CMPUT 399 student reading and in-class presentation

Purpose:

- Learn how to research for information about robotics projects.
  - *Search web, library books and research papers*
  - *Skim through many pages. Find a few sources of core info*
  - *Read core in detail*

- Learn how to summarize survey information.
  - *What is the common goal of projects/papers?*
  - *Do they share techniques? Do some use different techniqies for the same goal?*
  - *Unify notation and make it into a survey.*
- Make an interesting presentation for your classmates:
  - *Use visuals: images, diagrams, videos (google image and video search)*
- Get some practice for the course project and proposal.

CMPUT 399 student reading and in-class presentation

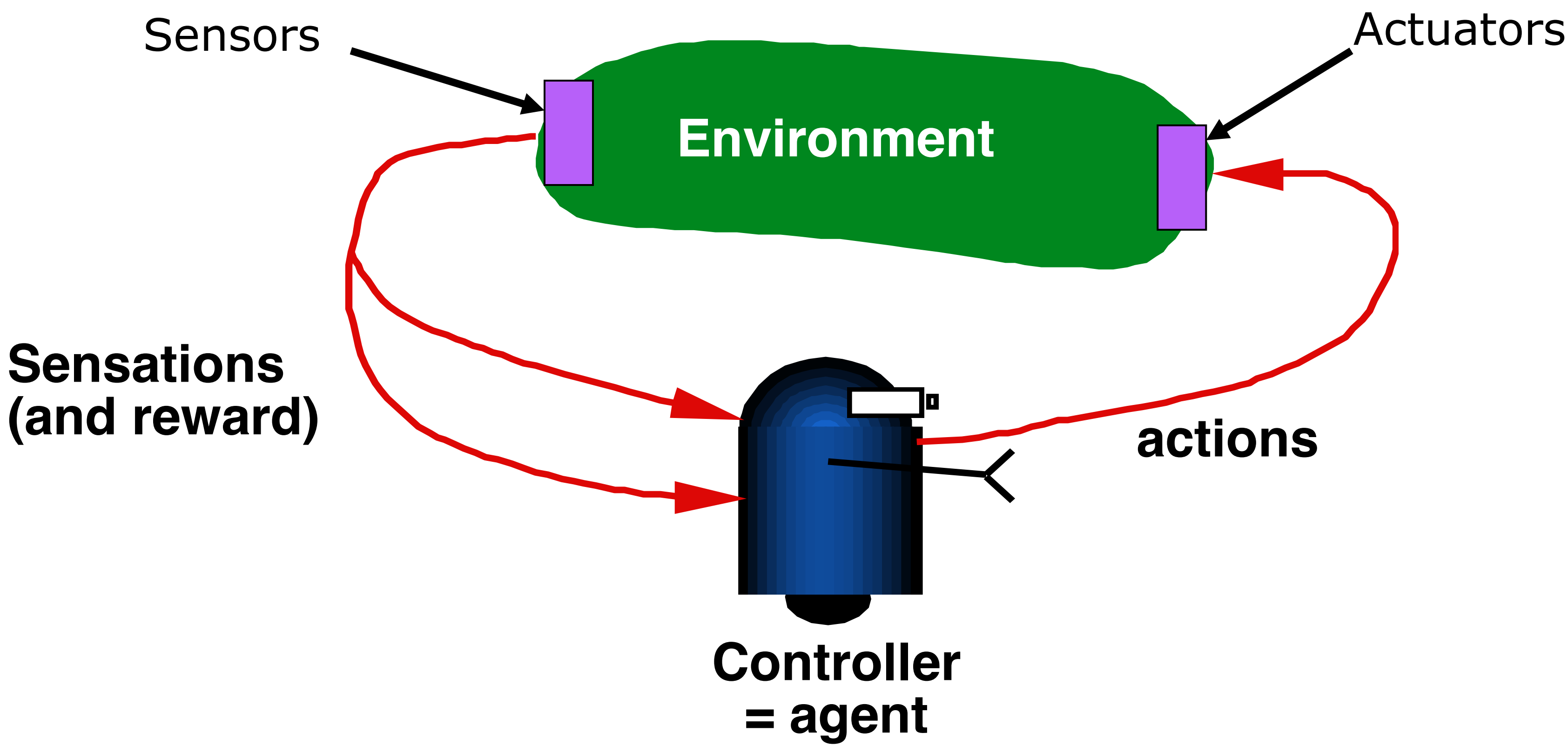
- Presentations of robotics literature or readings projects from web pages.
- The presentation is done individually. Each student books a 10 minute slot
- The presentation can focus on a paper, a project web page, or be a summary of a several papers/projects. Some visuals are expected, e.g. images and videos you find on the web.
- Find a title/topic, and list some sources, or give a web link to a web page you make with a source list.
  List not required at signup. You can add the resources as you go along
- In-class presentations: Tue Oct 9, Thu Oct 11

Robotics:
Sensors and Actuators

Cmput399

Martin Jagersand
With slides from Zach Dodds, Roland Siegwart, Csaba Szepesvári

Defining sensors and actuators



Related Concepts:

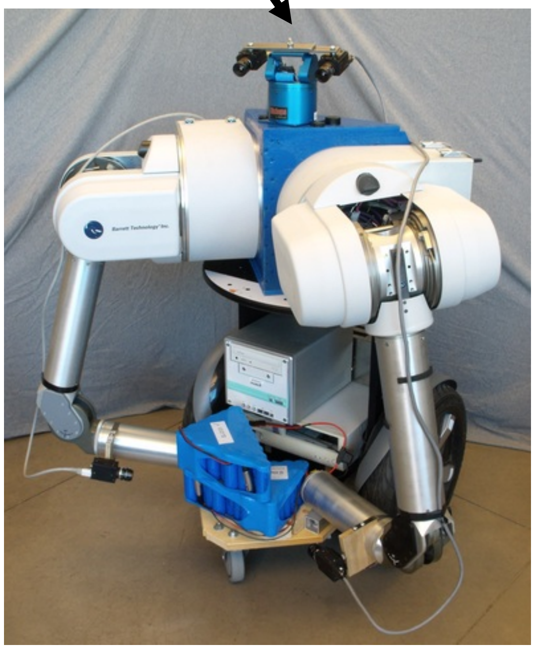
- Sensing -> Features -> Perception

Mobile manipulators in research

- Cameras

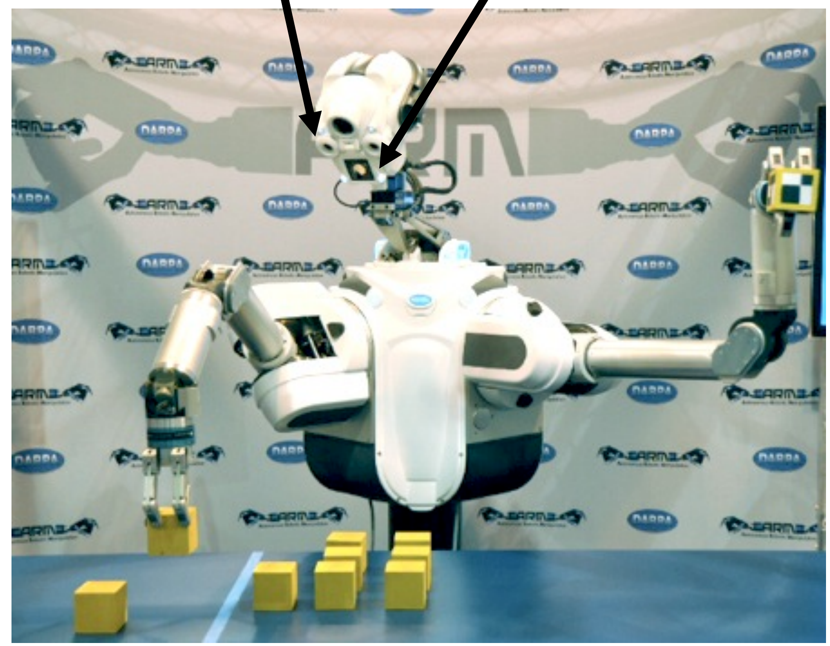
Laser range finder

Cameras and 3D TOF laser



Our robot

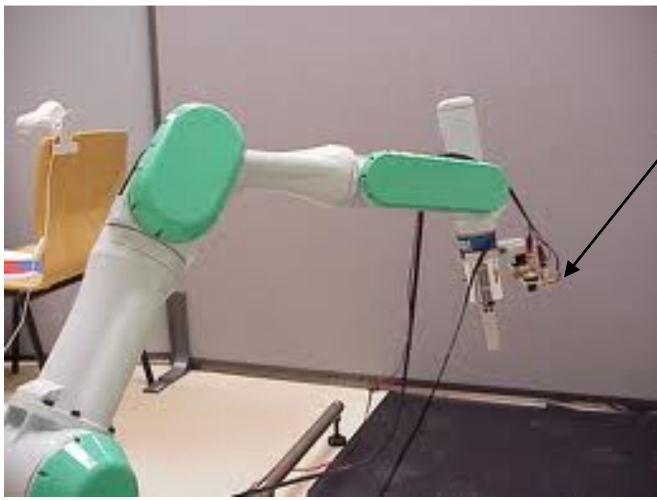
CMU Herb



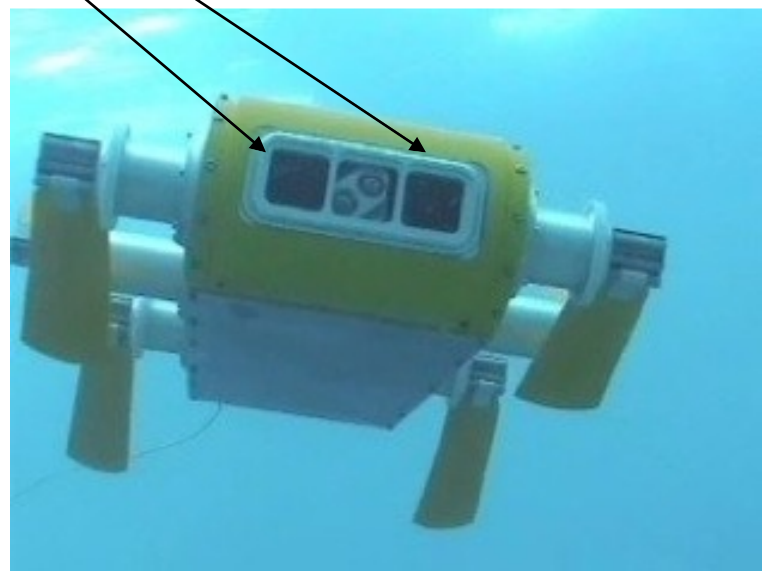
Darpa Manip challenge

Industrial robot **Underwater robot**

Cameras



Mitsubishi PA10



McGill Aqua

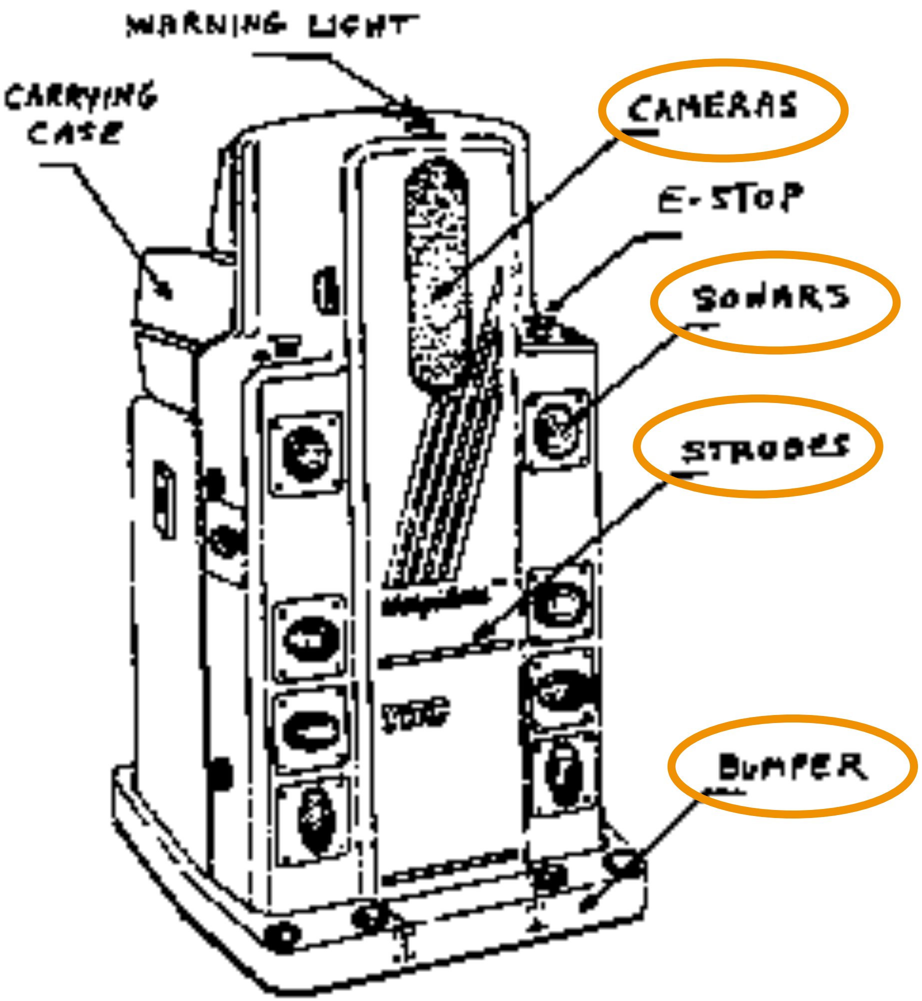
Sensors on a $300 UAV

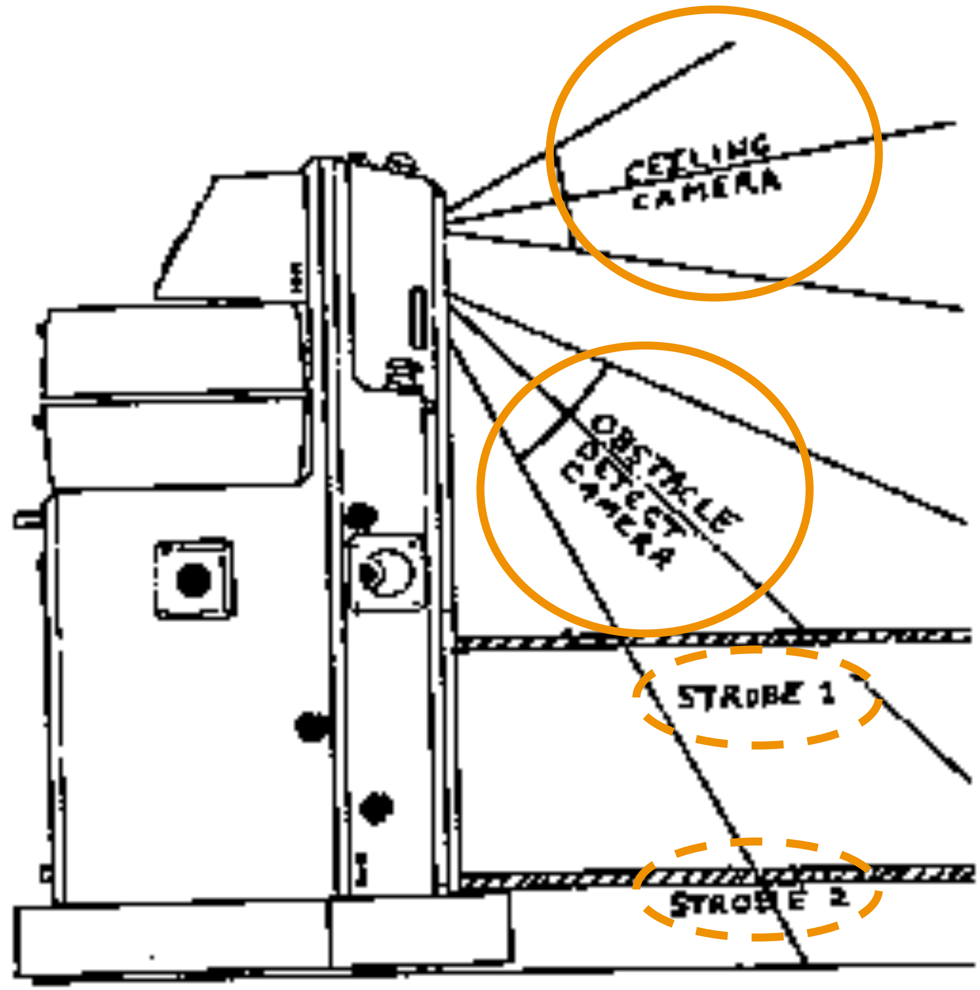
- AR.Drone

Front and down facing camera

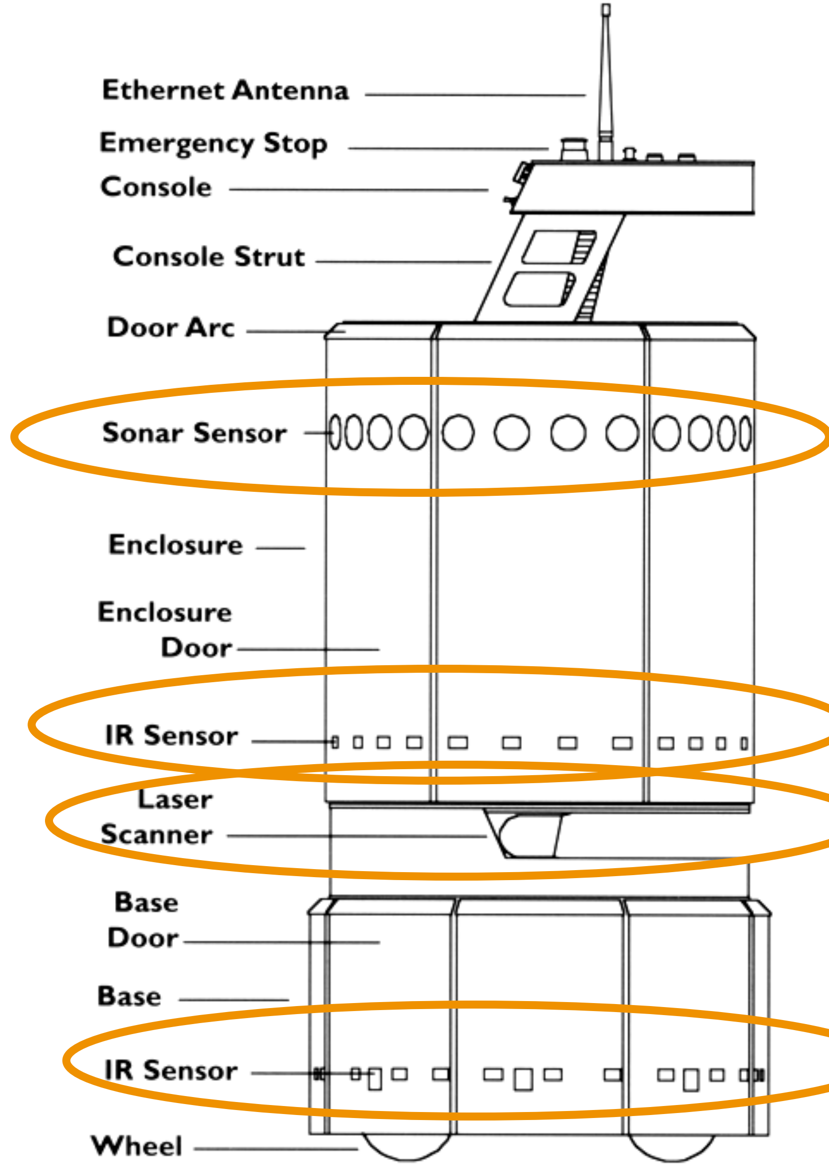
Ultrasonic distance (height)

HelpMate, Transition Research Corp.

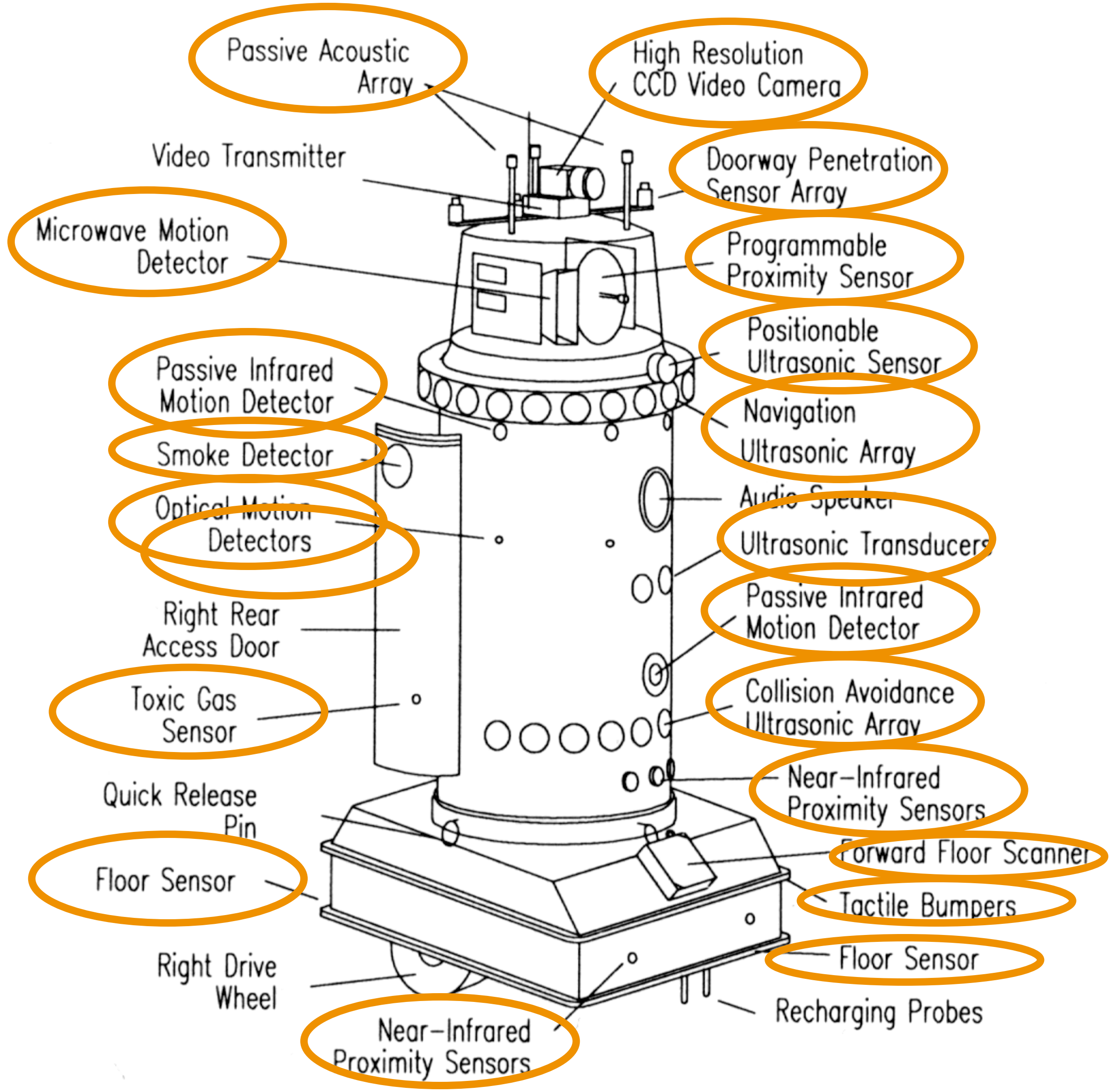




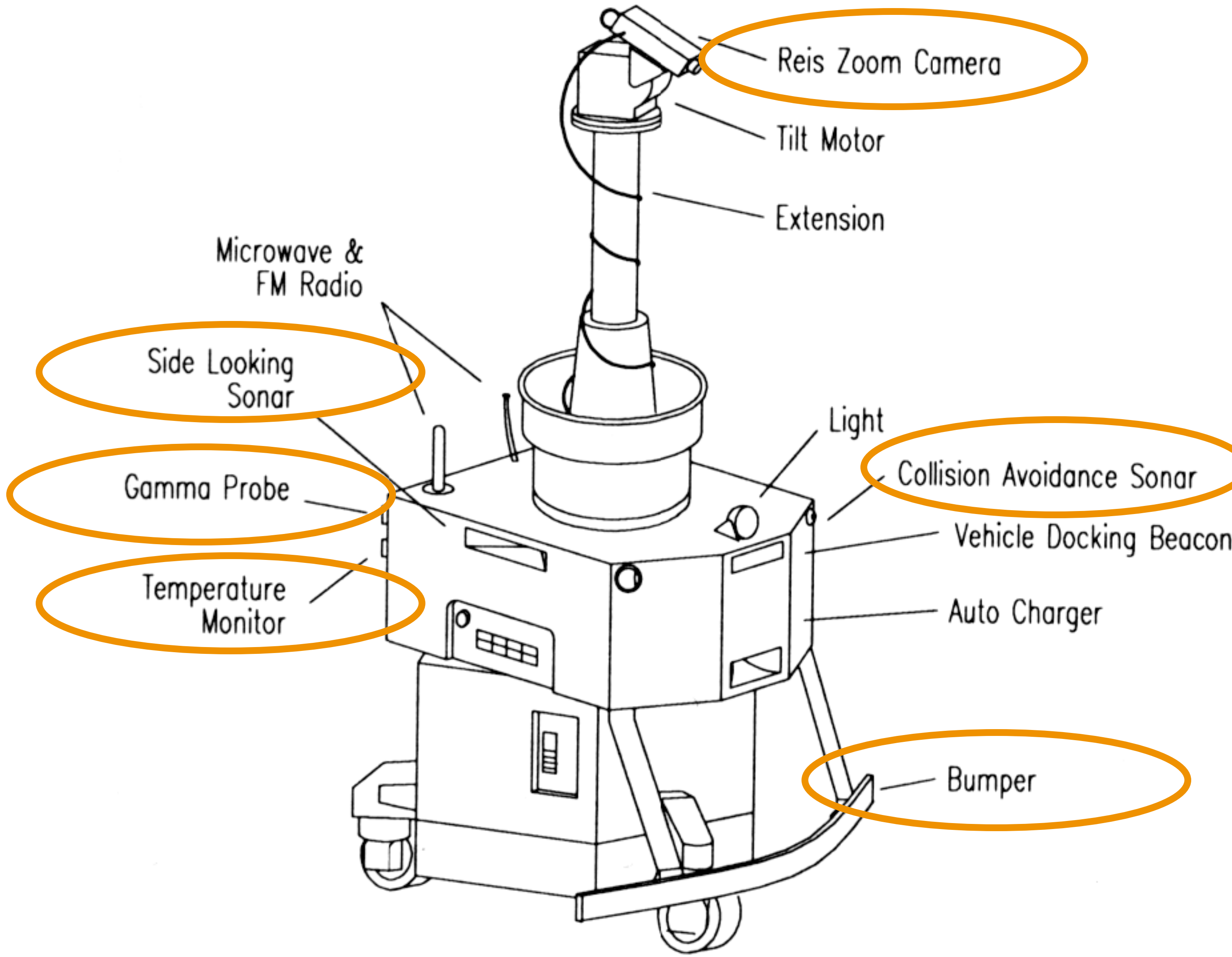
B21, Real World Interface



Robart II, H.R. Everett



Savannah, River Site Nuclear Surveillance Robot

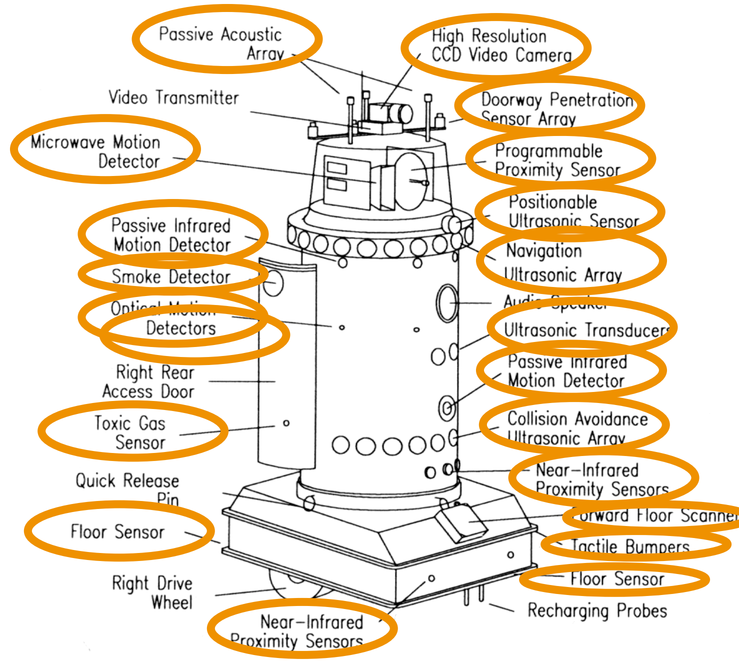


BibaBot, BlueBotics SA, Switzerland

Sensor Overload?

