64-424
Intelligent Robotics

https://tams.informatik.uni-hamburg.de/lectures/2019ws/vorlesung/ir

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Technical Aspects of Multimodal Systems

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Outline

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Measurement of distance

The ability to measure distance plays a crucially important role in the field of robotics - it is particularly important for mobile robots

- Obstacle detection/avoidance
- Localization
- ...

Several sensors can be used to determine the distance

- Infrared/Ultrasonic sensor
- Laser rangefinder
- Camera-based
- ...

Measurement of distance (cont.)

The predominant underlying physical principles for measurement of distance using sensor devices are:

- Time-of-flight (TOF)
  $\rightarrow$ Time required for a signal to travel through a medium
- Phase shift/difference
  $\rightarrow$ Difference in phase as a property of the reflected signal
- Triangulation
  $\rightarrow$ The geometric approach

Time-of-flight

Measurement of distance using the *time-of-flight* principle is a straightforward process

- Emit signal (impulse)
- Measure time (Δt) until reception of the echo/reflection
- Determine distance (D) using knowledge about the speed (v) of the signal

$$D = \frac{\Delta t \cdot v}{2}$$

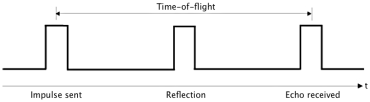
Time-of-flight (cont.)

Example: Distance measurement using light impulses

- *Signal*: Light impulse
- *Medium*: Air
- *Measured time*: 65 ns

Assuming $v = c$, where c is the speed of light (299792458 m/s) and a value of 65 ns for Δt the resulting distance is

$$9.74\, m \approx \frac{0.000000065\, s \cdot 299792458\, m/s}{2}$$



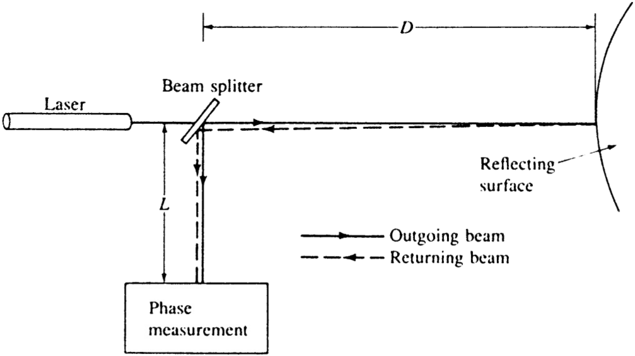
Phase shift/difference

As an alternative to *time-of-flight*, the phase shift approach is also very straightforward

- Emit signal with wave length(λ)
- Measure phase difference between received echo and signal
- Determine distance (D) based on the phase shift ($\Delta\theta$) between the reflected signal and the emitted signal
- For light modulated with frequency f_{mod}: $\lambda = \frac{c}{f_{mod}}$

$$D = \frac{1}{2} \cdot \frac{\Delta\theta}{2\pi} \cdot \lambda$$

Phase shift (cont.)



Phase shift (cont.)

Example: Distance measurement using light impulses

- *Signal*: Light impulse
- *Medium*: Air
- *Frequency*: 10 MHz
- *Measured phase shift*: 4.78rad

Assuming c the speed of light (299792458 m/s) the resulting distance is

$$11.45\,m \approx \frac{1}{2} \cdot \frac{4.78}{2\pi} \cdot \frac{299792458\,m/s}{10000000\,s^{-1}}$$

Phase shift (cont.)

Caution:

- Impossible to distinguish between all $D = n \cdot \lambda, n \in \mathbb{N}$
- To receive a distinct result, constraints $\Delta\theta < 360°$ and $2D < \lambda$ need to apply
- A modulation frequency of $f_{mod} = 10$ MHz results in a wavelength of about 30 m

Triangulation

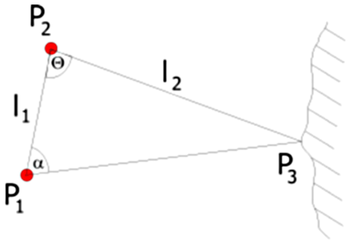
Triangulation is the process of calculation of distance to a point using knowledge about viewing angles

- Use two viewing points with the distance between them (baseline) known
- Align both "viewers" looking towards the point in question
- Determine the angles of both "viewers" to the baseline
- Calculate the distance using basic trigonometry

