a few nanoseconds
  - measure the time it takes for some of the emitted light to come back.

- **Indirect ToF:**
  - send out continuous, modulated light
  - measure the phase of the reflected light to calculate the distance to an object





https://www.terabee.com/time-of-flight-principle/

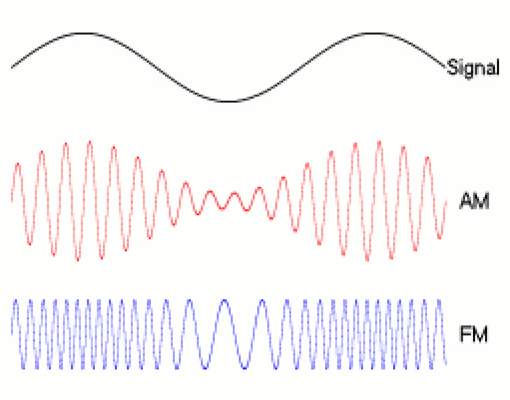
LiDAR: Operating Principles (II)

1. Amplitude Modulation (AM) LiDAR:

- The operating principle is the same as sonar
- A short pulse of (laser) light is emitted using amplitude modulation (note: **speed of light >> speed of sound**)
- The time elapsed between emission and detection is used to determine distance (using the speed of light)

2. Frequency Modulation (FM) LiDAR:

- Frequency of emitted light is modulated
- Distance is calculated based on the difference in emitted and received light frequencies
- More sensitive than AM-Lidar, but more complex transceivers



en.wikipedia.org/wiki/Frequency_modulation

LiDAR: Operating Principles (III)

Why is the signal modulated for both LiDAR operating principles

Answer:

- Some AM send a pulsed laser signal
- Distance R can be measured using the time elapsed (Δt) and the refracting index n

$$R = \frac{1}{2n} c\Delta t$$

- The **resolution** depends on the measurement uncertainty of the time and the spatial width of the pulse $w = c\tau$
- To measure distance with an accuracy in the cm range, the laser pulses should be in the region of $\tau = 10^{-10} s$
- Typical lasers can only produce pulses in the order of $\tau = 10^{-9} s$, smaller pulses require more expensive lasers

LiDAR: Amplitude Modulation Method (I)

- Uses a high frequency continuous signal with no information called a carrier wave $c(t)$ with Amplitude A_c and frequency f_c

$$c(t) = A_c \sin(2\pi f_c t)$$

- Information is added to the carrier wave by modulating its amplitude with a lower frequency signal $m(t)$
  - Can be a sinusoidal signal (but can also be any other form, e.g., noise, a song, etc.)

$$m(t) = A_m \sin(2\pi f_m t)$$

- The amplitude modulated signal is (in case of sinusoidal modulation)

$$S(t) = (A_c + A_m \sin(2\pi f_m t)) \sin(2\pi f_c t)$$
$$= A_c(1 + \mu \sin(2\pi f_m t)) \sin(2\pi f_c t), \qquad \mu = \frac{A_m}{A_c}$$

"An amplitude modulated laser rangefinder - Electronic circuit design and implementation" -Fazel Naser & Stefan Morin, 2022

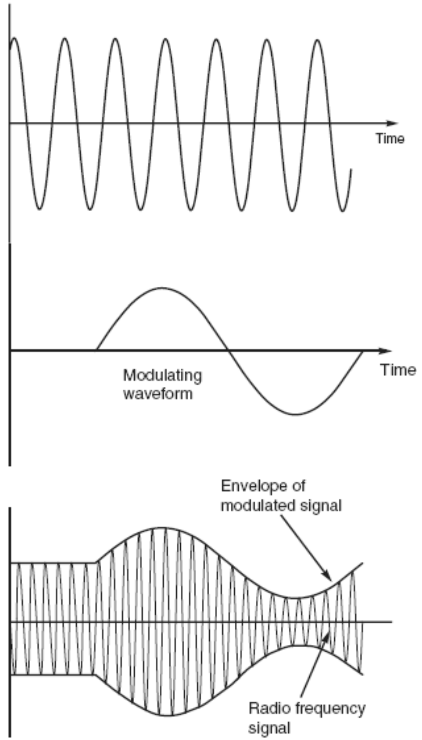
LiDAR: Amplitude Modulation Method (II)

- $\mu = \frac{A_m}{A_c}$ is called the modulation index
  - If $\mu > 1$ over-modulation occurs and causes data loss
- The signal that is reflected back is (only modulated part)

$$R(t) = \sin\big(2\pi f_m(t-\tau)\big) = \sin\left(2\pi f_m\left(t - \frac{2d}{c}\right)\right) = \sin(2\pi f_m t - \Delta\varphi), \qquad \Delta\varphi = Phase\ Shift$$

- From this the distance to the target can be calculated

$$d = \frac{c\Delta\varphi}{4\pi f_m}$$



https://www.edn.com/modulation-basics-part-1-amplitude-and-frequency-modulation/

LiDAR: Frequency Modulation Method (I)

Karlsruher Institut für Technologie

- Instead of pulsing the emitted signal, like the time-of-flight sensors, Frequency Modulated Continuous Wave (FMCW) systems emit a **continuous signal**
- The frequency of this signal is modulated over time.
- The frequency changes linearly between f_0 and f_1 over period T

$$f(t) = f_0 \left(1 - \frac{t}{T}\right) + f_1 \frac{t}{T} \; = \; f_0 + \frac{f_1 - f_0}{T} t$$

- The signal emitted from the sender takes time Δt to travel from the sender to the obstacle and back
- The signal velocity is c and the distance covered is $2r$ (2 times the distance to travel in both directions):

$$\Delta \mathrm{t} = \frac{2\mathrm{r}}{c}$$

LiDAR: Frequency Modulation Method (II)

- The frequency of the returned signal is measured: $f_R(t)$
- … and compared to the current emitted frequency: $\Delta f(t) = f(t) - f_R(t)$
- Since the frequency of the returned signal is the frequency of the emitted signal at $t - \Delta$t the equation can be written as

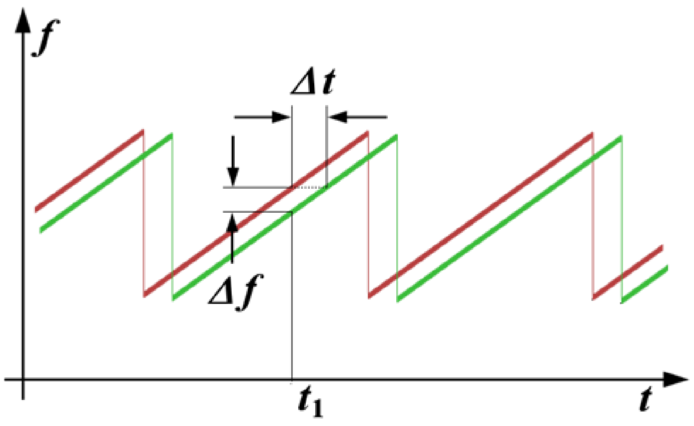
$$\Delta f(t) = f(t) - f(t - \Delta t)$$

- Using the equation for f we get:

$$\Delta f(t) = f_0 + \frac{f_1 - f_0}{T} t - f_0 - \frac{f_1 - f_0}{T}(t - \Delta \mathrm{t})$$

$$= \frac{f_1 - f_0}{T} t - \frac{f_1 - f_0}{T}(t - \Delta \mathrm{t})$$

$$= \frac{f_1 - f_0}{T} \Delta t$$



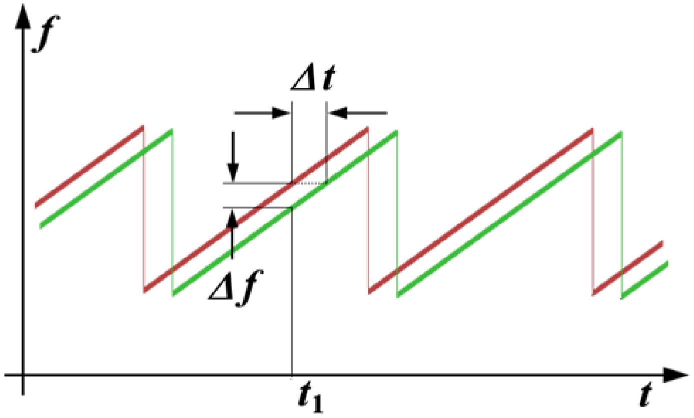
LiDAR: Frequency Modulation Method (III)

