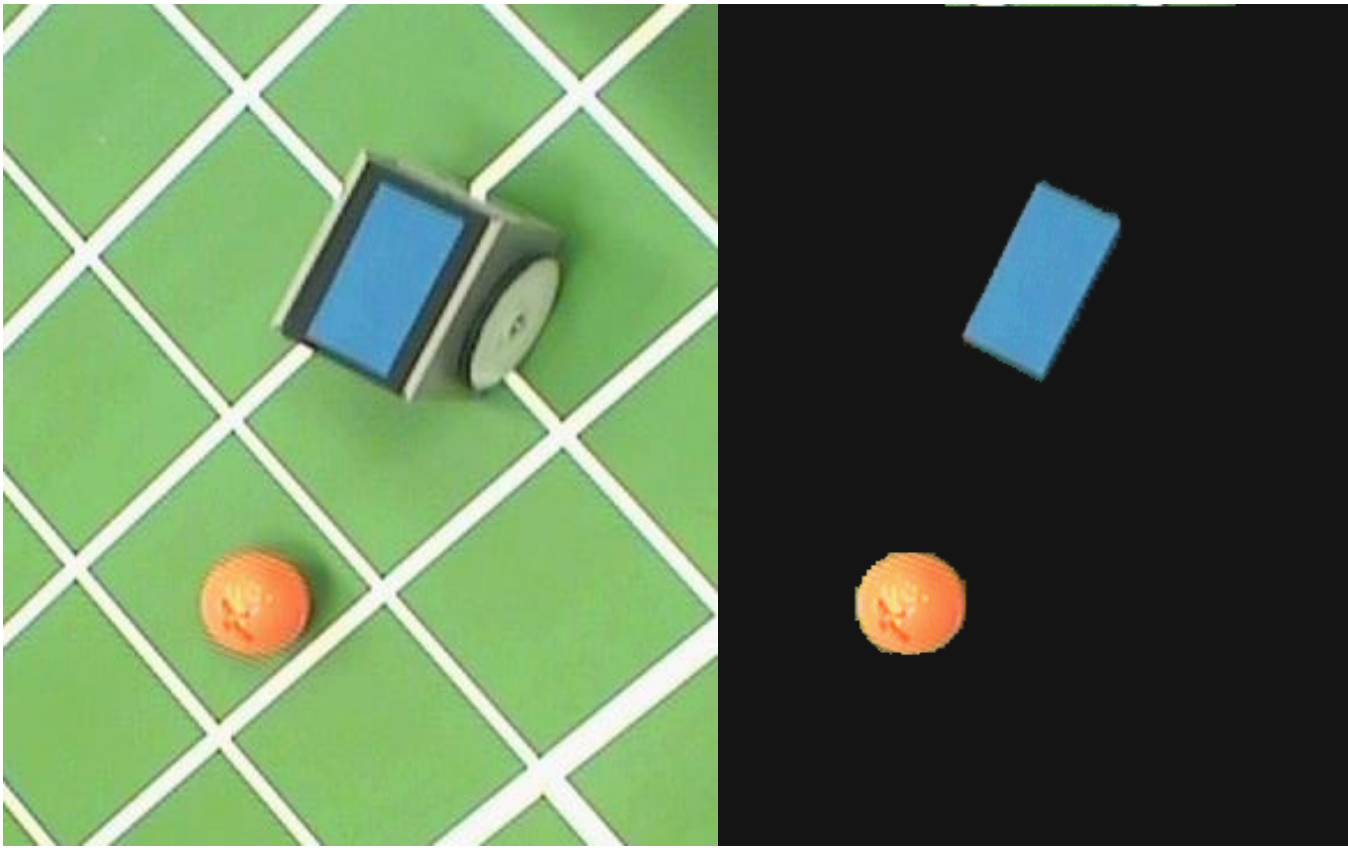
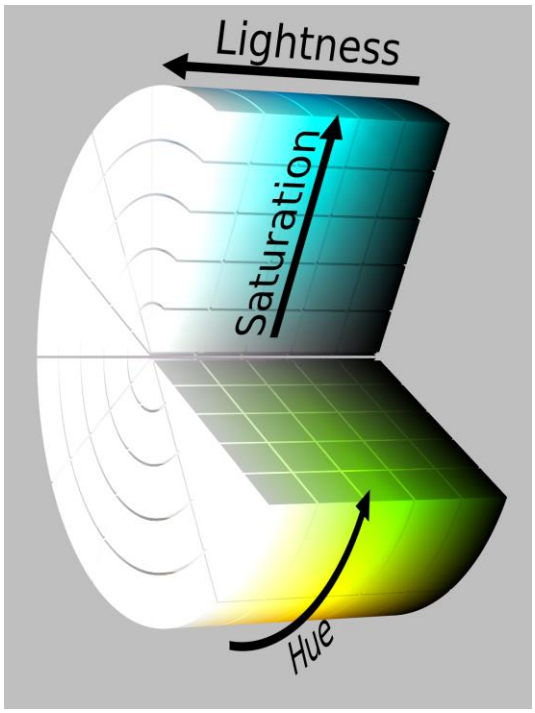
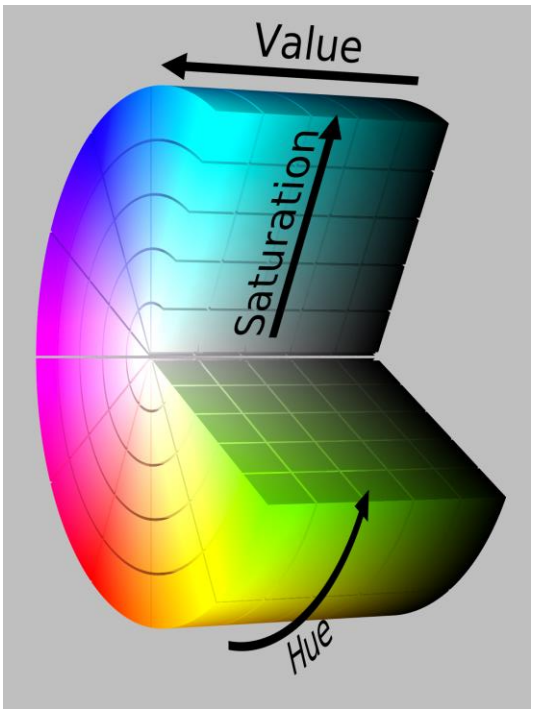



