DD2426 – Robotics and Autonomous Systems
Lecture 4: Robot Sensors and Perception

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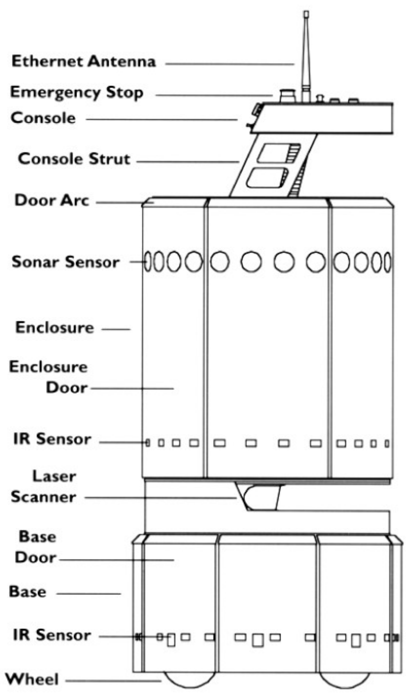
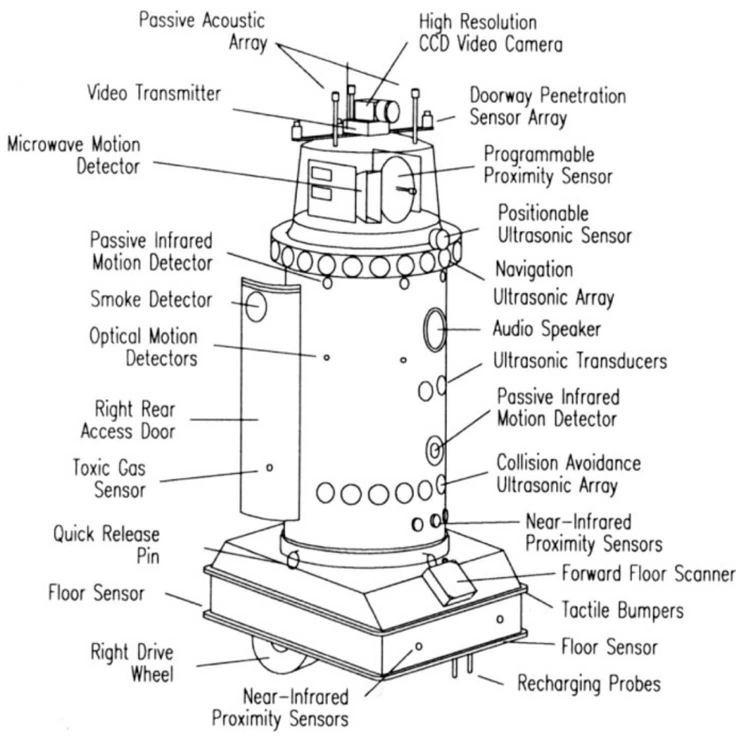
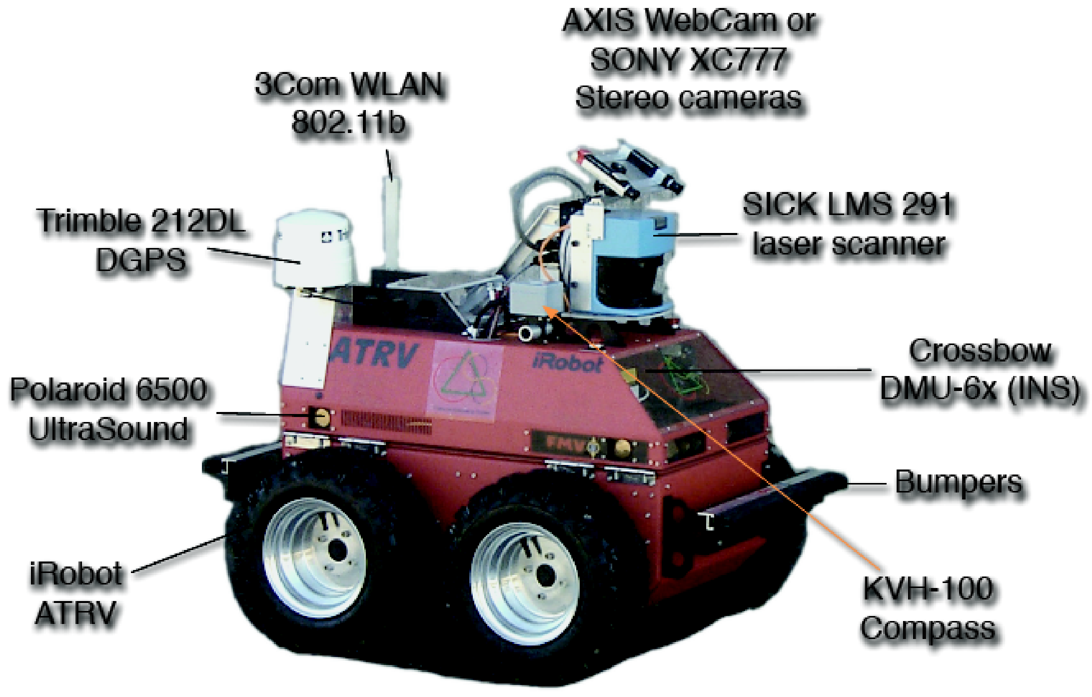
April 8,2008