Two viewing points may be obtained in a number of ways:

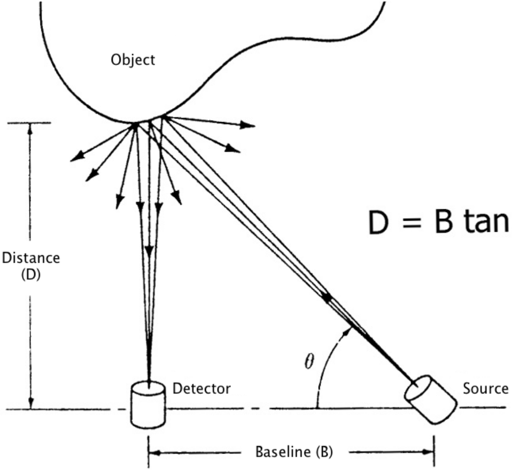
- Movement of a single sensor
- Special design of the sensor
- Multiple sensors

Triangulation (cont.)



$$D = l_2 = \frac{l_1 \sin(\alpha)}{\sin(\alpha + \Theta)}$$

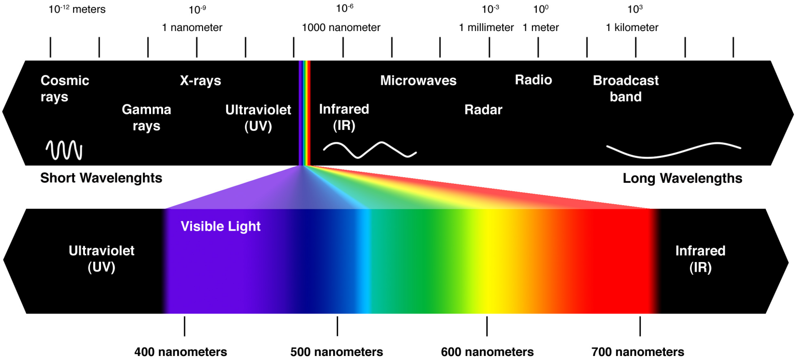
Triangulation (cont.)



$$D = B \tan \theta$$

Infrared sensors

- Infrared sensors are the most simple type of non-contact sensors
- Infrared sensors emit a signal in the infrared spectrum

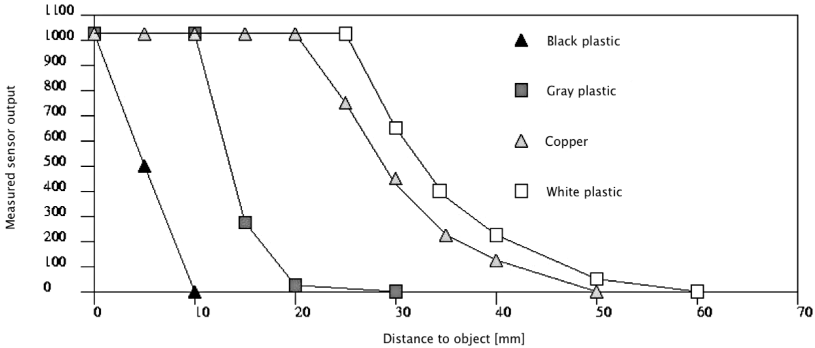


Infrared sensors (cont.)

Reflection of the emitted signal by objects in the vicinity:

- The intensity of the reflected light is inversely proportional to the squared distance
- To be able to distinguish the emitted signal from other infrared sources in the vicinity (e.g. fluorescent lamps or sunlight), it is usually modulated with a low frequency (e.g. 100 Hz)
- Assuming that all objects are equal in color and surface, the distance to the objects can be determined with usable accuracy

Infrared sensors (cont.)



Measured sensor output based on different object surfaces

Infrared sensors (cont.)

`Problem:` In realistic environments, surfaces are not equal in color

- Colored surfaces reflect different amounts of light
- Black surfaces are practically invisible
- In fact, IR-sensors can only be used for object detection, but not for exact distance measurement
- If an IR-signal is received by the sensor, one can assume, that there's an object in front of of the sensor
- `Note:` A missing IR-signal does not necessarily mean there is no object in front of the sensor

- IR-sensors are usually used for short distances (50 to 100 cm)

Ultrasonic sensors

Dolphins and Bats use various different **so**und **n**avigation **a**nd **r**anging (sonar) techniques:

- Fixed frequencies
- Varying frequencies

Note: Although artificial ultrasonic sensors are capable of creating frequencies similar to those in the animal world, the animal capabilities remain unmatched

Ultrasonic sensors (cont.)

