



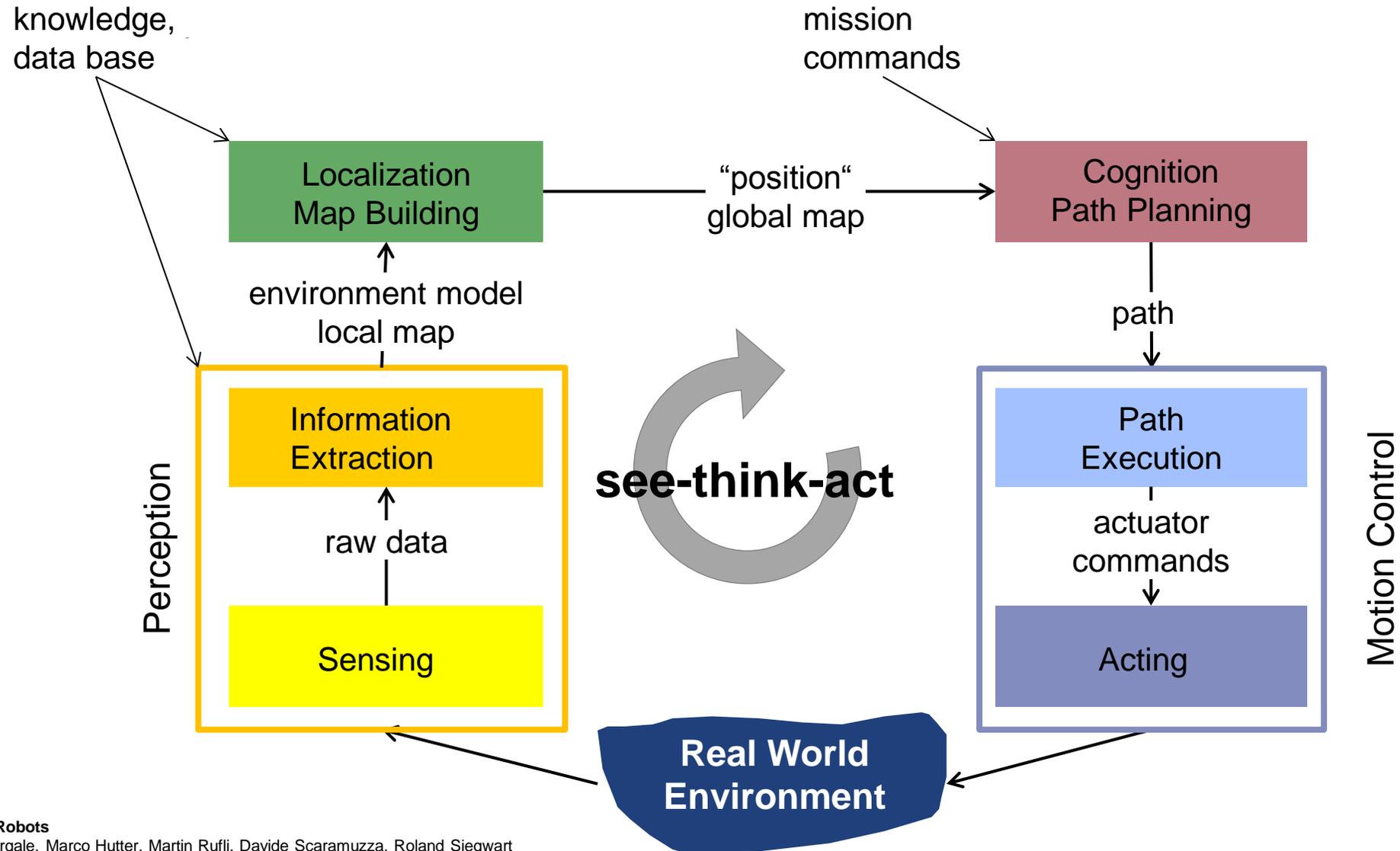
Perception: Sensors

Autonomous Mobile Robots

Davide Scaramuzza

Margarita Chli, Paul Furgale, Marco Hutter, Roland Siegwart

Mobile Robot Control Scheme

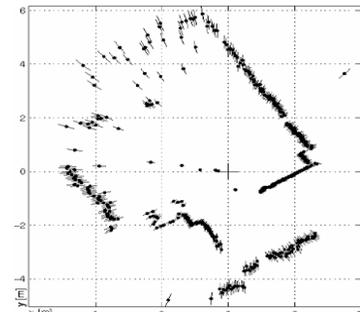
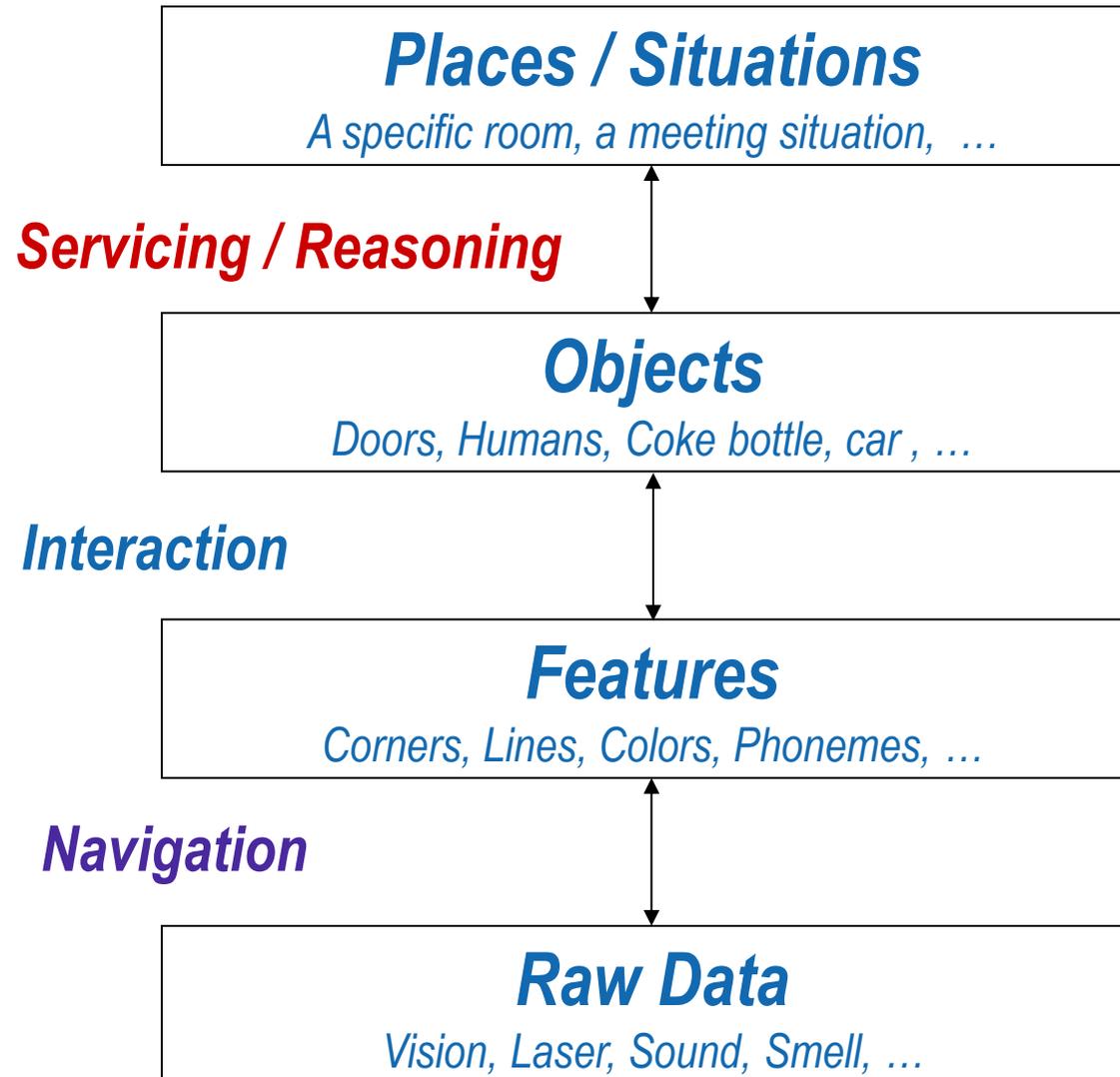


Perception is hard!

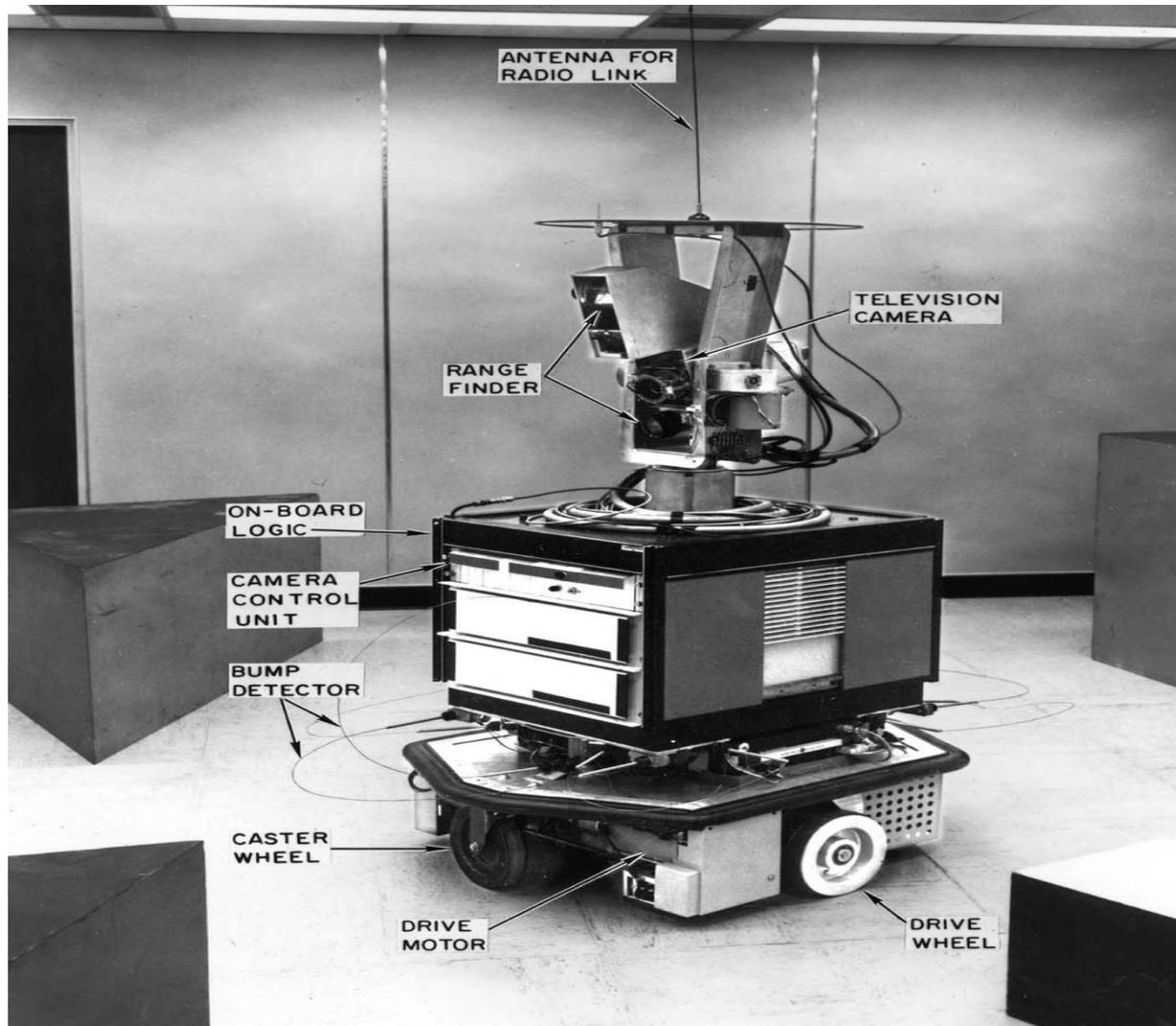
- **Understanding = raw data + (probabilistic) models + context**
- Intelligent systems interpret **raw data** according to **probabilistic models** and using **contextual information** that gives meaning to the data.



