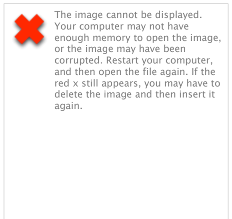
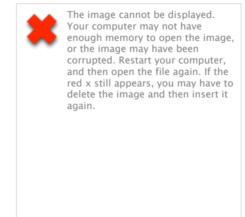
Sensing 2
Error

Many slides adapted from slides © R. Siegwart, ETH Zürich – Autonomous Systems Laboratory

Bookkeeping



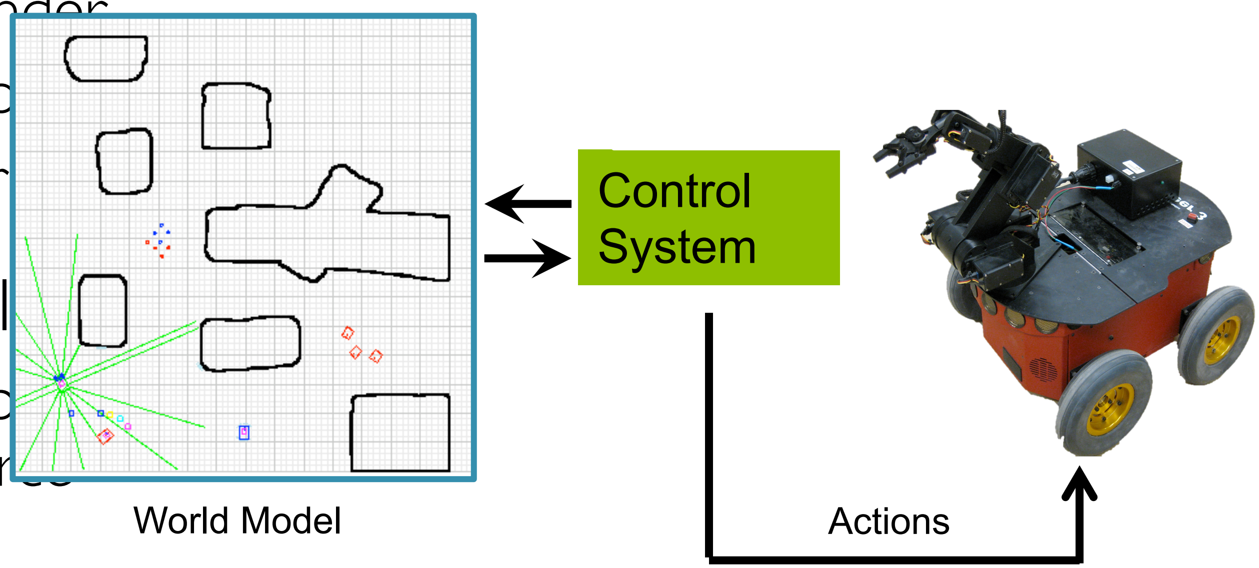
- Today
  - Quiz answers, quickly.
    - Pick up after class, discuss no sooner than tomorrow.
  - Assignment 1
    - http://tiny.cc/robotics-assignment
  - Group stuff
- Read SNS 4.2.1 – 4.2.3 (p. 142-159)



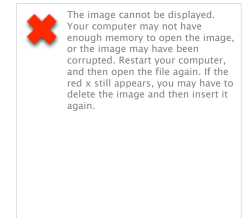
Quiz

- Active or passive?
  - Camera
  - Sonar
  - Microphone
  - Laser range-fin
  - E-field detecto
  - Thermometer
- What is compl
  - Motion in resp
    to external for

- Open vs. closed loop
  - Open: **no** feedback
  - Closed loop: feedback



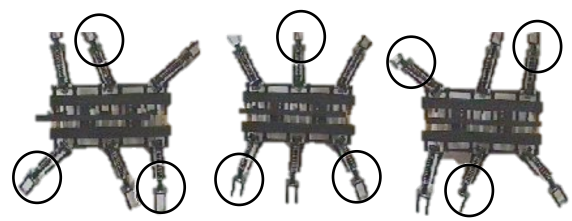
Quiz



- Gaits per leg?
  - What's a gait?
  - Distinct sequence of lift and release events of legs
- Number of possible events N with k legs is:

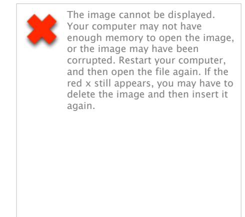
  N = (2k - 1)!

- Static/dynamic/passive walking
  - Passive: gravity
  - Static: always stable
  - Dynamic: energy to stabilize

