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Lecture 2: Sensors

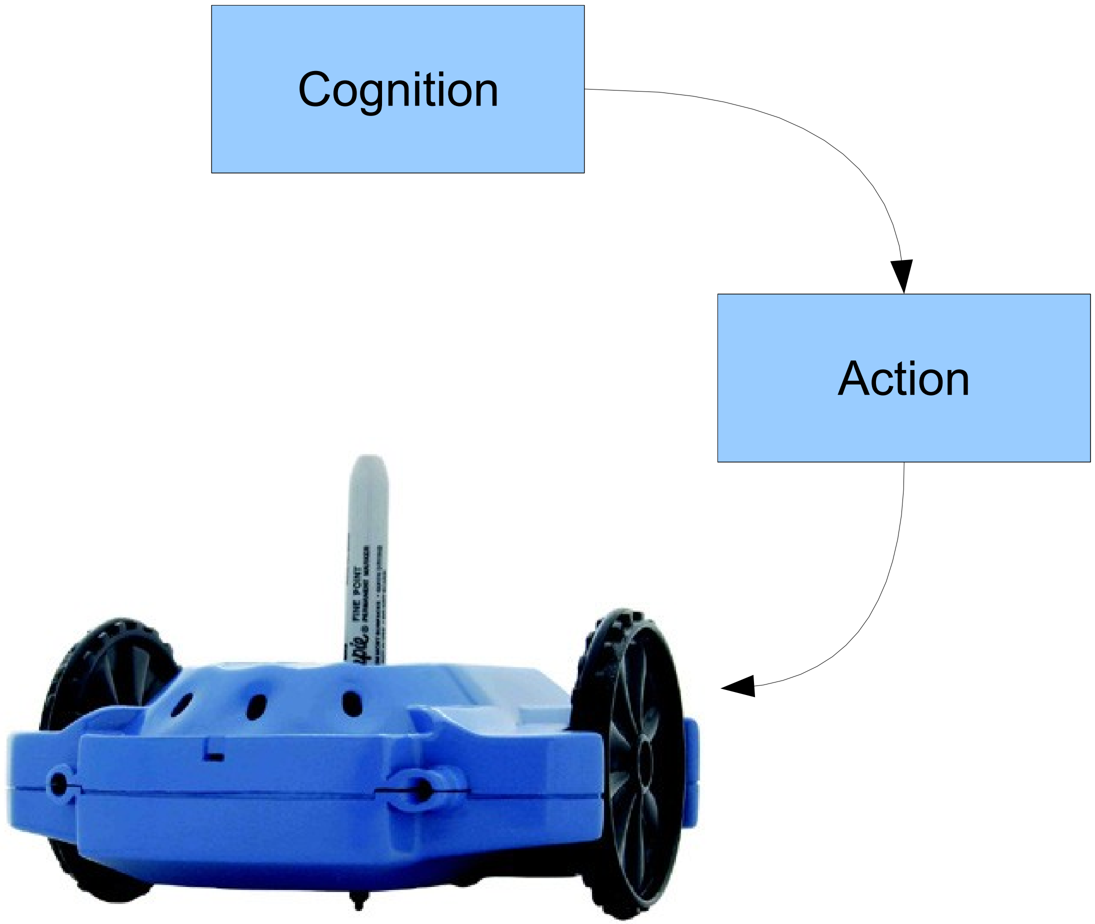
15-491, Fall 2007

Outline

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

Open Loop Control

- No sensing input

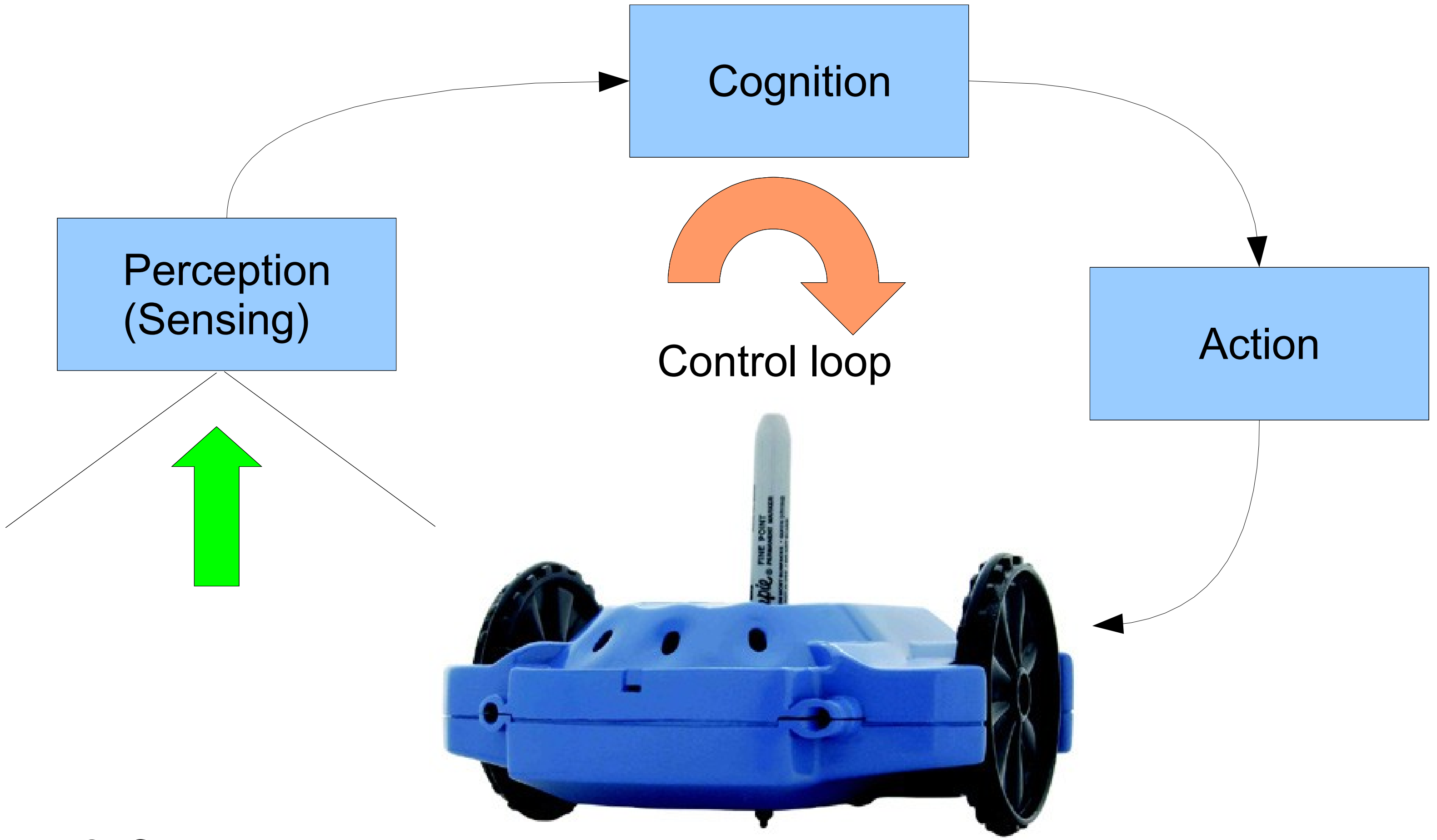


Why Sense?

- 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

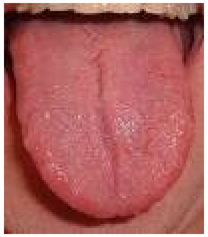
Sense:

- Vision
- Audition
- Gustation
- Olfaction
- Tactition

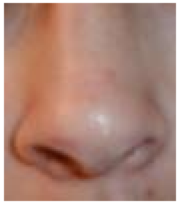
Sensor:

- Eyes

- Ears



- Tongue



- Nose

- Skin

Robot Sensors

Sense:

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

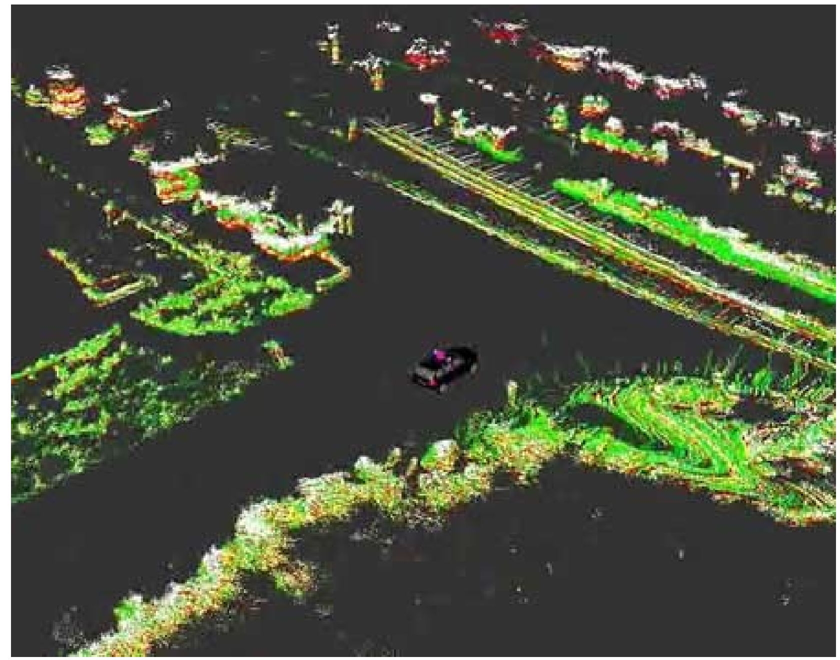
Sensor:

- 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

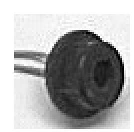
Popular Sensors in Robotics

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

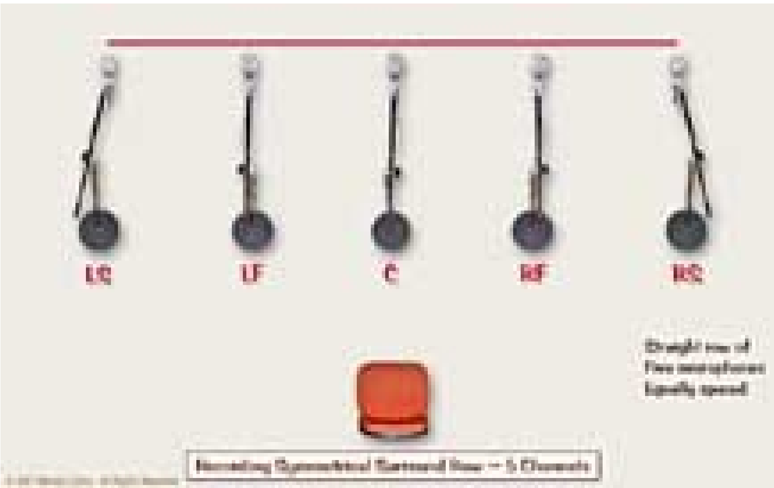


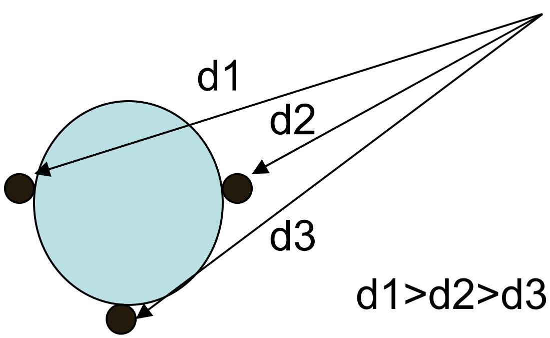


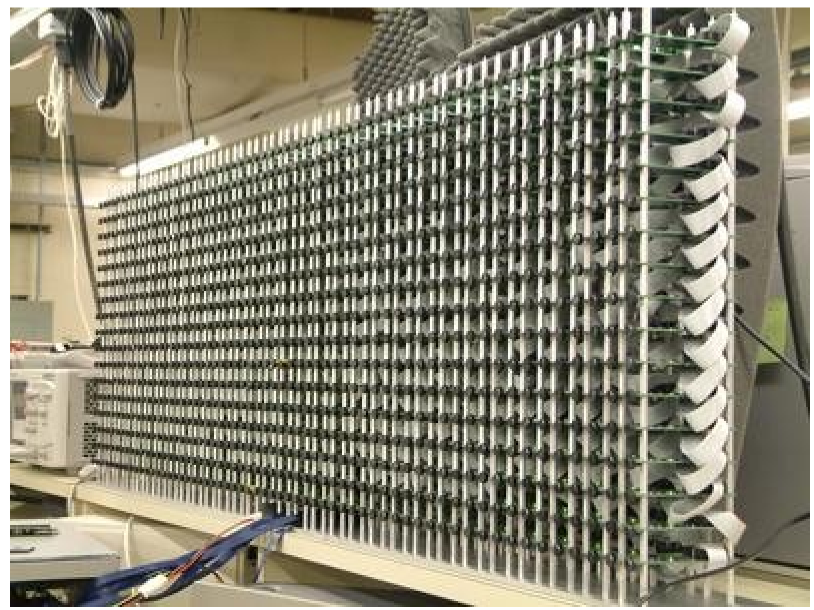




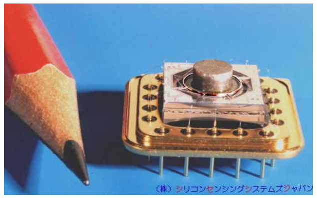
Auditory



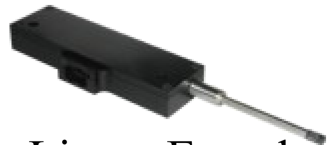




Other Robot Sensors


Gyroscope


Lever Switch


Linear Encoder

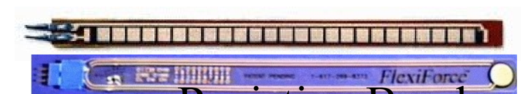

GPS


PIR


Piezo Bend


Rotary Encoder

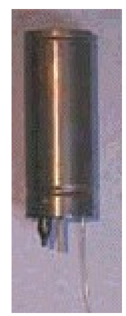

Accelerometer


Resistive Bend


Pendulum Resistive Tilt

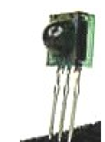

Pyroelectric Detector


Gas


Radiation


Pressure


UV Detector

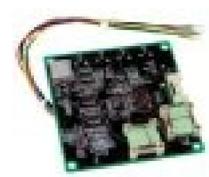

IR Modulator Receiver


Metal Detector


CDS Cell


Compass

Magnetic Reed Switch


Magnetometer

Sensing Classification

Extereoceptive

Active

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

Passive

- Vision
- Microphone array
- Chemical sensors
- Tactile sensor

Proprioceptive

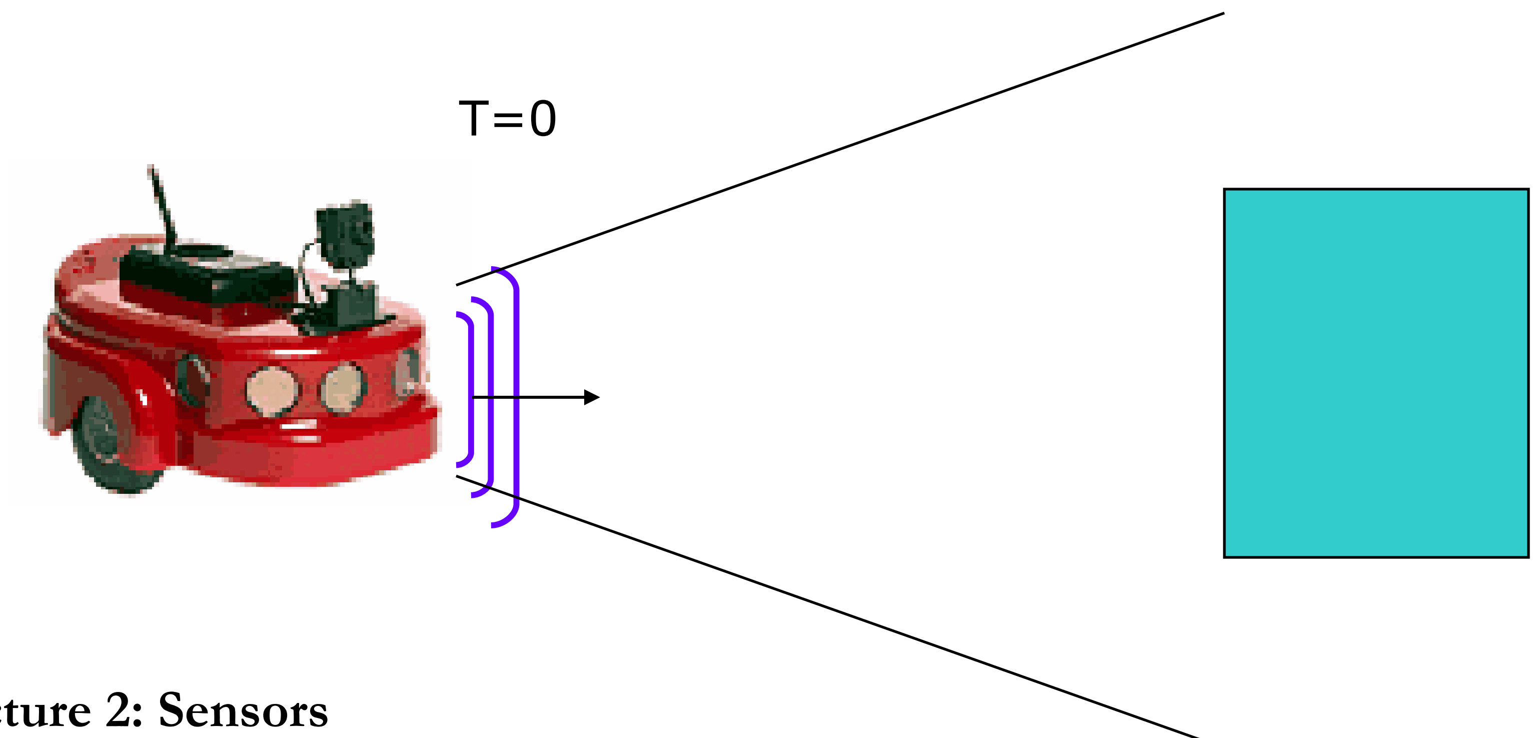
- Gyroscope
- Accelerometers
- Odometers
- Voltage sensors
- Stress/strain gauge

Sensors We Will Look At Today

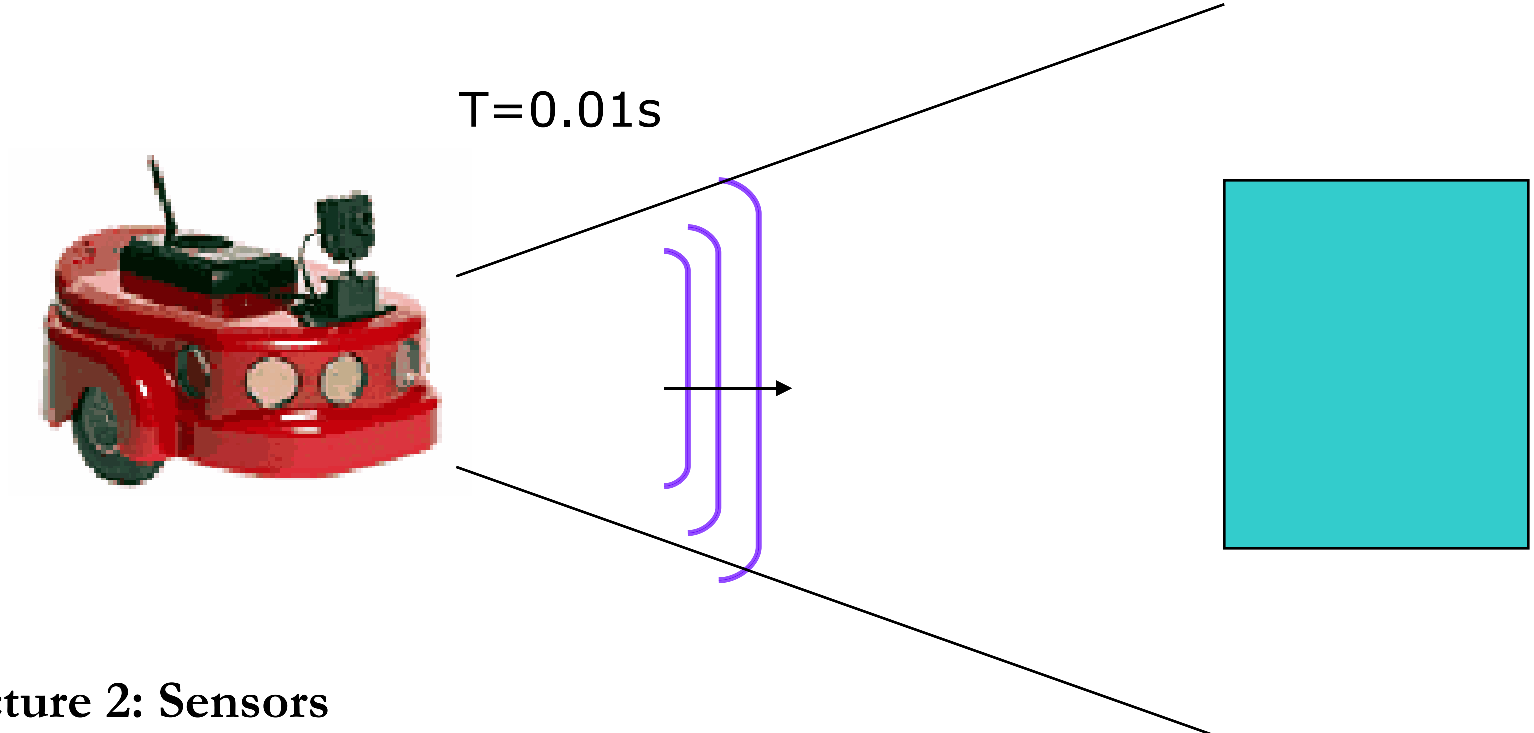
- Exterioceptive
  - Sonar, LiDar, IR
- Proprioceptive
  - Encoders
  - Accelerometers
  - Gyroscopes
  - GPS (hard to categorize)
  - Micro-switch