One design philosophy:

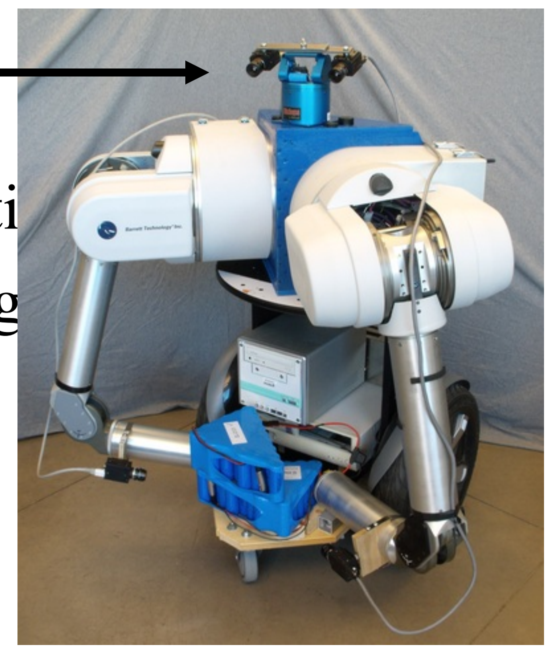
- Give each sensor a specific function
- Results in numerous special purpose sensors
- Like a car advertized as "fully loaded"



Another design philosophy:

- Use a few sensors intelligently (SPA or Smart reacti
- Typically sensors with rich, detailed information e.g
  - *Video cameras*
  - *Laser range finders ("3D depth cameras/vision)*

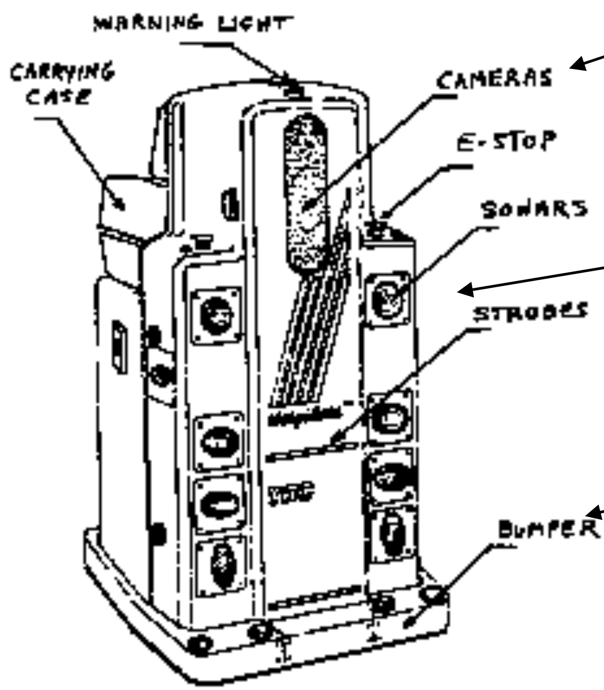
Cameras



Many sensors might suggests reactive/subsumption

One design philosophy:

- Give each sensor a specific function
- Results in numerous special purpose sensors
- Like a car advertized as "fully loaded"



Cameras:

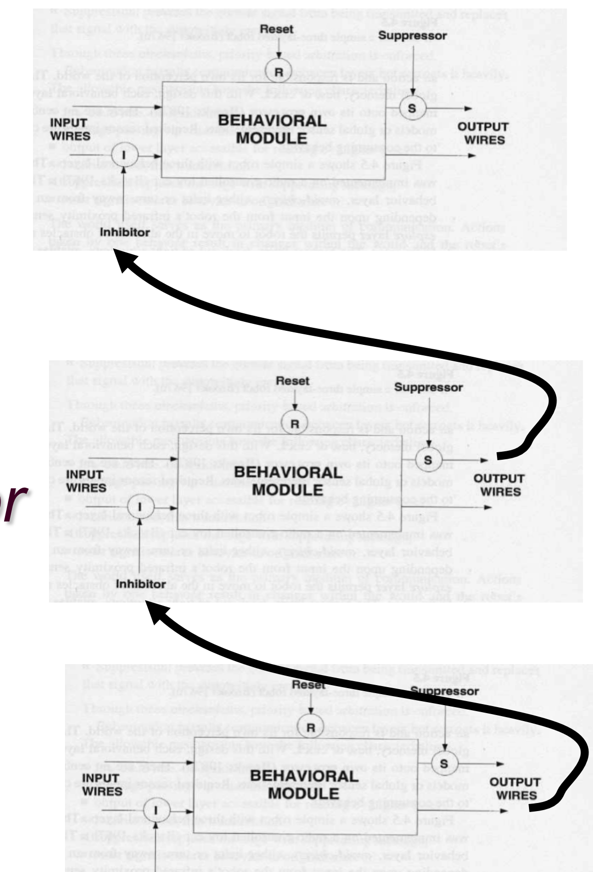
•Go to goal

Sonars:

Follow middle corridor

Bumper:

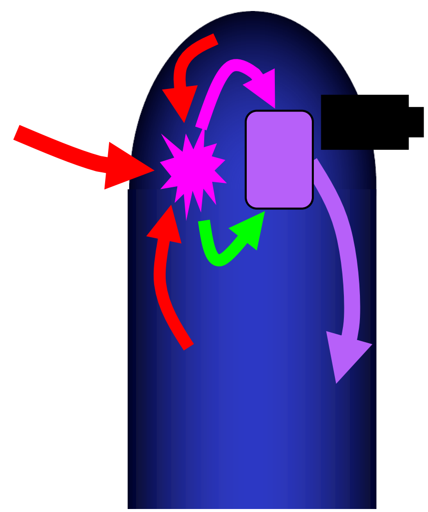
Stop and backup if hits a wall



Taxonomy of sensors

Classification of Sensors

- Where is the information coming from?
  - *Inside: Proprioceptive sensors*
    - *motor speed, wheel load, heading of the robot, battery status*
  - *Outside: Exteroceptive sensors*
    - *distances to objects, intensity of the ambient light, unique features*
- How does it work? Requires energy emission?
  - *No: Passive sensors*
    - *temperature probes, microphones, CCD*
  - *Yes: Active sensors*
    - *Controlled interaction -> better performance*
    - *Interference*
- Simple vs. composite (sonar vs. wheel sensor)



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

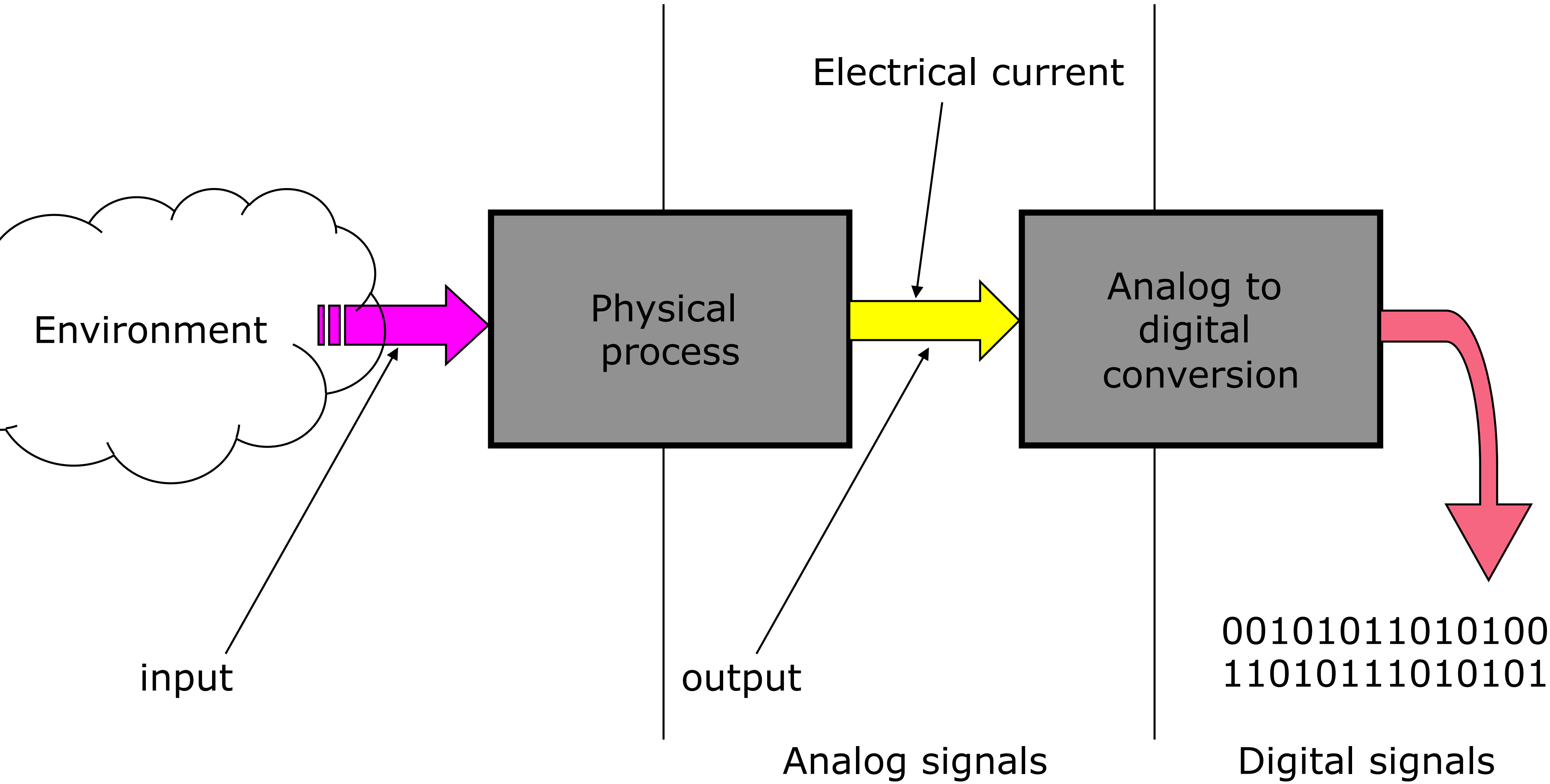
A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

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 geometric 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 analysis, segmentation, object recognition)	CCD/CMOS camera(s)	EC	P
	Visual ranging packages		
	Object tracking packages		

Sensor performance

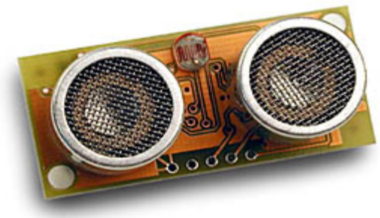
How Do (Simple) Sensors Work?



Sensor examples

Robots' link to the external world...

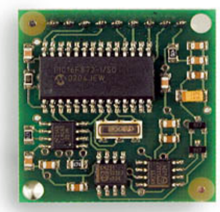
sonar rangefinder



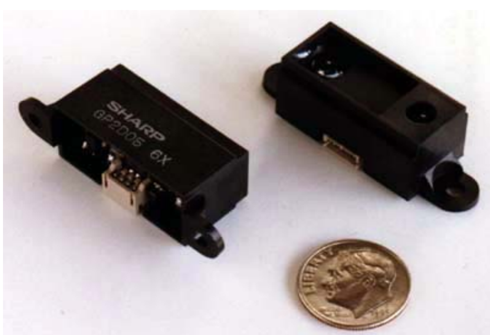
gyro

Sensors, sensors, sensors!

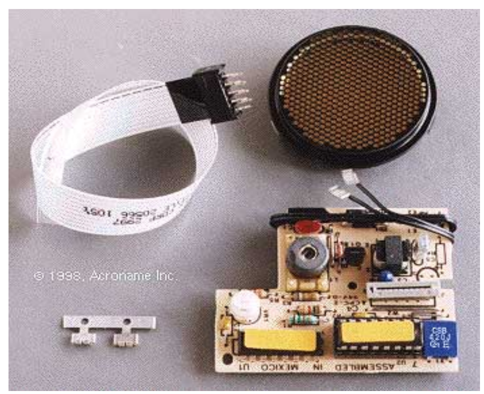
and tracking what is sensed: world models



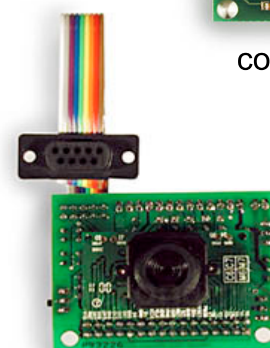
compass



IR rangefinder



sonar rangefinder

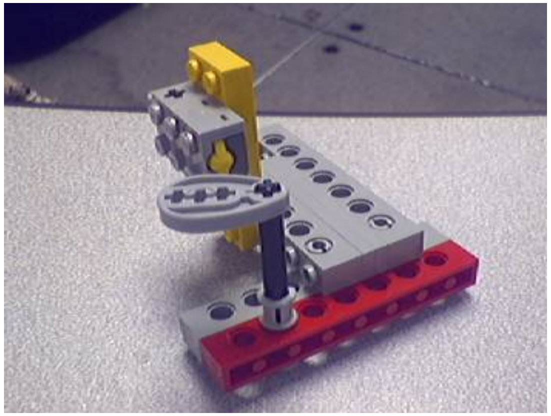


CMU cam with on-board processing

odometry…

Exteroceptive sensing

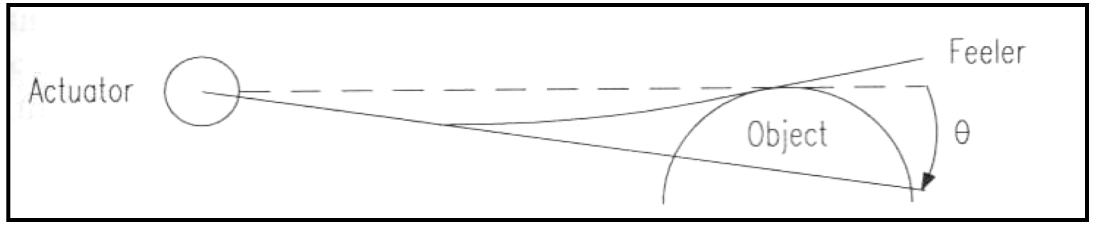
Tactile sensors

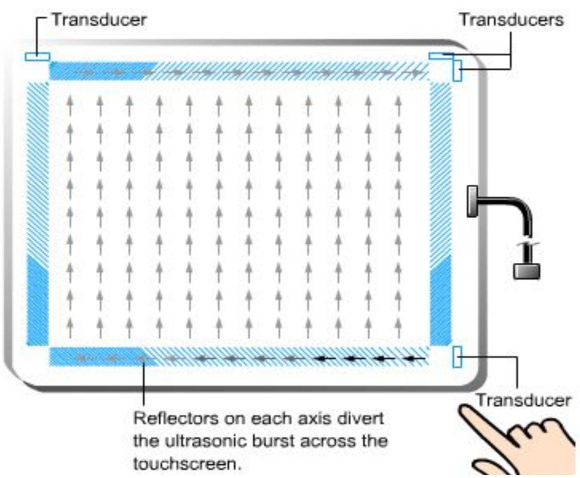


on/off switch

as a low-resolution encoder...

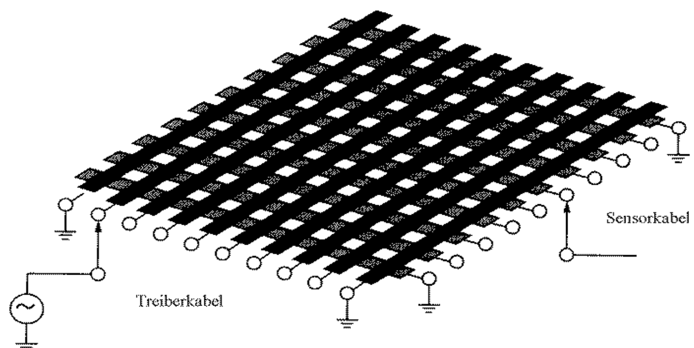
analog input: "Active antenna"