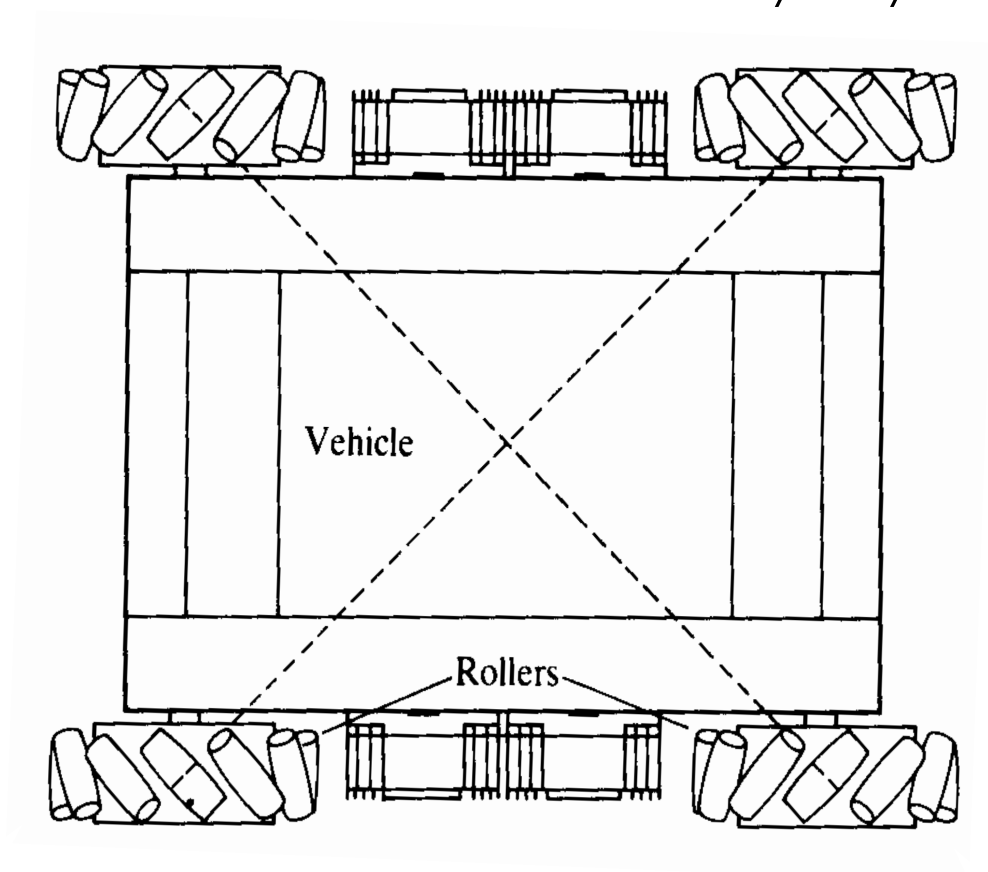


- Efficiency
  - Versus energy use
  - How do systems lose energy without furthering their goals?

Omni Wheels



- Omni wheels and directions: sideways by turning…



https://www.youtube.com/watch?v=o-j9TReI1aQ

Wheels

https://www.youtube.com/watch?v=o-j9TReI1aQ

Bookkeeping

- Lecture
  - Sensors to know about
  - Representing uncertainty
  - Cameras pt. I
- Read SNS 4.2.1 – 4.2.3 (p. 142-159)

Classification of Sensors

- Range
- Resolution
- Linearity
- Proprioceptive vs. exteroceptive
- Active vs. passive
- Incremental vs. absolute
- Sensitivity
- Cross-sensitivity
- Bandwidth
- Precision
- Accuracy and error

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Error and Accuracy

- Error
  - Difference between sensor output and true value

$$error = m\text{-}v \quad \begin{cases} m = measured\ value \\ v = true\ value \end{cases}$$

- Accuracy: unitless measure

error

$$\left(accuracy = 1 - \frac{|m - v|}{v}\right)$$

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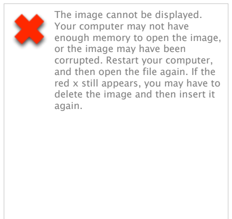
Characterizing Error

- Robots have to continuously perceive, analyze and interpret the state of their surroundings, *but*
- Measurements in real world: dynamic and error prone
- Examples:
  - Changing illuminations
  - Specular reflections
  - Light or sound absorbing surfaces
  - Cross-sensitivity of robot sensor to robot pose, robot-environment dynamics
    - Rarely possible to model → appear as random errors
    - Errors and can be well defined in lab – not in the real world

Error Modeling

- Systematic error → deterministic failures
  - Caused by factors that can (in theory) be modeled
    - So, *should* be predictable
  - Calibration of a laser sensor
  - Optic distortion for a particular camera
- Random error → non-deterministic failures
  - No modeling or prediction possible
  - However, can be *described* probabilistically
  - Black level noise of camera
  - Background sound for microphone

Precision (But Not Recall)

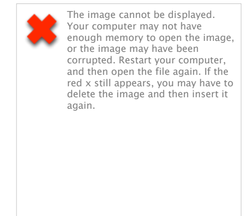


- Precision
  - Reproducibility of sensor results
- A distribution of error can be characterized by:
  - Mean error: **μ**
  - Standard deviation: **σ**
  - How similar are two outputs from same test?
    - Same sensor, same environment …

