COS 495 - Lecture 7
Autonomous Robot Navigation

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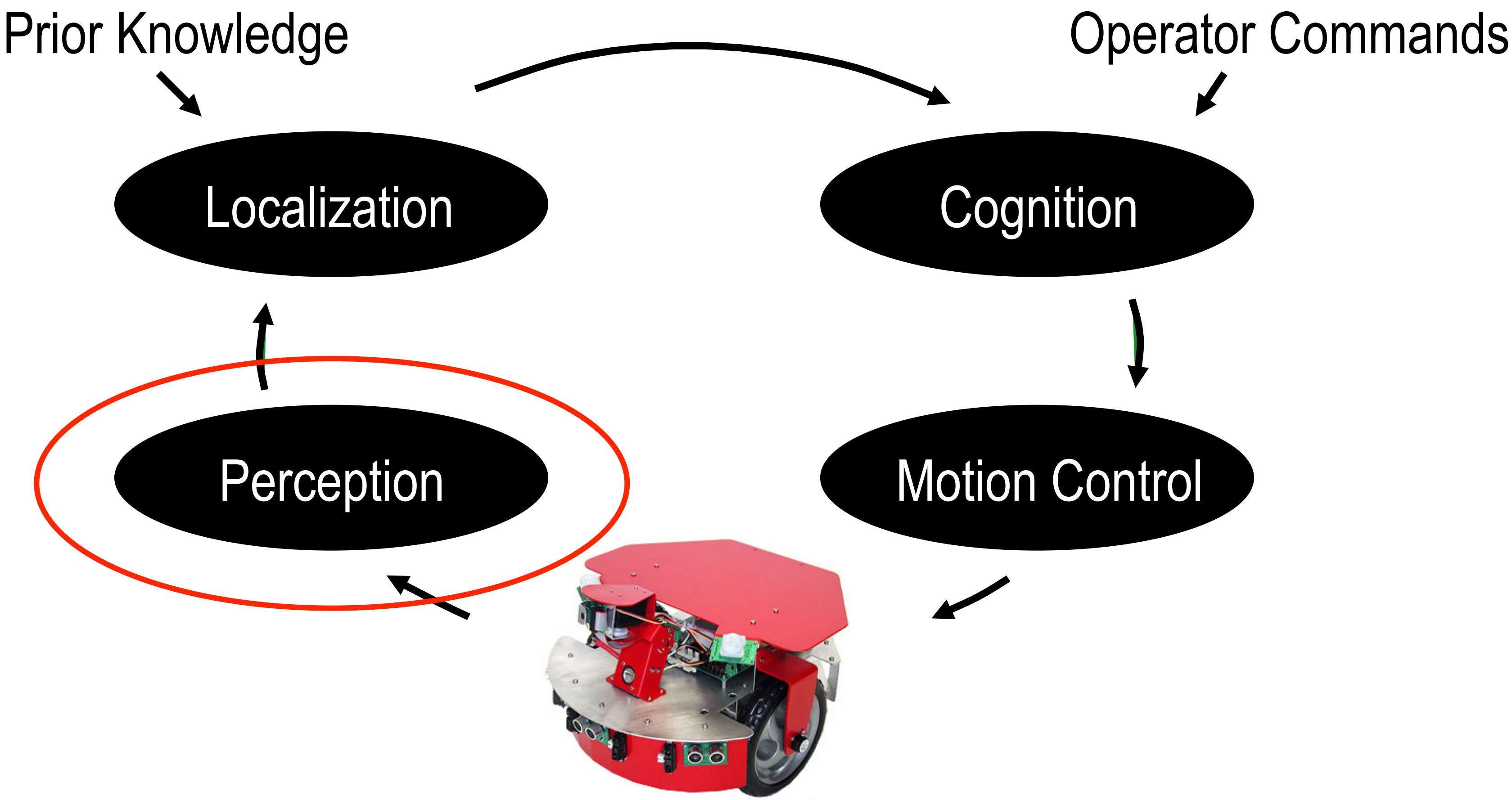
Figures courtesy of Siegwart & Nourbakhsh

Control Structure



Sensors

IMU
Inertial Measurement Unit

Emergency Stop Button

Wheel Encoders

Omnidirectional Camera

Pan-Tilt Camera

Sonar Sensors

Laser Range Scanner

Bumper

Courtesy of Siegwart & Nourbakhsh

Sensors: Outline

1. Sensors Overview
    1. Sensor classifications
    2. Sensor characteristics
2. Sensor Uncertainty

Sensor Classifications

- Proprioceptive/Exteroceptive Sensors
  - Proprioceptive sensors measure values internal to the robot (e.g. motor speed, heading, …)
  - Exteroceptive sensors obtain information from the robots environment (e.g. distance to objects)
- Passive/Active Sensors
  - Passive sensors use energy coming from the environment (e.g. temperature probe)
  - Active sensors emit energy then measure the reaction (e.g. sonar)

Sensor Classifications

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.

Sensor Classifications

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: Basic Characteristics

- Range
  - Lower and upper limits
  - E.g. IR Range sensor measures distance between 10 and 80 cm.
- Resolution
  - minimum difference between two measurements
  - for digital sensors it is usually the A/D resolution.
    - e.g. 5V / 255 (8 bit) = 0.02 V

Sensors: Basic Characteristics

- Dynamic Range
  - Used to measure spread between lower and upper limits of sensor inputs.
  - Formally, it is the ratio between the maximum and minimum measurable input, usually in decibals (dB)

    Dynamic Range = 10 log[UpperLimit / LowerLimit]
  - E.g. A sonar Range sensor measures up to a max distance of 3m, with smallest measurement of 1cm.

    Dynamic Range = 10 log[3 / 0.01]

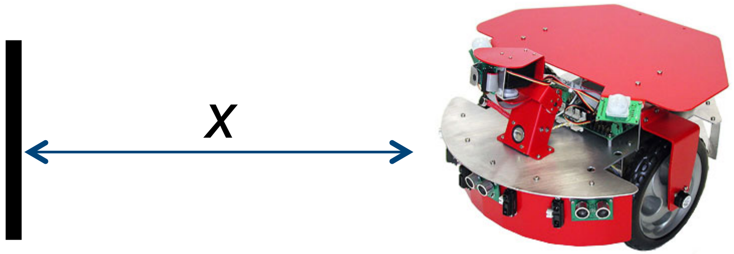
    = 24.8 dB

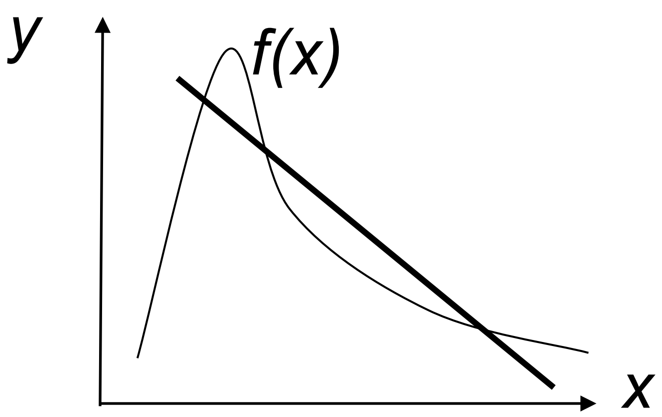
Sensors: Basic Characteristics

- Linearity
  - A measure of how linear the relationship between the sensor's output signal and input signal.
  - Linearity is less important when signal is treated after with a computer

Sensors: Basic Characteristics

- Linearity Example
  - Consider the range measurement from an IR range sensor.
  - Let *x* be the actual measurement in meters, let *y* be the output from the sensor in volts, and *y=f(x)*.





Sensors: Basic Characteristics

- Bandwidth or Frequency
  - The speed with which a sensor can provide a stream of readings
  - Usually there is an upper limit depending on the sensor and the sampling rate
    - E.g. sonar takes a long time to get a return signal.
  - Higher frequencies are desired for autonomous control.
    - E.g. if a GPS measurement occurs at 1 Hz and the autonomous vehicle uses this to avoid other vehicles that are 1 meter away.

Sensors: In Situ Characteristics

- Sensitivity
  - Ratio of output change to input change
    - E.g. Range sensor will increase voltage output 0.1 V for every cm distance measured.
  - Sensitivity itself is desirable, but might be coupled with sensitivity to other environment parameters.
- Cross-sensitivity
  - Sensitivity to environmental parameters that are orthogonal to the target parameters
    - E.g. some compasses are sensitive to the local environment.

Sensors: In Situ Characteristics

- Accuracy
  - The difference between the sensor's output and the true value (i.e. *error* = *m* - *v*).

$$accuracy = 1 - \frac{| m - v |}{v}$$

m = *measured value*

v = *true value*

Sensors: In Situ Characteristics

- Precision
  - The reproducibility of sensor results.

$$precision = \frac{range}{\sigma}$$

σ = *standard deviation*

Sensors: In Situ Characteristics

- Systematic Error
  - Deterministic
  - Caused by factors that can be modeled (e.g. optical distortion in camera.)
- Random Error
  - Non-deterministic
  - Not predictable
  - Usually described probabilistically

Sensors: In Situ Characteristics

- Measurements in the real-world are dynamically changing and error-prone.
  - Changing illuminations
  - Light or sound absorbing surfaces
- Systematic versus random errors are not well-defined for mobile robots.
  - There is a cross-sensitivity of robot sensor to robot pose and environment dynamics
  - Difficult to model, appear to be random

Sensors: Outline

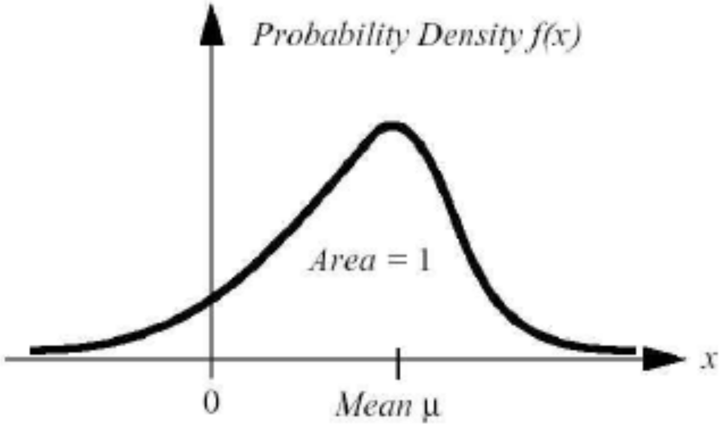
1. Sensors Overview
2. Sensor Uncertainty

Sensor Uncertainty

- How can it be represented?
  - With probability distributions.

Sensor Uncertainty

- Representation
  - Describe measurement as a random variable *X*
  - Given a set of *n* measurements with values ρ_I
  - Characterize statistical properties of *X* with a *probability density function f(x)*



Sensor Uncertainty

- Expected value of *X* is the mean μ

$$\mu = E[X] = \int_{-\infty}^{\infty} x\, f(x)\, dx$$

- The variance of *X* is σ^2

$$\sigma^2 = Var(X) = \int_{-\infty}^{\infty} (x - \mu)^2 f(x)\, dx$$

Sensor Uncertainty

- Expected value of *X* is the mean μ

$$\mu = E[X] = \frac{\sum^{n} x}{n}$$

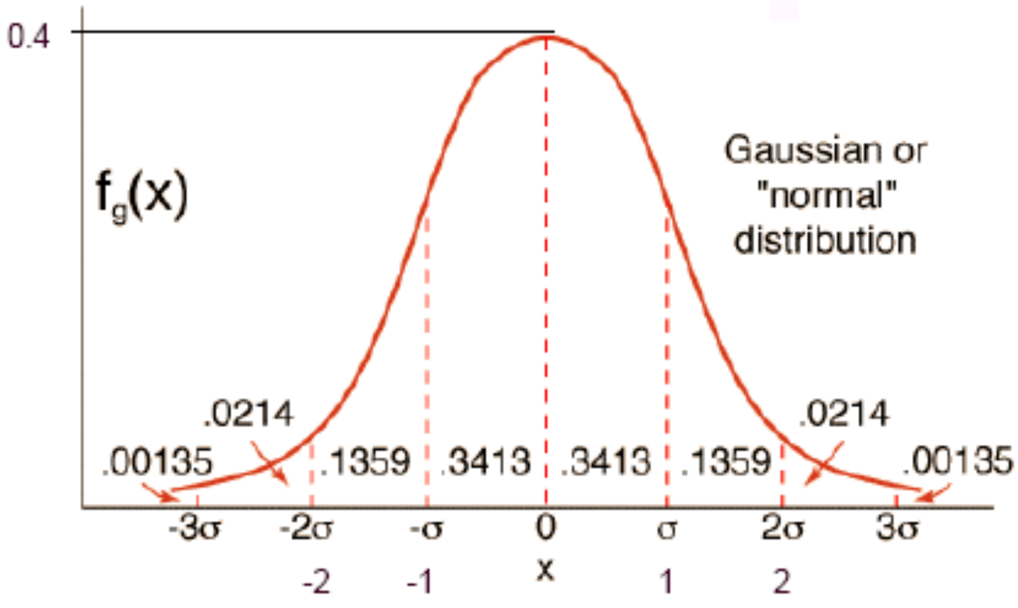
- The variance of *X* is σ^2

$$\sigma^2 = Var(X) = \frac{\sum^{n} (x - \mu)^2}{n}$$

Sensor Uncertainty

- Use a Gaussian Distribution

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-(x-\mu)^2}{2\sigma^2} \right)$$



Sensor Uncertainty

- How do we use the Gaussian?
  - Learn the variance of sensor measurements ahead of time.
  - Assume mean measurement is equal to actual measurement.
- Example:
  - If a robot is 1.91 meters from a wall, what is the probability of getting a measurement of 2 meters?

Sensor Uncertainty

- Example cont':
  - Answer – if the sensor error is modeled as a Gaussian, we can assume the sensor has the following probability distribution:
  - Then, use the distribution to determine P(x=2).