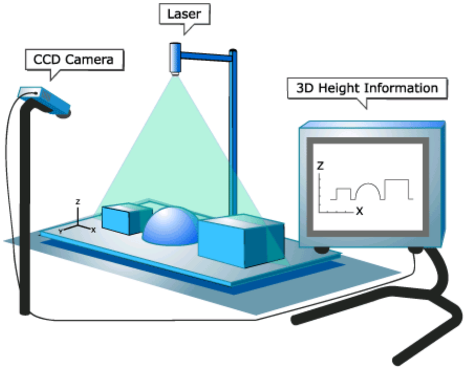
Range sensors

- Sonar

- Laser range finder

- Time of Flight Camera

- Structured light



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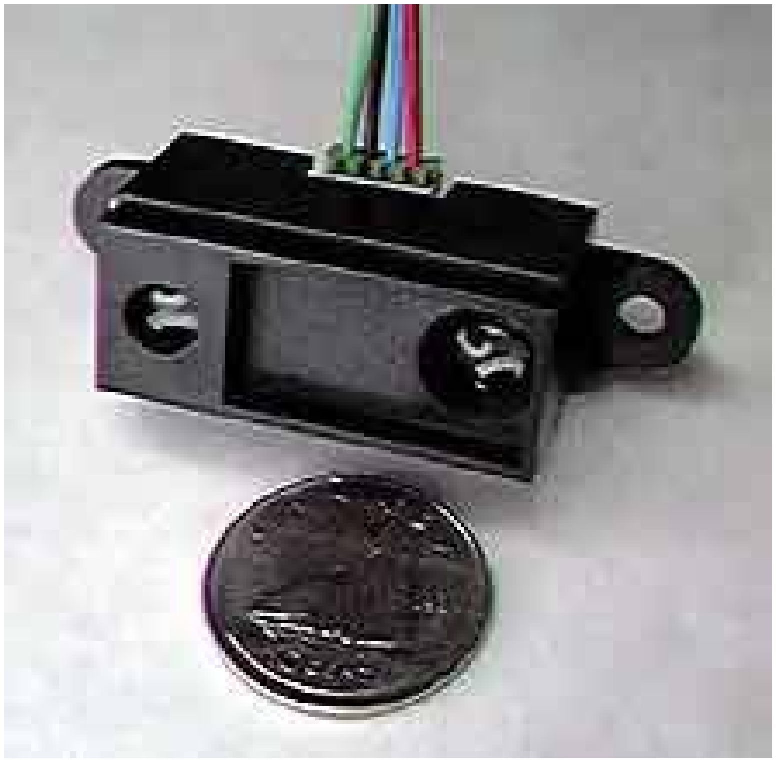
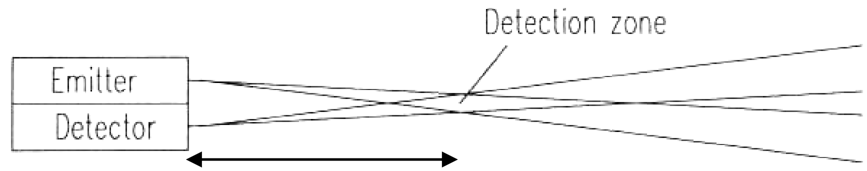
Infrared sensors

"Noncontact bump sensor"

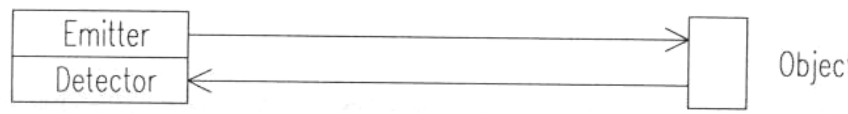


(1) sensing is based on light intensity.

"object-sensing" IR



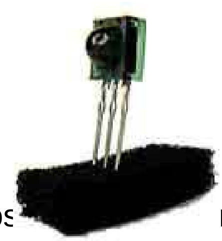
looks for changes
at this distance



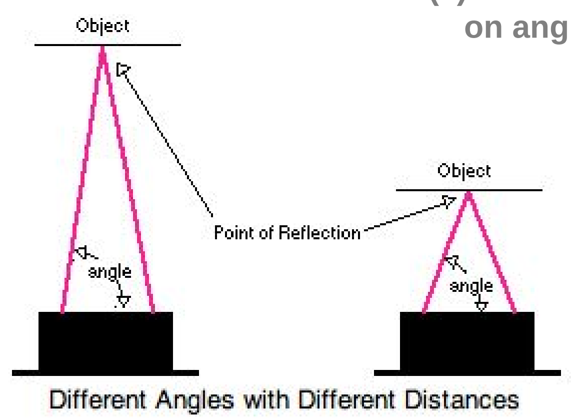
diffuse distance-sensing IR

(2) sensing is based
on angle receved.

IR emitter/detector pair

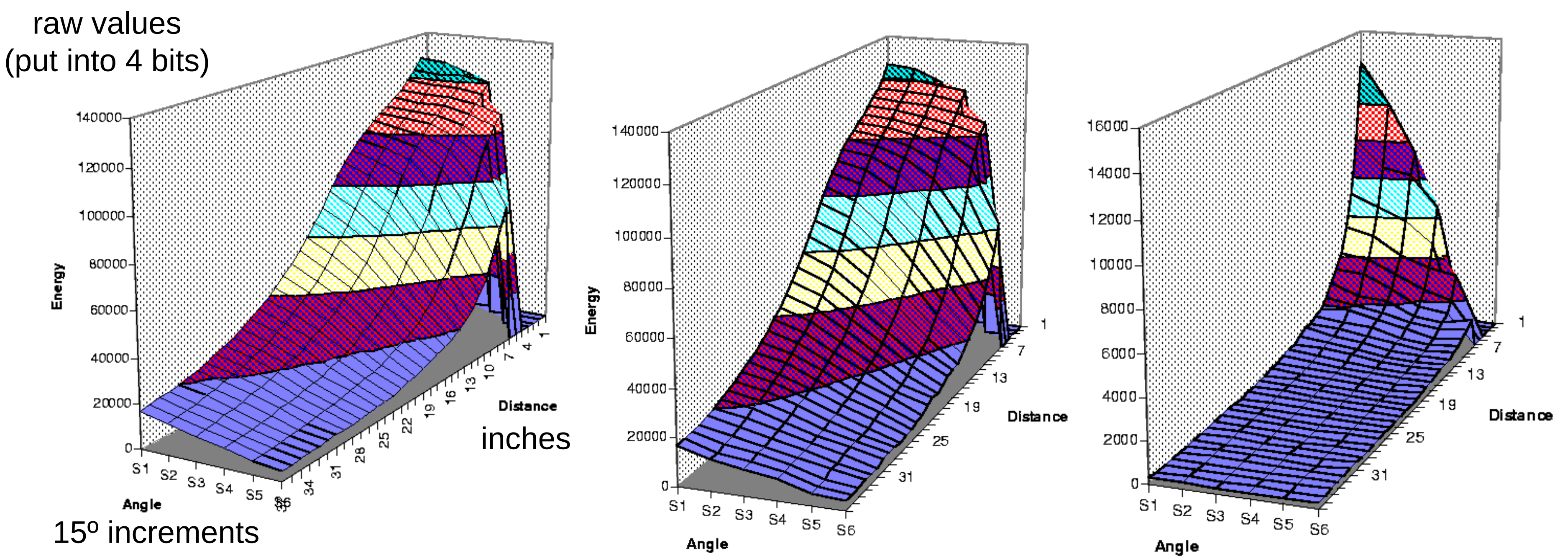


IR detector



Infrared calibration

The response to white copy paper
(a dull, reflective surface)

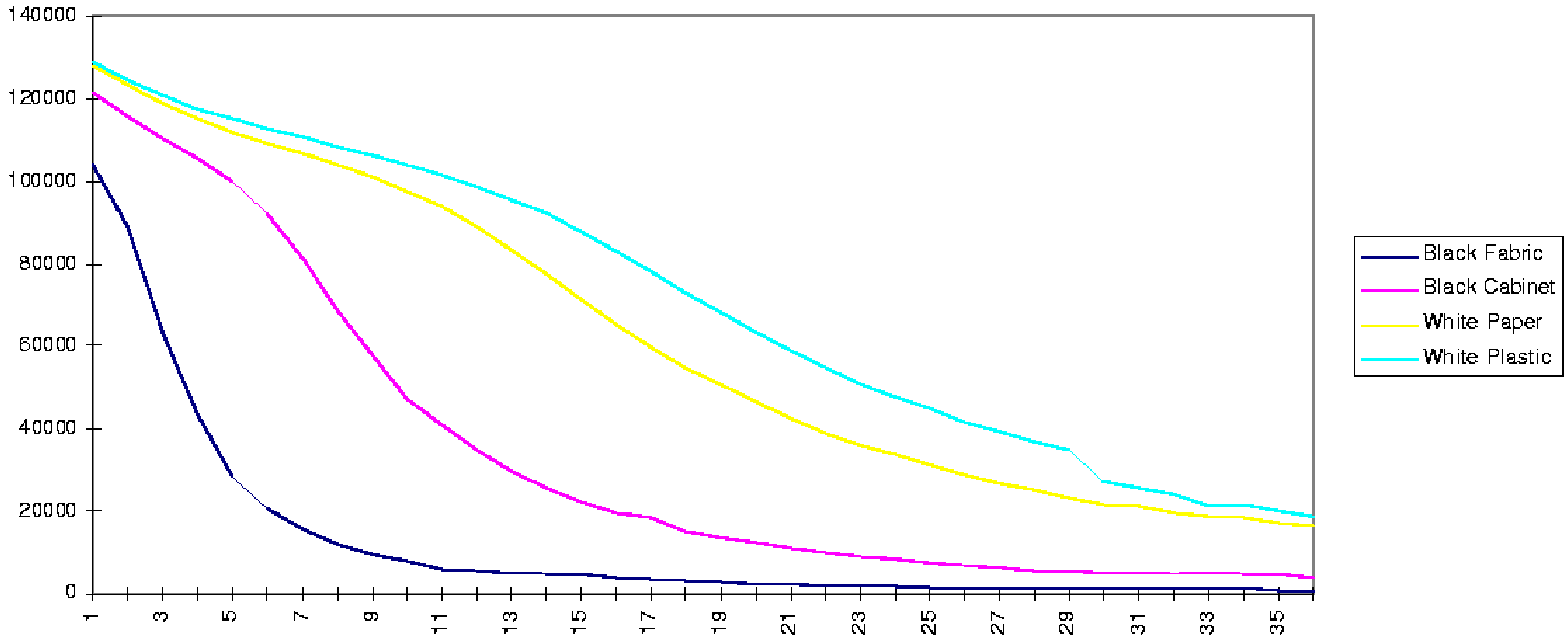


in the dark

fluorescent light

incandescent light

Infrared calibration



energy vs. distance for various materials

(the incident angle is 0º, or head-on)

(with no ambient light)

