COS 495 - Lecture 7
Autonomous Robot Navigation

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Figures courtesy of Siegwart & Nourbakhsh
Control Structure

Prior Knowledge

Localization

Perception

Operator Commands

Cognition

Motion Control
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 robot’s 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

<table>
<thead>
<tr>
<th>General classification (typical use)</th>
<th>Sensor System</th>
<th>PC or EC</th>
<th>A or P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tactile sensors (detection of physical contact or closeness; security switches)</td>
<td>Contact switches, bumpers</td>
<td>EC</td>
<td>P</td>
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<tr>
<td></td>
<td>Optical barriers</td>
<td>EC</td>
<td>A</td>
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<tr>
<td></td>
<td>Noncontact proximity sensors</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td>Wheel/motor sensors (wheel/motor speed and position)</td>
<td>Brush encoders</td>
<td>PC</td>
<td>P</td>
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<tr>
<td></td>
<td>Potentiometers</td>
<td>PC</td>
<td>P</td>
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<tr>
<td></td>
<td>Synchros, resolvers</td>
<td>PC</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Optical encoders</td>
<td>PC</td>
<td>A</td>
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<tr>
<td></td>
<td>Magnetic encoders</td>
<td>PC</td>
<td>A</td>
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<tr>
<td></td>
<td>Inductive encoders</td>
<td>PC</td>
<td>A</td>
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<tr>
<td></td>
<td>Capacitive encoders</td>
<td>PC</td>
<td>A</td>
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<tr>
<td>Heading sensors (orientation of the robot in relation to a fixed reference frame)</td>
<td>Compass</td>
<td>EC</td>
<td>P</td>
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<td></td>
<td>Gyroscopes</td>
<td>PC</td>
<td>P</td>
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<tr>
<td></td>
<td>Inclinometers</td>
<td>EC</td>
<td>A/P</td>
</tr>
</tbody>
</table>

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

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<th>Sensor Sensor System</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Ground-based beacons (localization in a fixed reference frame)</td>
<td>GPS</td>
<td>EC</td>
<td>A</td>
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<td></td>
<td>Active optical or RF beacons</td>
<td>EC</td>
<td>A</td>
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<td>Active ultrasonic beacons</td>
<td>EC</td>
<td>A</td>
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<tr>
<td></td>
<td>Reflective beacons</td>
<td>EC</td>
<td>A</td>
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<tr>
<td>Active ranging (reflectivity, time-of-flight, and geometric triangulation)</td>
<td>Reflectivity sensors</td>
<td>EC</td>
<td>A</td>
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<tr>
<td></td>
<td>Ultrasonic sensor</td>
<td>EC</td>
<td>A</td>
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<td></td>
<td>Laser rangefinder</td>
<td>EC</td>
<td>A</td>
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<td></td>
<td>Optical triangulation (1D)</td>
<td>EC</td>
<td>A</td>
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<td>Structured light (2D)</td>
<td>EC</td>
<td>A</td>
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<tr>
<td>Motion/speed sensors (speed relative to fixed or moving objects)</td>
<td>Doppler radar</td>
<td>EC</td>
<td>A</td>
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<td></td>
<td>Doppler sound</td>
<td>EC</td>
<td>A</td>
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<tr>
<td>Vision-based sensors (visual ranging, whole-image analysis, segmentation, object recognition)</td>
<td>CCD/CMOS camera(s)</td>
<td>EC</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>Visual ranging packages</td>
<td></td>
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<td></td>
<td>Object tracking packages</td>
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</table>
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)
    \[ \text{Dynamic Range} = 10 \log \left( \frac{\text{UpperLimit}}{\text{LowerLimit}} \right) \]
  - E.g. A sonar Range sensor measures up to a max distance of 3m, with smallest measurement of 1cm.
    \[ \text{Dynamic Range} = 10 \log \left( \frac{3}{0.01} \right) \]
    \[ = 24.8 \text{ dB} \]
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. \( \text{error} = m - v \)).

\[
\text{accuracy} = 1 - \left| \frac{m - v}{v} \right|
\]

- \( m = \text{measured value} \)
- \( v = \text{true value} \)
Sensors: In Situ Characteristics

- **Precision**
  - The reproducibility of sensor results.
  
  \[
  \text{precision} = \frac{\text{range}}{\sigma}
  \]

  \[
  \sigma = \text{standard deviation}
  \]
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 $\rho_i$
  - Characterize statistical properties of $X$ with a *probability density function* $f(x)$
Sensor Uncertainty

- Expected value of $X$ is the mean $\mu$
  \[ \mu = E[X] = \int_{-\infty}^{\infty} x f(x) \, dx \]

- The variance of $X$ is $\sigma^2$
  \[ \sigma^2 = Var(X) = \int_{-\infty}^{\infty} (x - \mu)^2 f(x) \, dx \]
Sensor Uncertainty

- Expected value of $X$ is the mean $\mu$

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

- The variance of $X$ is $\sigma^2$

$$
\sigma^2 = \text{Var}(X) = \sum_{x}^{n} (x - \mu)^2
$$
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 \( P(x=2) \).