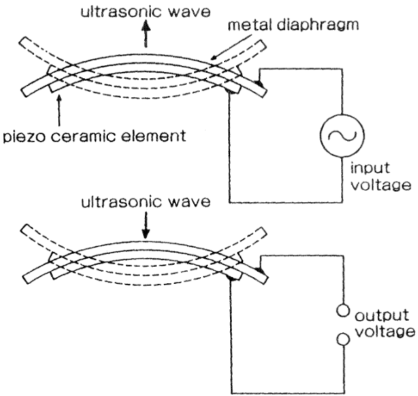
- Ultrasonic waves are differentiated from electromagnetic waves based on the following physical properties:
  - Medium
  - Speed (in medium)
  - Wavelength
- Ultrasonic waves require a medium like air or water
- Ultrasonic speed in air amounts to $331.3\,m/s + 0.6 \times \,^{\circ}C$
- *Time-of-flight* measurement is possible for short distances
- The wavelength of an ultrasonic sensor driven with a frequency of $50\,kHz$ amounts to $\approx 6.872\,mm$

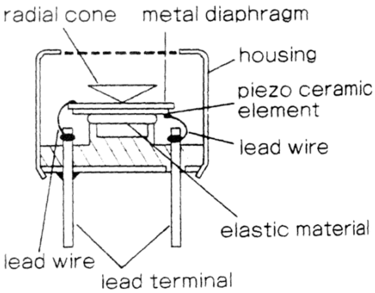
Ultrasonic sensors (cont.)

Piezoelectric ultrasonic transducer:

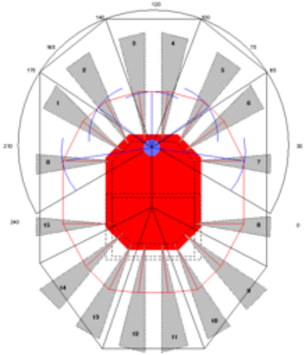
- To produce ultrasonic waves, the movement of a surface is required, leading to a compression or expansion of the medium
- One possibility to generate ultrasonic waves is the use of a piezoelectric transducer
- Applied voltage causes a bending of the piezoelectric element
- Piezoelectricity is *reversible*, therefore incoming ultrasonic waves produce an output voltage
- The opening angle (*beam angle*) of the ultrasonic signal, can be up to 30° wide

Ultrasonic sensors (cont.)





Piezoelectric ultrasonic transducer (cont.)



Example: Pioneer platform equipped with 16 ultrasonic (sonar) sensors

Ultrasonic precision

The minimum distance d_{min} which can still be measured, is specified as:

$$d_{min} = \frac{1}{2} v t_{Impulse}$$

v: Speed of the wave in the corresponding medium
$t_{Impulse}$: Duration of the emitted impulse in seconds The

maximum distance d_{max} which can still be measured, is specified as:

$$d_{max} = \frac{1}{2} v t_{Interval}$$

v: Speed of the wave in the corresponding medium
$t_{Interval}$: Time span between the single impulses

Ultrasonic sensors (cont.)

Reflection of ultrasonic waves from smooth (and flat) surfaces is well-defined However:

- Very rough structures lead to *diffuse* reflection of ultrasonic waves
- **Note:** A round rod produces a diffuse reflection

Ultrasonic precision (cont.)

Measurements with sonar sensors are subject to several inaccuracies

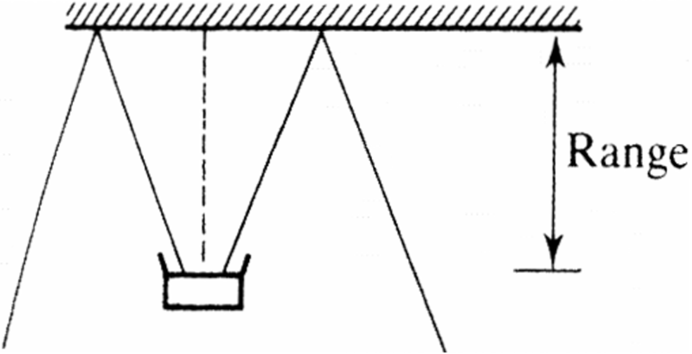
- An object perceived at a distance may be located at an arbitrary position within the sonar cone on the arc at a distance
- Mirror and total reflections cause flawed measurements
- If the sonar beam hits a smooth object in a flat angle, the signal will usually be deflected and no echo will reach the sensor

Ultrasonic precision (cont.)

