Today

- Last time we looked at motion, on the bottom right hand side.
- This time we’ll move round to the bottom left.
Perception

- So far we have programmed robots more or less “blind”
  - Almost no information from the environment.

- Perception is all about what can be sensed and what we can do with that sensing.

Classification of sensors

- Proprioceptive sensors
  - Measure values internally to the system (robot),
    (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 own energy and measure the reaction
  - Better performance, but some influence on environment
• Note that the robot has a number of different sensors.
Xavier

• Built at CMU.

Sensors include bump panels, a Denning sonar ring, a Nomadics laser light striper, and twin cameras mounted on a Directed Perception pan/tilt head for stereo vision.

• Also includes a 4-wheel synchrodrive.

BibaBot

• Omnidirectional and pan/tilt camera.
• Sonar
• Wheel encoders
• Laser range finder
• Bumpers

• BlueBotics SA, Switzerland
### 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>
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<td></td>
<td>Capacitive encoders</td>
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<td>Acceleration sensor</td>
<td>Accelerometer</td>
<td>PC</td>
<td>P</td>
</tr>
</tbody>
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A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

* Note: GPS receivers are passive (P) – see page 123 of the textbook. But the whole GPS system is active as GPS satellites must transmit (broadcast) microwave signals to receivers.

### General classification (2)

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<tbody>
<tr>
<td>Ground beacons (localization in a fixed reference frame)</td>
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<td></td>
<td>Active optical or RF beacons</td>
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<td>Active ultrasonic beacons</td>
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<td>Reflective beacons</td>
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<td>Active ranging (reflectivity, time-of-flight, and geometric triangulation)</td>
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<td>Laser rangefinder</td>
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<td>Optical triangulation (1D)</td>
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<tr>
<td></td>
<td>Structured light (2D)</td>
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<tr>
<td>Motion/speed sensors (speed relative to fixed or moving objects)</td>
<td>Doppler radar</td>
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<tr>
<td></td>
<td>Doppler sound</td>
<td>EC</td>
<td>A</td>
</tr>
<tr>
<td>Vision sensors (visual ranging, whole-image analysis, segmentation, object recognition)</td>
<td>CCD/CMOS camera(s)</td>
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<td>Visual ranging packages</td>
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Sensor characteristics (1)

- Range
  - The upper limit that a sensor can measure.
- Dynamic range
  - Ratio between lower and upper limits, usually in decibels (dB) which is a measure of power.
  - Power measurement from 1 Milliwatt to 20 Watts
    \[-10 \cdot \log\left(\frac{0.001}{20}\right) = 43 dB\]
  - Voltage measurement from 1 Millivolt to 20 Volt
    \[-20 \cdot \log\left(\frac{0.001}{20}\right) = 86 dB\]
  - 20 instead of 10 because square of voltage is equal to power.

Sensor characteristics (2)

- Linearity
  - Variation of output signal as function of the input signal.
  - Satisfy: \(f(ax+by) = af(x) + bf(y)\)
- Bandwidth or Frequency
  - The speed with which a sensor can provide readings.
  - Usually an upper limit. Depends on sensor and the sample rate.
  - Lower limit is also possible, e.g. acceleration sensor.
- Resolution
  - Minimum difference between two values. Usually the lower limit of dynamic range.
  - For digital sensors it is usually the A/D resolution. (e.g. \(5V / 255 \) (8 bit) = 19.6mv)
Sensor performance (1)

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

- Cross-sensitivity
  - Sensitivity to environmental parameters that are orthogonal to the target parameters - generally undesirable.

- Error / Accuracy
  - Difference between the sensors output and the true value
    \[
    \text{accuracy} = 1 - \left| \frac{m - v}{v} \right|
    \]
    
    where \( m \) = measured value, and \( v \) = true value.

Sensor performance (2)

- Systematic error \( \rightarrow \) deterministic errors
  - Caused by factors that can (in theory) be modeled \( \rightarrow \) prediction
    e.g. distortion caused by the optics of a camera.

- Random error \( \rightarrow \) non-deterministic
  - No prediction possible
  - However, they can be described probabilistically
    e.g. error in wheel odometry.

- Precision
  - Reproducibility of sensor results
    \[
    \frac{\text{range}}{\sigma}
    \]
**Bumpers**

- You should be a bit familiar with the bumper on the Create by now.
  - Each bumper says when it has hit something.
- Bumpers are just contact switches — indicate when they are pressed.
- While the Create has just two bumpers, a robot can have many.

