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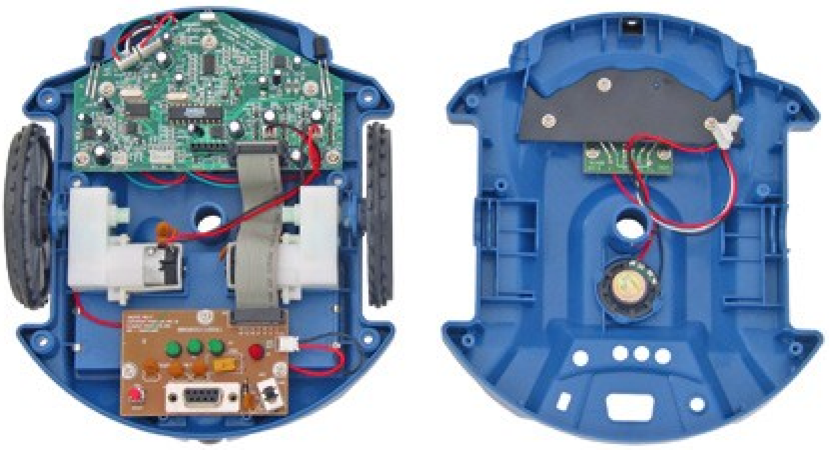
Lecture: Sensors

15-491, Fall 2008

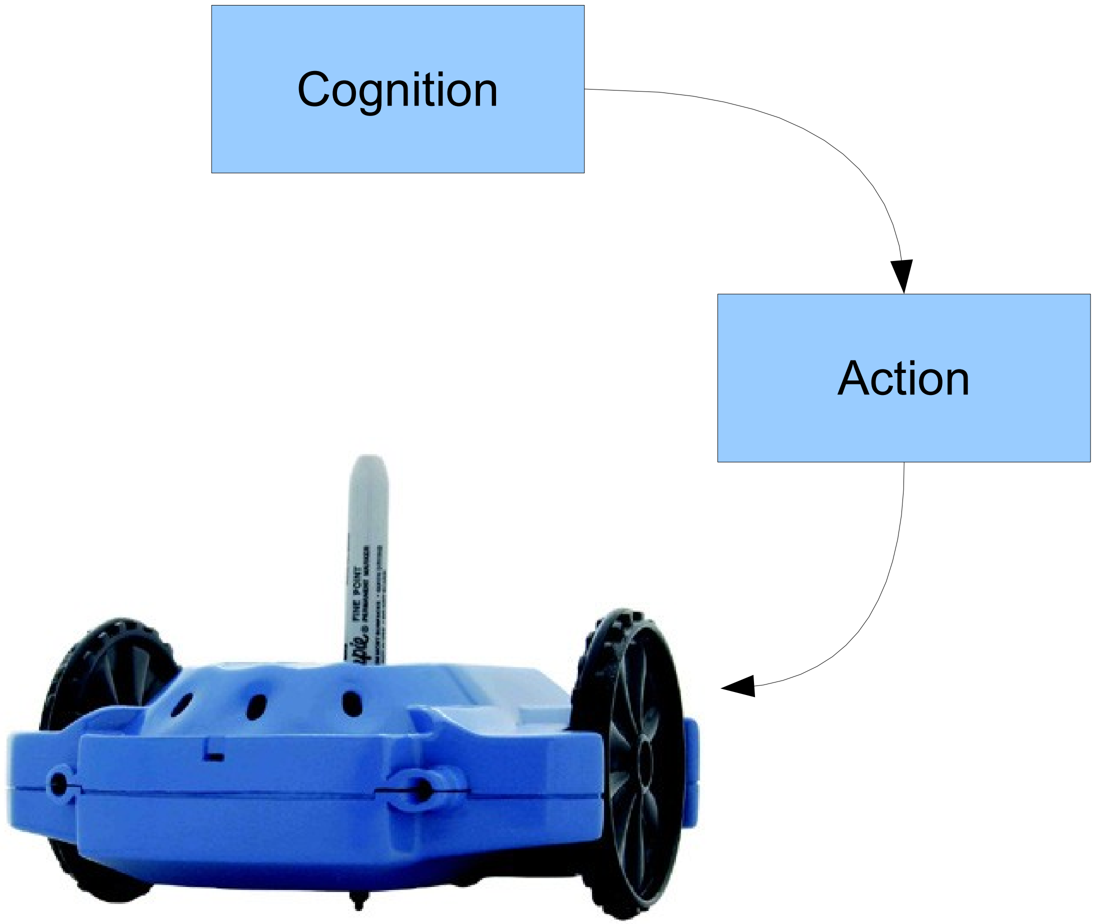


Outline

- Sensor types and overview
- Common sensors in detail
- Sensor modeling and calibration
- Perception processing preview
- Summary

Open Loop Control

- No sensing input

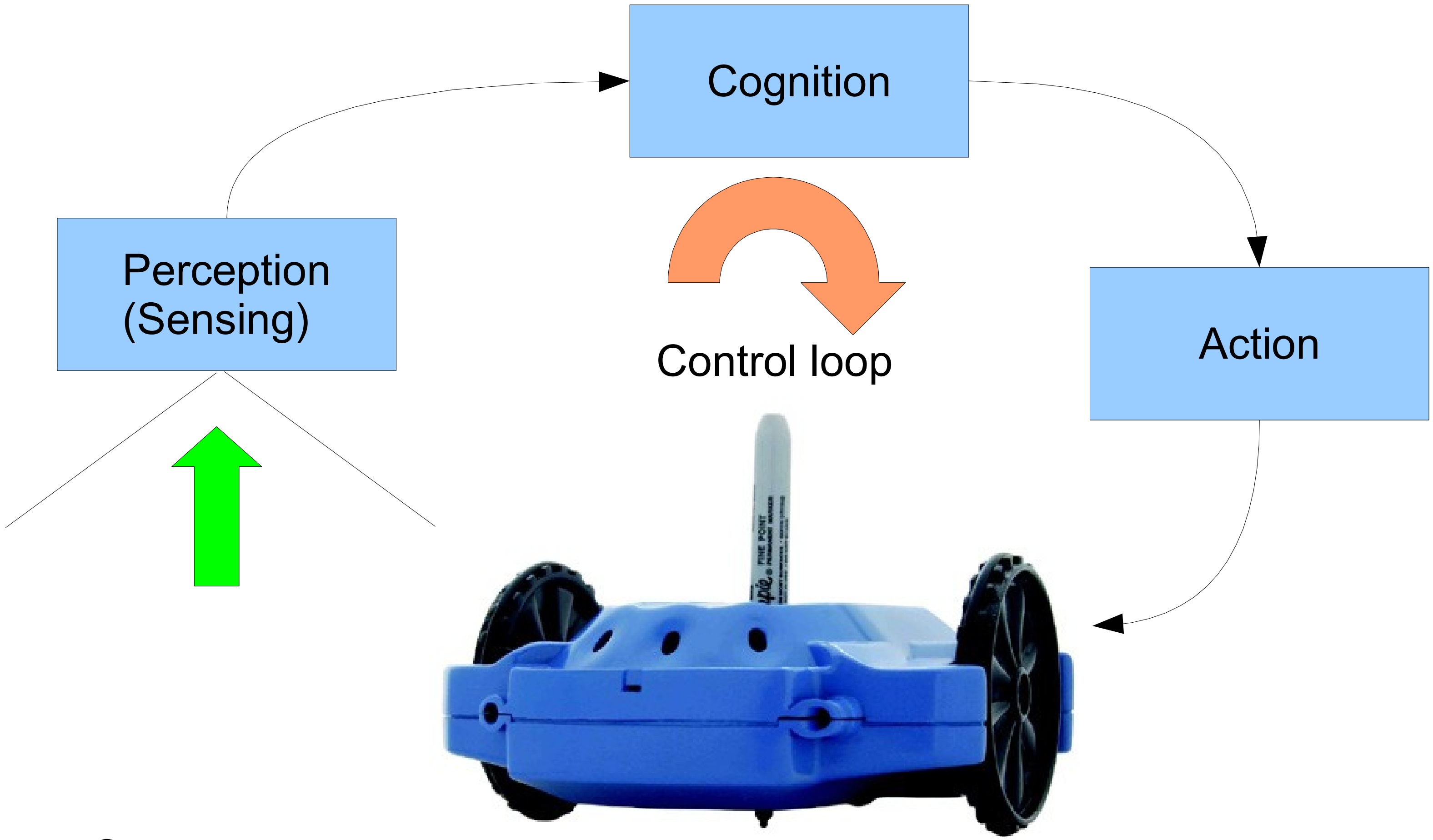


Why Sense?

- To acquire information about the environment and oneself
- Open loop control suffers from
  - Uncertainty, changes in the world
  - Error detection and correction

The Sensing Loop

- "Feedback" control



Issues to Address

- What sensors to use?
- How to model the sensor?
- How to calibrate intrinsic/extrinsic models?
- What low-level processing?
- What high-level processing (perception)?

Comparison: Human Sensors

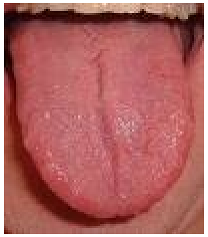
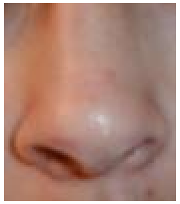
Sense:

- Vision
- Audition
- Gustation
- Olfaction
- Tactition

Sensor:

- Eyes
- Ears
- Tongue
- Nose
- Skin




Robot Sensors

Sense:

- Equilibrioception
- Proprioception
- Magnetoception
- Electroception
- Echolocation
- Pressure gradient

Sensor:

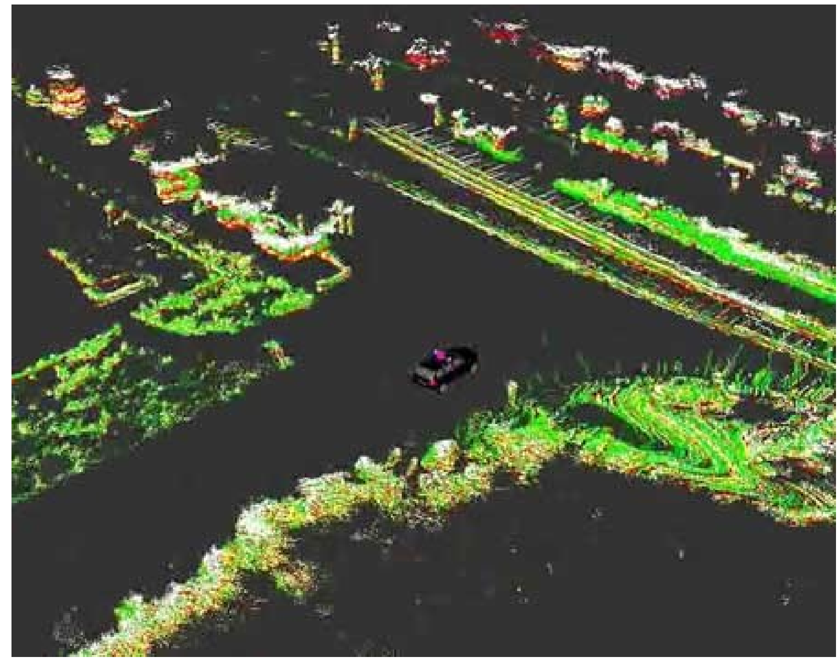
- Accelerometer

- Encoders

- Magnetometer
- Voltage sensor
- Sonar

- Array of pressure sensors

LiDar Sensing



LiDar Variations

Tartan Racing Team

Boss vehicle

Sensor Examples

- (CMU) Tartan Racing Urban Challenge vehicle
- Groundhog, subterranean mapping (CMU)
  - Carnegie Mellon Mine Mapping Project
- Ocean explorer www.oceanexplorer.noaa.gov

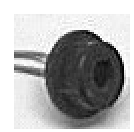
Popular Sensors in Robotics

- LiDar
- Infrared
- Radar
- Sonar
- Cameras
- GPS
- Accelerometers
- Gyros, encoders
- Contact switch