Example: Robots and sensors
B21 (Real world interfaces) and Robart II





Example: Robots and sensors
Pluto @ KTH (iRobot ATRV)



Example: Robots and sensors
Goofy @ KTH (ActivMedia PeopleBot)

- Typical indoor research platform
- Polaroid sonar sensors
- SICK LMS 200 laser scanner
- Bumpers
- Odometry (wheel encoders)
- On-board computer

Sensors

- Sensors are needed to cope with the uncertainty and provide an estimate of environment and "robot state"
- Uncertainty in the layout of the environment due to lack of models or unknown dynamics
- Execution of commands is uncertain due to imperfect actuation

Sensor classes

- Sensing can be divided according to what is measured:
  - Proprioceptive (PC) sensors:
    - measure values internal to the robot system
    - e.g. motor speed, wheel load, heading, battery status
  - Exteroceptive (EC) sensors
    - gives information from the robot's environment
    - e.g. distance to objects, light intensity, unique features,
- Can also divided based on measurement principle:
  - Passive (P) sensors
    - Energy coming from the environment
    - e.g. camera, microphone
  - Active (A) sensors
    - Emit their energy and measure the reaction
    - Better performance but some influence on the environment
    - e.g. laser scanner, sonar sensors

Sensors for mobile robots

Classification	Sensor type	PC/EC	A/P
Tactile sensors	switches/bumpers	EC	P
	optical barriers	EC	A
	non-contact proximity sensors	EC	A
Haptic sensors	contact arrays	EC	P
	force/torque	EC/PC	P
	capacitive	EC	A
Motor/axis sensor	brush encoders	PC	P
	potentiometers	PC	P
	resolvers	PC	A
	optical encoders	PC	A
	magnetic encoders	PC	A
	inductive encoders	PC	A
	capacitive encoders	PC	A

Sensors for mobile robots

Classification	Sensor type	PC/EC	A/P
Heading sensors	compass	EC	P
	gyroscopes	PC	P
	inclinometers	EC	A/P
Beacon based	GPS	EC	A
(Position wrt	active optical	EC	A
fixed frame)	RF beacons	EC	A
	ultrasound beacons	EC	A
	reflective beacons	EC	A
Ranging	Ultrasonic sensors	EC	A
	laser rangefinder	EC	P/A
	stereo camera	EC	P/A
	structured light	EC	A

Sensors for mobile robots

Classification	Sensor type	PC/EC	A/P
Speed/motion	Doppler radar	EC	A
	Doppler sound	EC	A
Identification	camera	EC	P
	RFID	EC	A
	laser	EC	A
	radar	EC	A
	ultra-sound	EC	A
	sound	EC	P

Sensing types

- Scalar
  Estimation of scalar / amplitude entity such as temperature, intensity, current, force, ...
- Position
  Estimation of 1D, 2D, 3D position. Typically in (x, y) or (ρ, θ), i.e. Cartesian or polar coordinates
- Derivatives
  Estimation of motion or acceleration

