Perception: Sensors

Autonomous Mobile Robots

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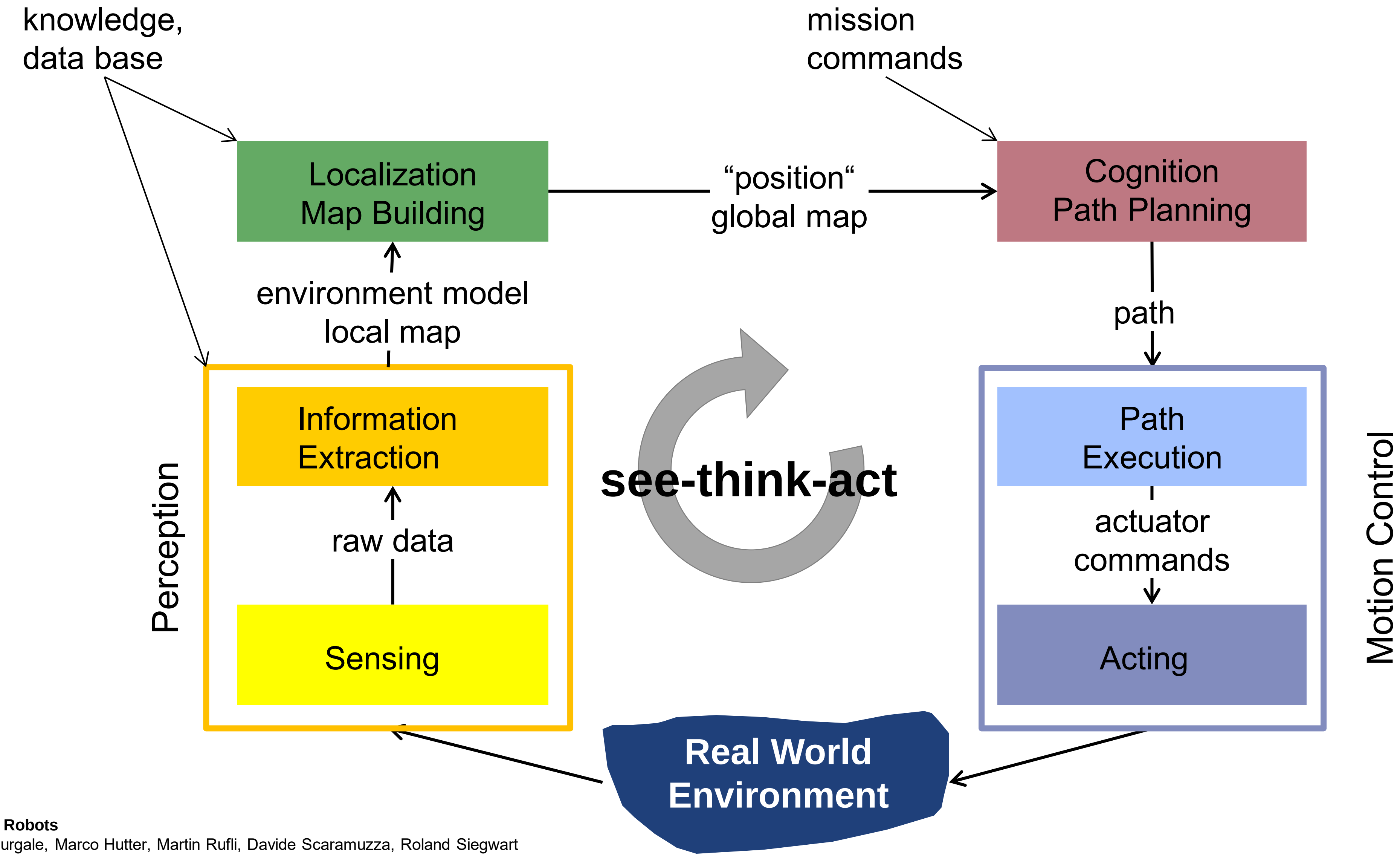
Mobile Robot Control Scheme



knowledge,
data base

mission
commands

Localization
Map Building

"position"
global map

Cognition
Path Planning

environment model
local map

path

Perception

Information
Extraction

raw data

Sensing

see-think-act

Path
Execution

actuator
commands

Acting

Motion Control

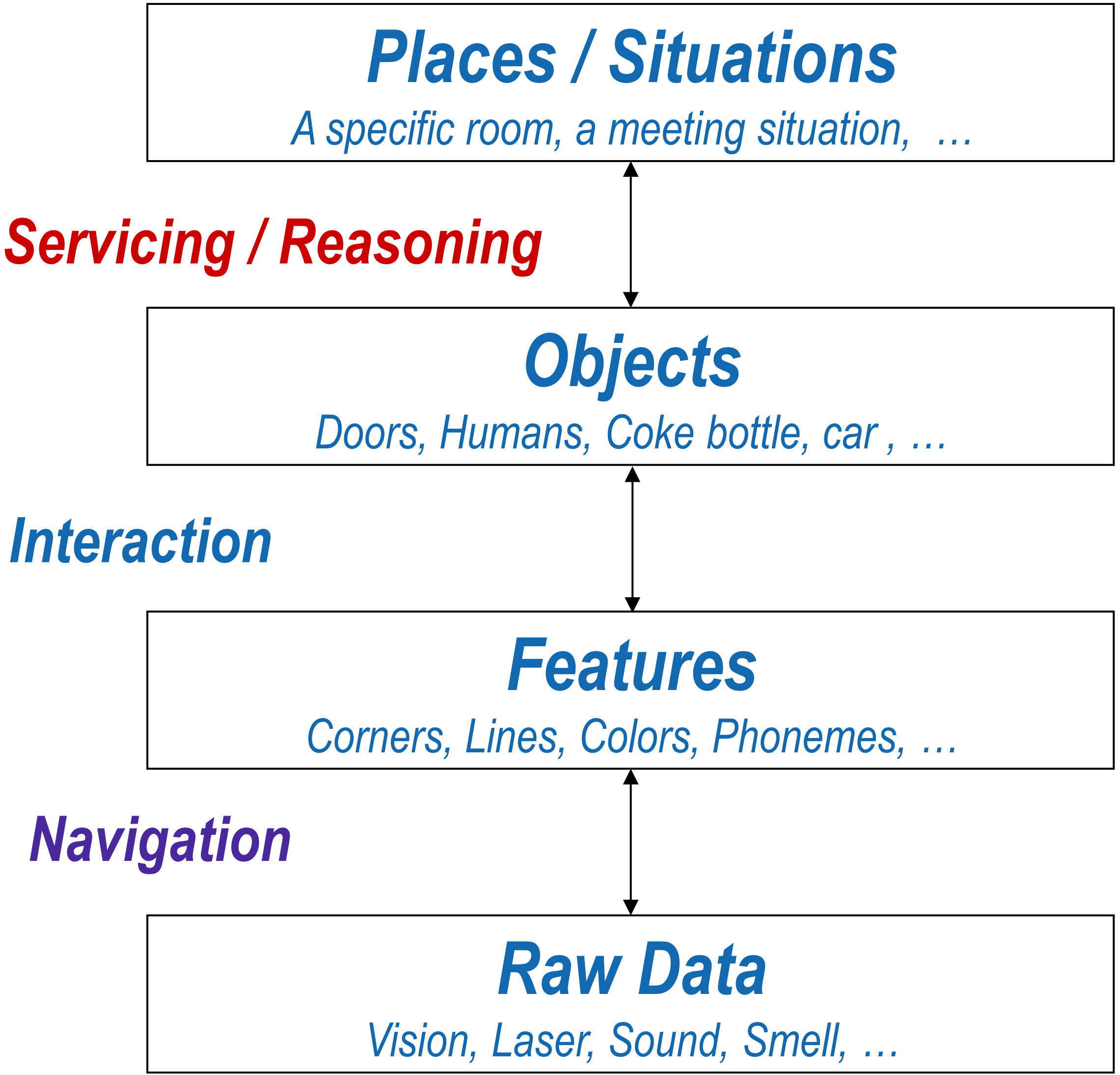
Real World
Environment

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



Places / Situations

A specific room, a meeting situation, …

Servicing / Reasoning

Objects

Doors, Humans, Coke bottle, car , …

Interaction

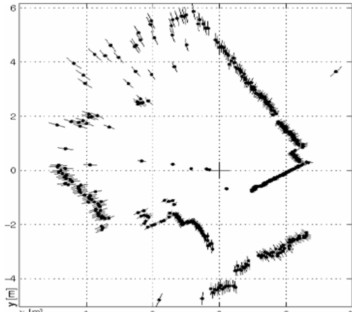
Features

Corners, Lines, Colors, Phonemes, …

Navigation

Raw Data

Vision, Laser, Sound, Smell, …



Sensors!

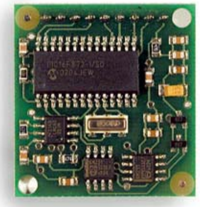
Robots' link to the external world...

sonar rangefinder

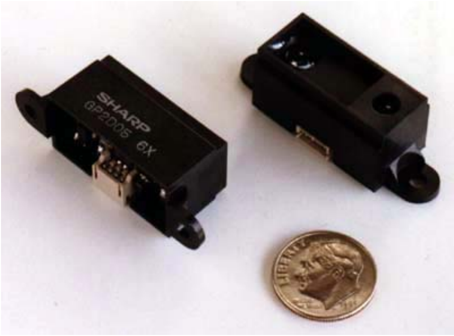
gyro

Sensors, sensors, sensors!

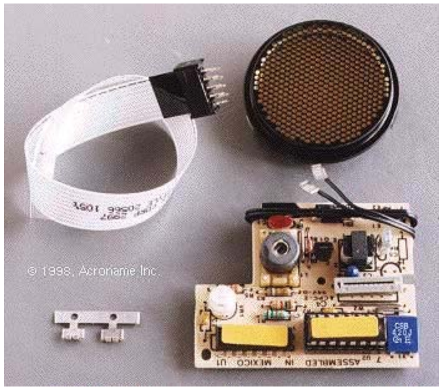
and tracking what is sensed: world models