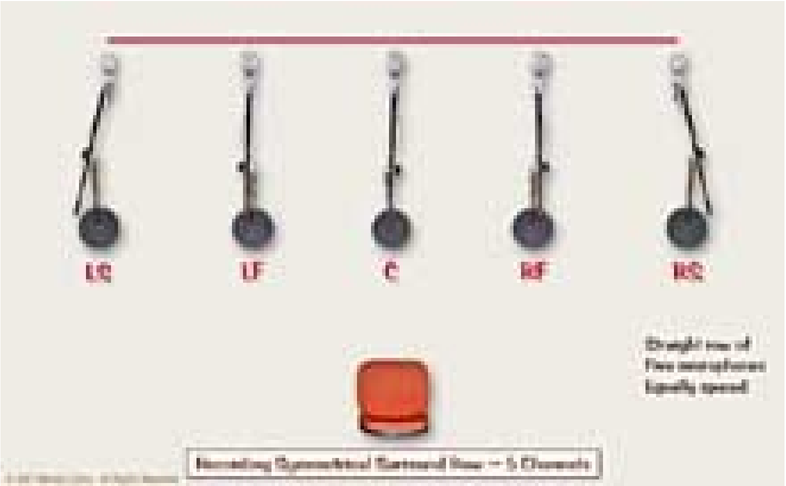


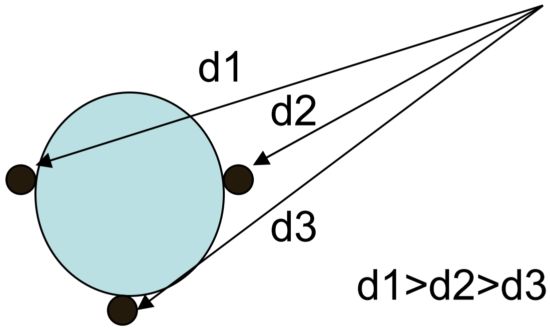


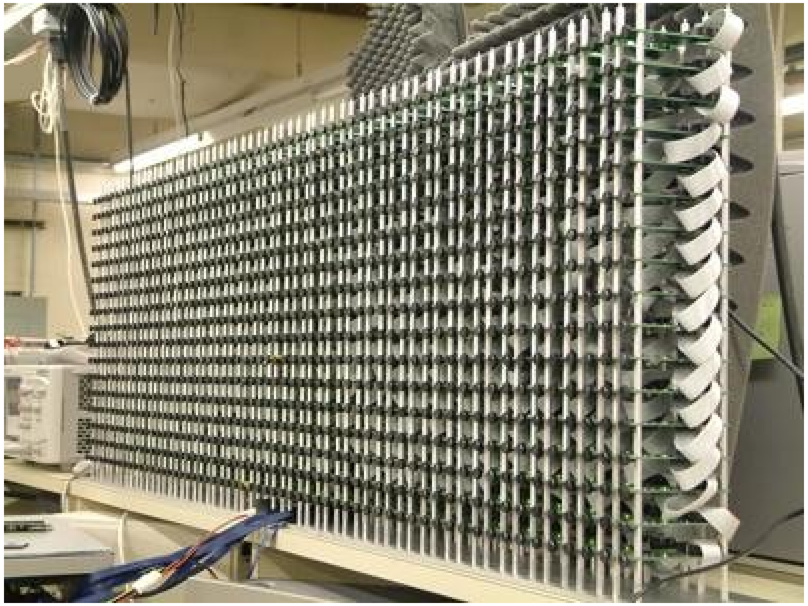




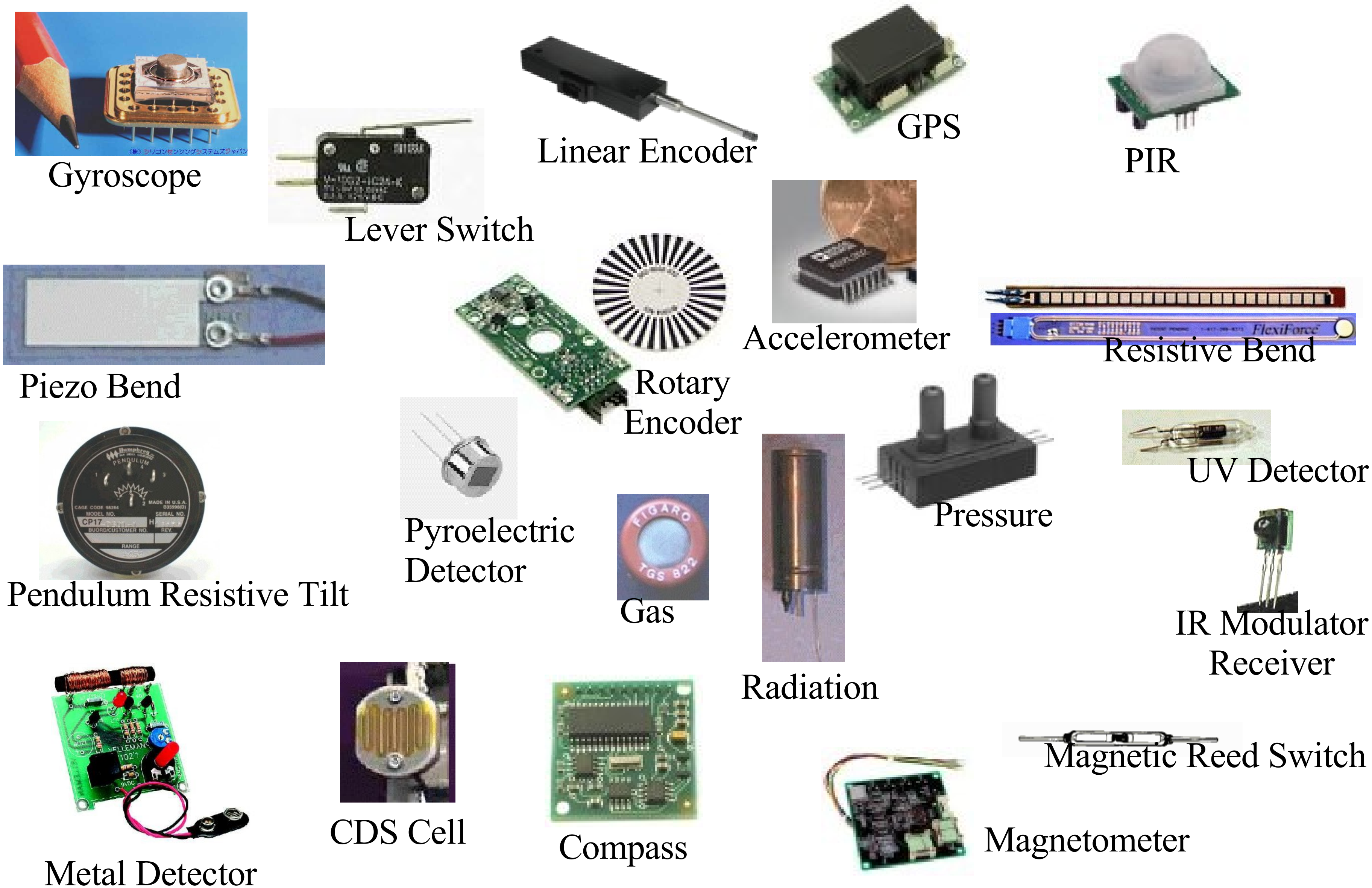
Auditory







Other Robot Sensors



Sensing Classification

Extereoceptive

Active

- Laser/LiDar
- Sonar
- Radar
- Structured light
- InfraRed

Passive

- Vision
- Microphone array
- Chemical sensors
- Tactile sensor

Proprioceptive

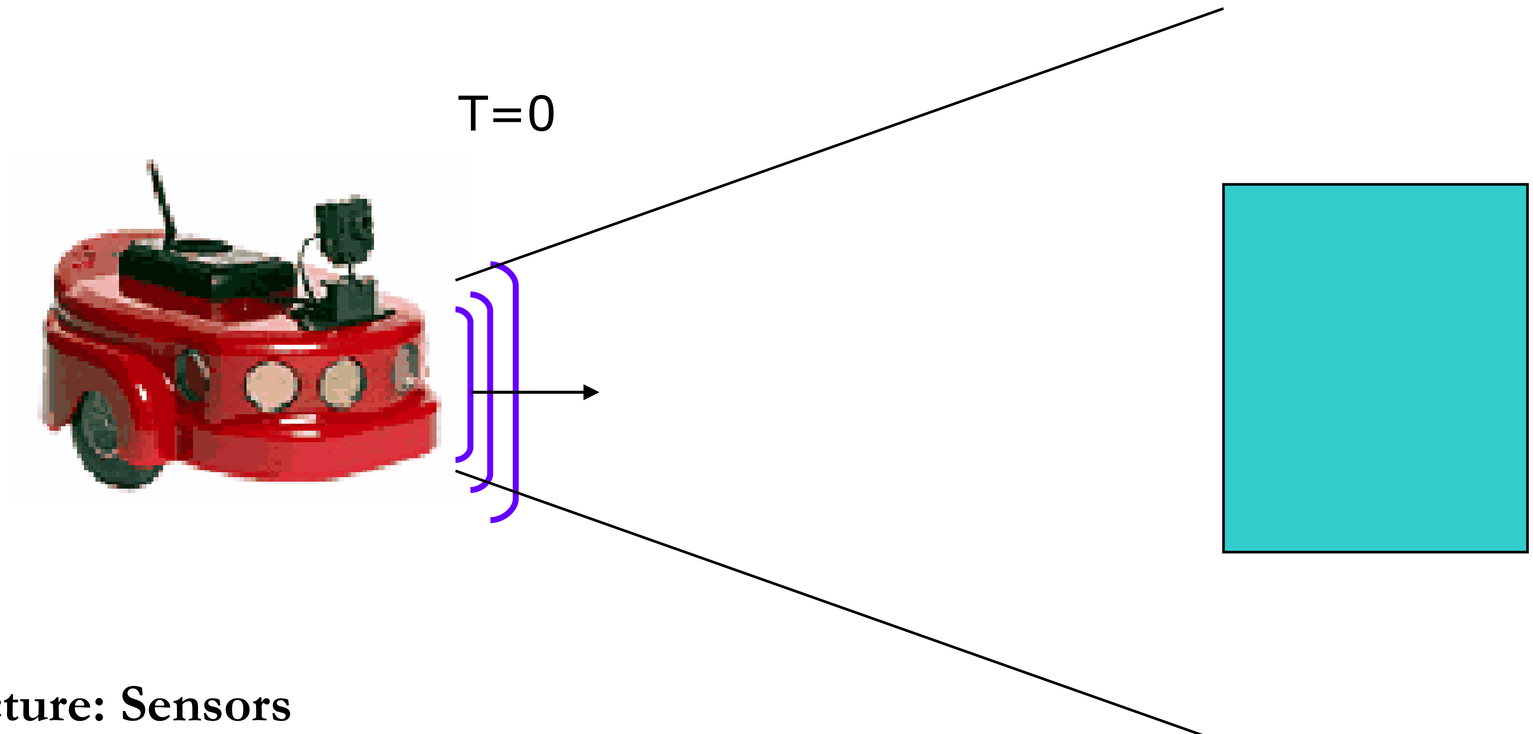
- Gyroscope
- Accelerometers
- Odometers
- Voltage sensors
- Stress/strain gauge