- By inserting $\Delta t = \frac{2r}{c}$ into $\Delta f(t) = \frac{f_1 - f_0}{T}\Delta t$, we get
-

$$\Delta f(t) = \frac{f_1 - f_0}{T} \cdot \frac{2r}{c}$$

- Solving for r:

$$r = \frac{c}{2} \cdot \frac{T \cdot \Delta f}{f_1 - f_0}$$

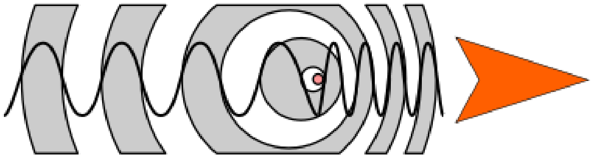


- Note: This solution is valid for static objects, that are not moving

LiDAR: Frequency Modulation Method for Moving Objects (I)

- If the obstacle **is not moving** the frequency difference Δf can be used to directly calculate the distance to the object
- If the obstacle **is moving** there is an additional source of frequency shift: **Doppler shift**

Change of wavelength caused by motion

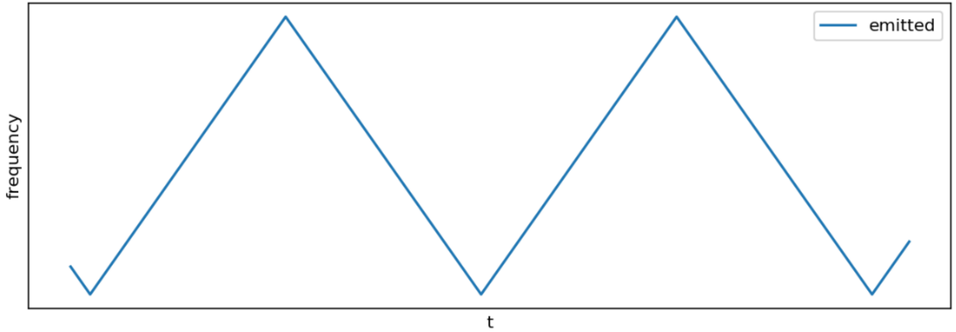


Source: Wikipedia

- Objects moving away: “Red shift” ➔ longer wavelength, lower frequency
- Objects moving closer: “Blue shift” ➔ shorter wavelength, higher frequency

LiDAR: Frequency Modulation Method for Moving Objects (II)

- If the Doppler shift is considered, the **distance and relative velocity of the obstacle can be measured simultaneously**.
- The frequency modulation is adapted to a triangle modulation

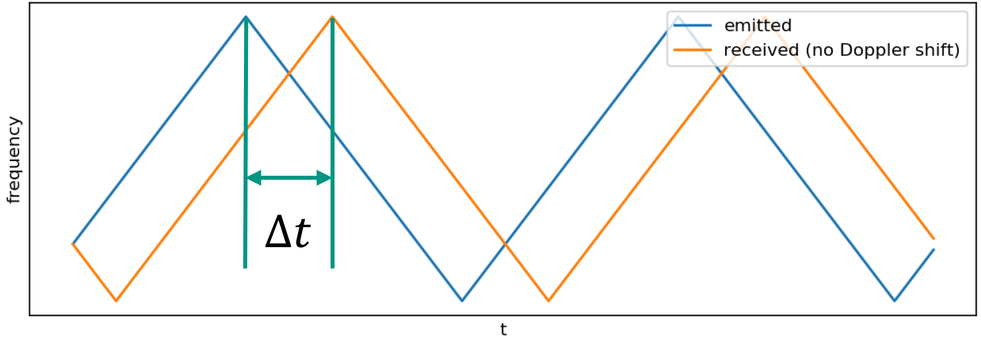


- If the obstacle is not moving relative to the sender, the frequency difference is the same for the rising and falling slope/edge of the signal

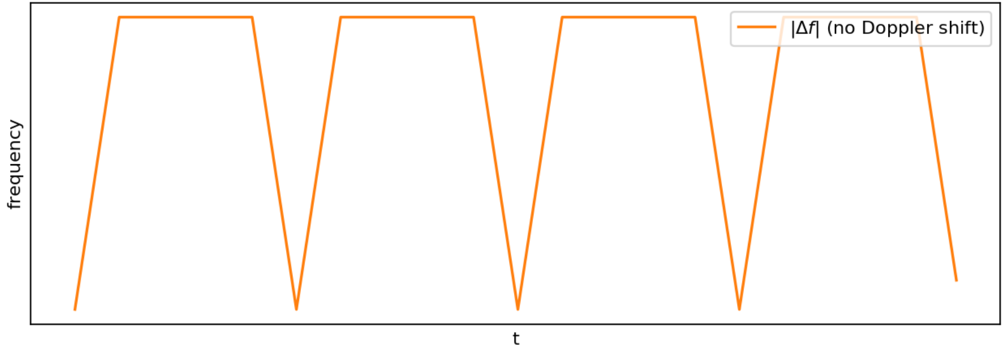
LiDAR: Frequency Modulation Method for Moving Objects (III)

Obstacle *not* moving

- Frequency difference due to Signal delay (Δt)



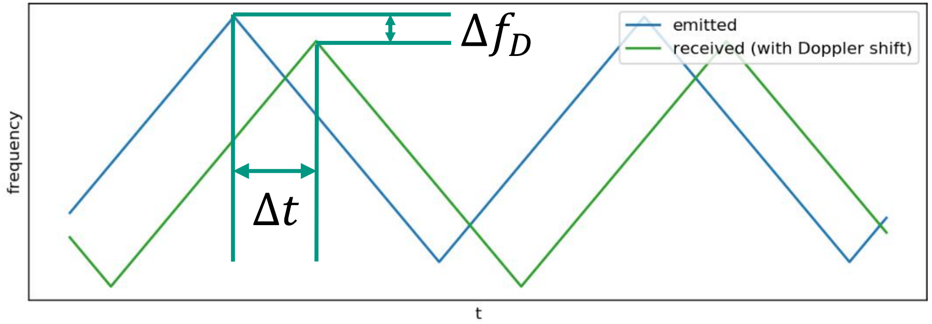
- Evaluation of delta between emitted and received signal frequency $|\Delta f|$:
  amplitude mostly constant
  ➔ obstacle not moving



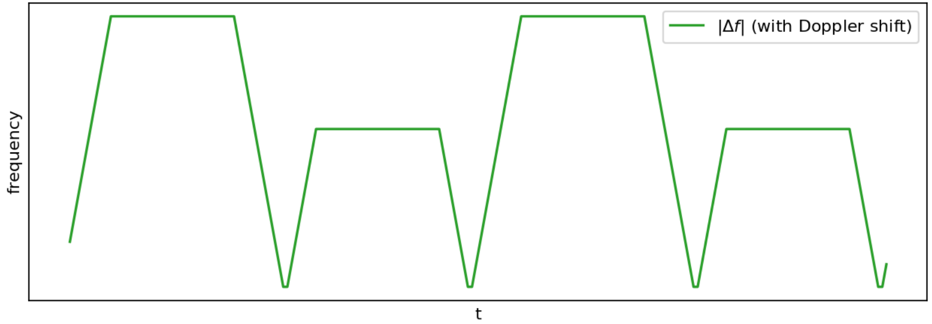
LiDAR: Frequency Modulation Method for Moving Objects (IV)

Obstacle *is moving*

- Frequency difference due to
  - Signal delay (Δt)
  - Doppler shift (Δf_D)



- Difference between emitted and received signal frequency $|\Delta f|$:
  alternating amplitude
  ➔ obstacle is moving



