Perception, Part 1
Sensors and Ranging

Computer Science 4766/6912

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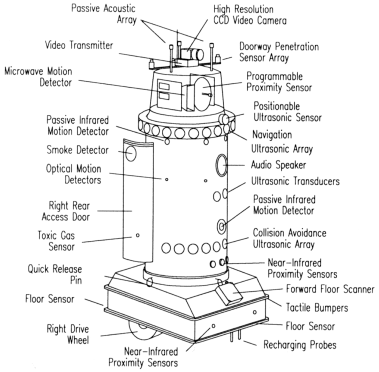


BIBA Robot, BlueBotics SA

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 respose 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

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Tactile sensors (detection of physical contact or closeness; security switches)	Contact switches, bumpers Optical barriers Noncontact proximity sensors	EC EC EC	P A A
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders Potentiometers Synchros, resolvers Optical encoders Magnetic encoders Inductive encoders Capacitive encoders	PC PC PC PC PC PC PC	P P A A A A A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass Gyroscopes Inclinometers	EC PC EC	P P A/P

A, active; P, passive; P/A passive/active;

PC proprioceptive; EC exteroceptive

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

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 V / 255 $\approx$ 20 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:* $error = m - v$, where m is measurement and v is the true value
- *Accuracy:* Degree to which measured values are correct,

$$accuracy = 1 - \frac{|error|}{v}$$

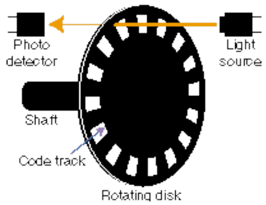
- *Precision:* Degree to which measured values agree,

$$precision = \frac{range}{\sigma}$$

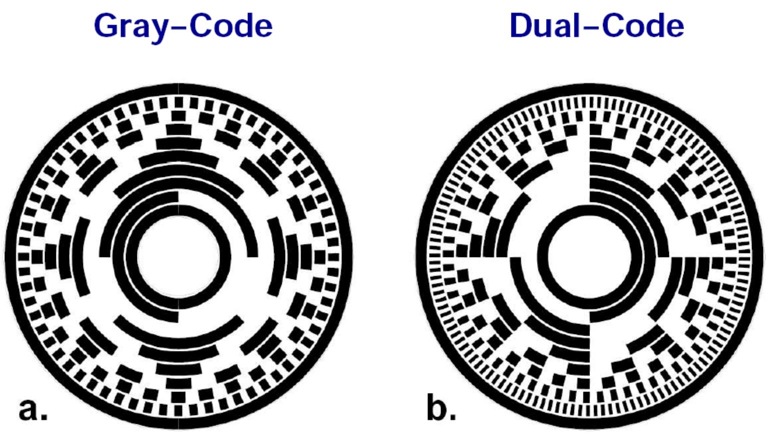
where σ is the standard deviation of the sensor's random error

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

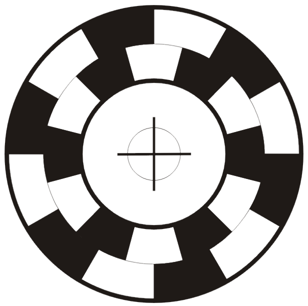


Absolute encoders require one photo-emitter / detector pair per bit of position resolution; Shown below are two common types of code disks

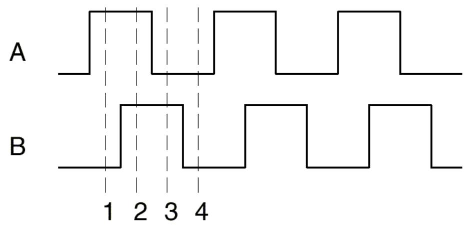


The dual-code disk is straight binary; The gray-code disk has the advantage that only one bit changes at a time

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°; 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')

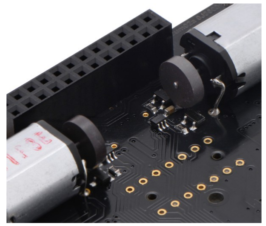


State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

- 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



Heading Sensors

- **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 → generally unsuitable for indoor environments

Global Positioning System (GPS)