Characterizing sensor performance I

- Range
  Upper limit of the measurement
- Dynamic range
  Ratio between upper and lower limits (usually in decibel)
  - Power measurements (e.g. 1mW to 20 W)

$$10 \log \frac{20}{0.001} = 43dB$$

  - Non-power measurements (e.g. 1mV to 20V)

$$20 \log \frac{20}{0.001} = 86dB$$

Characterizing sensor performance II

- Resolution
  - minimum difference between two values
  - often lower limit = resolution
  - for digital sensors often given by the A/D resolution, e.g., 5V/256 for 8-bit A/D
- Linearity
  - Variation of output as function of input
  - Ideally $Y = aX$ implies $Y = a(X_1 + X_2)$
  - Often true in some interval at least
- Bandwidth or frequency
  - Speed of response and data flow
  - Typically an upper limit depending on sensor and the sampling rate

Characterizing sensor performance III

- Sensitivity
  - What input change can be detected in output change
  - Often high sensitivity to other changes, e.g. illumination, temperature,...
- Cross sensitivity
  - variation with other changes such as temperature
  - e.g., very often have to compensate for temperature
- Error/accuracy
  - Difference between true value (v) and measured value (m)

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

Characterizing sensor performance IV

- Most sensors generate measurements that are contaminated by noise:
  - Systematic noise (deterministic errors)
    - errors that could (in theory) be modelled, e.g. through calibration
    - e.g. optical distortion in camera lens
  - Random noise (non-deterministic errors)
    - errors that cannot be predicted
    - Typically modelled in probabilistic fashion
- Precision: reproducibility of measurements

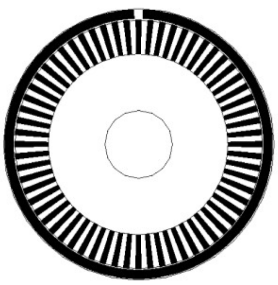
$$precision = \frac{range}{\sigma}$$

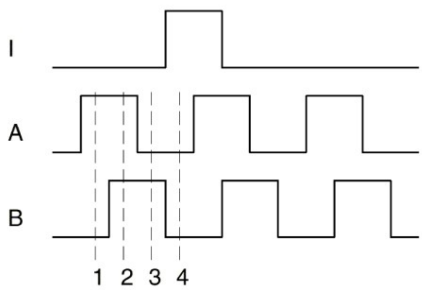
Characterizing errors

- Mobile robots have to perceive, analyze and interpret the state of the world
- Measurements are error prone and change over time, with temperature, etc
- Examples
  - changing illumination
  - specular reflections
  - light or sound absorbing surfaces
  - cross-sensitivity to robot pose or robot-environment dynamics

Wheel encoders

- Optical encoders: discs and diodes
- Measurement of discrete values
- Quadrature encoders enable detection of direction of motion
- Mobile robots often have encoder with around 100-500 ticks/rev
- Industrial manipulators may have 10,000 ticks/rev
- Mount before gear box $\Rightarrow$ better resolution
- N slots/rev gives 4N ticks/rev with quadrature encoder
- Need to be able to count the pulses!



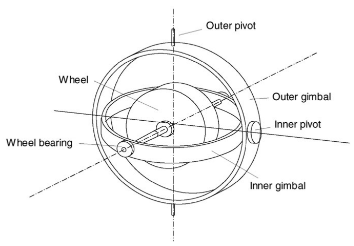


State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

Heading sensors

- Compass very old navigation tool (2000 B.C.)
- Today available in solid state technology
- Sensitive to ferro magnetic materials
- High environmental variation
- Very hard to use indoors
- Absolute angle information very valuable
- Can navigate by estimating distance (ship navigation)

Gyroscope



- Mechanical gyro: The inertia of a spinning wheel provides reference for orientation
- Rate gyro: measures the rotation speed
- Today available in optical and solid state versions
- Integration of rotation speed to get angle
- Typically drifts with temperature, etc
- Often combined with accelerometers

Accelerometers

- Measures the acceleration
- Can be used to detect vertical axis by looking for the gravity vector (like in your iPhone, camera, etc)
- Has to be integrated twice to get position
- As position sensor very sensitive to noise
- Can be used to detect impact, e.g. air bags in cars, hard drives in computers

Ranging

- Ranging for estimation of position is a very common methodology
- Several principles
  - Time of flight
  - Phase difference
  - Triangulation

Ranging: Time of flight (ToF)

- Measure travel time
- Speed of propagation c, distance d implies

$$d = ct \quad \Rightarrow \quad t\frac{t}{d}$$

- Travels back and forth, i.e. time for two trips

$$d = \frac{ct}{2}$$

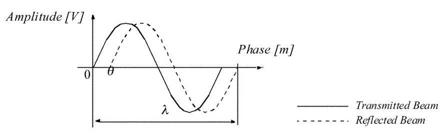
- Sound: c=344m/s ($c = 331.4 + 0.6T_C$)
- Light: c=299,792,458 m/s
- If the target/sensor is moving you may have to take that into account. Especially when using sound (slow)
- High accuracy with light require very fast timer circuits!