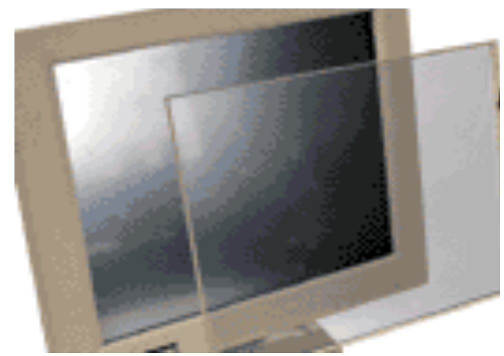
Surface acoustic waves

100% of light passes through



Capacitive array sensors

90% of light passes through

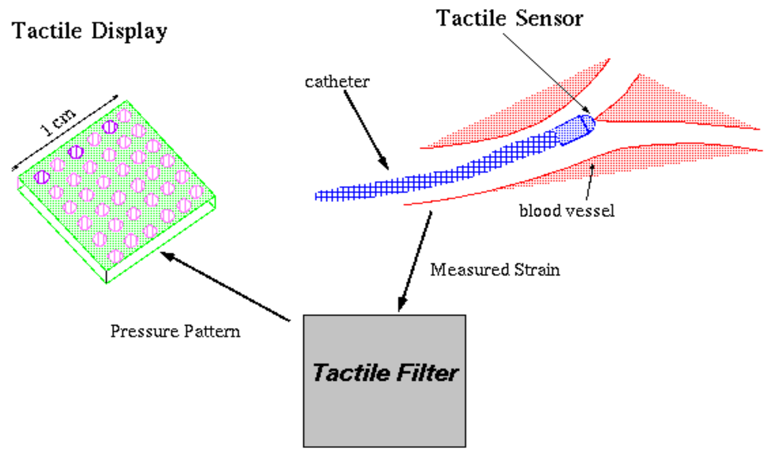


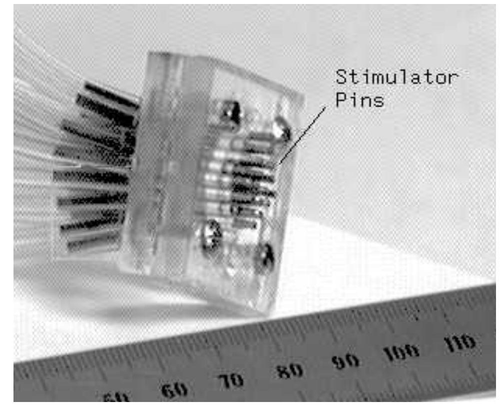
Resistive sensors

75% of light passes through

Tactile applications

daVinci medical system

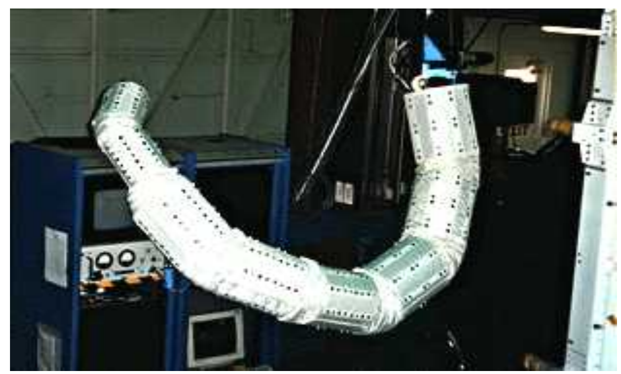




haptics

Medical
teletaction
interfaces

the Zeus robotic surgeon



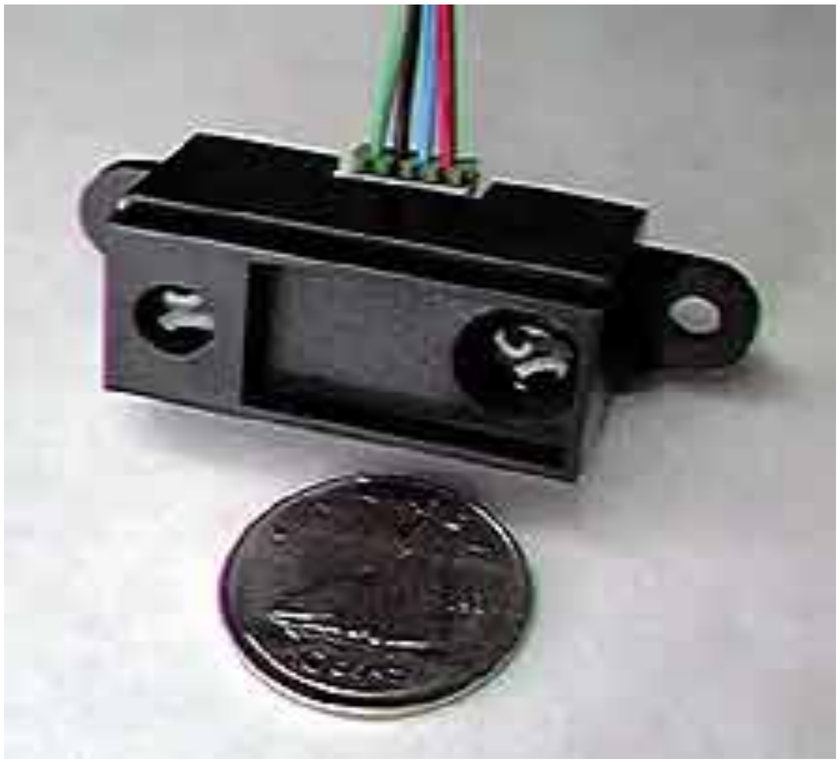
Robotic sensing

Merritt systems, FL

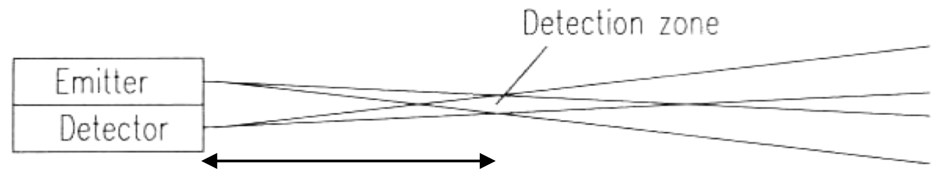
Infrared sensors

"Noncontact bump sensor"

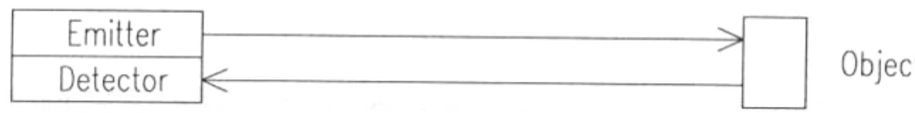
(1) sensing is based on light intensity.



"object-sensing" IR



looks for changes at
this distance



diffuse distance-sensing IR

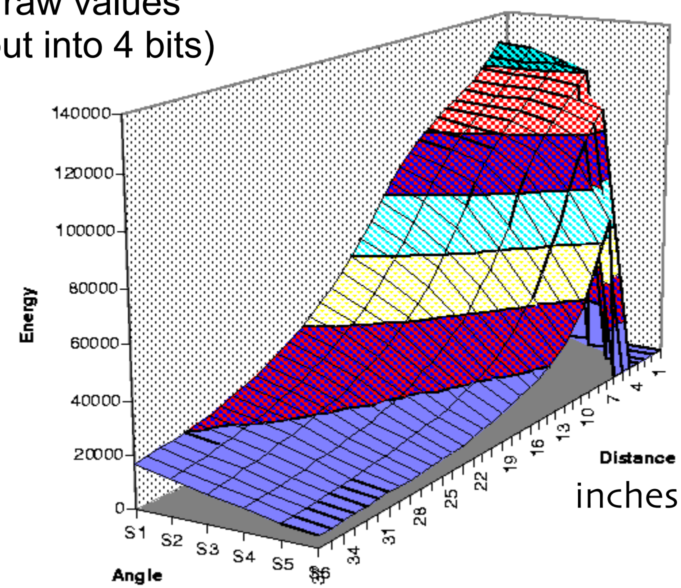
IR emitter/detector pair

IR detector

Infrared calibration

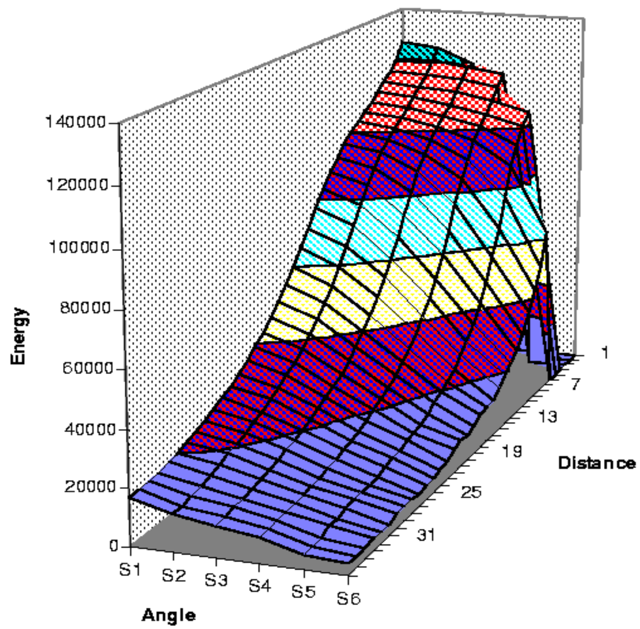
The response to white copy paper (a dull, reflective surface)

raw values
(put into 4 bits)

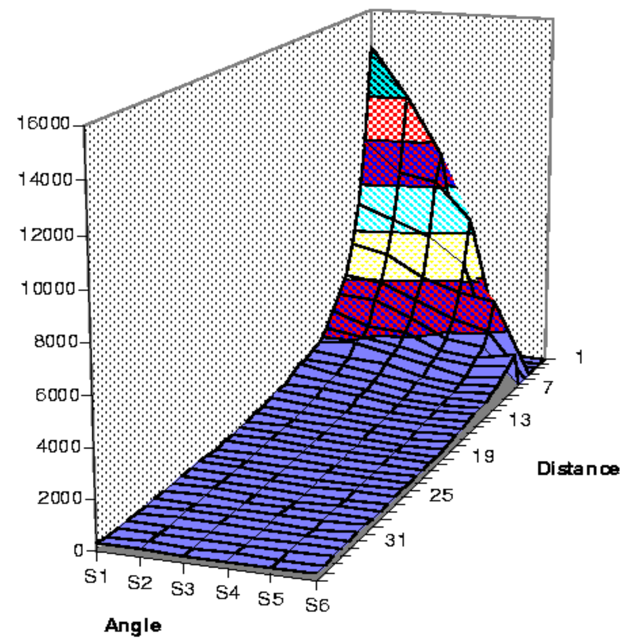


15º increments

in the dark

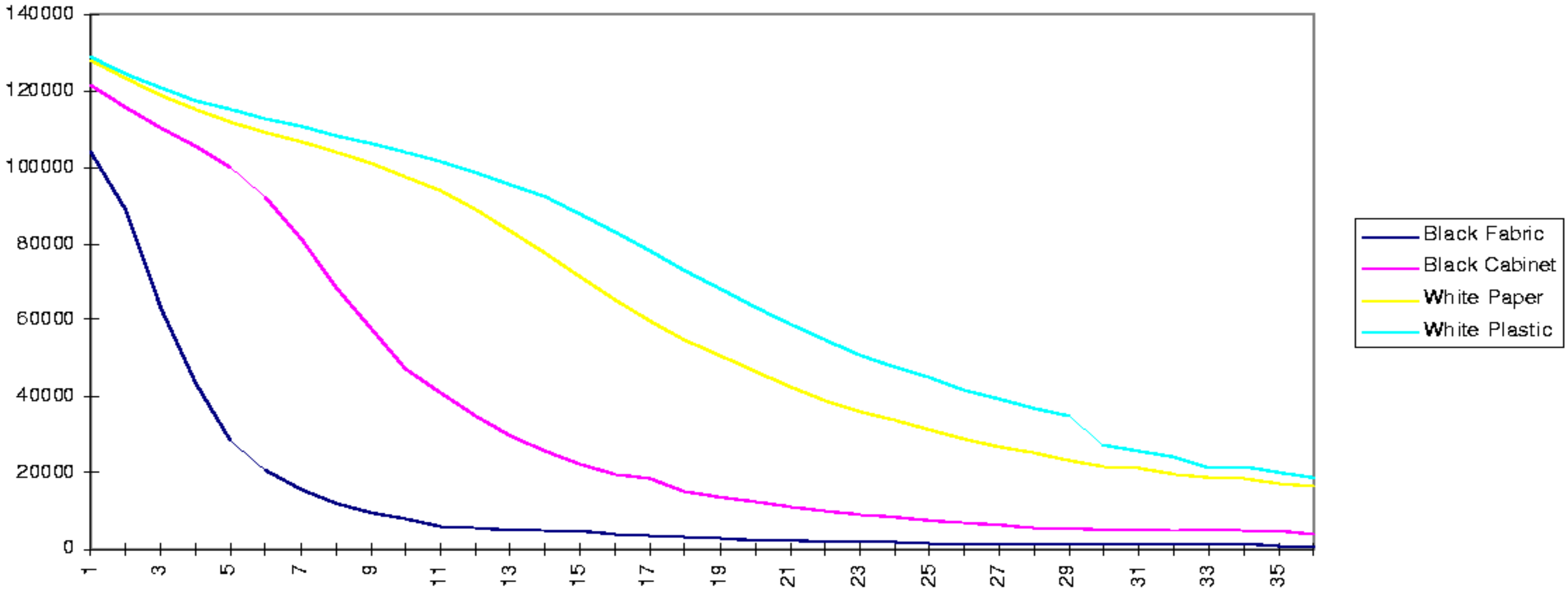


fluorescent light



incandescent light

Infrared calibration



energy vs. distance for various materials

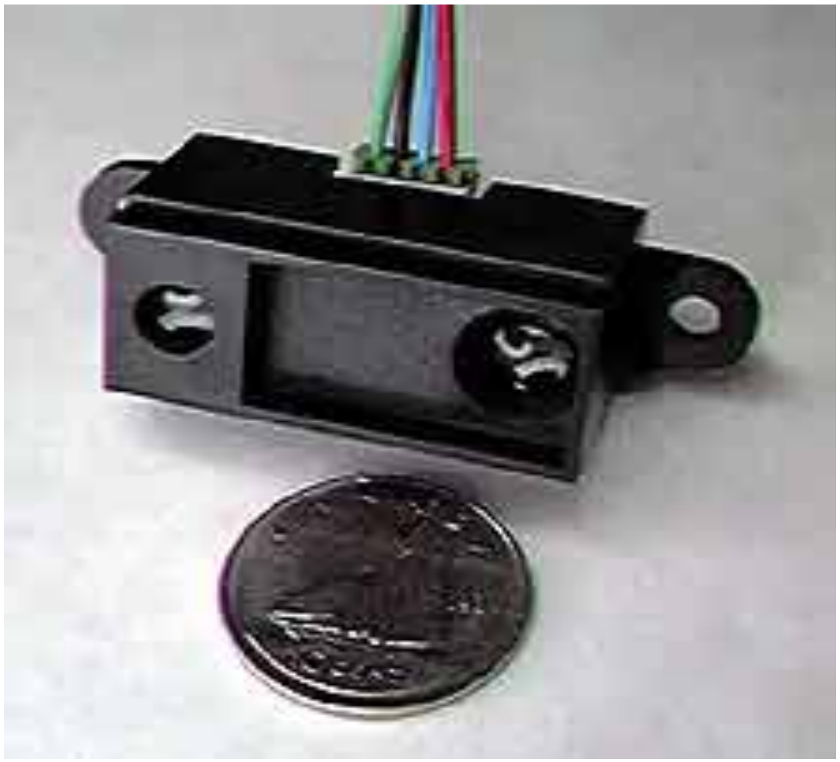
(the incident angle is 0º, or head-on)

(with no ambient light)

Infrared sensors

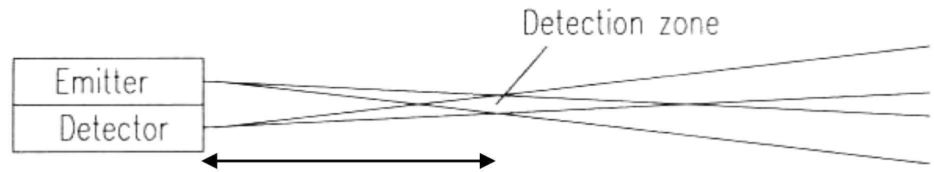
"Noncontact bump sensor"

(1) sensing is based on light intensity.

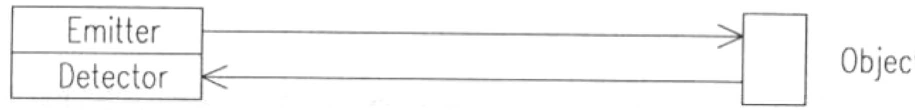


IR emitter/detector pair

"object-sensing" IR

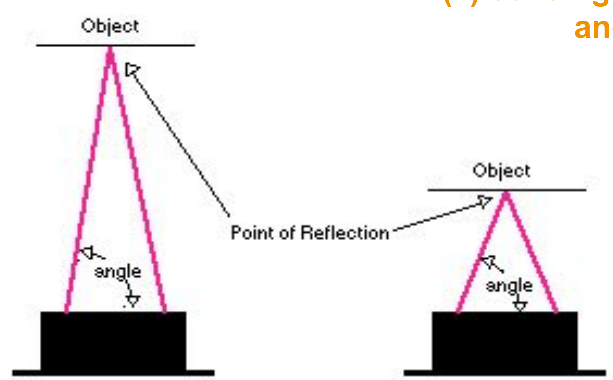


looks for changes at
this distance



diffuse distance-sensing IR

(2) sensing is based on
angle receved.