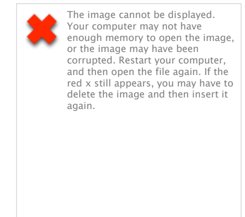
$$precision = \frac{range}{\sigma}$$

- Has other meanings in actuation *and* cognition

Error and Uncertainty

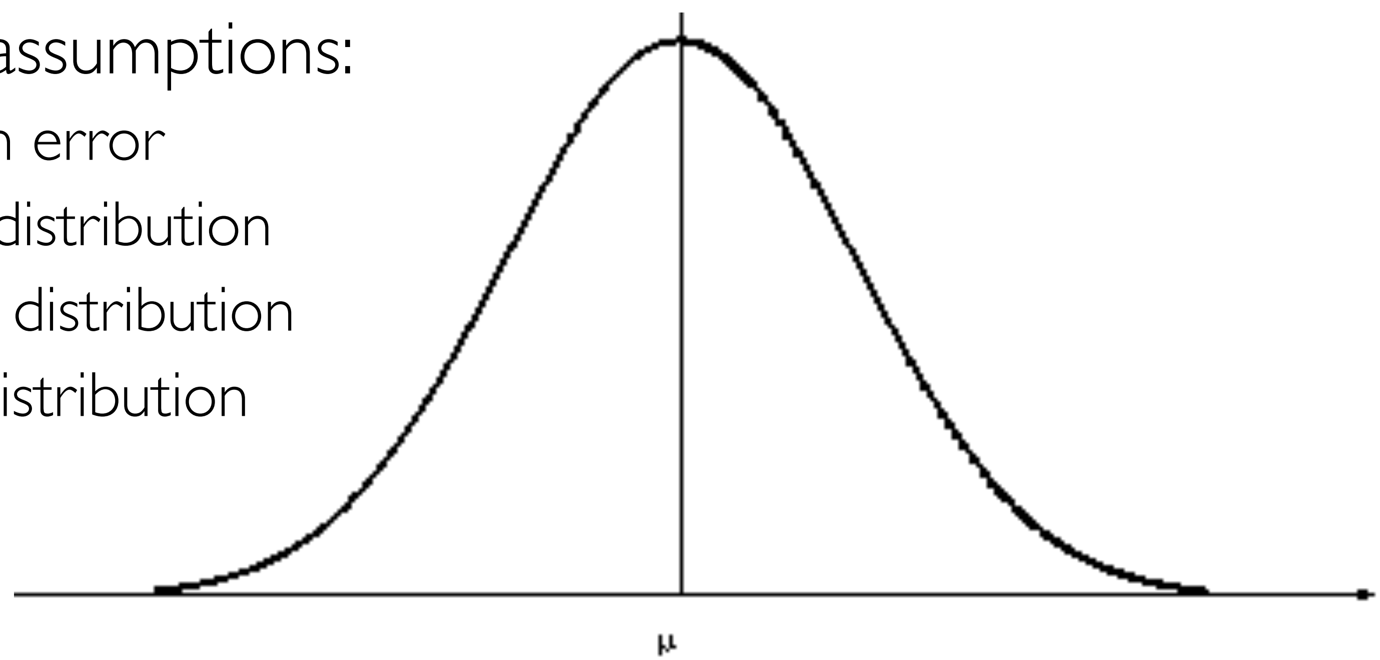


- Sensing is *always* related to uncertainty.
  - What are the sources of uncertainties?
  - How can uncertainties be represented / quantified?
  - How do they propagate?
    - Uncertainty of a function of uncertain values?
  - How do uncertainties combine if different sensor reading are fused?
  - What is the merit of all this for mobile robotics?



Error Distributions

- Random errors: behavior of sensors modeled by some probability distribution
- Causes and behavior of error usually unknown
  - So what do we do?
- Simplifying assumptions:
  - Zero-mean error
  - Unimodal distribution
  - Symmetric distribution
  - Gaussian distribution



Simplifying Assumptions

- Important to remember assumptions are wrong!

Examples

- Sonar (ultrasonic) sensor might overestimate distance in real environment
- Is therefore not symmetric
  - Might be better modeled by two modes:
    - Mode for the case that the signal returns directly
    - Mode for the case that the signals returns after reflections
- Stereo vision system might not correlate to images
  - Results that make no sense at all!

Uncertainty Representation

- Some definitions:
  - Sensitivity: G = out/in
  - Resolution: Smallest detectable change
  - Dynamic Range: $value_{max}$/ resolution (10^4 - 10^6)
  - Accuracy: $error_{max}$ = (measured value) - (true value)

- Errors are usually unknown:

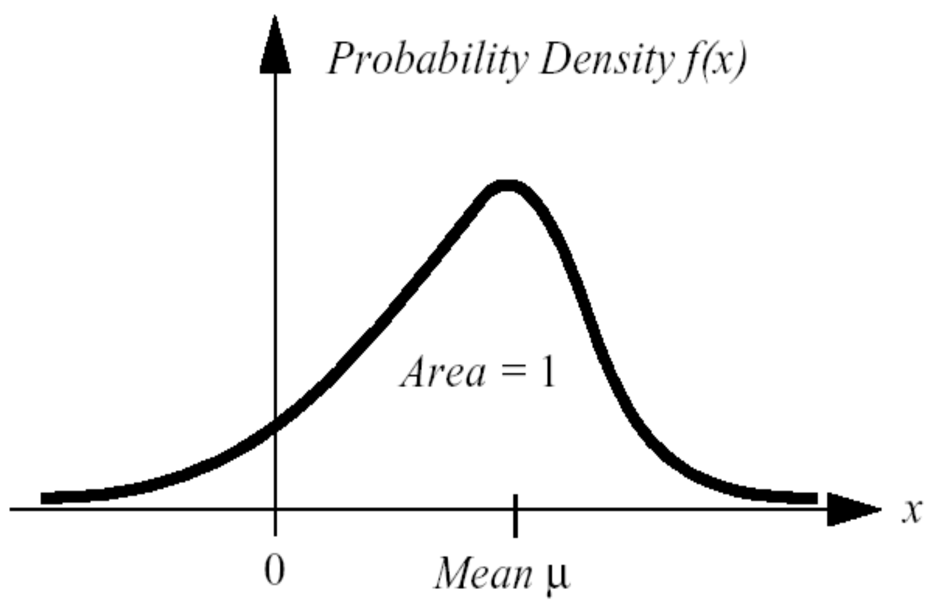
Deterministic ⟷ Non-deterministic (random) delete the image and then insert it again.