SoNaR: Sound Navigation and Ranging

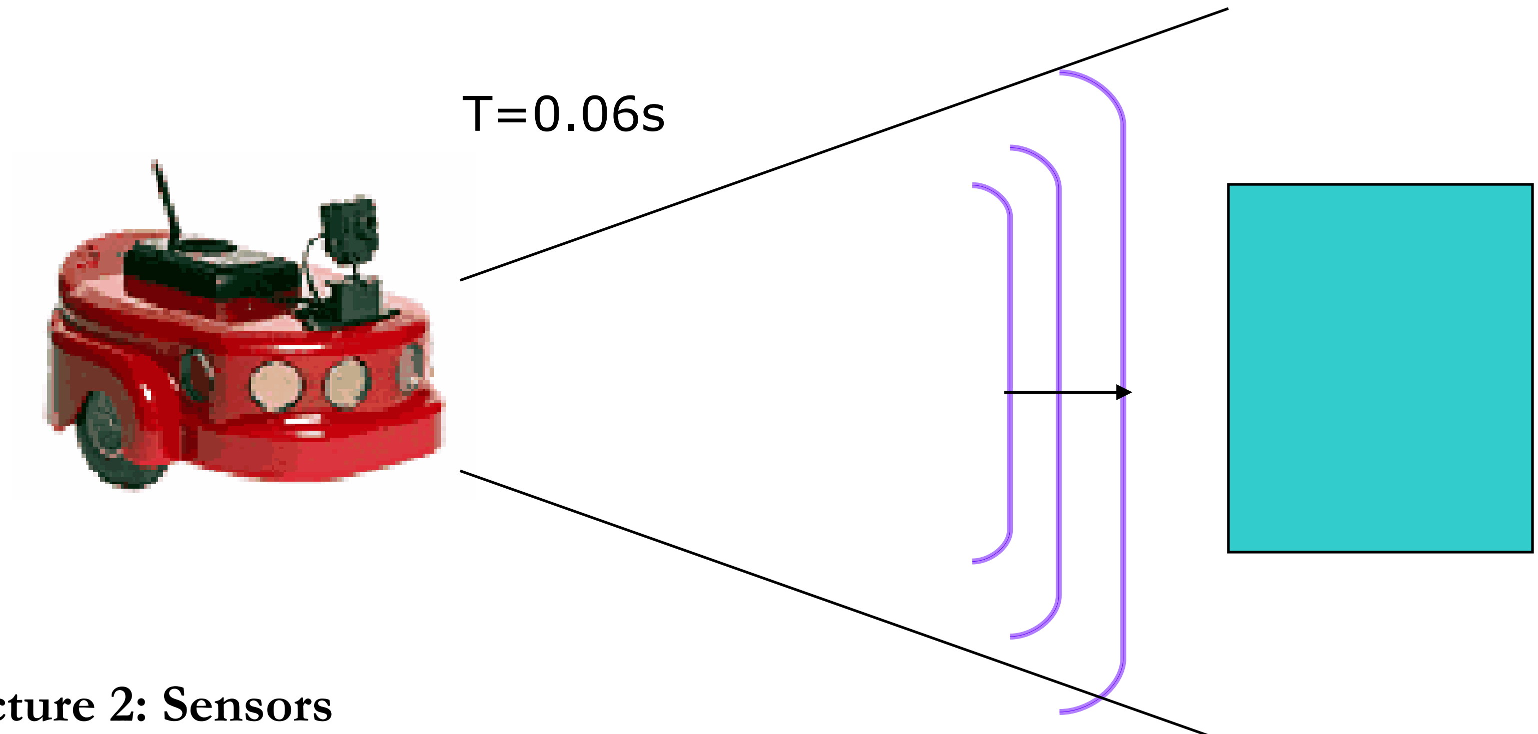
- Often called sonar, ultrasound, Sodar
- Emit a directional sound wave, and listen for echo(s), time the response