Different Angles with Different Distances

Infrared Vision

frame of a robot's IR scan of a room
(in search of people…)

head-tracking in an
IR video

Sonar sensing

sonar timeline

0

a “chirp” is emitted into the environment

75μs

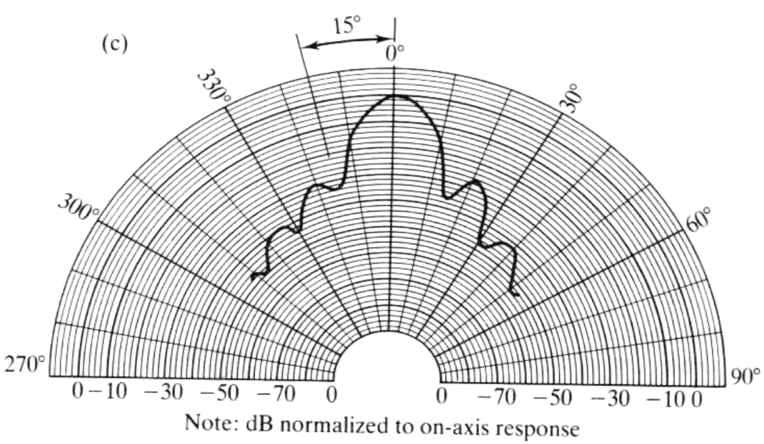
typically when reverberations from the initial chirp have stopped

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

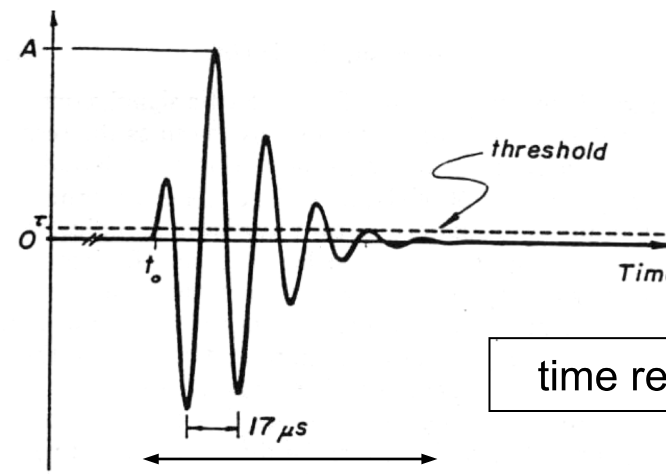
minimum distance

.5s

after a short time, the signal will be too weak to be detected



spatial response

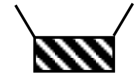


blanking time

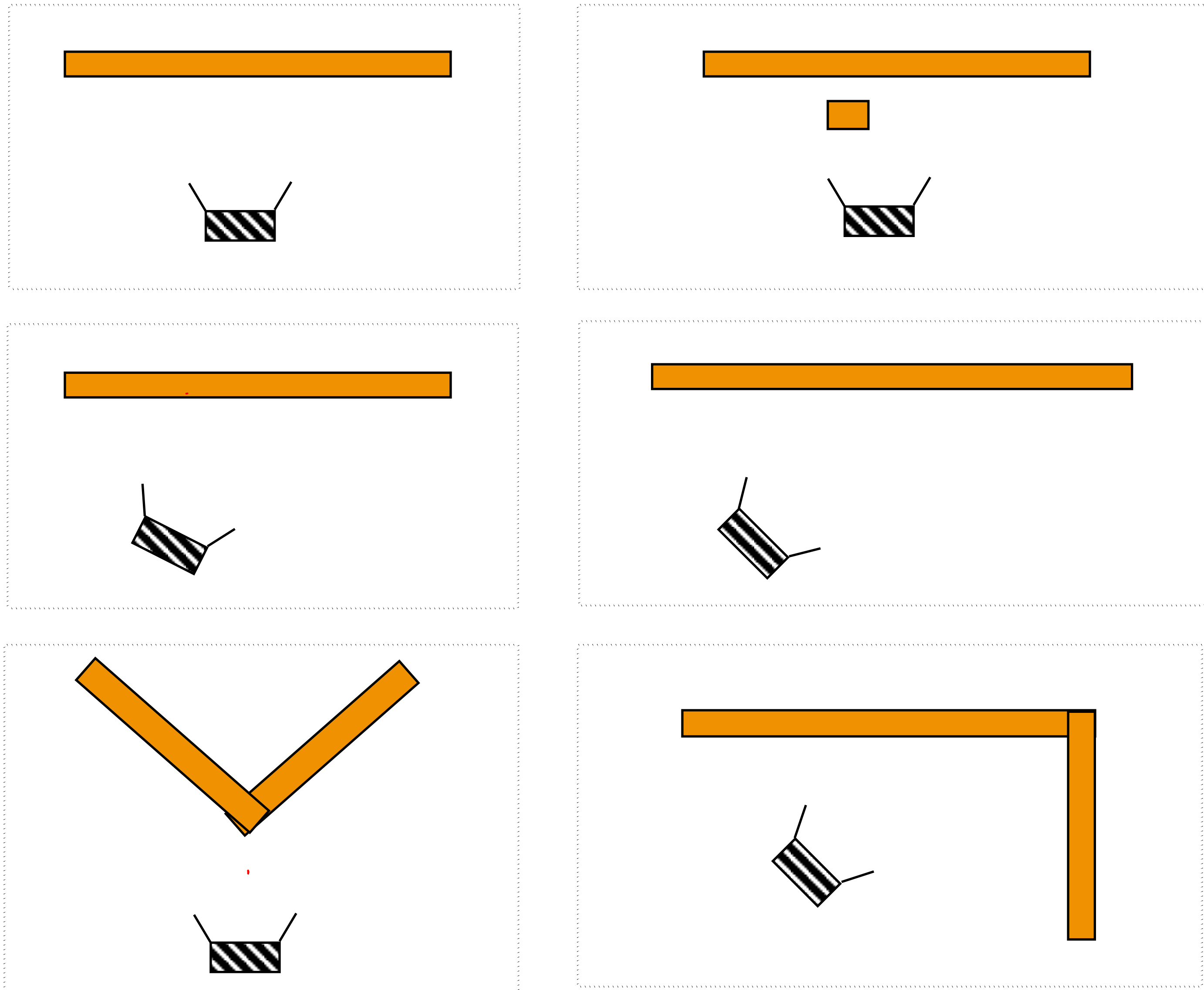
time response

walls
(obstacles)

Sonar effects



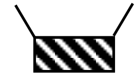
sonar



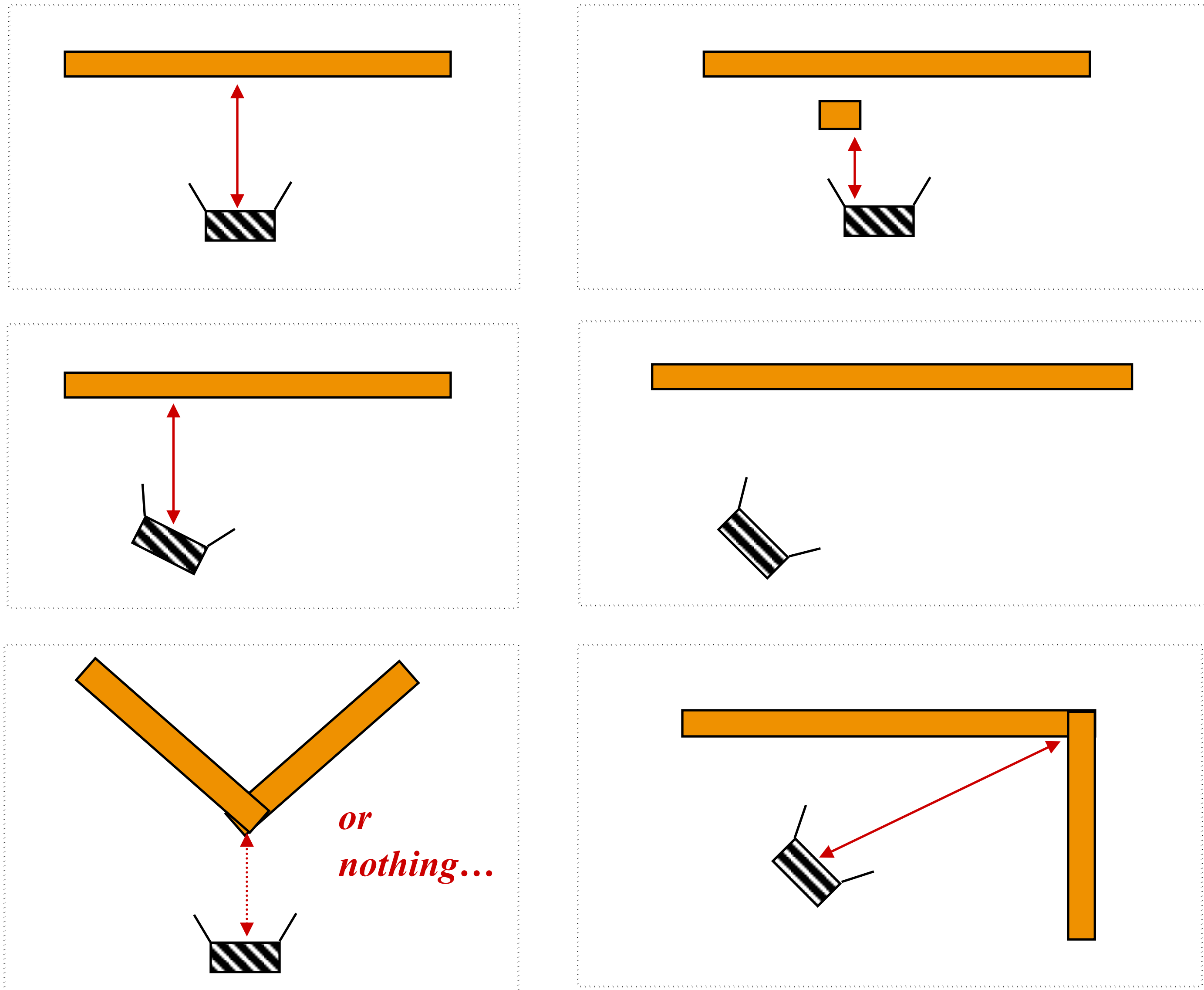
Draw the range reading that the sonar will return in each case…

walls (obstacles)

Sonar effects



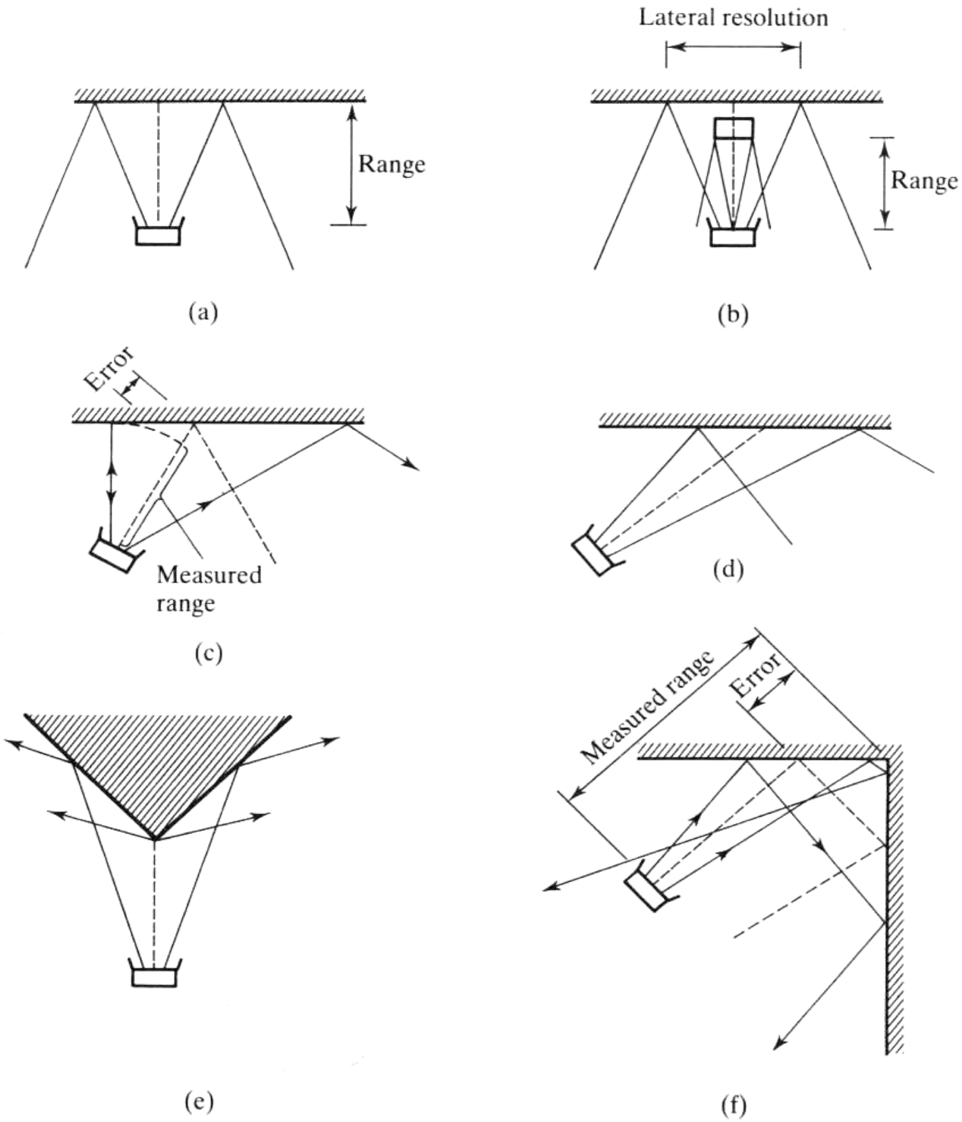
sonar



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

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

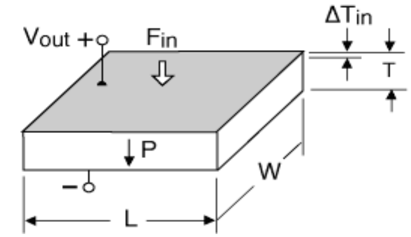
(d) Specular reflections cause walls to disappear