Representing Uncertainty

- Sensing as estimation problem:

$$\textit{true (unknown) error} = X$$
$$\textit{estimate of error} = E[X]$$

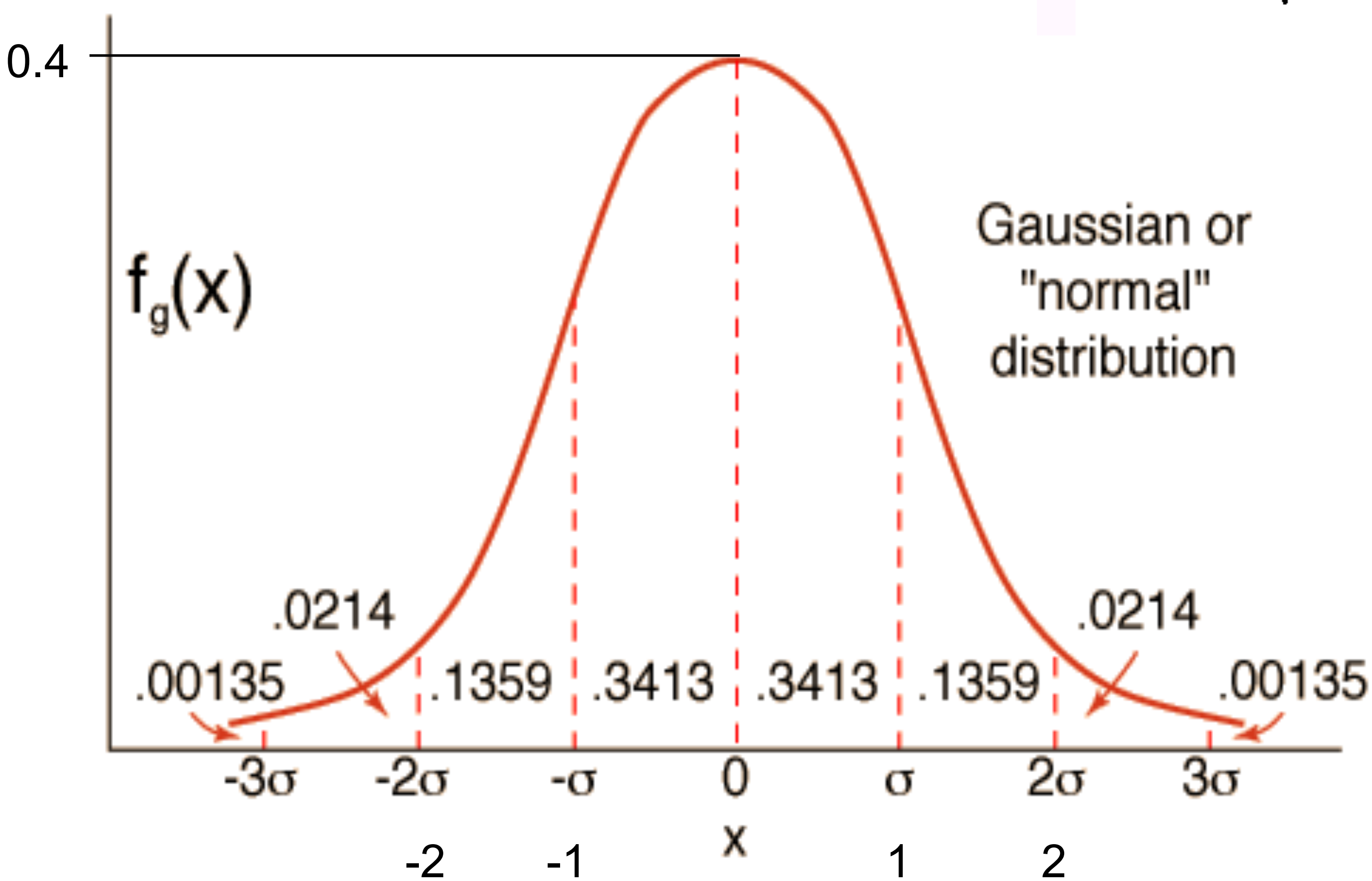
- Given n measurements with values : $\sigma_{[1\text{-}n]}$