Sonar sensing

single-transducer sonar timeline

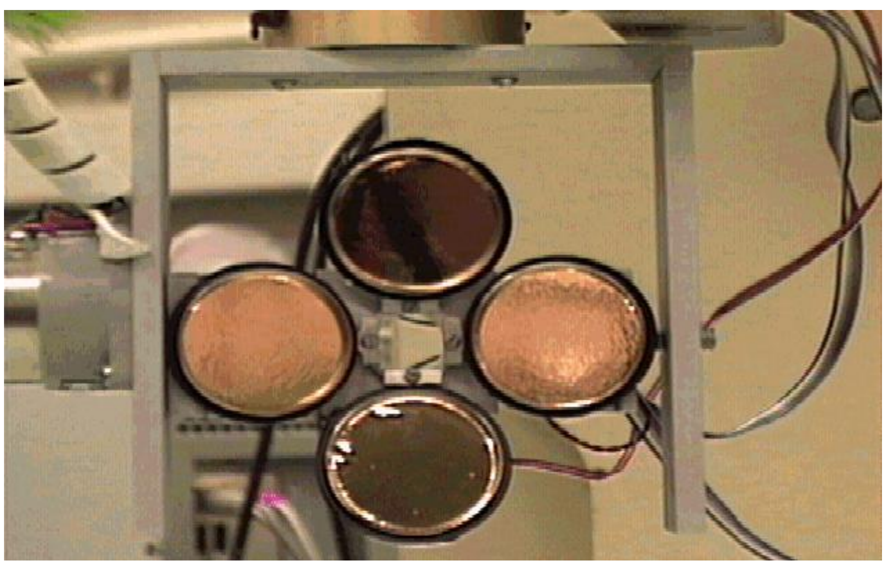
0 — a “chirp” is emitted into the environment

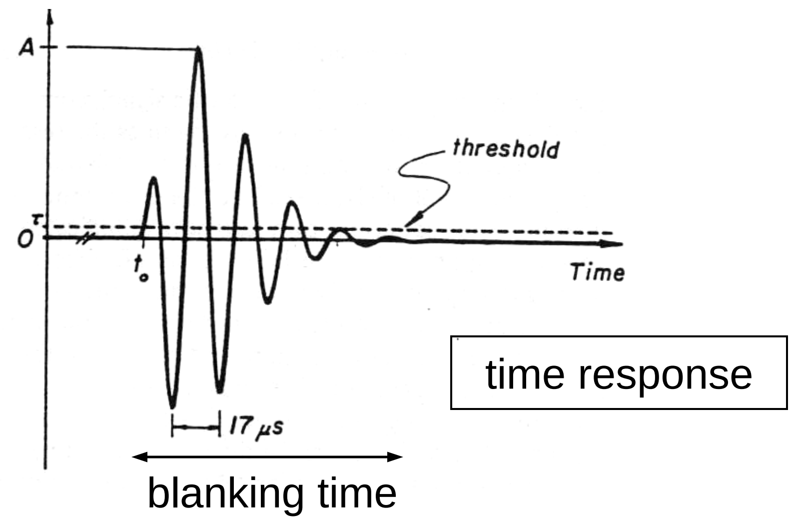
75μs — typically when reverberations from the initial chirp have stopped

the transducer goes into “receiving” mode and awaits a signal...

limiting range sensing

.5s — after a short time, the signal will be too weak to be detected





Polaroid sonar emitter/receivers

No lower range limit for *paired* sonars...

Range Sensors (time of flight) (1)

- Large range distance measurement → thus called range sensors
- Range information:
  - key element for localization and environment modeling
- Ultrasonic sensors as well as laser range sensors make use of propagation speed of sound or electromagnetic waves respectively.
- The traveled distance of a sound or electromagnetic wave is given by

$$d = c \cdot t$$

  - d = distance traveled (usually round-trip)
  - c = speed of wave propagation
  - t = time of flight.

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Range Sensors (time of flight) (2)

- It is important to point out
  - **Propagation speed v of sound: 0.3 m/ms**
  - **Propagation speed v of of electromagnetic signals: 0.3 m/ns,**
  - **Electromagnetic signals travel one million times faster.**
  - 3 meters
    - Equivalent to 10 ms for an ultrasonic system
    - Equivalent to only 10 ns for a laser range sensor
    - Measuring time of flight with electromagnetic signals is not an easy task
    - laser range sensors expensive and delicate

- The quality of time of flight range sensors mainly depends on:
  - **Inaccuracies** in the time of fight **measurement** (laser range sensors)
  - **Opening angle** of transmitted beam (especially ultrasonic range sensors)
  - Interaction with the target (surface, specular reflections)
  - **Variation of propagation speed (sound)**
  - **Speed of mobile robot and target (if not at stand still)**

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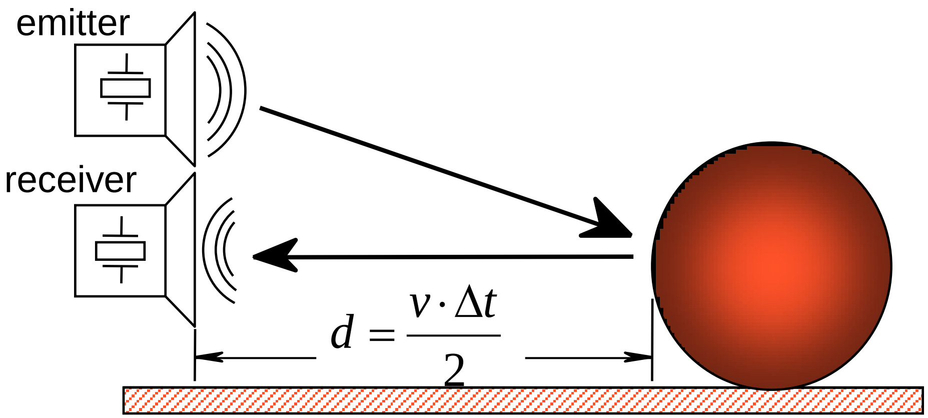
Factsheet: Ultrasonic Range Sensor



<http://www.robot-electronics.co.uk/shop/Ultrasonic_Rangers1999.htm>

1. Operational Principle

An ultrasonic pulse is generated by a piezo-electric emitter, reflected by an object in its path, and sensed by a piezo-electric receiver. Based on the speed of sound in air and the elapsed time from emission to reception, the distance between the sensor and the object is easily calculated.

2. Main Characteristics

- Precision influenced by angle to object (as illustrated on the next slide)
- Useful in ranges from several cm to several meters
- **Typically relatively inexpensive**

3. Applications

- Distance measurement (also for transparent surfaces)
- Collision detection

Ultrasonic Sensor (time of flight, sound) (1)

- transmit a packet of (ultrasonic) pressure waves
- distance *d* of the echoing object can be calculated based on the propagation speed of sound *c* and the time of flight *t*.

$$d = \frac{c \cdot t}{2}$$

- The speed of sound *c* (340 m/s) in air is given by

Where $c = \sqrt{\gamma \cdot R \cdot T}$

γ : adiabatic index (isentropic expansion factor) - ratio of specific heats of a gas

R: gas constant

T: temperature in degree Kelvin

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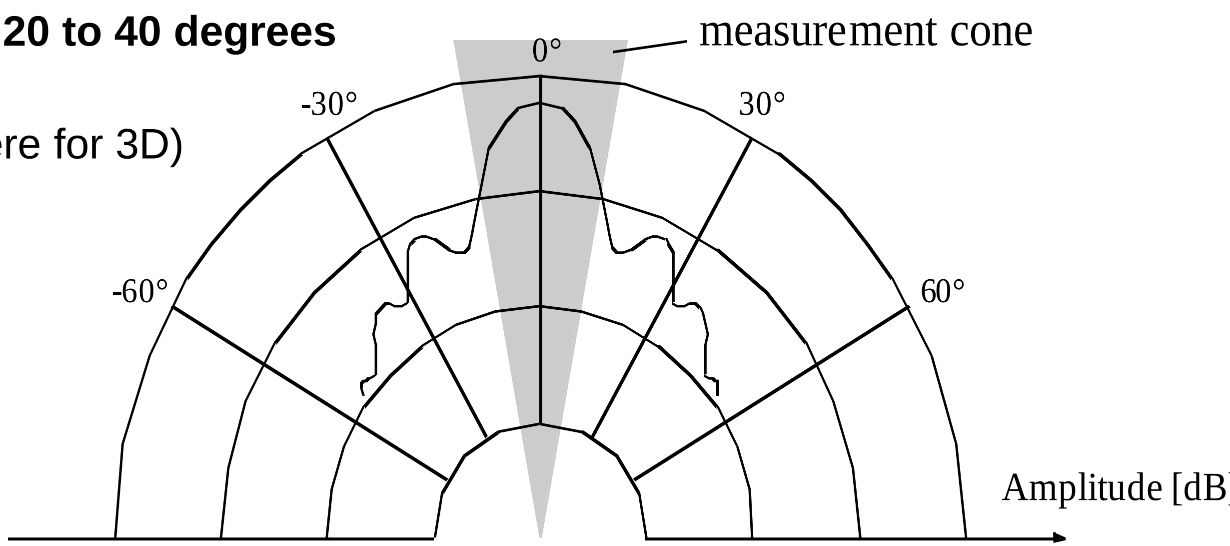
Ultrasonic Sensor (time of flight, sound) (2)

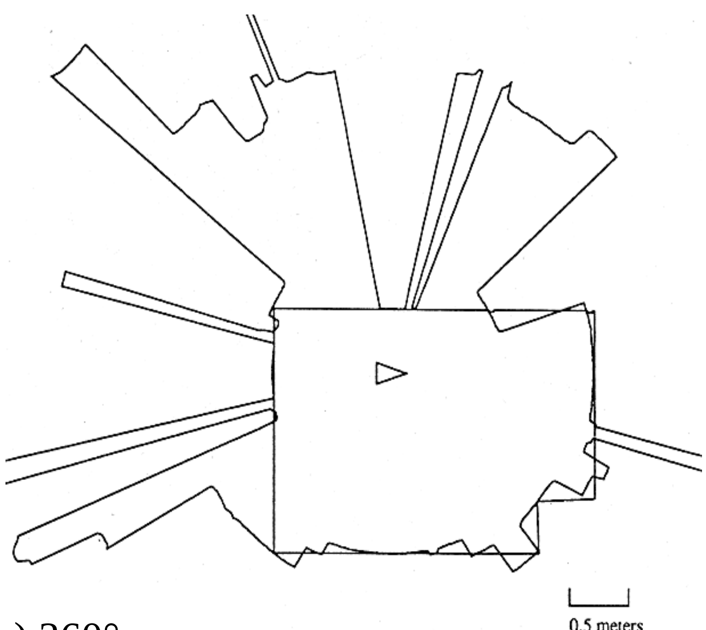
- typical frequency: 40kHz - 180 kHz
  - Lower frequencies correspond to longer maximal sensor range
- generation of sound wave via piezo transducer
  - transmitter and receiver can be separated or not separated
- **Range between 12 cm up to 5 m**
- **Resolution of ~ 2 cm**
- Accuracy 98% → relative error 2%
- sound beam propagates in a cone (*approx*.)
  - **opening angles around 20 to 40 degrees**
  - regions of constant depth
  - segments of an arc (sphere for 3D)