Caution:

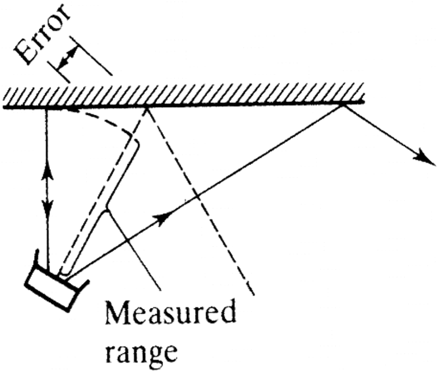
- If several sonar sensors are used simultaneously, specifically encrypted signals need to be used, because otherwise crosstalk may occur
- Since the measurement depends on the temperature of the medium, a change in air temperature will introduce measurement errors (e.g. a difference of 16°C will cause a measurement error of 30cm over a distance of 10m)

Ultrasonic precision (cont.)



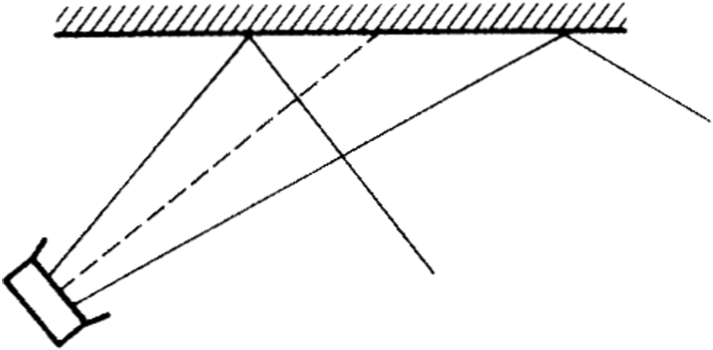
Measuring principle

Ultrasonic precision (cont.)



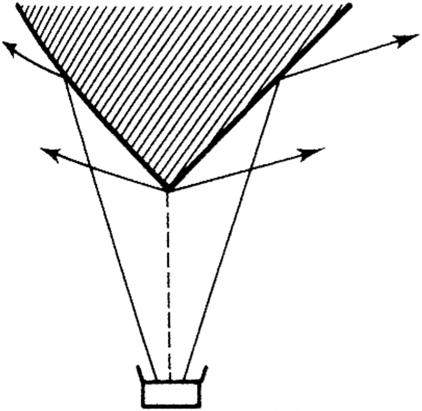
Measurement error

Ultrasonic precision (cont.)



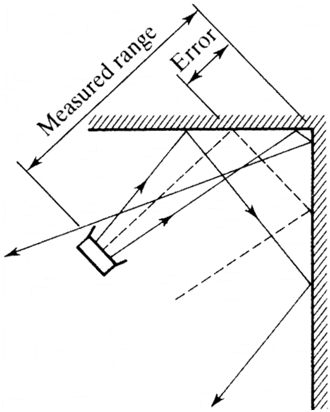
Invisible wall

Ultrasonic precision (cont.)



Invisible corner

Ultrasonic precision (cont.)



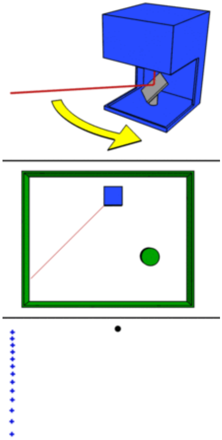
Corner error

Laser range finders

- Laser range finders (LRF) measure the distance, speed and acceleration of recognized objects
- Functional principle similar to that of a sonar sensor
- Instead of a short sonic impulse, a short light impulse is emitted from the laser range finder
- The time span between emission and reception of the reflected impulse is used for distance measurement (*time-of-flight*)

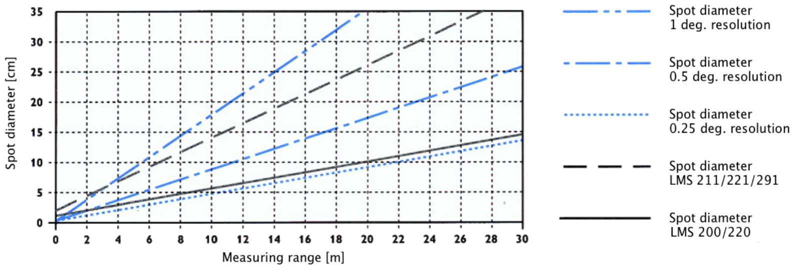
Laser range finders (cont.)