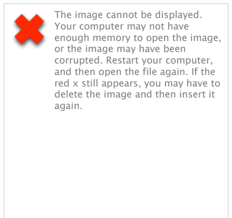
Gaussian Distribution

$\mu = 0$ and $\sigma = 1$

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

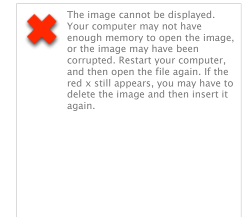


Wheel / Motor Encoders

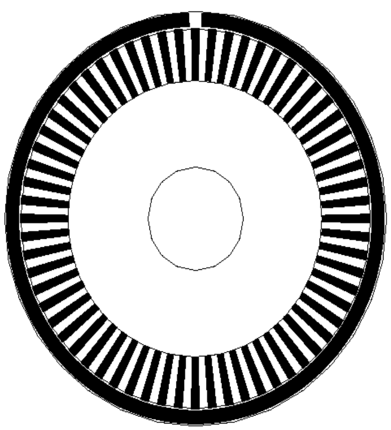


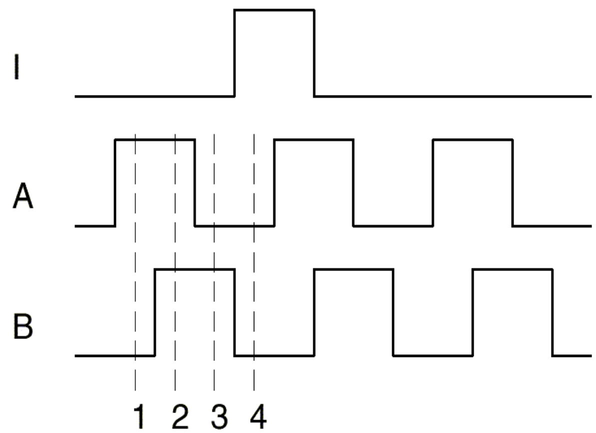
- Measure position or speed of the wheels or steering
- Wheel movements can be integrated to get an estimate of position: *odometry*
  - Terminology check: this is a type of…
- Optical encoders are proprioceptive sensors
  - Position estimation in relation to a fixed reference frame
  - Only good for short movements
    - Why?
- Typical resolutions: 2000 increments per revolution
  - For higher resolution: interpolation

Encoders



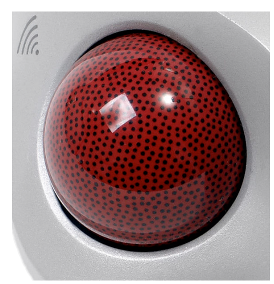
- Wheel and motor (and usually joint) encoders:



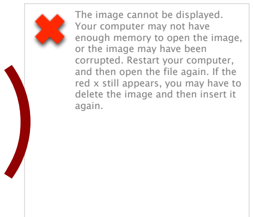


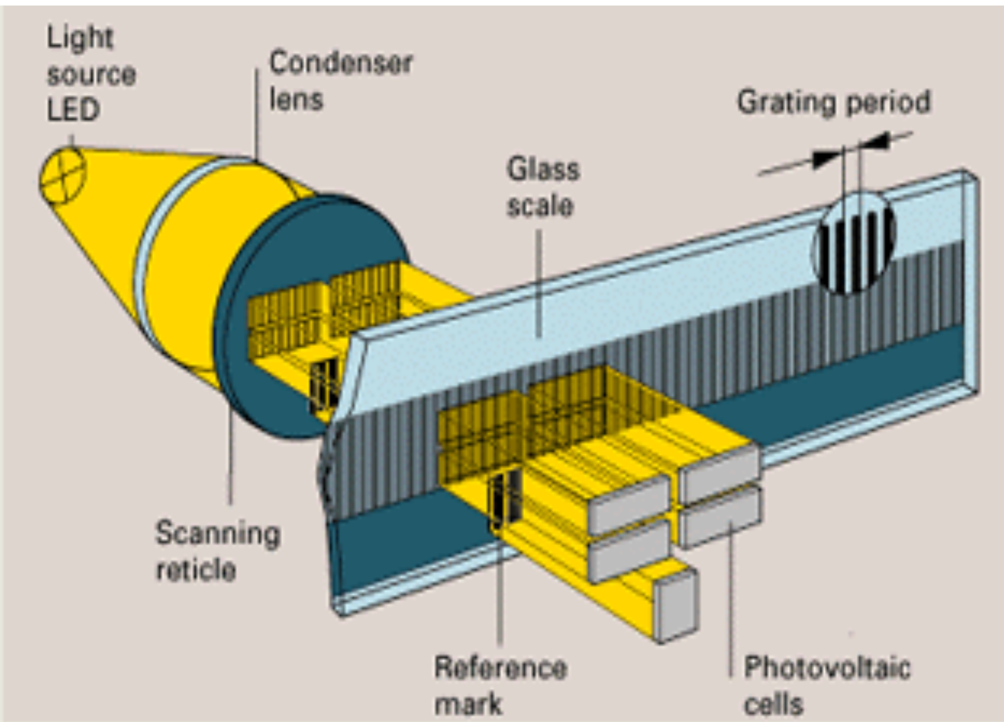
State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

