Brainstorm

• In addition to cameras / Kinect, what other kinds of sensors would be useful?
How do you evaluate different sensors?

**Brainstorm**

- In addition to cameras/Kinect, what other kinds of sensors would be useful?

- Biometric
- GPS
- Temp
- Altimeter
- Gyroscope
- Accelerometer
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
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 analog-to-digital conversion
      - e.g. 5V / 255 (8 bit)
  - **Linearity**
    - variation of output signal as function of the input signal
    - linearity is less important when signal is after treated with 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)

- **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 (e.g., compass responding to building materials)

- **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

- **Random error** → non-deterministic
  - no prediction possible
  - however, they can be described probabilistically

- **Precision**
  - reproducibility of sensor results

\[ \text{precision} = \frac{\text{range}}{\sigma} \]
Characterizing Error: Challenges in Mobile Robotics

• Mobile Robot: perceive, analyze and interpret state

• Measurements 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 may be well defined in controlled environment
Multi-Modal Error Distributions

• Behavior of sensors modeled by probability distribution (random errors)
  – usually very little knowledge about causes of random errors
  – often probability distribution is assumed to be symmetric or even Gaussian
  – however, may be very wrong....
  • Sonar (ultrasonic) sensor might overestimate the distance in real environment and is therefore not symmetric
  • Sonar sensor might be best modeled by two modes:
    1. the case that the signal returns directly
    2. 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
- Integrate wheel movements to get an estimate of robots position → odometry
- optical encoders are proprioceptive sensors
  - position estimation in relation to a fixed reference frame is only valuable for short movements
- typical resolutions: 2000 increments per revolution.
Wheel / Motor Encoders (2)

Ok, how does this work? Speed? Position?
Wheel / Motor Encoders (2)
Wheel / Motor Encoders (3)
Heading Sensors

• Proprioceptive (gyroscope, inclinometer) or Exteroceptive (compass)
• Determine the robot’s orientation
• Heading + velocity integrates to position estimate
  – Dead reckoning (ships)
  – Location + Orientation = *Pose*
Compass

• ~2000 B.C.
  – 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

• Major drawbacks
  – weakness of the earth field
  – easily disturbed by magnetic objects or other sources
  – not feasible for indoor environments
Gyrocompass

- Patented in 1885
- Practical in 1906 (Germany)
- Find true north as determined by Earth’s rotation
- Not affected by ship’s composition, variety in magnetic field, etc.
Gyroscope

• Heading sensors keep the orientation to a fixed frame
  – absolute measure for the heading of mobile system

• Mechanical Gyroscopes
  – Drift: 0.1° in 6 hours
  – Spinning axis is aligned with north-south meridian, earth’s rotation has no effect on gyro’s horizontal axis
  – If points east-west, horizontal axis reads the earth rotation

• Optical Gyroscopes (1980s)
  – 2 laser beams in opposite direction around circle
  – Bandwidth >100 kHz
  – Resolution < 0.0001 degrees/hr
Optical Gyroscopes

• Early 1980: first installed in airplanes
• Angular speed (heading) sensors using two monochromic light / laser beams from same source
• On is traveling clockwise, the other counterclockwise
• Laser beam traveling in direction of rotation
  – slightly shorter path -> shows a higher frequency
  – difference in frequency $\Delta f$ of the two beams is proportional to the angular velocity $\Omega$ of the cylinder
• New solid-state optical gyroscopes based on the same principle are build using microfabrication technology
• MUCH more accurate than mechanical
Ground-Based Active and Passive Beacons

- Beacons are signaling guiding devices with a precisely known positions.
- Beacon-base navigation is used since the humans started to travel.
  - Natural beacons (landmarks) like stars, mountains, or the sun
  - Artificial beacons like lighthouses
- Global Positioning System revolutionized modern navigation technology
  - Key sensor for outdoor mobile robotics
  - GPS not applicable indoors
- Major drawback with the use of beacons in indoor:
  - Beacons require environment changes: costly
  - Limit flexibility and adaptability to changing environments
- Key design choice in Robocup
  - https://www.youtube.com/watch?v=Kc8ty9moQ
Global Positioning System (GPS) (1)

• Developed for military use, now commercial
  – 24 satellites (including some spares)
  – Orbit earth every 12 hours at a height of 20.190 km
  – Location of GPS receiver determined through time of flight measurement

• Technical challenges:
  – Time synchronization between individual satellites and 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)

- How many satellites do you need to see?
Global Positioning System (GPS) (3)

- Time synchronization:
  - atomic clocks on each satellite, monitored from different ground stations
  - electromagnetic radiation propagates at light speed (0.3 m / nanosecond)
  - position accuracy proportional to precision of time measurement

- Real time update of exact location of satellites:
  - Monitoring satellites from a number of widely distributed ground stations
  - master station analyses all measurements & transmits actual position to each satellite

- Exact measurement of the time of flight:
  - quartz clock on the GPS receivers are not very precise
  - four satellite allows identification of position values (x, y, z) and clock correction $\Delta T$

- Position accuracies down to a ~2 meters

- Improvement: Differential GPS
  - ~10cm
  - Need fixed, known location
  - Piski: [http://swiftnav.com/piksi.html](http://swiftnav.com/piksi.html)
  - Project possibilities here!