- Using a rotating mirror, the pulsed laser beam is deflected and the environment is scanned in a fan-shaped area ("laser radar" or Lidar)
- In practice rotations between 0.1Hz and 100Hz are used



Laser range finders (cont.)

- Within its field (plane) of view the LRF emits a light impulse (spot) with a typical resolution of 0.25°, 0.5° or 1°
- Due to the geometry of the beam and the diameters of the single spots, they overlap on the measured object up to a certain distance

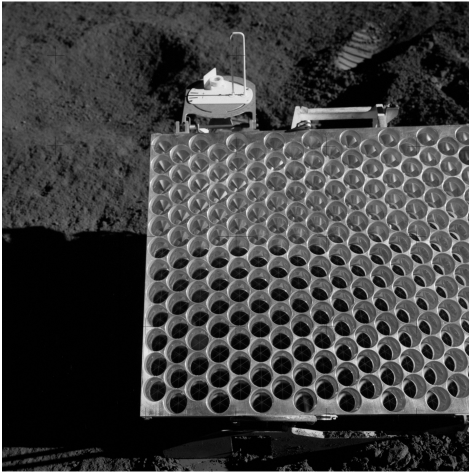


Laser range finders (cont.)

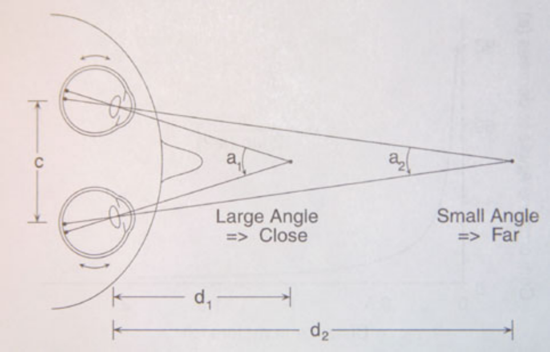
The range of the laser range finders depends on the *remission* (reflectivity) of the object and the transmitting power

Material	**Remission**
Cardboard, black	10 %
Cardboard, grey	20 %
Wood (fir raw, dirty)	40 %
PVC, grey	50 %
Paper, white dull	80 %
Aluminum, black	110...150 %
Steel, stainless glossy	120...150 %
Steel, high-gloss	140...200 %
Reflectors	>2000 %

Moon reflectors



Human Stereo Camera



$$d = c/(2*\tan(a/2))$$

Human performance: up to around 2m

Humans "Cheating" in 3D Vision

Humans use a lot of visual cues for 3D vision

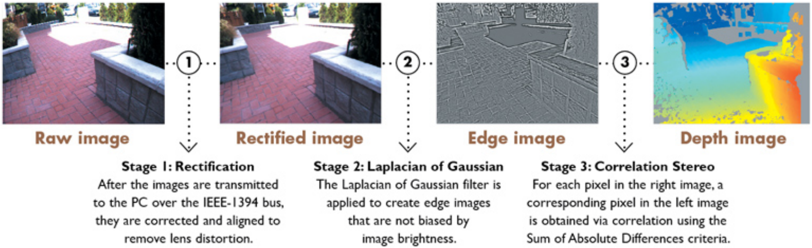
- Shading
- Texture
- Focus
- Motion
- Shadows
- Prior Knowledge
- ...