compass



IR rangefinder

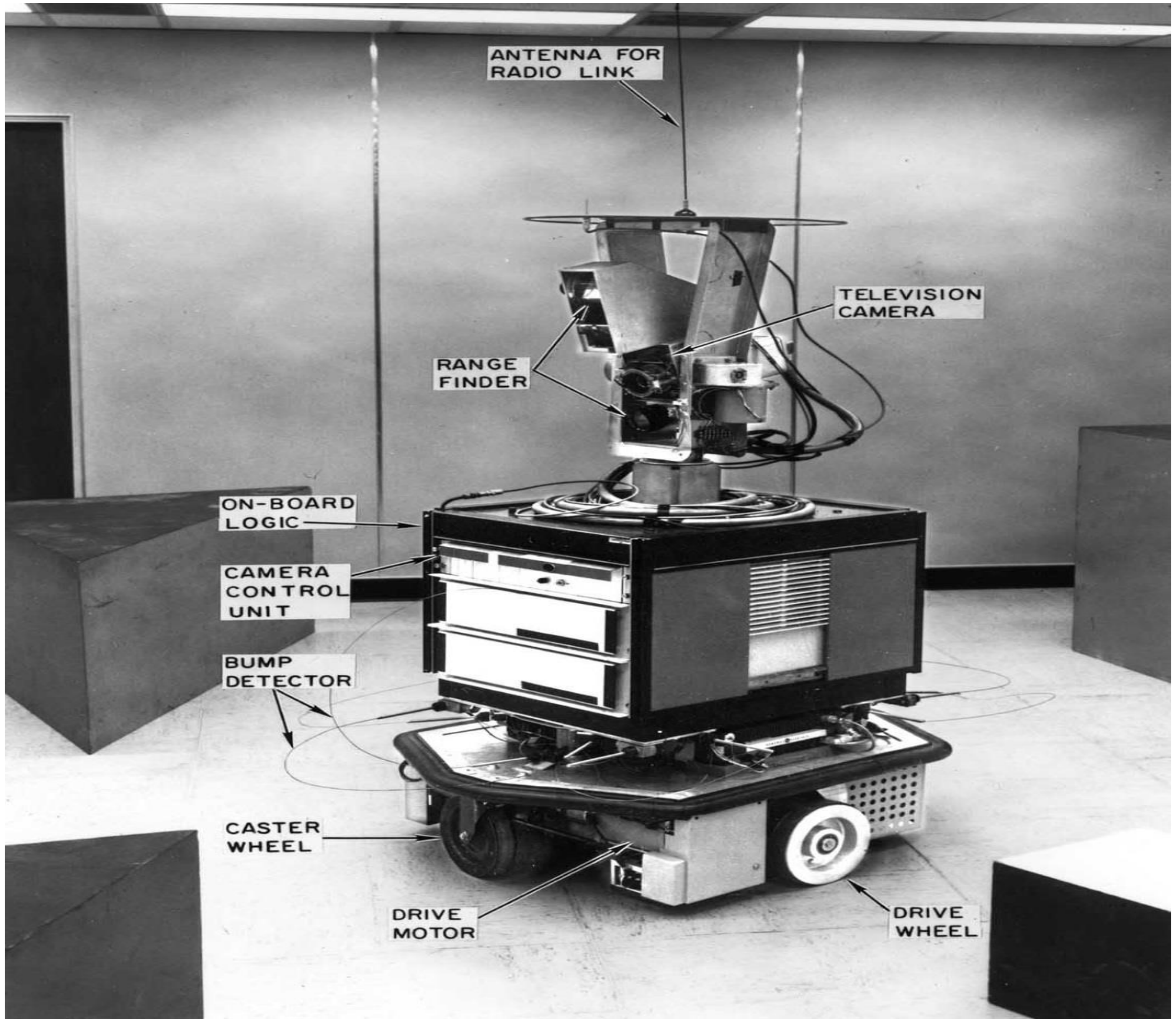


sonar rangefinder

CMU cam with on-board processing

odometry…

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

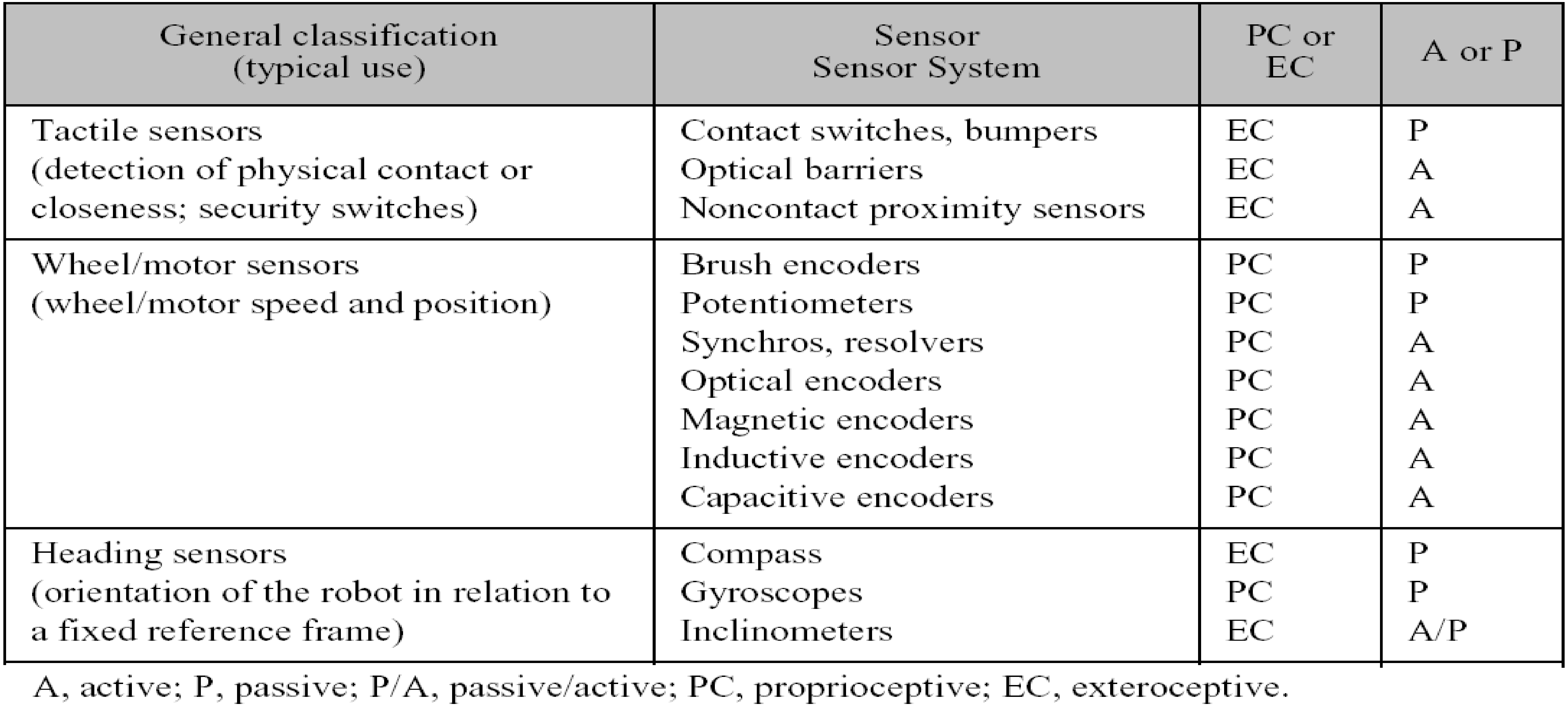
Camera for life video streaming

  - 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

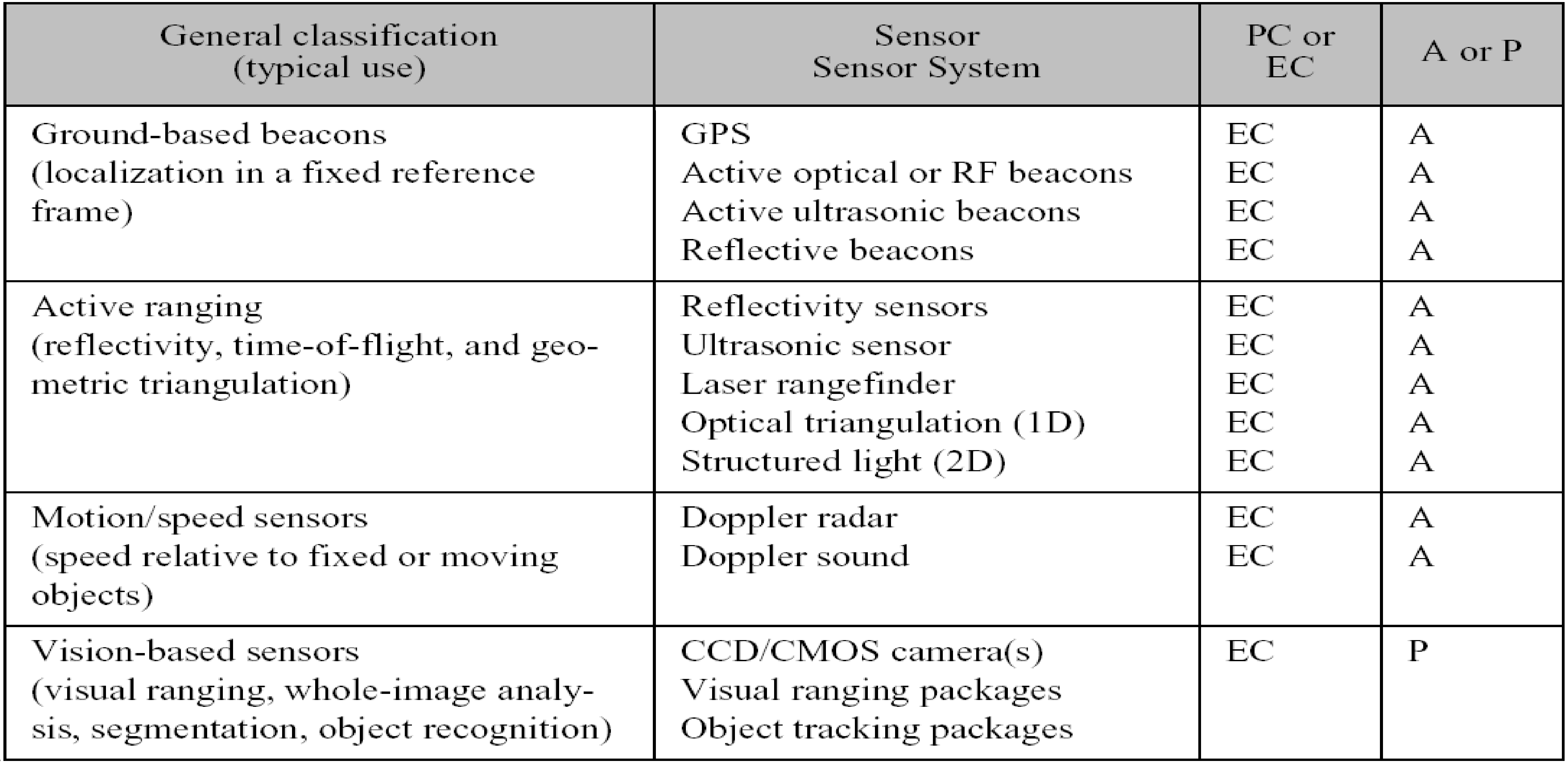
General Classification (1)



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)



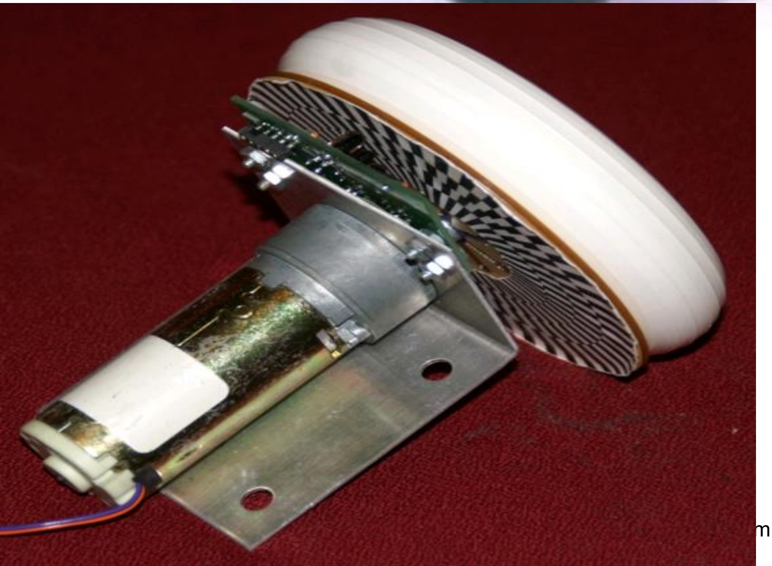
General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Ground-based beacons (localization in a fixed reference frame)	GPS Active optical or RF beacons Active ultrasonic beacons Reflective beacons	EC EC EC EC	A A A A
Active ranging (reflectivity, time-of-flight, and geometric triangulation)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

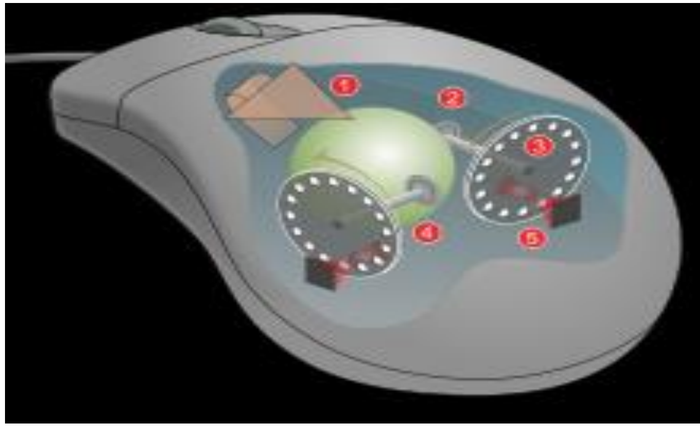
Sensors: outline

- 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/anglular transducer

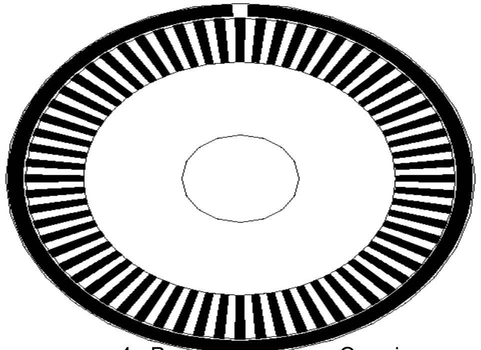


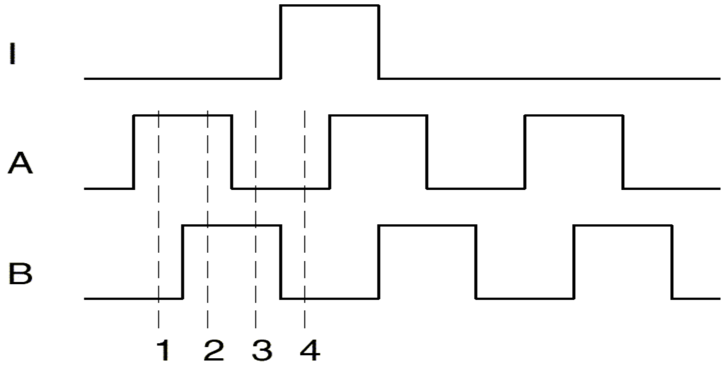


Wheel / Motor Encoders

- 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



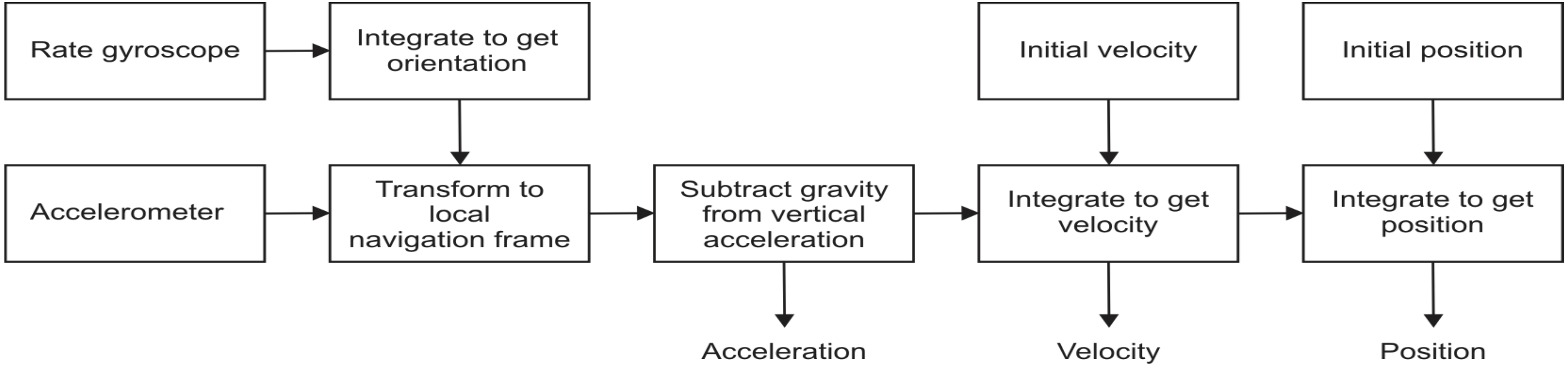


State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

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.



Rate gyroscope

Integrate to get orientation

Initial velocity

Initial position

Accelerometer

Transform to local navigation frame

Subtract gravity from vertical acceleration

Integrate to get velocity

Integrate to get position

Acceleration

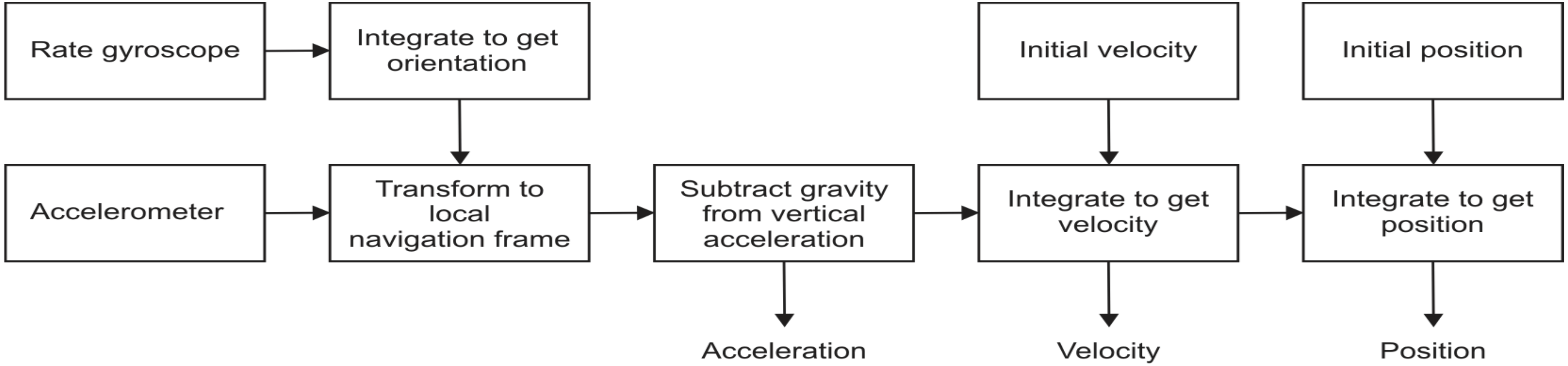
Velocity

Position

Inertial Measurement Unit (IMU)

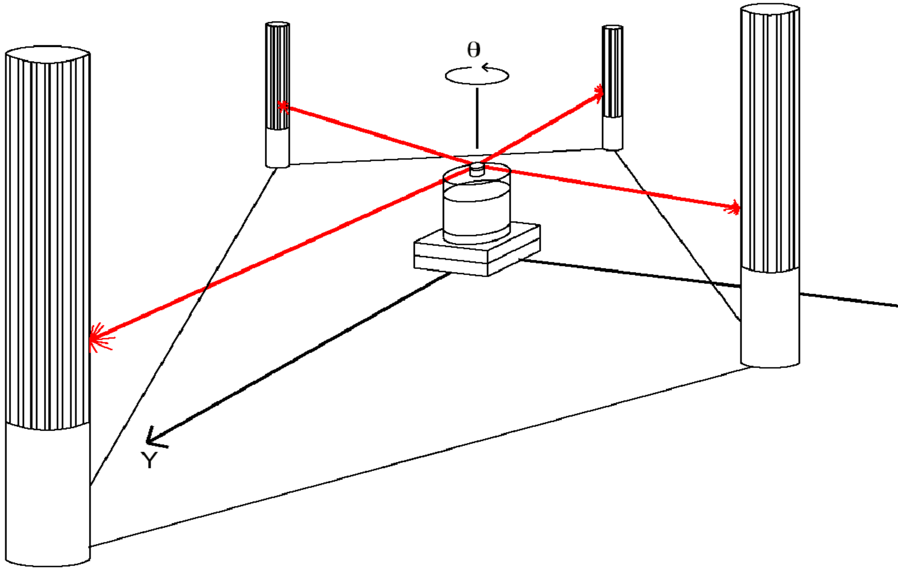
- **IMUs are extremely sensitive to measurement errors** in gyroscopes and accelerometers: **drift in the gyroscope** unavoidably undermines the estimation of the vehicle orientation relative to gravity, which results in incorrect cancellation of the gravity vector. Additionally observe that, because 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.