Sensors We Will Look At Today

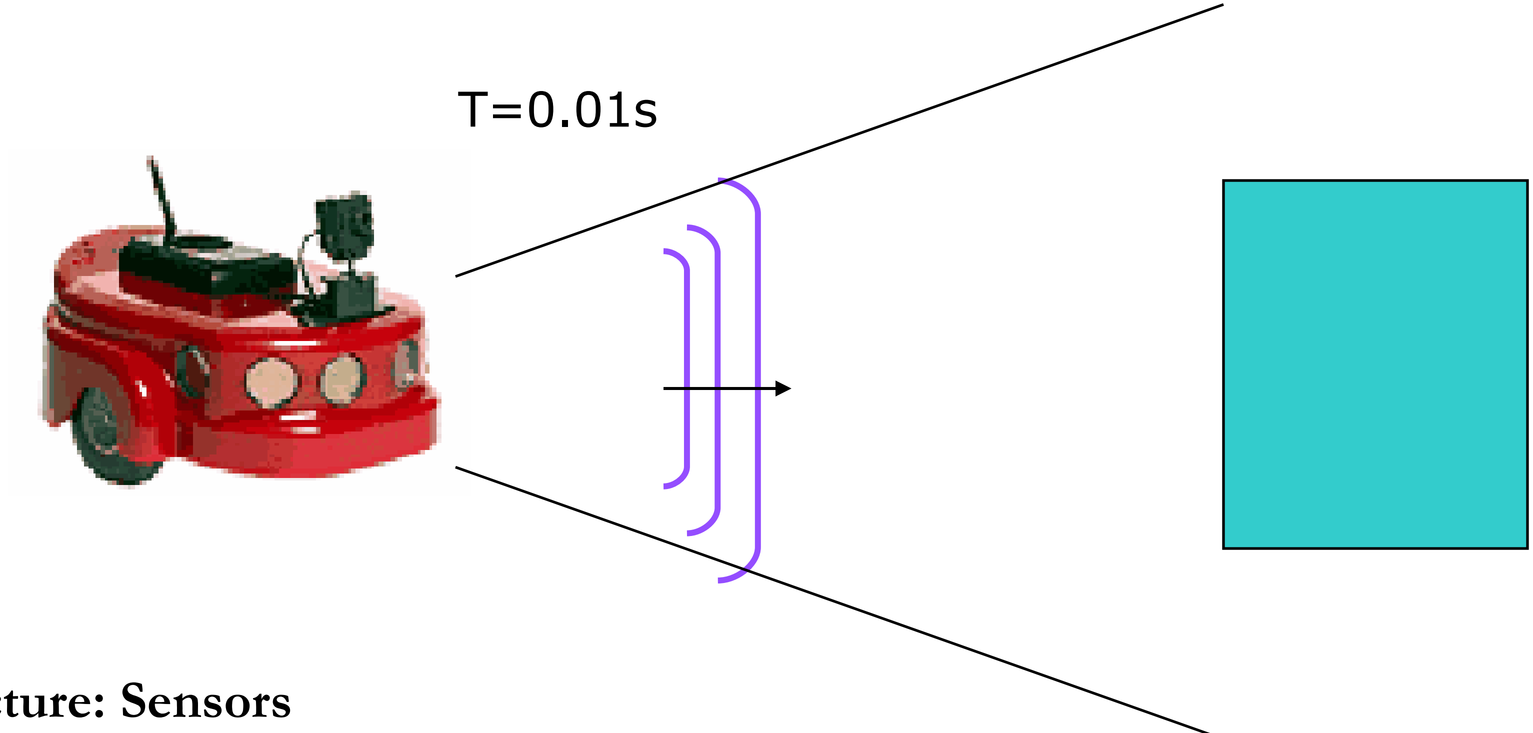
- Exterioceptive
  - Sonar, LiDar, IR
  - Vision comes later
- Proprioceptive
  - Encoders
  - Accelerometers
  - Gyroscopes
  - GPS (hard to categorize)
  - Micro-switch

SoNaR: Sound Navigation and Ranging

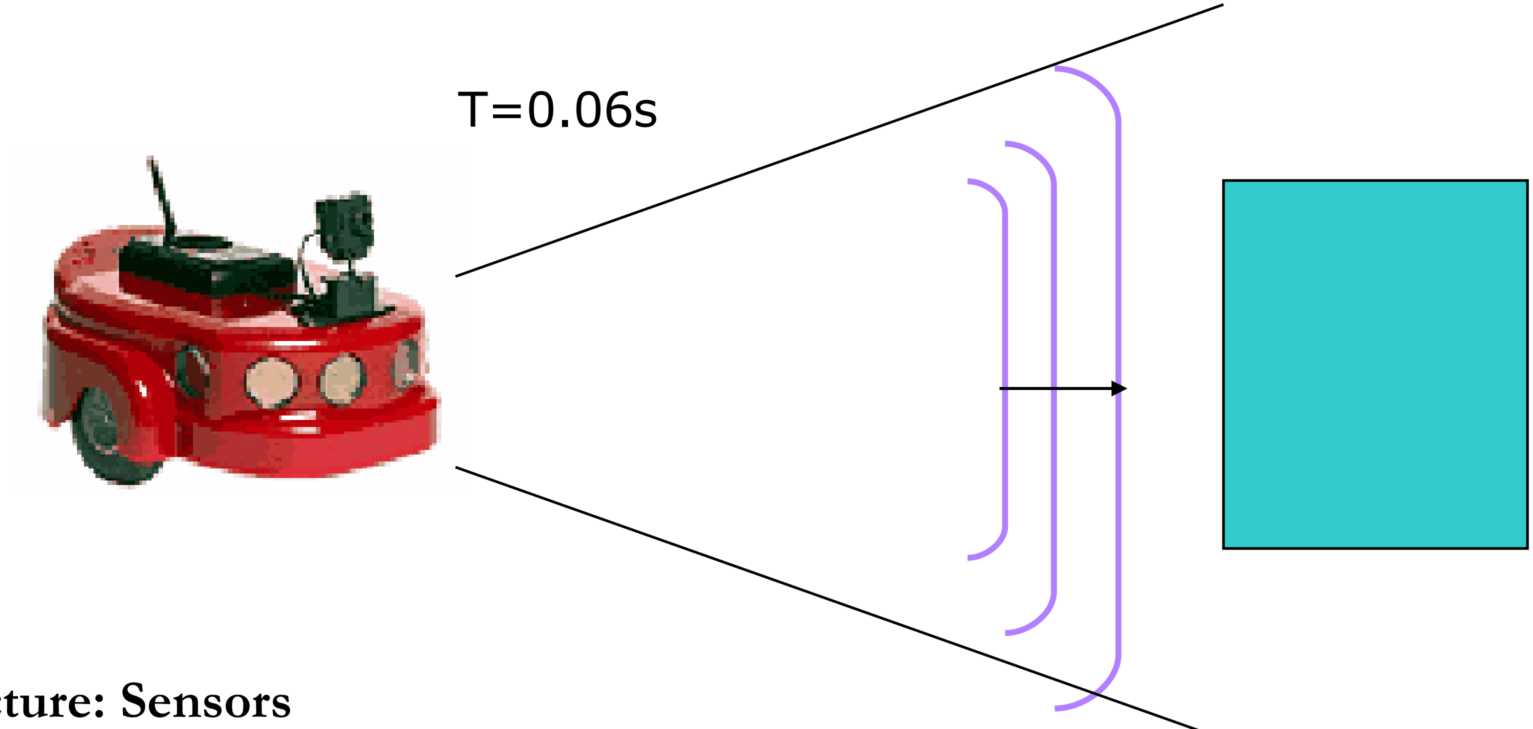
- Often called sonar, ultrasound, Sodar
- Emit a directional sound wave, and listen for echo(s), time the response