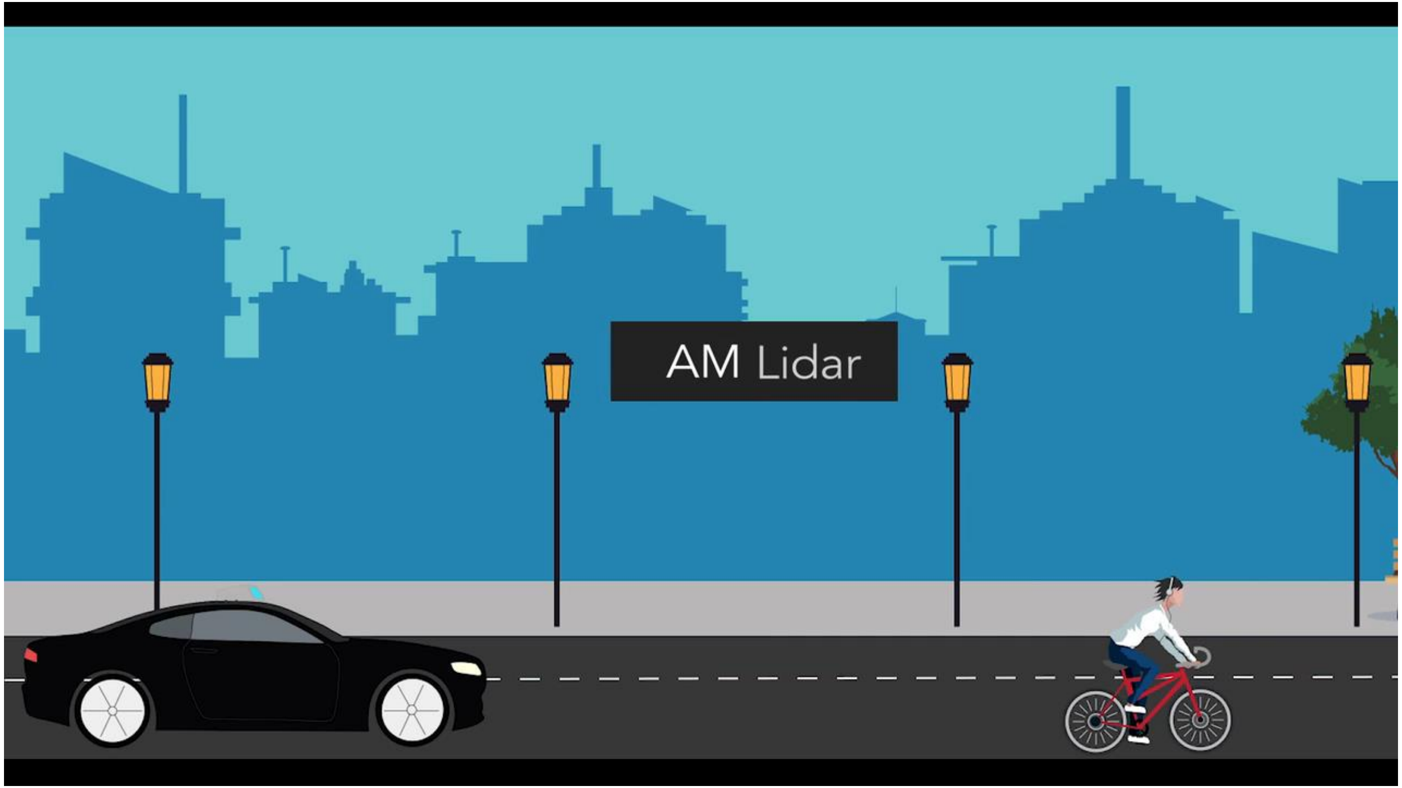
LiDAR: Frequency Modulation Method for Moving Objects (V)

- Using the difference of Δf_{rising} and $\Delta f_{falling}$, the Doppler shift can be computed
- From the Doppler shift the radial velocity of the obstacle can be computed

- By sweeping the emitted signal over the scene, a **distance and radial velocity map** can be computed

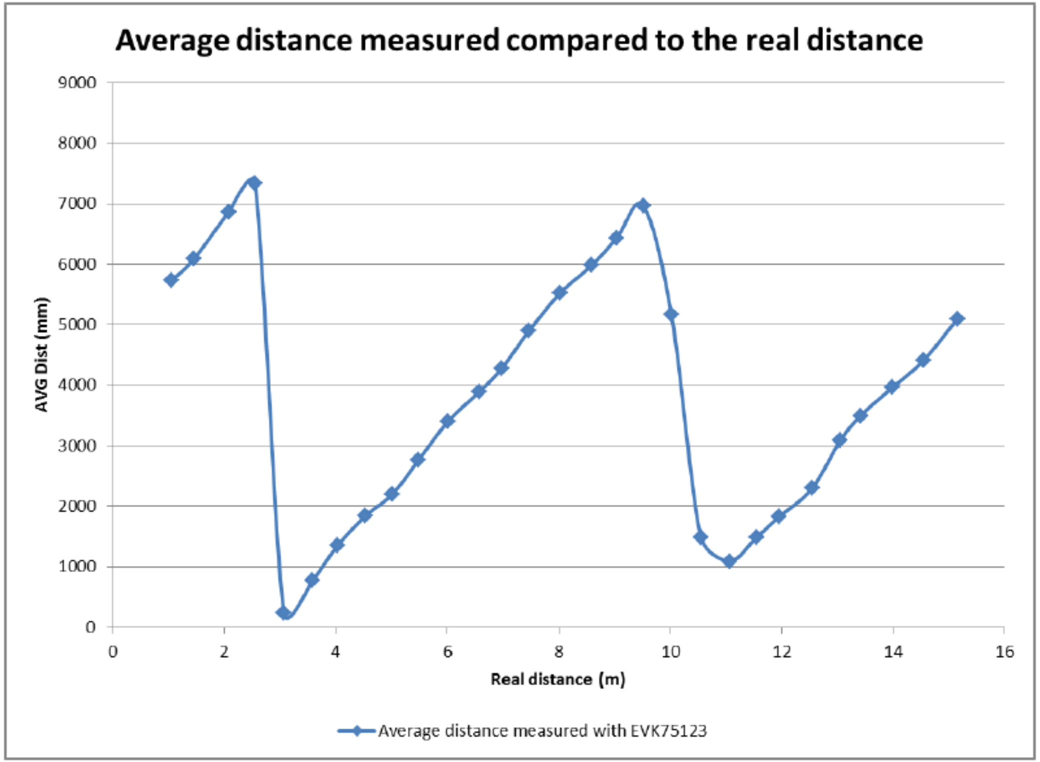
- Applications of FMCW Lidar:
  - Self driving cars ➔ detect other cars and their relative velocity
  - Robots ➔ Scene scanning, SLAM
  - Drones ➔ Terrain scanning
  - …

LiDAR: Comparison AM and FM Methods



Aliasing-Effect

- Distance calculations will lead to **ambiguous results** if the light travels back and forth during a longer period of time than the period of the modulated light

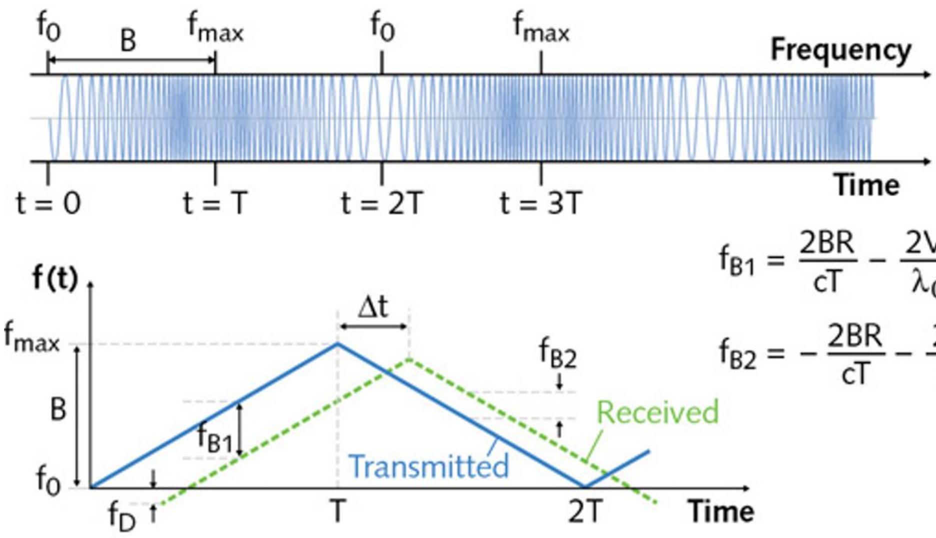


©Melexis

Nomenclature: Phase Difference & Frequency Modulation

FM-LiDAR:

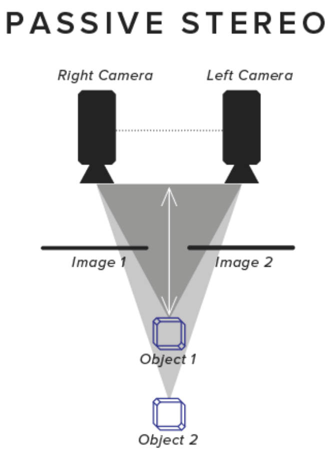
- The emitted laser light has a **modulated frequency**
- Measures the difference in the frequency (**not phase**) of the incoming and outgoing light
- A **single measurement** of the signal results in **distance and relative velocity** of the target