Lightness
Saturation
Hue


Value
Saturation
Hue

Brainstorm

- In addition to cameras / Kinect, what other kinds of sensors would be useful?

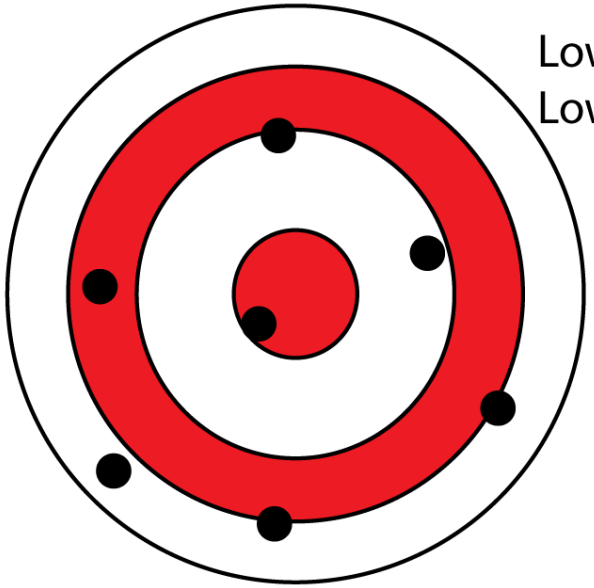
How do you evaluate different sensors?