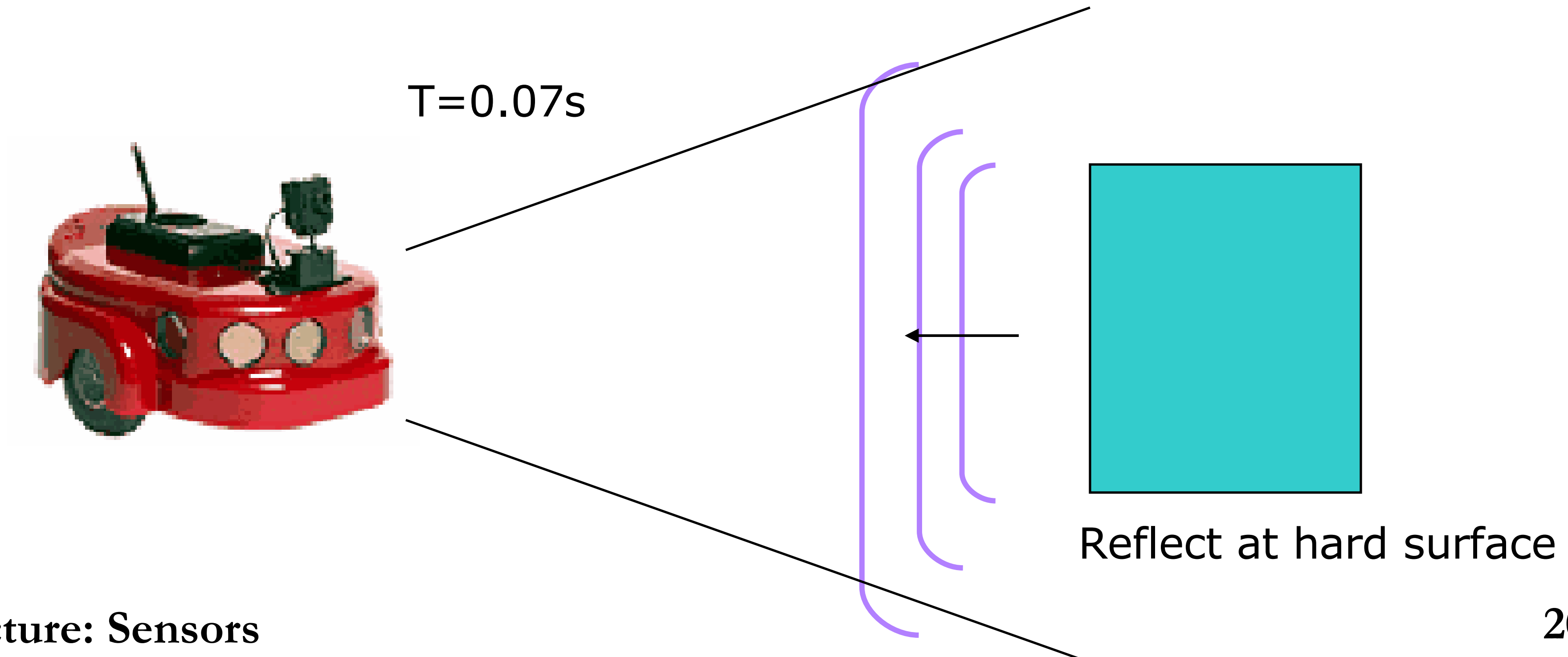
Sonar Sensors



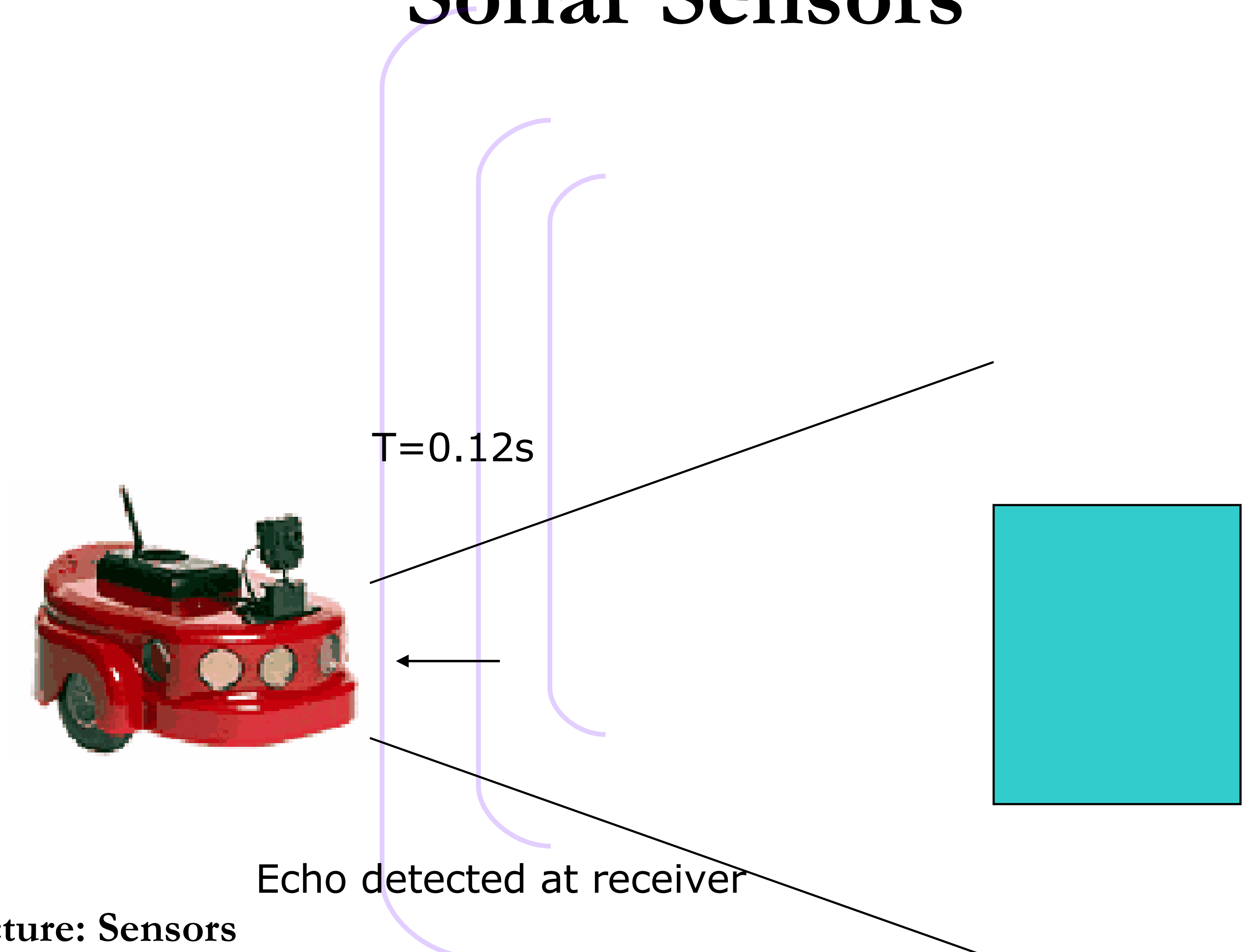
Sonar Sensors



Sonar Sensors



Sonar Sensors



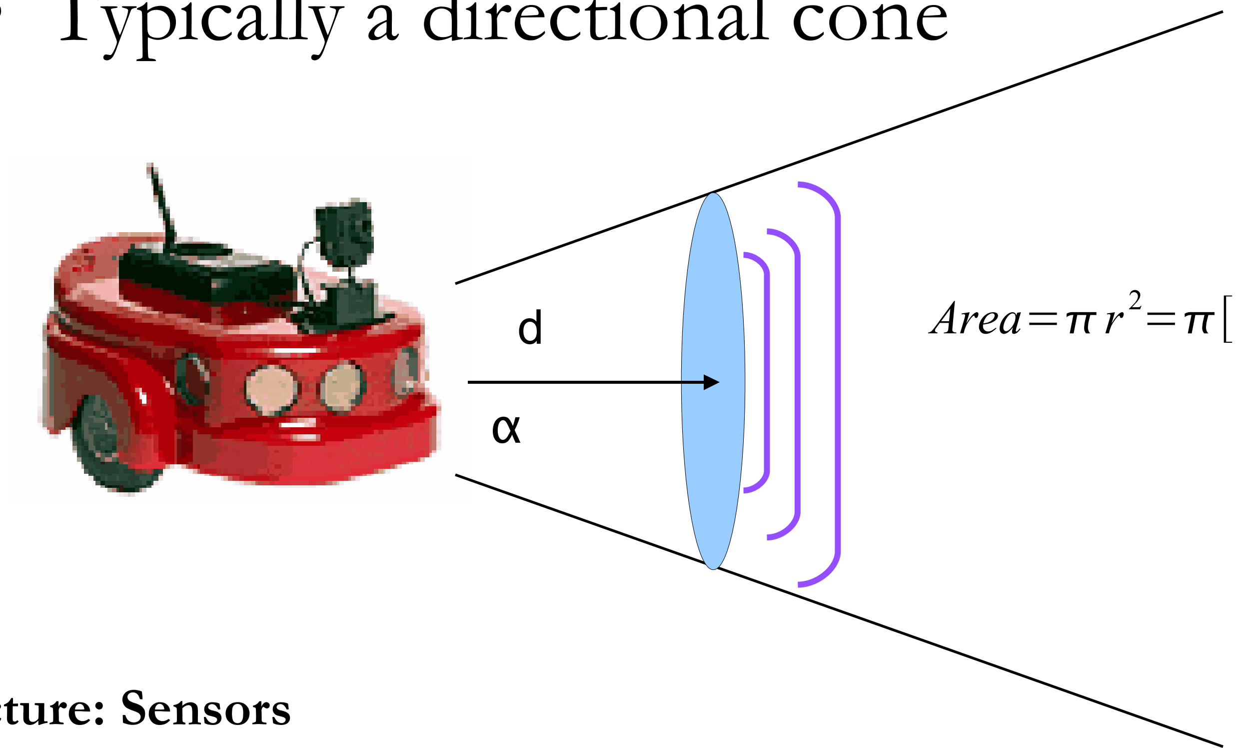
Sonar Sensors

- Key assumption: sound travels at constant speed
- v=344 m/s (dry air, 21C, sea-level)
- So we have

$$d = \frac{1}{2} v T$$

Power of Returned Signal

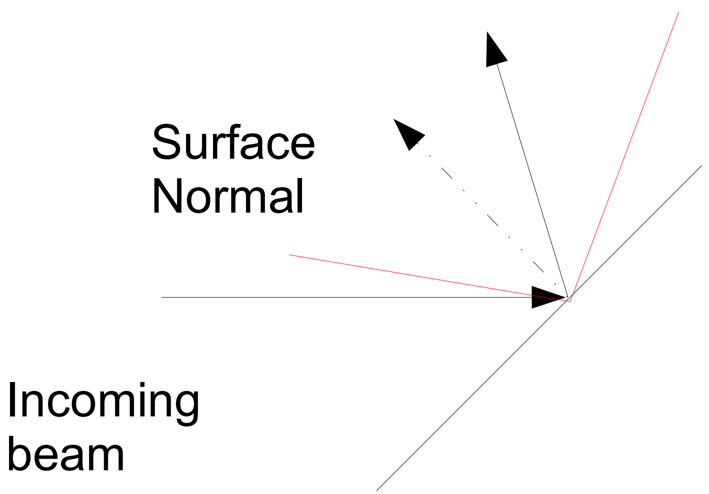
- Signal power dissipates as wave travels
  - Depends upon the shape of the wavefront
  - Driven by shape of transmitter (same for radar)
- Typically a directional cone

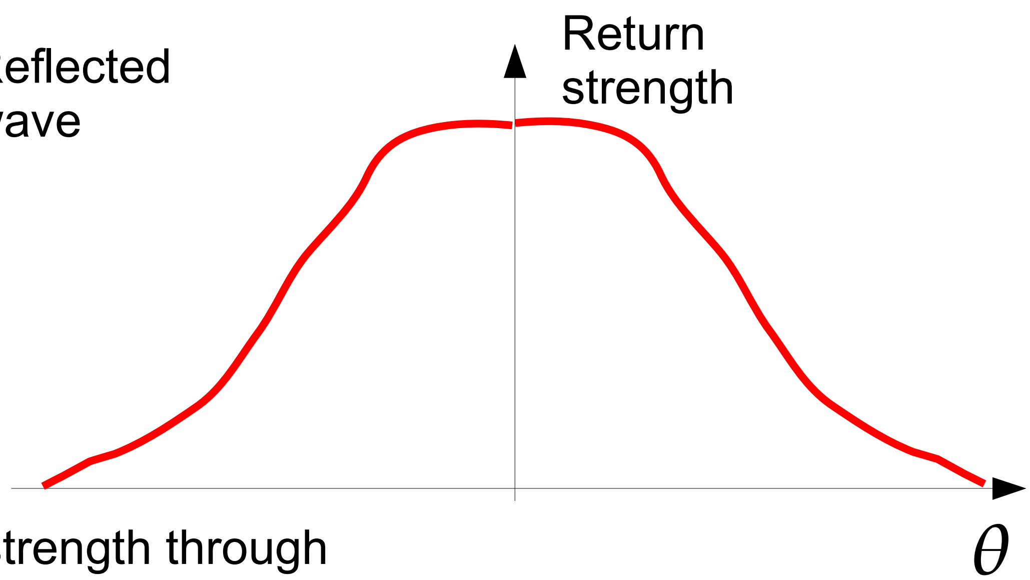


$$Area = \pi r^2 = \pi [d \tan(\frac{\alpha}{2})]^2 \propto d^2$$

Reflection Strength

- Function of surface angle and surface properties



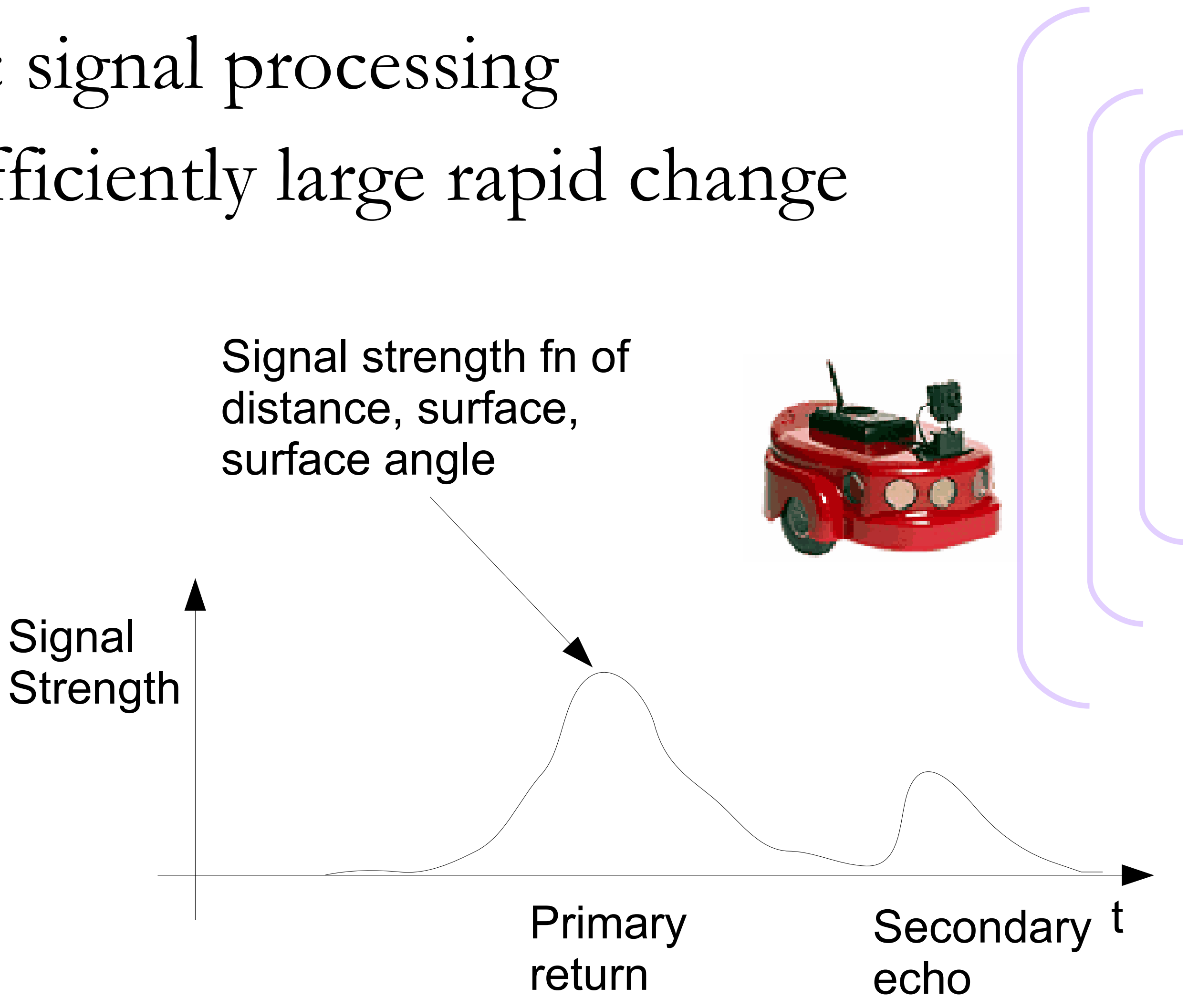


Loss of signal strength through
reflection e.g. cardboard vs. tile

Surface may disperse reflected
wave leading to reduced signal
strength and wider return beam

How To Detect the Echo?

- Electronic signal processing
- Detect sufficiently large rapid change



Imperfect Sensing

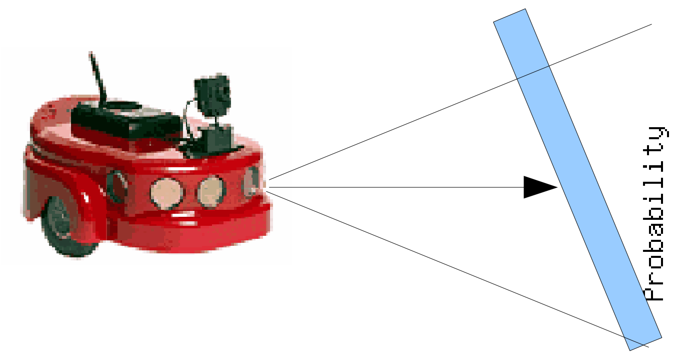
- What can go wrong?
  - Speed of sound changes with temperature, pressure, humidity

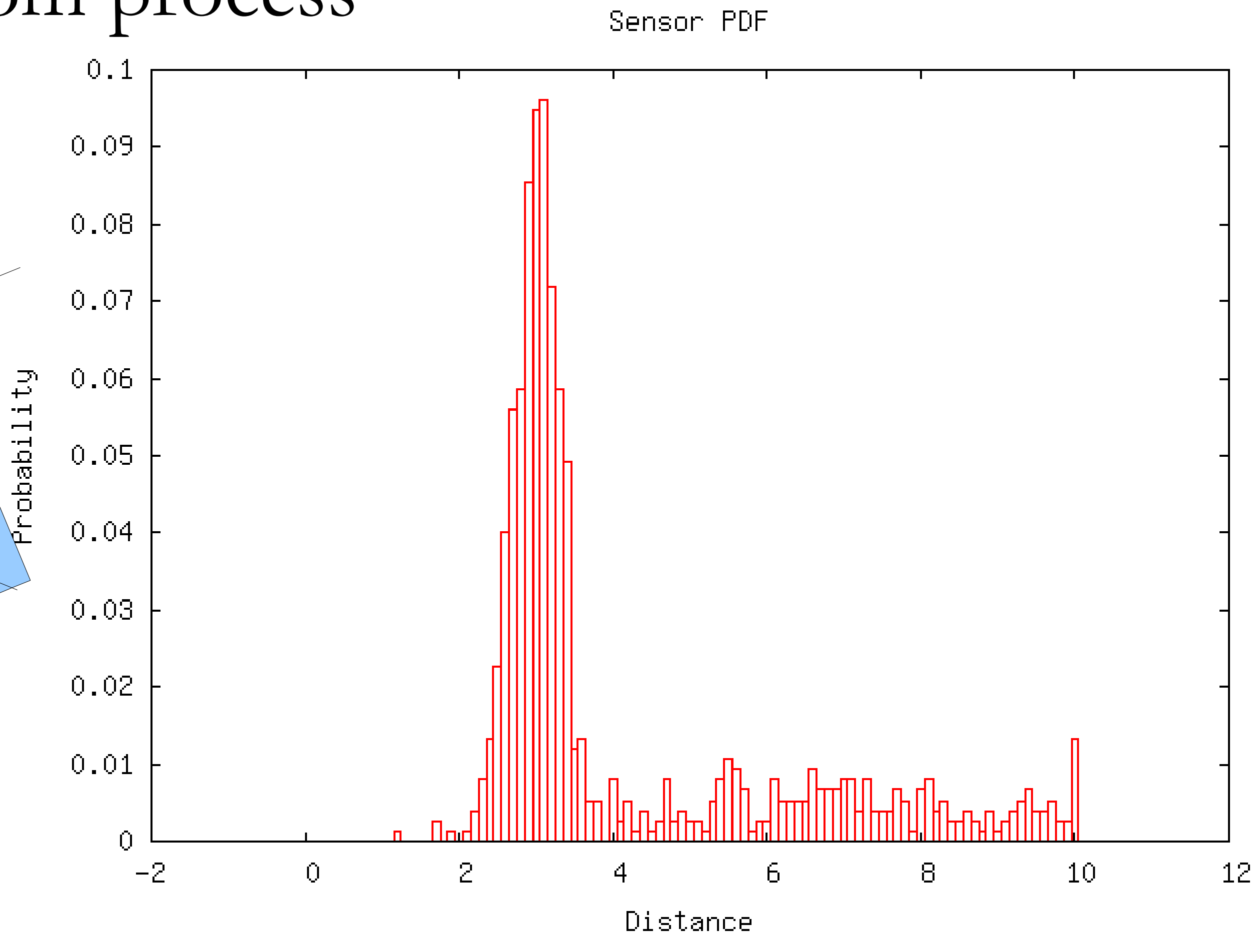
$$v_{ideal} = \sqrt{\frac{\gamma k T}{m}}$$

  - Surface reflection properties
  - Atmospheric attenuation (finite range)
  - Multiple echoees (multi-path)
  - Quantization in timing
  - Inaccuracies in detecting response signal onset
  - Cross-talk (echoes from other sensors)

Sensor Noise

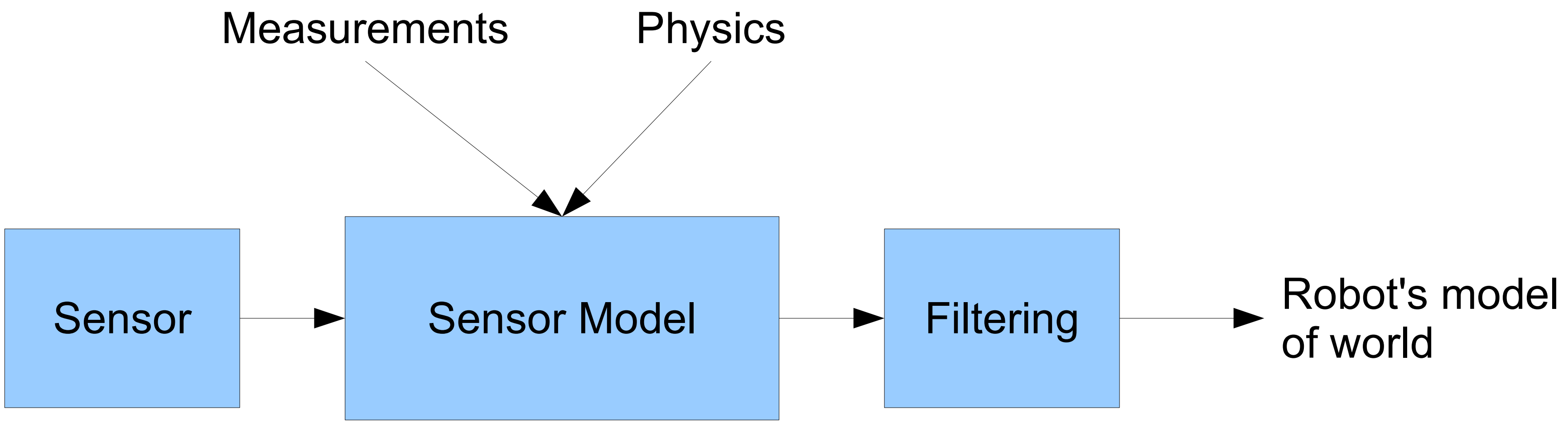
- Fixed object, sensor returns different values over time => random process





Bigger Picture: Perception

- Given sensor readings, how does robot determine the structure and content of the world?
- Usual way is to *model* the problem



Sensor Model

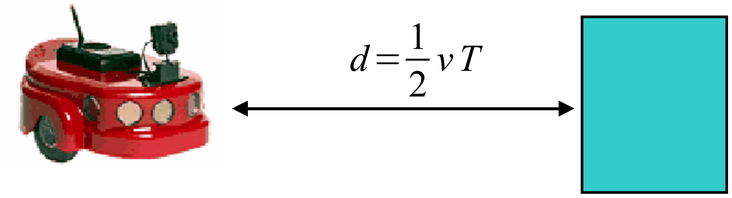
- Model the device physics to obtain the expected device properties and parameters
  - Intrinsic model: Device itself
  - Extrinsic model: Where the device is on the robot
- Collect data and *fit* model parameters
  - This is *calibration*
- Level of complexity is a trade off
  - Computation, accuracy, reliability, domain knowledge
- Often need to reason explicitly about *uncertainty*

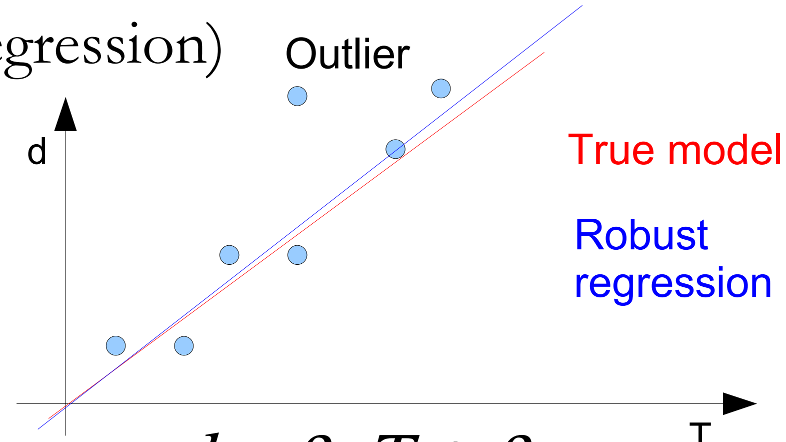
Modeling Sonar

- What should we model?
- Usually:
  - Mapping from time to range (first return only)
    - We have a physics model with parameters. Calibrate to get parameter values.
  - Model sensor uncertainty
    - How do we do this? What distribution should we use?
- Other possibilities:
  - Signal strength to surface orientation?
  - Using secondary peaks?
  - Profile of response?

Calibration

- We have a model
  - Derived from the physics (best approach)
  - Look at data and guess a low dimensional model
- Estimate the parameters from a known setup
  - Measure signal response at different distances
    - Optionally different angles, surfaces, humidity, altitude…
  - Fit parameters to the data (e.g. regression)





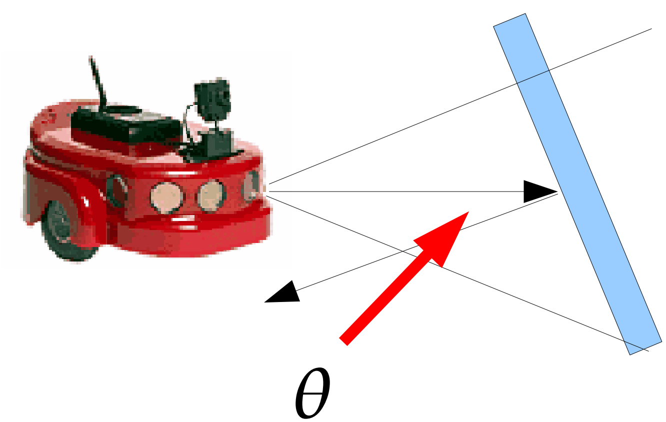
$$d = \beta_1 T + \beta_0$$

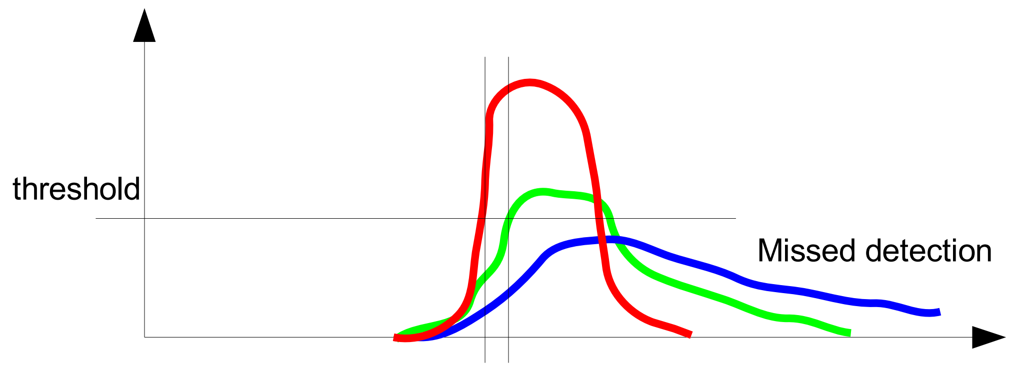
Sensor Noise Modeling

- Sensors are **never** perfect
  - Unmodeled effects
  - True randomness in the environment, robot, and sensing process
- Systematic errors (bias)
- Drift, jumps

Sensor Bias

- Return may vary as a function of physical setup
  - Surface material/color, orientation, range, atmosphere

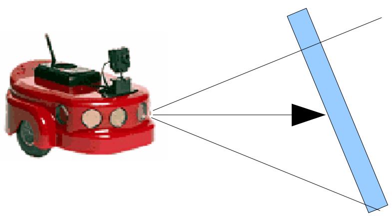


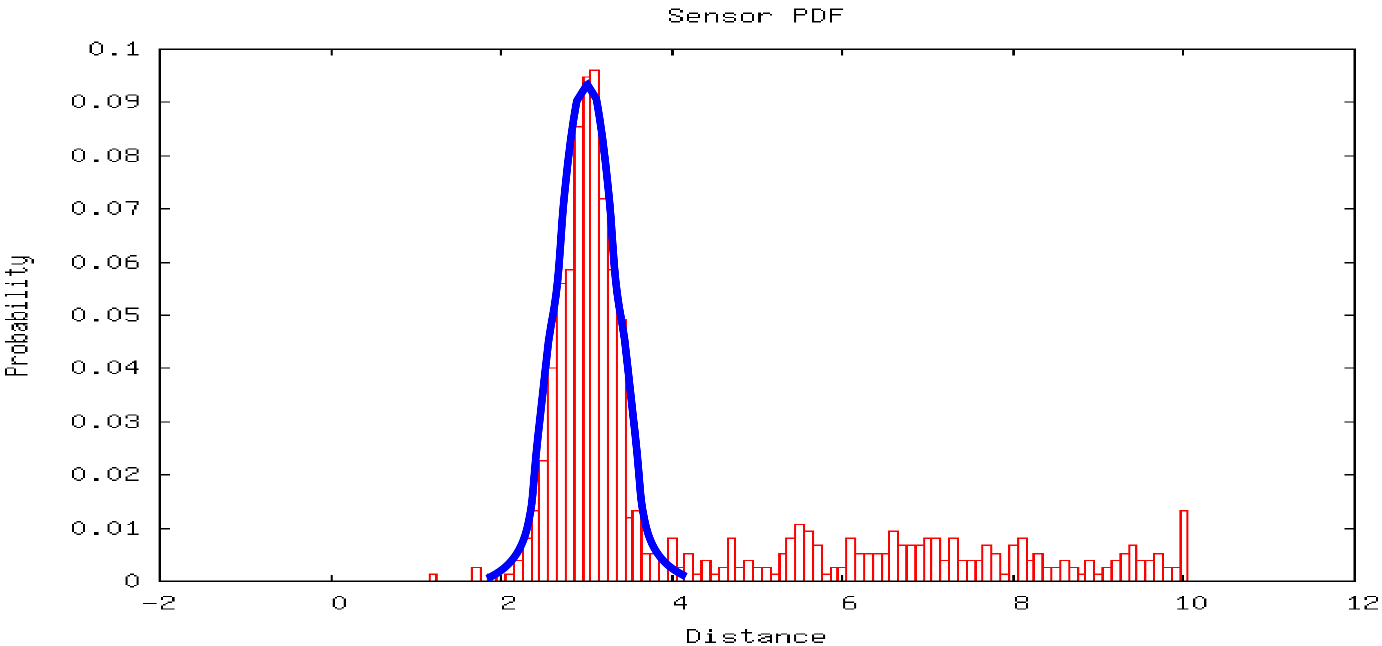


Changing shape of return signal due to surface properties/orientation affect how range is detected

Sensor Noise Model

- Enter the world of statistics
  - Usually choose a parametric model and estimate parameters e.g. Gaussian



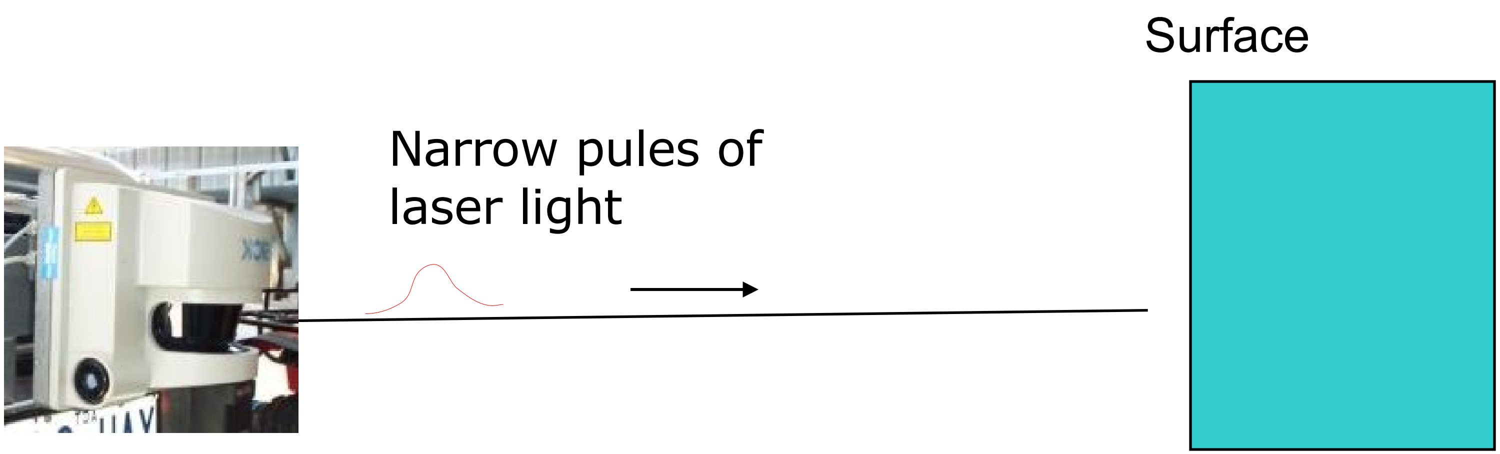


Sensor Filtering

- Usually apply some level of filtering to raw sensor data before feeding into rest of system
- Examples
  - Thresholding – you've already seen this
  - Smoothing – simple filters
  - Kalman filtering – more complex filter exploiting additional domain knowledge
- Resulting estimate used to build perception models
  - Occupancy grids, trackers, etc.

LiDar

- Light Detection and Ranging
- Different variants, we'll focus on time to return
  - Most common to robotics
  - Same model as Sonar

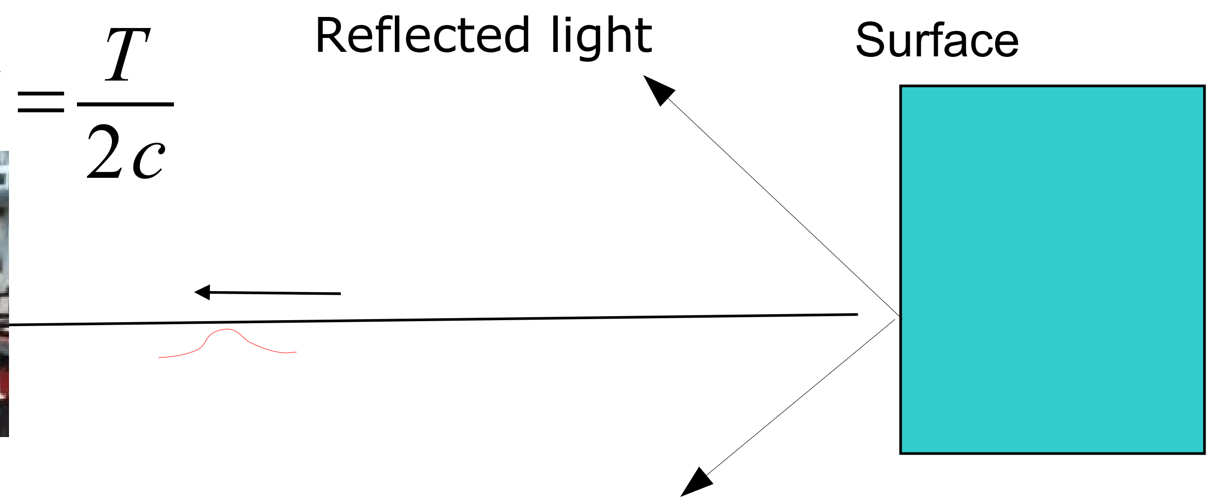


LiDar

- Timed “echo” from reflection
- Speed of light >> speed of sound

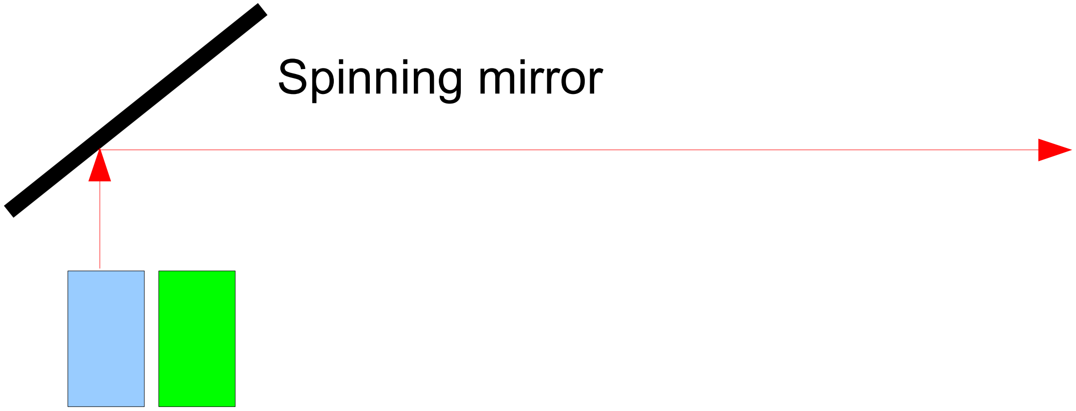
$$c_{vaccum} = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \approx 3\text{x}10^8\, m.s^{-1}$$

$$d = \frac{T}{2c}$$



SICK LiDar

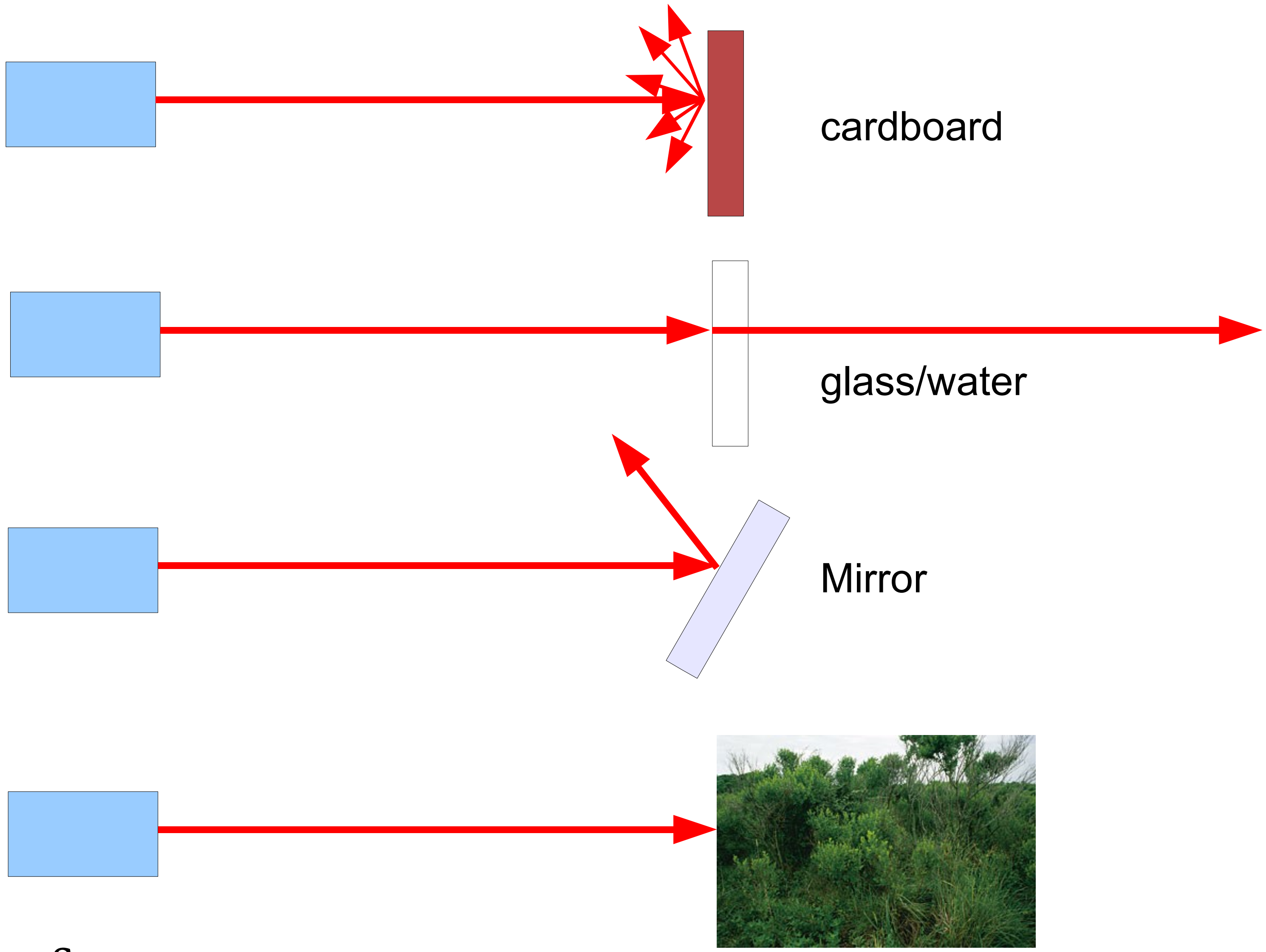
- Very common unit
- Spinning mirror assembly gives line scan
  - Ranges vary (90, 180 degree, 50+m)
  - Scanning rates vary (e.g. 20Hz, 75Hz)
  - Resolutions (e.g. 0.25 degree, 10mm)
  - Accuracy ~30mm stdev in range



SICK LiDar Internals

- From http://web.mit.edu/kvogt/www/lidar.html

LiDar Returns and Material



LiDar Variations

NREC Crusher Vehicle

Crusher with sensors

Colorized LiDar

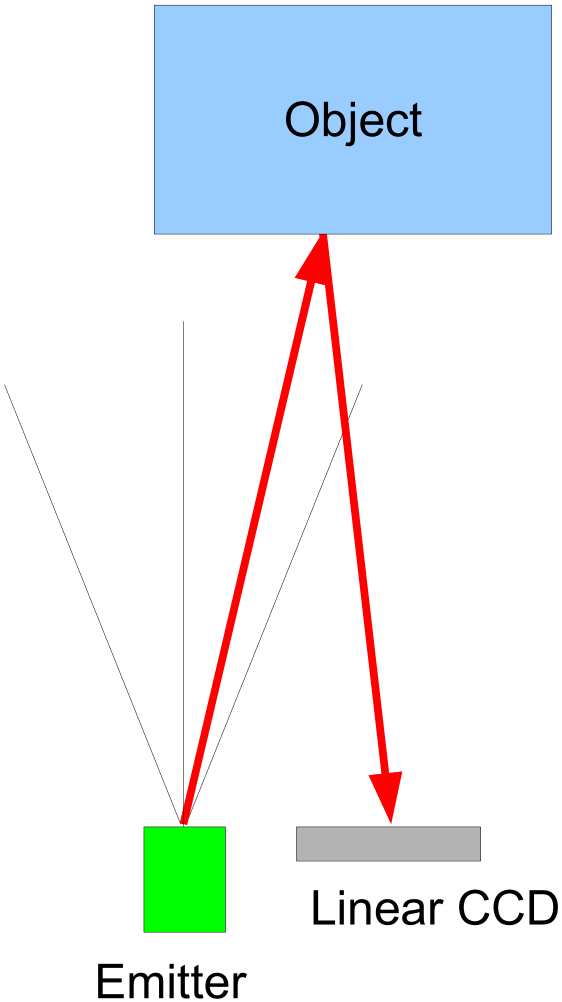
Used a lot on NREC robots

http://www.aerotecusa.com/

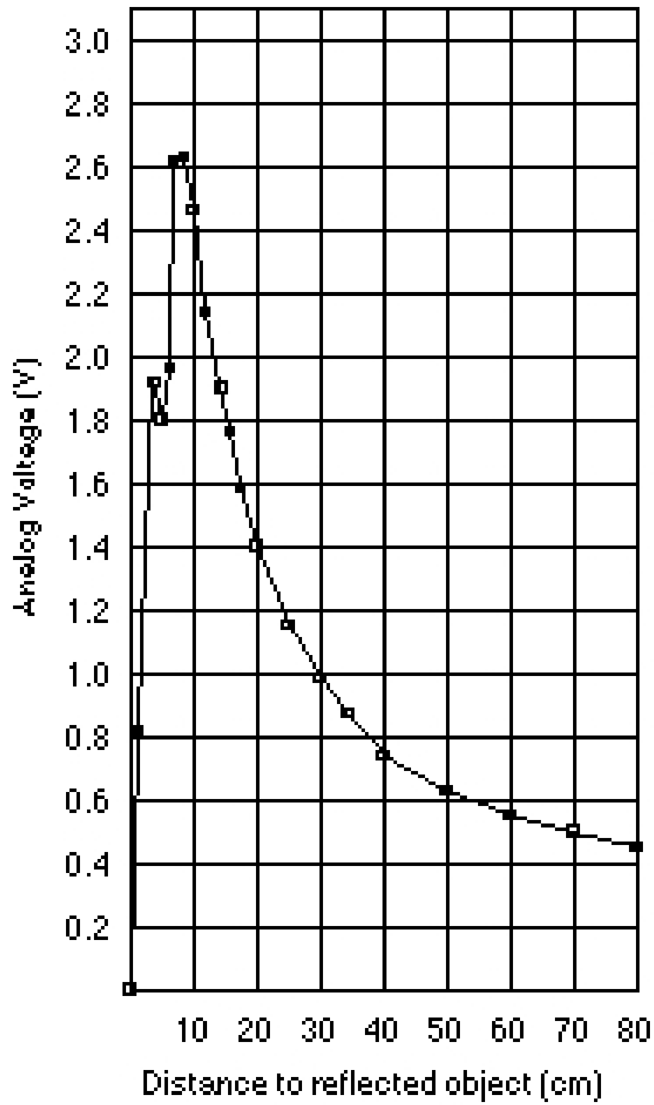
InfraRed

- Emitter/detector pair
- Output type
  - Digital (strength of return threshold)
  - Analog range using triangulation
- Usually short-range (<1m)
- Can be sensitive to IR sources e.g. sun

Sharp IR Sensor



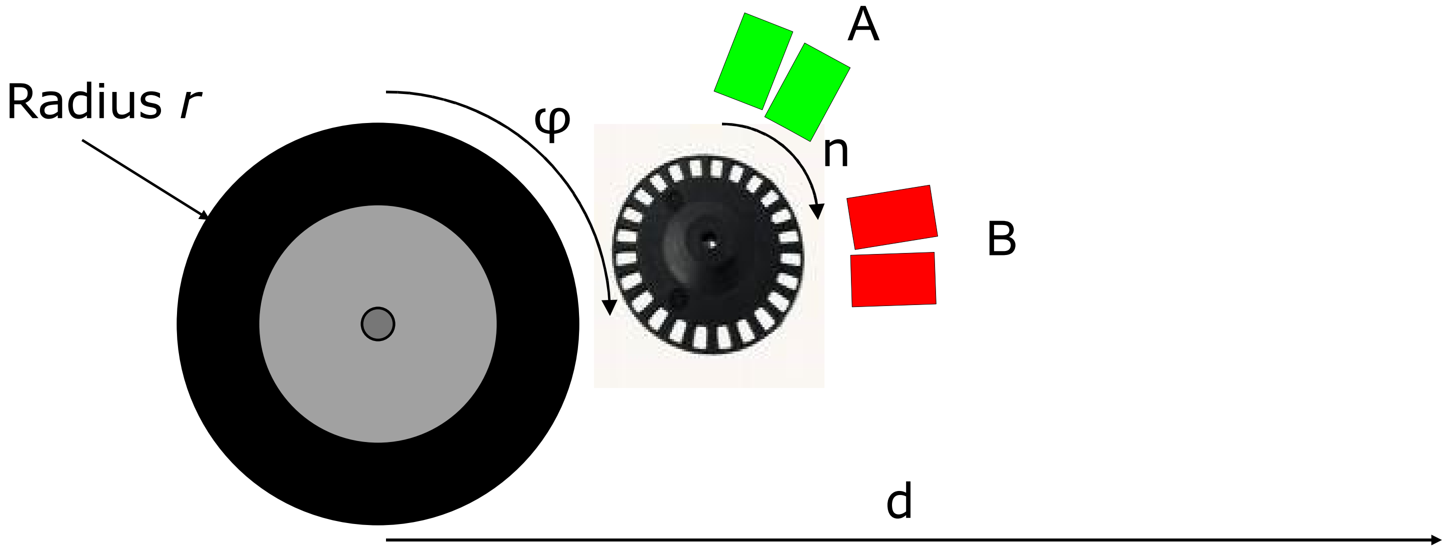
http://www.acroname.com



Proprioceptive Sensors

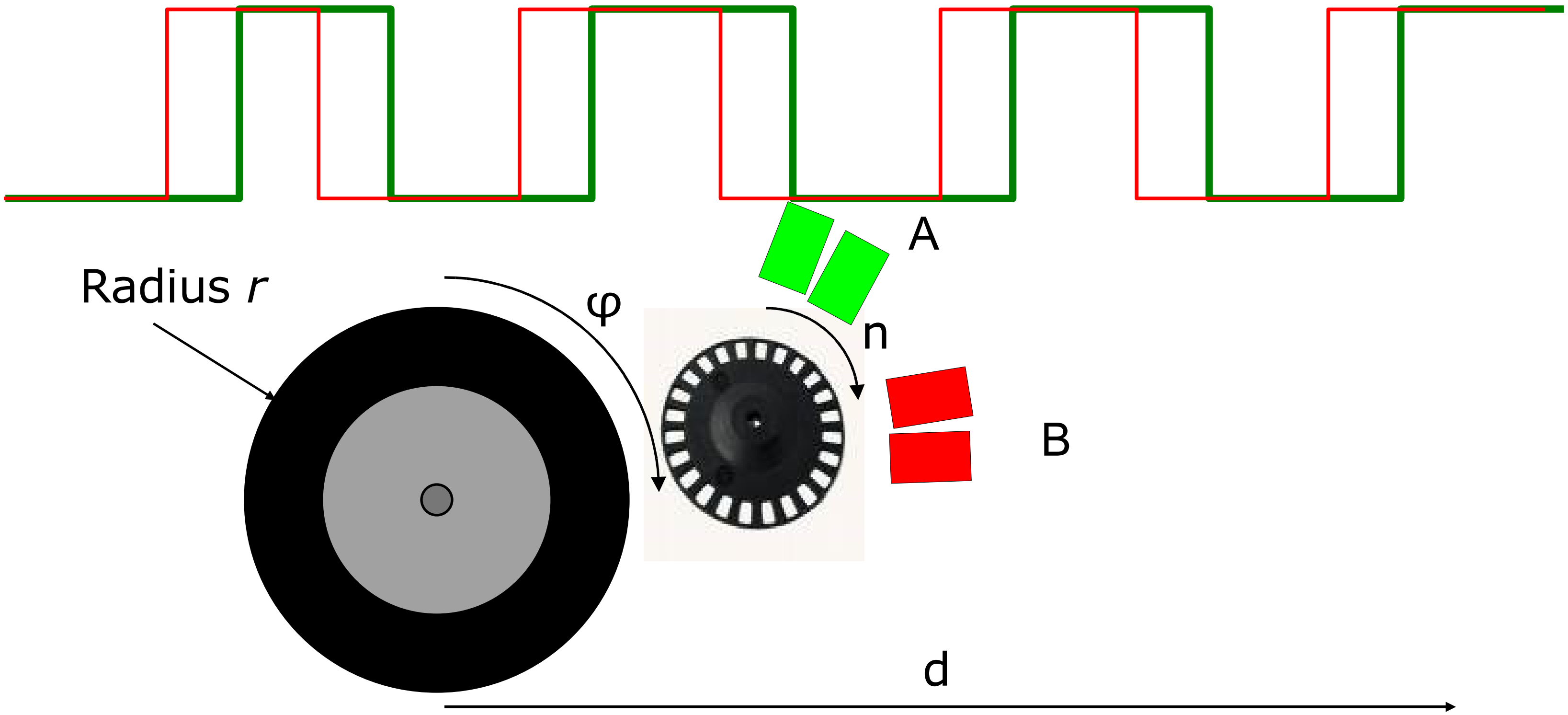
Optical Encoders

- Disc to measure *rotational* motion
- Out of phase IR emitter/detector pair



Optical Encoders

- Direction and amount of rotation from edge transitions



In Practice

- Electronic hardware (MCU or ASIC) provides counting, de-bouncing
- Estimate speed by sampling encoder counts
  – Model to provide wheel speed from encoder counts
- How to get vehicle speeds from wheel speeds?
  – This is kinematics! (Later in the course)

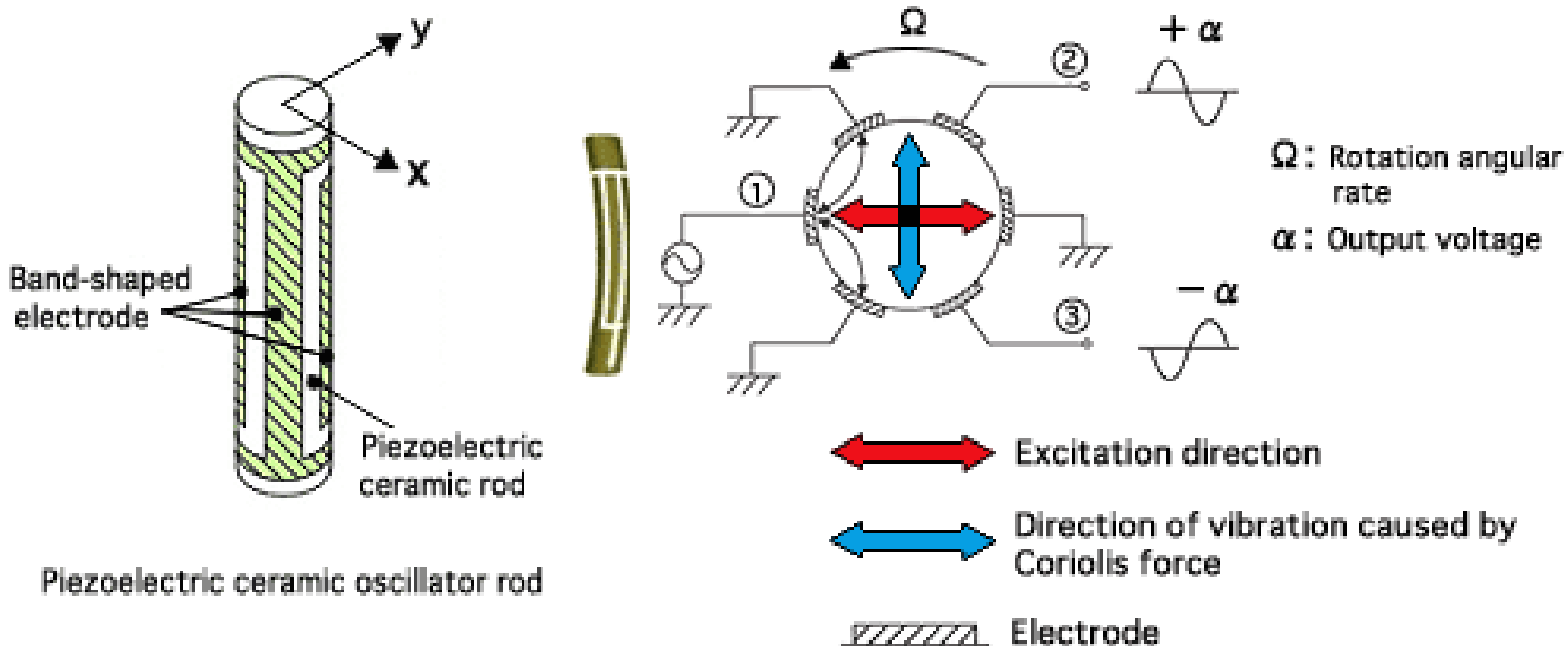
Gyroscopes

- Proprioceptive sensor
- Maintaining estimate of orientation
  - Mechanical devices
  - Fiber optic gyroscope
  - Vibrating gyroscope (e.g. MEMS)

http://www.nec-tokin.com/

Rotational Angular Velocity Sensor

Operation principle : An angular velocity sensor that works by using the phenomenon generated by Coriolis force when angular velocity is applied to a moving object in relation to velocity and orthogonal directions.



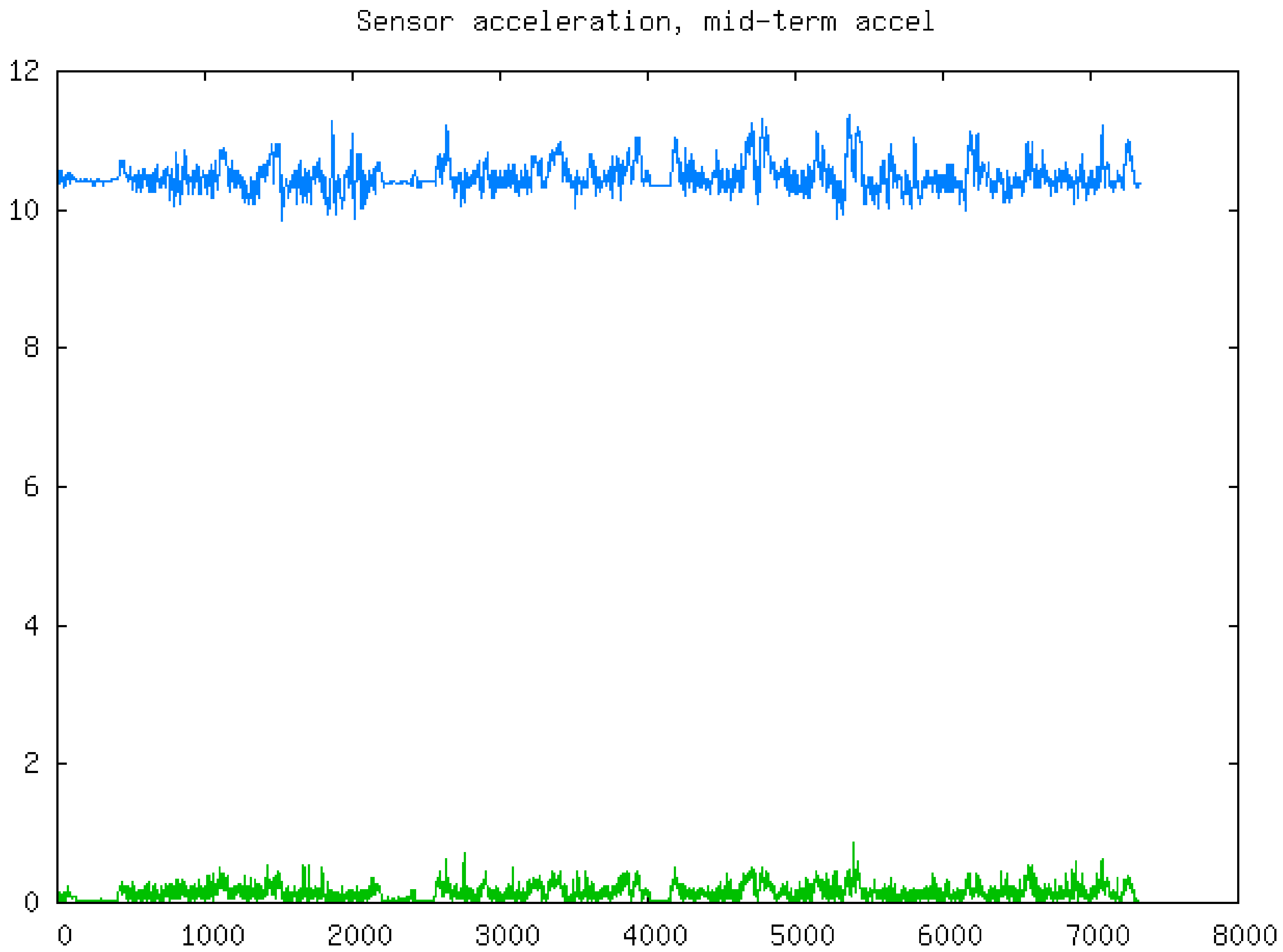
Piezoelectric ceramic oscillator rod

http://www.nec-tokin.com/

Accelerometers

- Measure acceleration in a direction of travel
  - Typically MEMS device
- Also measures gravity
  - Good old relativity...
  - Can use with gyroscopes to remove gravity component
- Typically very noisy
- Need to double integrate to get position

Accelerometers



Issues With Accelerometers/Gyros

- Noise
  - Output readings may have approximately additive Gaussian noise
- Drift
  - Signal drifts from true value over time – Gyro heading
  - Usually need to integrate accelerometers

GPS/Glonas/Galileo

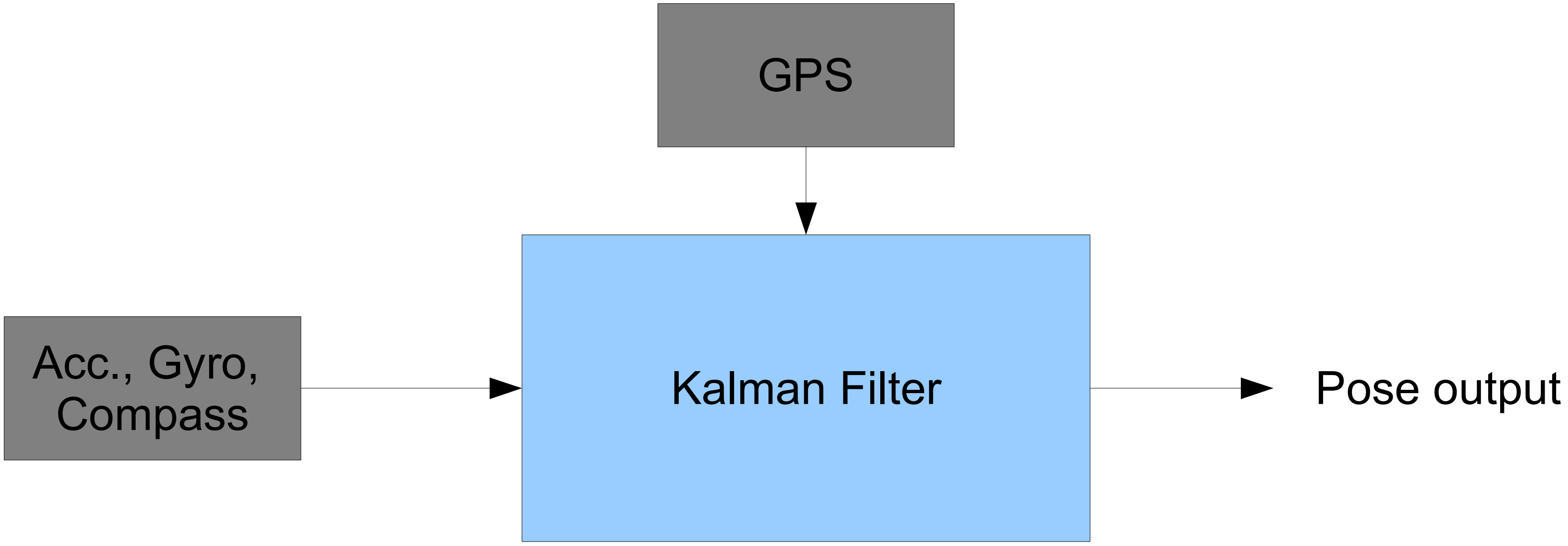
- Orbiting satellites
  - Known trajectories
  - Highly precise timers
- Transmit data in Ghz band
  - Ephemeris information
  - Develop pseudo range to satellite
- Solve for receiver position
- Can also solve for velocity

GPS Properties

- Many causes of error
  - Ionospheric effects, line of site clearance
  - Delays in satellite positional updates, multi-path
- Is it Gaussian?
  - Over hours, approximately Gaussian errors
  - Over short time, small error but strong bias
- Improvements
  - DGPS, WAAS (~3m accuracy at 3 sigma)
  - Use an INS (Accelerometers/gyros)

GPS/INS

- Commercial solutions exist (expensive!)
- Fuse integrated INS estimates with GPS
  - A big custom Kalman filter (more later)



Summary

- Know about
  - A whole class of sensors
  - Typical problems with sensors, and sensor uncertainty
  - Basic approach to modeling a sensor
  - Basic filtering techniques