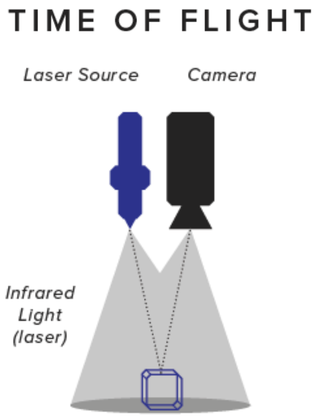


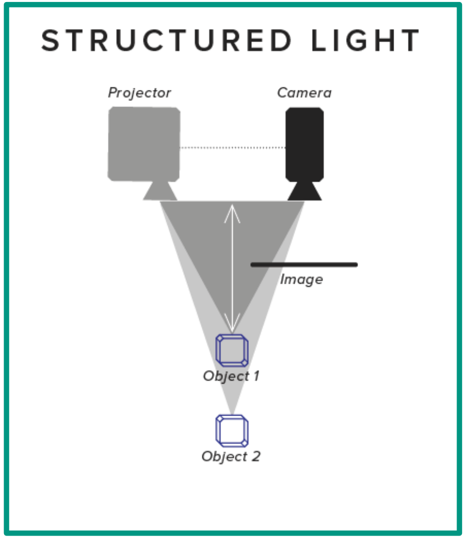
$$f_{B1} = \frac{2BR}{cT} - \frac{2V_r}{\lambda_0}$$

$$f_{B2} = -\frac{2BR}{cT} - \frac{2V_r}{\lambda_0}$$

Depth Sensors: Overview

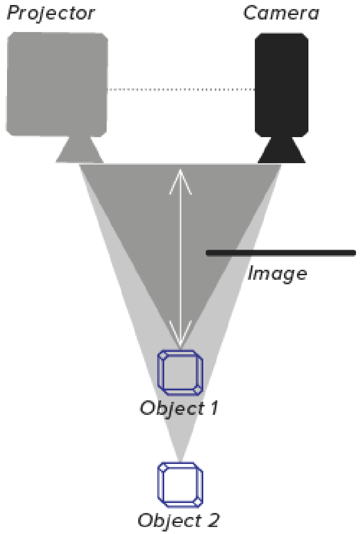






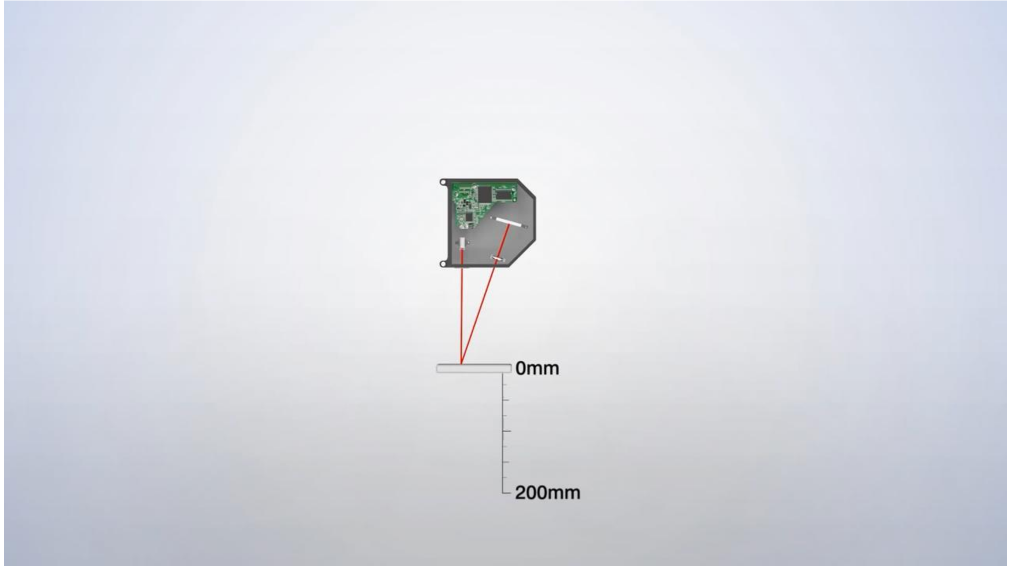
Structured Light Cameras: Overview

- **Active Triangulation**
  - Project the laser beam into the scene and record it using a **position-sensitive sensor**
  - Combination of **active light source** and **camera**
- Different projection schemes
  - Single light beam
  - Laser line (light section)
  - Projection of an encoded pattern (structured light)



Structured Light: Laser Triangulation (I)

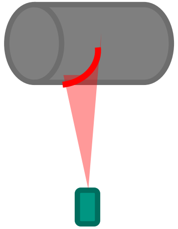
- A sensor emits a laser light that hits the object at some incidence angle, reflects from it and gets detected.
- Since light moves in straight lines, a triangle is formed between the laser source, the measured object, and the detector.
- By measuring the exact location at which the laser hits the detector we can calculate the distance to the object using simple geometry

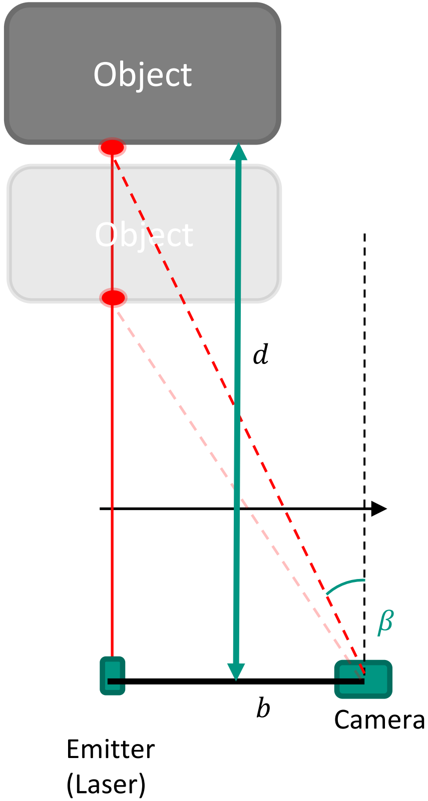


Structured Light: Laser Triangulation (II)

- Laser triangulation: Measurement of the deflection of the beam
- Emitter/receiver unit with **fixed distance b and orientation**:
  - Laser emitter: Beam orthogonal to baseline b
  - Laser-projection on object detected by camera at angle β
  - Triangulation of object distance:

  Trigonometry: $tan\,\beta = \frac{b}{d} \Rightarrow d = \frac{b}{tan\,\beta}$
- Laser-beam can be 2D (Line laser): **Projected stripe** on object

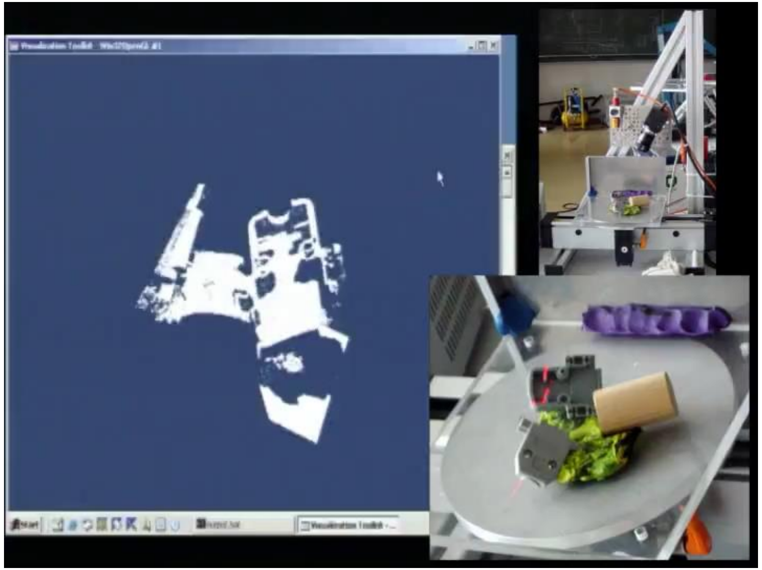




Structured Light: Laser Triangulation (III)