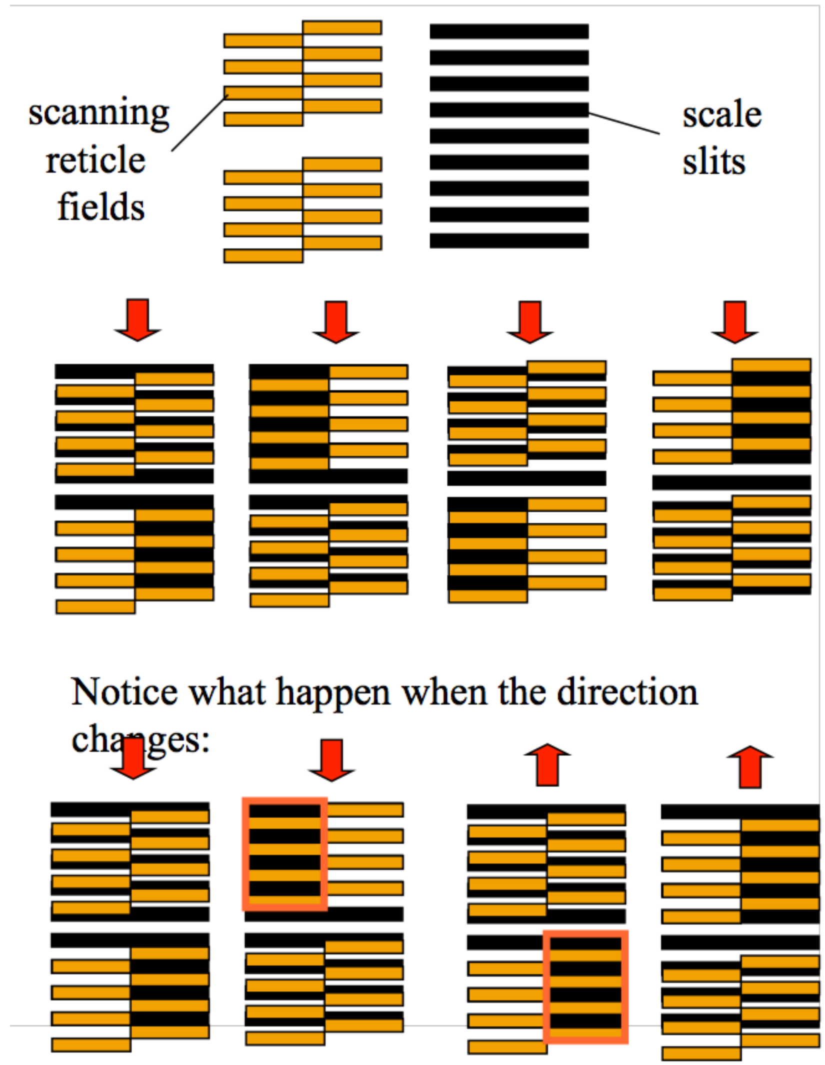
- Basically same as optical mice/trackballs/etc:



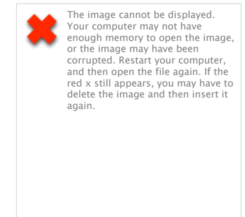
Wheel / Motor Encoders (2)







Heading Sensors



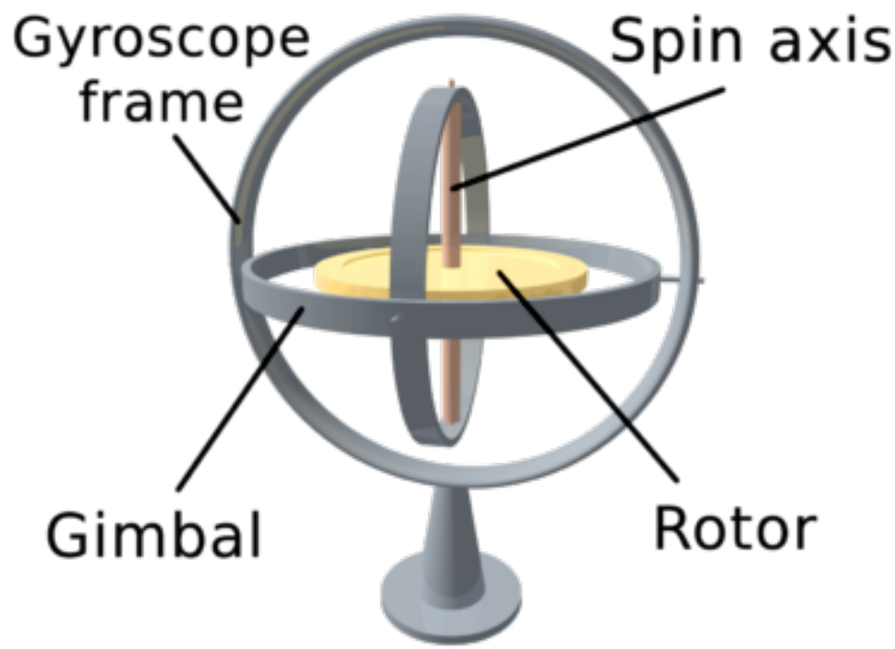
- Heading (direction wrt. some frame of reference)
  - Estimate robot's orientation + inclination
- Heading + approximate velocity:
  - Integrate the movement to position estimate
  - This procedure is called *dead reckoning* (ship navigation)
- Proprioceptive
  - Gyroscope, inclinometer
- Exteroceptive
  - Compass, sundial

Compasses

- Used since at least 2000 B.C.
  - Chinese suspended a piece of magnetite from a silk thread
  - Absolute measure for orientation
- Many solutions to measuring Earth's magnetic field
  - Mechanical magnetic compass
  - Direct measure of the magnetic field (Hall-effect, magnetoresistive sensors)
- Major drawbacks:
  - Weakness of the earth field
  - Easily disturbed by magnetic objects or other sources
    - Not feasible for indoor environments

