Perception

- Sensors
- Uncertainty
- Features
Example HelpMate, Transition Research Corp.
Example B21, Real World Interface
Example Robart II, H.R. Everett
Savannah, River Site Nuclear Surveillance Robot
BibaBot, BlueBotics SA, Switzerland

- Omnidirectional Camera
- Pan-Tilt Camera
- Sonar Sensors
- Laser Range Scanner
- Bumper

IMU

Inertial Measurement Unit

Emergency Stop Button

Wheel Encoders
Classification of Sensors

- Proprioceptive sensors
  - measure values internally to the system (robot),
  - e.g. motor speed, wheel load, heading of the robot, battery status

- Exteroceptive sensors
  - information from the robots environment
  - distances to objects, intensity of the ambient light, unique features.

- Passive sensors
  - energy coming for the environment

- Active sensors
  - emit their proper energy and measure the reaction
  - better performance, but some influence on environment
## General Classification (1)

<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</td>
<td>Contact switches, bumpers</td>
<td>EC</td>
<td>P</td>
</tr>
<tr>
<td>(detection of physical contact or</td>
<td>Optical barriers</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td>closeness; security switches)</td>
<td>Noncontact proximity sensors</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td>Wheel/motor sensors</td>
<td>Brush encoders</td>
<td>PC</td>
<td>P</td>
</tr>
<tr>
<td>(wheel/motor speed and position)</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>
</tr>
<tr>
<td>Heading sensors</td>
<td>Compass</td>
<td>EC</td>
<td>P</td>
</tr>
<tr>
<td>(orientation of the robot in relation to a fixed reference frame)</td>
<td>Gyroscopes</td>
<td>PC</td>
<td>P</td>
</tr>
<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.
## General Classification (2)

<table>
<thead>
<tr>
<th>General classification (typical use)</th>
<th>Sensor Sensor System</th>
<th>PC or EC</th>
<th>A or P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground-based beacons (localization in a fixed reference frame)</td>
<td>GPS</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Active optical or RF beacons</td>
<td>EC</td>
<td>A</td>
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<tr>
<td></td>
<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>
</tr>
<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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<tr>
<td></td>
<td>Laser rangefinder</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Optical triangulation (1D)</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Structured light (2D)</td>
<td>EC</td>
<td>A</td>
</tr>
<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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<tr>
<td></td>
<td>Doppler sound</td>
<td>EC</td>
<td>A</td>
</tr>
<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>
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<tr>
<td></td>
<td>Object tracking packages</td>
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</tr>
</tbody>
</table>
Characterizing Sensor Performance (1)

Measurement in real world environment is error prone

- Basic sensor response ratings
  - **Dynamic range**
    - *ratio between lower and upper limits, usually in decibels (dB, power)*
    - *e.g. power measurement from 1 Milliwatt to 20 Watts*
      
      \[ 10 \cdot \log \left( \frac{20}{0.001} \right) = 43 dB \]
    - *e.g. voltage measurement from 1 Millivolt to 20 Volt*
      
      \[ 20 \cdot \log \left( \frac{20}{0.001} \right) = 86 dB \]
    - 20 instead of 10 because square of voltage is equal to power!!
  - **Range**
    - *upper limit*
Characterizing Sensor Performance (2)

- Basic sensor response ratings (cont.)
  - Resolution
    - minimum difference between two values
    - usually: lower limit of dynamic range = resolution
    - for digital sensors it is usually the A/D resolution.
      e.g. 5V / 255 (8 bit)
  - Linearity
    - variation of output signal as function of the input signal
    - linearity is less important when signal is post-processed by a computer
  - 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
    - Lower limit is also possible, e.g. acceleration sensor
**In Situ Sensor Performance (1)**

Characteristics that are especially relevant for real world environments

- **Sensitivity**
  - ratio of output change to input change
  - however, in real world environment, the sensor has very often high sensitivity to other environmental changes, e.g. illumination

- **Cross-sensitivity**
  - sensitivity to environmental parameters that are orthogonal to the target parameters

- **Error / Accuracy**
  - difference between the sensor’s output and the true value

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

\(m = \text{measured value}\)
\(v = \text{true value}\)
In Situ Sensor Performance (2)

Characteristics that are especially relevant for real world environments

- **Systematic error** -> deterministic errors
  - caused by factors that can (in theory) be modeled -> prediction
  - e.g. calibration of a laser sensor or of the distortion caused by the optic of a camera

- **Random error** -> non-deterministic
  - no prediction possible
  - however, they can be described probabilistically
  - e.g. Hue instability of camera, black level noise of camera ..

- **Precision**
  - reproducibility of sensor results
  \[ precision = \frac{\text{range}}{\sigma} \]
Characterizing Error: The Challenges in Mobile Robotics

- Mobile Robot has to perceive, analyze and interpret the state of the surrounding.
- Measurements in real world environment are dynamically changing and error prone.
- Examples:
  - changing illuminations
  - specular reflections
  - 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!!
Multi-Modal Error Distributions: The Challenges in …

- Behavior of sensors modeled by probability distribution (random errors)
  - usually very little knowledge about the causes of random errors
  - often probability distribution is assumed to be symmetric or even Gaussian
  - however, it is important to realize how wrong this can be!
  - Examples:
    - **Sonar (ultrasonic) sensor** might overestimate the distance in real environment and is therefore not symmetric
      Thus the sonar sensor might be best modeled by two modes:
      - mode for the case that the signal returns directly
      - mode for the case that the signals returns after multi-path reflections.
    - **Stereo vision system** might correlate to images incorrectly, thus causing results that make no sense at all
Wheel / Motor Encoders (1)

- measure position or speed of the wheels or steering
- wheel movements can be integrated to get an estimate of the robots position -> odometry
- optical encoders are proprioceptive sensors
  - Thus the position estimation in relation to a fixed reference frame is only valuable for short movements.
- typical resolutions: 2000 increments per revolution.
  - For high resolution: interpolation

<table>
<thead>
<tr>
<th>State</th>
<th>Ch A</th>
<th>Ch B</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₁</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>S₂</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>S₃</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>S₄</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
Wheel / Motor Encoders (2)

Notice what happen when the direction changes:
Heading Sensors

- Heading sensors can be proprioceptive (gyroscope, inclinometer) or exteroceptive (compass).
- Used to determine the robot's 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 wheel's inertia $I$.
- No torque can be transmitted from the outer pivot to the wheel axis
  - spinning axis will therefore be space-stable
- Quality: $0.1^\circ$ in 6 hours

- 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

\[ \tau = I \omega \Omega \]
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.
Optical Gyroscopes

- First commercial use started only in the early 1980 when they were first installed in airplanes.
- Optical gyroscopes
  - *angular speed (heading) sensors using two monochromic light (or laser) beams from the same source.*
- One beam travels clockwise in a cylinder around a fiber, the other counterclockwise.
- The beam traveling in direction of rotation:
  - *slightly shorter path -> shows a higher frequency*
  - *difference in frequency Δf of the two beams is proportional to the angular velocity Ω of the cylinder/fiber.*
- New solid-state optical gyroscopes based on the same principle are build using microfabrication technology.
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
- Major drawback with the use of beacons in indoor:
  - Beacons require changes in the environment
    - costly.
  - Limit flexibility and adaptability to changing environments.
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)
Global Positioning System (GPS) (3)

- Time synchronization:
  - atomic clocks on each satellite
  - monitoring them from different ground stations.
- Ultra-precision time synchronization is extremely important
  - electromagnetic radiation propagates at light speed,
- Roughly 0.3 m per nanosecond.
  - position accuracy proportional to precision of time measurement.
- Real time update of the exact location of the satellites:
  - monitoring the satellites from a number of widely distributed ground stations
  - master station analyses all the measurements and transmits the actual position to each of the satellites
- Exact measurement of the time of flight
  - the receiver correlates a pseudocode with the same code coming from the satellite
  - The delay time for best correlation represents the time of flight.
  - quartz clock on the GPS receivers are not very precise
  - the range measurement with four satellite
  - allows to identify the three values \((x, y, z)\) for the position and the clock correction \(\Delta T\)
- Recent commercial GPS receiver devices allows position accuracies down to a couple meters.