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Sensors: inertial measurement unit, wheel encoders, omnidirectional camera, pan-tilt camera, sonars, laser rangefinder, bumpers
Sensors

- Sensors are classified along two main dimensions:
  - Proprioceptive / Exteroceptive
    - Proprioceptive: Sensors which measure quantities internal to the robot (e.g. wheel angle, motor speed, internal temperature, ...)
    - Exteroceptive: Sensors which measure properties of the environment (e.g. light intensity, sound level, distance of wall, ...)
  - Passive / Active
    - Passive: Sensors which measure the existing forces and energies in the environment (e.g. cameras, microphones, contact switches)
    - Active: Sensors which emit energy and measure the environment’s response to that energy (e.g. radar, ultrasonic sensors, laser rangefinders, ...)
    - Active sensors can sometimes achieve superior performance, but suffer from problems with interference and power consumption
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A, active; P, passive; P/A passive/active;

PC proprioceptive; EC exteroceptive
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A, active; P, passive; P/A passive/active; PC proprioceptive; EC exteroceptive
Sensor Characteristics

- **Range**: The minimum and maximum input values
- **Dynamic range**: Ratio of maximum to minimum input values
  - Example: the ratio in sound pressure from the loudest rock concert to the lowest audible tone is about 10,000,000,000.
  - Usually measured in decibels:
    
    \[
    10 \cdot \log_{10} \left( \frac{\text{max. input value}}{\text{min. input value}} \right)
    \]
  - Human hearing: 100 dB
  - Decibels describe the ratio between two quantities of power; If measuring something which has to be squared to be proportional to power (e.g. voltage), the 10 is replaced with 20
• **Resolution**: Minimum detectable difference between two values
  
  - e.g. 8 bits to measure a signal from 0 - 5 V;
    
    Resolution is $5 \text{ V} / 255 \approx 20 \text{ mV}$
  
• **Linearity**: Sensor is linear if two different inputs, $x$ and $y$, yield outputs $f(x)$ and $f(y)$, and an input that is some combination of the two, $ax + by$, yields output $af(x) + bf(y)$

• **Bandwidth or frequency**: Rate of sensor updates per second
  
  - e.g. Typical video frame rate is 30 Hz
• **Error**: $error = m - \nu$, where $m$ is measurement and $\nu$ is the true value

• **Accuracy**: Degree to which measured values are correct,

\[
accuracy = 1 - \frac{|error|}{\nu}
\]

• **Precision**: Degree to which measured values agree,

\[
precision = \frac{range}{\sigma}
\]

where $\sigma$ is the standard deviation of the sensor’s random error
Optical Encoders

- Optical encoders are used to measure angular position
- Encoders are ________ceptive sensors
- Wheel rotations can be integrated over time to estimate position, but positional estimate is subject to cumulative error
- A code disk rotates with the wheel, and a photo-emitter / detector pair senses the light being blocked and unblocked
Absolute encoders require one photo-emitter / detector pair per bit of position resolution; Shown below are two common types of code disks

**Gray–Code**

**Dual–Code**

The dual-code disk is straight binary; The gray-code disk has the advantage that only one bit changes at a time.
**Incremental encoders** operate by counting the number of ticks along one or more rings; A *quadrature encoder* is a type of incremental encoder which counts incoming pulse trains that are separated in phase by $90^\circ$; One way to achieve this is by using two code rings;

- For each ring there is a photo-emitter / detector pair
- Direction of rotation given by the phase difference between the emitter signals (i.e. by which one is ‘leading’)
The two rings allow four different states to be detected; this doubles the resolution over a one-ring incremental encoder.