Brainstorm

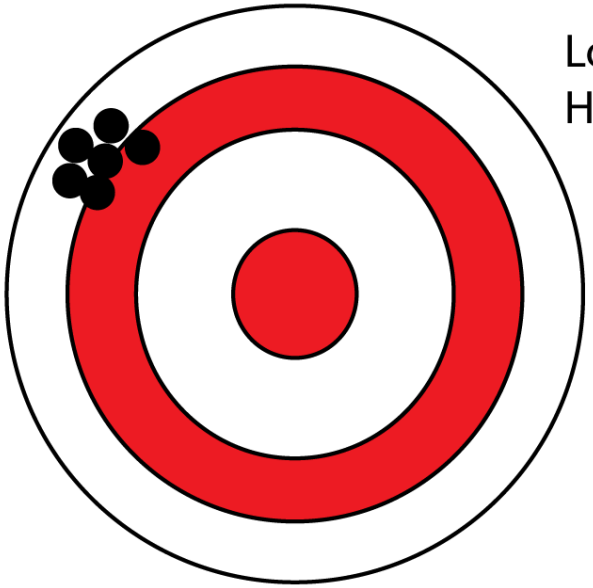
- In addition to cameras / Kinect, what other kinds of sensors would be useful?

haptic
heat
altimeter
gyroscope,
accelerometer

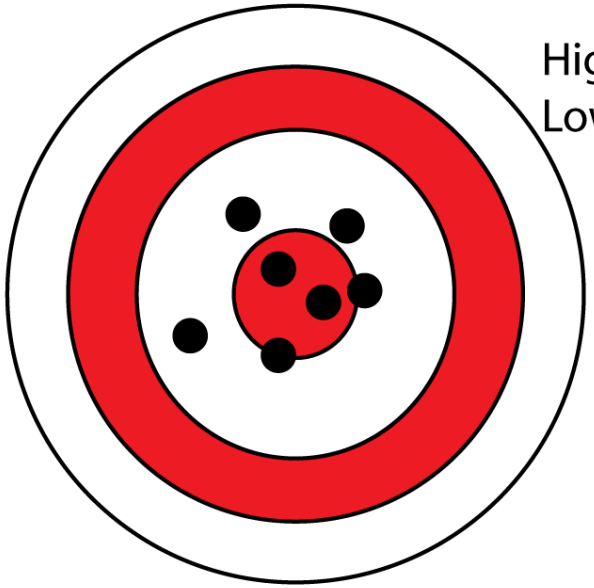
biometric
GPS
Temp



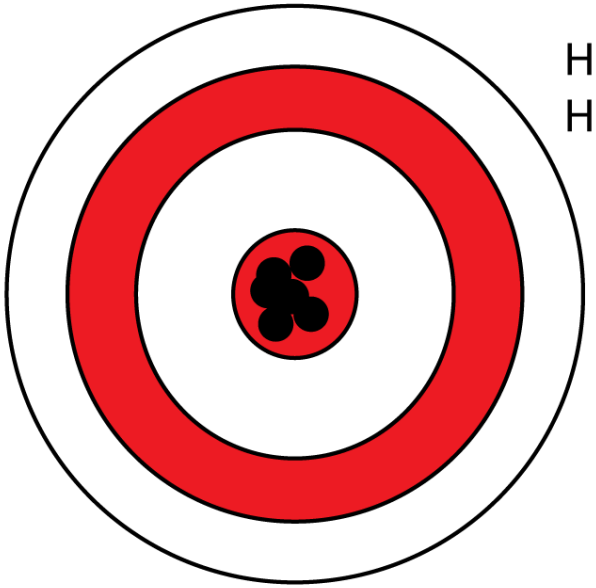
Low accuracy
Low precision



Low accuracy
High precision



High accuracy
Low precision



High accuracy
High precision

Classification of Sensors

- Proprioceptive sensors
  - measure values internally to the system (robot),
  - e.g. 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 proper energy and measure the reaction
  - better performance, but some influence on envrionment

Characterizing Sensor Performance (1)