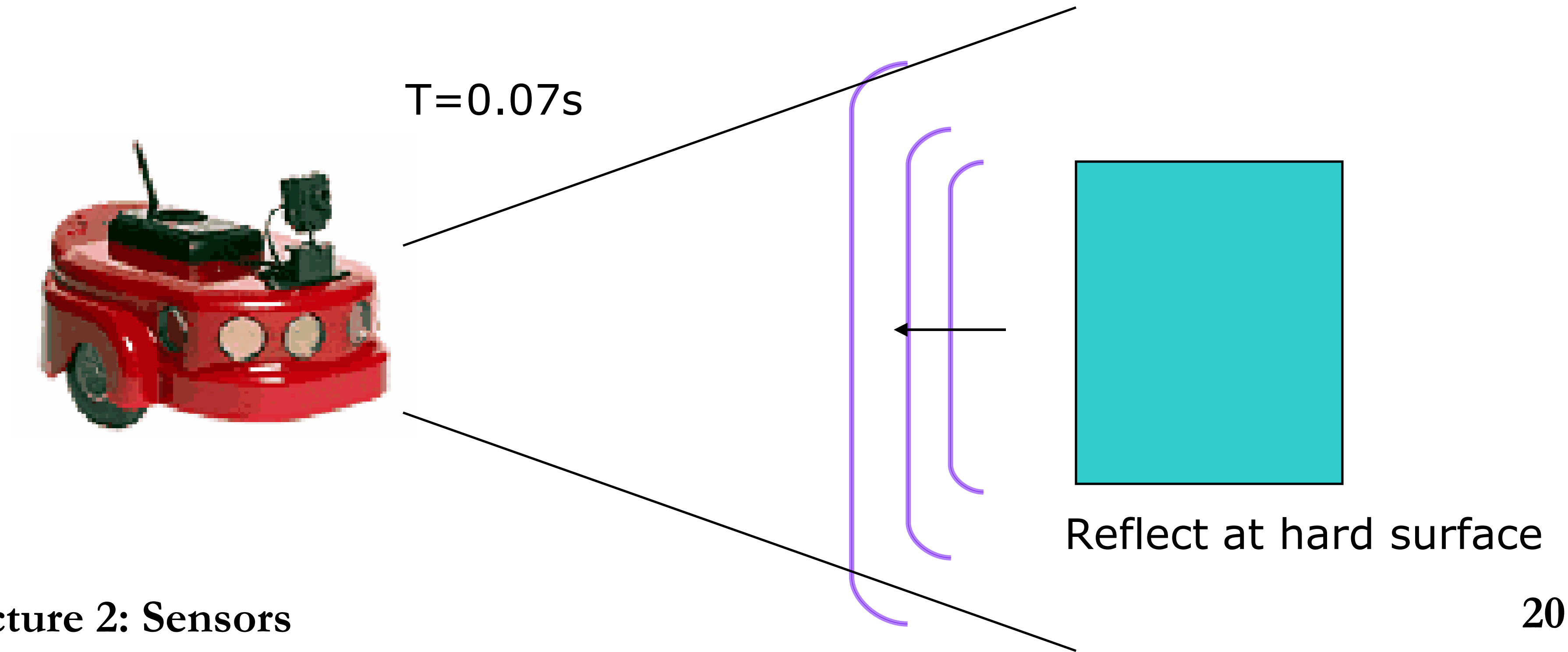
Sonar Sensors



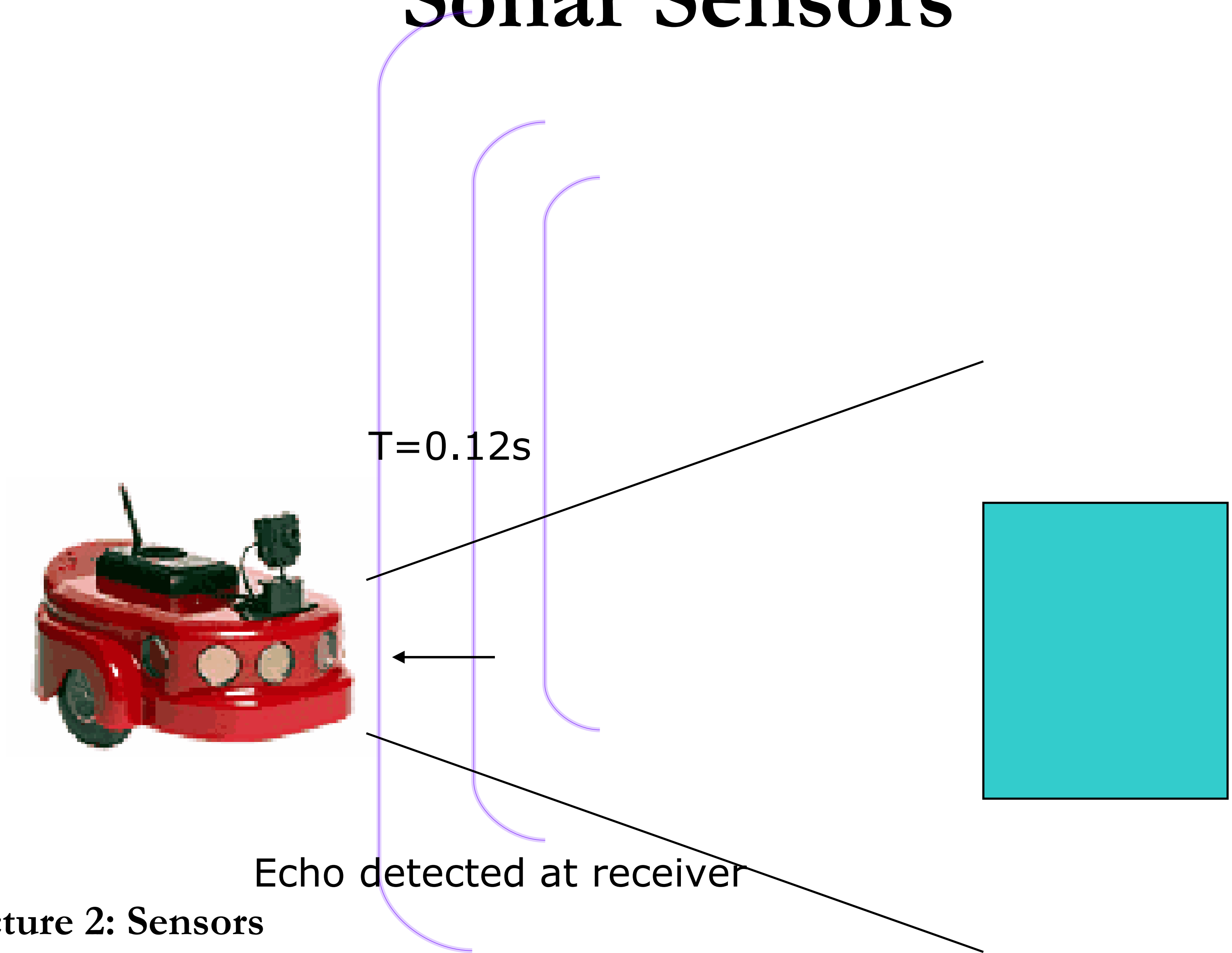
Sonar Sensors



Sonar Sensors



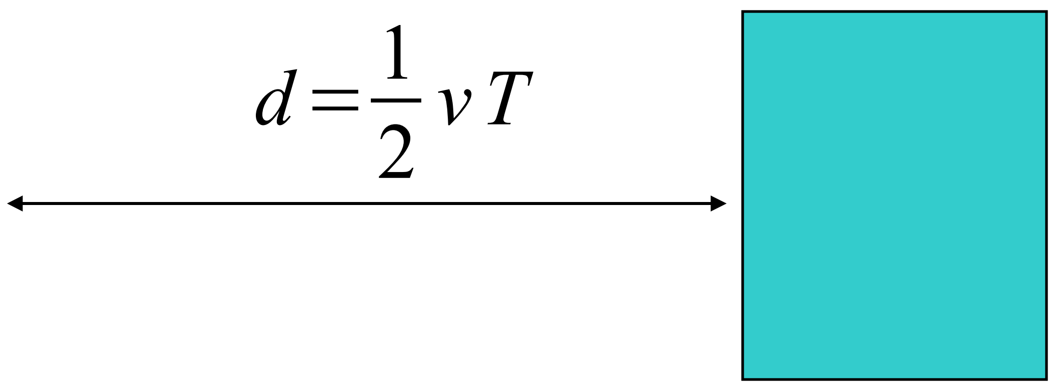
Sonar Sensors



Sonar Sensors

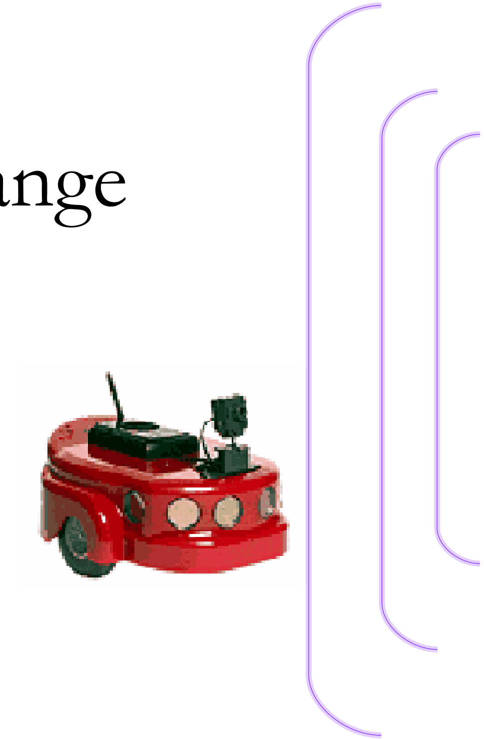
- Key assumption: sound travels at constant speed
- v=344 m/s (dry air, 21C, sea-level)
- So we have

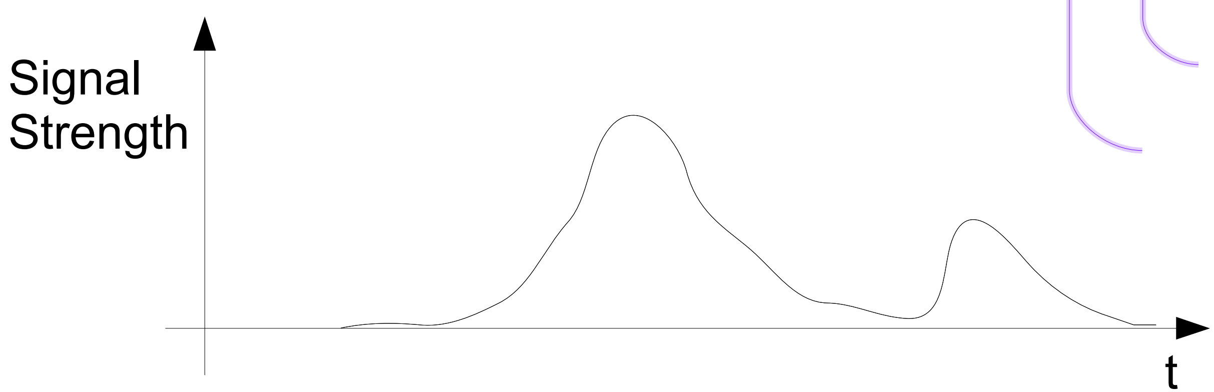
$$d = \frac{1}{2} v T$$



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

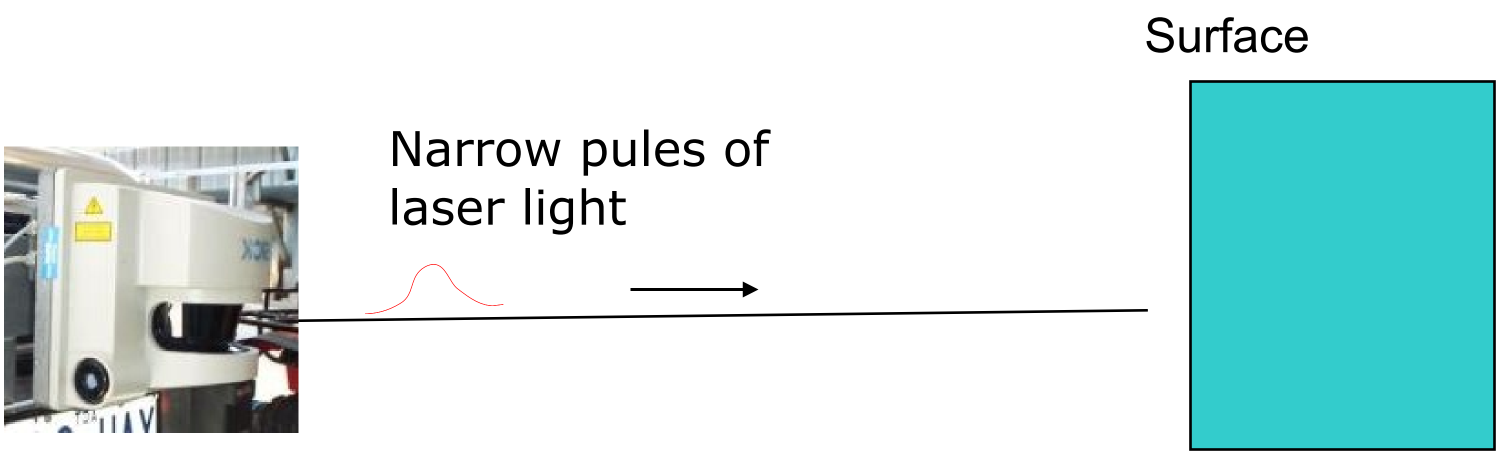
$$v_{ideal} = \sqrt{\frac{\gamma k T}{m}}$$

See wikipedia

  - Surface reflection properties
  - Atmospheric attenuation (finite range)
  - Multiple echos (multi-path)
  - Quantization in timing
  - Inaccuracies in detecting response signal onset

LiDar

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

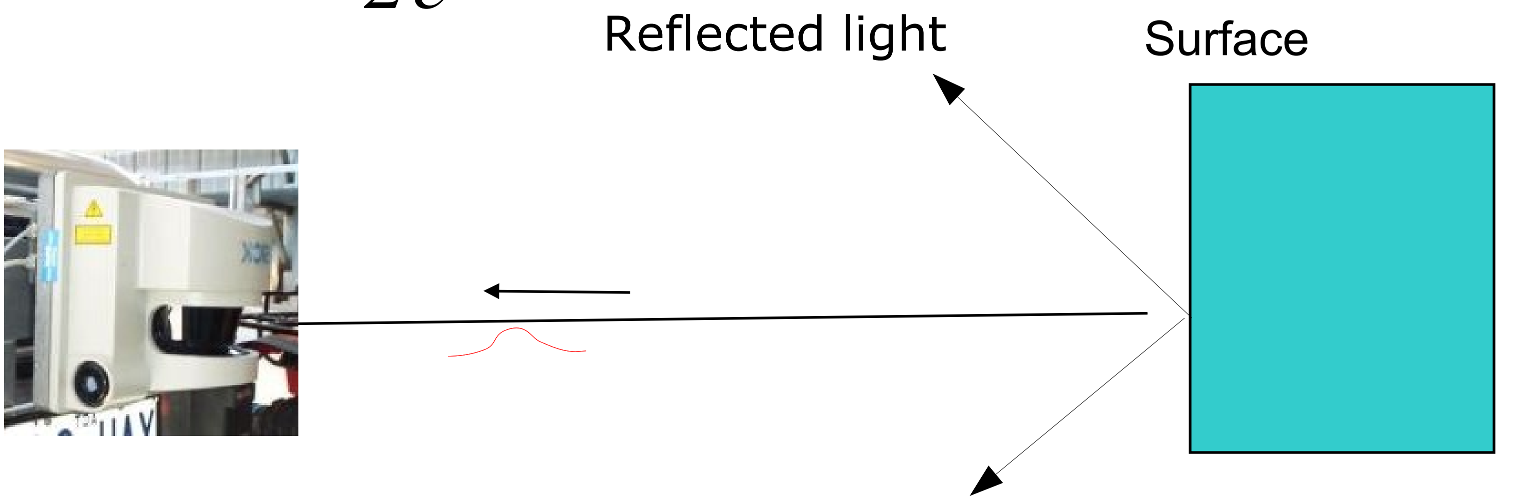


LiDar

- Timed “echo” from reflection

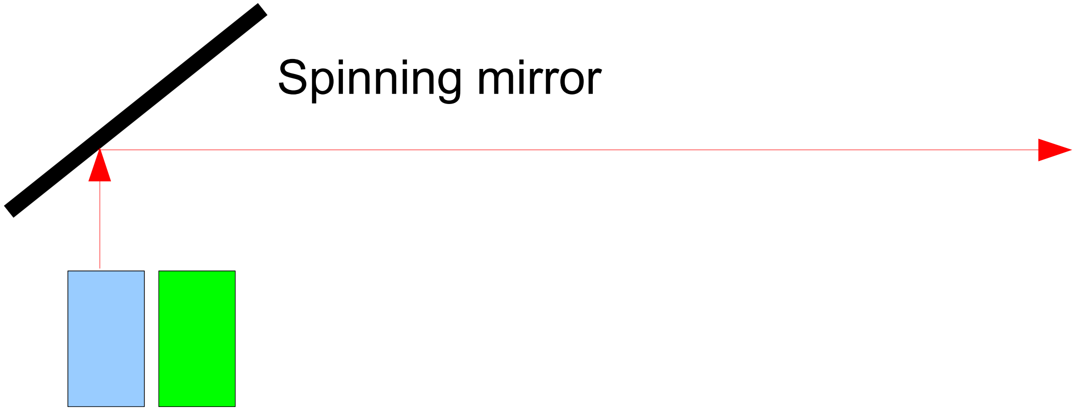
$$c_{vaccum} = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \approx 3\text{x}10^8 m.s^{-1}$$