(e) Open corners produce a weak spherical wavefront

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

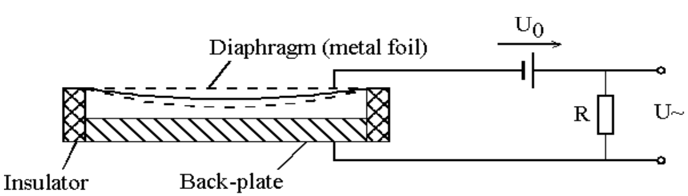
resolution: time / space

Ultrasonic Sensor

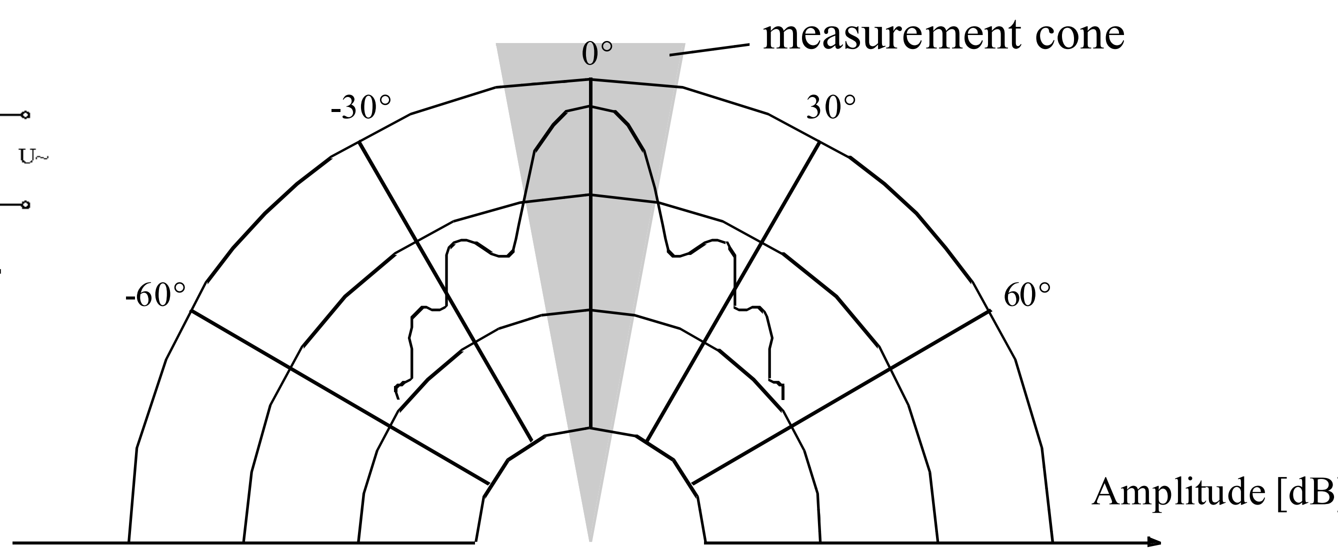


Piezo transducer

- Frequencies: 40 - 180 kHz
- Sound source: piezo/electrostatic transducer
  - *transmitter and receiver separated or not separated*
- Propagation: cone
  - *opening angles around 20 to 40 degrees*
  - *regions of constant depth*
  - *segments of an arc (sphere for 3D)*



Electrostatic transducer

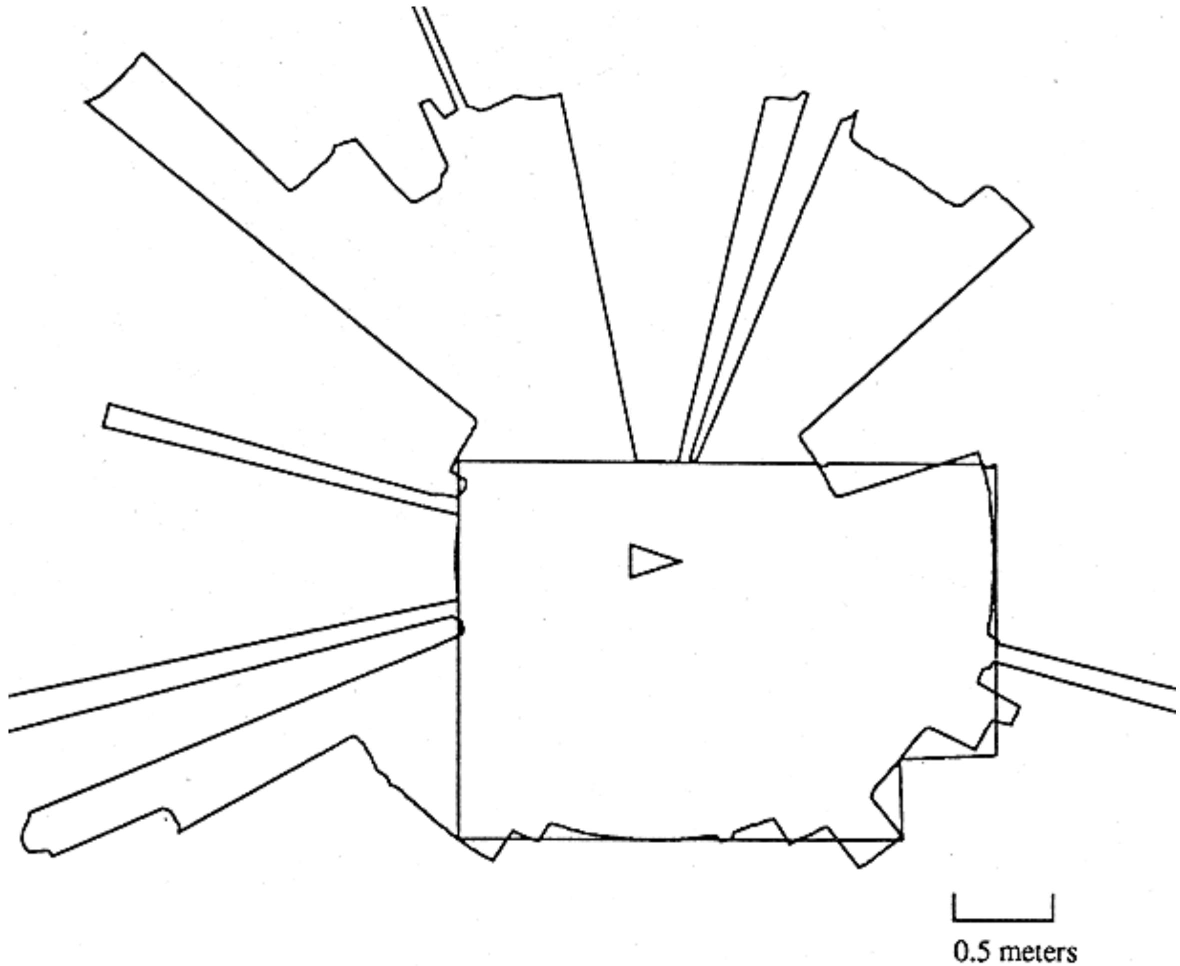


Typical intensity distribution of an ultrasonic sensor

Imaging with an US

Issues:

- Soft surfaces
- Sound surfaces that are far from being perpendicular to the direction of the sound -> specular reflection



a) 360° scan

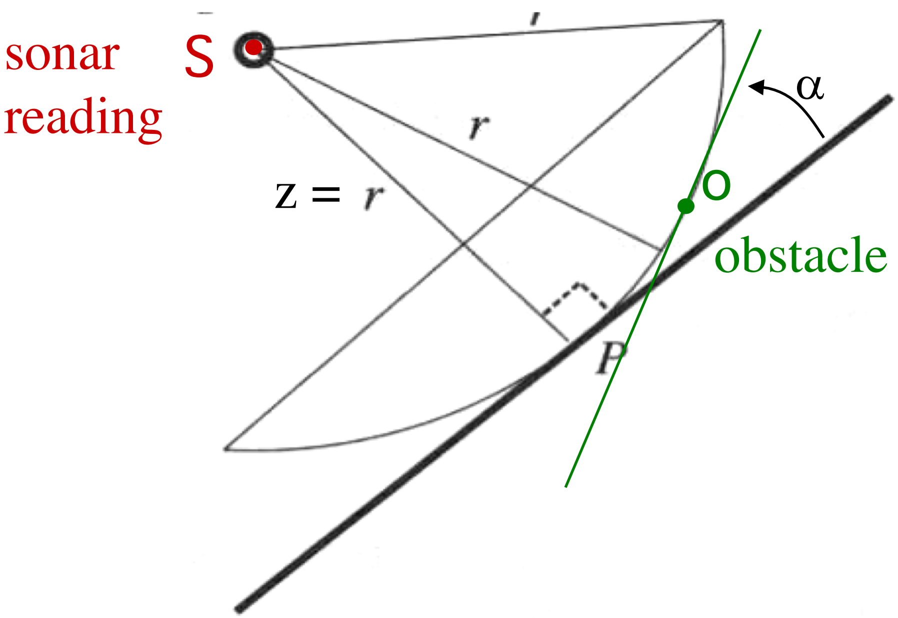
Characteristics

- Range: 12cm – 5 m
- Accuracy: 98%-99.1%
- Single sensor operating speed: 50Hz
  - *3m -> 20ms ->50 measurements per sec*
- Multiple sensors:
  - *Cycle time->0.4sec -> 2.5Hz*
    ->limits speed of motion (collisions)

Sonar Modeling

response model (Kuc)

$$h_R(t, z, a, \alpha) = \frac{2c\cos\alpha}{\pi a \sin\alpha}\sqrt{1 - \frac{c^2(t - 2z/c)^2}{a^2 \sin^2\alpha}}$$



- Models the response, h_R, with
  - c = speed of sound
  - a = diameter of sonar element
  - t = time
  - z = orthogonal distance
  - α = angle of environment surface

- Then, allow uncertainty in the model to obtain a probability:

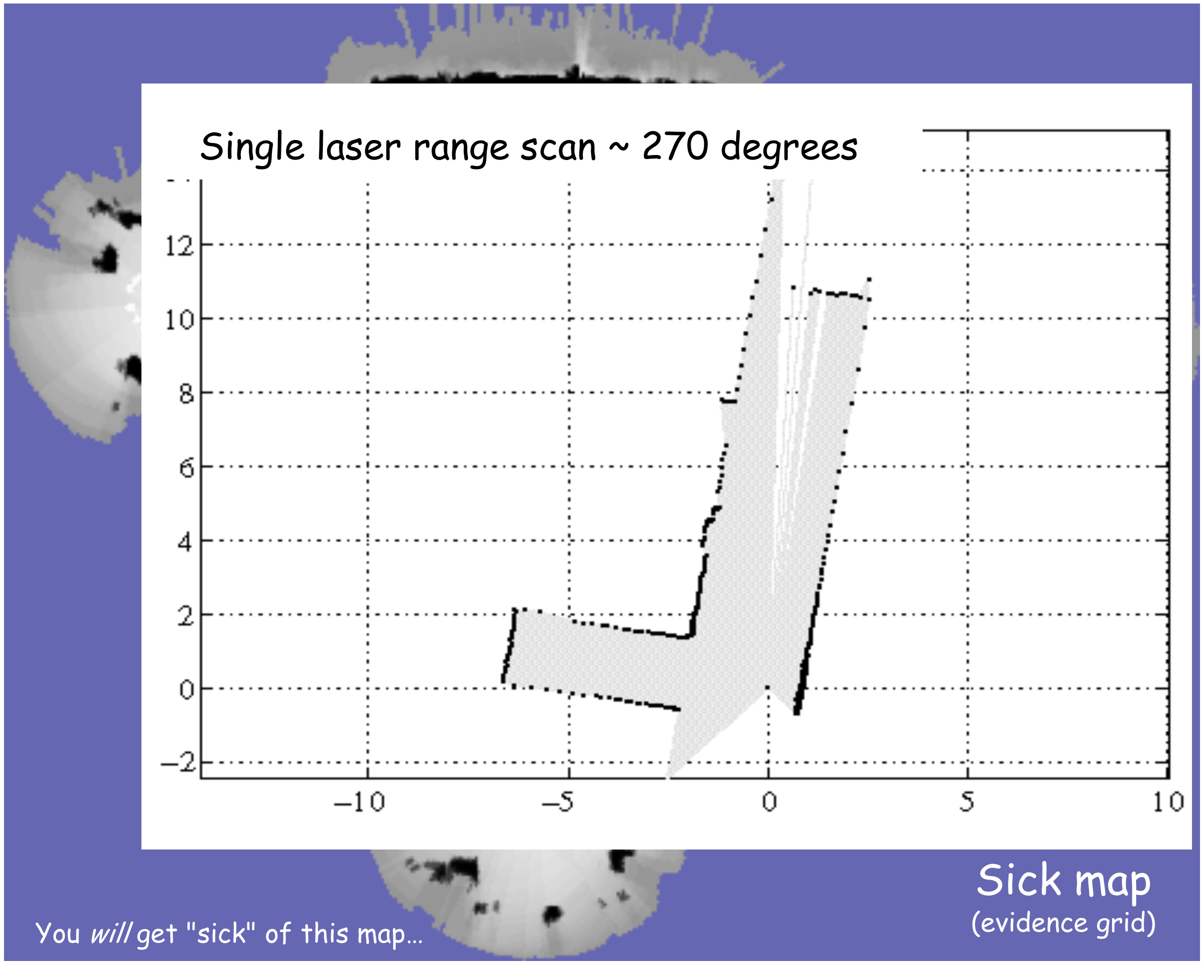
$$\boxed{p(S \mid o)}$$

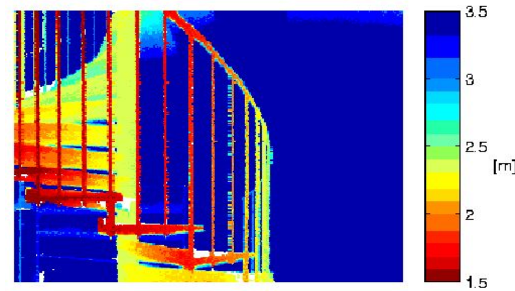
chance that the sonar reading is S, given an obstacle at location o

And beyond...

Sensing and perception is often limiting a robot's performance...

LIDAR





LIDAR map

Sick laser range finder

how do these compare to vision?
the most *computationally* challenging?