Measurement in real world environment is error prone

- Basic sensor response ratings
  - Dynamic range
    - ratio between lower and upper limits, usually in decibels (dB, power)
    - e.g. power measurement from 1 Milliwatt to 20 Watts

$$10 \cdot \log\left[\frac{20}{0.001}\right] = 43dB$$

    - e.g. voltage measurement from 1 Millivolt to 20 Volt

$$20 \cdot \log\left[\frac{20}{0.001}\right] = 86dB$$

    - 20 instead of 10 because square of voltage is equal to power

  - Range
    - upper limit

Characterizing Sensor Performance (2)

- Basic sensor response ratings (cont.)
  - Resolution
    - minimum difference between two values
    - usually: lower limit of dynamic range = resolution
    - for digital sensors it is usually the analog-to-digital conversion
      - e.g. 5V / 255 (8 bit)
  - Linearity
    - variation of output signal as function of the input signal
    - linearity is less important when signal is after treated with a computer
  - Bandwidth or Frequency
    - the speed with which a sensor can provide a stream of readings
    - usually there is an upper limit depending on the sensor and the sampling rate
    - Lower limit is also possible, e.g. acceleration sensor

In Situ Sensor Performance (1)

- Sensitivity
  - ratio of output change to input change
  - however, in real world environment, the sensor has very often high sensitivity to other environmental changes, e.g. illumination
- Cross-sensitivity
  - sensitivity to environmental parameters that are orthogonal to the target parameters (e.g., compass responding to building materials)
- Error / Accuracy
  - difference between the sensor's output and the true value

m = measured value
v = true value

error

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

In Situ Sensor Performance (2)

Characteristics that are especially relevant for real world environments

- Systematic error ➔ deterministic errors
  - caused by factors that can (in theory) be modeled ➔ prediction
- Random error ➔ non-deterministic
  - no prediction possible
  - however, they can be described probabilistically
- Precision
  - reproducibility of sensor results

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

Characterizing Error: Challenges in Mobile Robotics

- Mobile Robot: perceive, analyze and interpret state
- Measurements are dynamically changing and error prone
- Examples:
  - changing illuminations
  - specular reflections
  - light or sound absorbing surfaces
  - cross-sensitivity of robot sensor to robot pose and robot-environment dynamics
    - rarely possible to model ➔ appear as random errors
    - systematic errors and random errors may be well defined in controlled environment

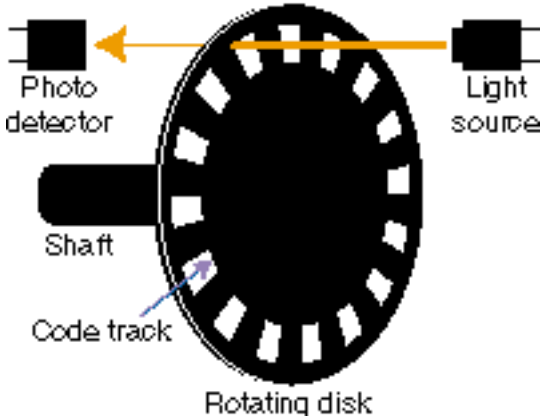
Multi-Modal Error Distributions

- Behavior of sensors modeled by probability distribution (random errors)
  - usually very little knowledge about causes of random errors
  - often probability distribution is assumed to be symmetric or even Gaussian
  - however, may be very wrong….
    - Sonar (ultrasonic) sensor might overestimate the distance in real environment and is therefore not symmetric
    - Sonar sensor might be best modeled by two modes:
      1. the case that the signal returns directly
      2. the case that the signals returns after multi-path reflections
    - Stereo vision system might correlate to images incorrectly, thus causing results that make no sense at all…

Wheel / Motor Encoders (1)