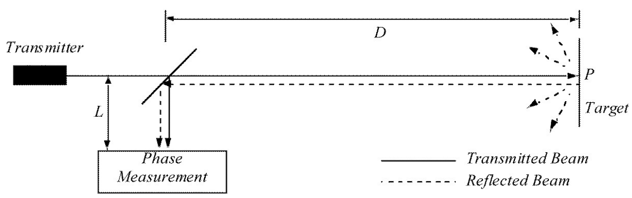
Ranging: Phase differencing

- Measure phase difference (θ) between reflected beam and the transmitted signals

$$D = \frac{\lambda}{4\pi}\theta$$

- Can measure distances up to the wavelength unambiguously
- Example: modulation frequency of 5MHz gives $\lambda = 60m$
- Can be implemented with PLL



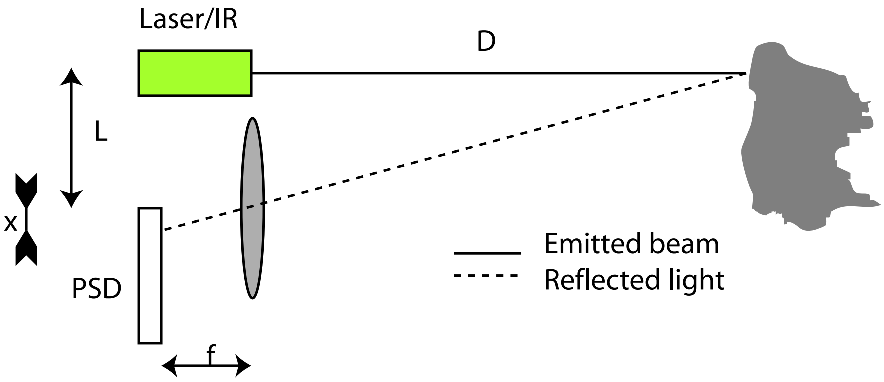


Ranging: Triangulation

- Use simple geometric relations to recover depth

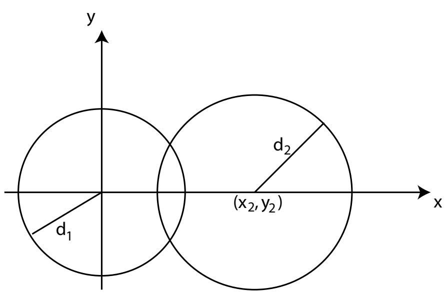
$$D = f\frac{L}{x}$$

- Example is IR/laser triangulation
- Can be implemented with PSD (position sensitive device)



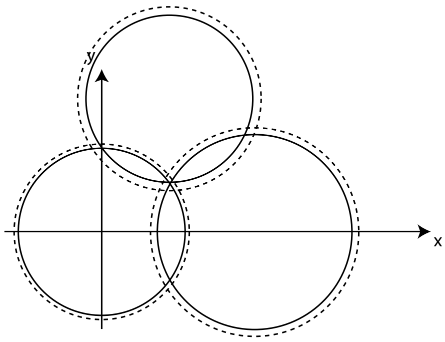
Position from range

- One of he most common approaches in robotics
- Consider handling of two range readings
- Can compute the intersection points (two solutions!!)