Art of Photography, Canon

Robot Stereo Camera

https://aemstatic-ww2.azureedge.net/content/dam/VSD/print-articles/2014/11/1412VSD_ProdFocus_Fig1b.jpg

Stereo Camera Example



https://www.ptgrey.com/stereo-vision-cameras-systems

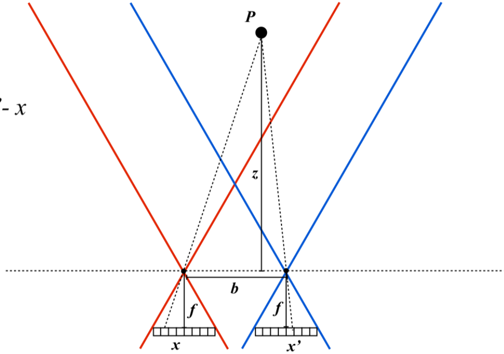
Computing Depth

Focal length: f

Baseline: b

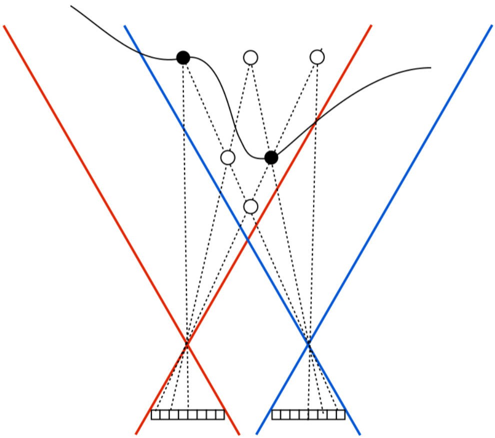
Disparity: $d = x' - x$

$$z = \frac{bf}{d}$$



http://graphics.cs.cmu.edu/courses/15869/fall2013content/lectures/19_depthcamera/depthcamera_slides.pdf

Correspondence Problem



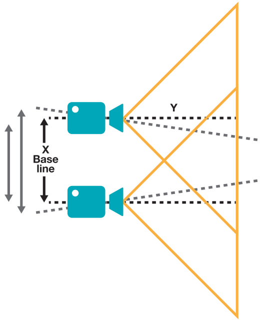
http://graphics.cs.cmu.edu/courses/15869/fall2013content/lectures/19_depthcamera/depthcamera_slides.pdf

Problems with Correspondence

Gregory Föll, Stereo Vision

Role of the Baseline

- Small Baseline
  - large depth error
- Large Baseline
  - difficult search problem
  - smaller area for depth information
- Multiple camera setups can provide small and large baselines at the same time
  - Increased complexity for processing multiple images

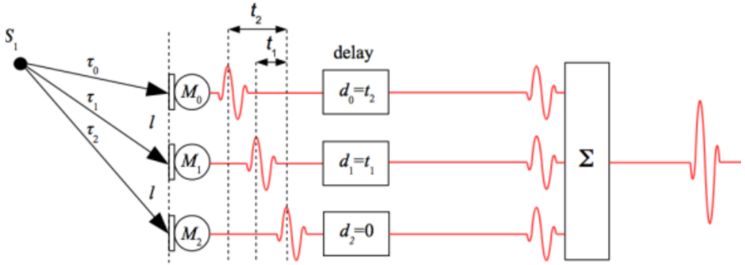


https://www.framos.com/en/news/stereo-applications-need-a-dedicated-lens-choosing

Audio Localization

- Basic idea similar to stereo camera
- Microphones can be used passively to get position of sound source
- At least two microphones necessary, typically more than two are used (microphone array)
- Typical robotic application: find position of human speaker
- Most difficult problem: correspondence of sound signal
- We will not go into depth, if interested visit signal processing lecture

Audio Localization



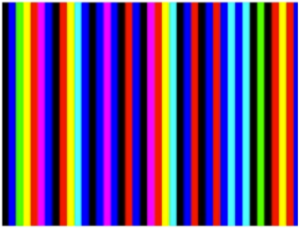
http://yuandenghub.com/wp-content/uploads/2018/07/figure2.png

Depth Camera

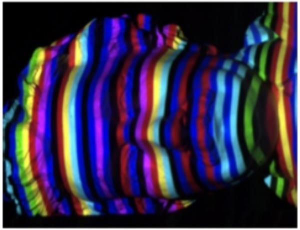
- Two different base principles
  - Structured light
  - Time-of-Flight
- A lot of cheap sensors
  - XBox Kinect (360 / One)
  - Intel RealSense
  - Asus Xtion
  - ...