Perception for Mobile Robots



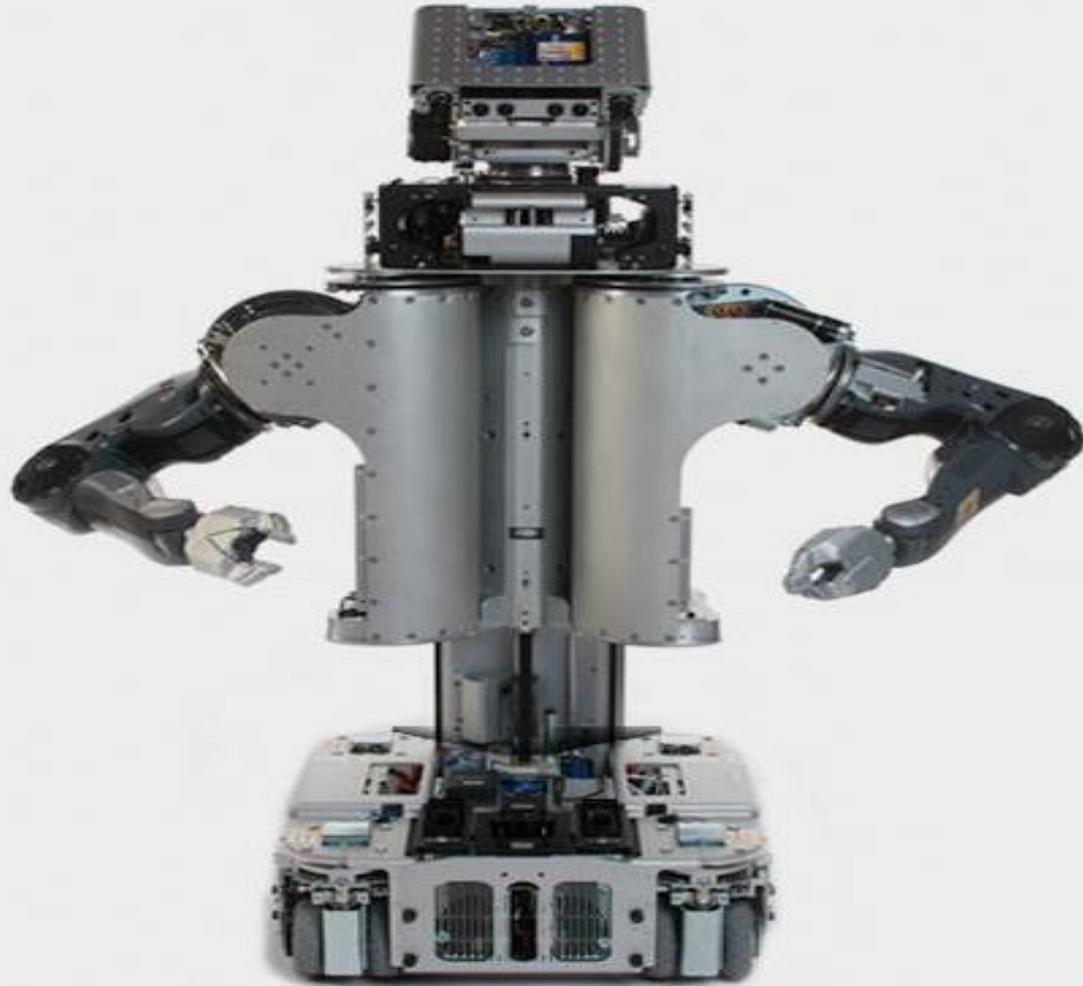
Shakey the Robot (1966-1972), SRI International



C SRI International

- Operating environment
 - Indoors
 - Engineered
- Sensors
 - Wheel encoders
 - Bump detector
 - Sonar range finder
 - Camera

PR2 (2010-),



C Willow Garage

- Operating environment
 - Indoors and outdoors
 - Onroad only
- Sensors
 - Wheel encoders
 - Bumper
 - IR sensors
 - Laser range finder
 - 3D nodding laser range finder
 - Inertial measurement unit
 - Pan-tilt stereo camera with texture projector (active)
 - Pressure sensor and accelerometer inside hands
 - ...

The SmartTer Platform (2004-2007)



- ▶ Three navigation SICK laser scanners
 - Obstacle avoidance and local navigation
- ▶ Two rotating laser scanners (3D SICK)
 - 3D mapping of the environment
 - Scene interpretation
- ▶ Omnidirectional camera
 - Texture information for the 3D terrain maps
 - Scene interpretation
- ▶ Monocular camera
 - Scene interpretation



Motion Estimation / Localization

- Differential GPS system (*Omnistar 8300HP*)
- Inertial measurement unit (*Crossbow NAV420*)
- **Optical Gyro**
- Odometry (wheel speed, steering angle)
 - Motion estimation
 - Localization

Internal car state sensors

- Vehicle state flags (engine, door, etc.)
- Engine data, gas pedal value

Camera for life video streaming

- Transmission range up to 2 km

Classification of Sensors

- What:
 - Proprioceptive sensors
 - measure values internally to the system (robot),
 - e.g. motor speed, wheel load, heading of the robot, battery status
 - Exteroceptive sensors
 - information from the robots environment
 - distances to objects, intensity of the ambient light, unique features.
- How:
 - Passive sensors
 - Measure energy coming from the environment; very much influenced by the environment
 - Active sensors
 - emit their proper energy and measure the reaction
 - better performance, but some influence on environment

General Classification (1)

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Tactile sensors (detection of physical contact or closeness; security switches)	Contact switches, bumpers	EC	P
	Optical barriers	EC	A
	Noncontact proximity sensors	EC	A
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders	PC	P
	Potentiometers	PC	P
	Synchros, resolvers	PC	A
	Optical encoders	PC	A
	Magnetic encoders	PC	A
	Inductive encoders	PC	A
	Capacitive encoders	PC	A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass	EC	P
	Gyroscopes	PC	P
	Inclinometers	EC	A/P

A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

General Classification (2)

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Ground-based beacons (localization in a fixed reference frame)	GPS	EC	A
	Active optical or RF beacons	EC	A
	Active ultrasonic beacons	EC	A
	Reflective beacons	EC	A
Active ranging (reflectivity, time-of-flight, and geo- metric triangulation)	Reflectivity sensors	EC	A
	Ultrasonic sensor	EC	A
	Laser rangefinder	EC	A
	Optical triangulation (1D)	EC	A
	Structured light (2D)	EC	A
Motion/speed sensors (speed relative to fixed or moving objects)	Doppler radar	EC	A
	Doppler sound	EC	A
Vision-based sensors (visual ranging, whole-image analy- sis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

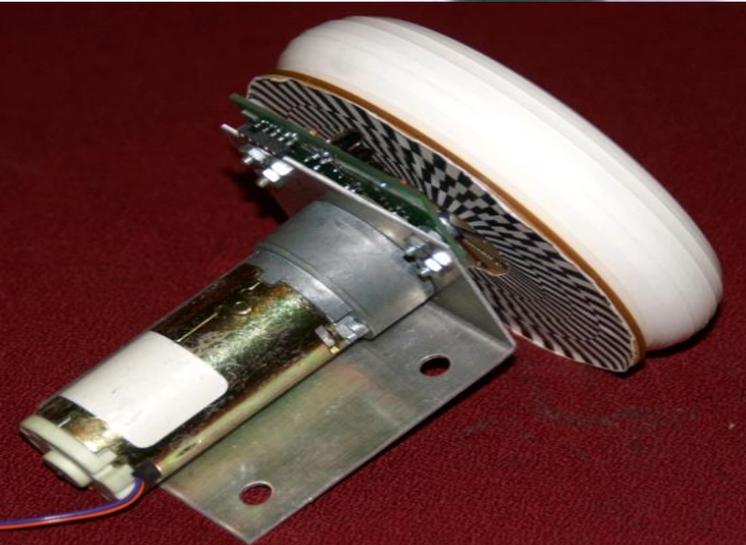
Sensors: outline

- Optical encoders
- Heading sensors
 - Compass
 - Gyroscopes
- Accelerometer
- IMU
- GPS
- Range sensors
 - Sonar
 - Laser
 - Structured light
- Vision (next lectures)

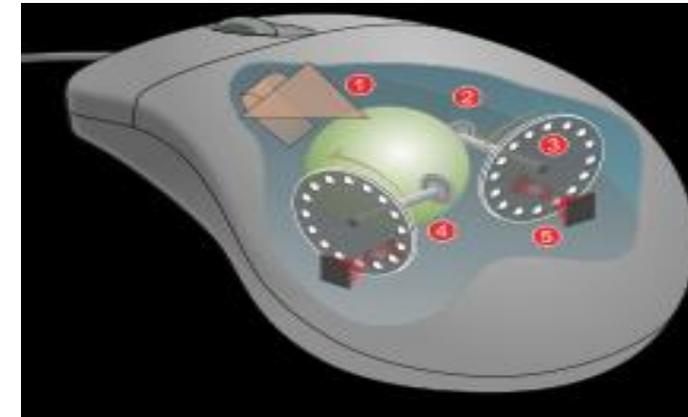


Encoders

- Definition:
 - **electro-mechanical device** that converts linear or angular position of a shaft to an analog or digital signal, making it an linear/angular transducer



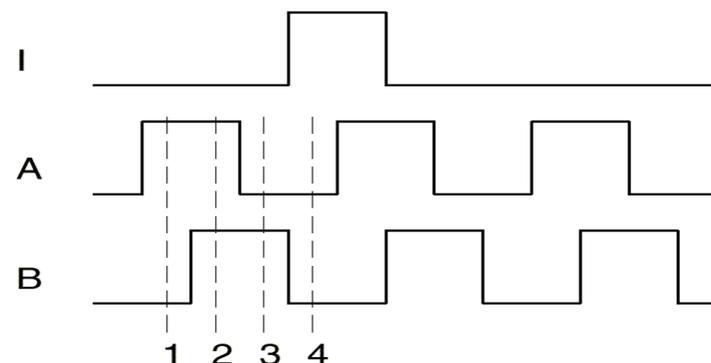
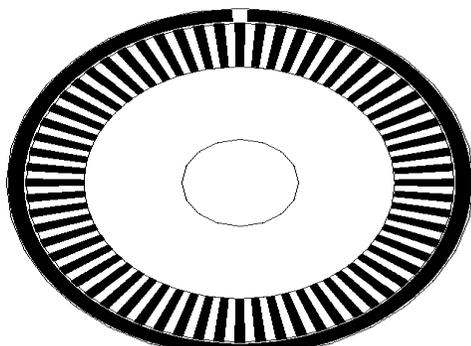
muzza, Rolar



Wheel / Motor Encoders

- Use cases
 - **measure position** or speed of the wheels or steering
 - **integrate wheel movements** to get an estimate of the position -> odometry
 - optical encoders are proprioceptive sensors
 - typical resolutions: 64 - 2048 increments per revolution.
 - for high resolution: interpolation

- Working principle of optical encoders
 - regular: counts the number of transitions but cannot tell the direction of motion
 - quadrature: uses two sensors in quadrature-phase shift. The ordering of which wave produces a rising edge first tells the direction of motion. Additionally, resolution is 4 times bigger
 - a single slot in the outer track generates a reference pulse per revolution

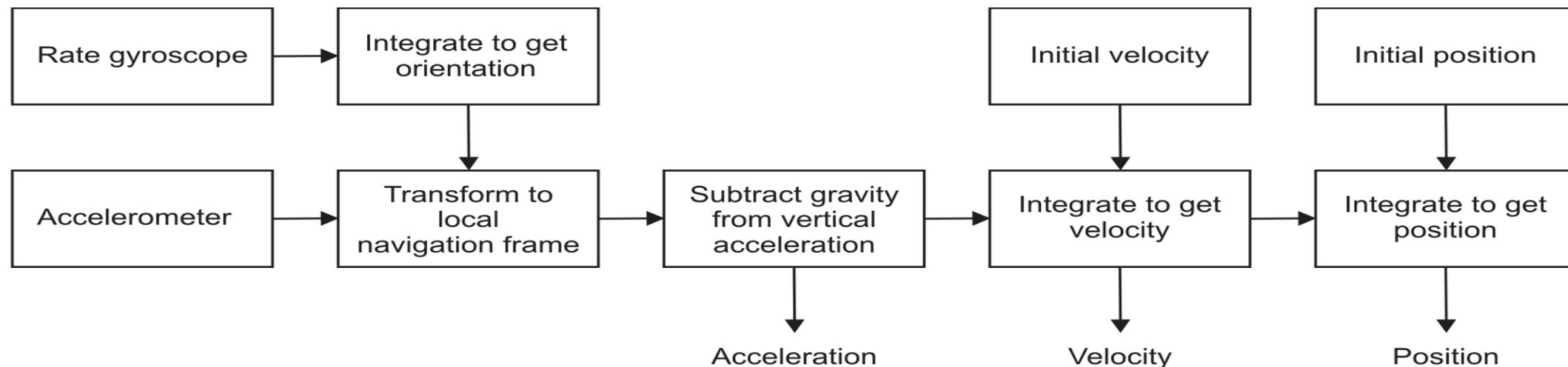


State	Ch A	Ch B
S ₁	High	Low
S ₂	High	High
S ₃	Low	High
S ₄	Low	Low

Inertial Measurement Unit (IMU)

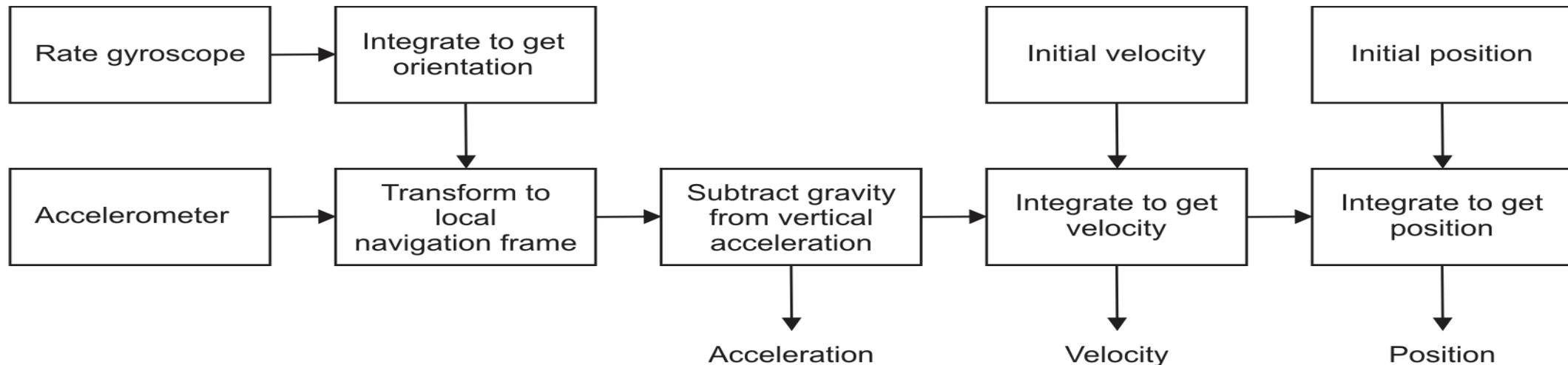
Definition

- An inertial measurement unit (IMU) is a device that uses measurement systems such as **gyroscopes** and **accelerometers** to estimate the relative position (x, y, z), orientation (roll, pitch, yaw), velocity, and acceleration of a moving vehicle with respect to an inertial frame
- In order to estimate motion, the gravity vector must be subtracted. Furthermore, initial velocity has to be known.