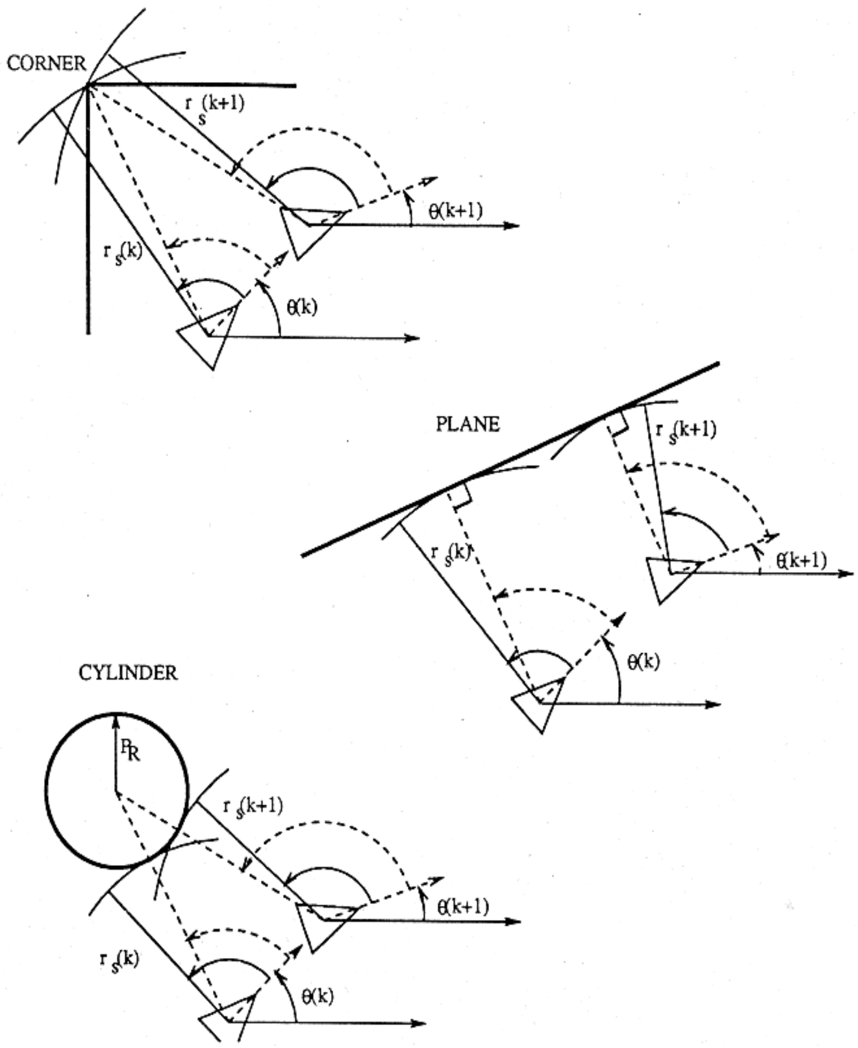
Typical intensity distribution of a ultrasonic sensor

Ultrasonic Sensor (time of flight, sound) (3)

- Other problems for ultrasonic sensors
  - soft surfaces that **absorb** most of the sound energy
  - surfaces that are fare from being perpendicular to the direction of the sound → **specular reflections**



a) 360° scan



b) results from different geometric primitives

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Ultrasonic Sensor (time of flight, sound) (4)

- Bandwidth
  - **measuring the distance to an object that is 3 m away will take such a sensor 20 ms, limiting its operating speed to 50 Hz**. But if the robot has a **ring of 20 ultrasonic sensors**, each firing sequentially and measuring to minimize interference between the sensors, then the ring's cycle time becomes 0.4 seconds => frequency of each one sensor = **2.5 Hz.**
  - This update rate can have a measurable impact on the maximum speed possible while still sensing and avoiding obstacles safely.

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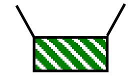
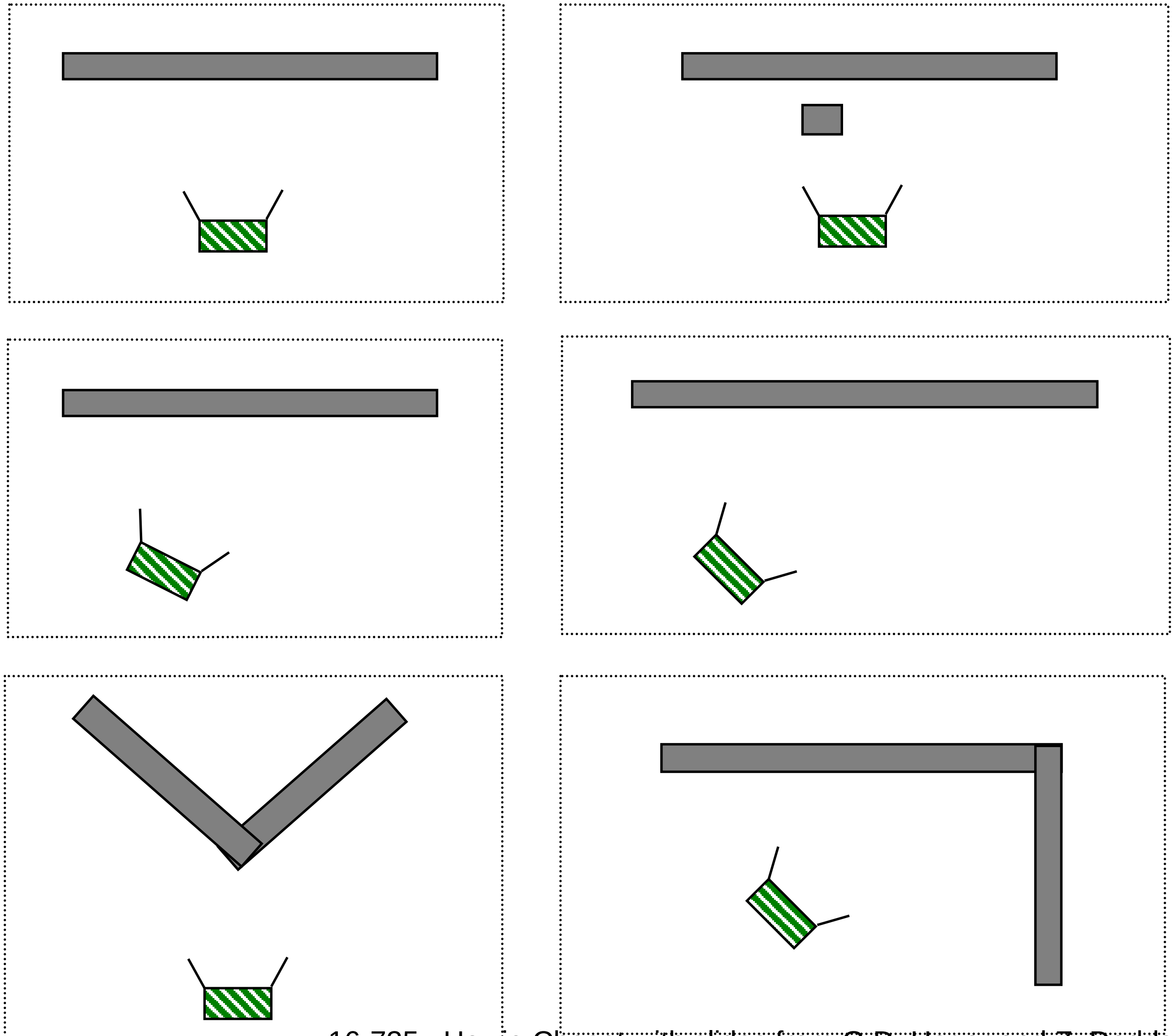
walls (obstacles)

Sonar effects

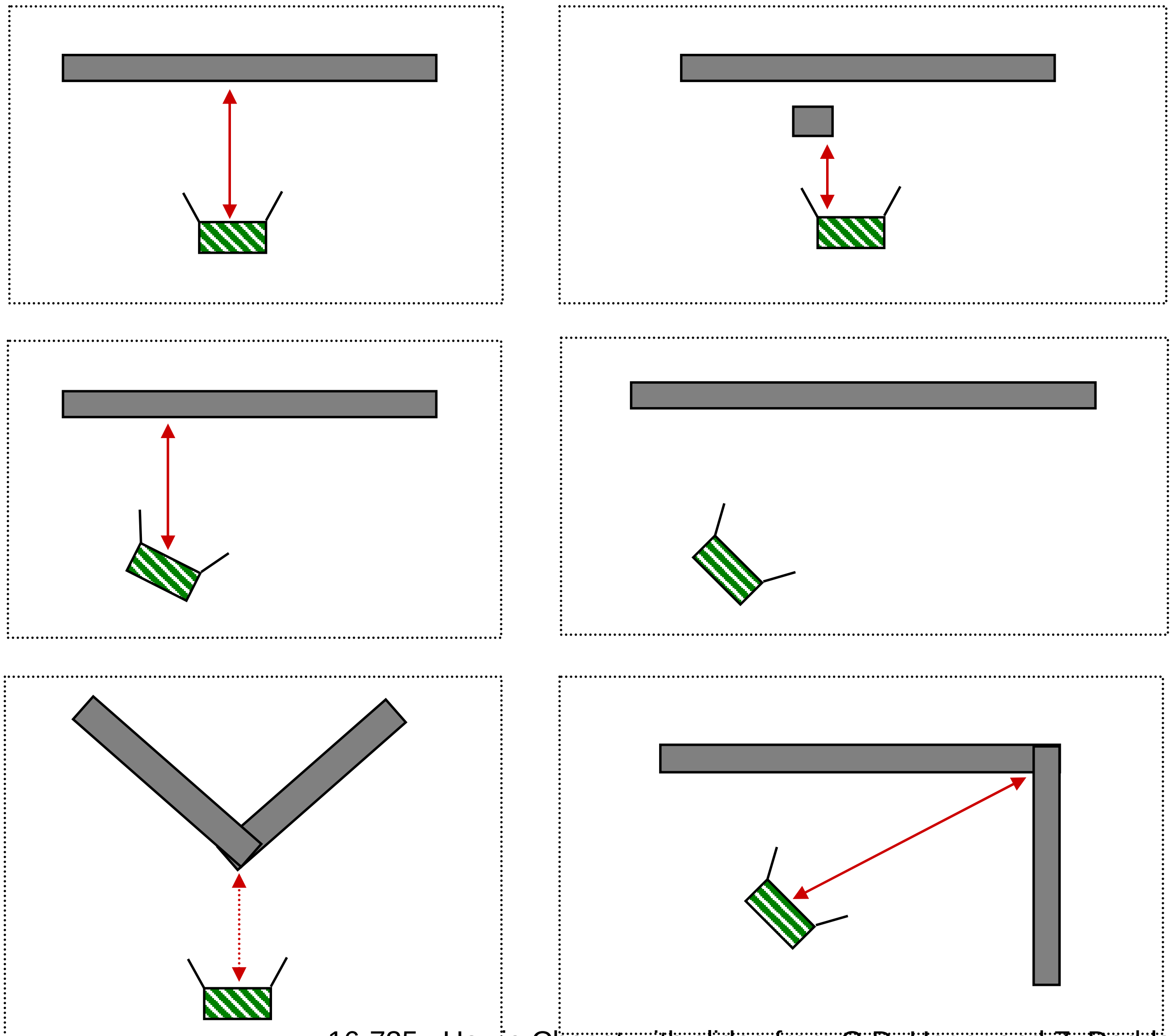


sonar



Draw the range reading that the sonar will return in each case…

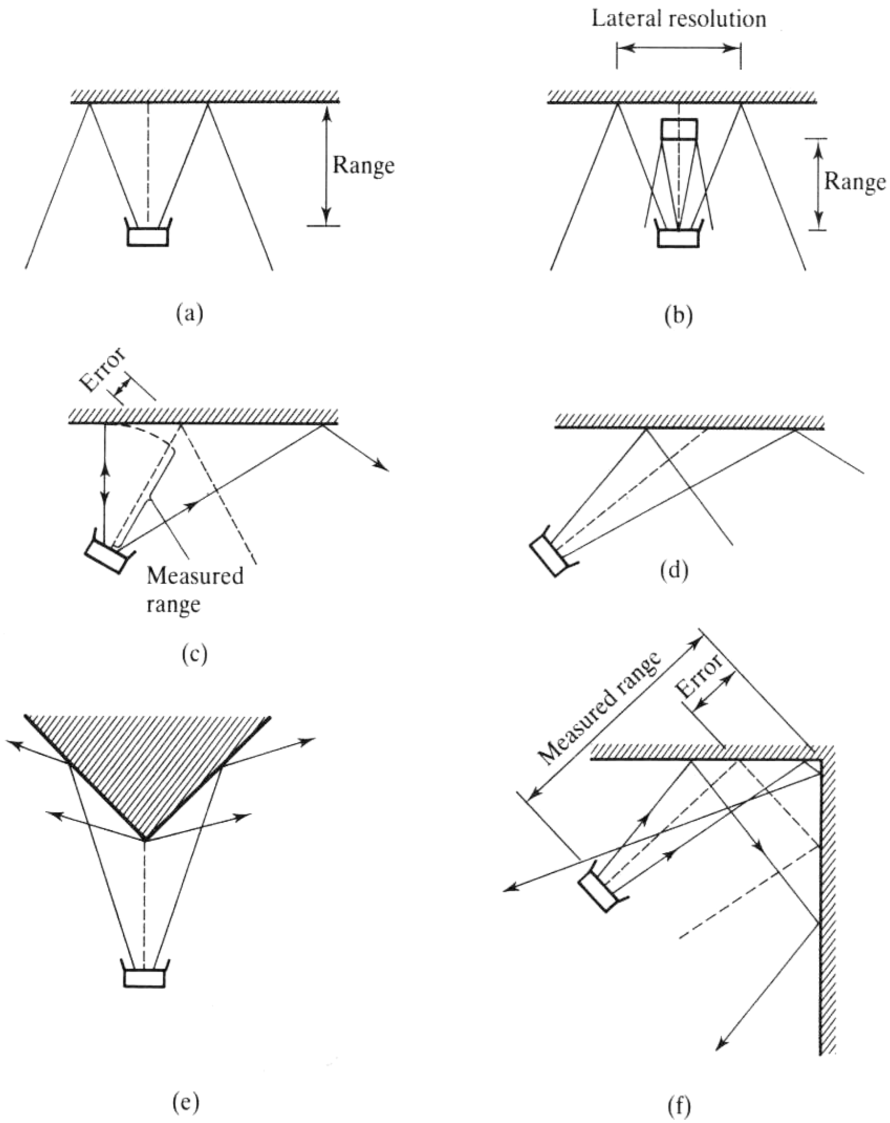
Sonar effects



Draw the range reading that the sonar will return in each case…

holding a sponge…

Sonar effects



(a) Sonar providing an accurate range measurement

(b-c) Lateral resolution is not very precise; the closest object in the beam's cone provides the response

(d) Specular reflections cause walls to disappear

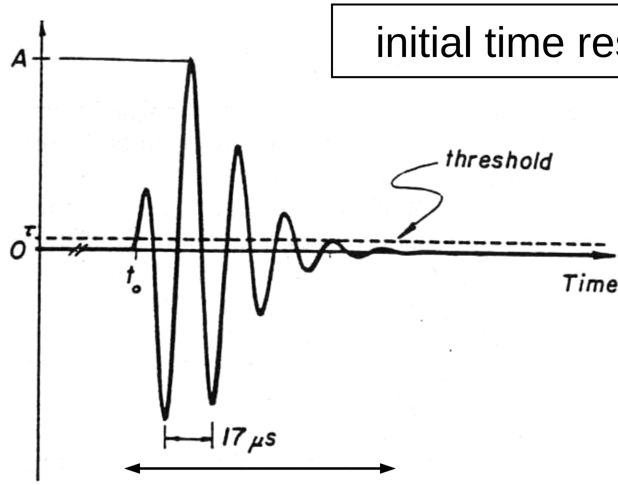
(e) Open corners produce a weak spherical wavefront

(f) Closed corners measure to the corner itself because of multiple reflections --> sonar ray tracing

resolution: time / space

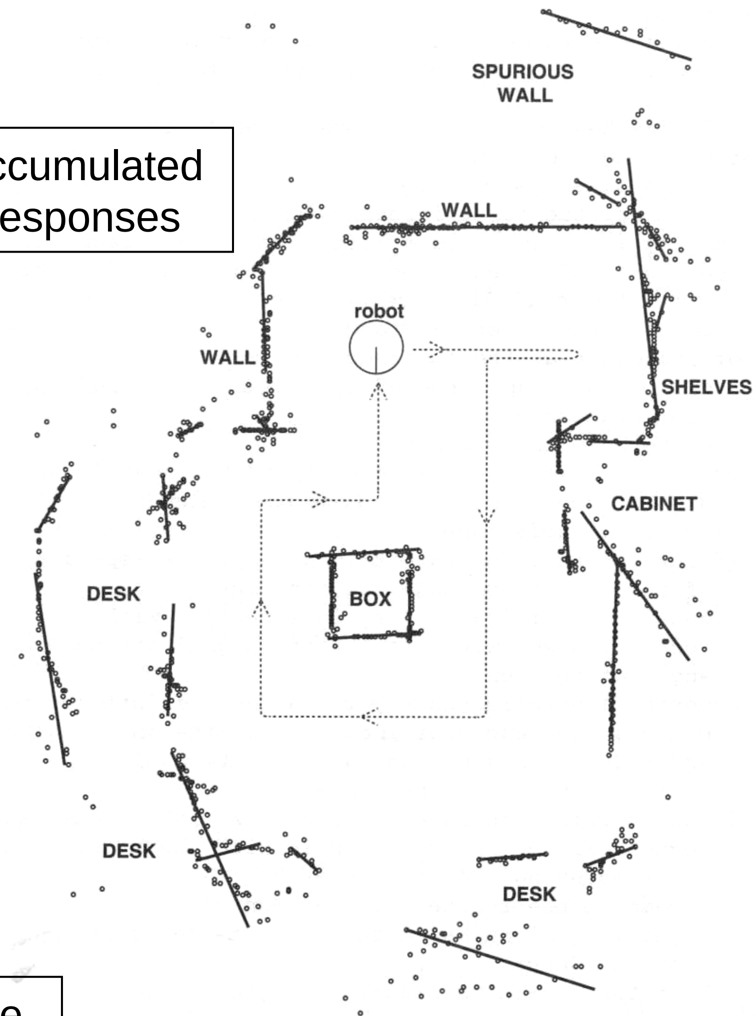
Sonar modeling

initial time response

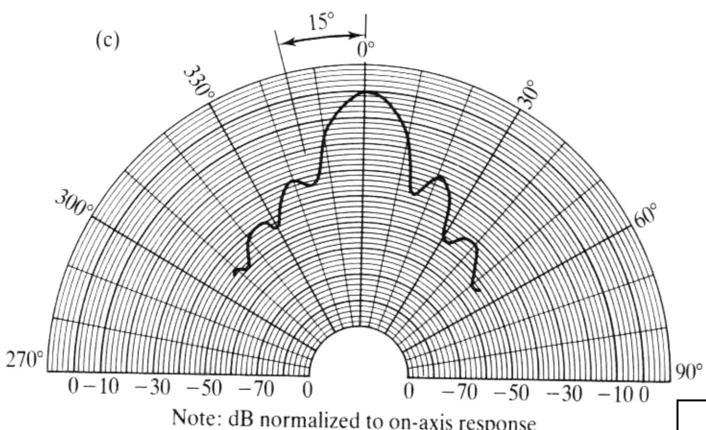


blanking time

accumulated responses



cone width



spatial response

Laser Range Sensor (time of flight, electromagnetic) (1)

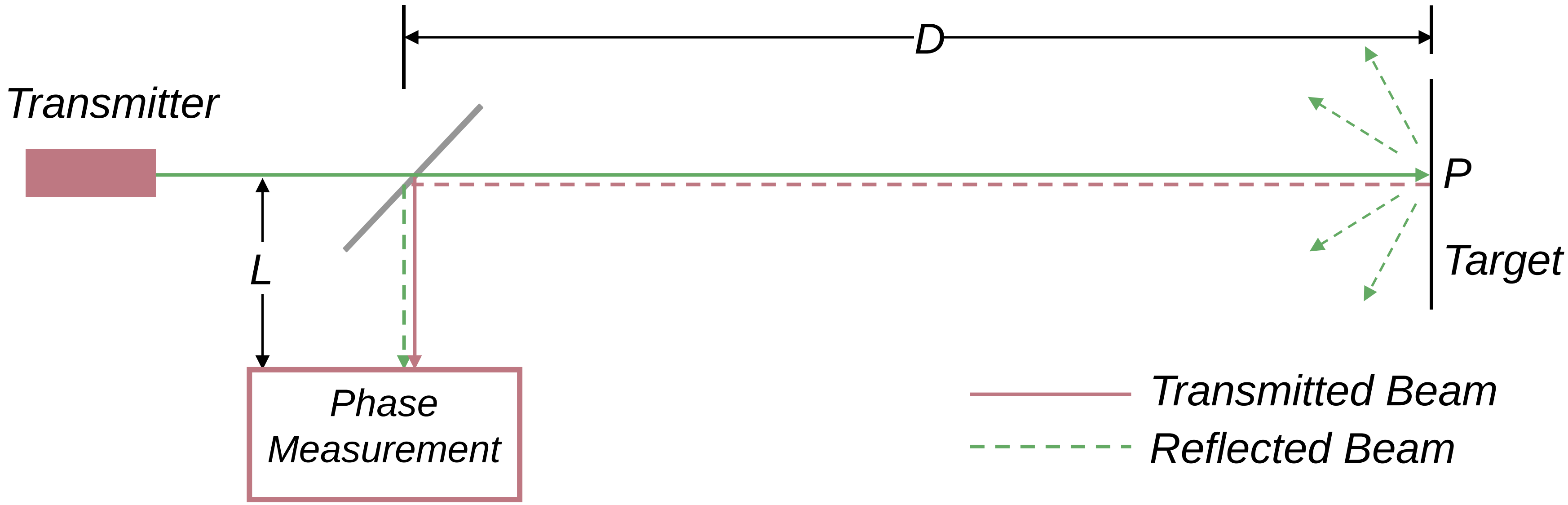
- Laser range finder are also known as Lidar (LIght Detection And Ranging)

SICK

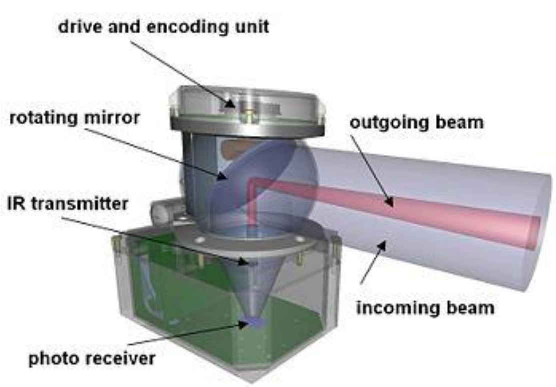
Alaska-IBEO

Hokuyo

Laser Range Sensor (time of flight, electromagnetic) (1)



- Transmitted and received beams coaxial
- Transmitter illuminates a target with a collimated laser beam
- Receiver detects the time needed for round-trip
- A mechanical mechanism with a mirror sweeps
  - 2D or 3D measurement



Laser Range Sensor (time of flight, electromagnetic) (2)

- Operating Principles:
  - Pulsed laser (today the standard)
    - measurement of elapsed time directly
    - resolving picoseconds
  - Phase shift measurement to produce range estimation
    - technically easier than the above method

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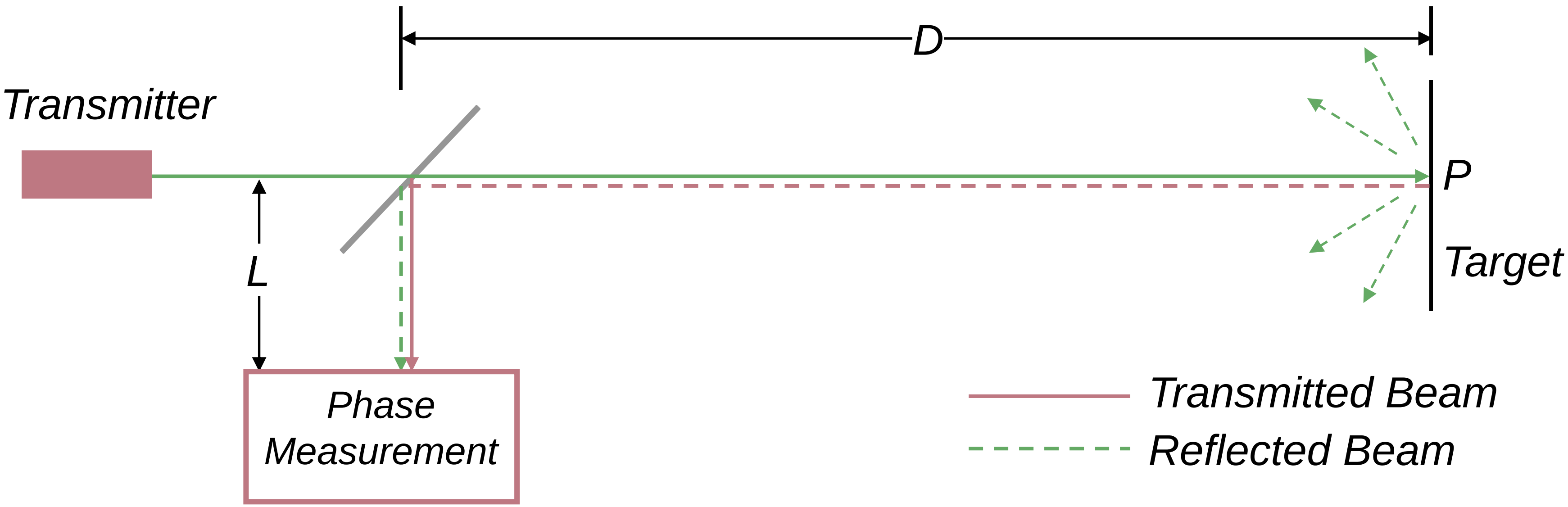
Laser Range Sensor (time of flight, electromagnetic) (3)

- *Phase-Shift Measurement*



$$D' = L + 2D = L + \frac{\theta}{2\pi}\lambda \qquad \lambda = \frac{c}{f}$$

Where:

c: is the speed of light; *f* the modulating frequency; *D'* the distance covered by the emitted light is.

- for f = 5 MHz (as in the A.T&T. sensor), λ = 60 meters

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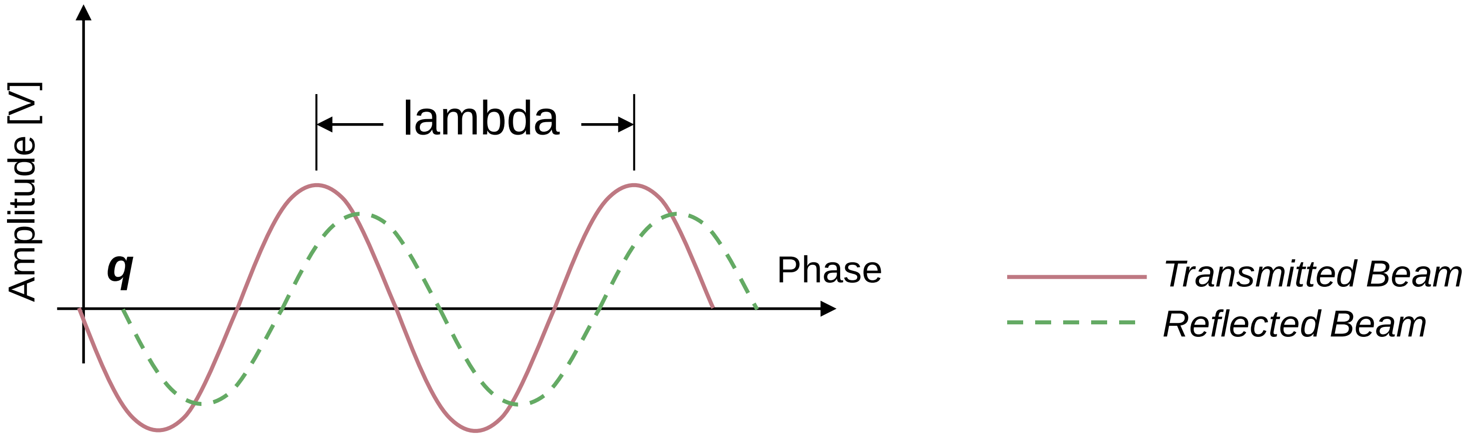
Laser Range Sensor (time of flight, electromagnetic) (4)

- Distance D, between the beam splitter and the target

$$D = \frac{\lambda}{4\pi}\theta$$

- where
  - θ: phase difference between transmitted and reflected beam
- Theoretically ambiguous range estimates
  - since for example if λ = 60 meters, a target at a range of 5 meters = target at 35 meters



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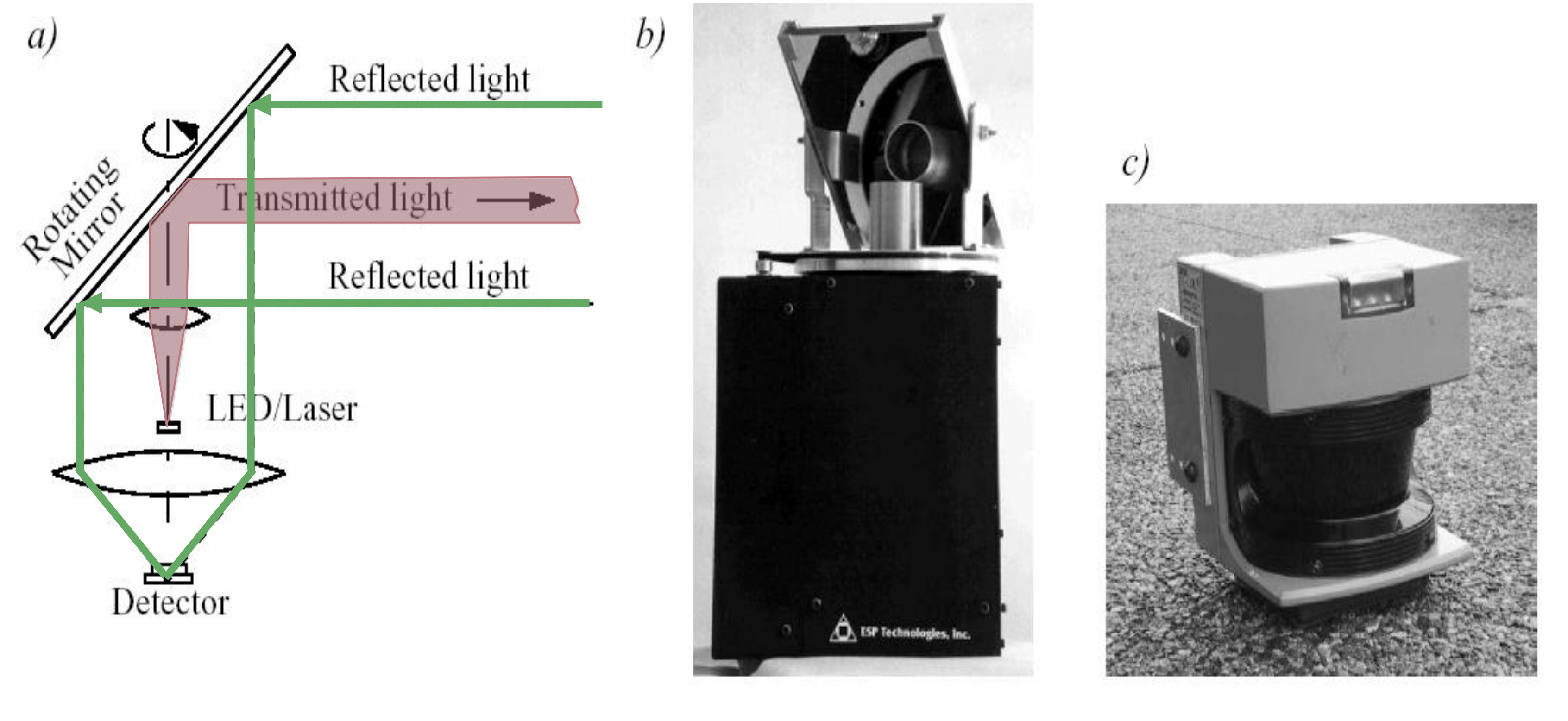
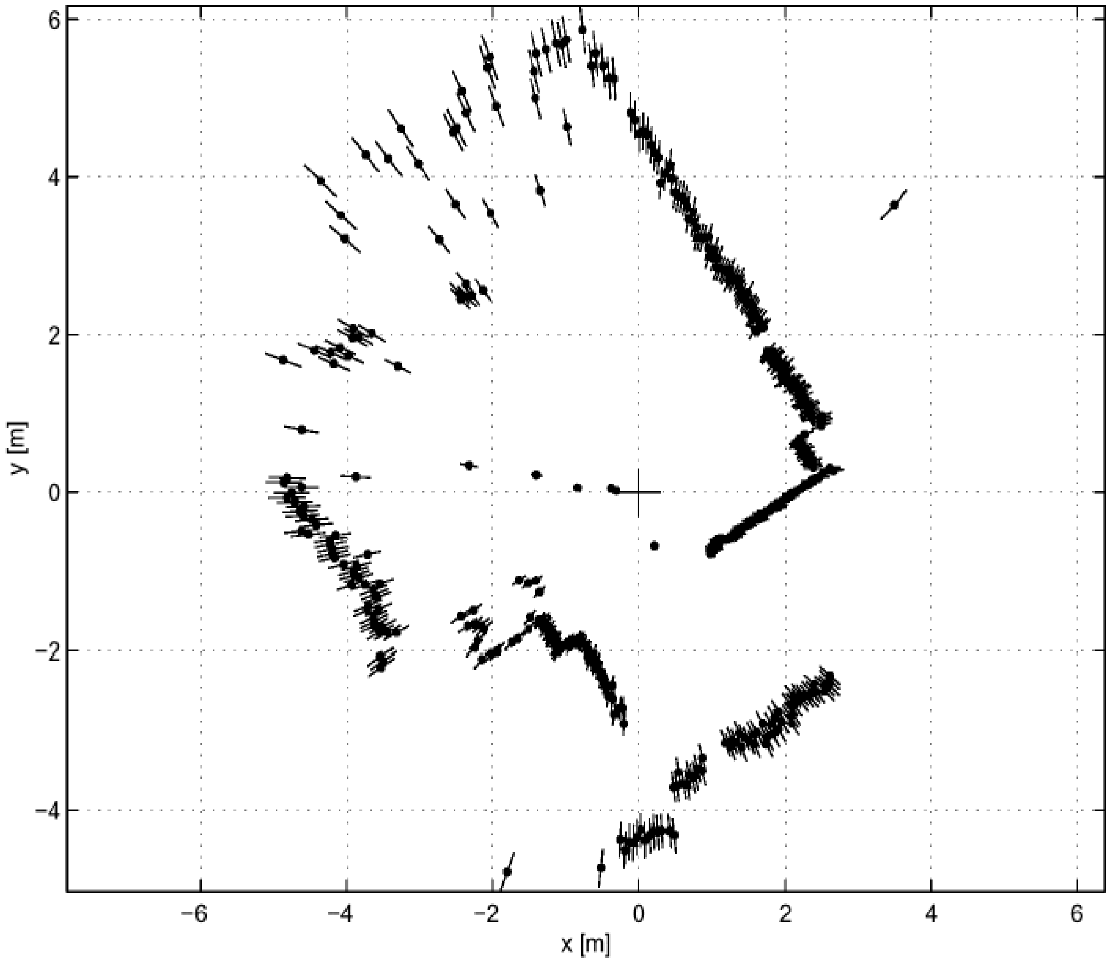
Laser Range Sensor (time of flight, electromagnetic) (5)

- Uncertainty of the range (phase/time estimate) is inversely proportional to the square of the received signal amplitude.
  - Hence dark, distant objects will not produce such good range estimated as closer brighter objects …



Laser Range Sensor (time of flight, electromagnetic)

- Typical range image of a 2D laser range sensor with a rotating mirror. The length of the lines through the measurement points indicate the uncertainties.

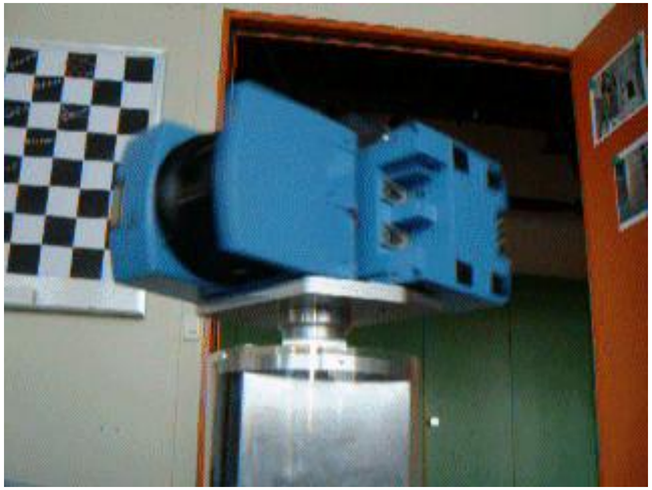


The SICK LMS 200 Laser Scanner

- Angular resolution 0.25 deg
- Depth resolution ranges between 10 and 15 mm and the typical accuracy is 35 mm, over a range from 5 cm up to 20 m or more (up to 80 m), depending on the reflectivity of the object being ranged.
- This device performs seventy five 180-degrees scans per second

3D Laser Range Finder (1)

- **A 3D laser range finder is a laser scanner that acquires scan data in more than a single plane.**
- Custom-made 3D scanners are typically built by nodding or rotating a 2D scanner in a stepwise or continuous manner around an axis parallel to the scanning plane.
- By lowering the rotational speed of the turn-table, the angular resolution in the horizontal direction can be made as small as desired.
- A full spherical field of view can be covered (360° in azimuth and +/-90° in elevation).
- **However, acquisition takes up to some seconds!**
  For instance, if our laser takes 75 plane-scans/sec and we need an azimuthal angular resolution of 0.25 degrees, the period for a half rotation of the turn-table necessary to capture a spherical 3D scan with two Sicks is then 360 / 0.25 / 75 / 2 = 9.6 seconds. If one is satisfied with an azimuthal angular resolution of 1 degree, then the acquisition time drops down to 2.4 seconds, which is still too high for 3D mapping during motion!



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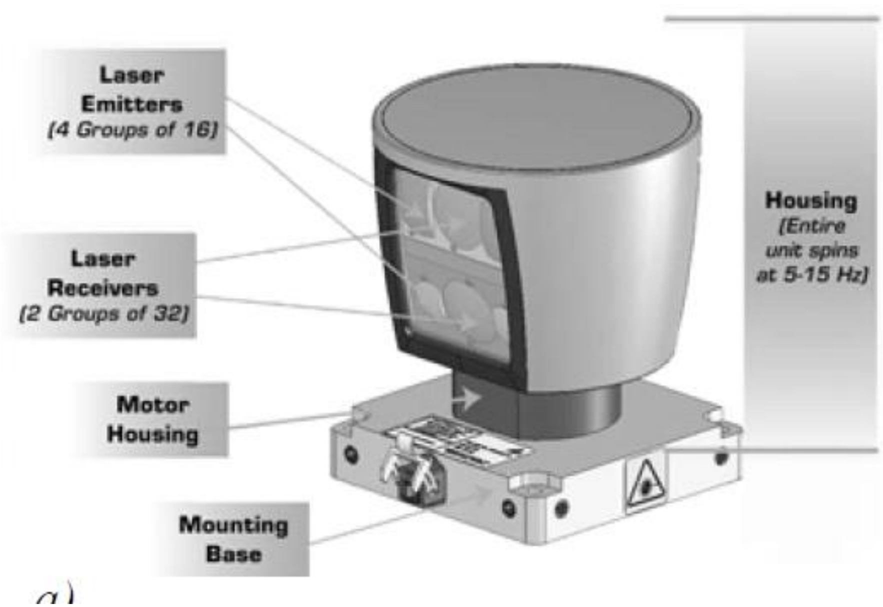
3D Laser Range Finder (3)

- The **Alasca XT laser scanner** splits the laser beam into **four vertical layers** with an aperture angle of 3.2°.
- This sensor is typically used for obstacle and pedestrian detection on cars. Because of its multi-layer scanning principle, it allows us any pitching of the vehicle

C Carnegie Mellon University

3D Laser Range Finder (2)

- The Velodyne HDL-64E uses 64 laser emitters.
  - Turn-rate up to 15 Hz
  - The field of view is 360° in azimuth and 26.8° in elevation
  - Angular resolution is 0.09° and 0.4° respectively
  - **Delivers over 1.3 million data points per second**
  - The distance accuracy is better than 2 cm and can measure depth up to 50 m
  - This sensor was the primary means of terrain map construction and obstacle detection for all the top DARPA 2007 Urban Challenge teams. However, the Velodyne iscurrently still much more expensive than Sick laser range finders (SICK ~ 5000 Euros, Velodyne ~50,000 Euros!)



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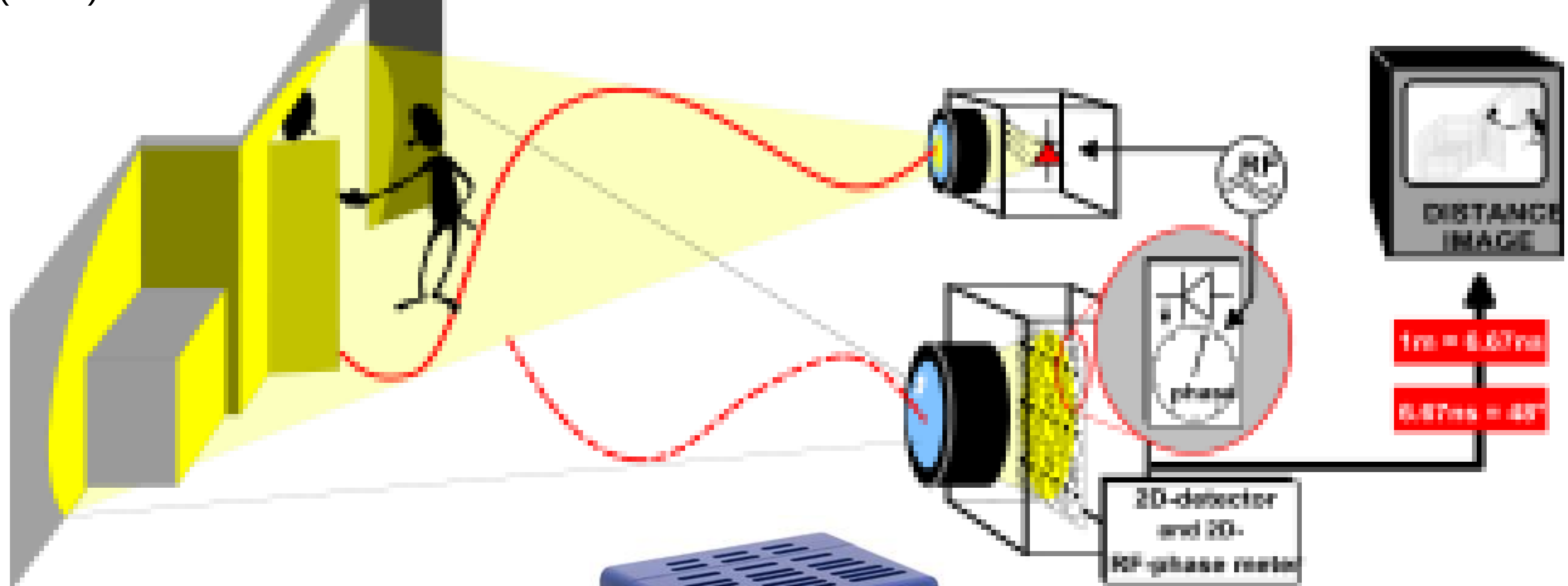
3D Range Sensor (4): Time Of Flight (TOF) camera

- A Time-of-Flight camera (TOF camera, figure) works similarly to a lidar with the advantage that **the whole 3D scene is captured at the same time and that there are no moving parts.** This device uses a modulated infrared lighting source to determine the distance for each pixel of a Photonic Mixer Device (PMD) sensor.



Swiss Ranger 3000
(produced by MESA)

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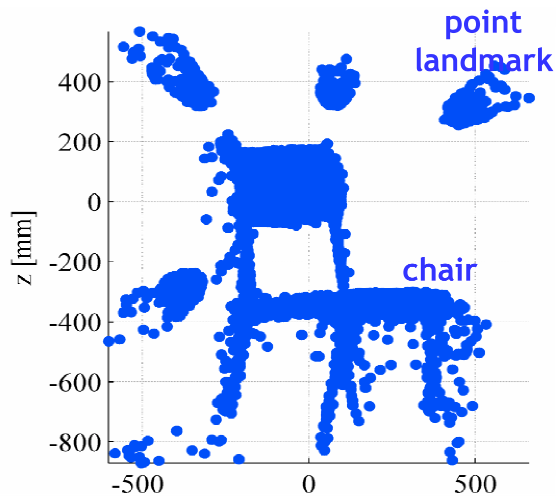
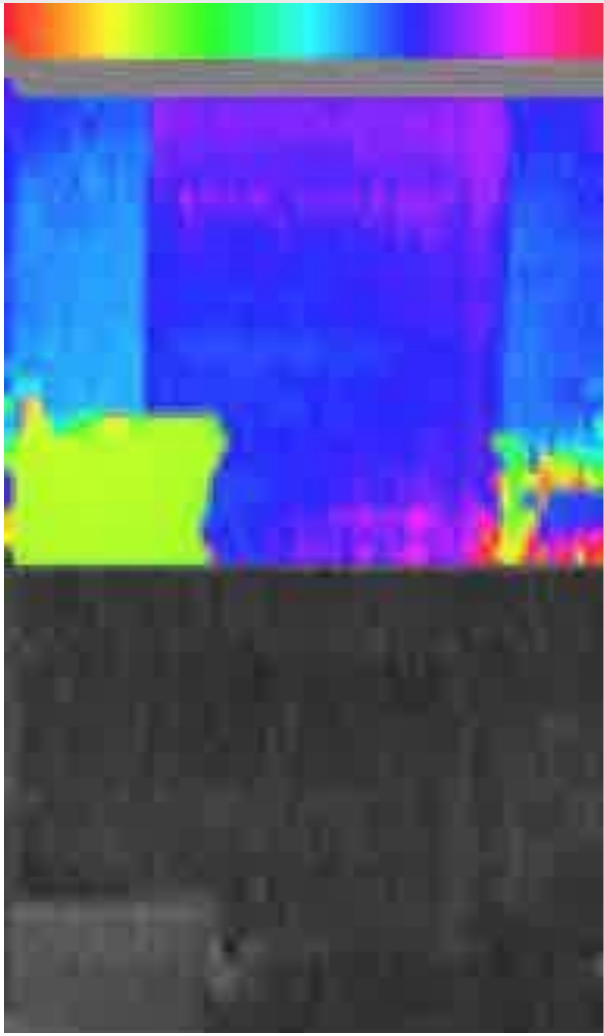
Incremental Object Part Detection

- Range Camera
  - 3D information with high data rate (100 Hz)
  - Compact and easy to manage
  - High, non-uniform measurement noise
  - High outlier rate at jump edges
  - However very low resolution (174x144 pixels)



3D Point Cloud

Range Camera SR-3000



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Triangulation Ranging

- Use of **geometrical properties** of the image to establish a **distance measurement**
- If a well defined light pattern (e.g. point, line) is projected onto the environment.
  - reflected light is then captured by a photo-sensitive line or matrix (camera) sensor device
  - simple triangulation allows to establish a distance.
- If size of a captured object is precisely known
  - triangulation without light projecting

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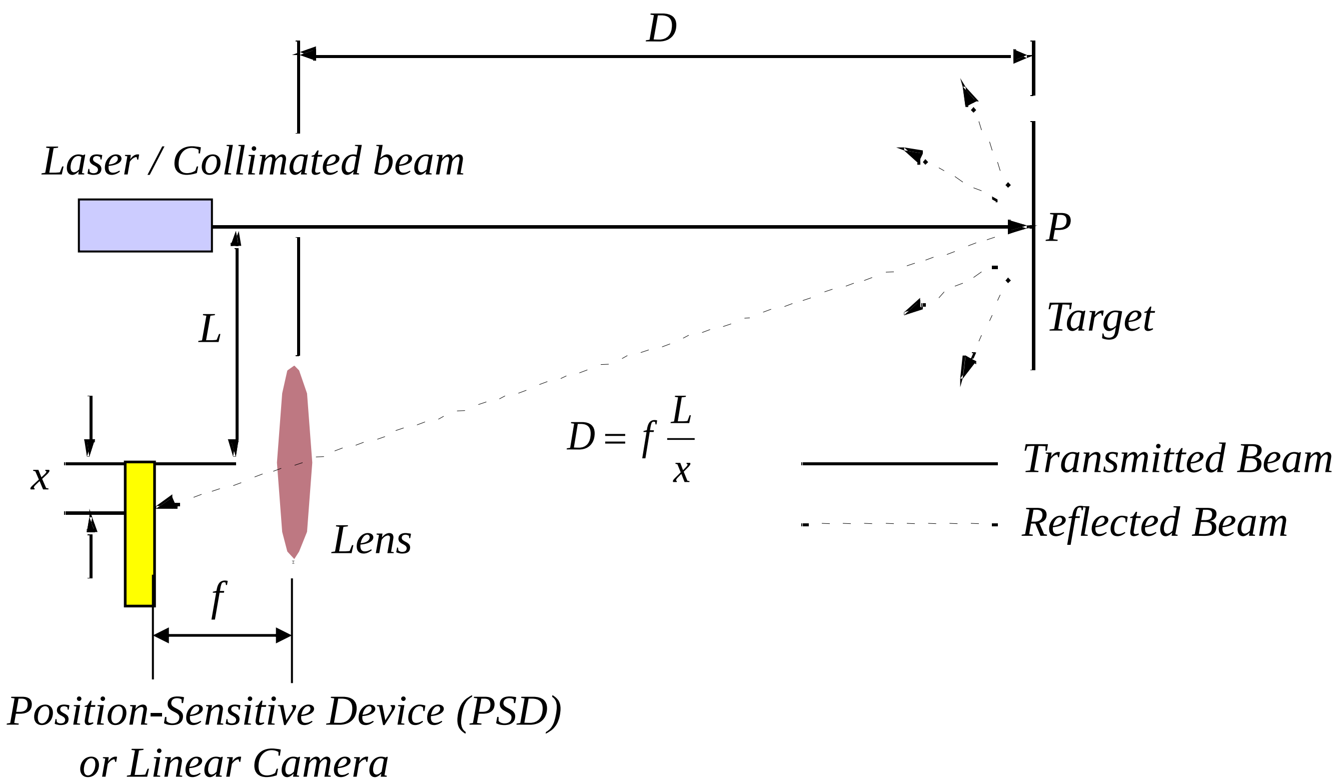
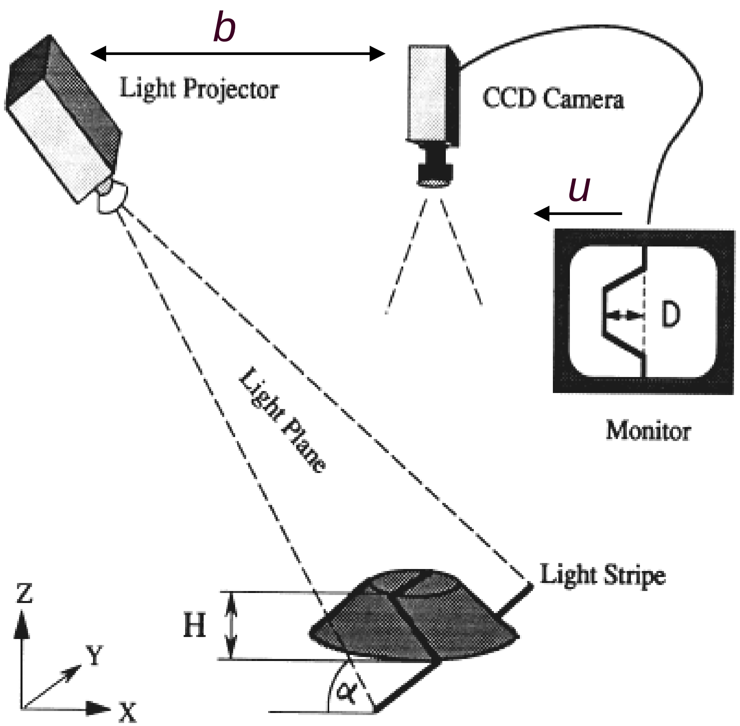
Laser Triangulation (1D)



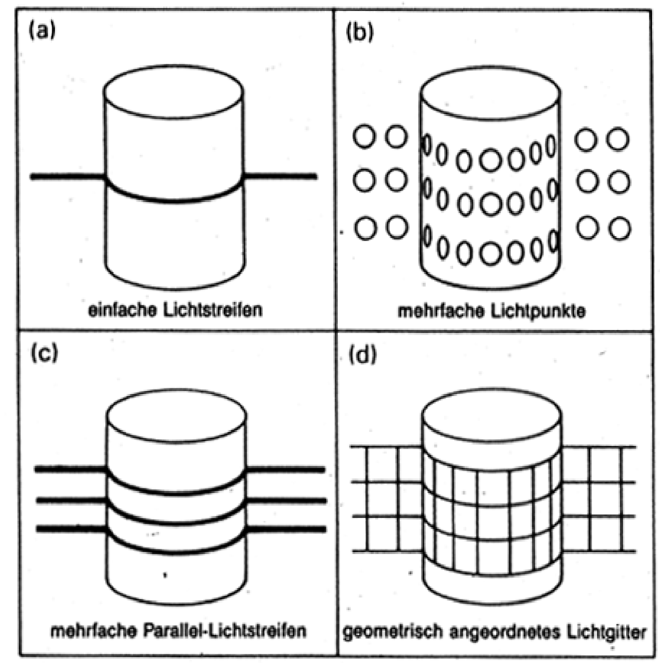
- Principle of 1D laser triangulation: $D = f \dfrac{L}{x}$

Structured Light (vision, 2D or 3D): Structured Light

a



b



- Eliminate the correspondence problem by projecting structured light on the scene.
- Slits of light or emit collimated light (possibly laser) by means of a rotating mirror.
- Light perceived by camera
- Range to an illuminated point can then be determined from simple geometry.

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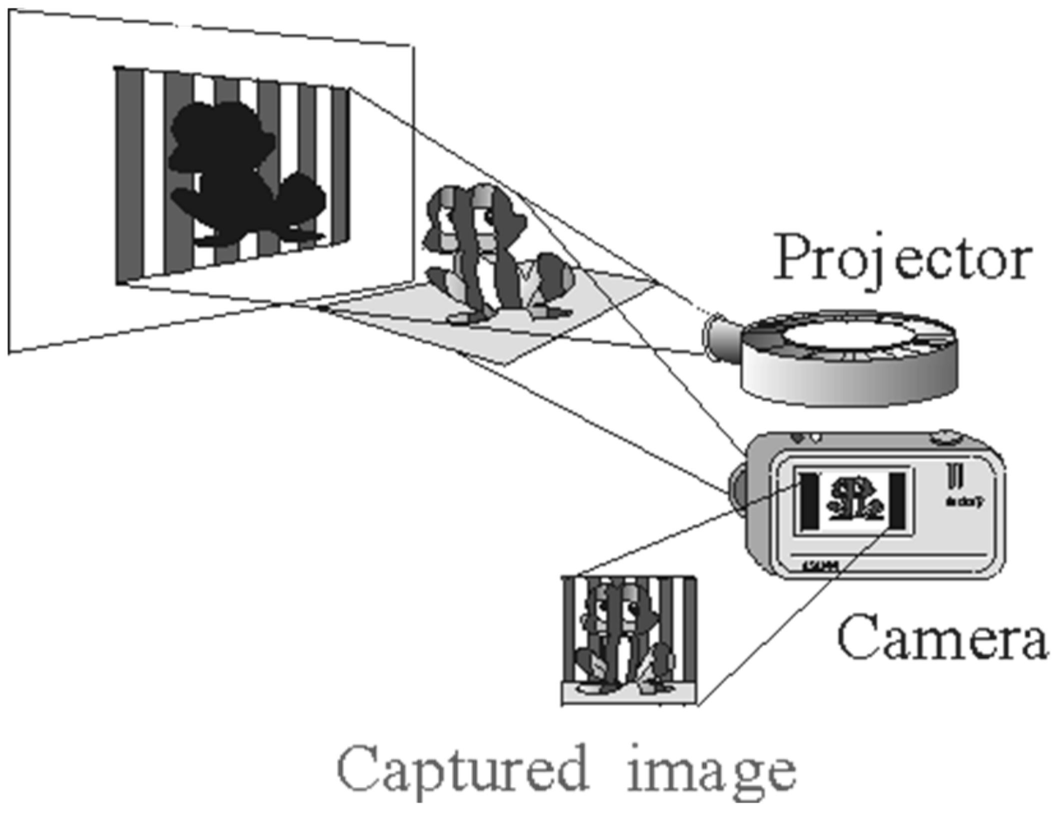
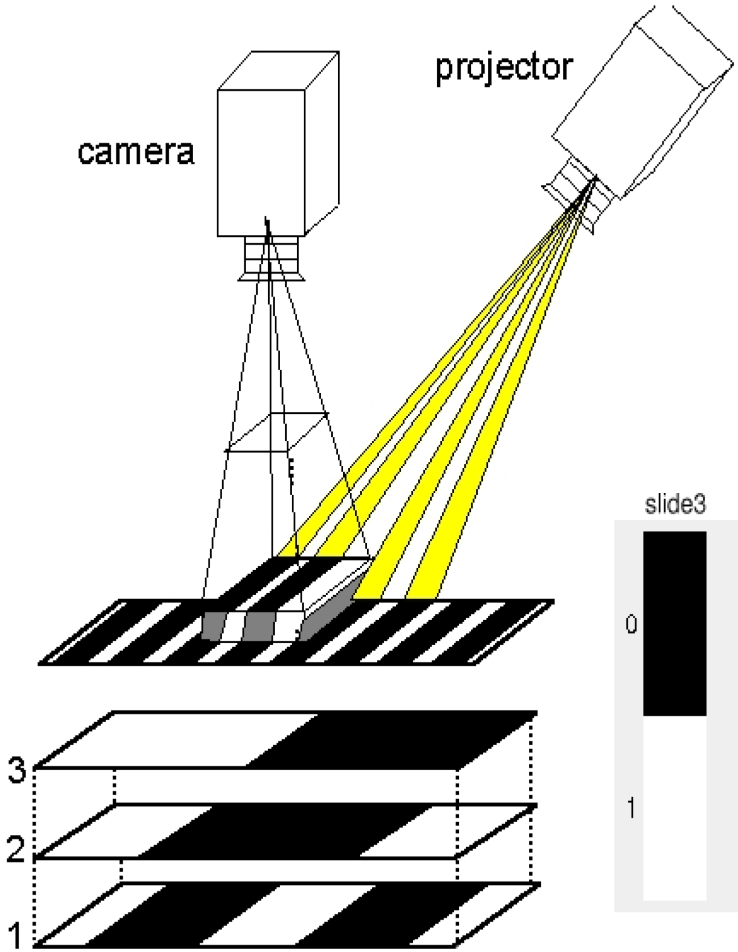
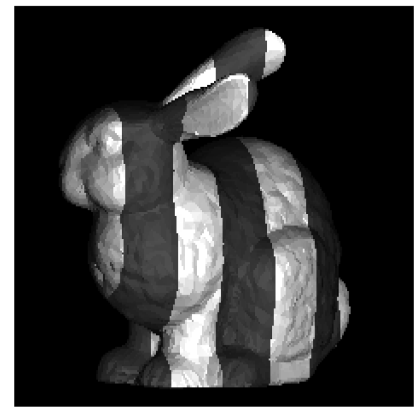
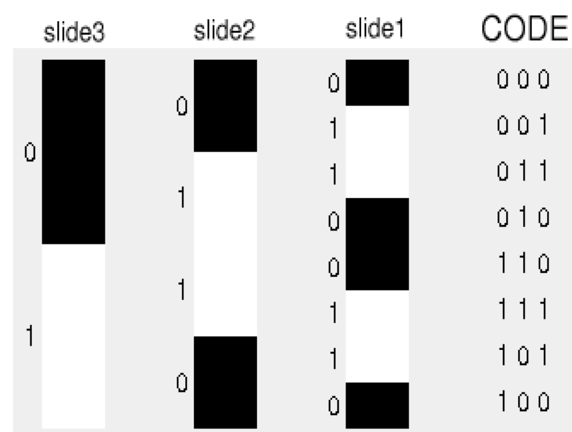
Coding structured light



Gray Code


projector
camera
3
2
1




slide3
slide2
slide1
CODE
0
1
0
1
1
0
0
1
1
0
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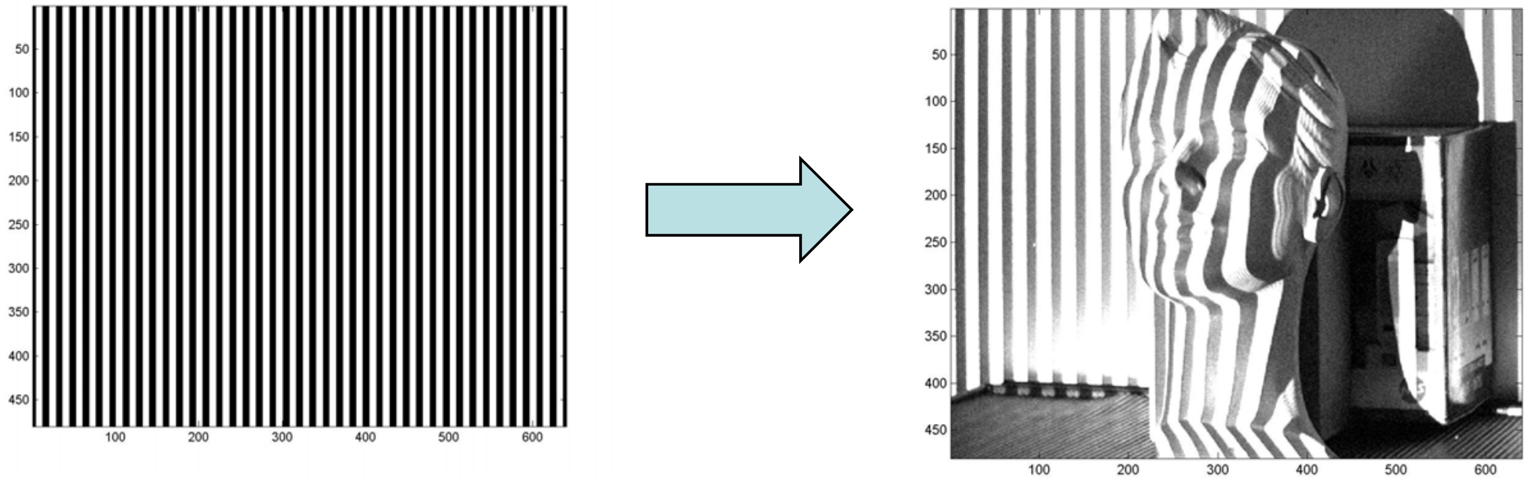
1
1
0
0 0 0
0 0 1
0 1 1
0 1 0
1 1 0
1 1 1
1 0 1
1 0 0

…in practice:



50
100
150
200
250
300
350
400
450
100
200
300
400
500
600
50
100
150
200
250
300
350
400
450
100
200
300
400
500
600

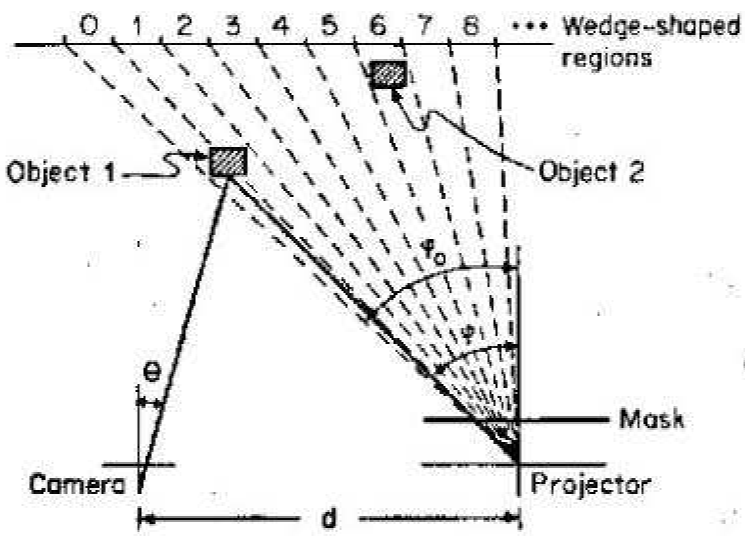
Structured Light – Light Striping

= illuminated   = dark – not seen

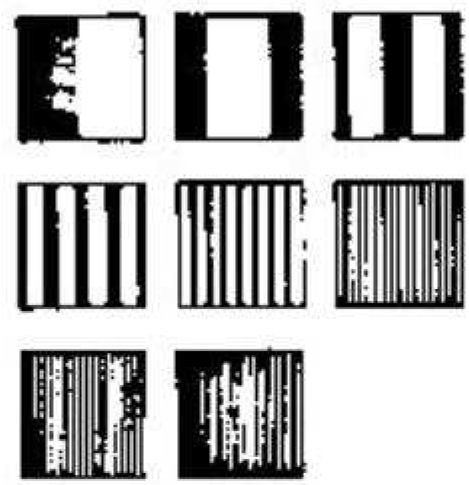
Mask1								
Mask2								
Mask3								
Vis. 1	1	1	1	1	0	0	0	0
Vis. 2	1	1	0	0	1	1	0	0
Vis. 3	1	0	1	0	1	0	1	0
Region	A	B		C	D			
Bit Code	111	110	101	100	011	010	001	000

Use coded masks of light/dark to determine regions of space

Structured Light Using Coded Light Striping



Geometry of Camera and Projector



Gray Code Projection Masks