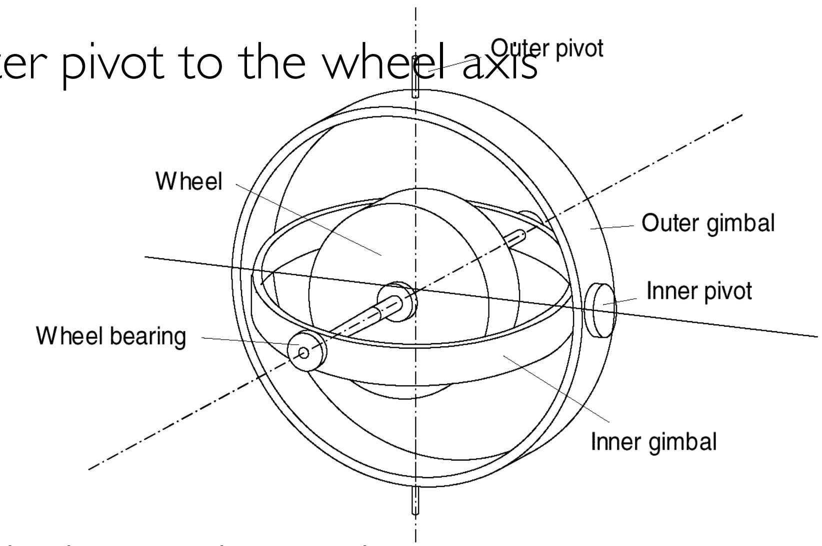
Gyroscope

- Heading sensors that keep *orientation* wrt. a fixed frame
  - Absolute measure of heading of a mobile system
- Two categories, the mechanical and the optical gyroscopes
  - Mechanical Gyroscopes
    - Standard gyro
    - Rated gyro
  - Optical Gyroscopes
    - Rated gyro



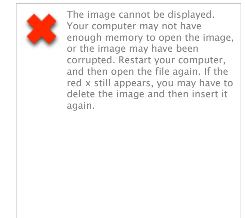
Mechanical Gyros

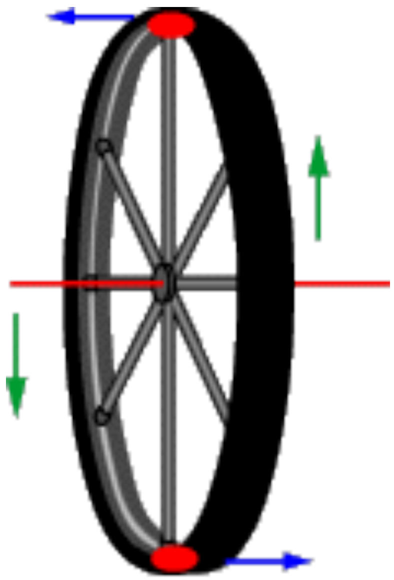
- Concept: inertial properties of a fast spinning rotor
  - "Gyroscopic precession"
- Angular momentum associated with a spinning wheel keeps the axis of the gyroscope inertially stable.
- Reactive torque t (tracking stability) is proportional to spin speed, precession speed and wheel inertia
- No torque can be transmitted from the outer pivot to the wheel axis
- Quality: 0.1° in 6 hours
- If the spinning axis is aligned with the north-south meridian, the earth's rotation has no effect on the gyro's horizontal axis



- If it points east-west, the horizontal axis reads the earth rotation

Mechanical Gyroscopes





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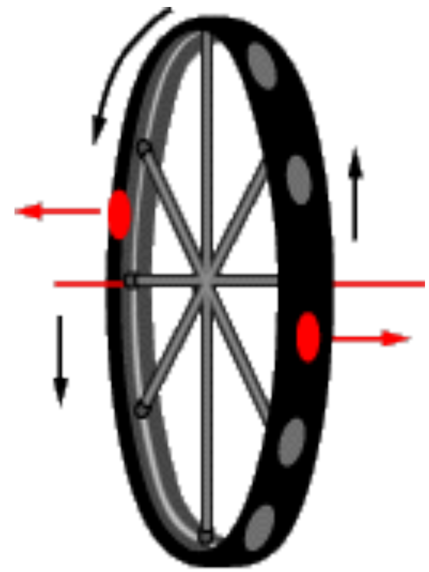

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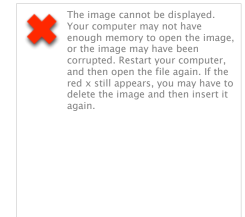
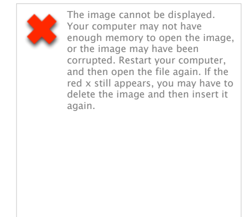
Newton's First Law: Every object in a state of uniform motion tends to remain in that state of motion unless an external force is applied to it.

Optical Gyroscopes

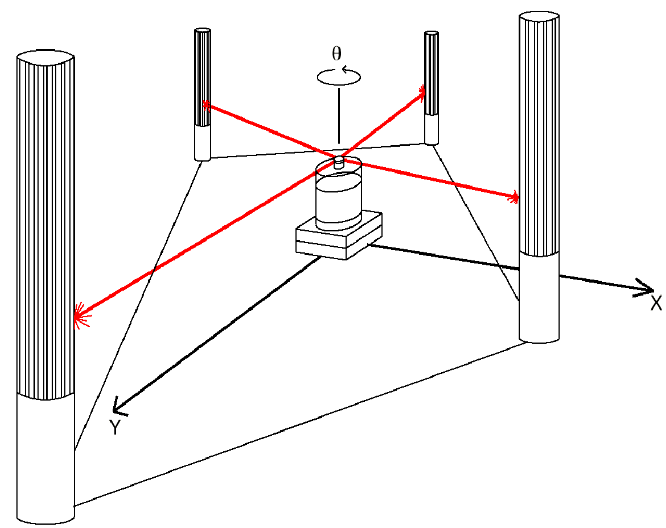


- First commercial use: 1980's on airplanes
- Optical gyroscopes
  - Angular speed (heading) sensors using two laser beams from same source
- One is traveling in a fiber clockwise, the other counterclockwise around a cylinder
- Laser beam traveling in direction of rotation
  - Slightly shorter path → shows a higher frequency
  - difference in frequency Δf of the two beams is proportional to the angular velocity Ω of the cylinder
- There are solid-state variants!