Heading Sensors

- Heading sensors can be proprioceptive (gyroscope, inclinometer) or exteroceptive (compass).
- Used to determine the robots orientation and inclination.
- Allow, together with an appropriate velocity information, to integrate the movement to an position estimate.
  - *This procedure is called dead reckoning (ship navigation)*

Compass

- Since over 2000 B.C.
  - *when Chinese suspended a piece of naturally magnetite from a silk thread and used it to guide a chariot over land.*
- Magnetic field on earth
  - *absolute measure for orientation.*
- Large variety of solutions to measure the earth magnetic field
  - *mechanical magnetic compass*
  - *direct measure of the magnetic field (Hall-effect, magnetoresistive sensors)*
- Major drawback
  - *weakness of the earth field*
  - *easily disturbed by magnetic objects or other sources*
  - *not feasible for indoor environments*

Gyroscope

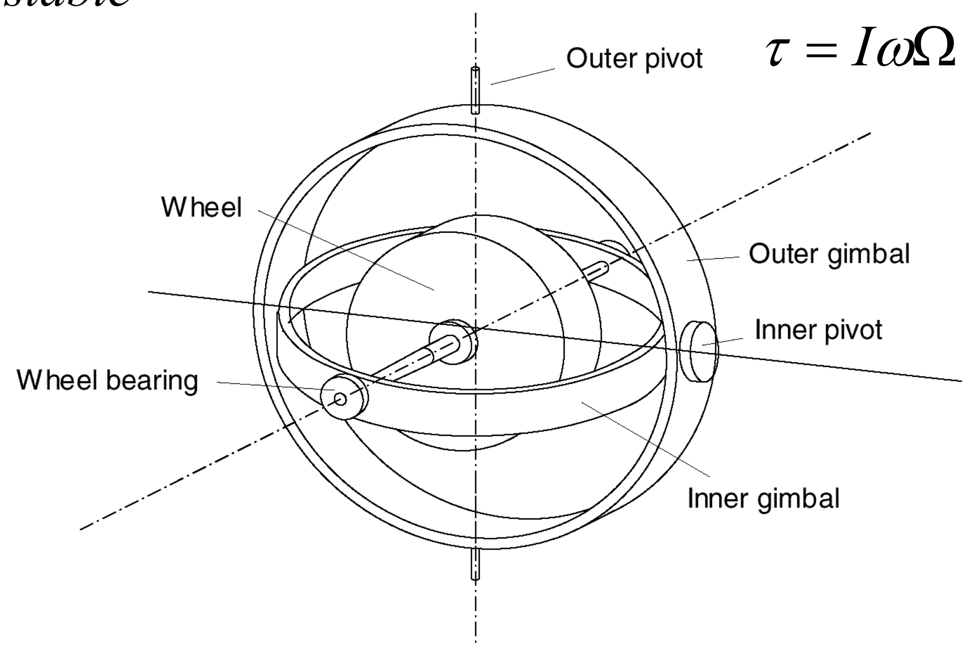
- Heading sensors, that keep the orientation to a fixed frame
  - *absolute measure for the heading of a mobile system.*
- Two categories, the mechanical and the optical gyroscopes
  - *Mechanical Gyroscopes*
    - *Standard gyro*
    - *Rated gyro*
  - *Optical Gyroscopes*
    - *Rated gyro*

Mechanical Gyroscopes

- Concept: inertial properties of a fast spinning rotor
  - *gyroscopic precession*
- Angular momentum associated with a spinning wheel keeps the axis of the gyroscope inertially stable.
- Reactive torque t (tracking stability) is proportional to the spinning speed w, the precession speed W and the wheels inertia I.
- No torque can be transmitted from the outer pivot to the wheel axis
  - *spinning axis will therefore be space-stable*
- Quality: 0.1° in 6 hours

$$\tau = I\omega\Omega$$

- If the spinning axis is aligned with the north-south meridian, the earth's rotation has no effect on the gyro's horizontal axis
- If it points east-west, the horizontal axis reads the earth rotation



Rate gyros

- Same basic arrangement shown as regular mechanical gyros

- But: gimble(s) are restrained by a torsional spring
  - *enables to measure angular speeds instead of the orientation.*

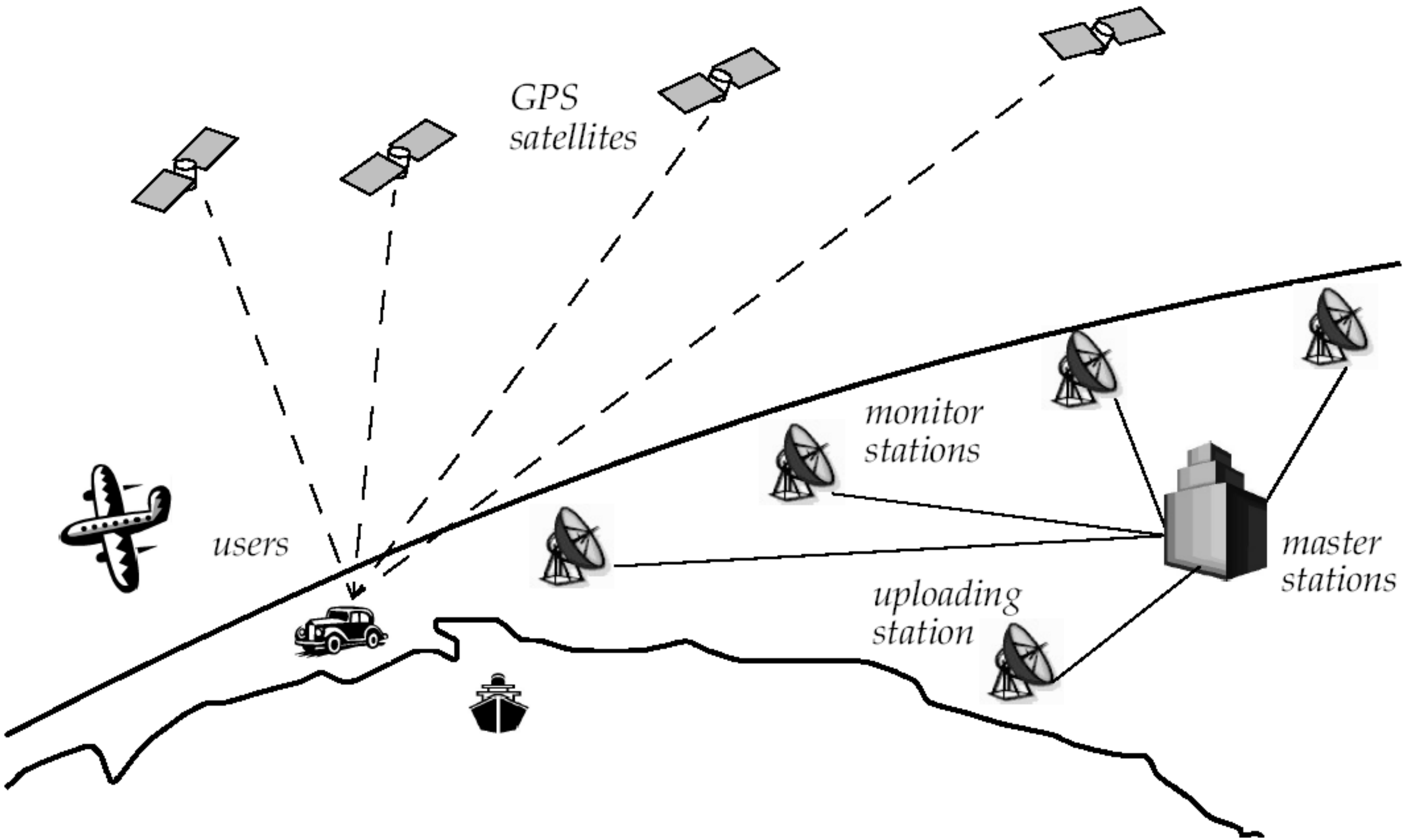
- Others, more simple gyroscopes, use Coriolis forces to measure changes in heading.

Global Positioning System (GPS) (1)

- *Developed for military use*
- *Recently it became accessible for commercial applications*
- *24 satellites (including three spares) orbiting the earth every 12 hours at a height of 20.190 km.*
- *Four satellites are located in each of six planes inclined 55 degrees with respect to the plane of the earth's equators*
- *Location of any GPS receiver is determined through a time of flight measurement*

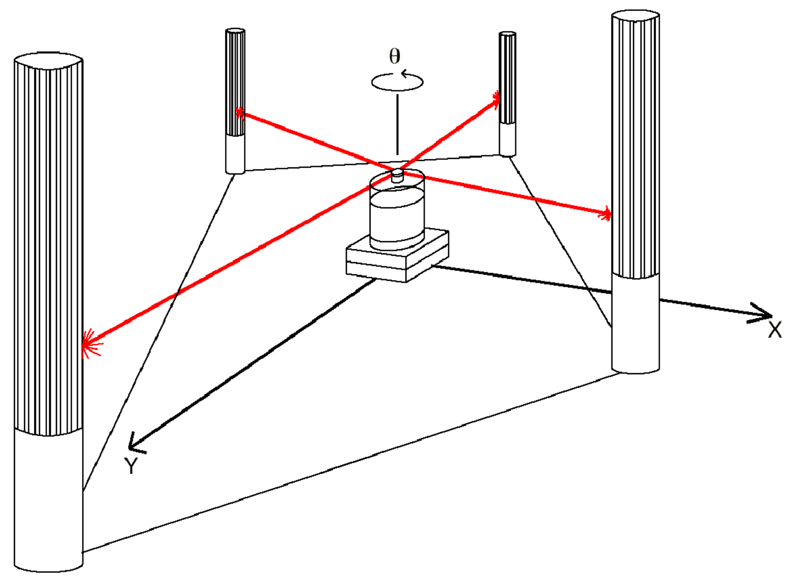
- Technical challenges:
  - *Time synchronization between the individual satellites and the GPS receiver*
  - *Real time update of the exact location of the satellites*
  - *Precise measurement of the time of flight*
  - *Interferences with other signals*

Global Positioning System (GPS) (2)



Ground-Based Active and Passive Beacons

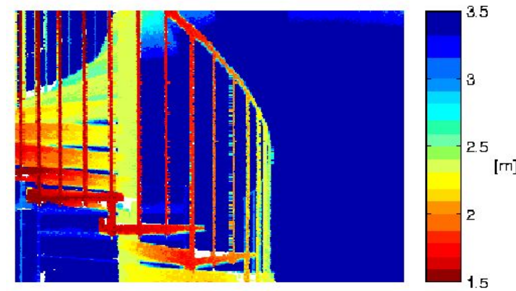
- Elegant way to solve the localization problem in mobile robotics
- Beacons are signaling guiding devices with a precisely known position
- Beacon base navigation is used since the humans started to travel
  - *Natural beacons (landmarks) like stars, mountains or the sun*
  - *Artificial beacons like lighthouses*
- The recently introduced Global Positioning System (GPS) revolutionized modern navigation technology
  - *Already one of the key sensors for outdoor mobile robotics*
  - *For indoor robots GPS is not applicable,*
- Your own beacons:
  - *LED/bulbs, coils emitting magnetic field…*
- Drawback with the use of beacons in indoor:
  - *Beacons require changes in the environment*
  - *Limit flexibility and adaptability to changing environments.*



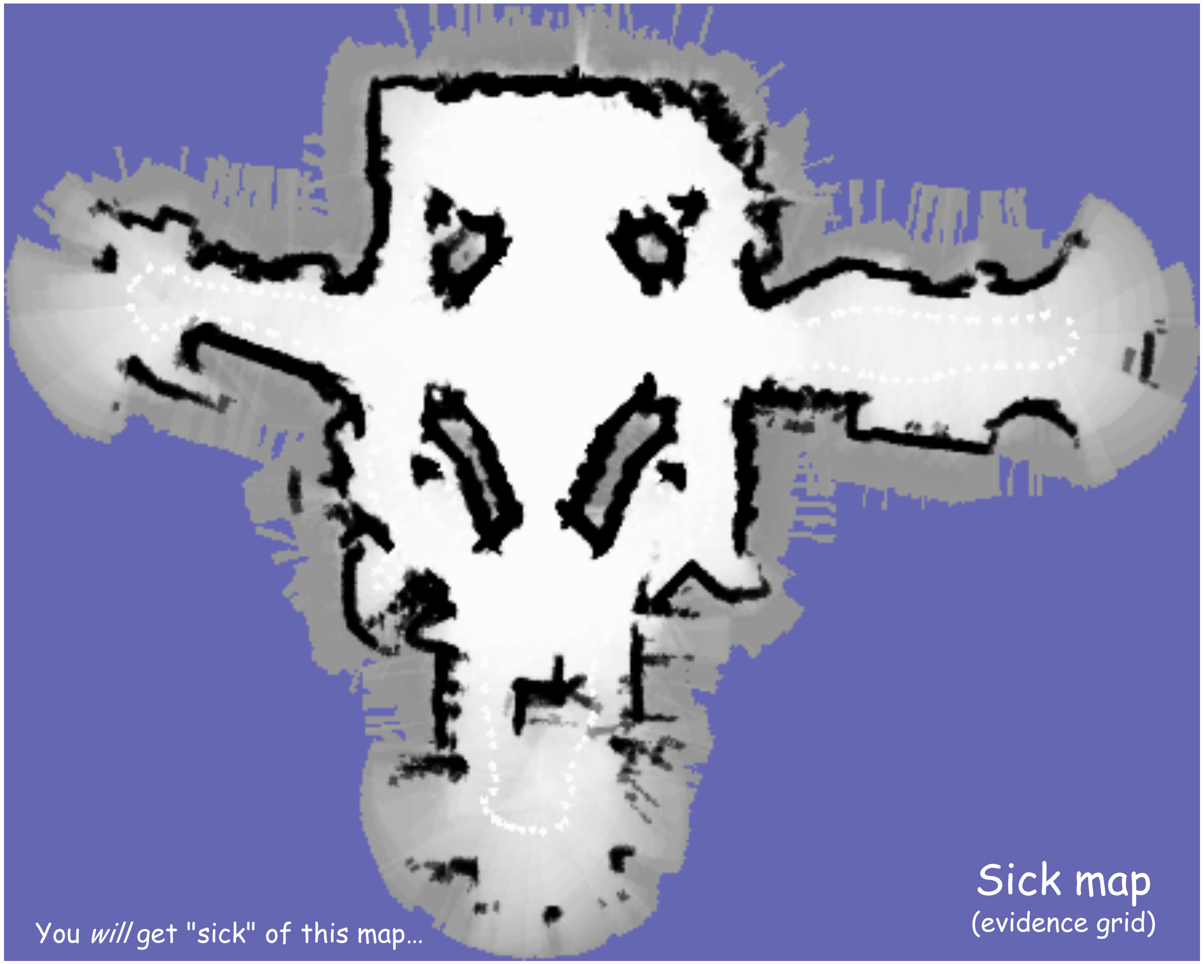
And beyond...

Sensing and perception is often limiting a robot's performance...

LIDAR



LIDAR map



Sick map
(evidence grid)

You *will* get "sick" of this map...

Sick laser range finder

how do these compare to vision?
the most *computationally* challenging?

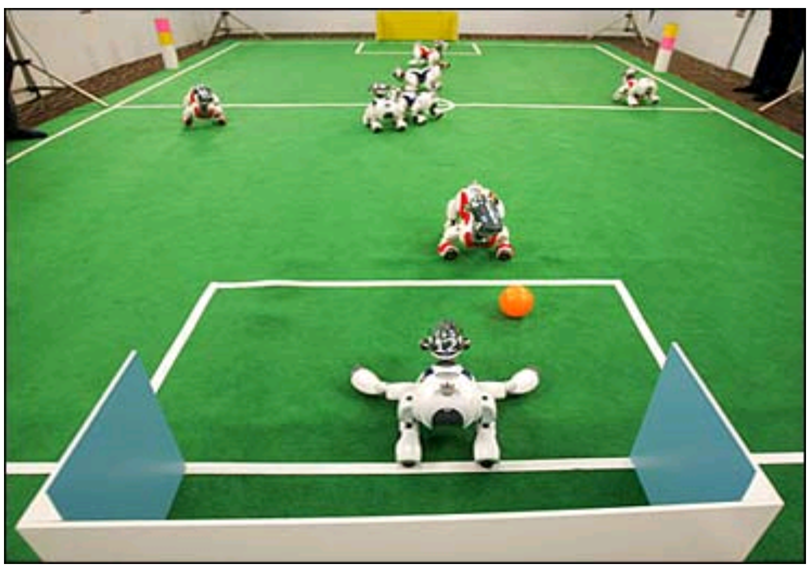
Camera Vision: The *ultimate* sensor?

A camera offers a compelling mix of promise and frustration!

not only 2d information: 3d structure, surface properties, lighting conditions, object status, et al., is there somewhere!

- Computer vision has always had close ties to robotics and AI.
- A quick introduction to get you thinking about using vision…

There are vision applications and algorithms throughout robotics



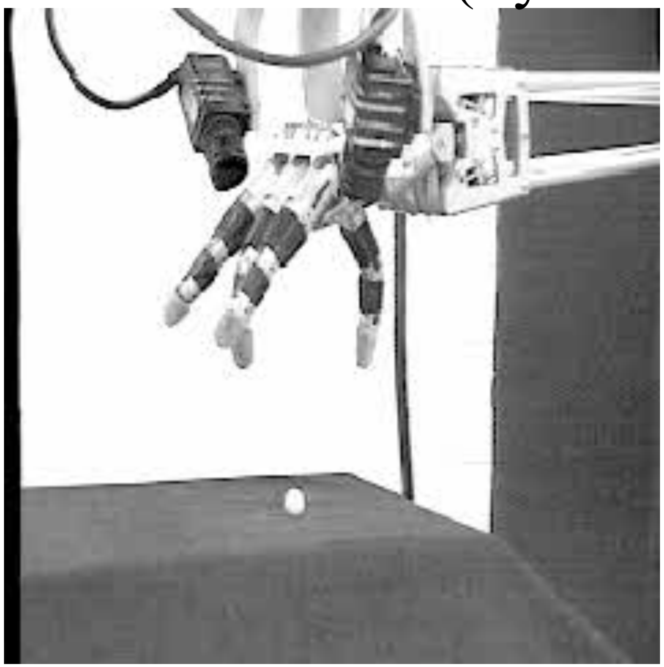
visual landmarks used in robot soccer

Lec6/dogFullFps...