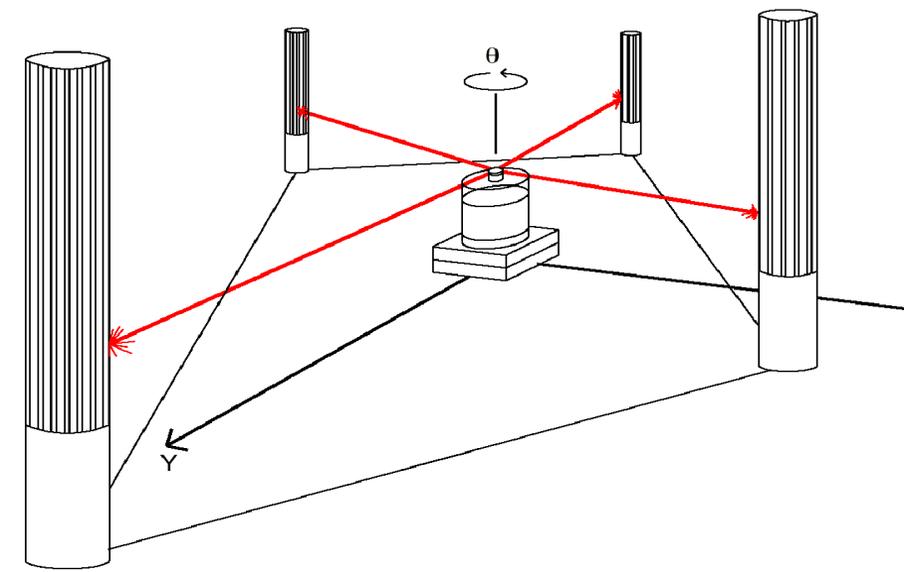
Inertial Measurement Unit (IMU)

- **IMUs are extremely sensitive to measurement errors** in gyroscopes and accelerometers: **drift in the gyroscope** unavoidably undermines the estimation of the vehicle orientation relative to gravity, which results in incorrect cancellation of the gravity vector. Additionally observe that, because the **accelerometer data is integrated twice** to obtain the position, any residual gravity vector results in a quadratic error in position.
- After long period of operation, **all IMUs drift**. To cancel it, some external reference like GPS or cameras has to be used.



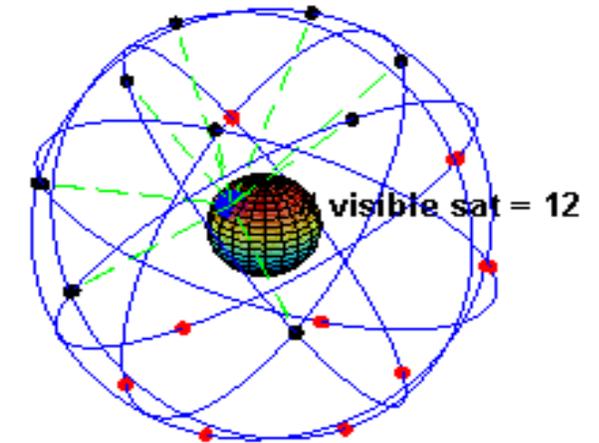
Ground-Based Active and Passive Beacons

- “Elegant” way to solve the localization problem in mobile robotics
- **Beacons are signaling guiding devices with a precisely known position**
- Beacon base navigation is used since the humans started to travel
 - Natural beacons (landmarks) like **stars, mountains or the sun**
 - Artificial beacons like **lighthouses**
- The recently introduced Global Positioning System (GPS) revolutionized modern navigation technology
 - Key sensors for outdoor mobile robotics
 - For indoor robots GPS is not applicable,
- Major drawback with the use of beacons in indoor:
 - Beacons require changes in the environment -> costly.
 - Limit flexibility and adaptability to changing environments.



Global Positioning System (GPS) (1)

- Facts
 - Became accessible for commercial applications in 1995
 - Initially there were 24 satellites orbiting the earth every 12 hours at a height of 20.190 km.
 - 4 satellites were located in each of 6 orbits with 60 degrees orientation between each other.
- Working Principle
 - Location of any GPS receiver is determined through a time of flight measurement (satellites send orbital location (*ephemeris*) plus time; the receiver computes its location through **trilateration** and **time correction**)
- Technical challenges:
 - **Time synchronization** between the individual satellites and the GPS receiver
 - Real time update of the exact location of the satellites
 - Precise measurement of the time of flight
 - **Interferences** with other signals



Range sensors

- Sonar

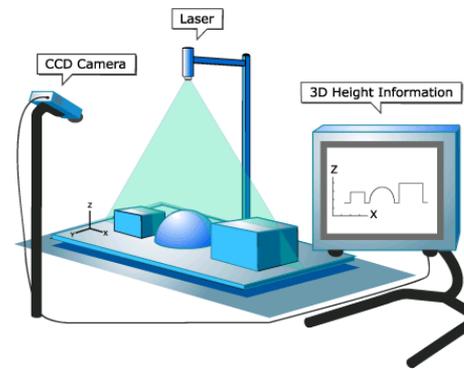


- Laser range finder



- Time of Flight Camera

- Structured light



46 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.

47 Range Sensors (time of flight) (2)

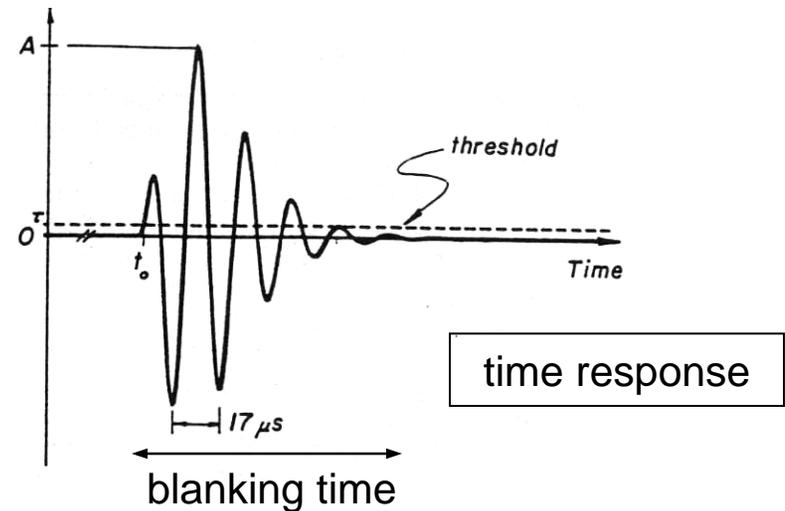
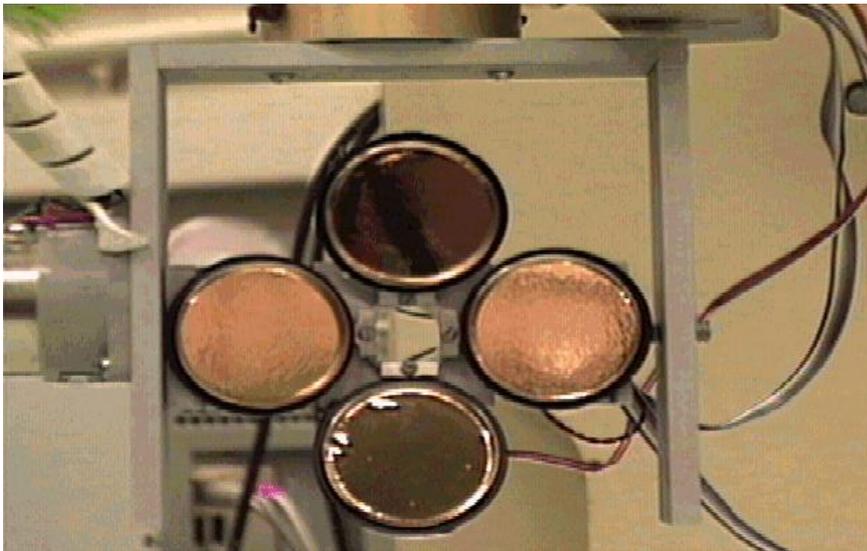
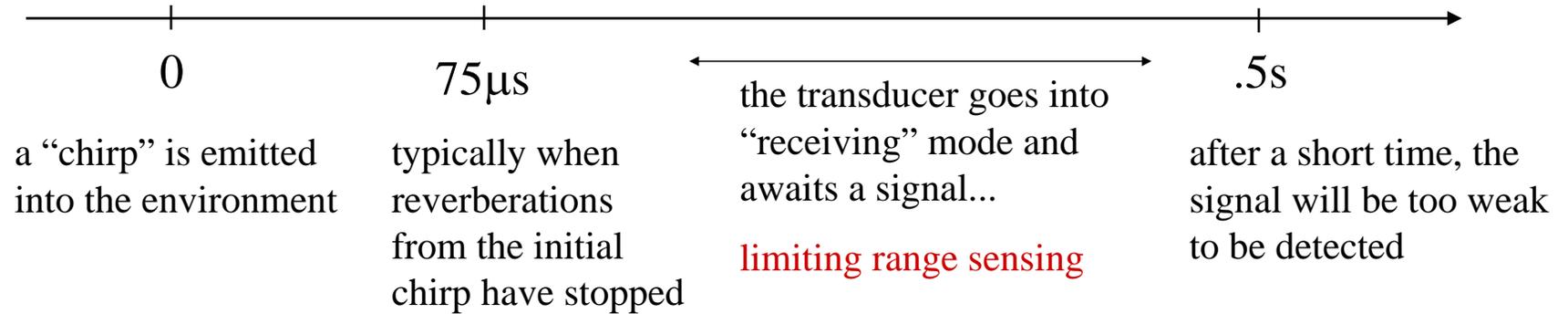
- It is important to point out
 - **Propagation speed v of sound: 0.3 m/ms**
 - **Propagation speed v of electromagnetic signals: 0.3 m/ns,**
 - **Electromagnetic signals travel one million times faster.**
 - 3 meters
 - Equivalent to 10 ms for an ultrasonic system
 - Equivalent to only 10 ns for a laser 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 flight **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)**



Sonar sensing

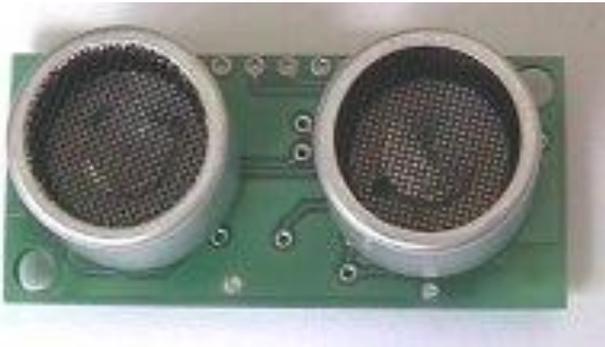
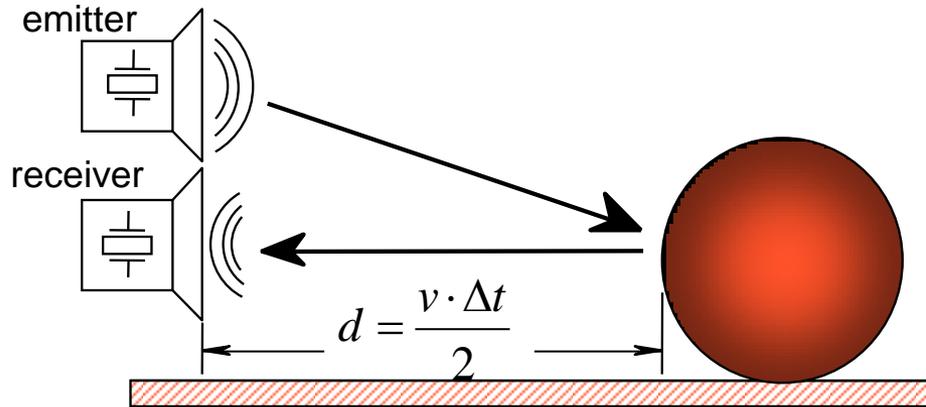
single-transducer sonar timeline



Polaroid sonar emitter/receivers

No lower range limit for paired sonars...

48 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

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

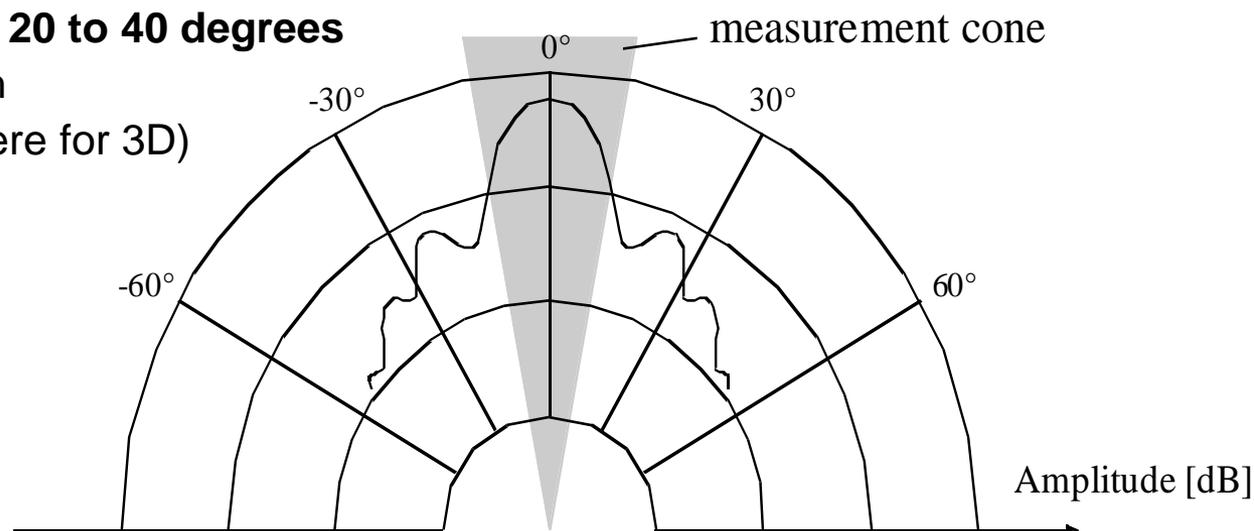
γ : adiabatic index (isentropic expansion factor) - ratio of specific heats of a gas