- Scanning with laser stripes

© Micro-Epsilon 2020

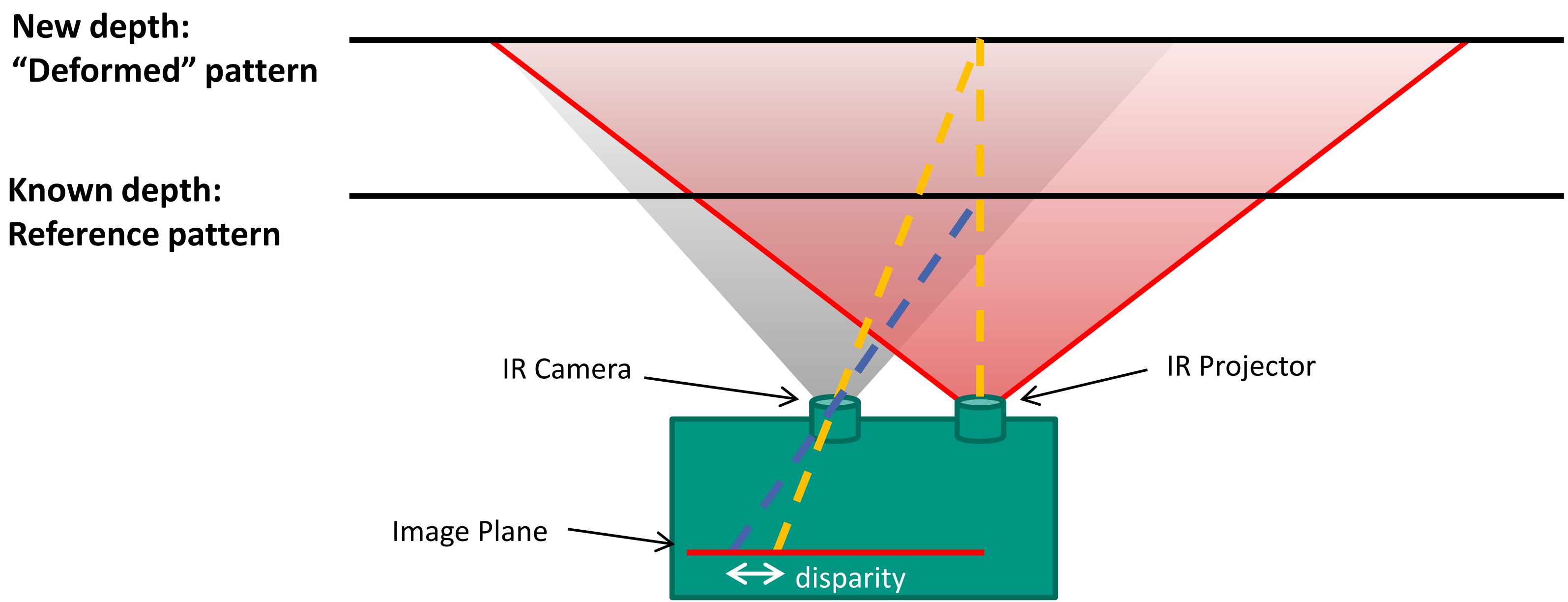


KIT, IAR

Structured Light: Depth Cameras

Karlsruher Institut für Technologie

- **Idea:** Project pattern with identifiable features onto scene and calculate depth map using triangulation between reference and deformed pattern



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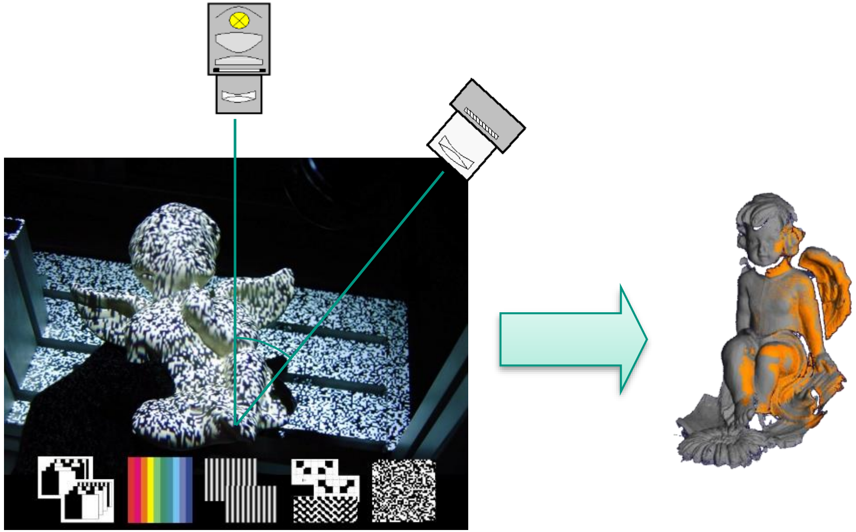
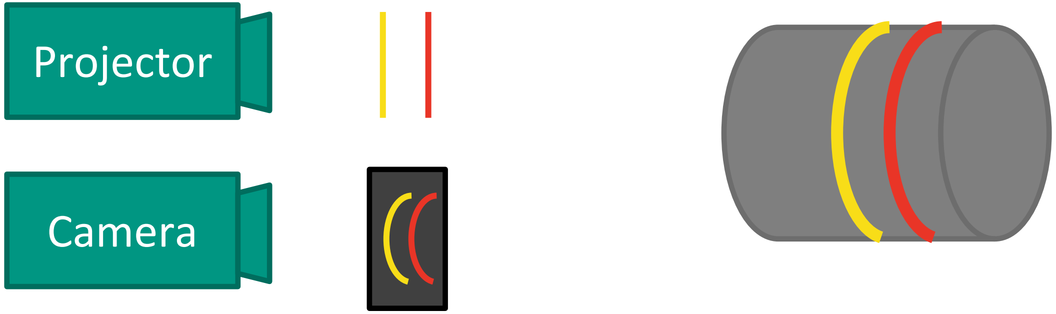
Pattern Types: Pattern Encoding/Decoding

- Projection of identifiable features onto scene
- **Correspondence problem:** Which pixel in the camera image corresponds to which pixel of the projector?
- **Answer:** Coded patterns



Pattern Types: Wavelength Encoding

- Projected pattern made of different colors (wavelengths),
- Project a known pattern onto the scene and infer depth from the deformation of that pattern
- **Example:** pattern with two different color encoded columns

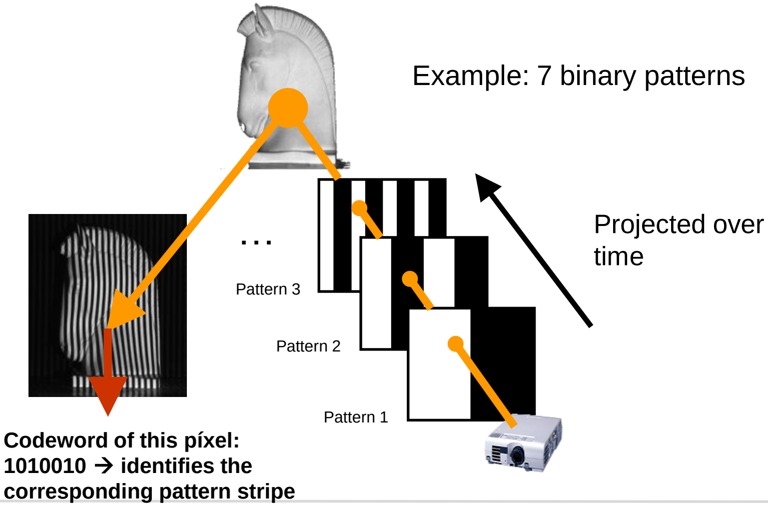


- The process of matching an image region with its corresponding pattern region is known as **pattern decoding** -> similar to searching correspondences

Pattern Types: Binary Coding

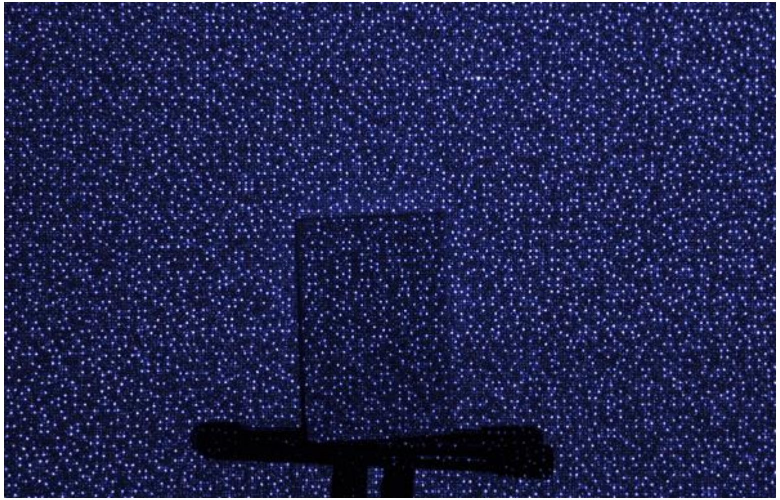
- Assign each stripe a unique illumination code over time
- Only two illumination levels are commonly used, which are coded as 0 and 1.
- $2^n - 1$ stripes in n images
- Advantage: Easy to segment the image patterns
- Drawback: Long scanning time (no real-time capture of moving objects), i.e. static objects only

1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
1	1	1	1	0	0	0	0	1	1	1	1	0	0	0	0
1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0
1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0



Pattern Types: Spatial Patterns

- Projection of a special uniquely identifiable pattern
- Infrared Patterns captures by IR-filtered camera
- Internal processor computes depth-map from reference frame and deformed pattern
- Used with different coding types/patterns