- Typically around 2000 CPR (cycles per revolution)
- "Industrial optical encoders present no bandwidth limitation to mobile robot applications"
Magnetic Encoders

- Magnetic encoders operate quite similarly to optical encoders, except that the code disk is replaced with a magnetic disk with multiple poles (North-South pairs)
- A stationary hall effect sensor detects the magnetic polarity of the rotating disk
- The following shows the magnetic encoders on the Zumo 32U4 robot which uses 6-pole disks, leading to 12 counts per revolution
**Compasses** are exteroceptive

- Hall effect compasses measure the voltage difference induced by the magnetic field in two orthogonal directions
  - Cheap, but resolution and accuracy are poor
  - Filtering circuits can improve performance (e.g. by averaging values over time), but reduce bandwidth
- Flux gate compasses measure the phase difference induced by the magnetic field in two coils with applied alternating current
  - Improved resolution and accuracy, but larger and more expensive
- All magnetic compasses are subject to local variations in magnetic field $\rightarrow$ generally unsuitable for indoor environments
Global Positioning System (GPS)

- GPS was developed for use by the US military, but is now also available for civilian use.
- 24+ satellites orbiting the planet in six planes inclined at 55° to the equator.
- Each satellite transmits...
  - Time (measured by atomic clock).
  - Its position and the positions of all other GPS satellites.
- A GPS receiver is passive and exteroceptive; it measures the time of flight and uses this to estimate the pseudorange to the satellites; This is not a true range because of the offset of the receiver’s inexpensive quartz clock from satellite time; Four satellites must be in view so that the variables x, y, z, and Δt can be estimated.
- The requirement of four line-of-sight satellites means that GPS information is unavailable in confined spaces → generally not useful indoors.
Active Ranging: Ultrasonic Sensor

- An ultrasonic sensor transmits a high-frequency sound packet and measures the time it takes for the sound to rebound back to the sensor.
- The time of flight, $t$, along with the speed of sound, $c$, give the distance,
  \[ d = \frac{c \cdot t}{2} \]
  we need the division by two because the sound actually travels twice as far as the distance we wish to measure.
- $c = 343 \text{ m/s}$ at standard air pressure and 20° C
- Operation:
  - Emit wave packet
  - Start integrator to measure time
  - Threshold value initially high during “blanking period”
  - If reflected echo (with the right frequency) exceeds threshold, read the integrator’s value to determine $t$
The sound propagates in the shape of a cone
- Opening angle $20^\circ - 40^\circ$
- Obtain the depth of regions, as opposed to points
Disadvantages:

- **Accuracy**: Diminishes with increasing angle between viewpoint and surface
  - Coherent reflection of the sound causes the distance to be grossly overestimated

- Some materials simply absorb the sound (e.g. foam or cloth) and therefore are reported to be at the maximum range

- **Bandwidth**:
  - Single sensor: To allow time to detect object at 12 m, requires 70 ms → 14.3 Hz
  - 20 sensors: Apply each in sequence to avoid interference, requires 20 * 70 ms → 0.7 Hz
Laser Rangefinders

- Like ultrasonic sensors, laser rangefinders measure the time of flight for emitted energy to strike a surface and return, converting this time into a distance.
- Transmitter emits a collimated beam of light in one direction.
- Receiver detects light which returns from the same direction.
- Surfaces with roughness greater than the wavelength of incident light will scatter the light in all directions.
  - Therefore some will get reflected back to the receiver.
  - Coherent reflection only for extreme angles and/or highly polished surfaces.
Unlike ultrasonic sensors, measuring time of flight directly is difficult:
- Speed of sound $\approx 0.3 \, \text{m} / \text{ms}$; Speed of light $\approx 0.3 \, \text{m} / \text{ns}$
- A single “pulse” would take 20 ns to return after hitting a wall 3 m away
- Measuring events that take place within 10’s of nanoseconds requires expensive electronics
- Easier to impose a known frequency on the laser and measure the phase shift in the reflected beam
The laser can be swept in a plane using a rotating mirror to obtain a one-dimensional image of the environment.

**Figure 4.11**
(a) Schematic drawing of laser range sensor with rotating mirror; (b) Scanning range sensor from EPS Technologies Inc.; (c) Industrial 180 degree laser range sensor from Sick Inc., Germany

3D information can be obtained by pitching the apparatus upwards and downwards.
• **General principle:** We are more confident in measuring large signals than small signals which can get ‘lost in the noise’
  
  • For laser r-f’s: More confident about bright nearby objects than dark distant objects ones

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Line length ≡ uncertainty
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• e.g. Characteristics: Hokuyo URG-04LX-UG01
  
  • Angular resolution: 0.36°
  • Accuracy: ± 3 cm
  • Angular range: 240°
  • Depth range: 2 cm - 5.6 m
  • Bandwidth: 10 Hz