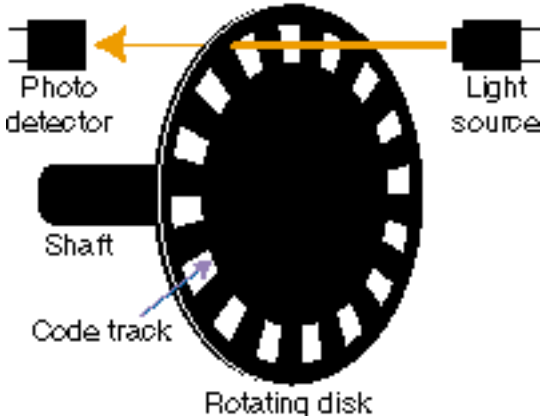
- measure position or speed of the wheels
- Integrate wheel movements to get an estimate of robots position ➔ odometry
- optical encoders are proprioceptive sensors
  - position estimation in relation to a fixed reference frame is only valuable for short movements
- typical resolutions: 2000 increments per revolution.

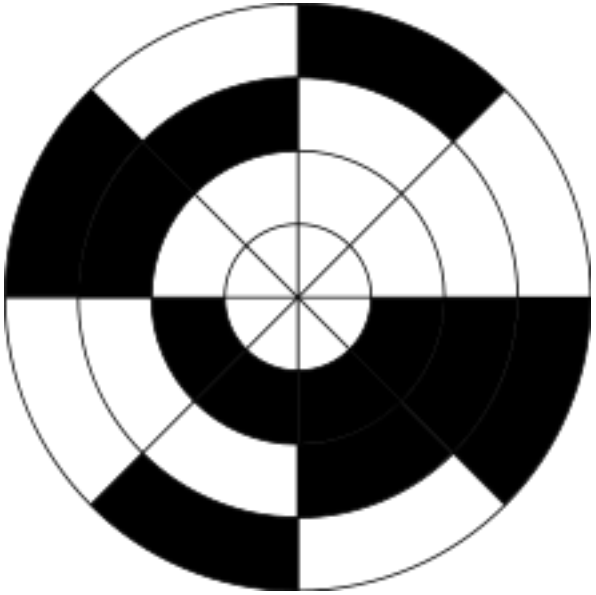
Wheel / Motor Encoders (2)



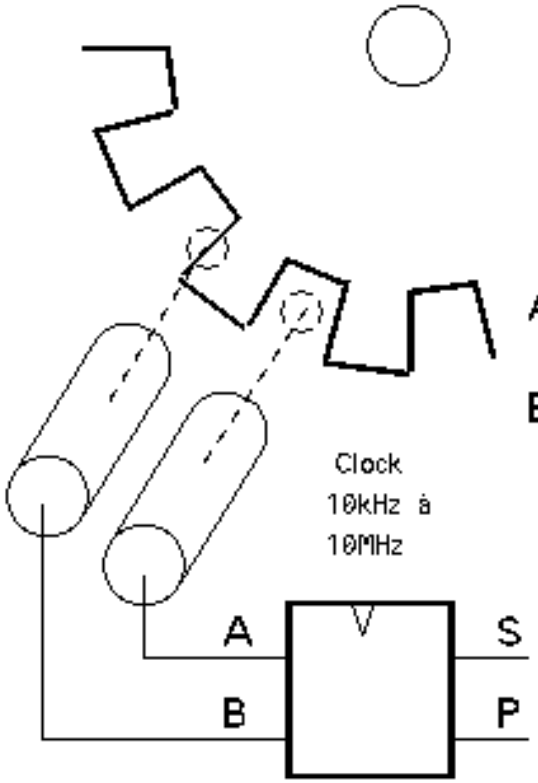
Ok, how does this work? Speed? Position?