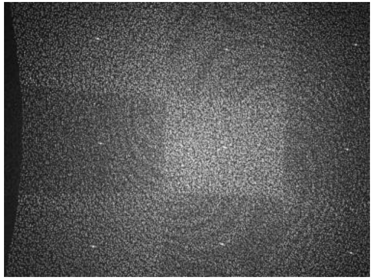


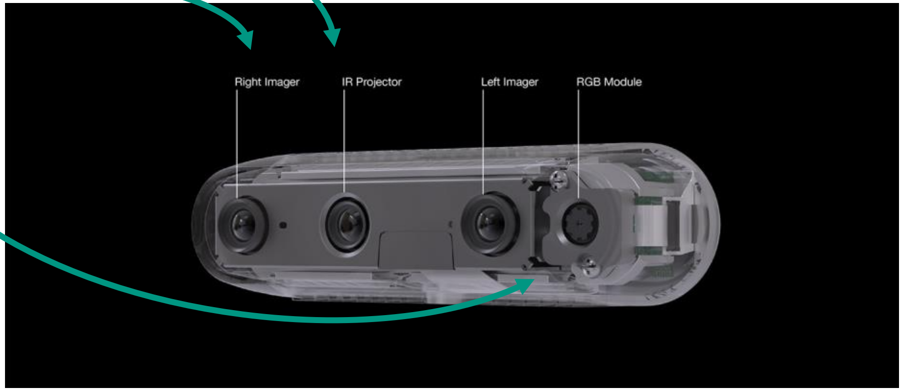
xandrox.github.io/jax-digital-signage-kinect

Depth Camera: Example

- For example: Microsoft Kinect, Intel RealSense, Asus Xtion…

- Use of structured (IR) Light for Depth Reconstruction:
  - Projector emits IR pattern
  - IR camera captures pattern on object
  - Additional Camera for RGB image





Depth Camera: Summary

- Kinect:
  - Measuring range: 0,8m – 3,5m
  - Resolution: 640 x 480 pixel
  - Frequency: 30Hz
  - Depth accuracy: 1cm (2m distance)
  - Spatial resolution: 3mm (2m distance)

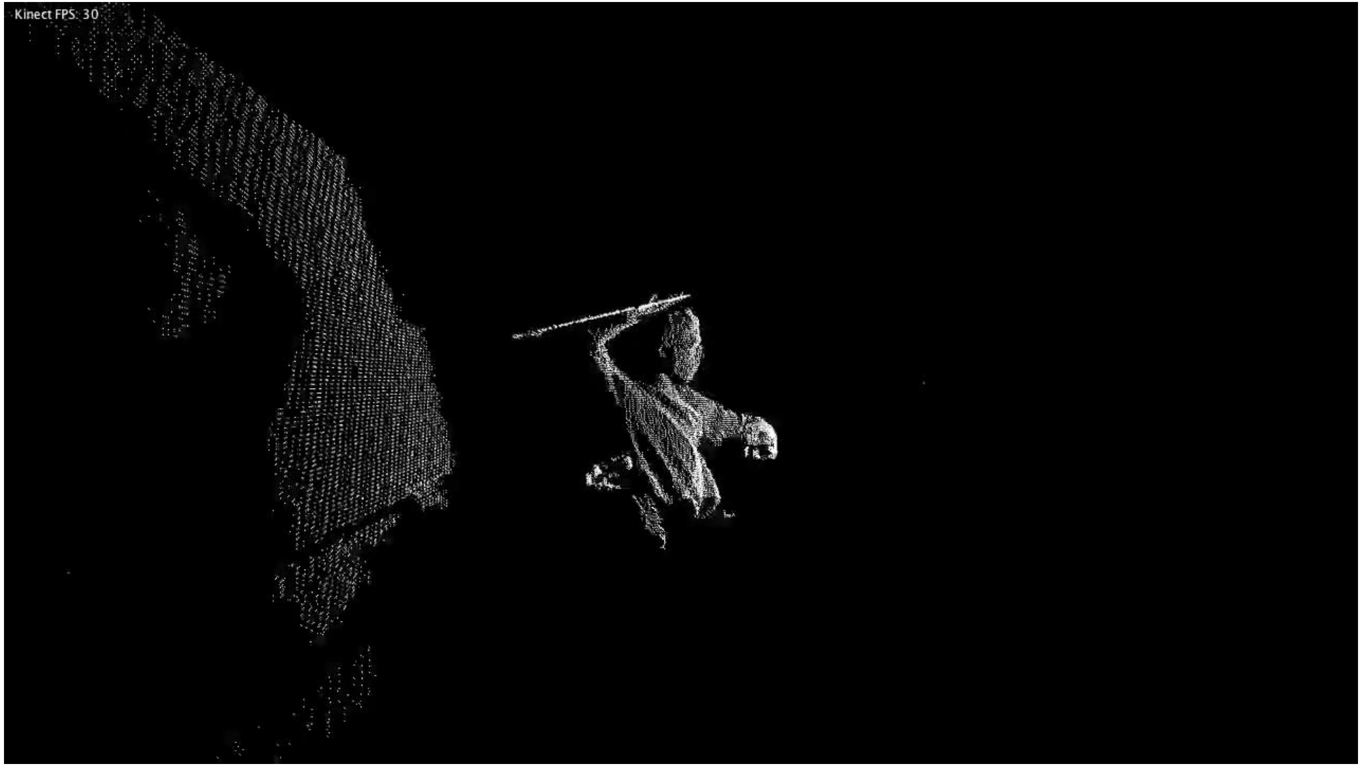
Advantages

- Cheap
- No correspondence problem on homogeneous surfaces

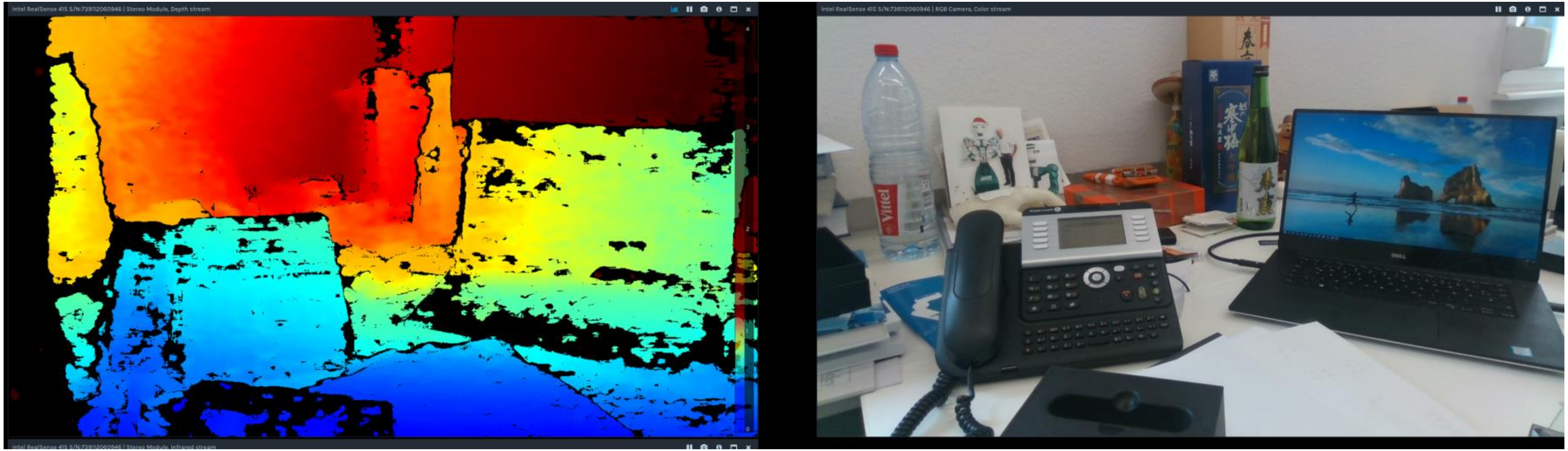
Disadvantages

- Limited distance (2m)
- Requires good lighting control (restricted to indoor environments)
- Use of multiple cameras: Projected pattern can disturb each other

Depth Camera: Example Image



RealSense Live Demo



LiDAR vs. Structured Light

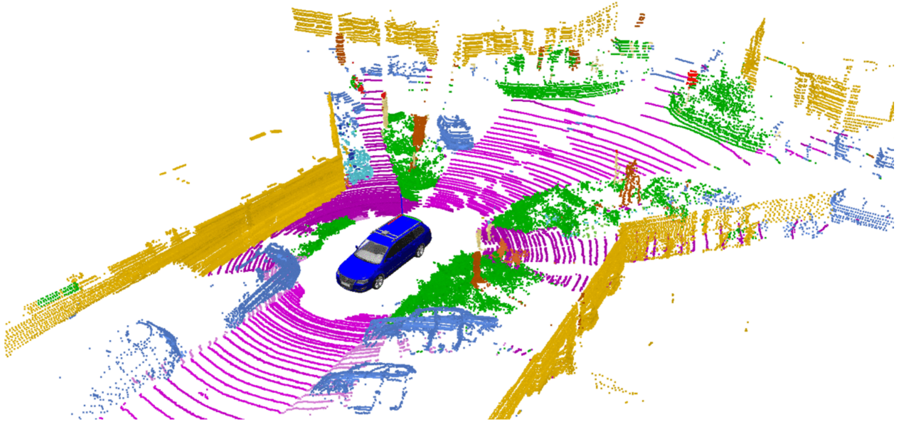
LiDAR:

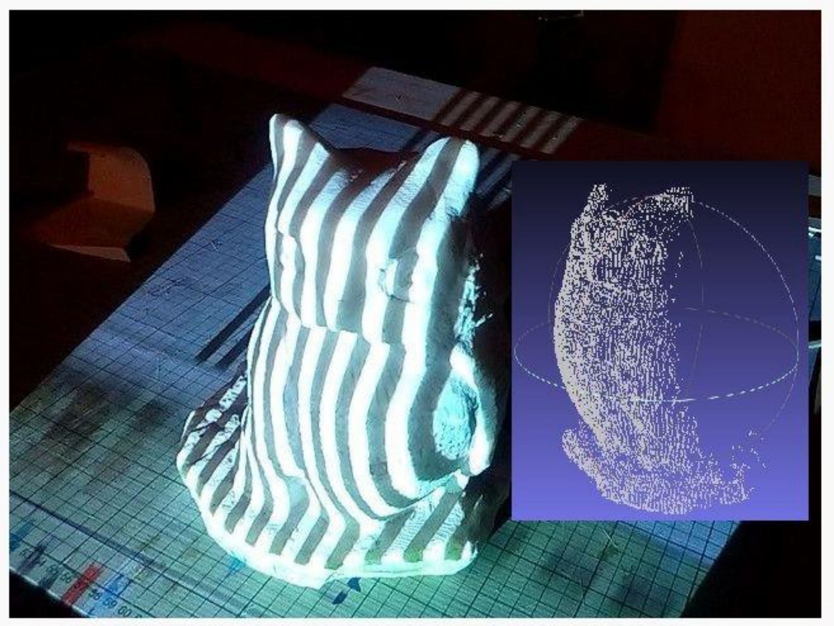
- Advantages
  - Constant error model
  - Long range
  - General wide horizontal FOV
- Disadvantages
  - High cost
  - Larger scan time
  - Limited angular density & asymmetric density

Structured Light:

- Advantages
  - Very high resolution and density
  - „Instantaneous“ horizontal & vertical capture
  - Monochrome or color
  - No moving parts
- Disadvantages
  - Quality dependent on scene texture
  - Non-linear error model
  - Computationally expensive

LiDAR vs. Structured Light: Point Clouds





pythonawesome.com/semantic-and-instance-segmentation-of-lidar-point-clouds-for-autonomous-driving/

cdn.instructables.com/F9F/T7PP/I88LJCRP/F9FT7PPI88LJCRP.LARGE.jpg

Scanning with Laser Stripes: Ex. Minolta Vi-900

Karlsruher Institut für Technologie

- Uses the light-stripe method to emit a horizontal stripe light through a cylindrical lens to the object.
- The reflected light from the object is received by the CCD, and then converted by triangulation into distance information.
- This process is repeated by scanning the stripe light vertically on the object surface using a mirror, to obtain a 3D image data of the object.
- Light-cut process – Laser swings in the device
- Characteristics
  - Measuring range: 60cm – 120cm
  - Resolution: 640 x 480 pixel
  - Measuring time: 0,3s – 2,5s
  - Accuracy: ~0,047mm (at 60 cm distance)
  - Weight: approx. 11kg

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Scanning with Laser Stripes: Ex. Minolta Vi-900

Object Modeling with Minolta

KIT Object Modeling Center

- Generation of point 3D clouds using a laser scanner
- Post-processing with triangulation results in high-quality meshes
- Stored in several file formats (Open Inventor, VRML, Wavefront)
- Generation of multiple object views using stereo cameras

Web databas e

http://h2t-projects.webarchiv.kit.edu/Projects/ObjectModelsWebUI

3D Scanning Object Scanning @ H^2T

- Artec Eva 3D Hand-held 3D Scanner
- Use of structured light: Static line-pattern projected onto object and captured by IR-camera
  - Capture rate: 16 Frames per second
  - 2 millions points per second
  - Object distance: 0,4 – 1 m
  - Weight: 0,9 kg
  - Additional RGB camera + flash for object-texture scanning
- Software for multi-frame model reconstruction and post-processing

3D Scanning Object Scanning @ H²T

External (Exteroceptive) Sensors

Karlsruher Institut für Technologie

External sensors

Proximity sensors
- Capacitive Sensors
- Optical Sensors
- Acoustic Sensors

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Depth sensors
- Time-of-Flight based
- Triangulation based

© Microsoft (2020)

Visual sensors
- Photodiodes
- CCD/CMOS
- Stereo

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Position sensors
- GPS
- Natural/artificial Landmarks

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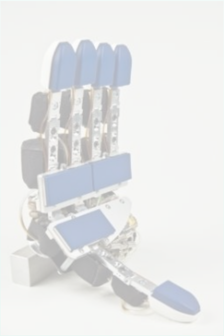
Tactile sensors
- Touch & Slip Sensors
- Force/Torque Sensors



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Visual Sensors – Artificial Eyes

- Used in
  - Mobile robotics (autonomous vehicles)
  - Humanoid robotics
  - Industrial robotics
  - Safety systems
  - Quality control

- Tasks
  - Object recognition
  - Classification
  - Detection
  - Motion tracking
    - 3D-vision
    - Obstacle detection

Digital Cameras (I)

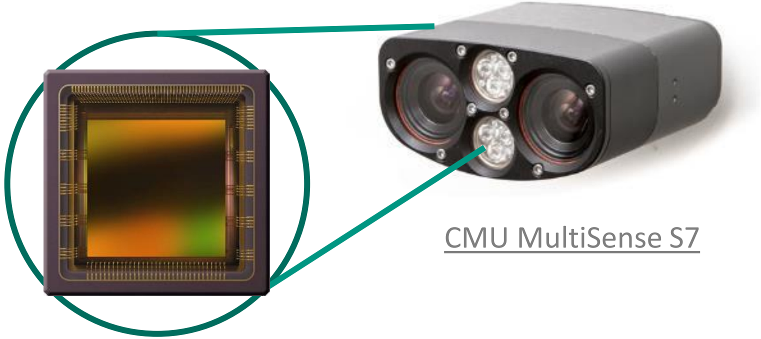
- Cameras differ in:
  - **Image quality** (Quality of CCD-Chip (respectively CMOS-Chip), but also: Lense-setup)
  - **Color mode**: Grey-value image or multi channel color
  - Resolution (typically 640×480, 1024×768, 2048 x 1088)
  - **Color Resolution**: Color depth of image values (8bit, 16bit, 24bit)
  - **Framerate**:
    Number of images captured per second (typically15/30/60/120/200 Hz)
    Typically framerate and resolution are depending on each other

Digital Cameras (II)

Data interface	Transfer rate
USB 3.0	5000 Mbit/s
USB 2.0	480 Mbit/s (430 Mbit/s payload)
Gigabit Ethernet (GigE):	1000 Mbit/s (720 Mbit/s payload)
Camera Link	up to 5,44 Gbit/s
Firewire IEEE1394a	400 Mbit/s (320 Mbit / s payload)
Firewire IEEE1394b	800 Mbit/s (640 Mbit / s payload)

- Cameras support different encoding of image data:
  - B/W-Cameras: mostly 8 bit grey value
  - Color Cameras: Either Bayer-Pattern or often internally converted to RGB24, YUV422, etc.

Camera Examples



CMU MultiSense S7

Karlsruhe Humanoid Head

PointGrey Flea3 USB3

roboception rc_visard 65

External (Exteroceptive) Sensors

Karlsruher Institut für Technologie

External sensors

Proximity sensors
- Capacitive Sensors
- Optical Sensors
- Acoustic Sensors

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Depth sensors
- Time-of-Flight based
- Triangulation based

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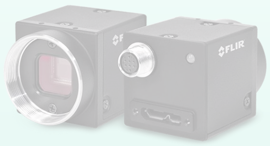
Visual sensors
- Photodiodes
- CCD/CMOS
- Stereo



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Position sensors
- GPS
- Natural/artificial Landmarks

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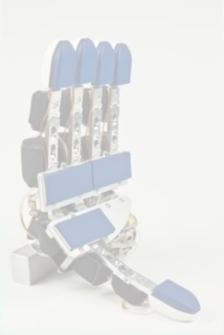
Tactile sensors
- Touch & Slip Sensors
- Force/Torque Sensors



Absolute Position

- Requires **active beacons**:
  Signal transmitted from known positions

- Used in transportation, airplanes and ships, …

- Examples:
  - Position lights, terrestrial wireless networks, satellite based, …