Structured Light

- Simplify correspondence problem by encoding spatial position in light pattern



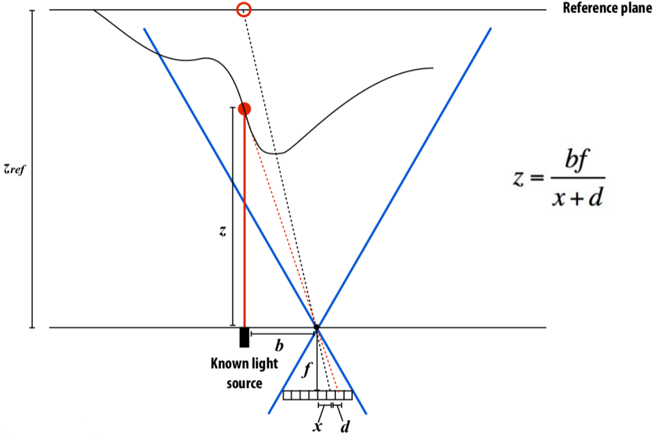
Projected light pattern



Camera image

http://graphics.cs.cmu.edu/courses/15869/fall2013content/lectures/19_depthcamera/depthcamera_slides.pdf

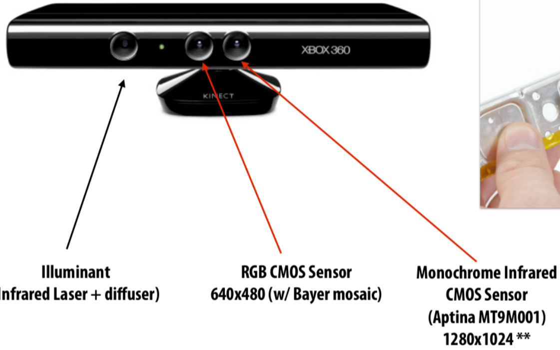
Structured Light



$$z = \frac{bf}{x+d}$$

http://graphics.cs.cmu.edu/courses/15869/fall2013content/lectures/19_depthcamera/depthcamera_slides.pdf

Structured Light Application



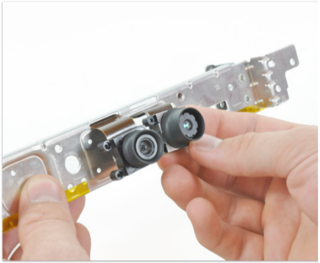
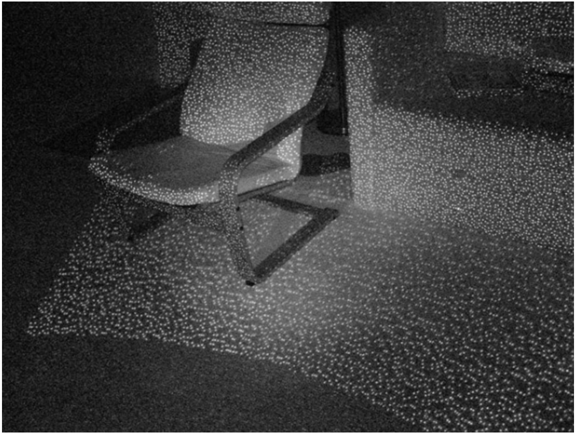


Image credit: iFixIt

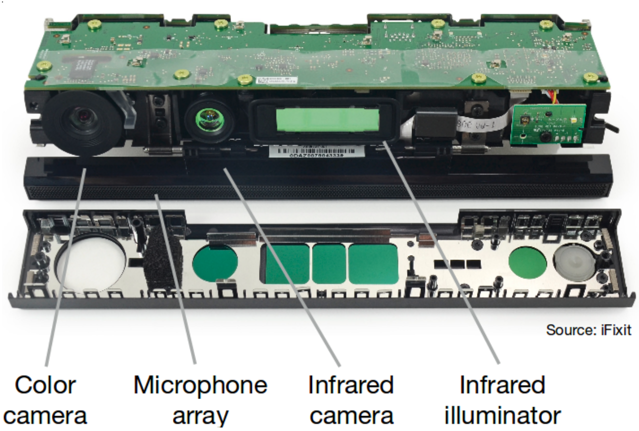
http://graphics.cs.cmu.edu/courses/15869/fall2013content/lectures/19_depthcamera/depthcamera_slides.pdf