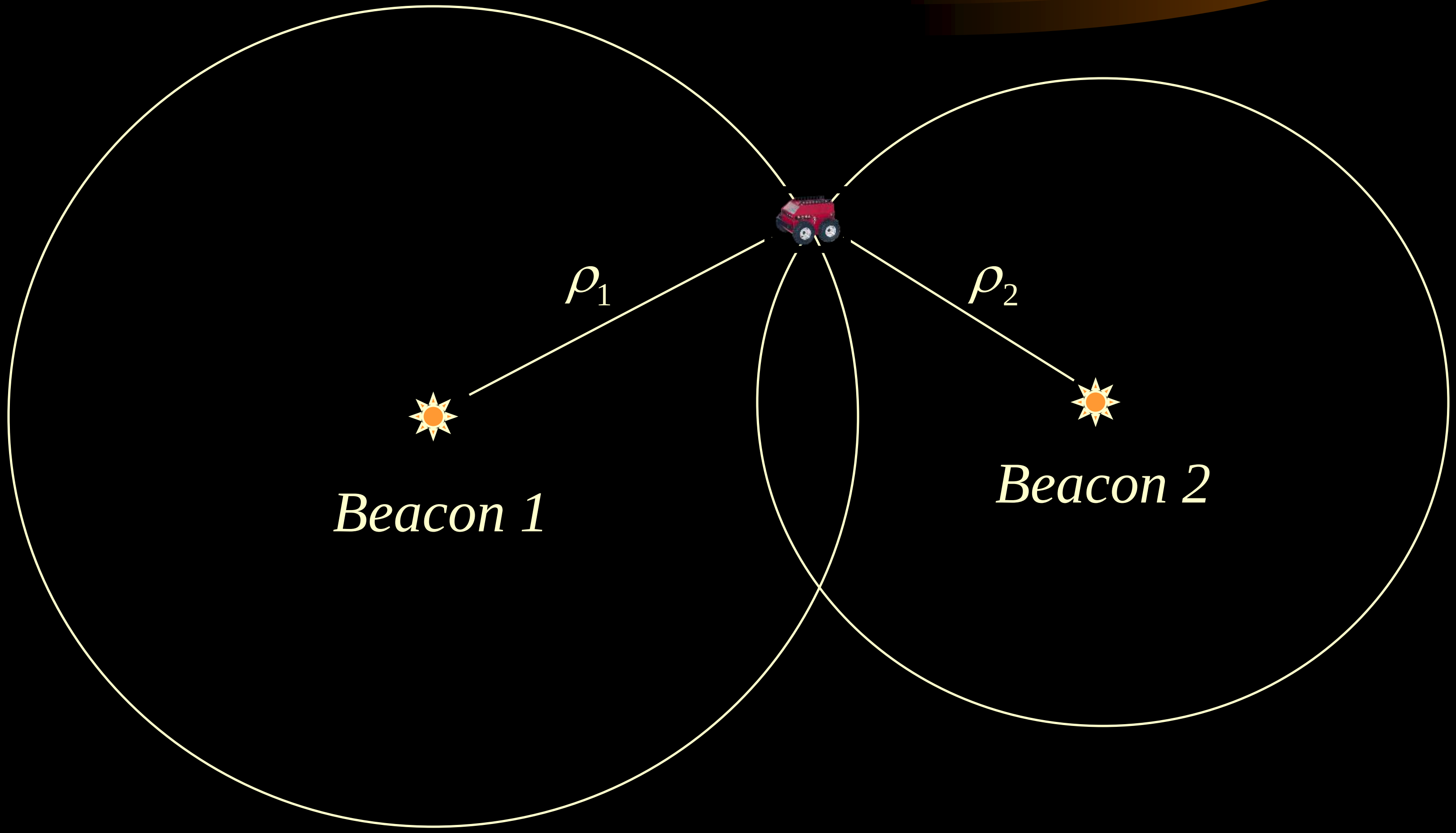
Ground-Based Active and Passive Beacons

- “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.

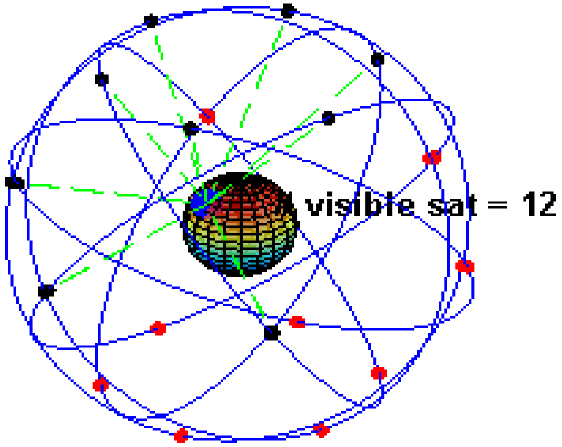


Triangulation

- An example in 2D:



Global Positioning System (GPS) (1)



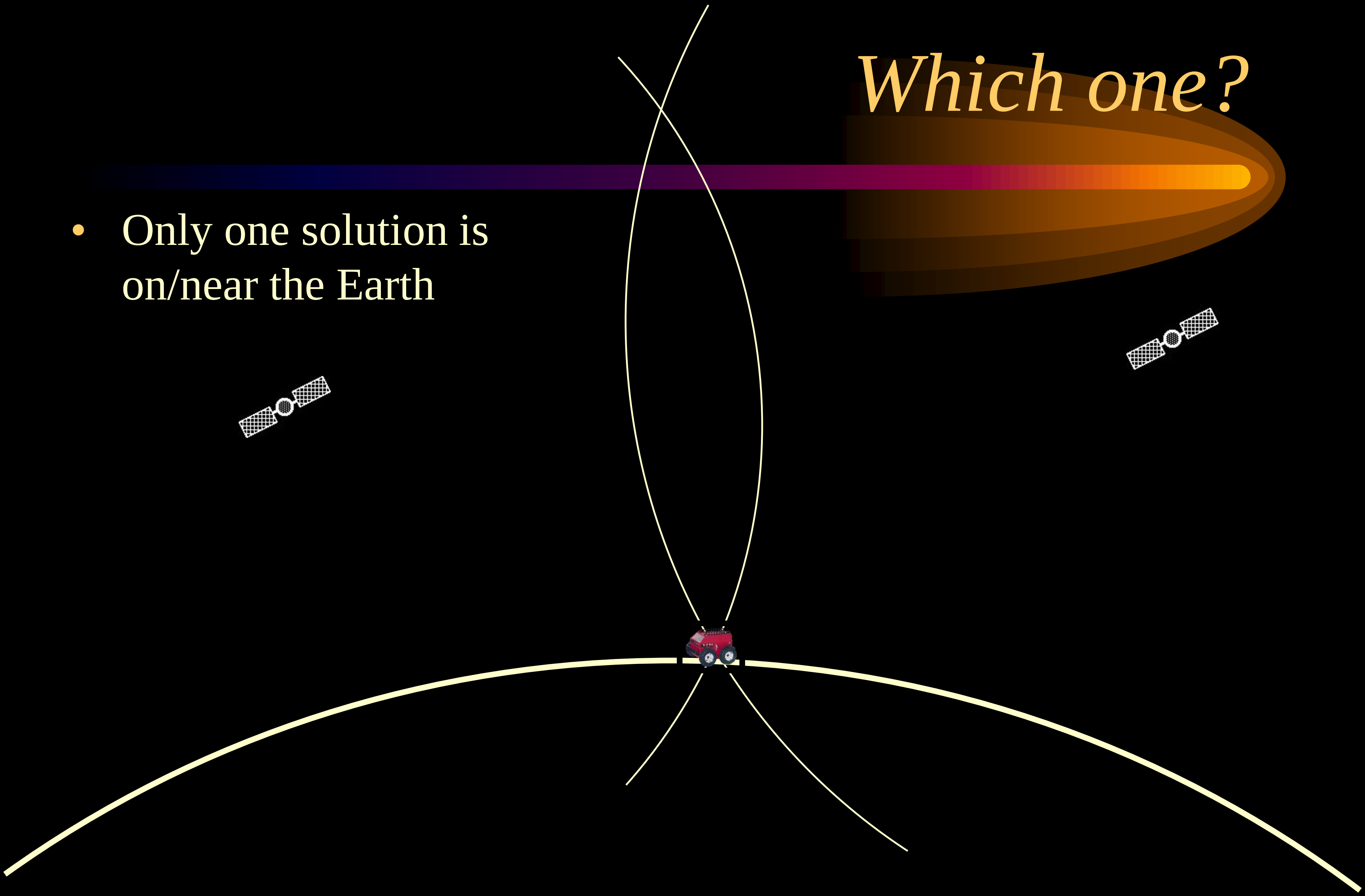
- Facts
  - Became accessible for commercial applications in 1995
  - Initially there were 24 satellites orbiting the earth every 12 hours at a height of 20.190 km.
  - 4 satellites were located in each of 6 orbits with 60 degrees orientation between each other.

- 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

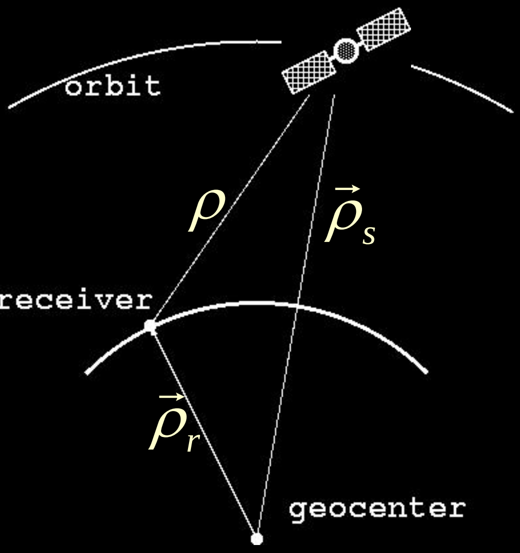
Which one?

- Only one solution is on/near the Earth



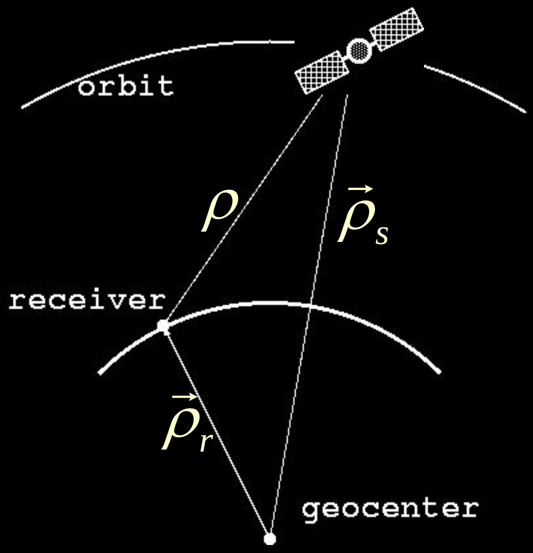
Position computation using GPS

- Signal sent at time t_s, received at t_r
- TOF: $\Delta t = t_r - t_s$
- Range: $\rho = c\Delta t$
- Also $\rho = \left|\vec{\rho}_s - \vec{\rho}_r\right|$
- Three unknowns: latitude, longitude and height
- Need ≥3 satellites



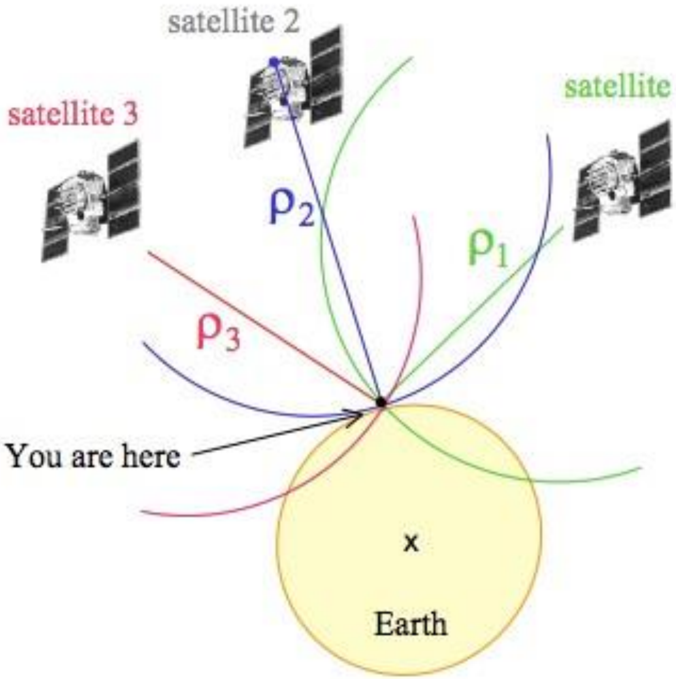
Time issues

- Satellite clocks are synchronized and extremely accurate
- Receiver clock may be offset
- TOF: $\Delta t = t_r - t_s + \delta$
- Pseudo-range: $R = c\Delta t = \rho + c\delta$
- Also $R = \left|\vec{\rho}_s - \vec{\rho}_r\right| + c\delta$
- Four unknowns: latitude, longitude, height and time offset
- Need ≥4 satellites



GPS positioning

- Simple positioning principle
- Satelites send signals, receivers received them with delay



$$\rho = (t_r - t_e) \times speed\ of\ \ light$$

$$\rho = \sqrt{(X_s - X_r)^2 + (Y_s - Y_r)^2 + (Z_s - Z_r)^2}$$

If we know at least three distance measurements, we can solve for position on earth.

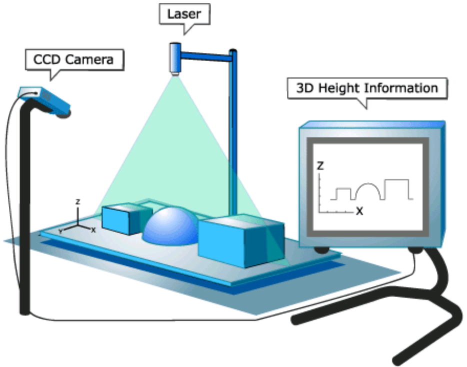
In practice four are used the time difference between the GPS receiver's clock and the synchronized clocks of the satellites is unknown.

Range sensors

- Sonar

- Laser range finder

- Time of Flight Camera
- Structured light



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.