R : gas constant

T : temperature in degree Kelvin

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

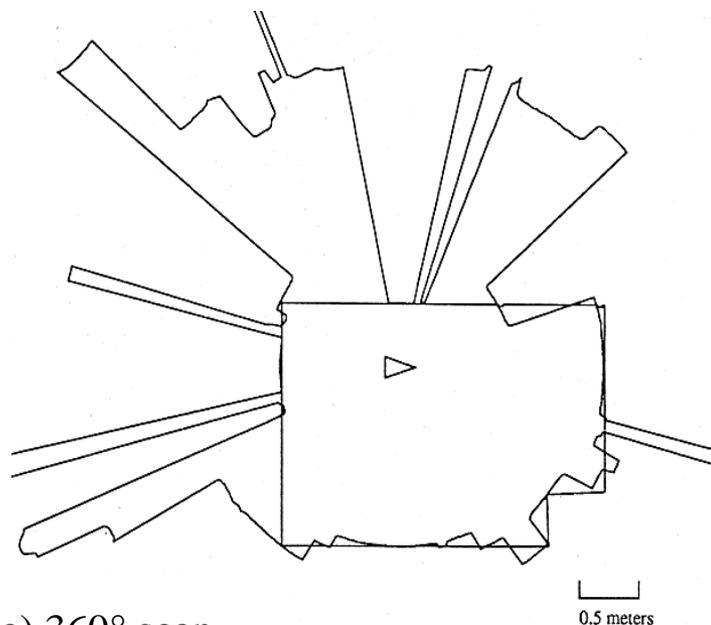
- typical frequency: 40kHz - 180 kHz
 - Lower frequencies correspond to longer maximal sensor range
- generation of sound wave via piezo transducer
 - transmitter and receiver can be separated or not separated
- **Range between 12 cm up to 5 m**
- **Resolution of ~ 2 cm**
- Accuracy 98% → relative error 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)



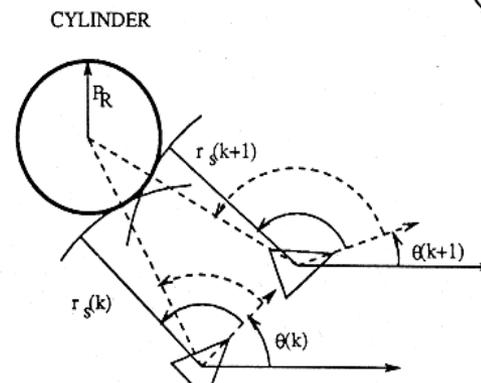
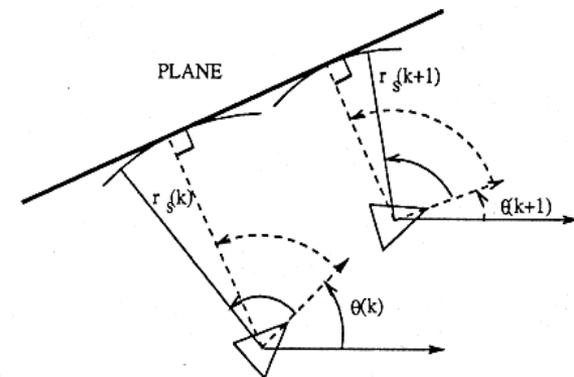
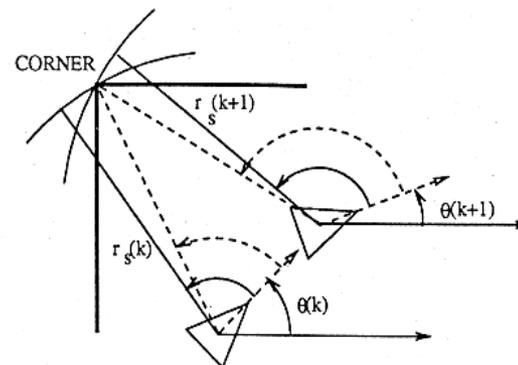
Typical intensity distribution of a ultrasonic sensor

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

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



a) 360° scan



b) results from different geometric primitives

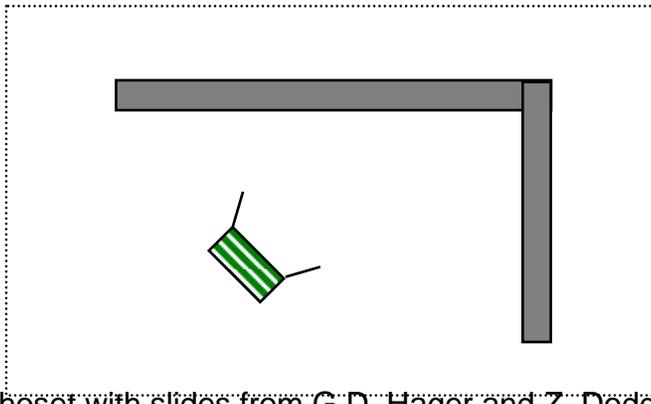
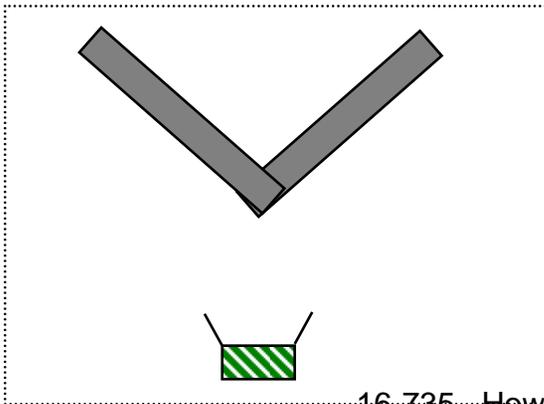
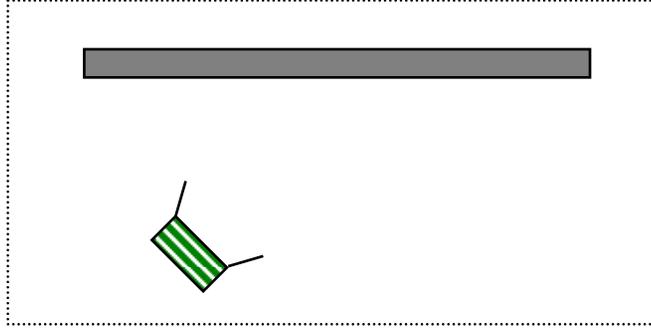
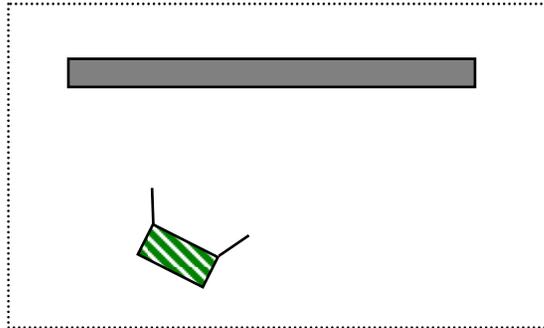
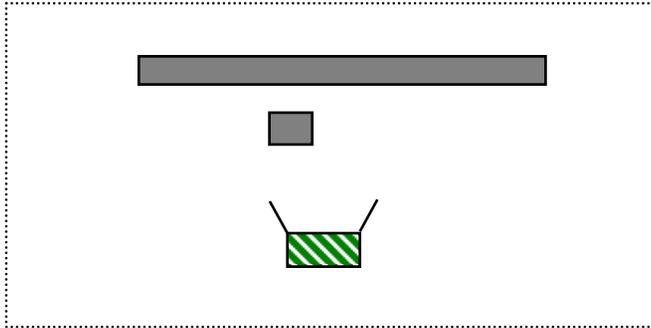
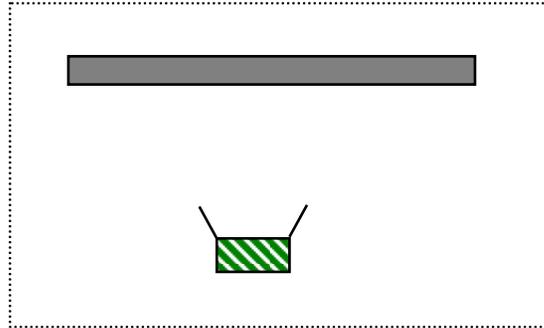
Ultrasonic Sensor (time of flight, sound) (4)

- 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.

 walls
(obstacles)

Sonar effects

 sonar

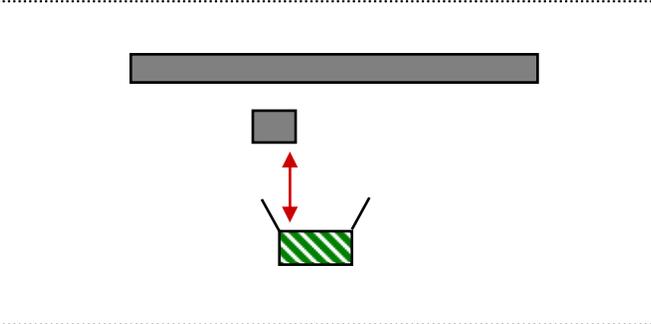
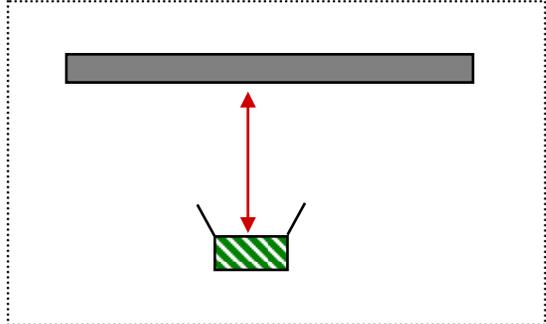


Draw the range
reading that the
sonar will return
in each case...

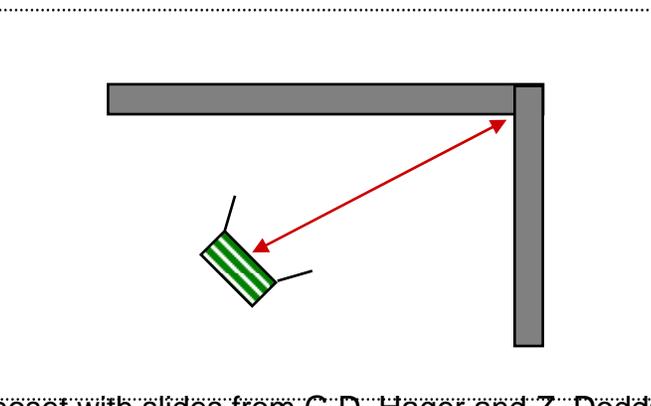
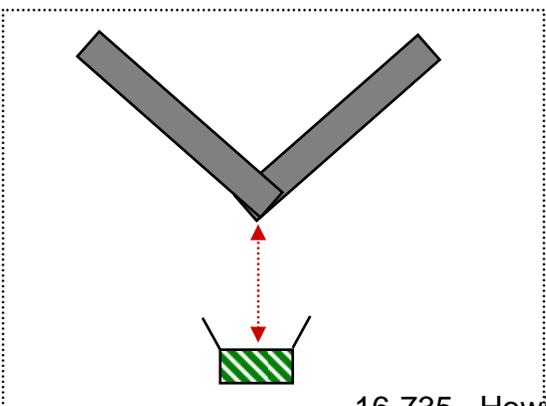
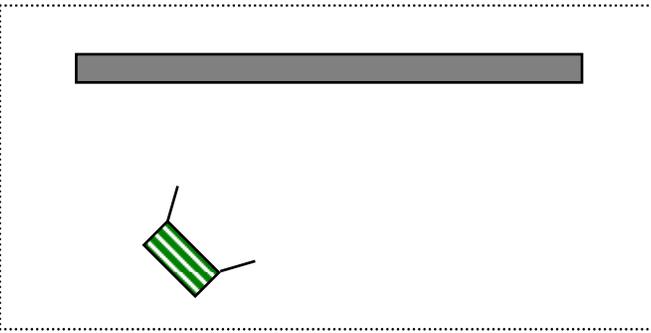
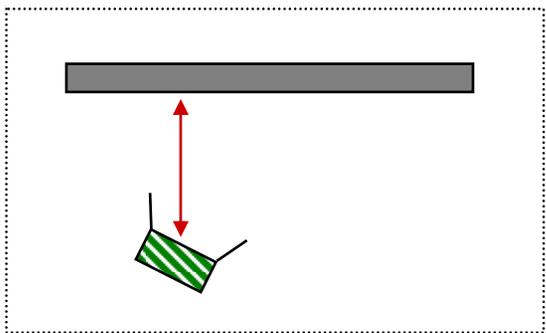
 walls
(obstacles)