XBox Infrared Output

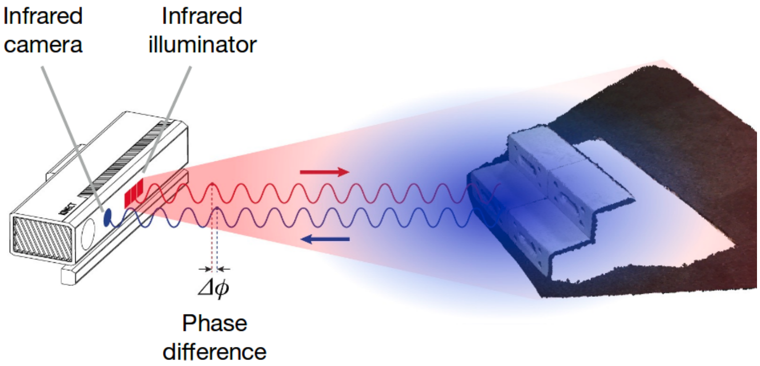


hackengineer.com

Time of Flight Cameras



Time of Flight Cameras



Peter Fankhauser, Kinect v2 for Mobile Robot Navigation Evaluation and Modeling, ETH Zürich

Time of Flight vs. Phase difference

- Kinect One uses phase difference
- Microsoft calls it "Time of Flight Camera" anyway
- Phase difference is simpler to measure for a whole picture
  - since you can get complete image at one time point

Calibration of Kinect for Xbox One and Comparison between the Two Generations of Microsoft Sensors, Diana Pagliari and Livio Pinto

Time of Flight Cameras

RGB **Infrared** **Depth**

with active IR illumination

Source: XboxViewTV

Time of Flight Cameras

Live demo

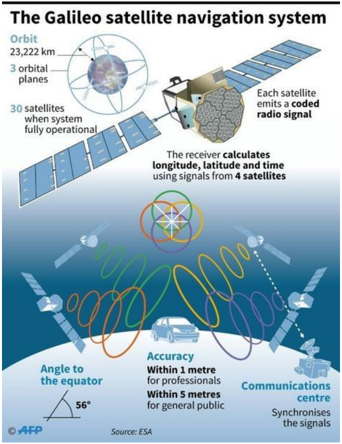
In reality

- A lot of different products available
- Integrated combination of multiple cameras and structured pattern
- Depth processing sometimes onboard
- (Proprietary) driver software usually provides depth information
- Open source software for generic stereo camera
  - ROS (stereo_image_proc)
  - OpenCV
- Improvement of these sensors still active field of research

Radio Landmark Tracking

- Use radio signals to get current position
- Mostly by satellites (GPS, GALILEO, GLONASS, ...)
- Also possible with earth bound signals, e.g. WiFi
- Getting absolute position by getting distance to multiple sources and then using triangulation
- The absolute position over time can be used to compute velocity and acceleration

GALILEO



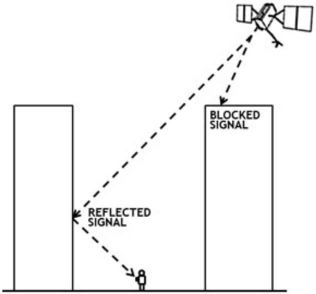
https://phys.org/news/2017-07-europe-galileo-satnav-problems-clocks.html

Satellite Based Radio Landmark Tracking

- Accuracy depends on multiple factors
  - Satellite coverage
  - Signal blockage
  - Atmospheric conditions
  - Receiver design
- Typical accuracy
  - GPS
    - Smartphone: 5m
    - Dual-receiver: few cm
    - Long-term measurement: few mm
  - Galileo, GLONASS similar
  - Much better results and robustness when using combination

Typical Problems

- Most frequent problems
  - Signal blocked by building, trees
  - Indoor, underground use
  - Signal reflected on buildings or walls
- Less frequent problems
  - Solar storms
  - Radio interference or jamming
  - Satellite maintenance



https://www.gps.gov/systems/gps/performance/accuracy/

Summary

- Different methods to measure distance
  - Time of flight
  - Phase shift
  - Triangulation
- Multiple sensors based on these methods
  - Infrared sensors
  - Ultrasonic sensors
  - Laser range finders
  - Stereo cameras
  - Structured light cameras
  - Time of flight cameras

Summary (cont.)

- Problems
  - Material properties
  - Invisible corners/walls
  - Sunlight
  - Multiple active sensors
  - Correspondence