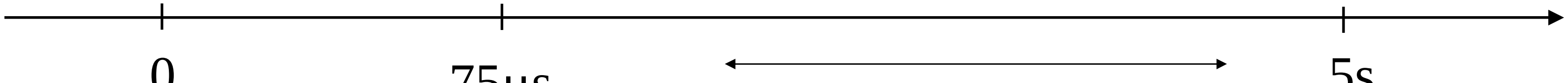
Range Sensors (time of flight) (2)

- 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

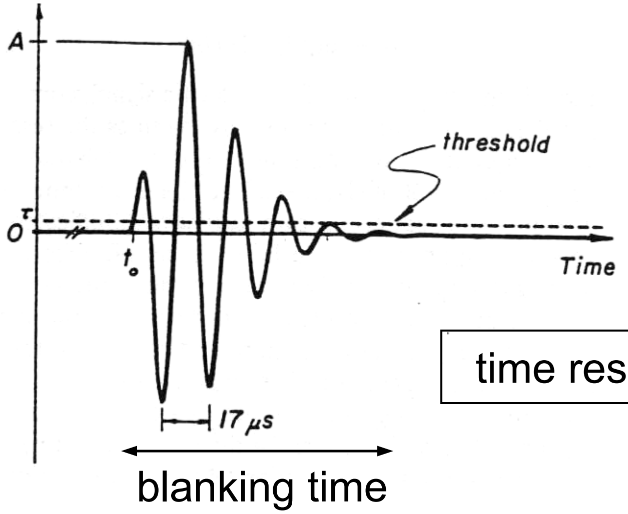
- The quality of time of flight range sensors mainly depends on:
  - **Inaccuracies** in the time of fight **measurement** (laser range sensors)
  - **Opening angle** of transmitted beam (especially ultrasonic range sensors)
  - Interaction with the target (surface, specular reflections)
  - **Variation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

Sonar sensing

single-transducer sonar timeline



0	75µs		.5s
a “chirp” is emitted into the environment	typically when reverberations from the initial chirp have stopped	the transducer goes into “receiving” mode and awaits a signal... limiting range sensing	after a short time, the signal will be too weak to be detected

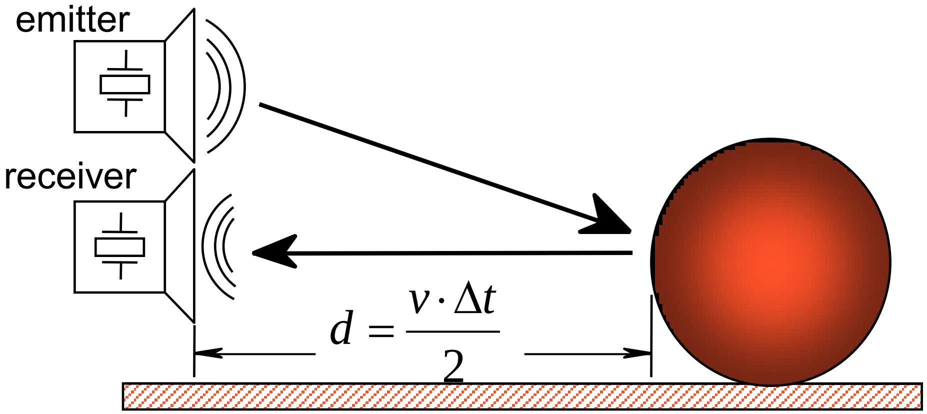


time response

Polaroid sonar emitter/receivers

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

Factsheet: Ultrasonic Range Sensor



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

<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*.

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

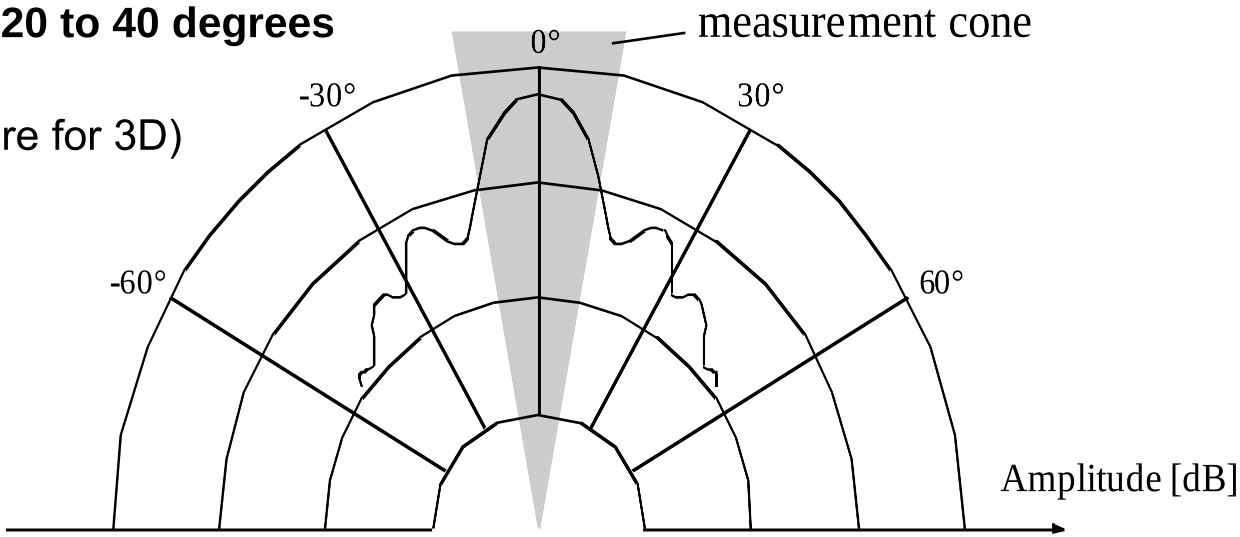
- The speed of sound *c* (340 m/s) in air is given by

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

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

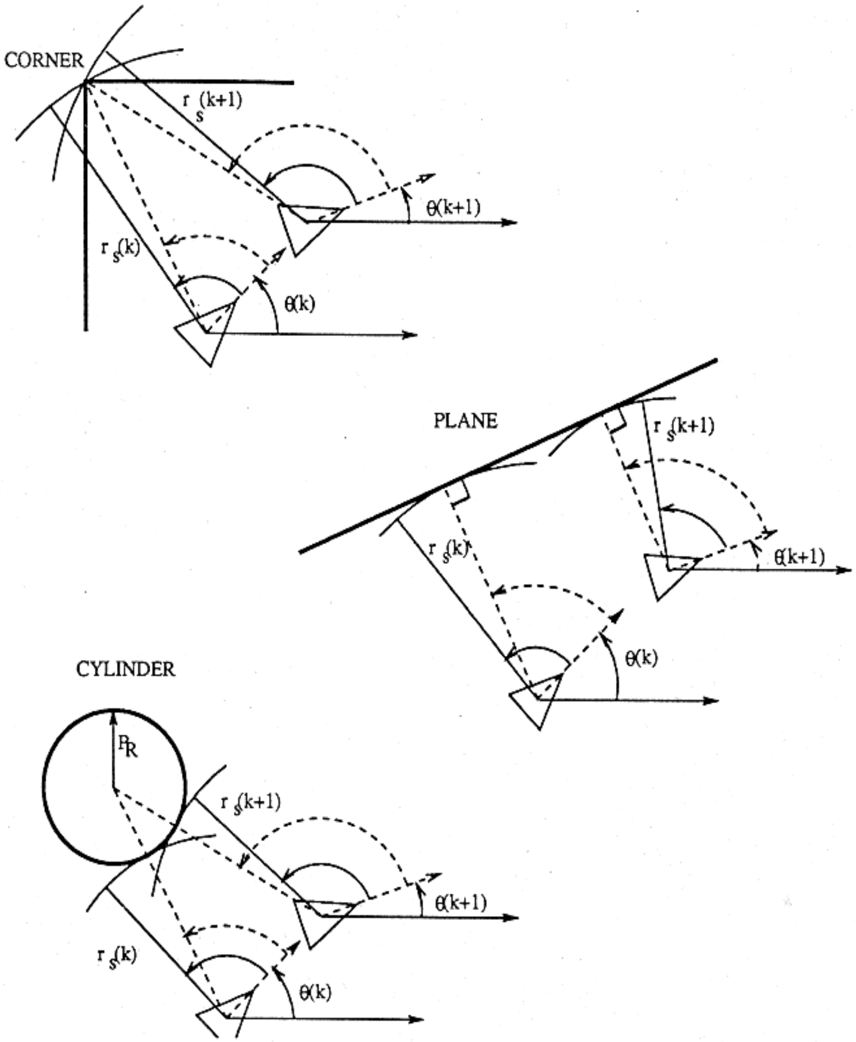
- typical frequency: 40kHz - 180 kHz
  - Lower frequencies correspond to longer maximal sensor range
- generation of sound wave via piezo transducer
  - transmitter and receiver can be separated or not separated
- **Range between 12 cm up to 5 m**
- **Resolution of ~ 2 cm**
- Accuracy 98% → relative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

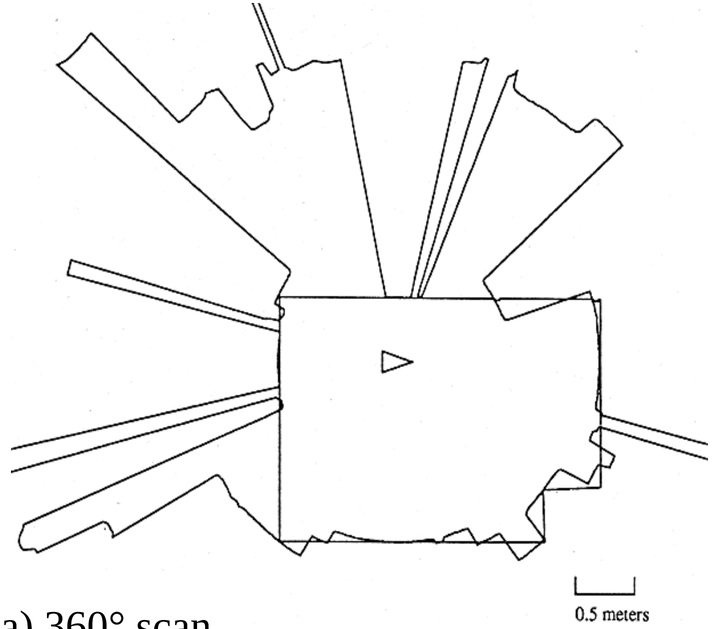


Typical intensity distribution of a ultrasonic sensor

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

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





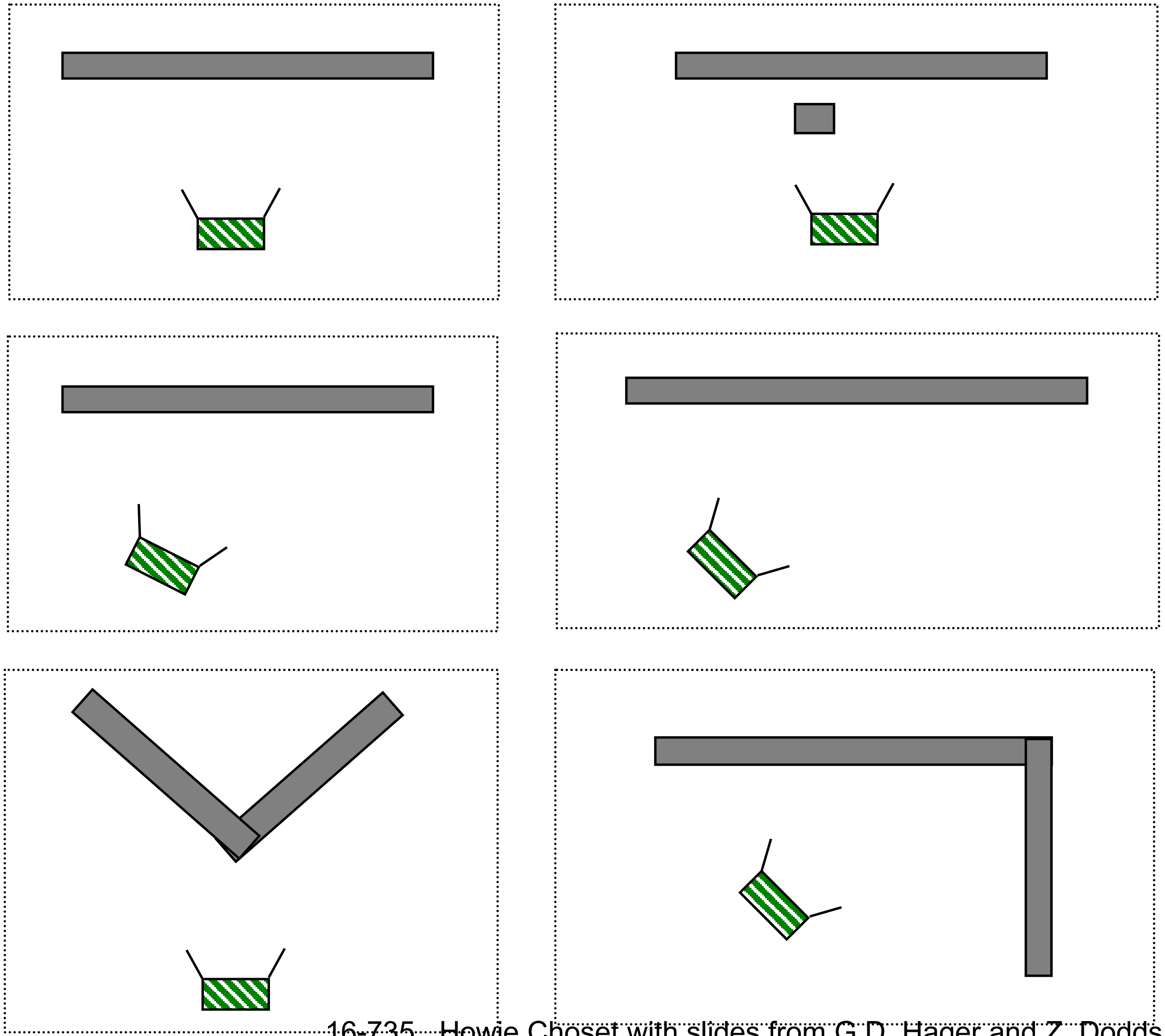
a) 360° scan

b) results from different geometric primitives

▬ walls (obstacles)

Sonar effects

▨ sonar

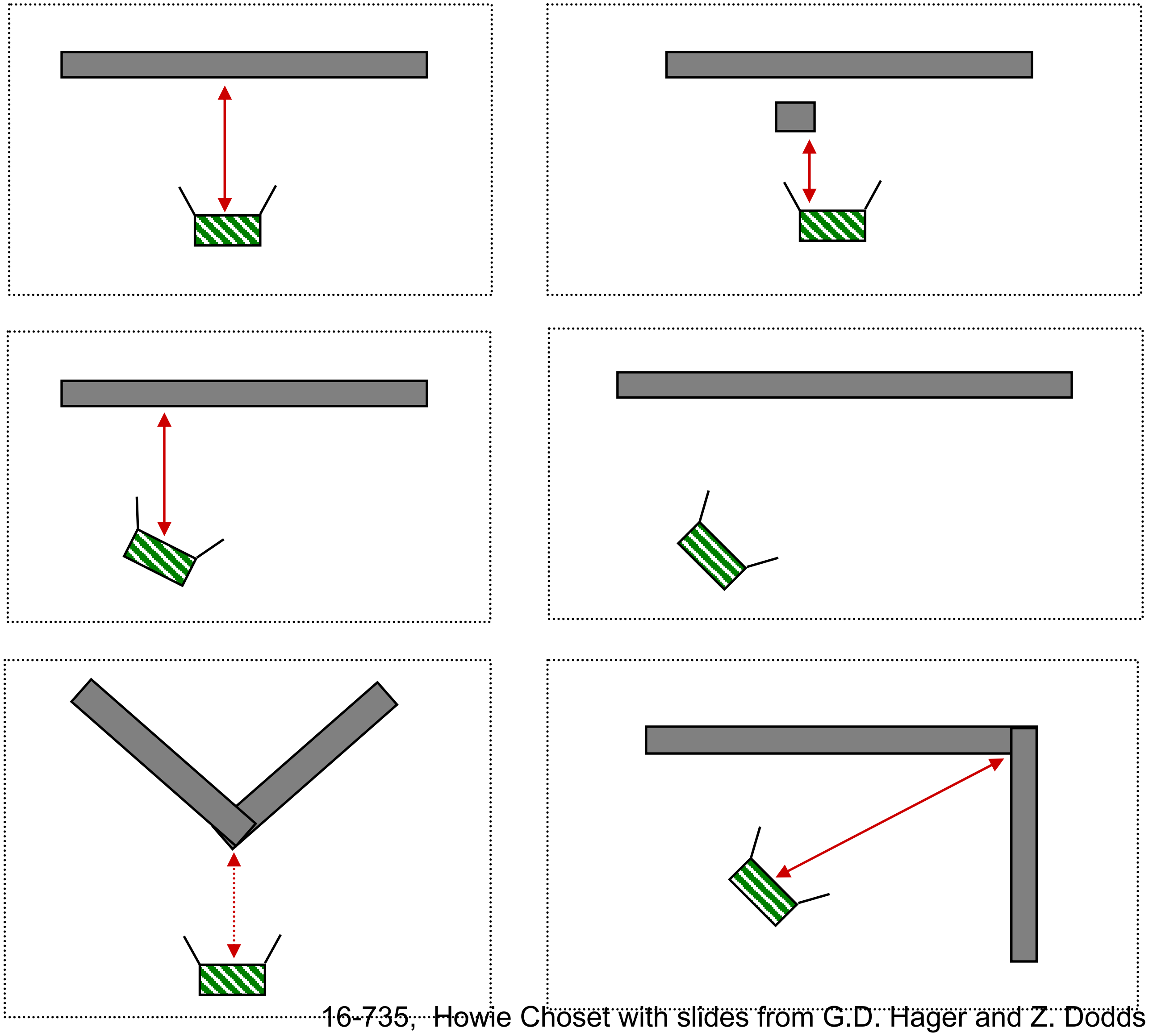


Draw the range reading that the sonar will return in each case…

walls
(obstacles)