Ground-Based Beacons



- Beacons: guiding devices with precisely known position
- Active or passive
  - Do they signal, or are they detectable?
- Beacons used since the humans started to travel
  - Natural beacons (landmarks) like stars, mountains or the sun
  - Artificial beacons like lighthouses
- Major drawback:
  - Require instrumenting environment!
    - Costly
    - Limits flexibility and adaptability to novel or dynamic environments



Global Positioning System

- 24 satellites (including three spares)
  - orbiting the earth every 12 hours at a height of 20.190 km
  - Four in each of six planes inclined 55° wrt. earth's equator
  - Location of any GPS receiver is determined through a 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

GPS

4.1.5

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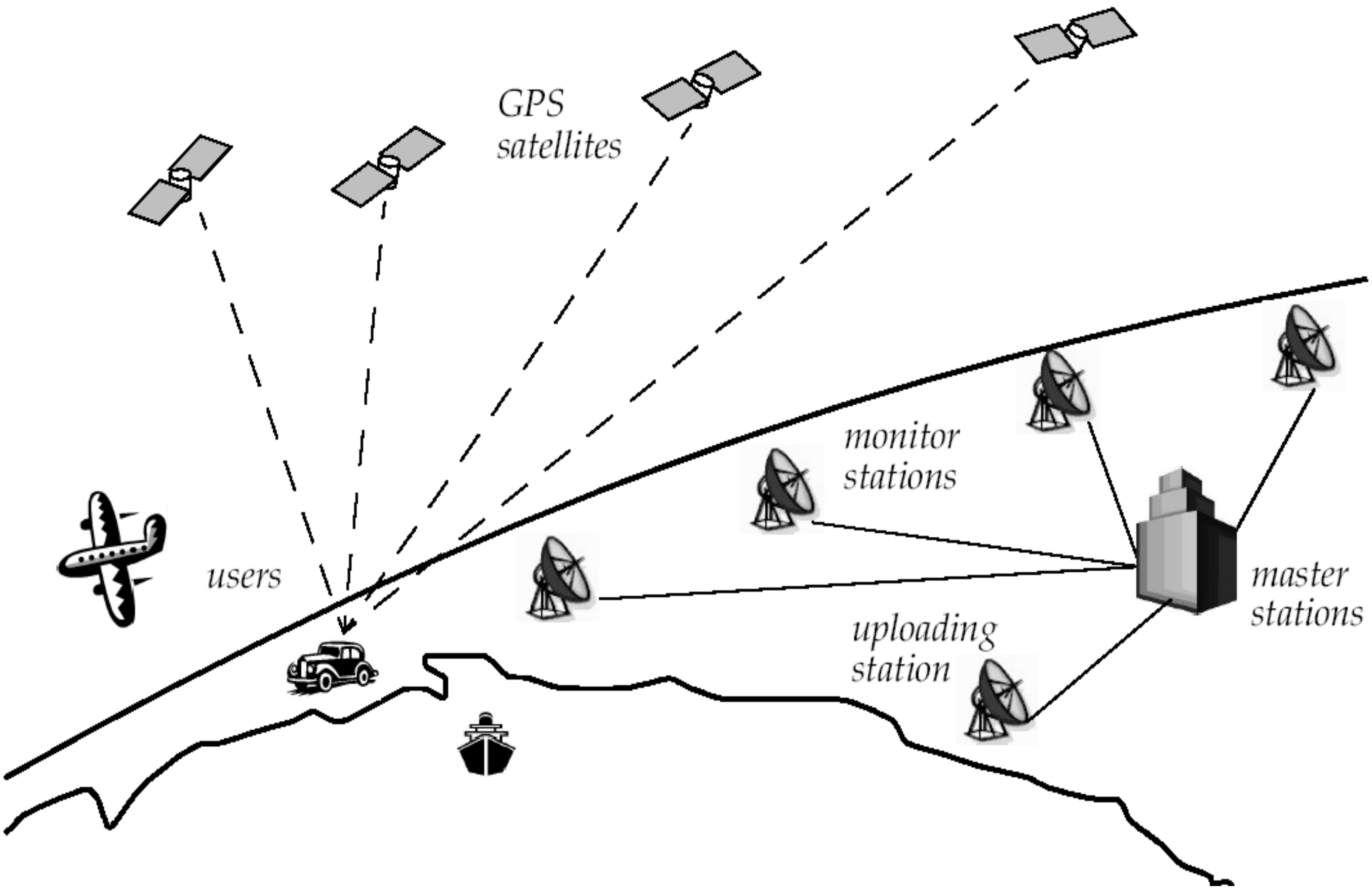
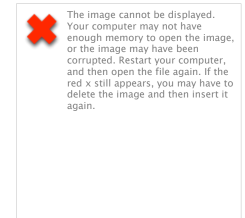


GPS



- Time synchronization:
  - Atomic clocks on each satellite
  - Monitoring them from different ground stations
- Real time update of exact location of satellites:
  - Master station analyses all measurements, transmits the actual position to each satellite
- Ultra-precise time synch extremely important
  - Electromagnetic radiation propagates at light speed
    - Roughly 0.3 m per nanosecond
  - Position accuracy proportional to precision of time measurement

GPS

4.1.5

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- Exact measurement of the time of flight
  - Receiver correlates a code with same code from satellite
  - Delay time for best correlation represents time of flight
  - Quartz clock on the GPS receivers are not very precise
    - Range measurement with four satellites allows three position values (x, y, z) and clock correction ΔT to be calculated
- Recent commercial GPS receiver devices allows position accuracies down to a couple meters.