Unique position estimates

- With 3+ range estimates the intersection point is unique
- Noise can make it hard to find intersection
- Large "baselines" make triangulations more stable

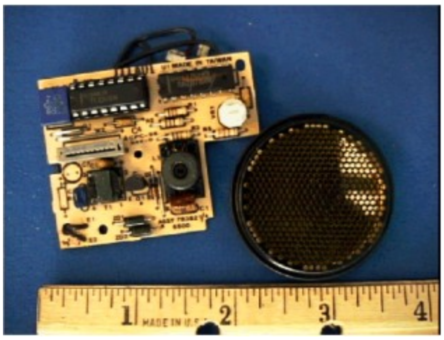


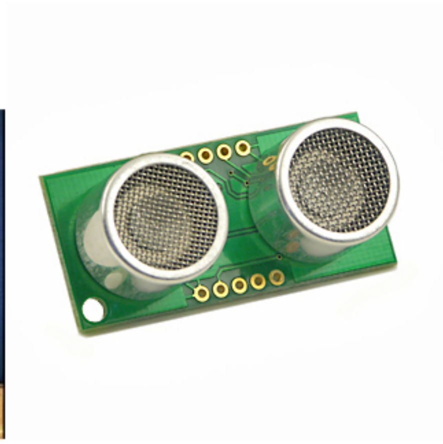
Triangulation

- Known landmarks ⇒ can estimate sensor position
- Known sensor posistions ⇒ can estimate landmark position from range only measurements

Ultra-sonic ranging

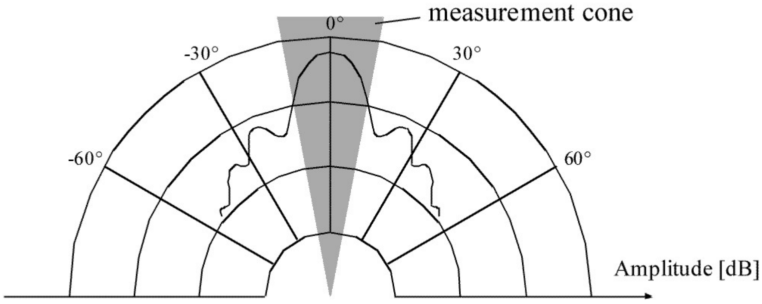
- Widely used in underwater mapping and navigation (sound travels faster in water)
- Distance measure for cameras used to be the main application in air (Polaroid)
- Time-of-flight measurements
- Relatively cheap technology





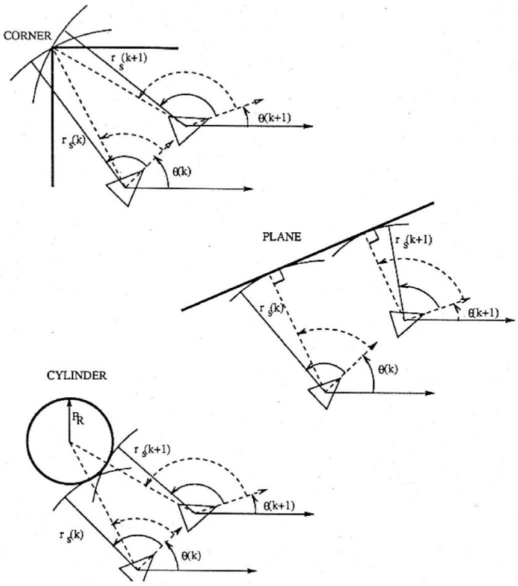
Sonar ranging

- Typical frequency 40-180kHz
- Transmitter and receiver separated or not
- Sound wave propagates in a cone like manner
- Typically 25-45 degrees opening angle