**Wheel encoders**

- Measure position or speed of the wheels or steering.
- Wheel movements can be integrated to get an estimate of the robot’s position
  - Odometry (this is what the position proxy is doing)
- Optical encoders are proprioceptive sensors
  - Position estimate is only useful for short movements.
- Typical resolutions: 2000 increments per revolution.
Heading sensors

- Heading sensors can be:
  - proprioceptive (gyroscope, accelerometer); or
  - exteroceptive (compass, inclinometer).
- Used to determine the robot's orientation and/or inclination.
- Allow, together with an appropriate velocity information, to integrate the movement to a position estimate.
  - A bit more sophisticated than just using odometry.

Compass

- Used since before 2000 B.C.
  - Chinese suspended a piece of natural 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 in general.

• Modern devices can give 3D orientation relative to Earth’s magnetic field and integrate to give distance.
• MEMS (micro-electro-mechanical system): micro machines with wide applications including magnetometers and IMUs
• IMU (inertial measurement unit) incorporates gyroscopes and accelerometers to estimate the 6-DOF pose of a vehicle

 Gyroscope

• Heading sensors, that keep the orientation to a fixed frame
  – Provide an absolute measure for the heading of a mobile system.
  – Unlike a compass doesn’t measure the outside world.
• Two categories, mechanical and optical gyroscopes
• Mechanical Gyroscopes
  – Standard gyro
  – Rate gyro
• Optical Gyroscopes
  – Rate gyro
• 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.
• No torque can be transmitted from the outer pivot to the wheel axis
• Spinning axis will therefore be space-stable
• Quality: 0.1 degrees in 6 hours
• In rate gyros, gimbals are held by torsional springs.
  – Measuring angular velocity instead of absolute orientation.

Optical gyroscopes
• Use two monochromatic 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 $\Delta f$ of the two beams is proportional to the angular velocity $\Omega$ of the cylinder/fiber.
• Newest optical gyros are solid state.
Ground-based beacons

- Elegant way to solve the localization problem in mobile robotics
- Beacons are objects with a precisely known position
- Used since the humans started to travel
  - Natural beacons (landmarks) like stars, mountains or the sun
  - Artificial beacons like lighthouses

- Cost prohibits too much reliance on beacons.

GPS

- Extension of the beacon idea, developed for military use
- 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 equator
- 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
  - Interference with other signals
• Time synchronization:
  – Atomic clocks on each satellite
  – Monitored 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 ground stations
  – Master station analyses all the measurements and transmits the actual position to each of the satellites
Range sensors

- Large range distance measurement → called range sensors.
- Range information is the key element for localization and environment modeling.
- Ultrasonic sensors, infra-red sensors and laser range sensors make use of propagation speed of sound or electromagnetic waves respectively.
- The distance traveled by a sound or electromagnetic wave is given by

\[ d = c \cdot t \]

- Where:
  - \( d \): distance traveled (usually round-trip)
  - \( c \): speed of wave propagation
  - \( t \): time of flight.

Ultrasound (sonar) sensor

- Transmit a packet of (ultrasonic) pressure waves
- Distance \( d \) of the echoing object can be calculated based on the propagation speed of sound \( c \) and the time of flight \( t \).

\[ d = \frac{c \cdot t}{2} \]

- The speed of sound \( c \) in air (343 m/s) is given by:

\[ c = \sqrt{\gamma \cdot R \cdot T} \]

where:

- \( \gamma \): ratio of specific heats
- \( R \): gas constant
- \( T \): temperature in degrees Kelvin
Sonar timing

What gets measured

- Sound beam propagates in a cone.
- Opening angles around 20 to 40 degrees
- Detects regions of constant depth on segments of an arc

- Piezo electric transducer generates frequency: 40 – 180 kHz
**Typical sonar scan**

- Specular reflection from non-perpendicular surfaces.
- Absorption from soft surfaces.
- Note that in places the result is far from accurate.

**Laser range finder**

- A laser range-finder uses light rather than sound.

*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

- The rotating mirror allows the laser to take many measurements.
• Resolving picoseconds is very expensive, and surface with roughness > wavelength of the incident light causes diffusion, so the easier method is to measure phase shift of amplitude-modulated light.

• For any wave, speed is related to frequency and wavelength by: 
  \[ c = f \cdot \lambda, \]
  if modulating \( f = 5 \text{MHz} \), then \( \lambda = 60\text{m} \) (light speed = 300Mil m/s)

\[ \lambda = \frac{c}{f} \]

- The total distance covered by the light is:
  \[ \text{distance} = L + 2D = L + \frac{\theta \lambda}{2\pi} \]

- The distance of the target is then:
  \[ D = \frac{\lambda \theta}{4\pi} \]

where \( \theta \) is the phase shift in radian. If \( \theta \) is \( 2\pi \) then the distance is \( \lambda / 2 \) – “ambiguity interval”, so the range of the sensor must be lower than that.

• Length of bars is an estimate of the error.
Distance is inversely proportional to $x$

$$D = \frac{fL}{x}$$

State of the art

- Hokuyu manufacture a cheap laser scanner.
- The Kinect has made accurate range-finder data much cheaper to acquire.
Vision

• Vision is the sense that humans rely upon most.
• It provides the means to gather lots of data very quickly.
• Attractive for use on robots which are often data-poor.
• However, presents a new challenge
  – How can we extract data from an image
  – Or from a sequence of images.

Cameras

• Today, with cheap CMOS cameras, the hardware cost of adding a camera to a robot is negligible.
• Although vision seems to be easy for humans, it is hard for machines.
  (as always, remember how long it takes us to learn to “see”).
• Reasons include:
  – variable illumination,
  – uncontrolled illumination,
  – shadows,
  – irregular objects,
  – occlusion of objects,
  – noisy sensors,
  – …
• Typically these problems are worse outside.

• The lens produces a *perspective projection* of the scene.
• The 3-d scene becomes a 2-d image:
  \[ I(x, y, t) \]
  \( x \) and \( y \) are the co-ordinates of the array, \( t \) is time.
• The image is just an array.
• Well, typically 3 arrays — each with one entry per pixel in the image.
  – Why?
• These must be processed to extract the information that we need.
Problems in processing

• The projection from 3D to 2D introduces massive ambiguity.

• What the camera sees in one view can be generated by many different scenes.
Vision techniques

• We will look briefly at a couple of basic computer vision techniques.
• These don’t come close to solving the general vision problem.
  – Nobody has come close to solving that.
• However, they give us some ways to extract data that can help our robots in some domains.
• Where we know what to expect, we can look for it.

Color segmentation

• An image is a two dimensional array of pixels.
• Each pixel is a set of three values:

  \[(red, green, blue)\]

  typically with a value between 0 and 255 (8 bit).
• (Well, most computer vision uses something other than RGB, but the principle is the same.)
• Define a color you want to recognise as a box in RGB space:

  \[
  \begin{align*}
  red & \in [30, 100] \\
  blue & \in [70, 120] \\
  green & \in [150, 230]
  \end{align*}
  \]

  Label each pixel 1 if it falls in the box, 0 if it falls outside the box.
• Result is a set of “blobs” which, if you calibrated correctly, identify objects of interest.

• Example: segmentation in robot soccer

What you can do with a segmented image

• Object identification:
  – “I see an orange blob” means “I see the ball”.

• Object tracking:
  – Keep the orange blob in the center of the frame.

• Limited navigation:
  – Walk towards the orange blob.
  – When you get to the orange blob, kick it towards the blue blob.

• Localization.
  – Measure angles of blue and yellow blobs to me.
  – If I know the location of the blobs, I can tell where I am.
Works well enough for some applications

Edge detection

- We often want to identify edges.
- We can then use the edges to identify shapes that we are looking for in an image.
- What we do has a mathematical interpretation in terms of convolution, but there’s also a simple way to think about this.
- Edges are all about changes in color (in a color image) or intensity (in a black and white image).
- So identifying pixels that are on an edge is relatively easy.
  - We look for sudden changes in R, G and B in a color image or the single value in a b/w image.
• Gives us something like:

• Often edge detection gives us many mini-edges that need to be merged or removed:
• Pre-processing the image can also help.
• For example, noise can be removed by *smoothing* the image.
  – Averaging across the pixel values.
• For example we might replace the value of every pixel by the average of the values of the 8 pixels around it.
• The larger the area we average over, the more robust the results are against noise.
• They also lose more information (see [http://nskye.com/](http://nskye.com/)).
• Of course, all this processing is expensive, and slows down the speed of reaction of the robot.

**Stereo vision**

• Two cameras, spaced as widely as possible.
• Can get depth information if we can identify the common point(s) in two images.
\[ x = b \left( \frac{x_l + x_r}{2(x_l - x_r)} \right) \]
\[ y = b \left( \frac{y_l + y_r}{2(x_l - x_r)} \right) \]
\[ z = b \left( \frac{f}{x_l - x_r} \right) \]

- The accuracy of the depth estimate increases with increasing baseline \( b \).

**Using stereo vision**

- Also equipped with several other sensors.
• Omnidirectional cameras allow robots to see all around them.
  – Usually mounted with the lens above the camera.

• Presents new challenges in machine vision.
Summary

• This lecture discussed perception, how the robot views its world.
• This means sensors.
• We looked at a range of different sensor types.
  – Including range sensors
• In particular we looked at cameras, and that led to a discussion of some simple techniques from computer vision.