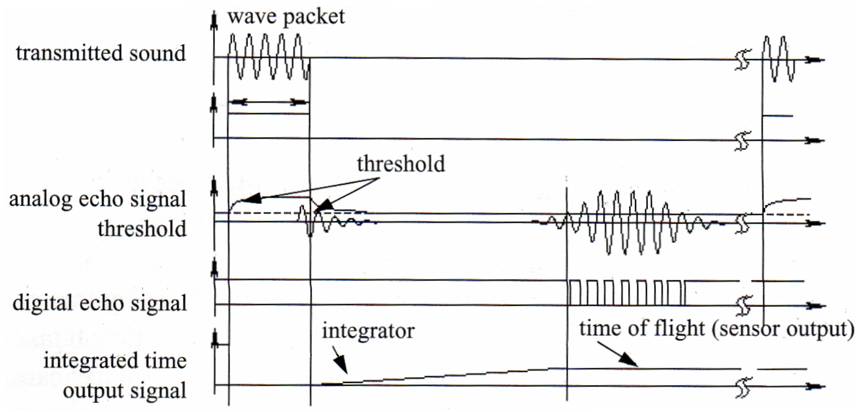
- GPS was developed for use by the US military, but is now also available for civilian use
- 24+ satellites orbiting the planet in six planes inclined at 55° to the equator
- Each satellite transmits...
  - Time (measured by atomic clock)
  - Its position and the positions of all other GPS satellites
- 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

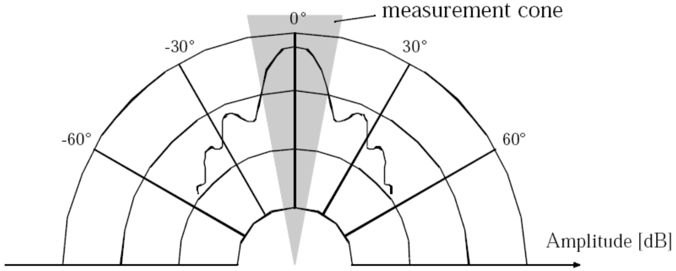
- An ultrasonic sensor transmits a high-frequency sound packet and measures the time it takes for the sound to rebound back to the sensor
- The time of flight, t, along with the speed of sound, c, give the distance,

$$d = \frac{c \cdot t}{2}$$

  we need the division by two because the sound actually travels twice as far as the distance we wish to measure
- $c = 343 m/s$ 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

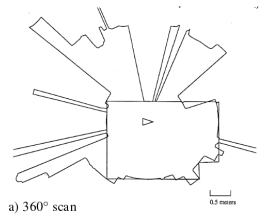


- The sound propagates in the shape of a cone
  - Opening angle $20^\circ - 40^\circ$
  - Obtain the depth of regions, as opposed to points



Disadvantages:

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

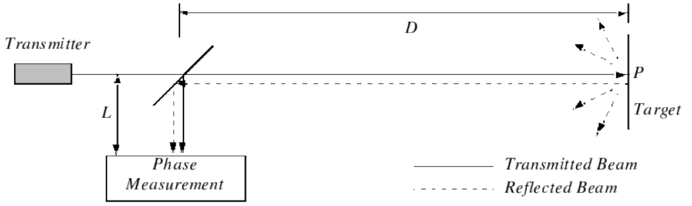


- Some materials simply absorb the sound (e.g. foam or cloth) and therefore are reported to be at the maximum range
- Bandwidth:
  - Single sensor: To allow time to detect object at 12 m, requires 70 ms $\rightarrow$ 14.3 Hz
  - 20 sensors: Apply each in sequence to avoid interference, requires 20 * 70 ms $\rightarrow$ 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 ≈ 0.3 m / ms; Speed of light ≈ 0.3 m / 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

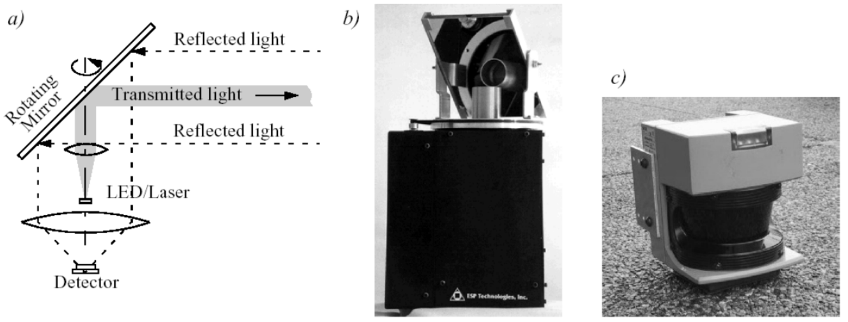
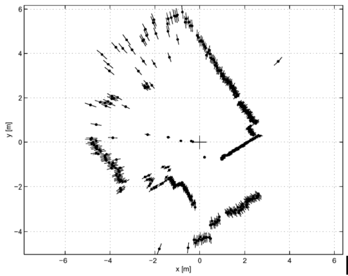


Figure 4.11
(a) Schematic drawing of laser range sensor with rotating mirror; (b) Scanning range sensor from EPS Technologies Inc.; (c) Industrial 180 degree laser range sensor from Sick Inc., Germany

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



Line length ≡ uncertainty

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