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



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 in range



SICK LiDar Internals

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

LiDar Variations

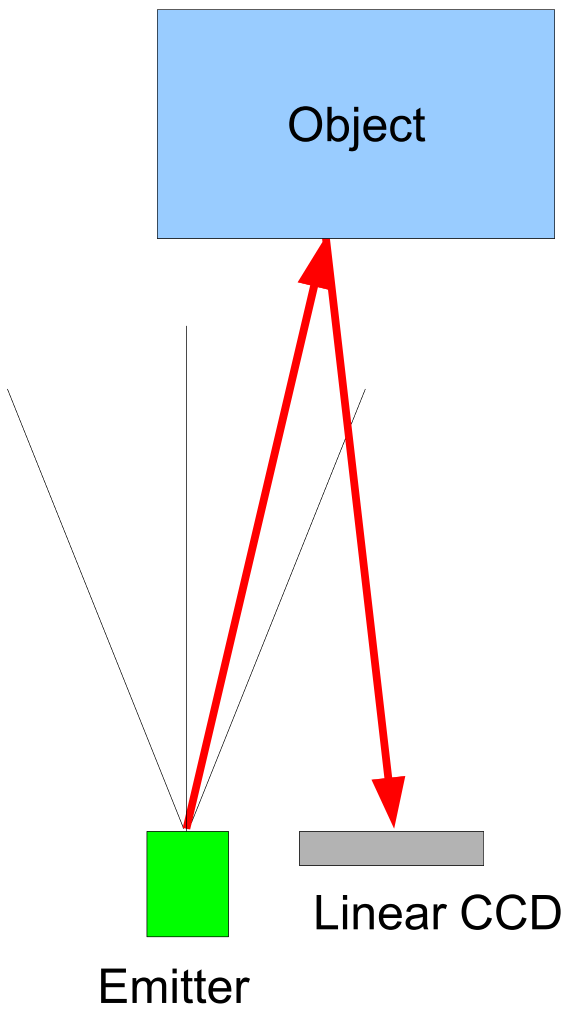
NREC Crusher Vehicle

Crusher with sensors

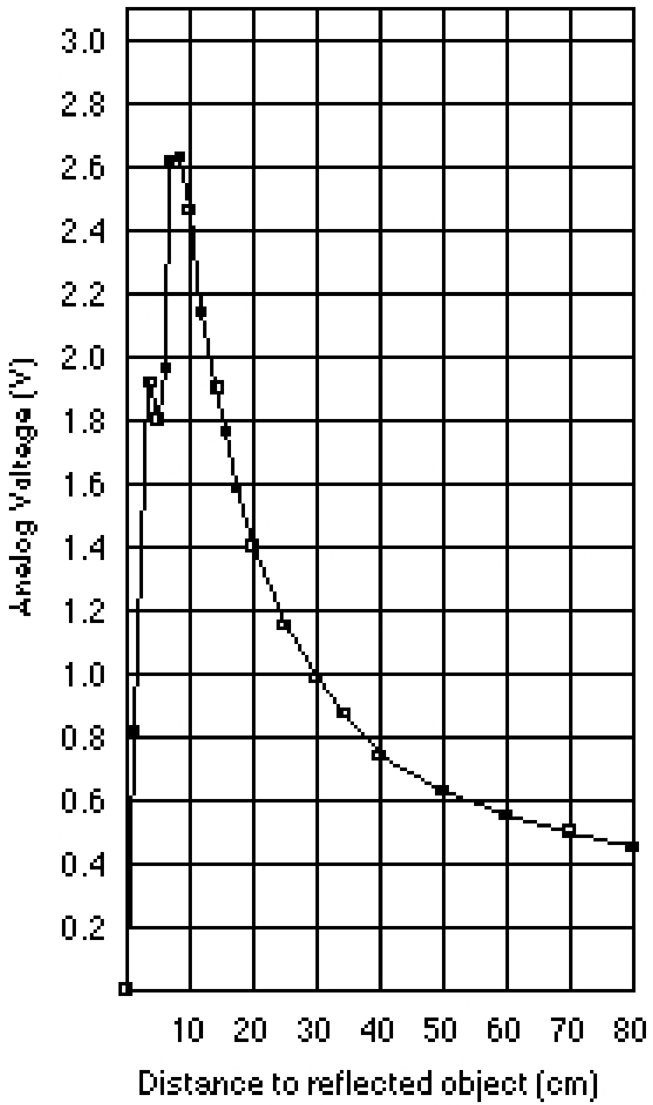
InfraRed

- 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



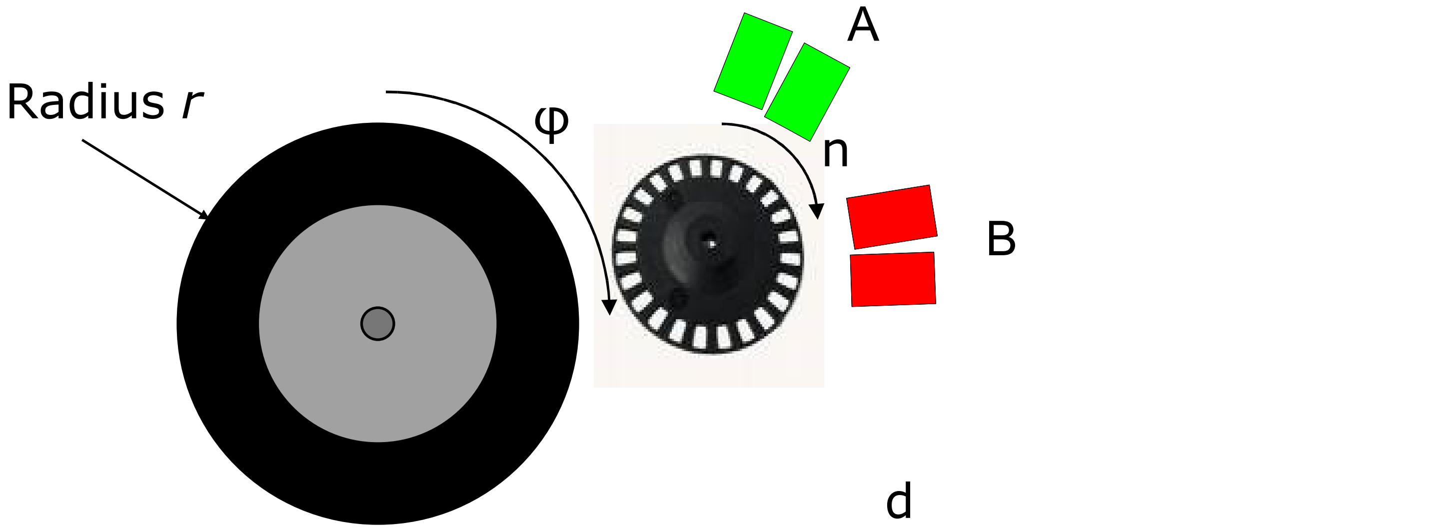
http://www.acroname.com



Proprioceptive Sensors

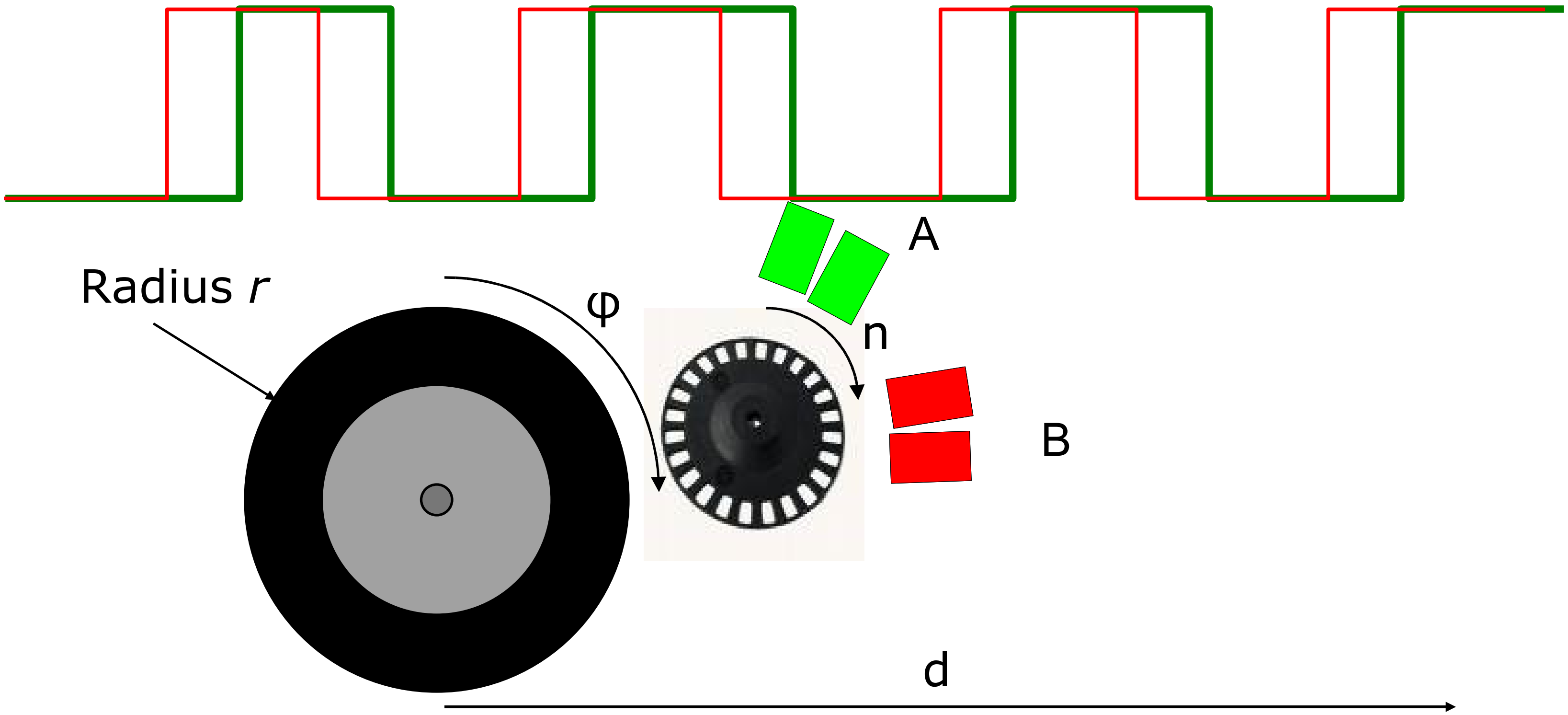
Optical Encoders

- 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)

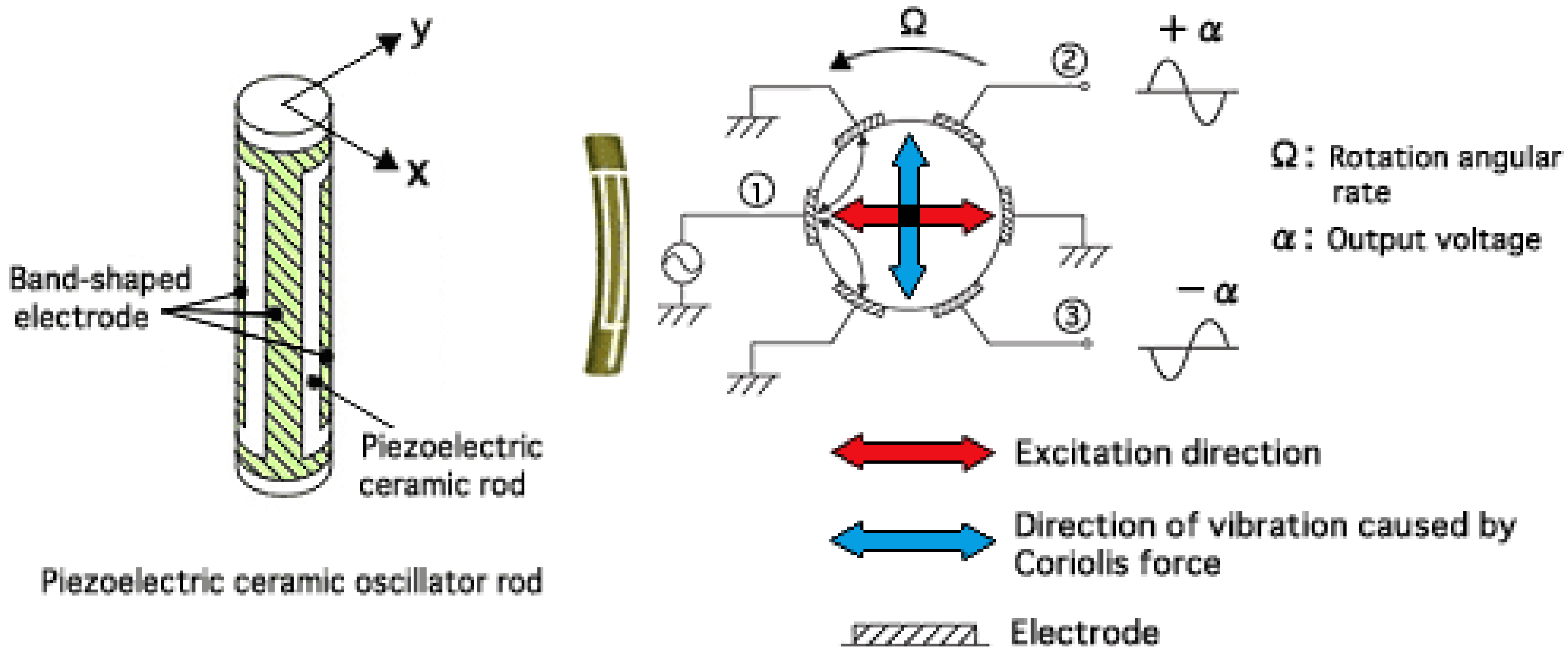
Gyroscopes

- 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.

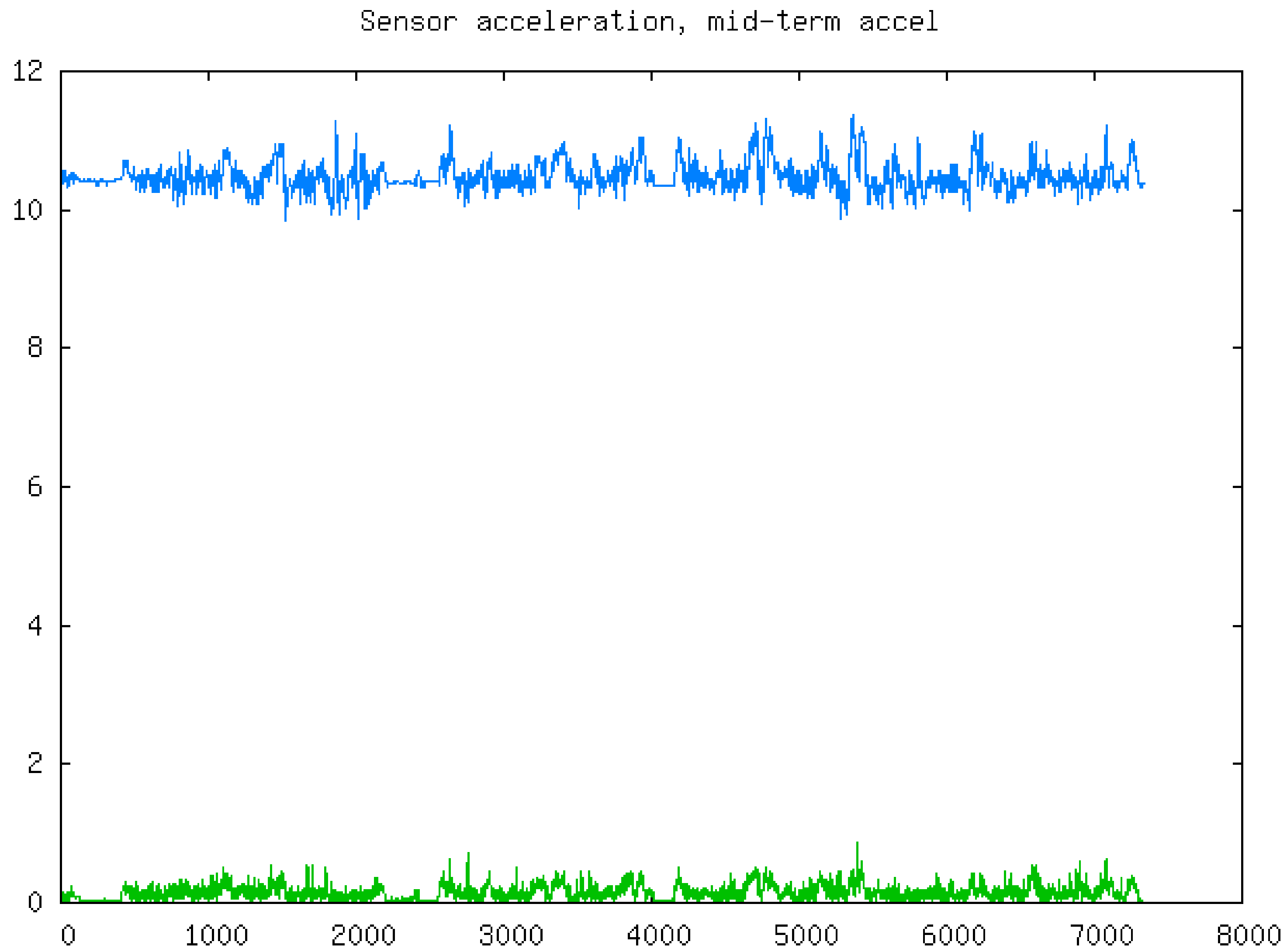


http://www.nec-tokin.com/

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



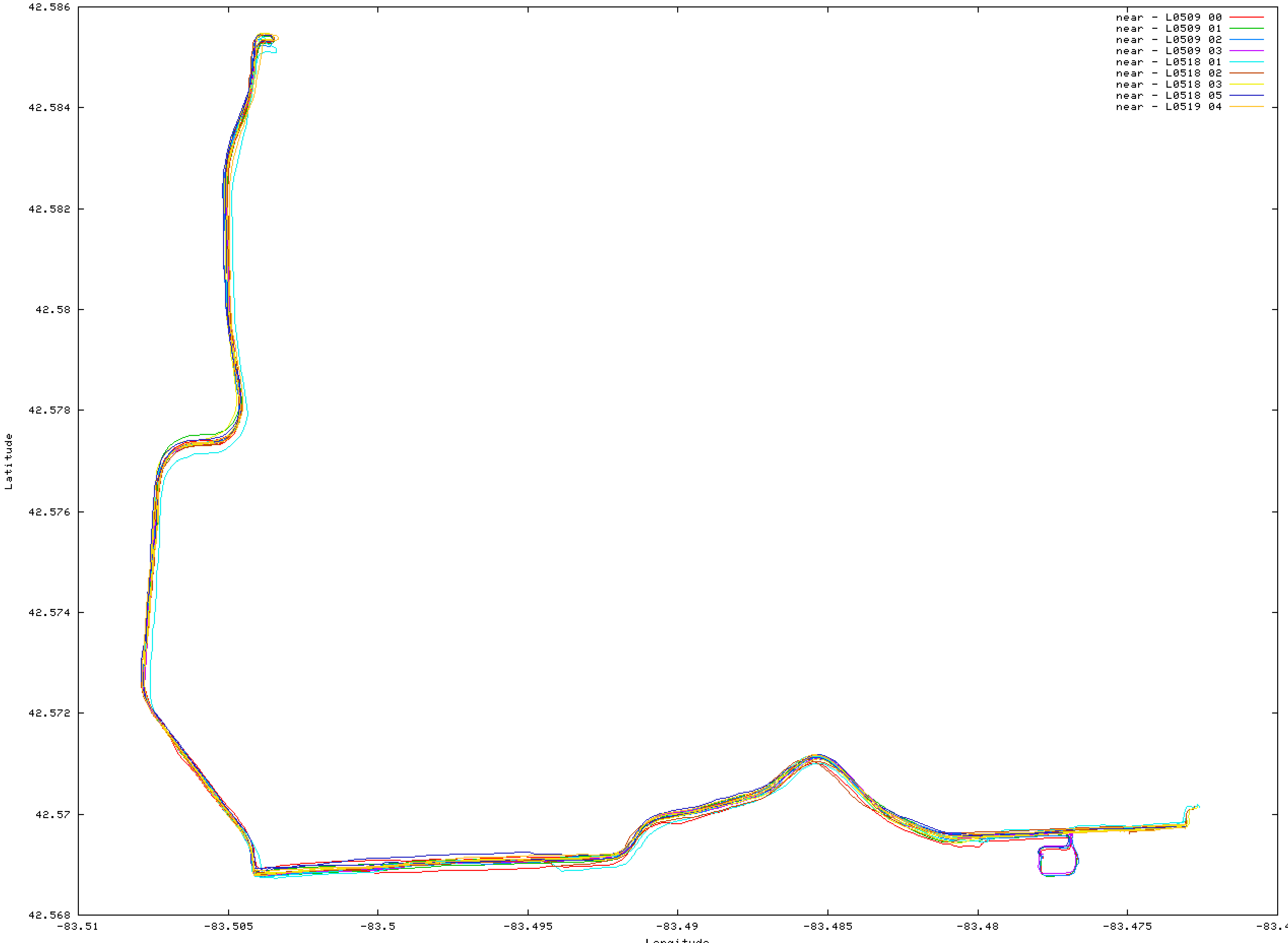
Issues With Accelerometers/Gyros

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

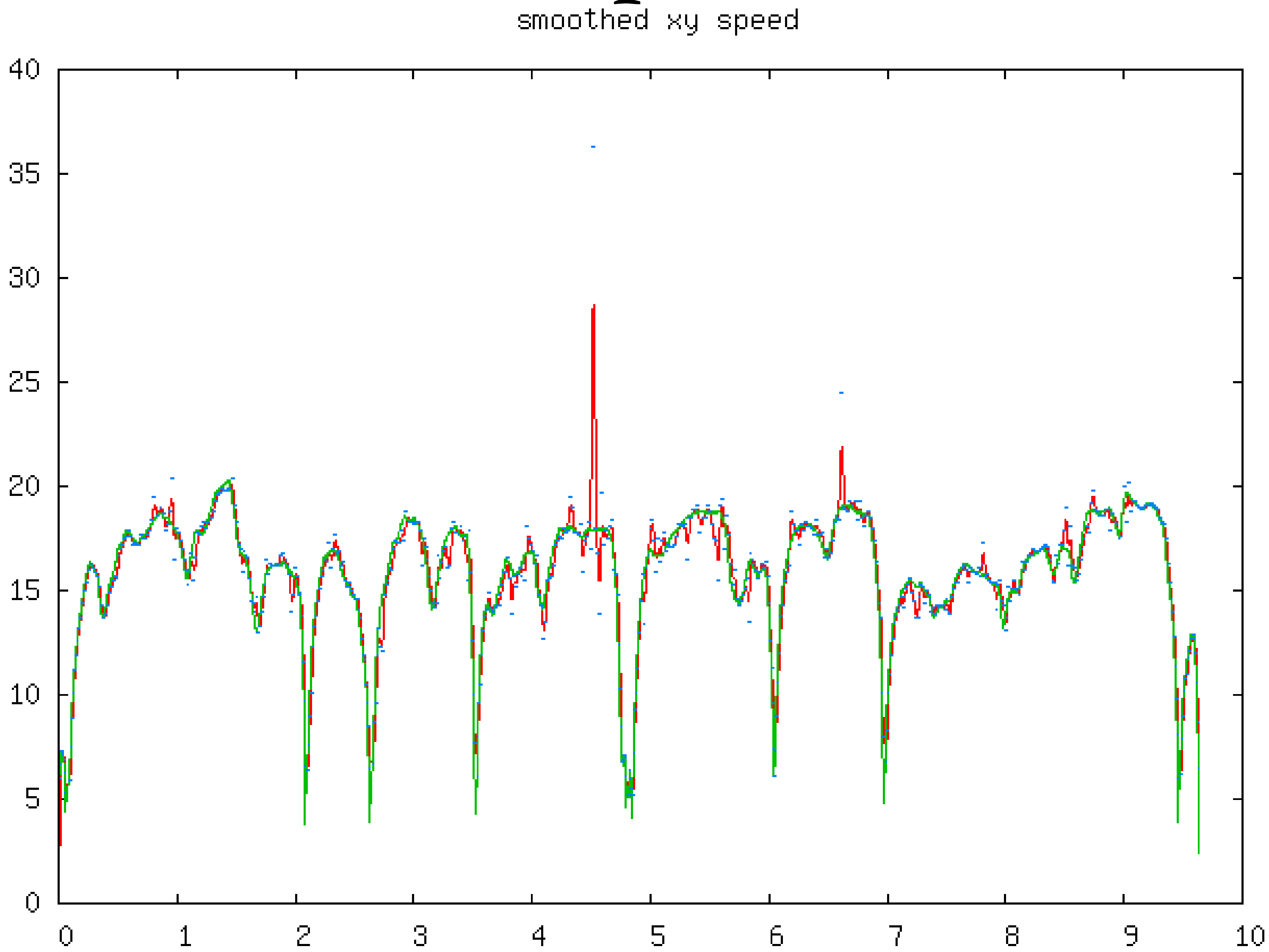
GPS/Glonas/Galileo

- 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

Longitude vs Latitude (near) --- All Data sets



Ground Speed Profile

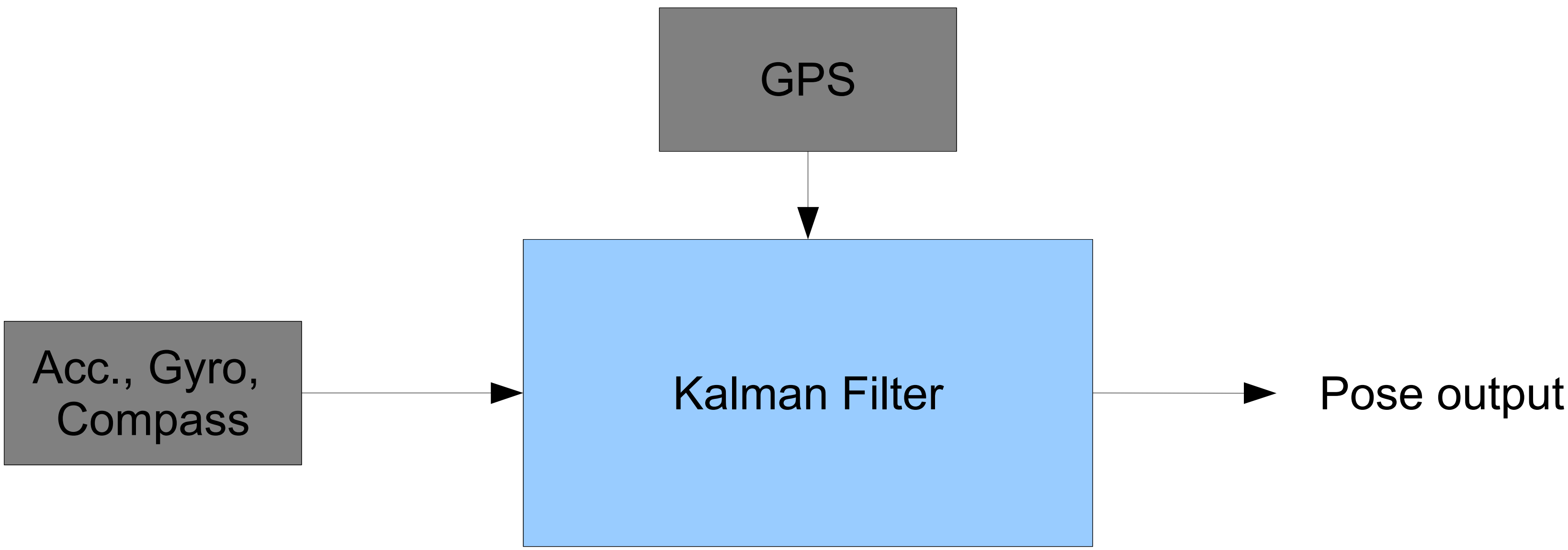


GPS Properties

- 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)

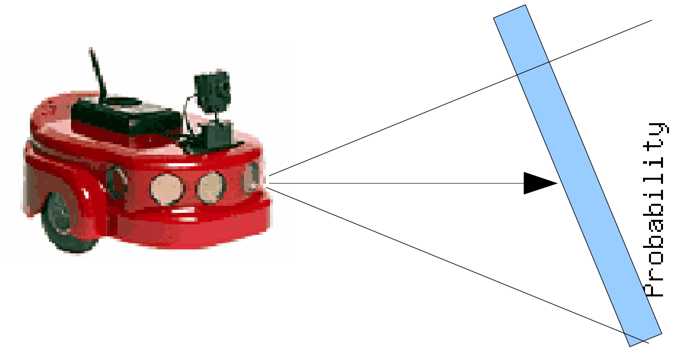


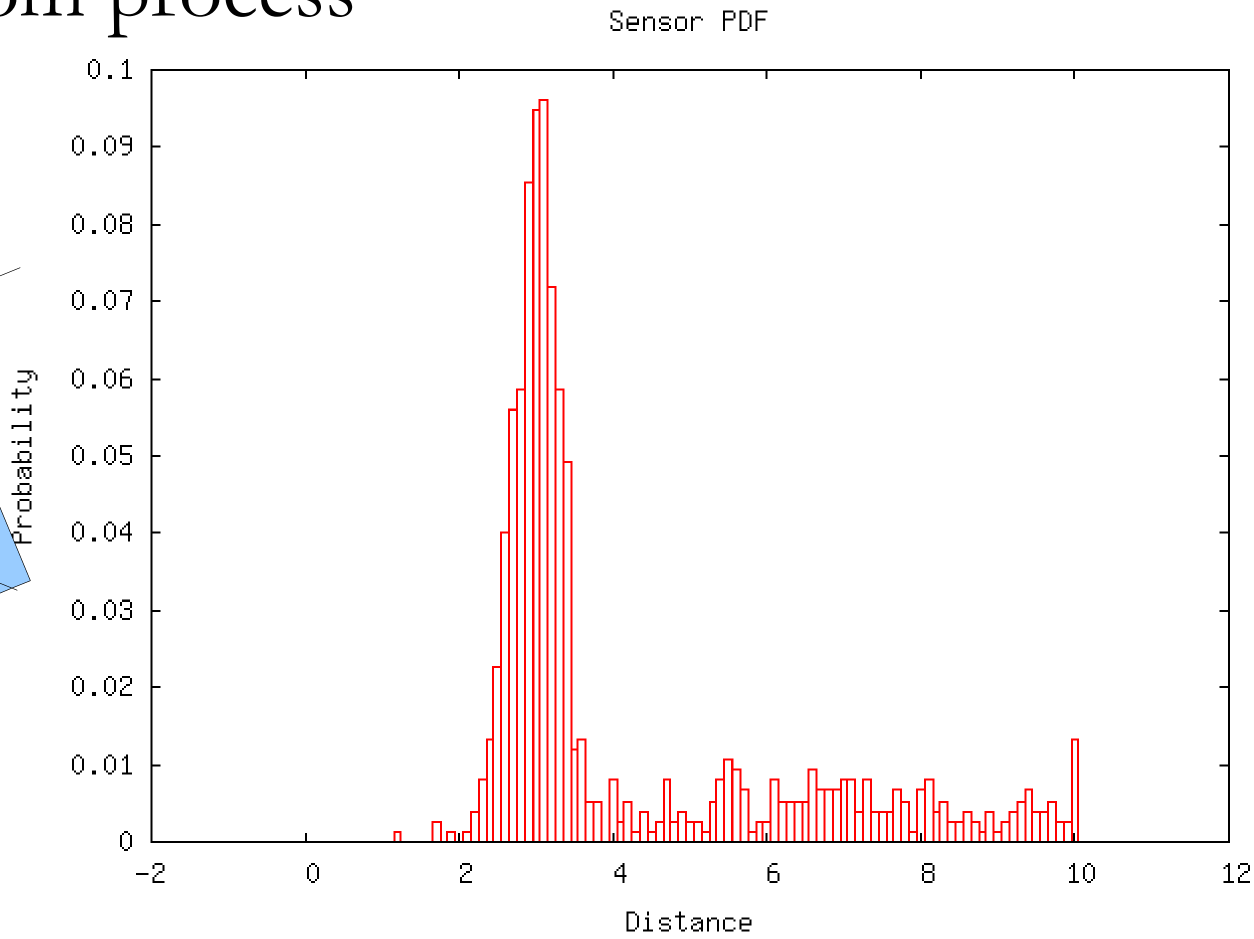
Sensor Processing and Modeling

- Sensors are **never** perfect
- Noise
- Systematic errors (bias)
- Drift, jumps
- Unmodeled artifacts (looks like bias)

Sensor Noise

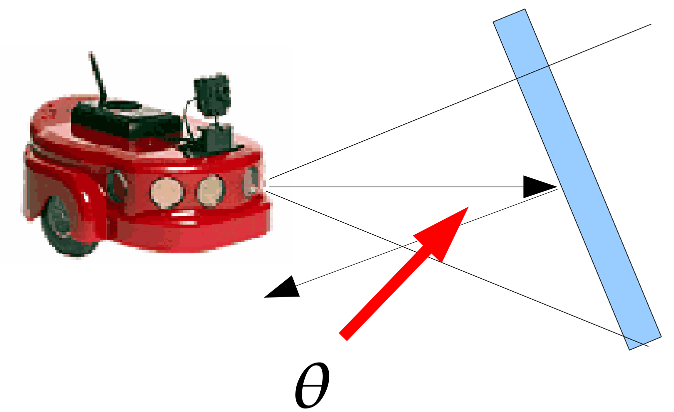
- Fixed object, sensor returns different values over time => random process

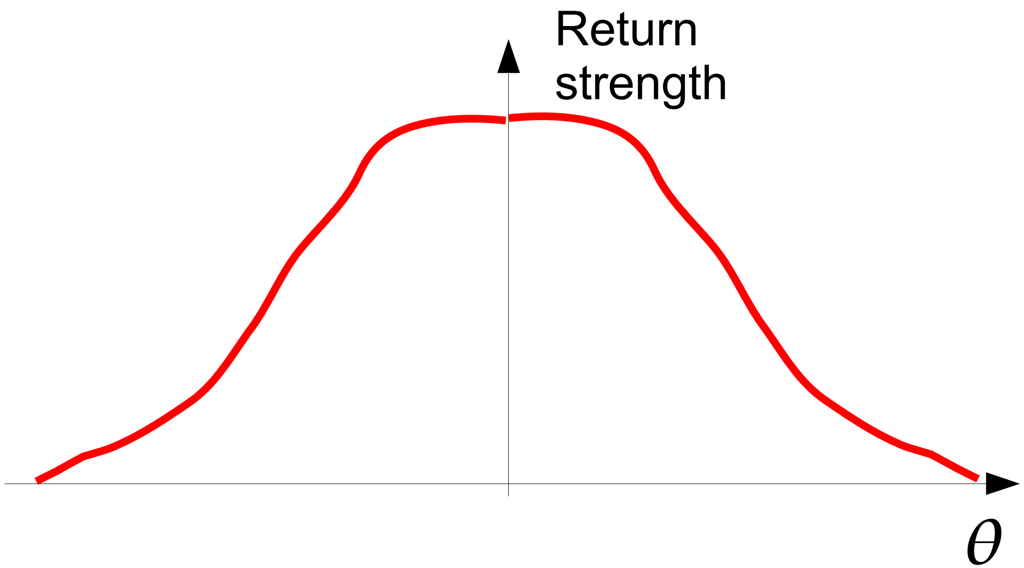




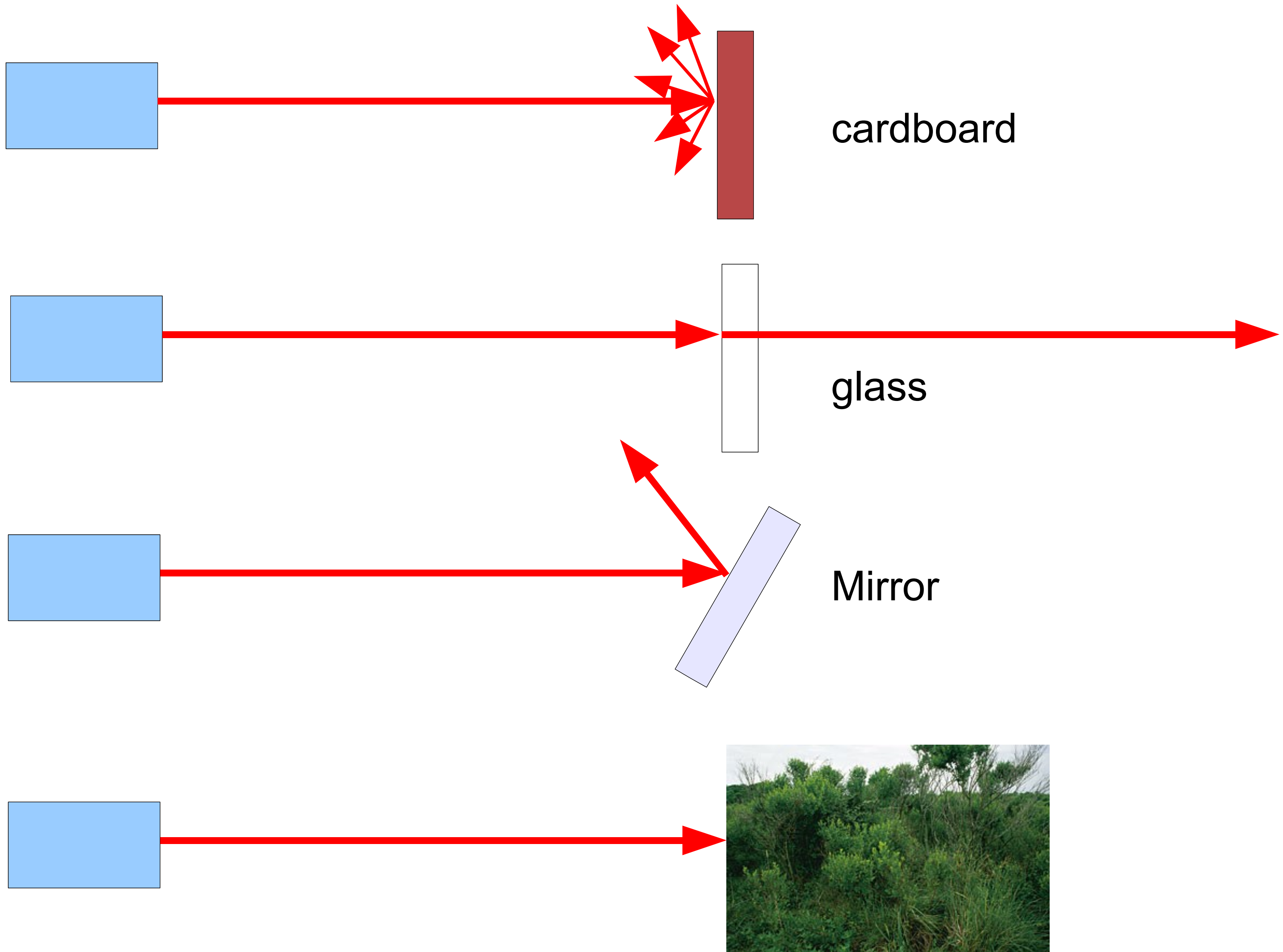
Sensor Bias

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





LiDar Returns and Material



Colorized LiDar

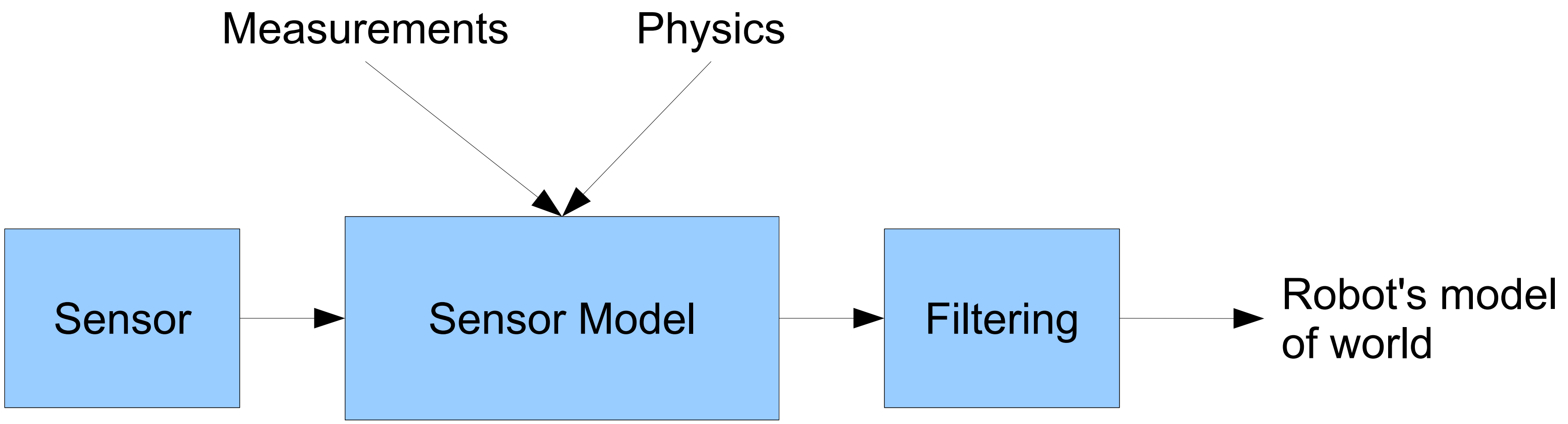
http://www.aerotecusa.com/

Helicopter Example

http://robots.stanford.edu

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
- 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*

Sensor Model Components

- Intrinsic model
  - Model of how sensor operates
- Extrinsic model (most sensors)
  - Putting measurements into robot coordinate frame

An Example

- IR range sensor: triangulated range
- Intrinsic model
  - Given a return, what does it mean for depth?
- Extrinsic model
  - Given depth, where is the obstacle?
- Process
  - Sample data from known "standard" configuration
  - Estimate model/parameters from the data/physics
  - Test the result

Sensor Uncertainty

- Systematic errors (material, orientation etc.)
- Random errors (any other unknowns)
- Combine into uncertainty model
- Uncertainty model
  – Full pdf (e.g. Particles, histograms)
  – Parametric representation e.g. Gaussian
- Need to use probabilistic algorithms!

Filtering Approaches

- Often useful to apply initial filtering to signal
  - Use known constraints: domain knowledge
- Thresholding
  - Hystersis
  - Adaptive thresholds (hard)
- Smoothing
  - Linear filter
  - Kalman filter (later)
- Outlier rejection

Summary

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

Icreate and Scribbler

- ICreate
  - IR sensors
  - Bump sensor
  - Encoders
- Scribbler
  - Encoders
  - IR sensors