Vision: The *ultimate* sensor?

- Puma robot and 2 cameras + tracking and visual servoing

Cam's on robot (Eye-in-hand)



Fixed cameras (Eye-to-hand)

Lec6/dogFullFps...

http://www.cs.cmu.edu/~coral-downloads/legged/movies/0_Research/Vision/DogFullFpsNoSound.mpg

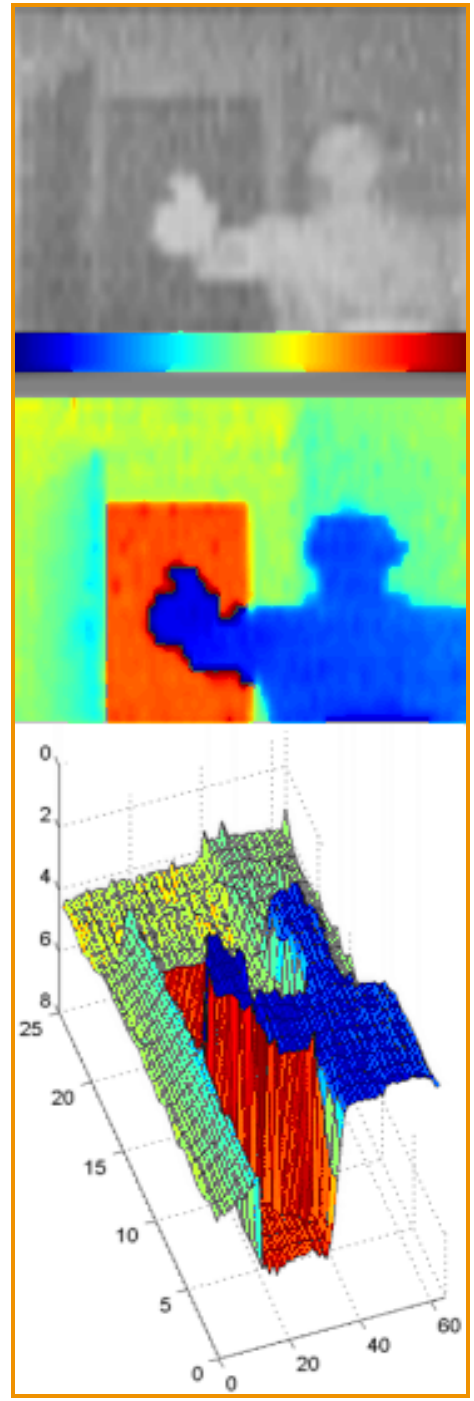
Visual landmarks used in robot sc

3d from 2d?

The 3d “time-of-flight” cameras

http://www.swissranger.ch/index.php

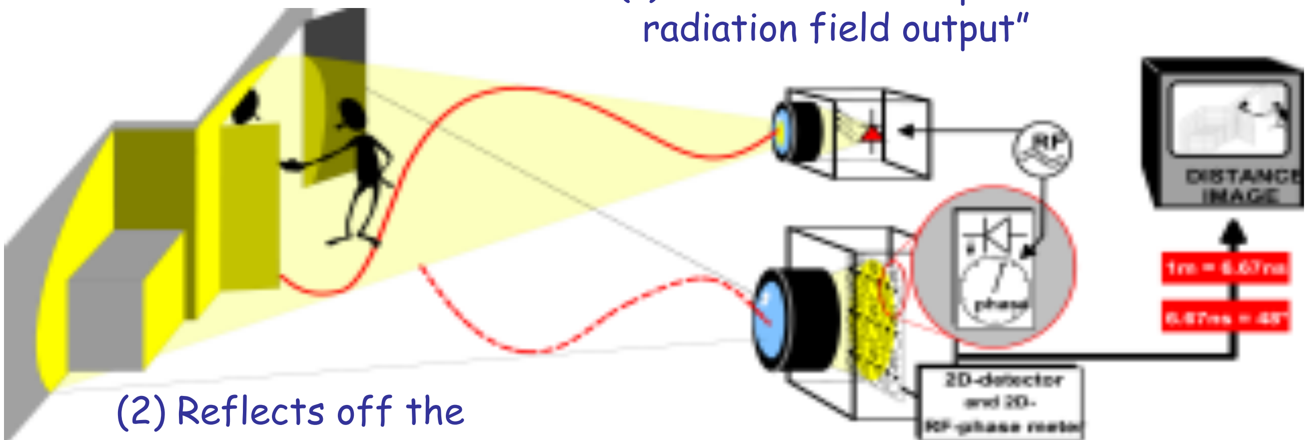
http://www.advancedscientificconcepts.com



3d from 2d?

The 3d "time-of-flight" camera

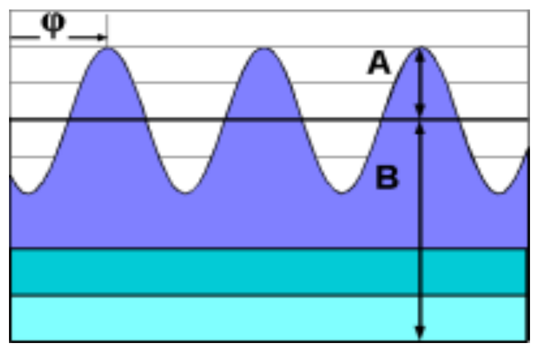
(1) "RF-modulated optical radiation field output"



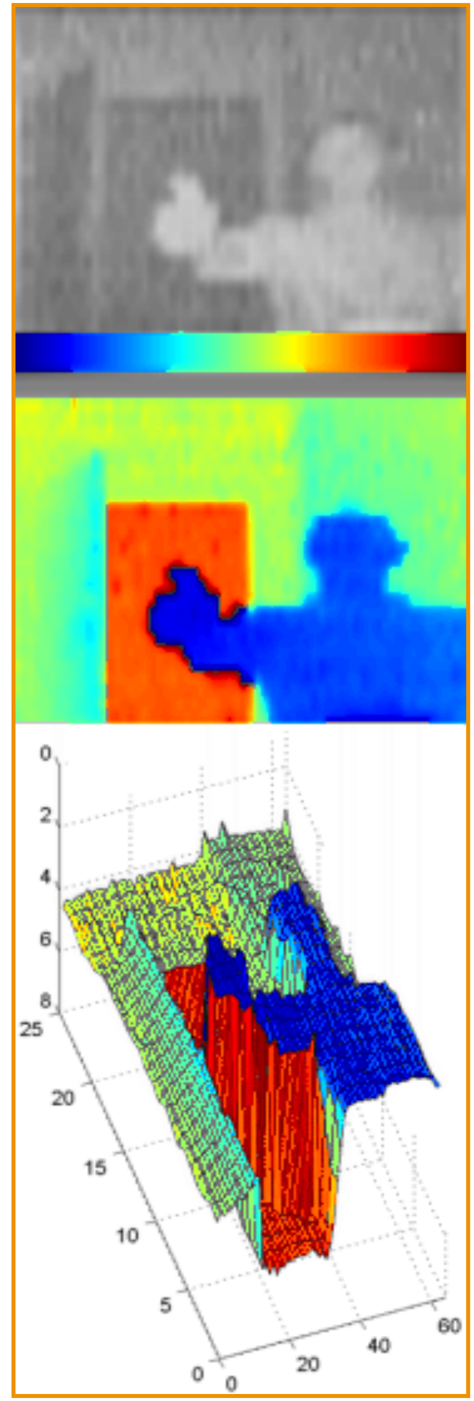
(2) Reflects off the environment

(3) Time-interval input measurements provides data (not time-integrated!)

How does this information get used?

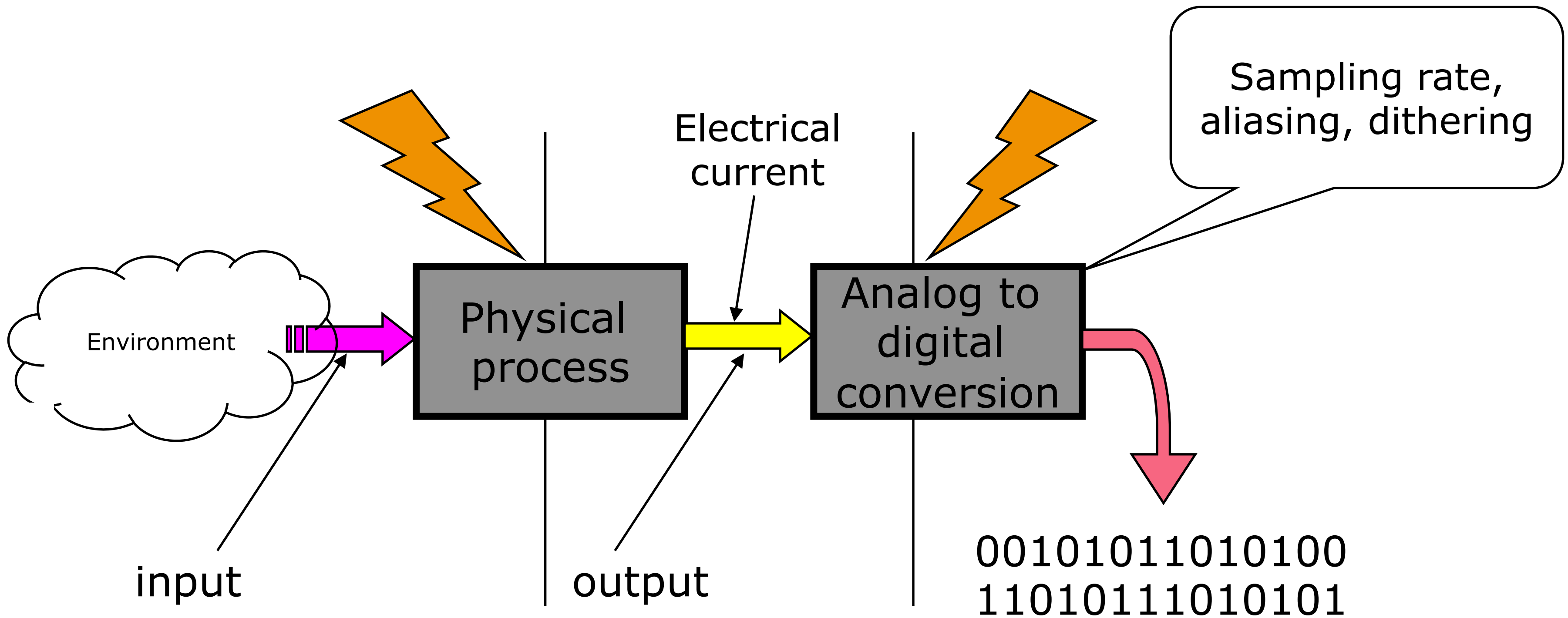


http://www.csem.ch/detailed/p_531_3d_cam.htm



Mathematical Models

- Signal in => signal out: response
  - *Memoryless:* $V_{out} = S(E_{in}, Noise_t)$
  - *With memory:* $V_{out} = f(V_{out}, E_{in}, Noise_t)$



Nominal Sensor Performance

- Valid inputs
  - E_{min}: *Minimum detectable energy*
  - E_{max}: *Maximum detectable energy*
  - *Dynamic range* = E_{max}/E_{min} , *or* $10 \log(E_{max}/E_{min})$ *[dB]*
    - *power measurement or volt?* (V^2 ~ *power*) . *Dr* = $20 \log(v_{max}/v_{min})$
  - *Useful dynamic range (limited by noise)* = E_{max}/E_{noise}
  - *Operating range* (N_{min}, N_{max}): $E_{min} \cdot N_{min} \cdot N_{max} \cdot E_{max}$
    - *No aliasing in the operating range (e.g., distance sens.)*
- Response
  - *Sensor response*: $S(E_{in})=?$
    - *Linear? (or non-linear)*
    - *Hysteresis*
  - *Resolution* (¢):
    - E_1-E_2· ¢) $S(E_1)$¼ $S(E_2)$; *often* ¢=min(E_{min} , ¢$_{A/D}$)
  - *Timing*
    - *Response time (range): delay between input and output [ms]*
    - *Bandwidth: number of measurements per second [Hz]*

In Situ **Sensor Performance: Sensitivity**

Characteristics .. especially relevant for real world environments

- Sensitivity:
  - *How much does the output change with the input?*
  - *Memoryless sensors: min{ [d/dE S] (E_{in}) | E_{in} }*
  - *Sensors with memory: min{ f(V,E_{in})/E_{in} | V, E_{in} }*
- Cross-sensitivity
  - *sensitivity to environmental parameters that are orthogonal to the target parameters*
  - *e.g. flux-gate compass responds to ferrous buildings, orthogonal to magnetic north*
- Error: ²(t) = S(t) - S(E_{in}(t))
  - *Systematic: ²(t) = D(E_{in}(t))*
  - *Random: ²(t) is random, e.g., ²(t) ~ N(¹,¾²)*
- Accuracy (systemacity): 1-|D(E_{in})|/E_{in}, e.g., 97.5% accuracy
- Precision (reproducability): $Range_{out}$/ Var(²(t))$^{1/2}$

In Situ Sensor Performance: Errors

Characteristics .. especially relevant for real world environments

- Error: ²(t) = S(t) - S(E_{in}(t))
  - *Systematic: ²(t) = D(E_{in}(t))*
    - *Predictable, deterministic*
    - *Examples:*

      Calibration errors of range finders

      Unmodeled slope of a hallway floor

      Bent stereo camera head due to an earlier collision
  - *Random: ²(t) is random, e.g., ²(t) ~ N(¹,¾2)*
    - *Unpredictable, stochastic*
    - *Example:*

      Thermal noise ~ hue calibration, black level noise in a camera
- Accuracy – accounts for systemic errors
  - *1-|D(E_{in})|/E_{in}, e.g., 97.5% accuracy*
- Precision – high precision ~ low noise
  - *$Range_{out}$/ Var(²(t))$^{1/2}$*

Systematic vs. Random?

- Sonar sensor:
  - *Sensitivity to: material, relative positions of sensor and target (cross-sensitivity)*
  - *Specular reflections (smooth sheetrock wall; in general material, angle)*
  - *Systematic or random? What if the robot moves?*
- CCD camera:
  - *changing illuminations*
  - *light or sound absorbing surfaces*
- Cross-sensitivity of robot sensor to robot pose and robot-environment dynamics
  - *rarely possible to model -> appear as random errors*
  - *systematic errors and random errors might be well defined in controlled environment.* This is not the case for mobile robots !!

Error Distributions

- A convenient assumption: $^2(t) \sim N(0,\S)$
- WRONG!
  - *Sonar (ultrasonic) sensor*
    - *Sometimes accurate, sometimes overestimating*
    - *Systematic or random? "Operation modes"*
    - *Random => Bimodal:*
      - mode for the case that the signal returns directly
      - mode for the case that the signals returns after multi-path reflections.
  - *Errors in the output of a stereo vision system (distances)*
- Characteristics of error distributions
  - *Uni- vs. Multi-modal,*
  - *Symmetric vs. asymmetric*
  - *Independent vs. dependent (decorrelated vs. correlated)*