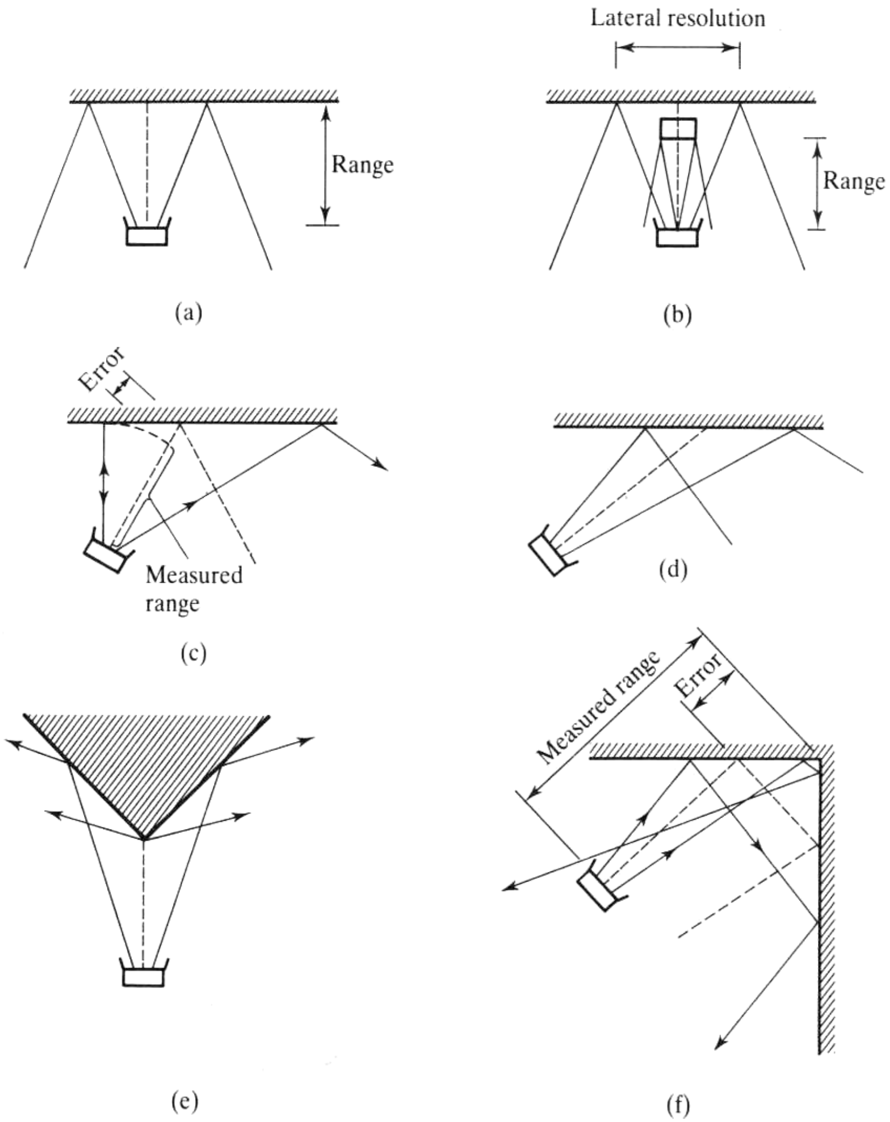
Sonar effects

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

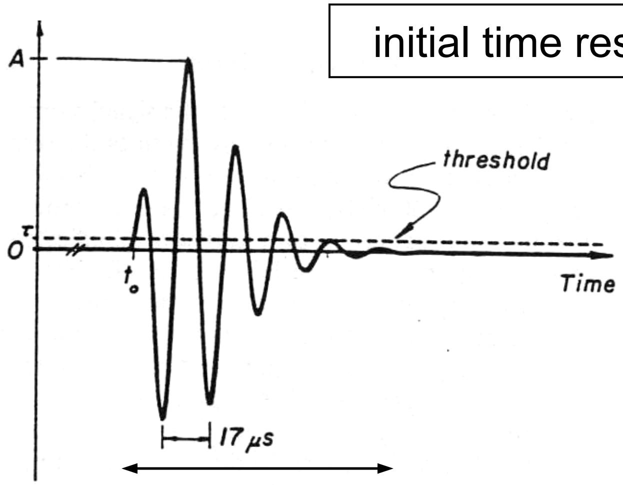
(f) Closed corners measure to the corner itself because of multiple reflections --> sonar ray tracing

s from G.D. Hager and Z. Dodds

resolution: time / space

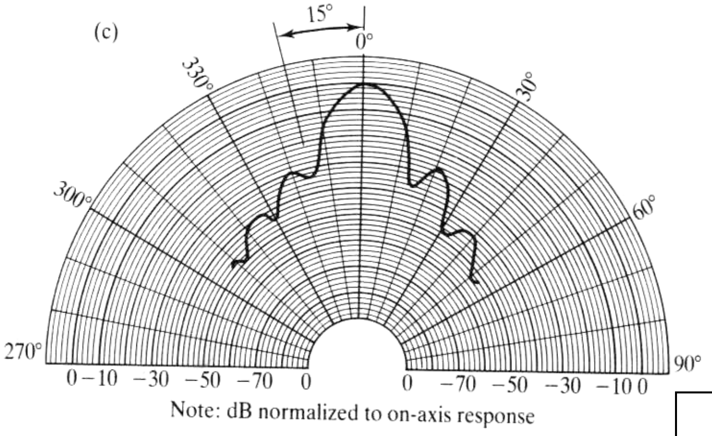
Sonar modeling

initial time response

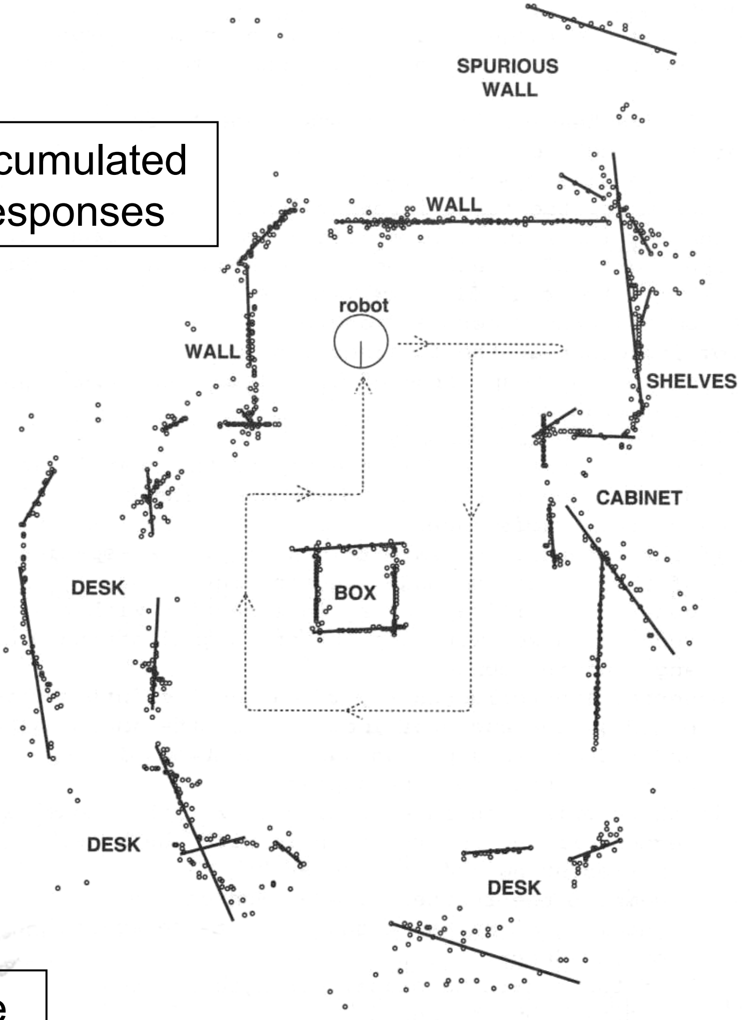


blanking time

cone width



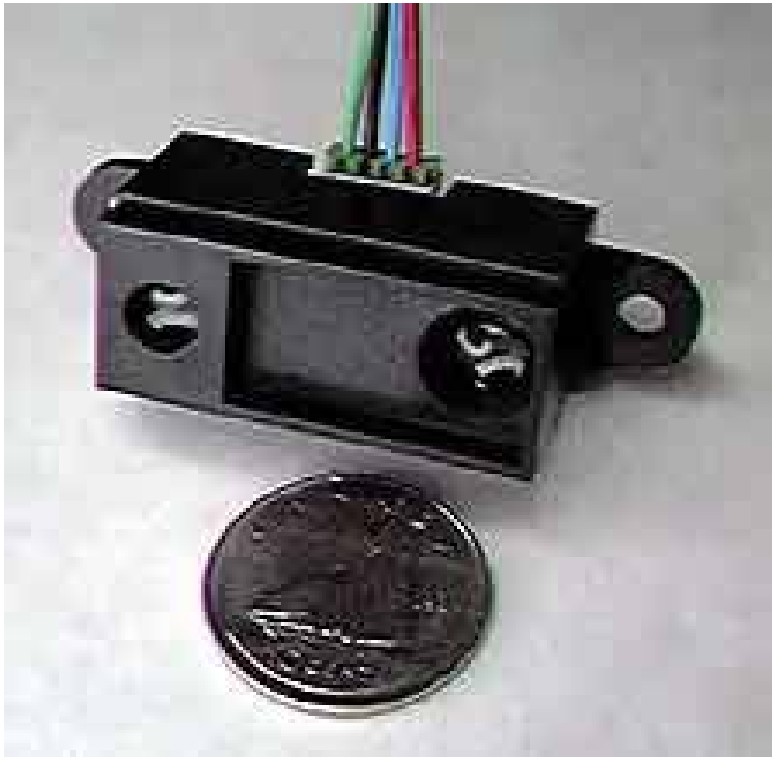
accumulated responses



spatial response

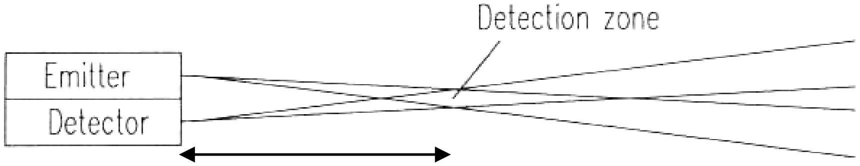
Infrared sensors

"Noncontact bump sensor"

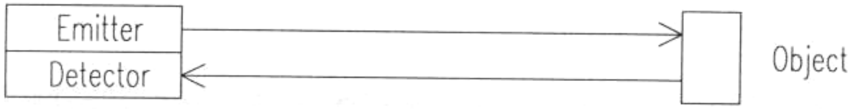


(1) sensing is based on light intensity.

"object-sensing" IR

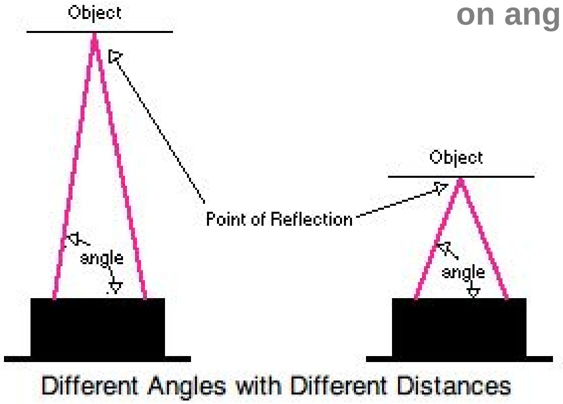


looks for changes
at this distance



diffuse distance-sensing IR

**(2) sensing is based
on angle receved.**

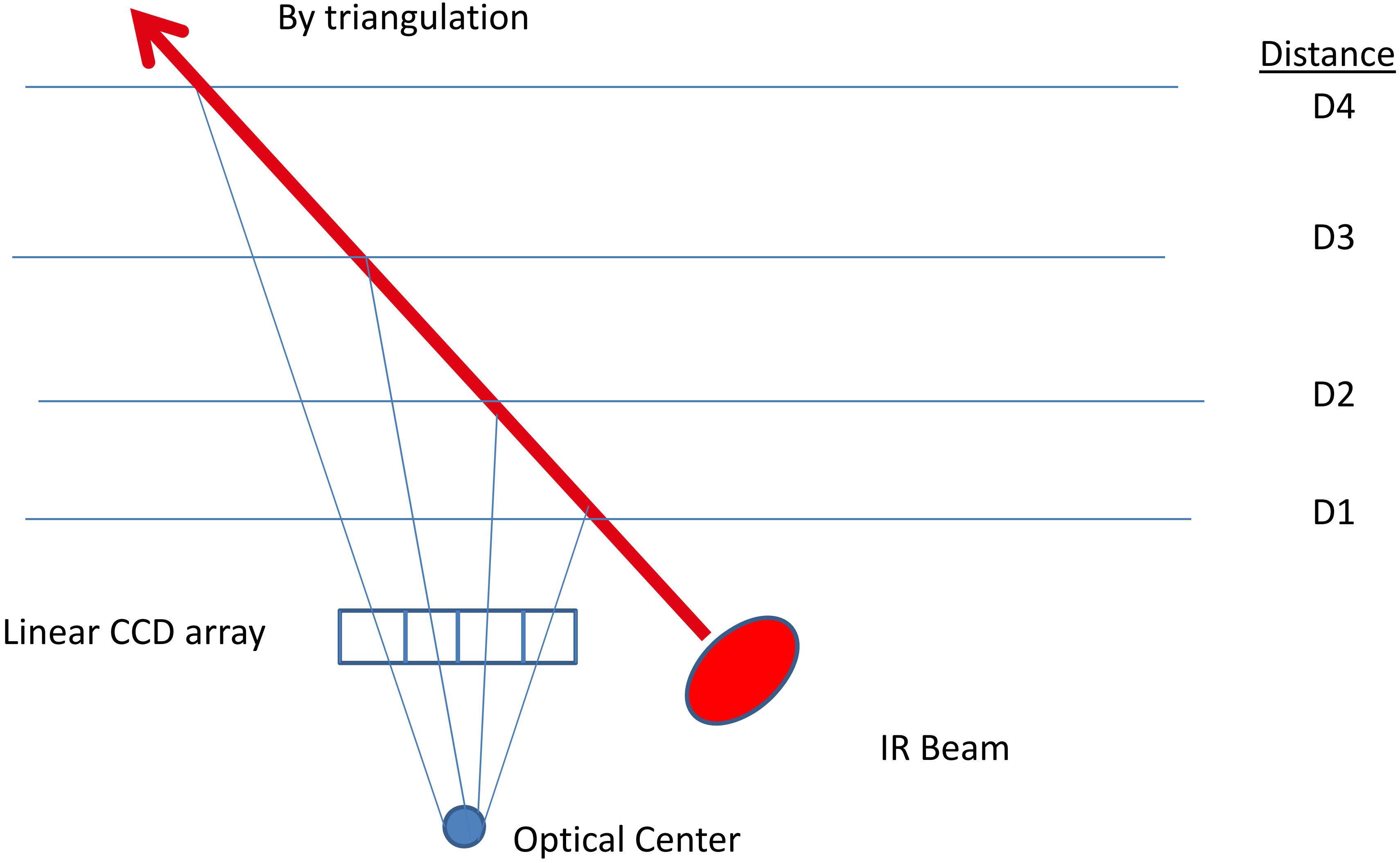


IR emitter/detector pair

IR detector

InfraRed (IR) Distance Sensor

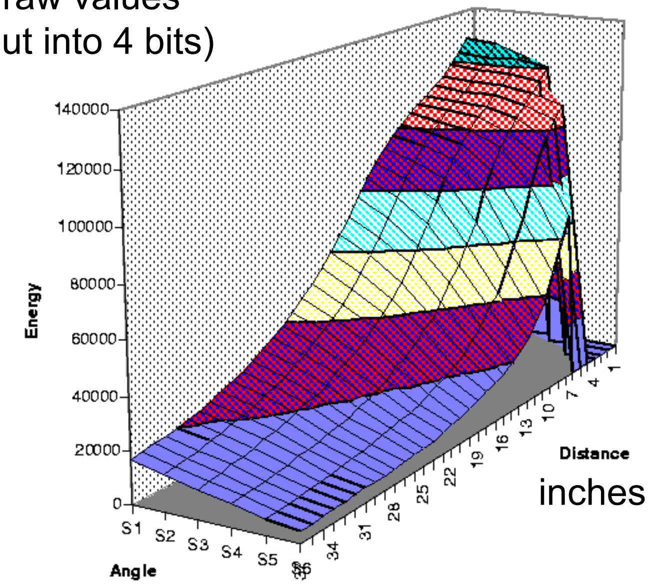
The IR beam causes a particular pixel in the linear CCD array to give maximum response (peak). The distance can then be computed By triangulation



Infrared calibration

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

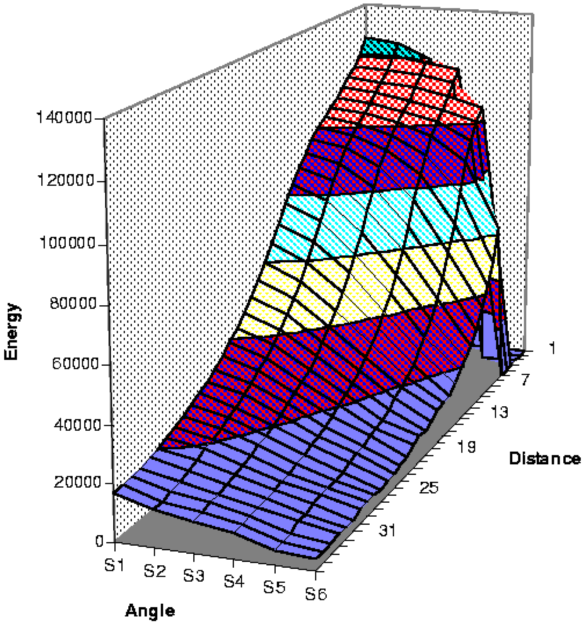
raw values
(put into 4 bits)



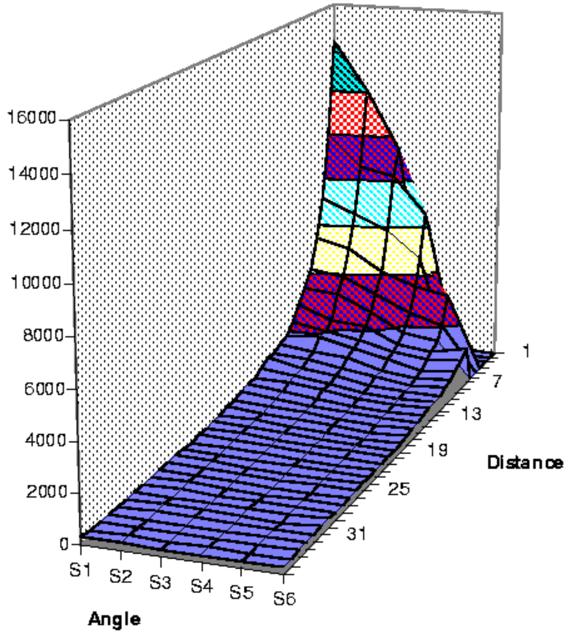
inches

15º increments

in the dark

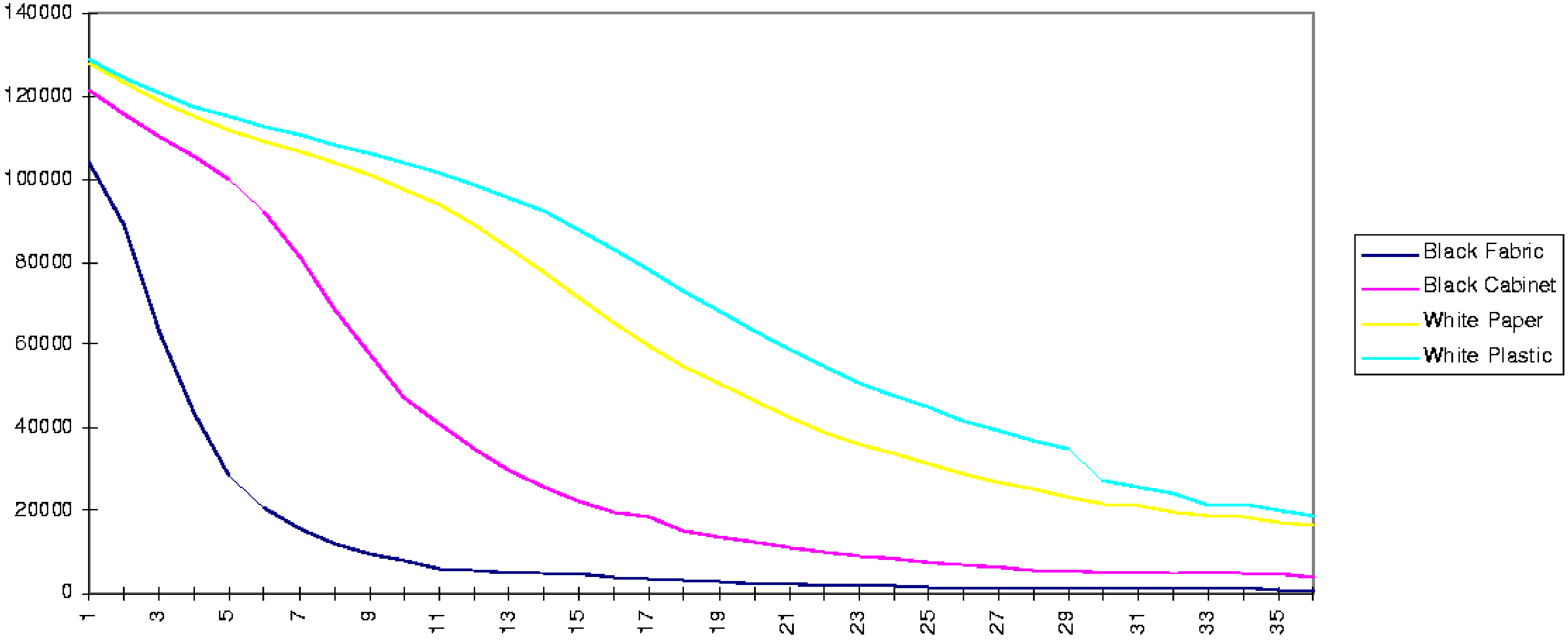


fluorescent light



incandescent light

Infrared calibration



energy vs. distance for various materials

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

(with no ambient light)

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

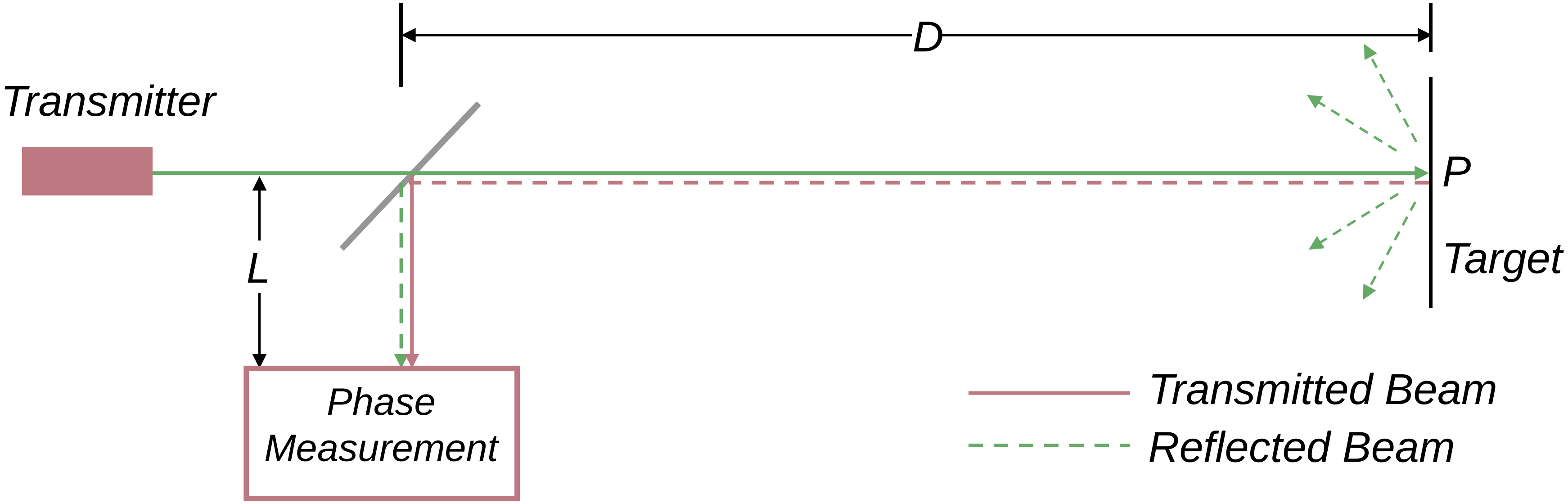
- Laser range finder are also known as Lidar (LIght Detection And Ranging)

SICK

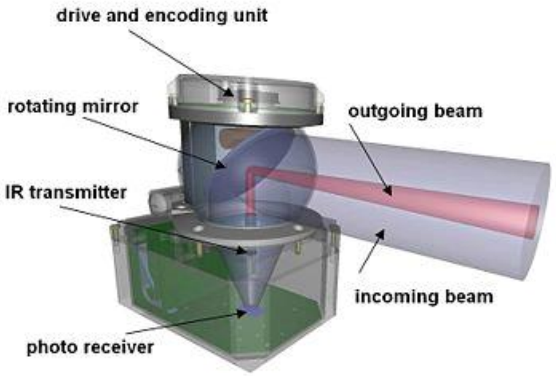
Alaska-IBEO

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

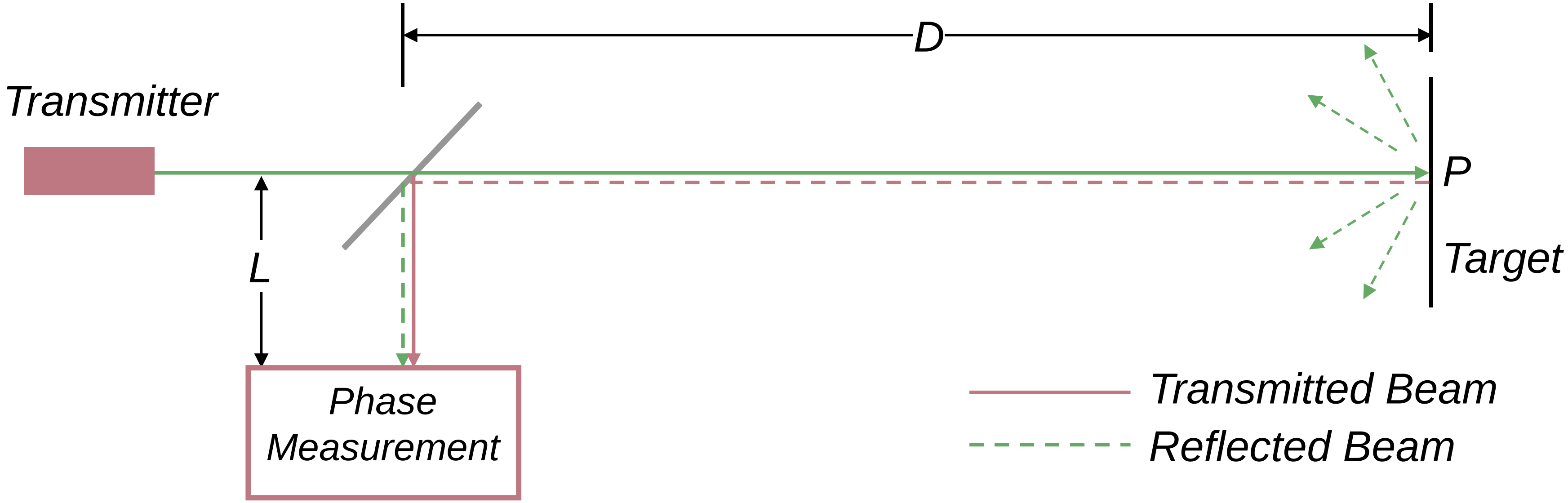


Laser Range Sensor (time of flight, electromagnetic) (2)

- 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

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.

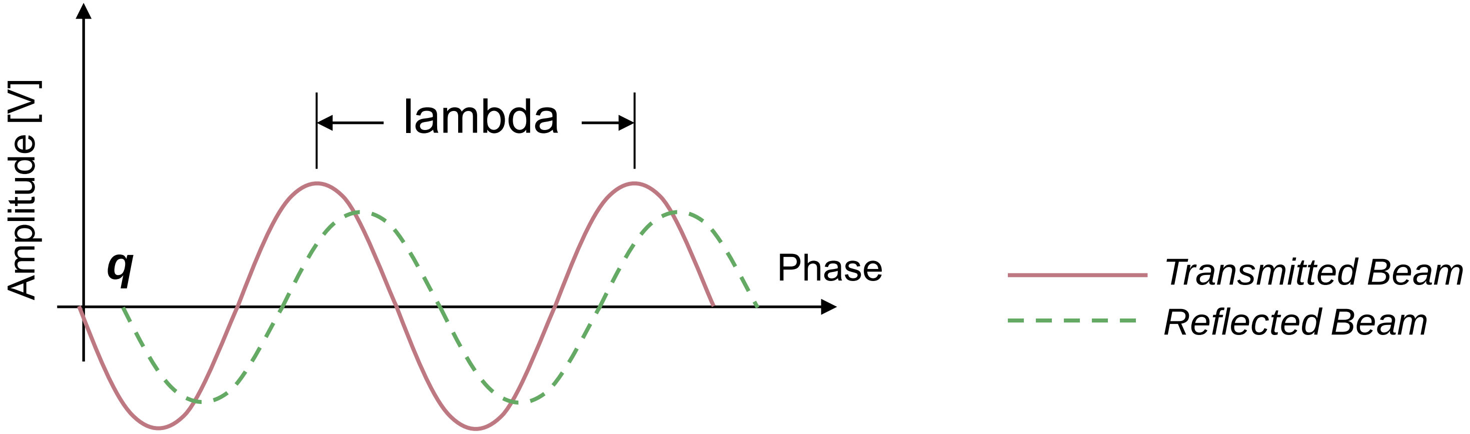
  - for f = 5 MHz (as in the A.T&T. sensor), λ = 60 meters

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

- Distance D, between the beam splitter and the target

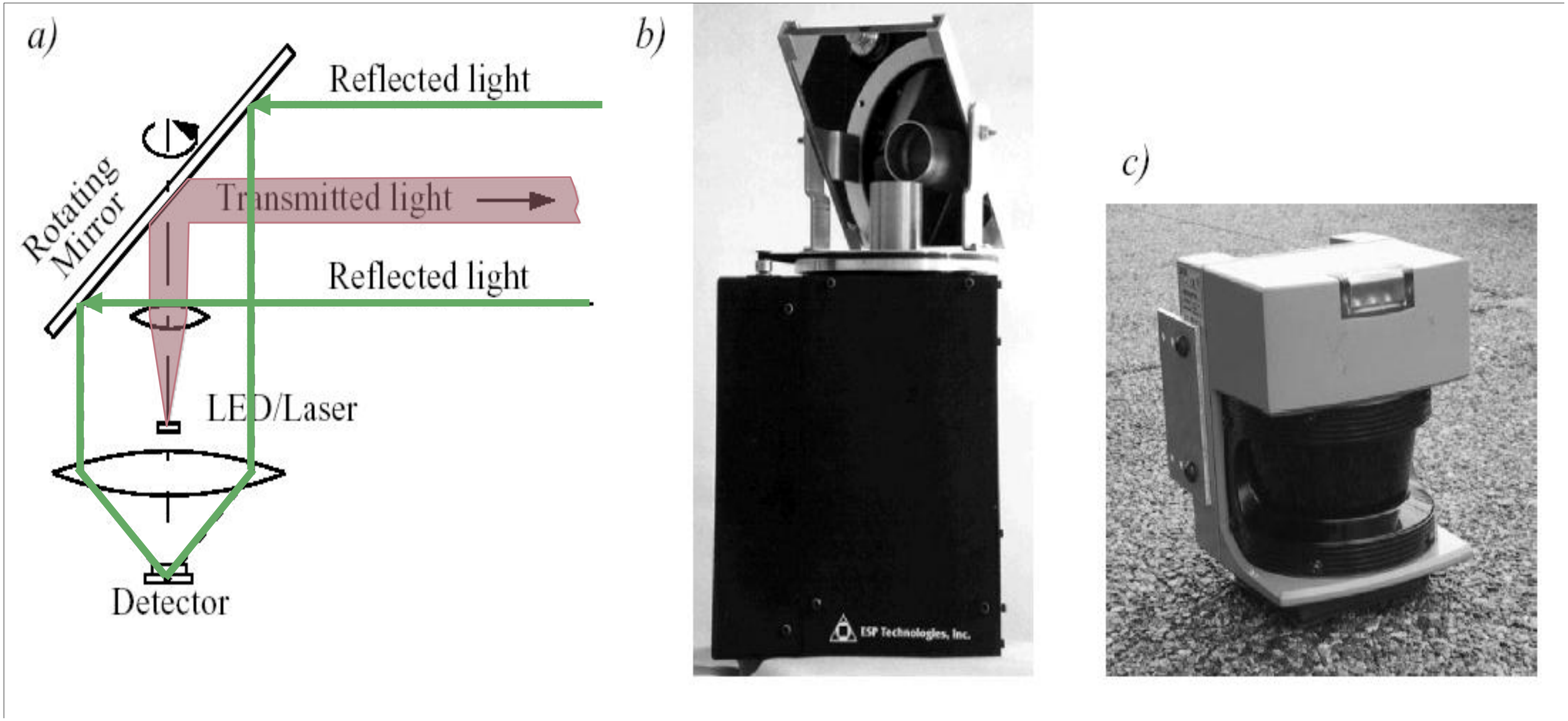
$$D = \frac{\lambda}{4\pi}\theta$$

- 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



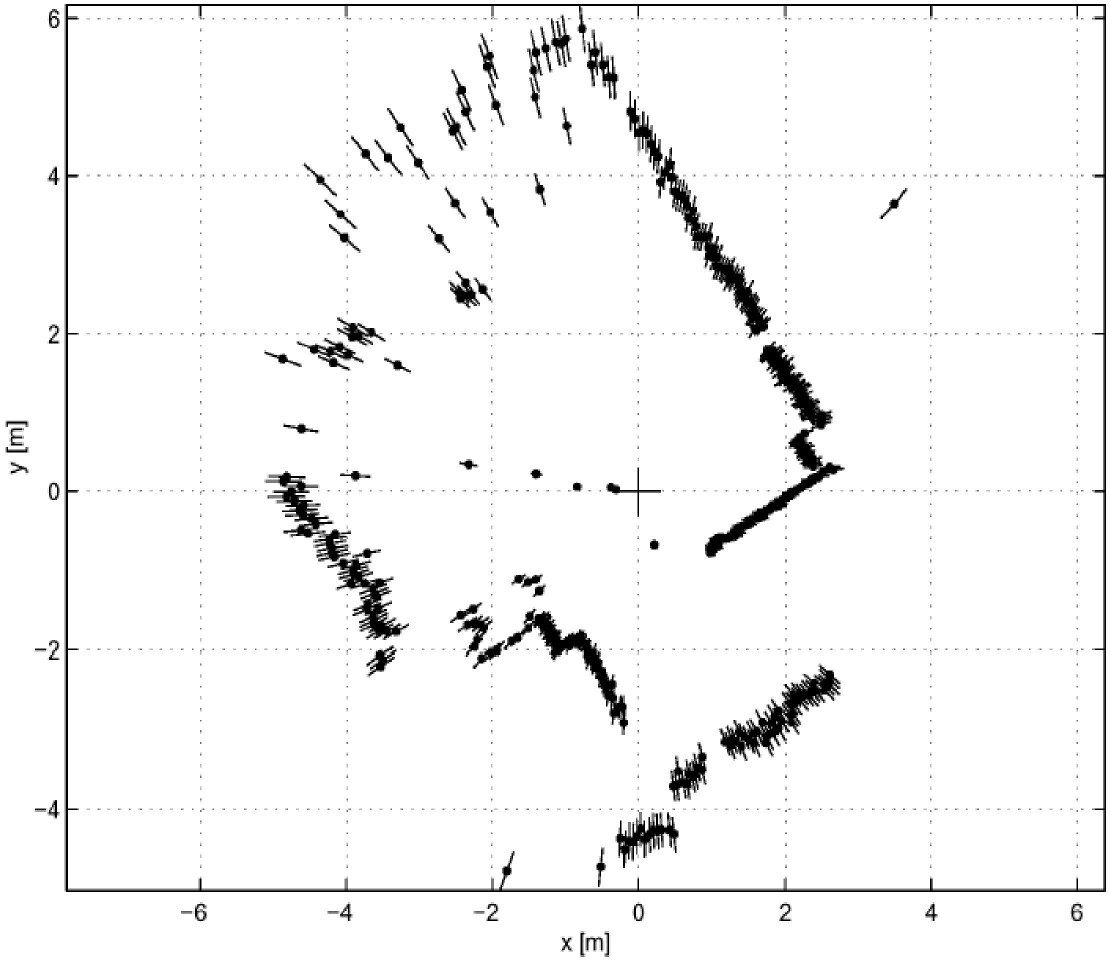
Laser Range Sensor (time of flight, electromagnetic) (5)

- 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.

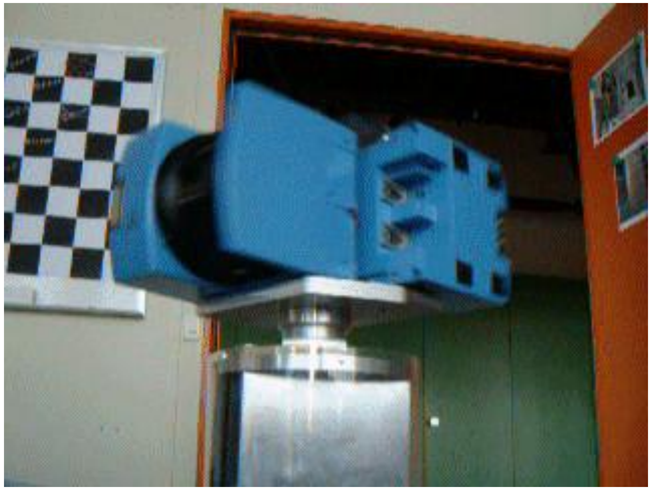


The SICK LMS 200 Laser Scanner

- 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

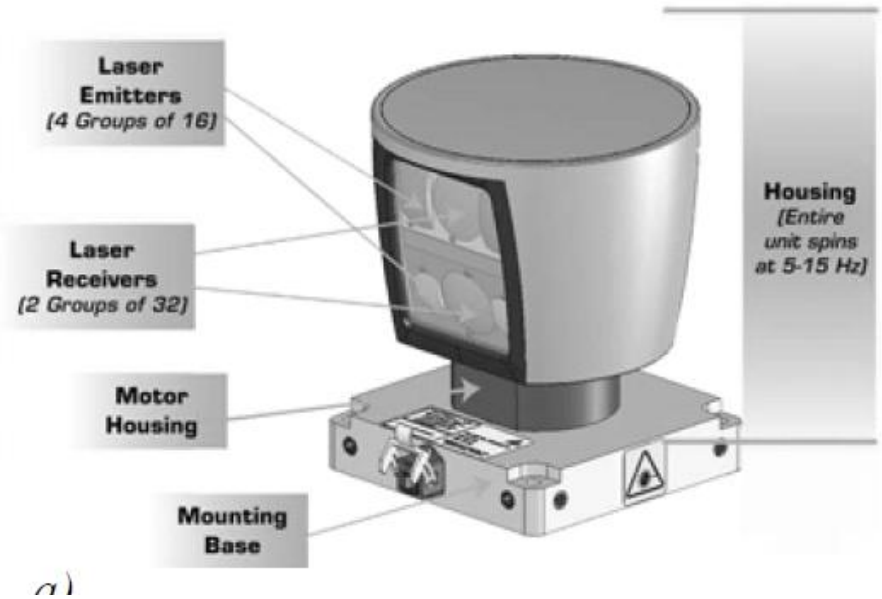
3D Laser Range Finder (1)

- **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!



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!)

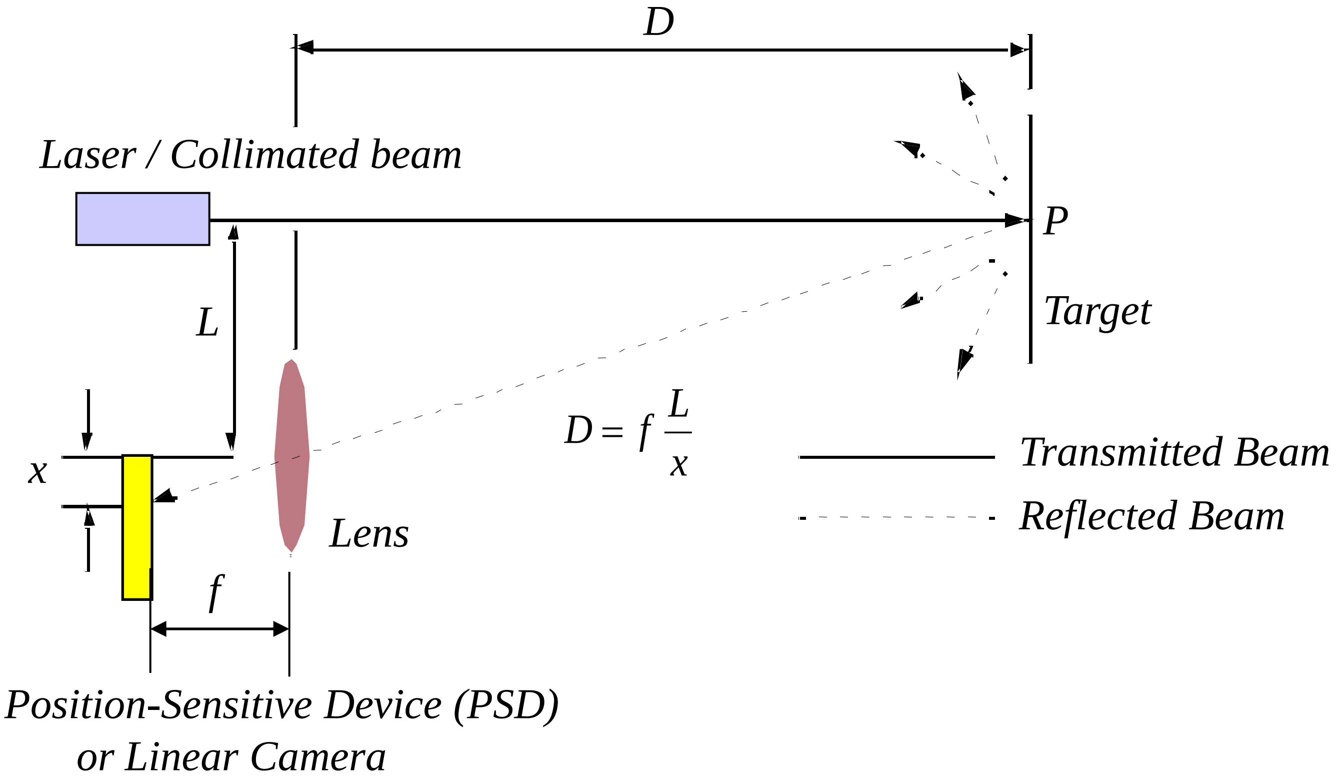


C Carnegie Mellon University

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

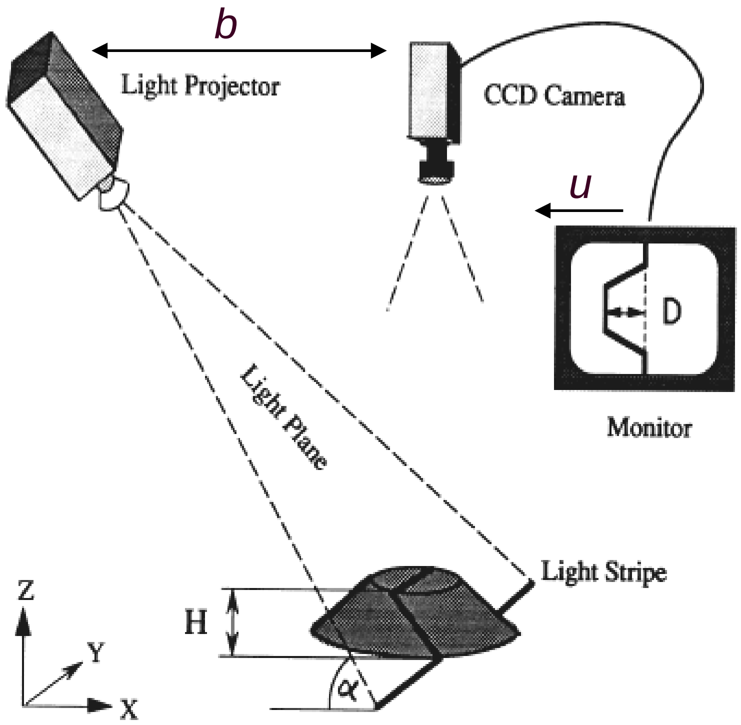
Laser Triangulation (1D)



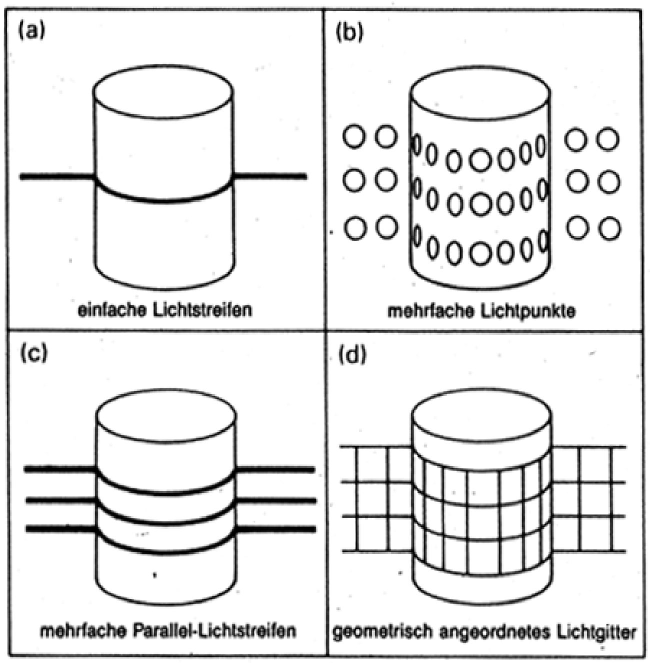
- Principle of 1D laser triangulation: $D = f\frac{L}{x}$

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

a

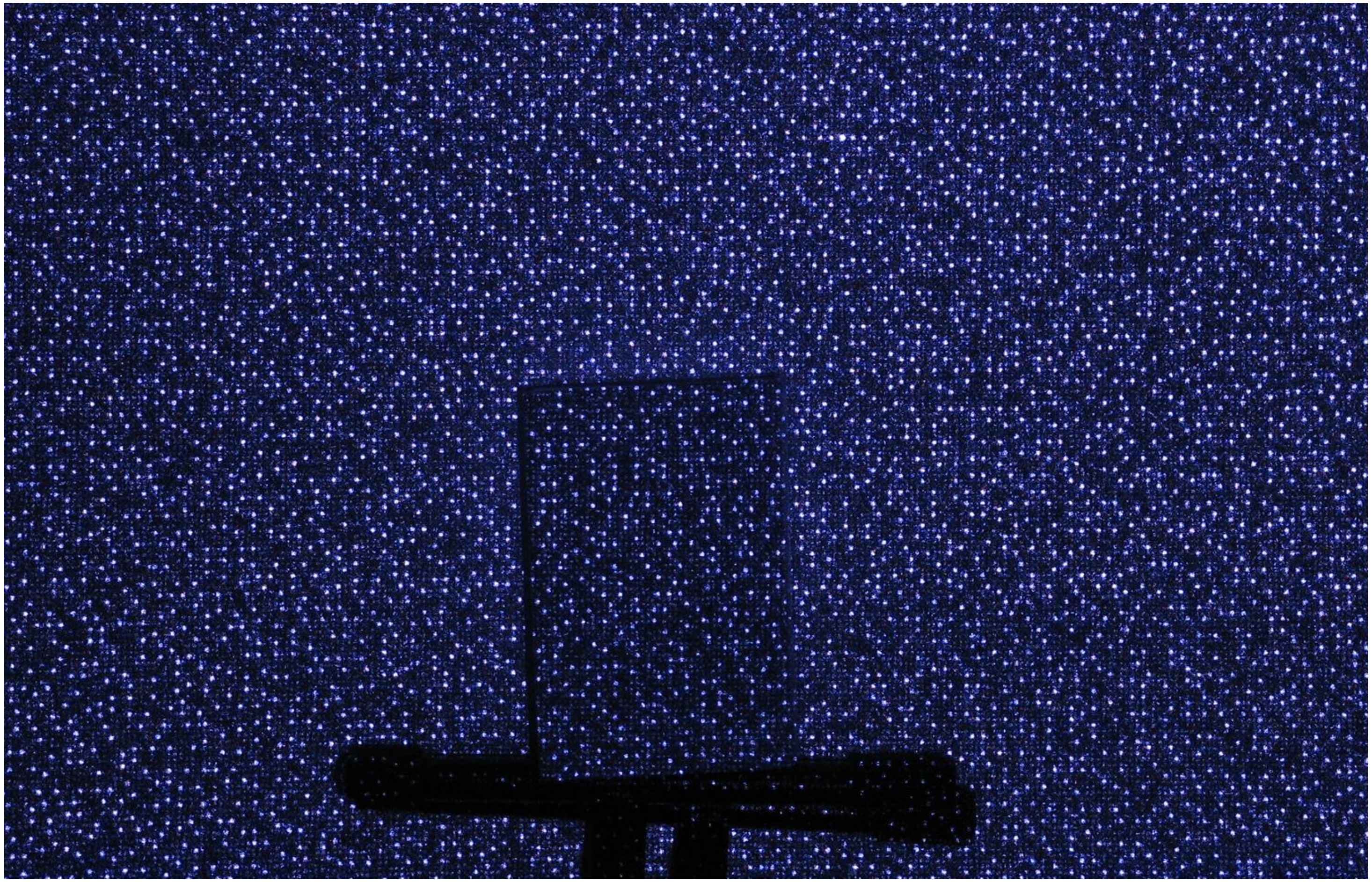


b

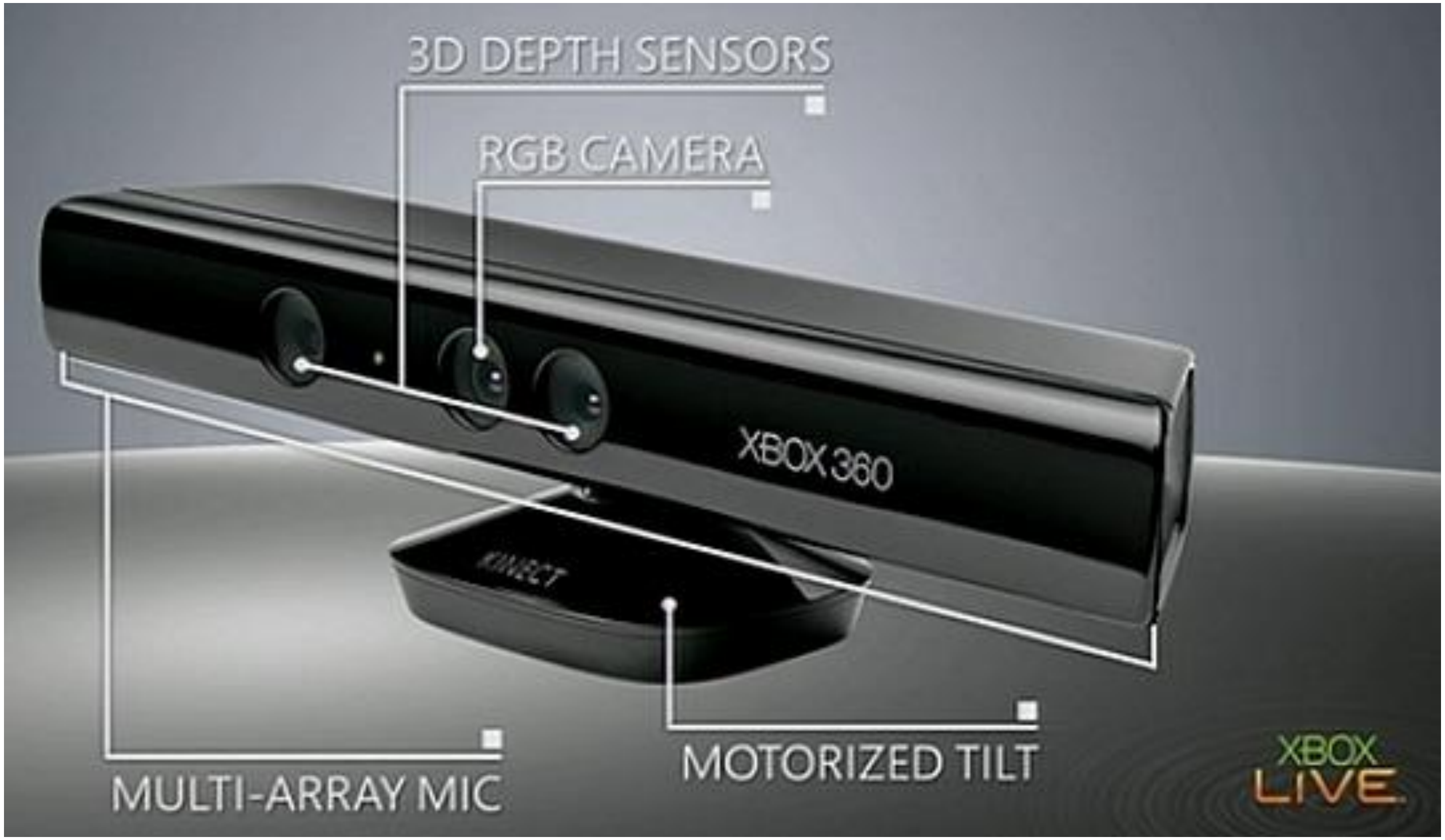


- Eliminate the correspondence problem by projecting structured light on the scene.
- Slits of light or emit collimated light (possibly laser) by means of a rotating mirror.
- Light perceived by camera
- Range to an illuminated point can then be determined from simple geometry.

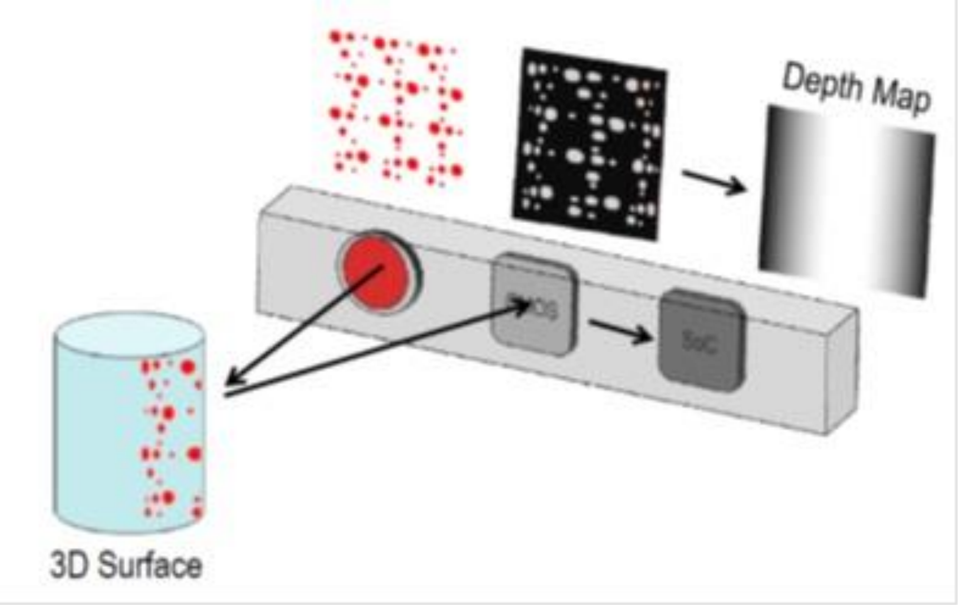
Microsoft Kinect



Kinect


3D DEPTH SENSORS
RGB CAMERA
XBOX 360
KINECT
MULTI-ARRAY MIC
MOTORIZED TILT
XBOX LIVE

Kinect 1

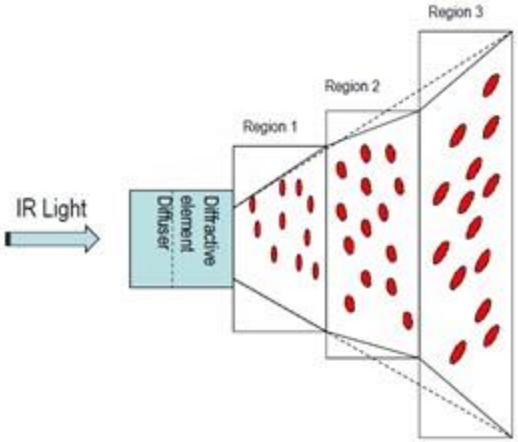


Kinect uses a speckle pattern of dots that are projected onto a scene by means of an IR projector, and detected by an IR camera.

Each IR dot in the speckle pattern has a unique surrounding area and therefore allows each dot to be easily identified when projected onto a scene. The processing performed in the Kinect in order to calculate depth is essentially a stereo vision computation.

web link

Kinect 1



IR speckles are of three different sizes that are optimised for use in different depth ranges, meaning . The Kinect can operate between approximately 1m and 8m.

In addition to pure pixel shift the Kinect also compares the observed size of a particular dot with the original size in the reference pattern. Changes in size or shape are also factored into the depth calculations. These calculations are all performed on the device in real time as part of a system on chip (SOC) and results in a depth image of 640×480 pixels and a frame rate of 30fps.

Reading the Laser Scanner: rostopic echo scan

```
header:
  seq: 4614
  stamp:
    secs: 1447
    nsecs: 770000000
  frame_id: /camera_depth_frame
angle_min: -0.521567881107
angle_max: 0.524276316166
angle_increment: 0.00163668883033
time_increment: 0.0
scan_time: 0.0329999998212
range_min: 0.449999988079
range_max: 10.0
ranges: [nan, nan, nan, nan, nan, nan, nan,
nan, nan, nan, nan, nan, nan, nan, n
an, nan, nan, nan, nan, nan, nan, nan, nan,
nan, nan, nan, nan, nan, nan, nan, n
an, nan, nan, nan, nan, nan, nan, nan, nan,
nan, nan, nan, nan, nan, nan, nan, n
an, nan, nan, nan, nan, nan, nan, nan, nan,
nan, nan, nan, nan, nan, nan,
```

Angle_min = -0.52 rad. = -30 deg.

Angle_max = +0.52 rad. = +30 deg

Angle_increment = 0.0016366 rad.

Angle_increment = .093 deg.

Scan array is filled from min_angle to max_angle (scan is filled right to left).

msg.ranges[0] = rightmost scan
msg.ranges[len(msg.ranges) -1] = leftmost

Reading the Laser Scanner: range_ahead.py

```
#!/usr/bin/env python
import rospy
from sensor_msgs.msg import LaserScan
# BEGIN MEASUREMENT
def scan_callback(msg):
    range_center = msg.ranges[len(msg.ranges)/2]
    range_left = msg.ranges[len(msg.ranges)-1]
    range_right = msg.ranges[0]
    print "range ahead: left - %0.1f" %range_left, " center- %0.1f" %range_center,
        " right - %0.1f" %range_right
#END MEASUREMENT

rospy.init_node('range_ahead')
scan_sub = rospy.Subscriber('scan', LaserScan, scan_callback)
rospy.spin()
```