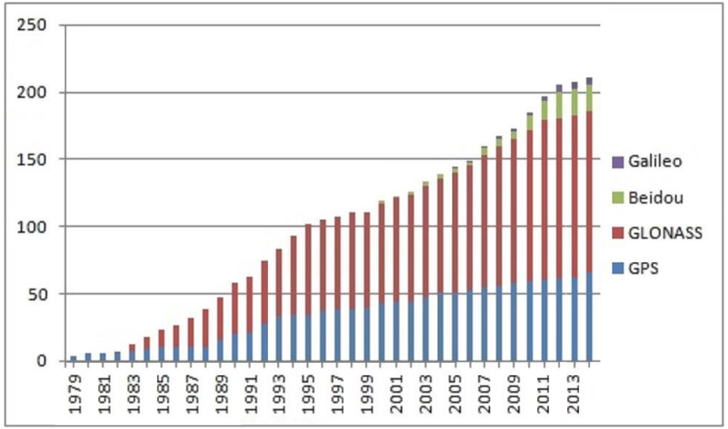
Satellite Navigation

Karlsruher Institut für Technologie

- Four existing Global Navigation Satellite Systems (GNSS):
  - GPS (USA)
  - GLONASS (Russia)
  - Galileo (European Union)
  - BeiDou (China)

- Overall, more than 200 GNSS satellites (1978-2014)

- Each satellites includes an atomic clock and sends its **position** and **timing** reference



https://de.wikipedia.org/wiki/Globales_Navigationssatellitensystem#/media/Datei:Launched_GNSS_. 2014jpg

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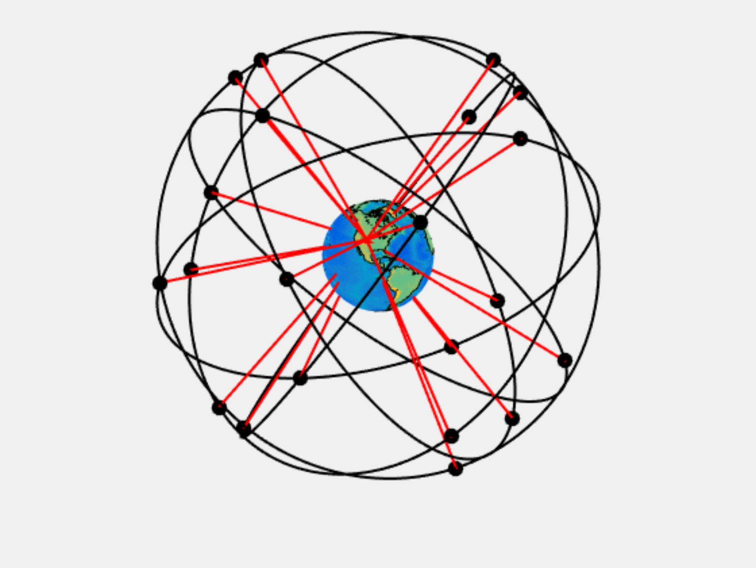
Absolute Position

- At least 4 satellites needed for position estimation
- As GNSS signals are weak, satellites need to be **within line of sight**



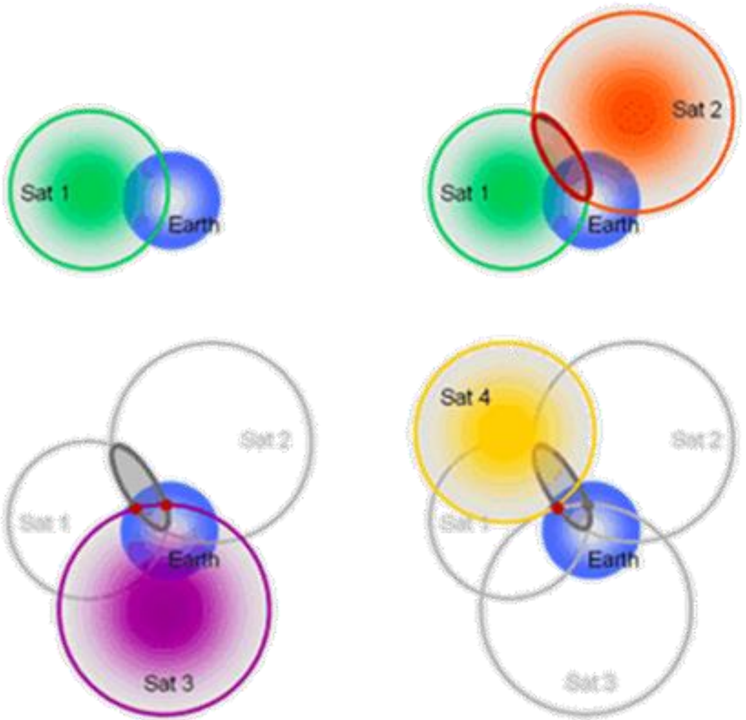
https://commons.wikimedia.org/wiki/File:GPS24golden.gif

Satellite Navigation

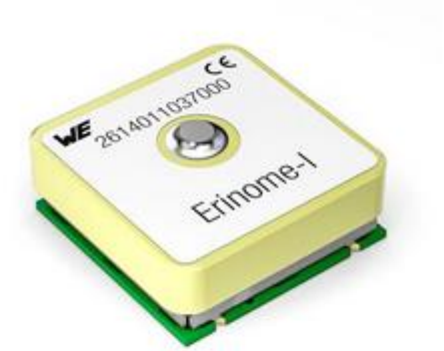
- Different methods of position estimation
- Condition: **Signal from at least four satellites needed**
- Position estimation:
  - Code phase (Pseudo distance)
    - ΔT between transmission from satellite and receiving
    - Time error; Signal speed. ~ c in vacuum → $\Delta T \cdot c \neq$ real distance
      → systematic error
      → pseudo distance
  - Doppler-Count
    - Speed estimation
  - Carrier mixed phase
    - Determination of position with phase shift between signals

Trilateration in Satellite Navigation

- Why are 4 Satellites needed?
  - Intuition: 3-dimensional space requires 3 satellites
- Positioning via GNSS uses trilateration
  - First satellite places the receiver somewhere on a sphere
  - Second satellite narrows it down to a circle (intersection between 2 spheres)
  - Third narrows it down to 2 points
  - Fourth is used to choose the correct point
- If the altitude of the receiver is known (e.g., when driving in a car) 3 satellites are enough
  - However, as very precise time is needed (most consumer grade GPS receivers are not precise enough), the fourth one is still required to level out the error introduced by “relative” time



GPS Receiver Example

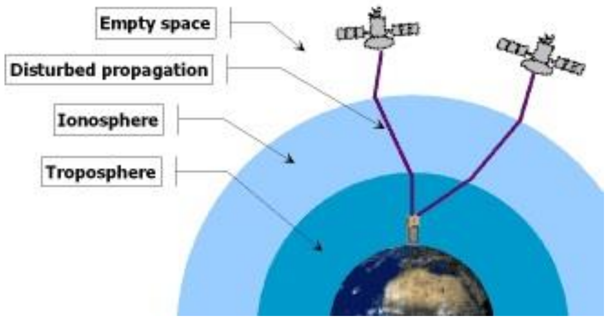


- Receiver available as System on Chip (SoC)
  - 18mm x 18mm
- Multiple GNSS systems supported in one module: GPS, GLONASS, Galileo, BeiDou
- Accuracy up to 1,5m
- Max update rate: 10Hz
- Time to first position: Up to 28s
- Price: ~30€

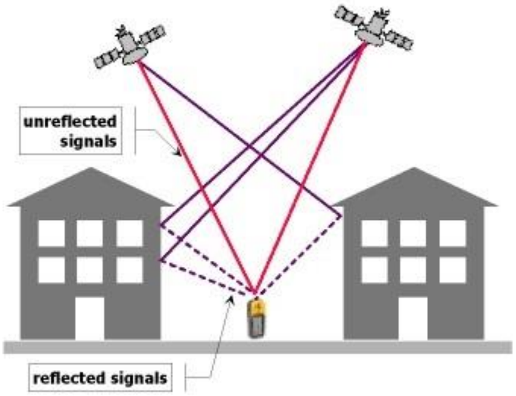
Error with Pseudo Distance

- Errors depending on satellite position and environment conditions

- Atmospheric refraction



- Multipath reflection



https://www.aboutcivil.org/sources-of-errors-in-gps.html

GPS Error

Error reason	Standard deviation [m]
Satellite Position	3
Ionospheric refraction	5
Tropospheric refraction	2
Multi-reflection	5
„selective availability“ (intended error until 1. Mai 2000)	30

- Accuracy is also strongly depending on surrounding terrain (Houses, trees, …)

Differential GPS

- Significantly lower error (Exception: Multipath reflection)
- Premise: Second GPS receiver with known position in range of less than 10km, experiences same error (same reference satellite)
- Comparison of errors and calculation of error vector, transmission of correction value to first receiver
- Effective accuracy can reach several centimetre