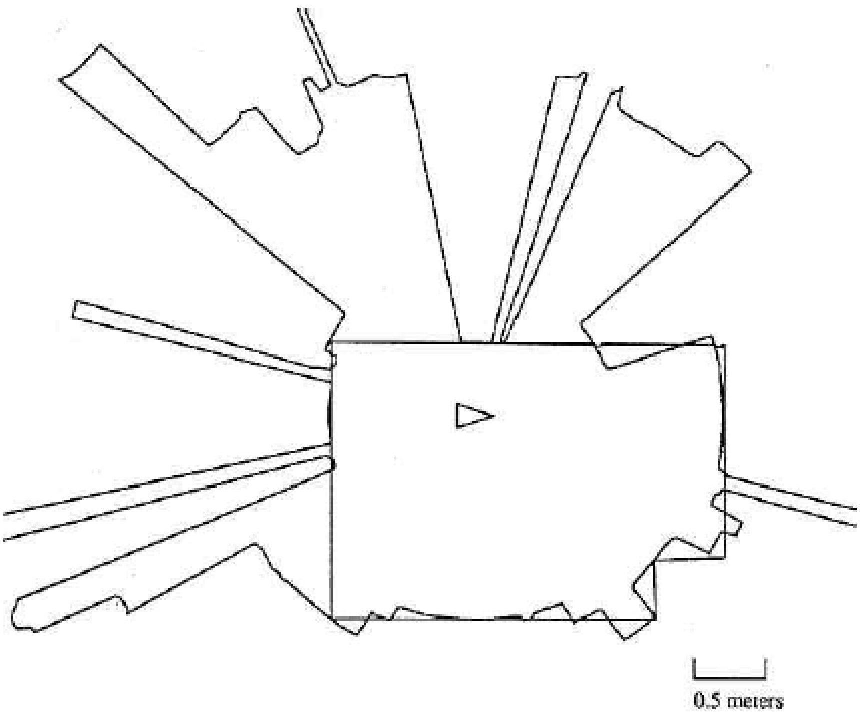


More on sonar

- Soft surfaces absorb most of the sound energy
- Specular reflection on surface far from perpendicular to sound
- Can detect geometric primitives by integrating measurements

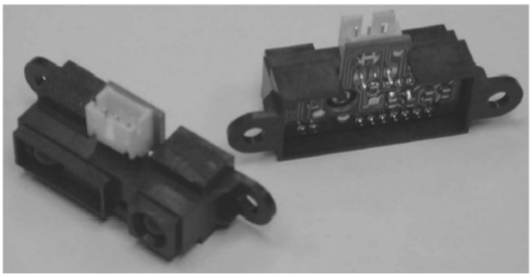


Example: Dense sonar scan



IR ranging

- Two common principles
  - Intensity (very sensitive to reflectance)
  - Triangulation
- Quite inexpensive and easy to interface
- Close range obstacle detection
- Common choice for stair detector



Time of flight laser scanning SICK LMS

- Rotating mirror (75Hz)
- Pulsed laser (higher power, less energy)
- Long range (typ 80m) (depends on reflectivity)
- Accuracy $\approx$ 1cm
- Samples with 1°
- Often used in interlaced mode (combine two scans shifted 0.5°)
- Safety classified
- Expensive: 40000SEK + VAT

Small laser range finder
Hokuyo URG

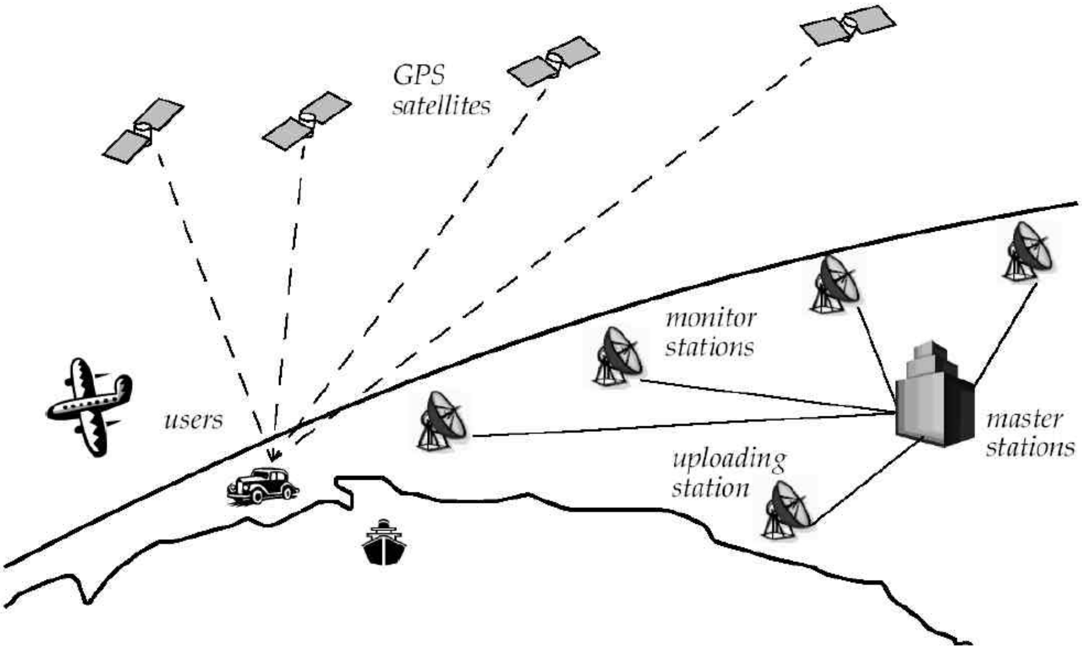
- Smaller and cheaper
- Shorter range 20mm - 4m

Global Positioning System (GPS)

- Developed for military use
- Now accessible for commercial and private applications
- There are 24 GPS (NAVSTAR) satellites orbiting the Earth every 12 hours at 20200km altitude

- Location of the GPS receivers are determined through time of flight and triangulation
- Challenges
  - Time synchronization between satellites
  - Real time update of exact satellite positions
  - Precise measurement of time of flight
  - Interference with other signals

GPS

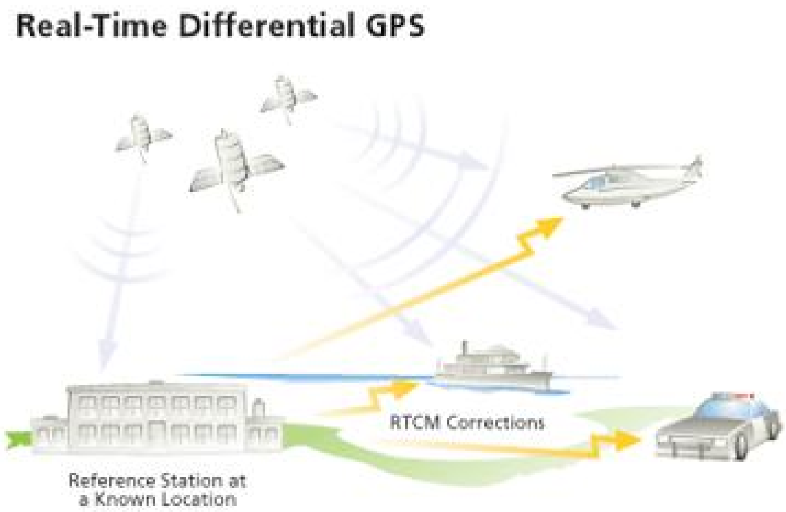


GPS

- Time synchronization
  - Atomic clocks on each satellite
  - Monitoring from ground stations
  - Ultra-precision time synchronization extremely important
  - Position accuracy proportional to precision of time measurement
  - Light travels 0.3m per nanosecond
- Simpler clock in the receiver
- Needs to receive signals from at least 3 satellites to calculate the position and 1 additional to get the altitude. More satellites gives better accuracy.
- GPS is now widely spread technology

Differential GPS (DGPS)

- Correction with local reference information
- Local station coverage 100m-3km
- Accuracy in the order of a meter

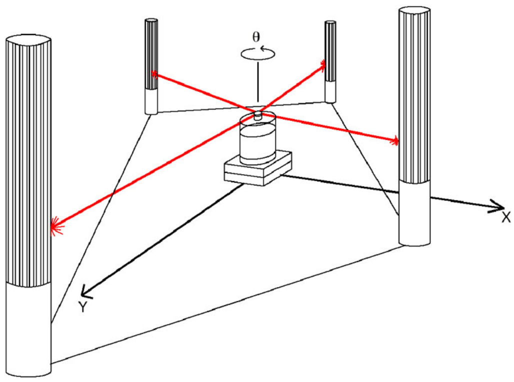


RTK-GPS

- Network of base stations with accurately known positions (ca 70 km apart)
- GPS receiver with radio (e.g. GPRS)
- Sends approximate position to server
- Gets local corrections from server
- Can get cm accuracy
- Used in civil engineering applications, e.g., building roads

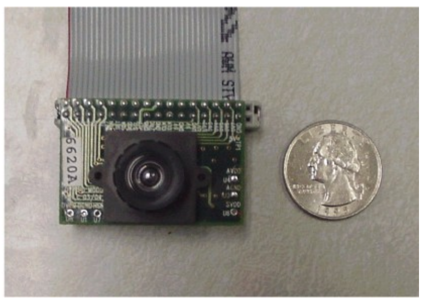
Beacon based laser scanning

- Known landmarks
- Measures the angle very accurately
- Used in factory settings for AGV systems
- Example: Automatic fork lifts
- More than 15000 units sold



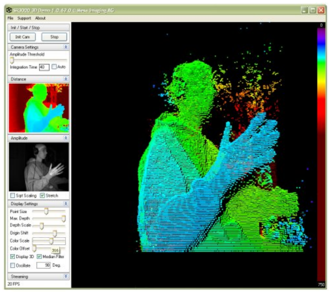
Camera

- Most flexible sensory modality
- Complex sensory processing
- There are several course on image processing and computer vision (a large research field in itself)
- Relatively inexpensive (driven by mass market)
- Vision is our main sensory modality
- Far from human level visual perception
- Robustness major issue (illumination etc)
- Several ways to get depth from the camera
  - Depth from focus, structured light, stereo vision, time-of-flight



3D Range Camera
Swiss Ranger

- Can combine ideas from cameras and lasers range finders
- Ex: Swiss Ranger gives 176x144 images with range information
- Modulated IR light, camera measures time-of-flight in each pixel



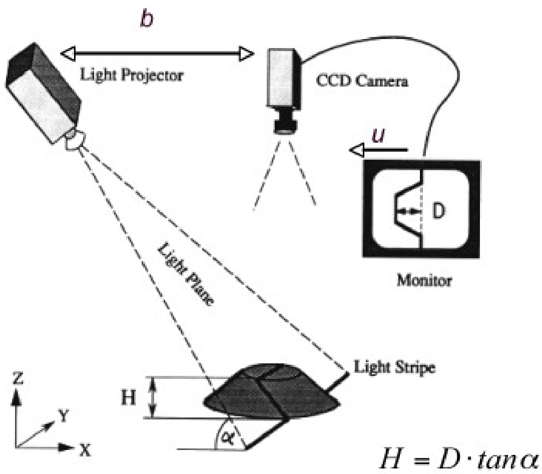
Stereo vision

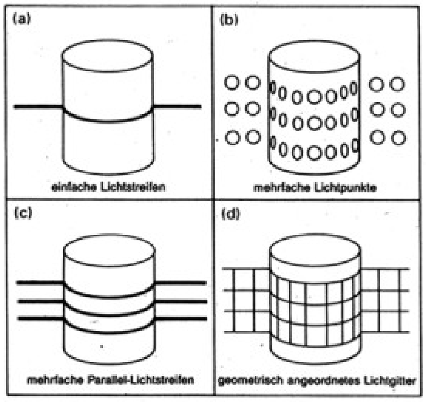
- Distance is inversely proportional to disparity (difference in image position in the two images)
- Disparity i proportional to baseline (b)
- $\Rightarrow$ large baseline better depth accuracy
- but correspondence more difficult
- Need to calibrate
  - Internal camera parameters (focal length, distortion, etc)
  - External camera parameters (relative positions)

BumbleBee from Point Grey and STH from Videre design

Structured light

- Many task require finding correspondences in images
- Idea: Project your own light pattern on the scene
- Can be used as obstacle detector
  (obstacles will deform the projected lines of light)





Object recognition

- Many tasks require the robot to recognize objects
- Can be done in simple and controlled environments with a limited number of objects
- Categorization a very hard problem!
- How many chairs?

Wide angle vision

- Normal camera rather small field of view
- Larger field of view with
  - Wide angle lens
  - Fish-eye lens
  - Omni-directional camera with mirror
- Image distorted
- Some applications can work with raw image, some require undistortion

Uncertainty

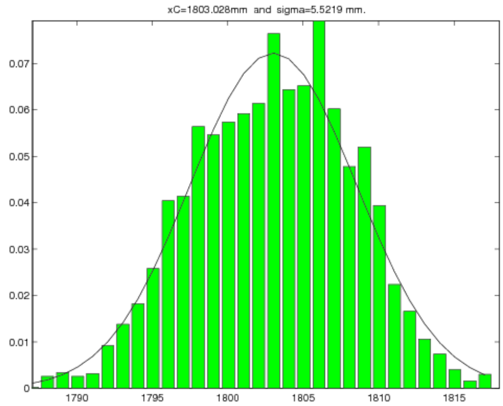
- All sensors have associated uncertainty
  - How is the uncertainty represented?
  - How should measurements be fused when there is uncertainty?
  - How can uncertainties be integrated?
- Examples of uncertainty
  - Noise in measurements
  - Non-linearities
  - Timing jitter
  - Un-modeled dependencies
  - Uncertain data association

White noise assumption

- