Autonomous systems

Sensors

Sensing

- **Key requirement** of autonomous systems.
  - An AS should be connected to the outside world.
- Convert a physical value to an electrical value.
  - **From** temperature, humidity, light, …

    to current, voltage, …

Classification

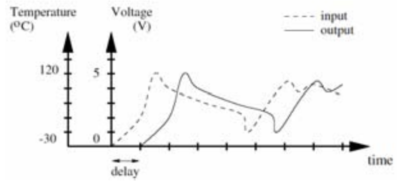
- Classification 1
  - Internal sensor
    Provides feedback on internal state of the robot (battery level, wheel positions, joint angles of a robot arm). Also called *proprioception*.
  - External sensor
    Provides feedback on external state of robot (light in the environment, temperature, humidity).
- Classification 2
  - Passive sensors
    Passively receive energy from the environment (light sensor, camera).
  - Active sensors
    Make observations by emitting energy or by modifying the environment (ultrasonic sensor, laser range scanner).

Properties

- **Input range:** the operating range to which the sensor is sensitive.
  - E.g. Temperature sensor operating reliably from -5°C to 40°C. Outside this range the sensor's fault tolerance is exceeded.
- **Output range:** range of the output signal.
  - E.g. Temperature sensor returns voltage between 0 and 5 V.
- **Sensitivity:** How is a change in the input signal mapped to the output signal?
  - E.g. an inclination sensor produces a change in output voltage of 1mV for every 2.30°.

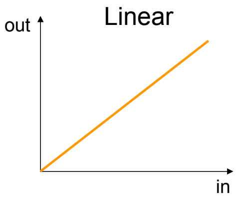
Properties (2)

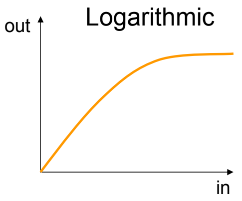
- **Latency:** Speed with which the sensor reacts to change.
  - E.g. A temperature sensor having a latency of 14 s per 10°C.

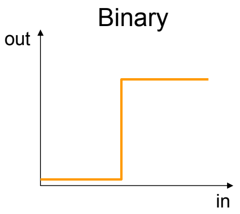


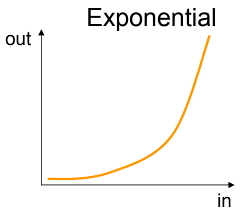
- **Stability:** insensitivity to factors other than the measured physical quantity.
  - Noise: undesired change from ideal output value. E.g. thermal noise in the sensor.
  - Distortions. E.g. radioactive radiation influencing the sensor.
  - Environmental influences. E.g. temperature, air pressure, …

Operating regimes









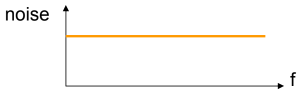
Operating regimes (2)

- Just as interesting fact… Human sensors exhibit a logarithmic operating regime.
  - Very sensitive to small changes when signal is small.
  - Less sensitive to changes as soon as amplitude of signal is large.

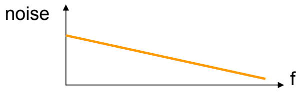
Noise

- Anything that obscures a desired signal.
- External noise
  - Part of the environment
  - Eg: temperature, electromagnetic interference (power lines, combustion engines, electric motors, radio & TV), sun light, gravitational flux, …
- Internal noise
  - White noise (uniform)
    - E.g. thermal noise

$$P = k.T.\Delta f$$



  - Pink noise (1/f)



Modeling sensors and noise

- Ideal sensor

  r = reading
  f = sensor function
  e = physical property

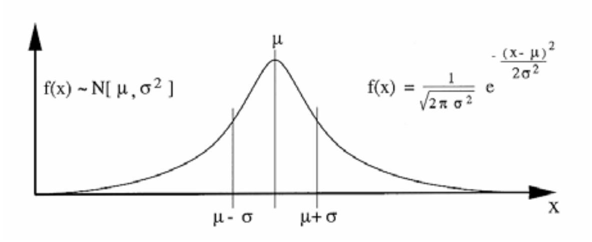
$$r = f(e)$$

- Sensor with noise

$$r = f(e) + n$$

How to estimate the noise term n?

- Often noise can be estimated with a Normal distribution



Sampling

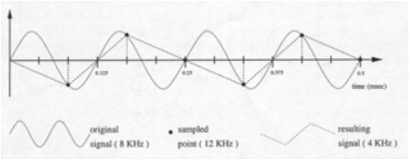
- What is **sampling**?

  Discrete reading of sensor values.

- Why sample?
  - Converting to digital value. Very obvious: needed for digital processing by computer.
  - Latency of sensors. **Some sensors**
  - Send-wait-sense cycle.

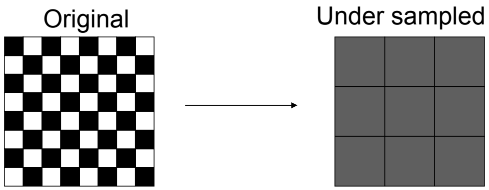
Sampling rate

- **Nyquist theorem**
  - The sampling rate has to be at least **twice as high** as the fastest changes. If not, you are going to miss relevant information.



  - E.g. If sound signal changes at 3 kHz, you have to sample at at least 6 kHz to not miss anything of the signal.

Nyquist: example



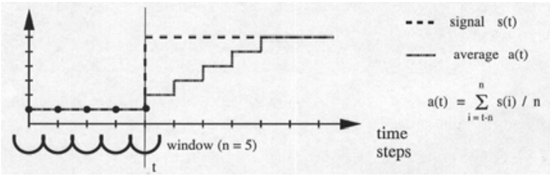
•Under sampling results in *aliasing* (in computer imaging this is tackled by anti-aliasing).

Cancelling out Normal distributed noise

- By increasing sample rate and averaging
  - One sample $v_i^{out} = v_i^{in} + de_i$
  - Average of *n* samples $v_i^{avg} = \sum_{i=1}^{n} \frac{v_i^{in} + de_i}{n} = \sum_{i=1}^{n} \frac{v_i^{in}}{n} + \sum_{i=1}^{n} \frac{de_i}{n}$
  - If the noise if symmetrical around the average sensor reading, the noise will eventually cancel out.
  - However, this only works if noise is symmetrically distributed (such as with the Normal distribution). Some systematic noise produces a constant positive or negative offset, which can not be cancelled out with averaging.

Disadvantages of averaging

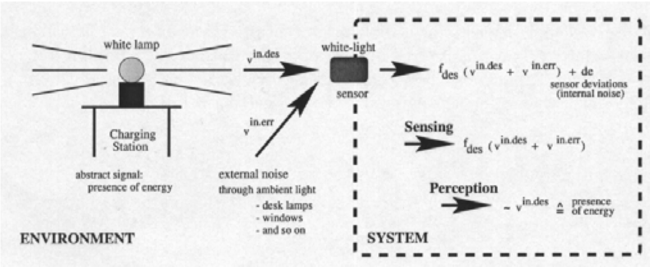
- Delay in detecting change in the input.
- Loosing fast changes in the input signal.



Calibration

- Getting rid of noise through **calibration**.
  - A trusted calibration signal is needed. E.g. when calibrating a scale a well known and precise calibration weight is used.
- What can be eliminated with calibration?
  - Long-term drift and slow changing noise of sensors.
  - (Near) constant environmental influences.
- What can be detected with calibration, but not repaired?
  - Malfunctioning sensors.

External noise



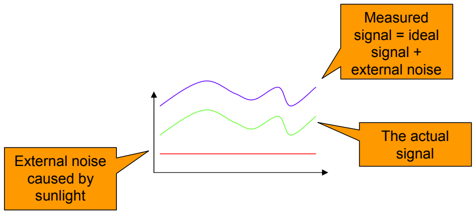
Cancelling out external noise

- Is often very difficult!
  - If it has no random or Normal distribution.
  - Dependant on complex environmental interactions.
- Three possible solutions
  - **(1)** Calibration of sensors.
  - **(2)** Making a sensor reading independent of external noise.

    E.g. robot emits infrared light to perceive obstacles, but unfortunately infrared sensors are also sensitive to sunlight. So, if there is sunlight, the robot always perceives obstacles; even when there is no obstacle in front.

Cancelling out external noise (2)

- This is what our problem look like



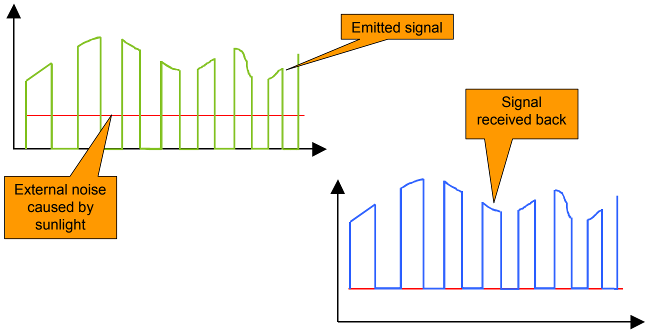
Measured signal = ideal signal + external noise

The actual signal

External noise caused by sunlight

- Solution: modulate the signal (= multiply it with a block wave), so later on you can distinguish infrared returning from obstacles from infrared from sunlight.

Cancelling out external noise (3)



Emitted signal

Signal received back

External noise caused by sunlight

By detecting signal of the modulation frequency, one only perceives modulated IR and **not** sunlight.

Cancelling out external noise (2)

- **(3)** Sensor fusion. Using different sensors to get a more accurate combined measurement.

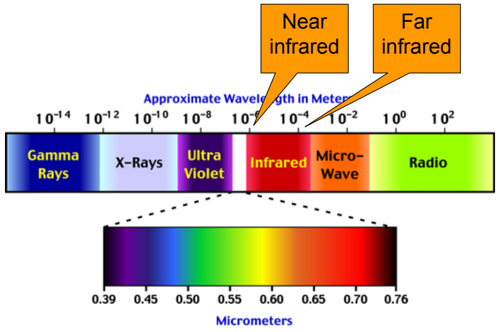
  E.g. when looking for obstacles, do not rely on infrared alone. But combine the information gained through infrared with information gained through ultrasound.

Sensor technologies

- Light sensing
- Contact and proximity
- Distance sensing

Light sensing

- The electromagnetic spectrum

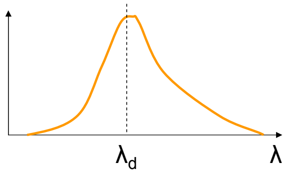


Light sensors

- Photo diode
  - Diode embedded in translucent plastic package.
  - Conductivity influenced by photons hitting n-p junction.
- Photo transistor
  - Transistor embedded in translucent plastic package.
  - Transistor amplifies (100 to 1000 times), can be hooked up to AD converter.
- Light dependant resistor (LDR)
  - Resistance decreases when light falls on it.
  - Not sensitive to infrared light.
- Light to frequency converter
  - Diode combined with IC to convert current to pulses.
  - Accurate, light intensity on one wire.

Properties of light sensors

- Sensitivity of light sensors.

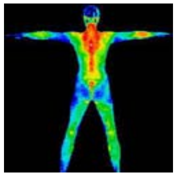


- Logarithmic or linear versions.
- Sensitivity.
- Angle (8 to 60 degrees).

Far IR sensors

- Also called *pyro sensors*, because they are sensitive to infrared heat, or *passive IR sensor*.
- Each body emits heat, according to Boltzman equation

$$E = \varepsilon.\sigma.T^4$$



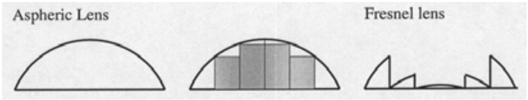
- ε is the emissivity of a body, σ is the Boltzman constant ($5.670.10^{-8}$ W/(m^2K^4)), and T is the temperature (K)
- Humans emit 80 to 100 W at 10 µm.
- Consists of two layers converting heat to a current, a differential current can be detected.
- Pyro sensors are *motion sensors*, not *presence sensors*.

Far IR emitted by living tissue

The Infrared Zoo (http://sirtf.caltech.edu/EPO/Zoo/zoo.html)

Far IR sensors (2)

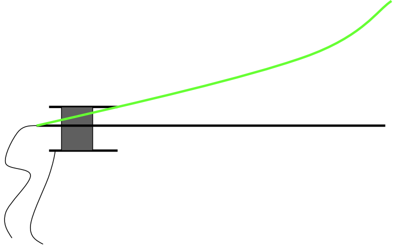
- Photons need to be focussed on the sensor: lens is needed.
- Glass is not translucent for wavelengths under 5 µm, instead a polymer is used.
- Fresnel lens



  - Saves volume.
  - Creates corridors where sensor is insensitive (both a disadvantage and an advantage).

Contact sensors

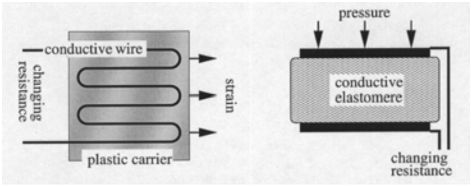
- Binary or analog
  - Binary sensors are just switches. Either pressed or not.
  - Analog sensors are often spring-loaded. A force F is needed for pressing the switch, the force translates into a value.
- Sizes: from micro switch to power switch.
- Can be mechanically extended to get whiskers



Force sensors

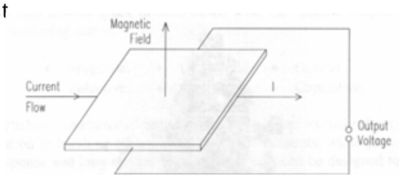
- Strain sensors and pressure sensors. Operate on principle expressed in Kelvin's law. Resistance of a conductor depends on length *l* and area *A*, and conductivity *r*.

$$R = r.\frac{l}{A}$$



Proximity sensors

- Hall sensor detects the proximity of objects which generate an electromagnetic field.
- Hall effect



- When a magnet provides the magnetic field, ferromagnetic objects can be detected.

Active infrared

- Active in the sense that the sensor emits infrared and then measure the reflected infrared (instead of passively measuring infrared).
- Problem: how to distinguish your own IR from other IR in the environment?
  - Solution: modulation of emitted IR and filtering of received infrared.
- Reflected IR depends on material and refraction angle.
  - Wood or cloth ("fuzzy surfaces") and dark objects are bad reflectors.
  - Hard and light surfaces are good reflectors.
  - Flat surfaces reflect perfectly, while other shapes tend to disperse or reflect infrared away from the sensor.

Ultrasound or sonar

- **So**und **Na**vigation and **R**anging
- Combination of speaker and microphone.
- Sensing distance based on time-of-flight or phase shift.
- Sensing speed of bodies based on Doppler effect.
- Depends on
  - Reflection strength, depends on type of material.
  - Multiple echos: system needs to wait until echos dies out.
  - Low angular resolution, eg. Not able to see doorways.
  - Polution.
- Low sampling rate, due to echos and “blanking”.

Ultrasound (2)

Ultrasound (3)

- Time-of-flight distance measurement

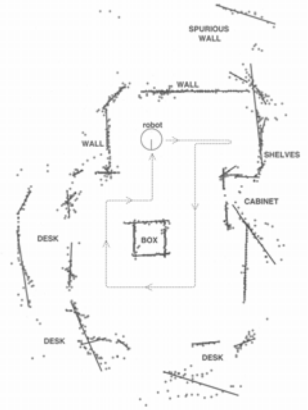
$$d = \frac{1}{2} ct$$

- Time-of-flight depends on speed of sound

$$v_{sound} = 331.4\, {}^{m}\!/\!_{s} \cdot \sqrt{\frac{T}{273\mathrm{K}}}$$

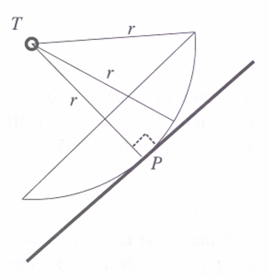
- Commercial frequencies: 40kHz – 50kHz
- Spatial resolution depends on frequency (minimal detected detail = one wavelength).
- High frequencies attenuate quickly.
- Performance depends on acoustic reflectance (eg. concrete = 98%, acoustic tile = 30%) and distance.

Ultrasound (4)



Ultrasound (5)

- Problem: region of constant distance (DCT).



- Can be solved by taking multiple readings from different positions.

Laser range finder

- Active laser emitter and sensor.
- Time-of-flight computed indirectly.
  - Discharging capacitor.
  - Phase-shift between emitted and received light.
- Very accurate distance measurements (< 1 cm).
- High angular resolution.
- Multi-angular measurements through using rotating mirror.

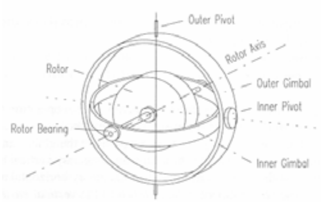
Laser range finder (2)

- Cheap through semiconductor laser diodes.
- Laser light easy to distinguish from ambient light.
- Accurate, fast and directed.

- Potential safety problem: intense and invisible beam.
- Reflection depends on reflective material (eg. glass, fabric, …).
- Atmospheric influence on laser light.

Gyroscopes

- Several types exist (mechanical and optical).
- Mechanical example: flywheel gyroscope
  - Conservation of angular momentum
  - Torque on axes depends on $T = I.\omega.\Omega$



Gyroscopes (2)

- Gyroscopes are no longer rotating wheels.
- Solid state gyroscopes are sturdier and smaller.

Accelerometers

- Spring-mounted mass.
- Newton’s law and spring-mass relation