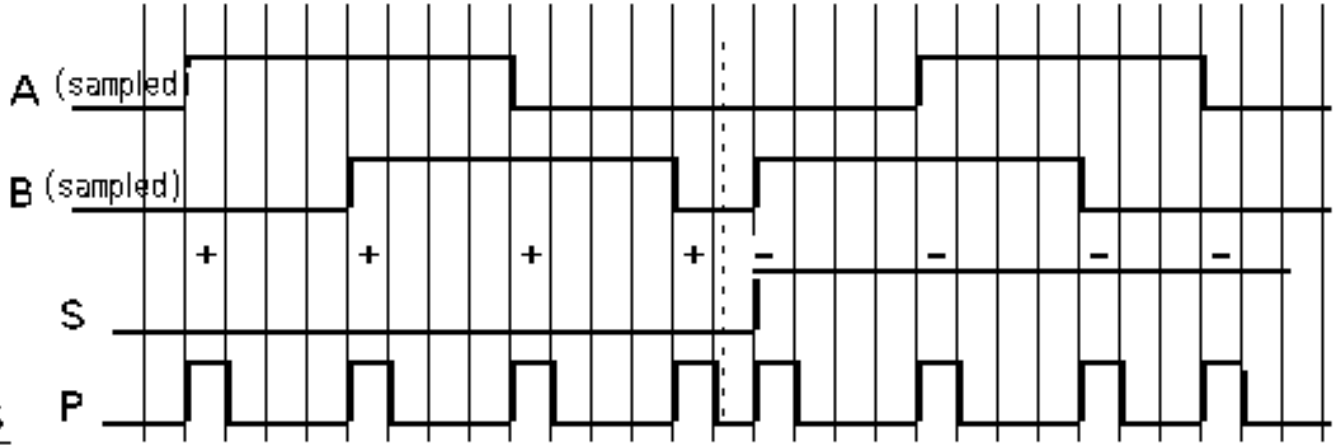
Wheel / Motor Encoders (2)

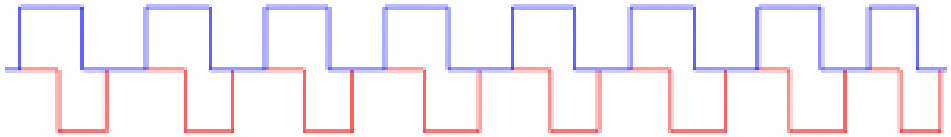


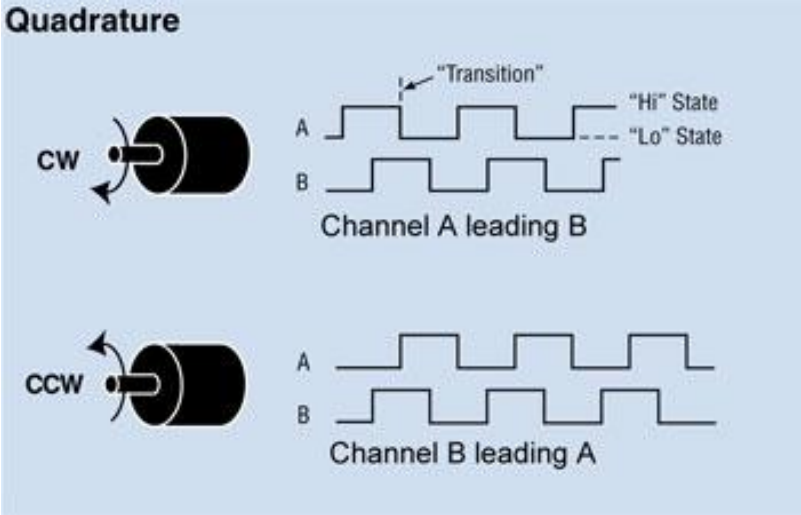


Wheel / Motor Encoders (3)









Heading Sensors

- Proprioceptive (gyroscope, inclinometer) or Exteroceptive (compass)
- Determine the robot's orientation
- Heading + velocity integrates to position estimate
  - Dead reckoning (ships)
  - Location + Orientation = *Pose*

Compass

- ~2000 B.C.
  - Chinese suspended a piece of naturally 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
- Major drawbacks
  - weakness of the earth field
  - easily disturbed by magnetic objects or other sources
  - not feasible for indoor environments

Gyrocompass

- Patented in 1885
- Practical in 1906 (Germany)
- Find true north as determined by Earth's rotation
- Not affected by ship's composition, variety in magnetic field, etc.

Gyroscope

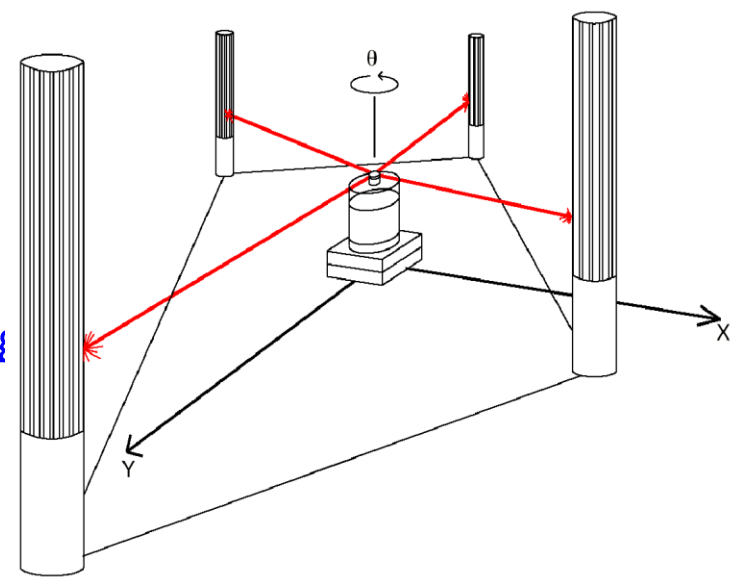
- Heading sensors keep the orientation to a fixed frame
  - absolute measure for the heading of mobile system
- Mechanical Gyroscopes
  - Drift: 0.1° in 6 hours
  - Spinning axis is aligned with north-south meridian, earth's rotation has no effect on gyro's horizontal axis
  - If points east-west, horizontal axis reads the earth rotation
- Optical Gyroscopes (1980s)
  - 2 laser beams in opposite direction around circle
  - Bandwidth >100 kHz
  - Resolution < 0.0001 degrees/hr

Optical Gyroscopes

- Early 1980: first installed in airplanes
- Angular speed (heading) sensors using two monochromic light / laser beams from same source
- On is traveling clockwise, the other counterclockwise
- 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
- New solid-state optical gyroscopes based on the same principle are build using microfabrication technology
- MUCH more accurate than mechanical

Ground-Based Active and Passive Beacons

- Beacons are signaling guiding devices with a precisely known positions
- Beacon-base navigation is used since the humans started to travel
  - Natural beacons (landmarks) like stars, mountains, or the sun
  - Artificial beacons like lighthouses
- Global Positioning System revolutionized modern navigation technology
  - key sensor for outdoor mobile robotics
  - GPS not applicable indoors
- Major drawback with the use of beacons in indoor:
  - Beacons require environment changes: costly
  - Limit flexibility and adaptability to changing environments
- Key design choice in Robocup
  - https://www.youtube.com/watch?v=Kc8ty9mo



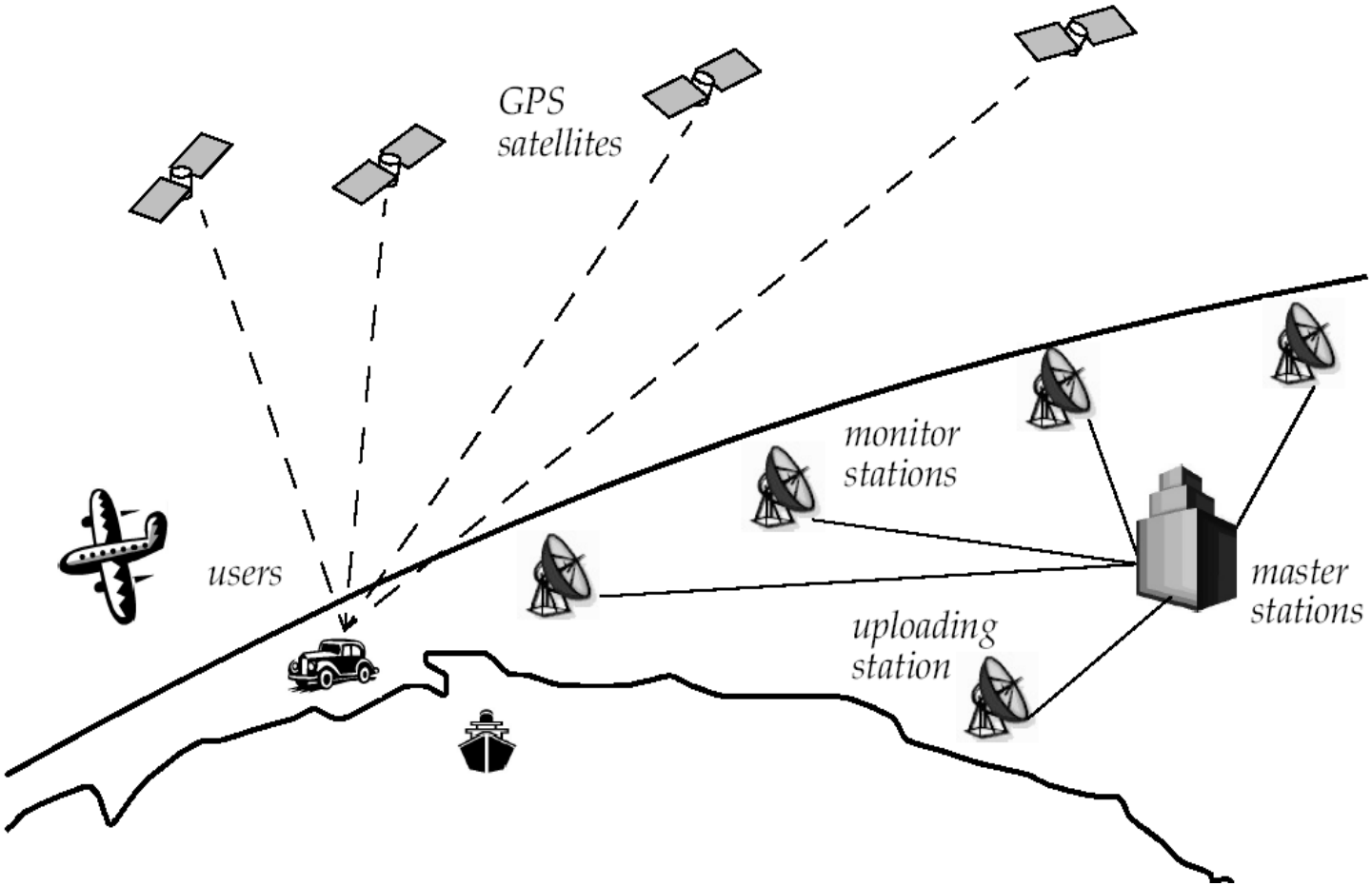
Global Positioning System (GPS) (1)

- Developed for military use, now commercial
  - 24 satellites (including some spares)
  - Orbit earth every 12 hours at a height of 20.190 km
  - Location of GPS receiver determined through 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

Global Positioning System (GPS) (2)

- How many satellites do you need to see?



Global Positioning System (GPS) (3)

- Time synchronization:
  - atomic clocks on each satellite, monitored from different ground stations
  - electromagnetic radiation propagates at light speed (0.3 m / nanosecond)
  - position accuracy proportional to precision of time measurement
- Real time update of exact location of satellites:
  - Monitoring satellites from a number of widely distributed ground stations
  - master station analyses all measurements & transmits actual position to each satellite
- Exact measurement of the time of flight:
  - quartz clock on the GPS receivers are not very precise
  - four satellite allows identification of position values (x, y, z) and clock correction ΔT
- Position accuracies down to a ~2 meters

- Improvement: Differential GPS
  - ~10cm
  - Need fixed, known location
  - Piski: http://swiftnav.com/piksi.html
  - Project possibilities here!