Sonar effects

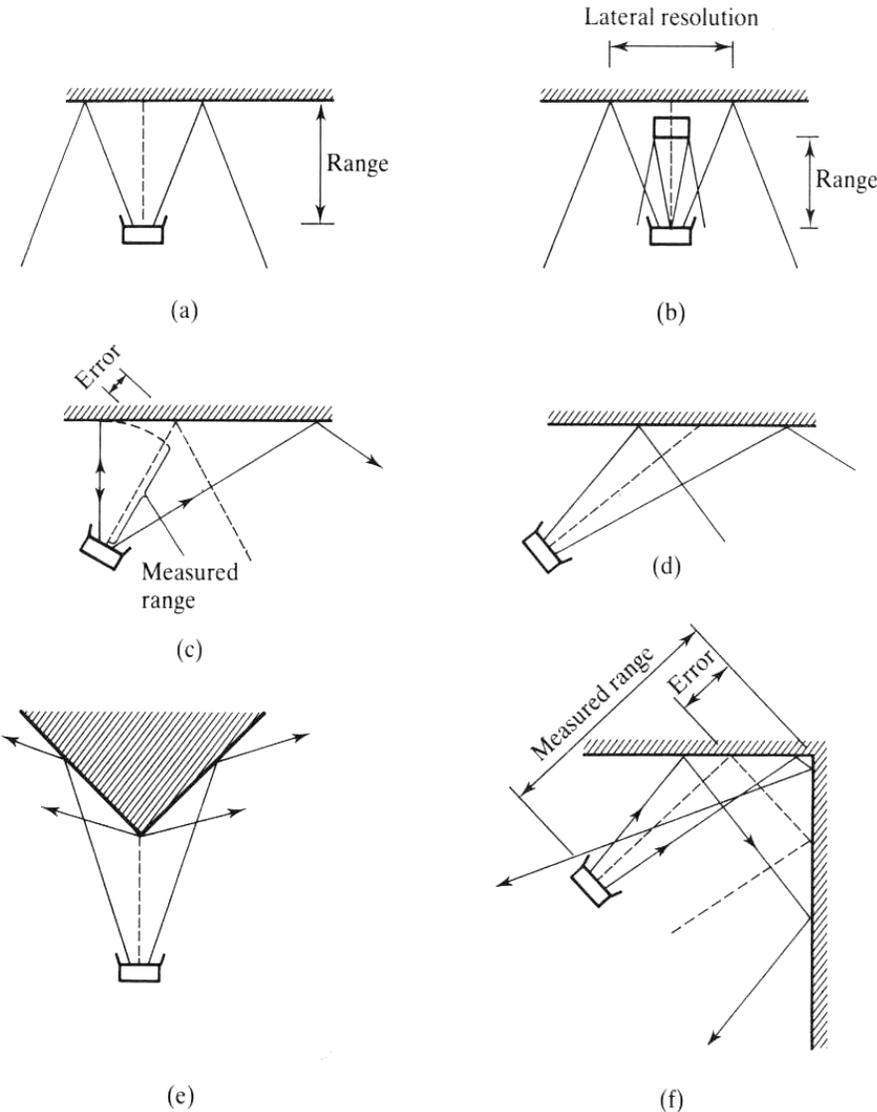
 sonar



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



Sonar effects



(a) Sonar providing an accurate range measurement

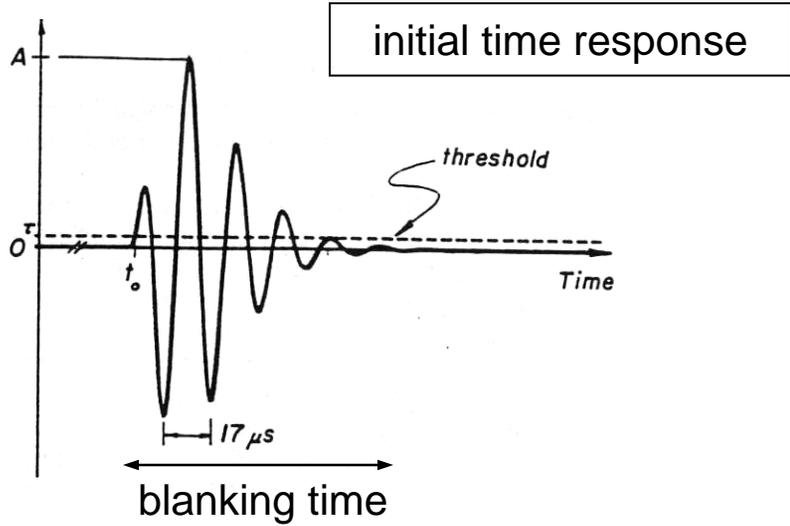
(b-c) Lateral resolution is not very precise; the closest object in the beam's cone provides the response

(d) Specular reflections cause walls to disappear

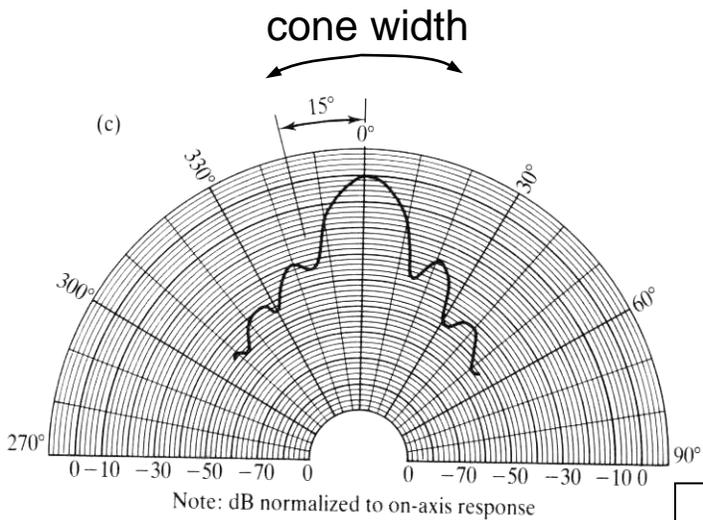
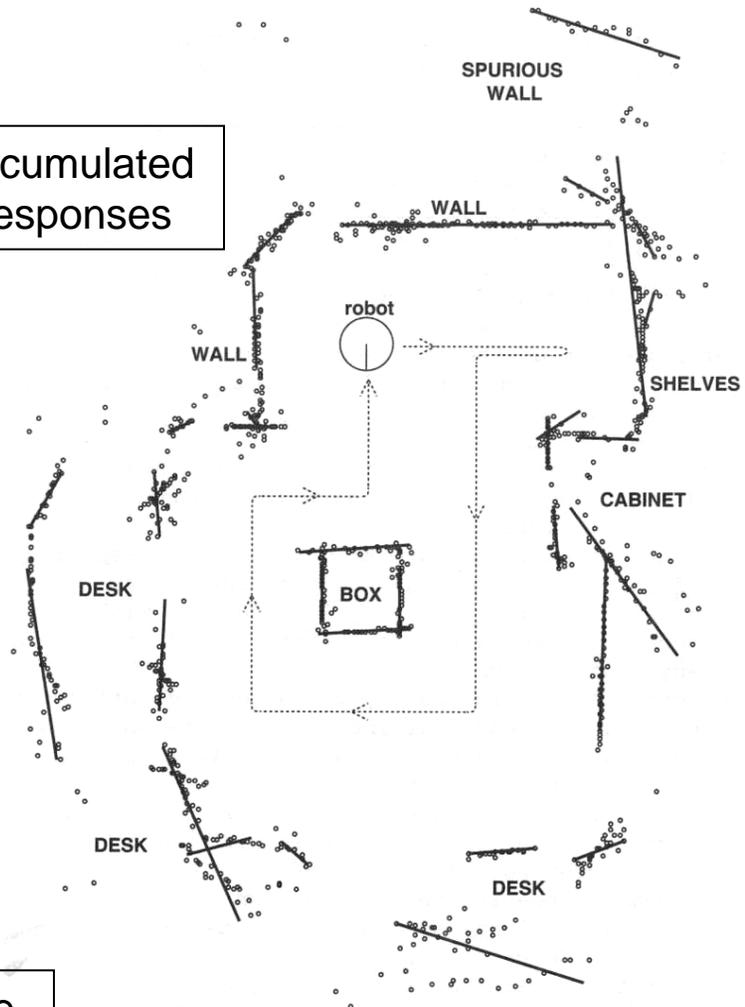
(e) Open corners produce a weak spherical wavefront

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

Sonar modeling



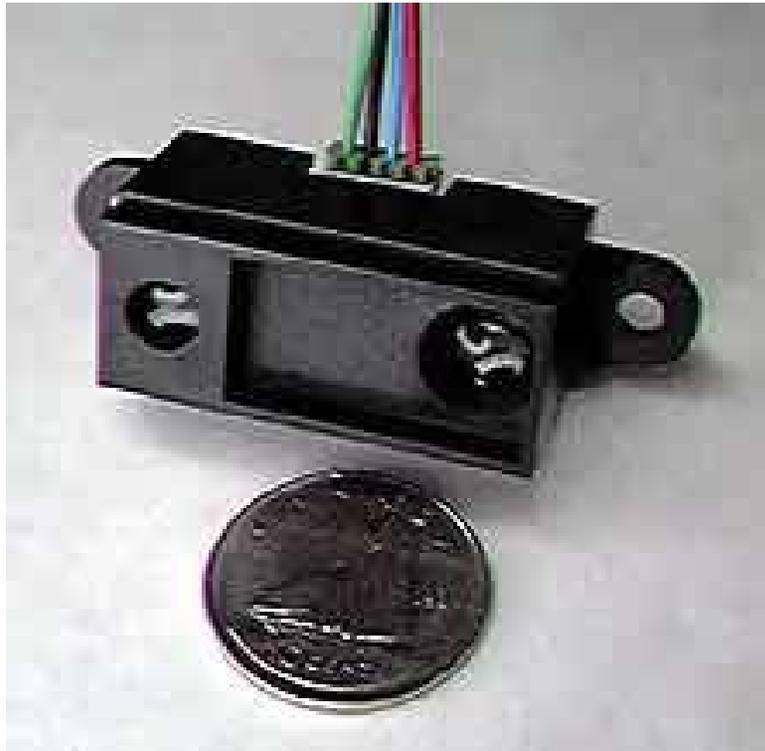
accumulated responses



spatial response

Infrared sensors

“Noncontact bump sensor”



IR emitter/detector pair

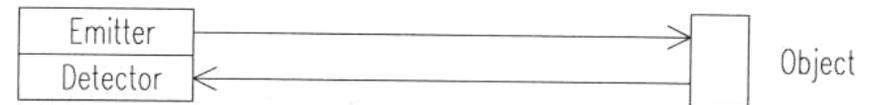
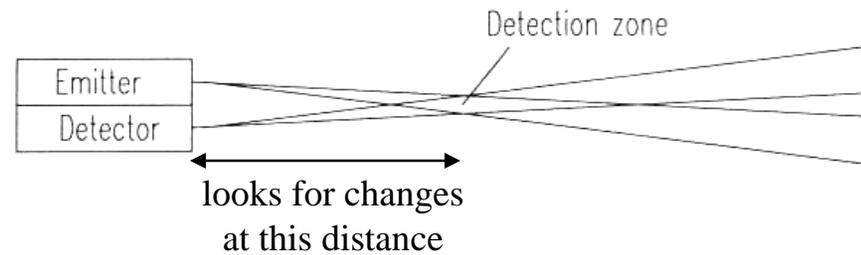
IR detector



16-735, Howie Chosrom G.I

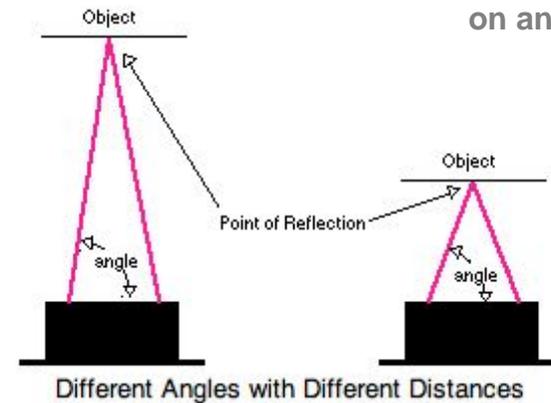
(1) sensing is based on light intensity.

“object-sensing” IR



diffuse distance-sensing IR

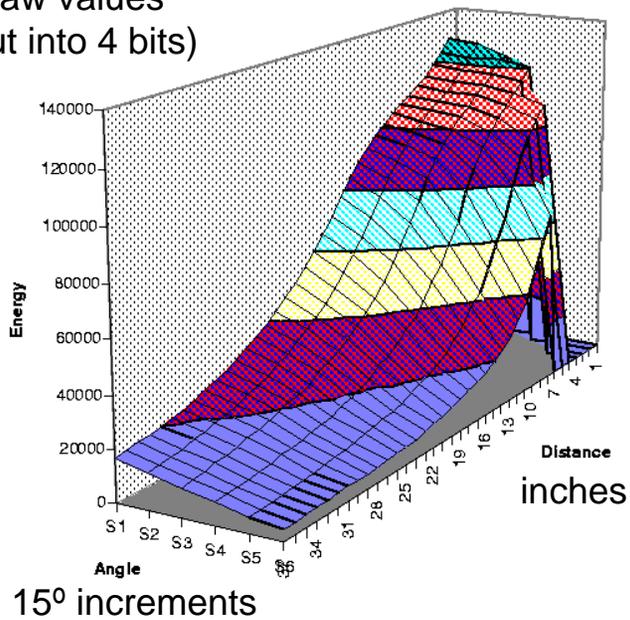
(2) sensing is based on angle received.



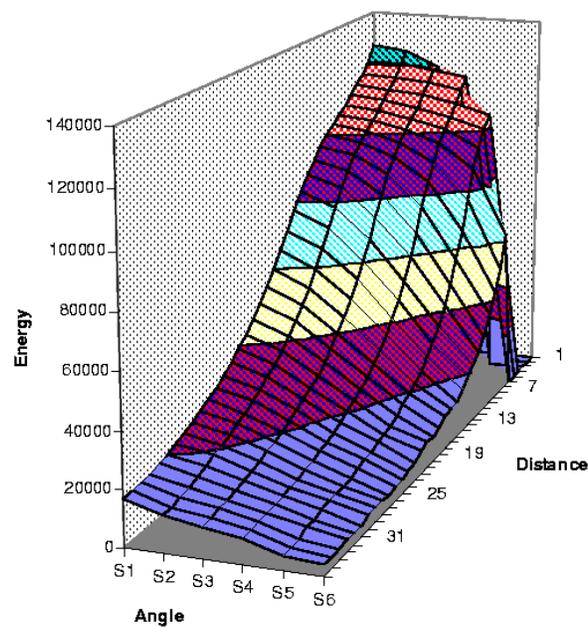
Infrared calibration

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

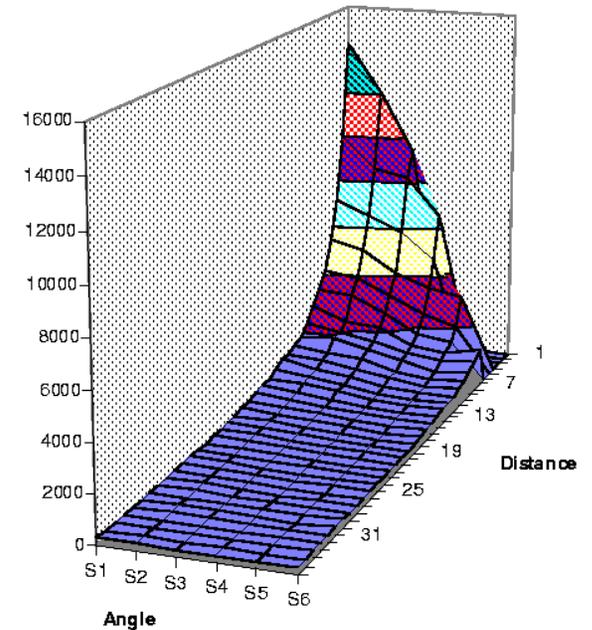
raw values
(put into 4 bits)



in the dark

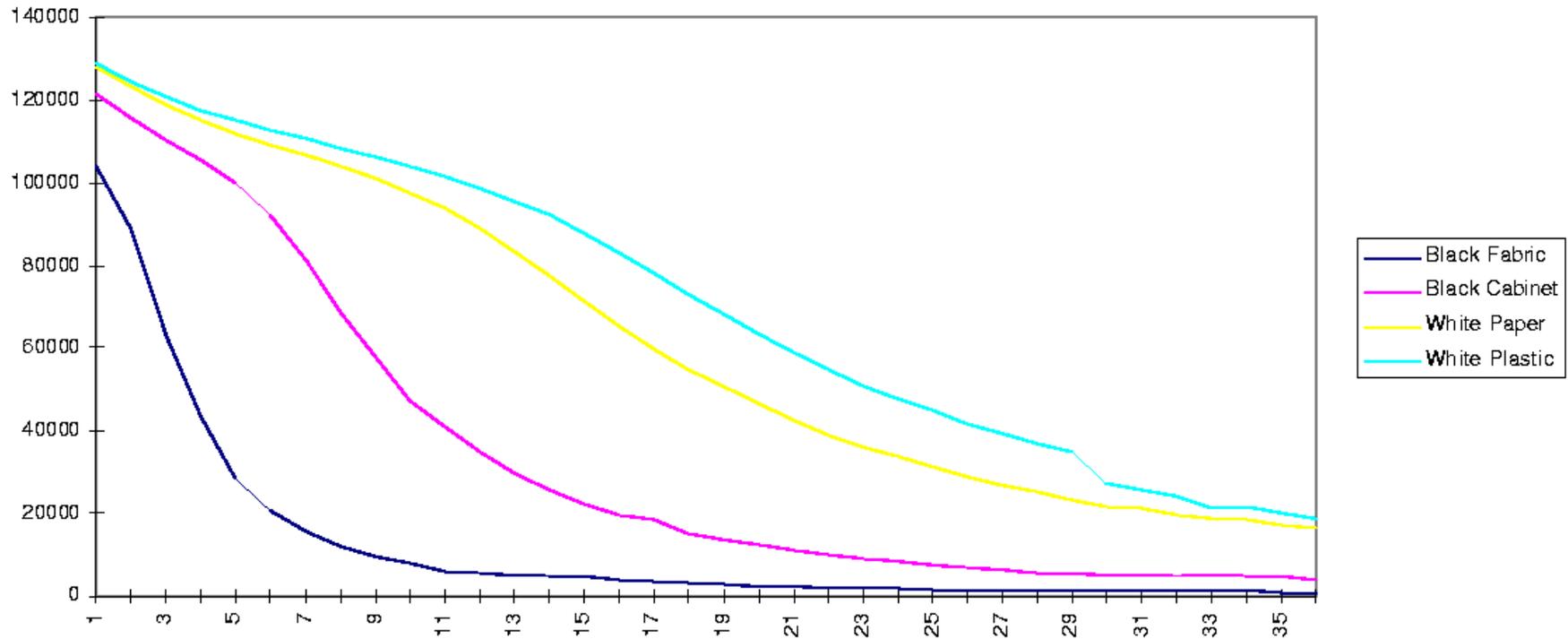


fluorescent light



incandescent light

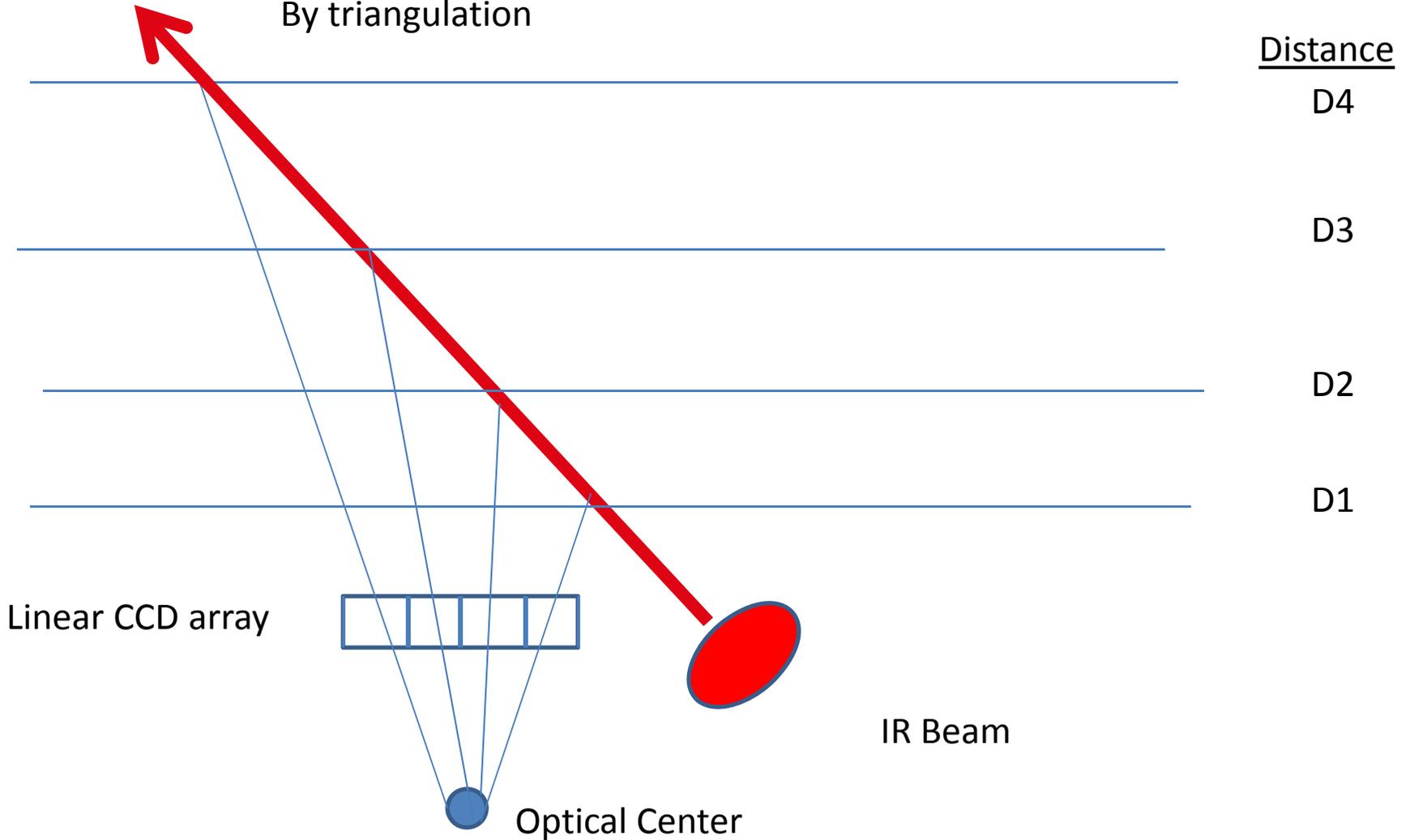
Infrared calibration



energy vs. distance for various materials
(the incident angle is 0° , or head-on)
(with no ambient light)

InfraRed (IR) Distance Sensor

The IR beam causes a particular pixel in the linear CCD array to give maximum response (peak). The distance can then be computed By triangulation



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

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



SICK



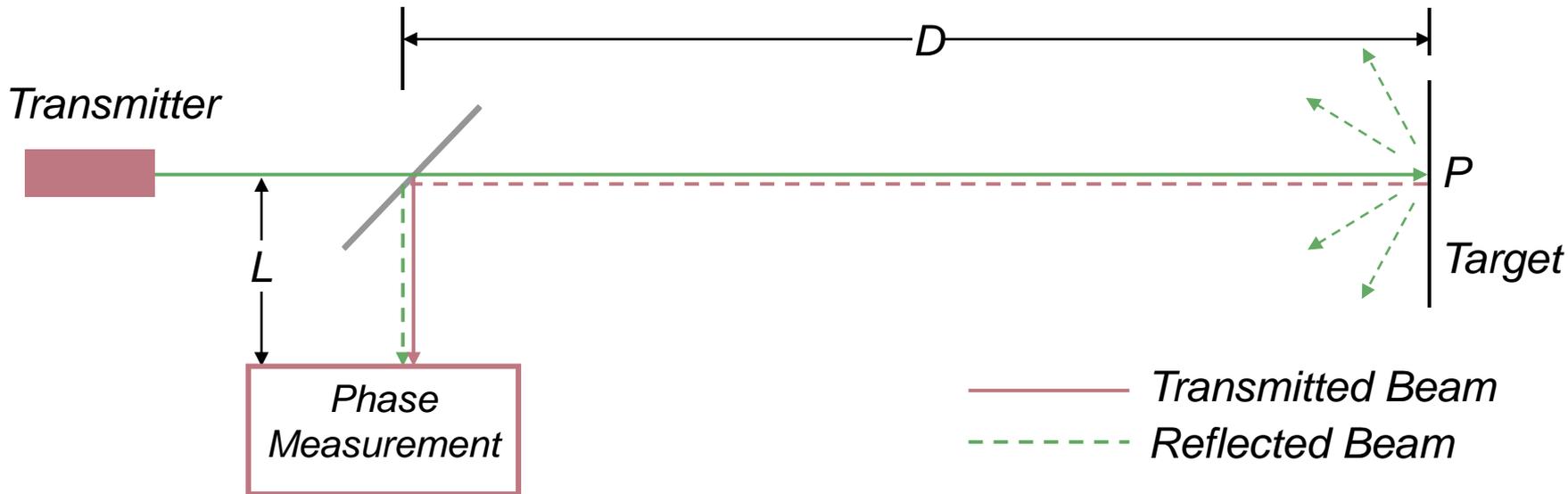
Alaska-IBEO



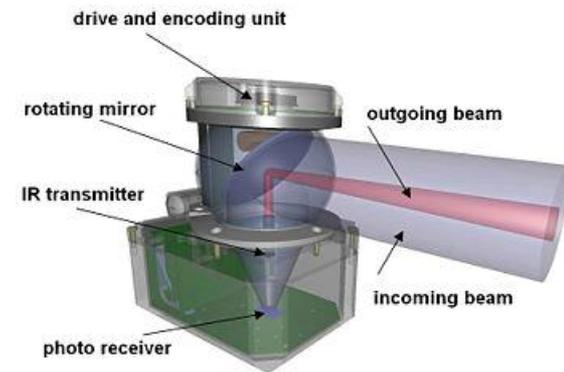
Hokuyo



55 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

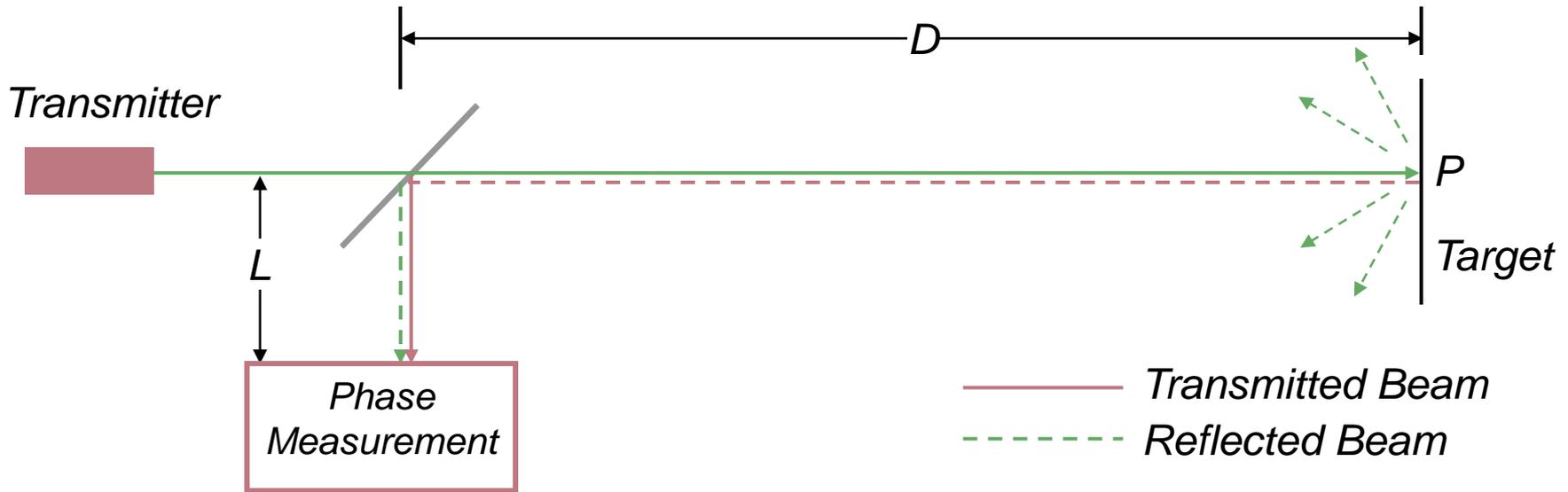


Laser Range Sensor (time of flight, electromagnetic) (2)

- 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

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

- Phase-Shift Measurement



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

$$\lambda = \frac{c}{f}$$

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), $\lambda = 60$ meters

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

- Distance D , between the beam splitter and the target

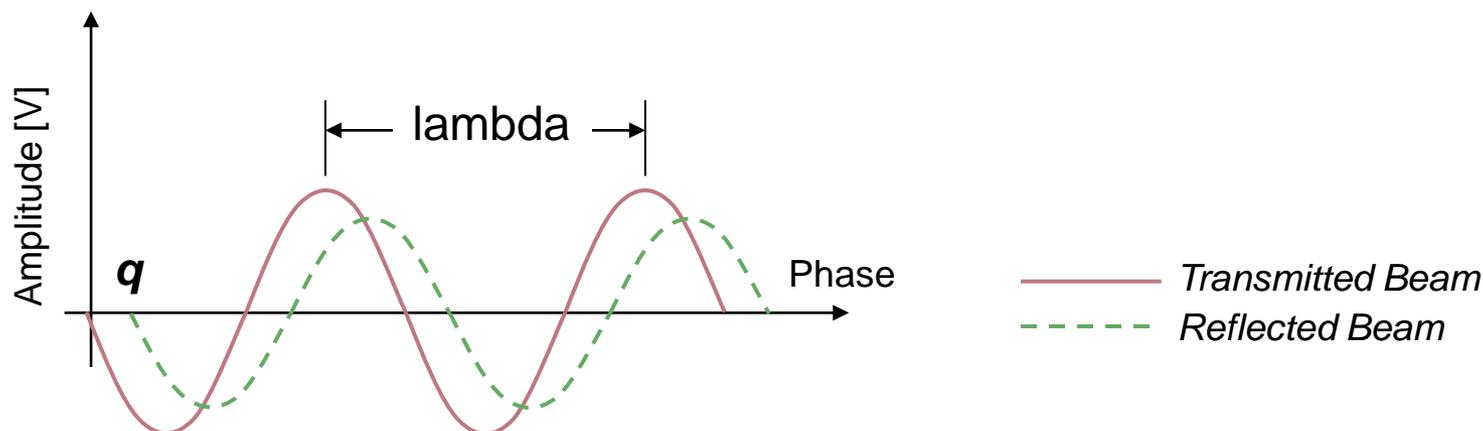
$$D = \frac{\lambda}{4\pi} \theta$$

- where

- θ : phase difference between transmitted and reflected beam

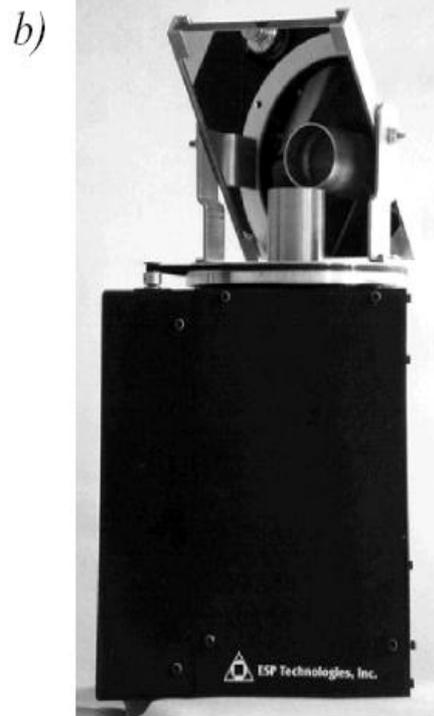
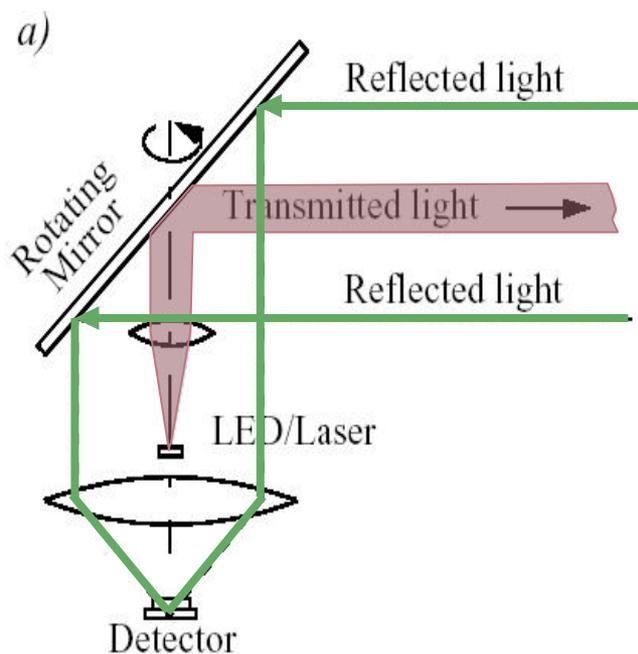
- Theoretically ambiguous range estimates

- since for example if $\lambda = 60$ meters, a target at a range of 5 meters = target at 35 meters



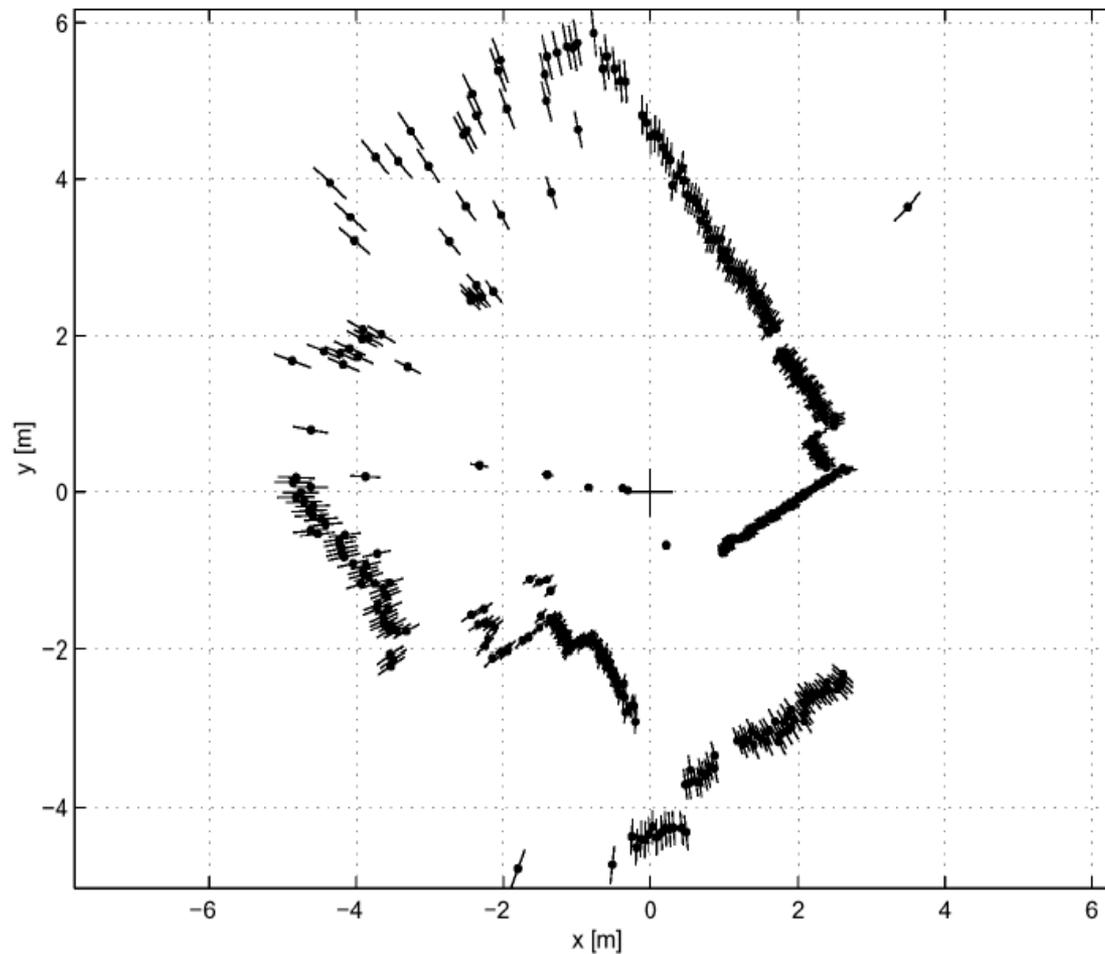
59 Laser Range Sensor (time of flight, electromagnetic) (5)

- 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 ...



60 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-degree scans per second



3D Laser Range Finder (1)

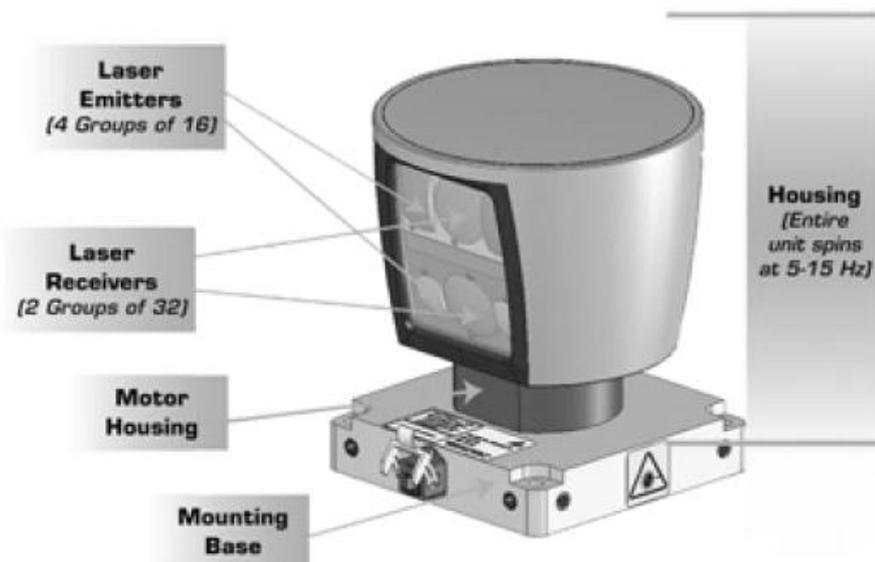
- A 3D laser range finder is a laser scanner that acquires scan data in more than a single plane.
- Custom-made 3D scanners are typically built by nodding or rotating a 2D scanner in a stepwise or continuous manner around an axis parallel to the scanning plane.
- By lowering the rotational speed of the 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 $\pm 90^\circ$ 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!



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 is currently still much more expensive than Sick laser range finders (SICK ~ 5000 Euros, Velodyne ~50,000 Euros!)

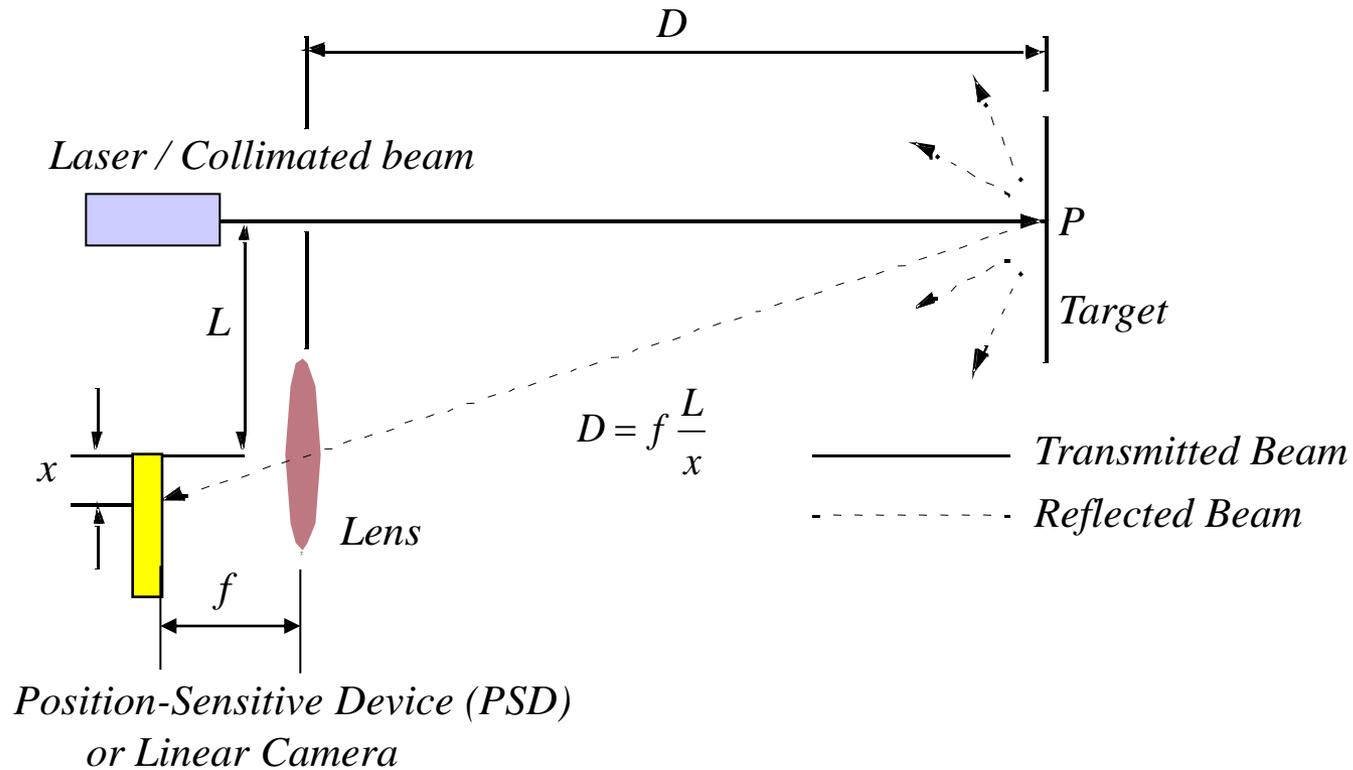


C Carnegie Mellon University

67 Triangulation Ranging

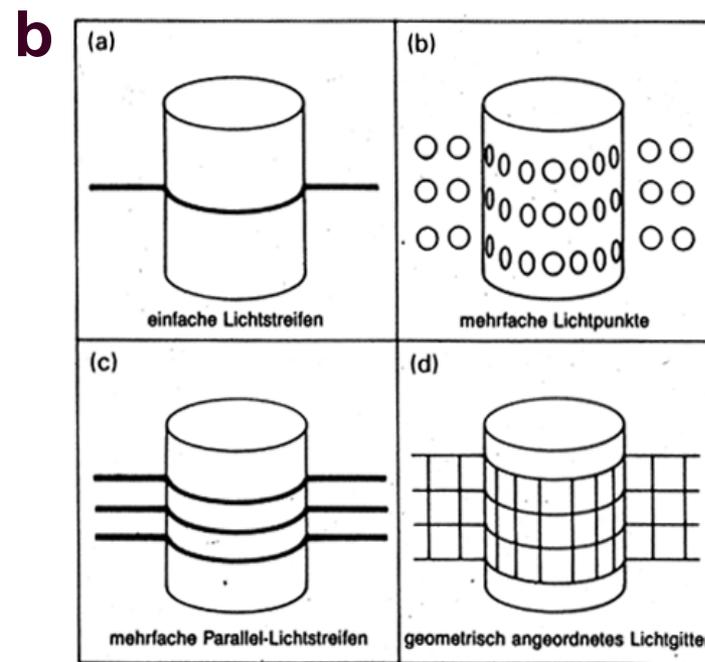
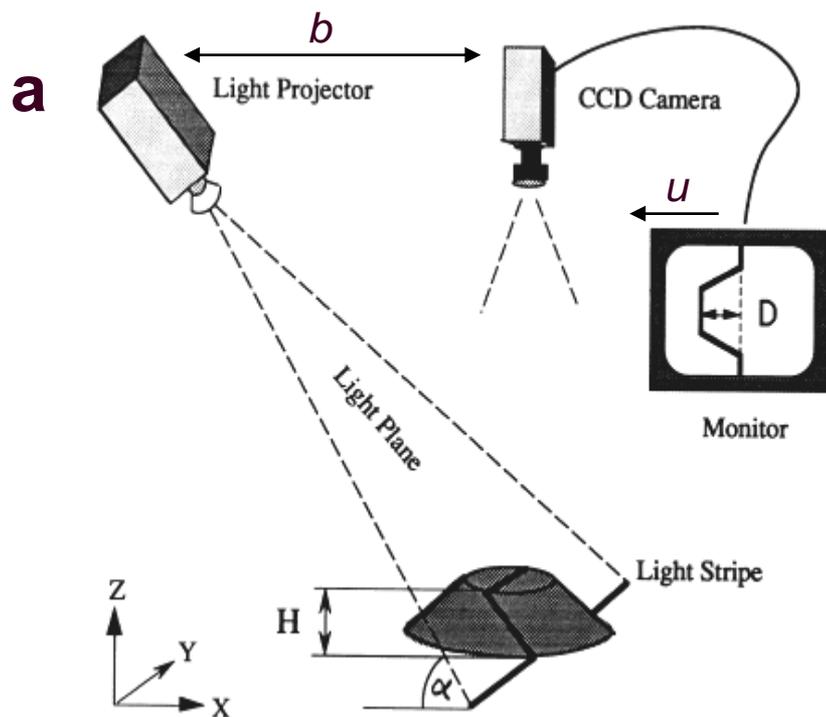
- Use of **geometrical properties** of the image to establish a **distance measurement**
- If a well defined light pattern (e.g. point, line) is projected onto the environment.
 - reflected light is then captured by a photo-sensitive line or matrix (camera) sensor device
 - simple triangulation allows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

68 Laser Triangulation (1D)



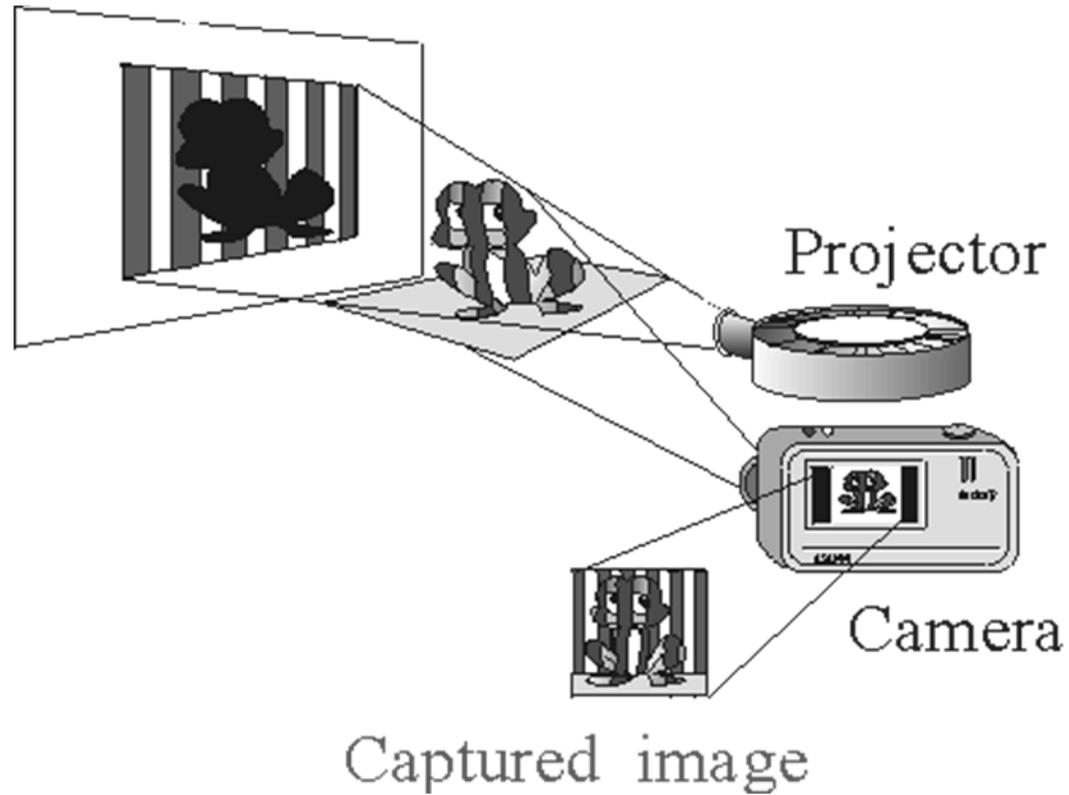
- Principle of 1D laser triangulation: $D = f \frac{L}{x}$

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

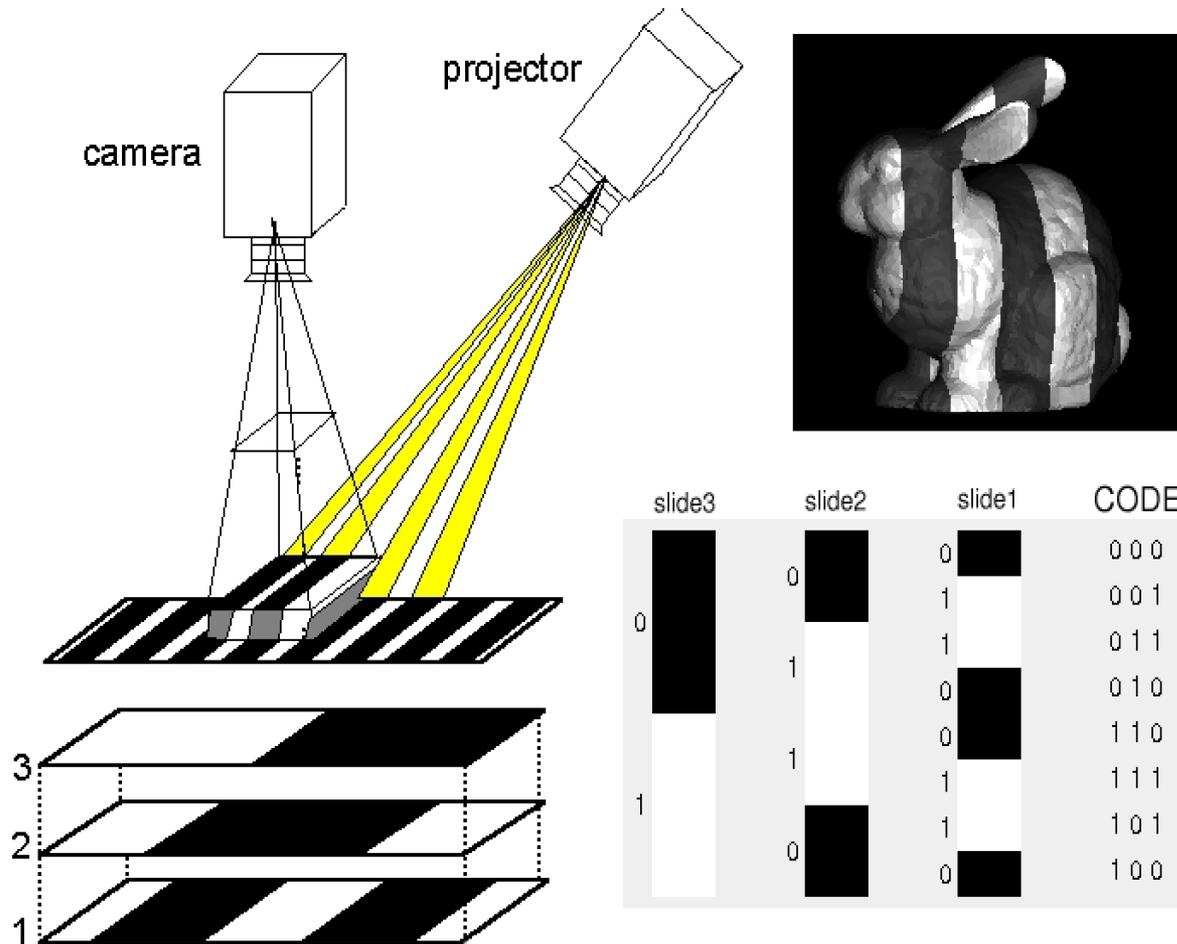


- Eliminate the correspondence problem by projecting structured light on the scene.
- Slits of light or emit collimated light (possibly laser) by means of a rotating mirror.
- Light perceived by camera
- Range to an illuminated point can then be determined from simple geometry.

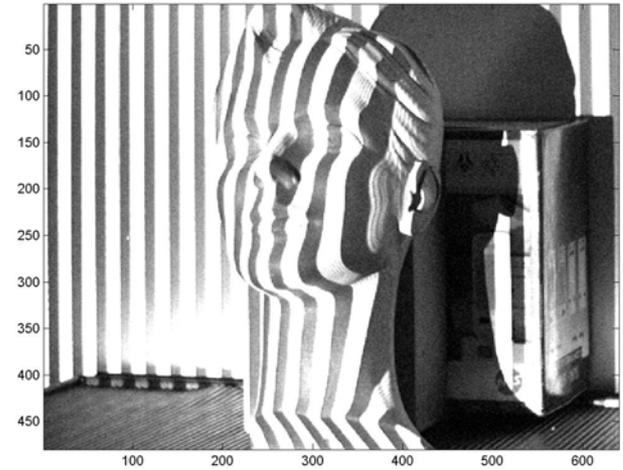
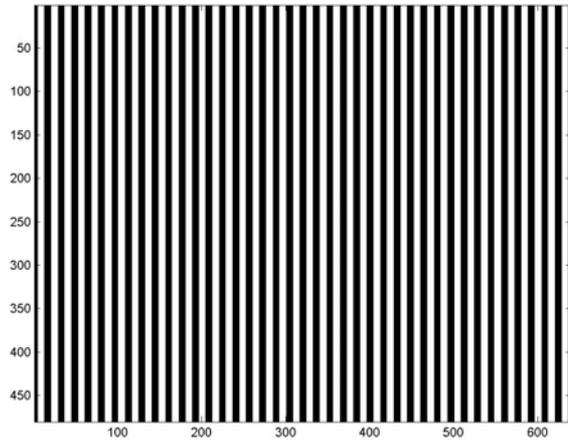
Coding structured light



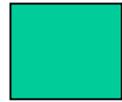
Gray Code



...in practice:



Structured Light – Light Striping



= illuminated

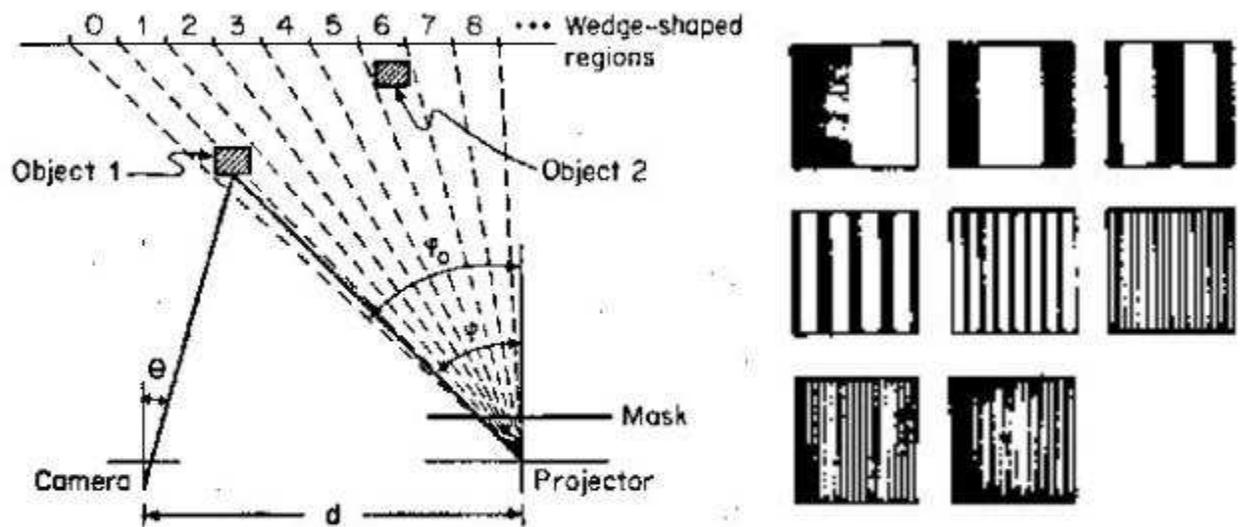


= dark – not seen

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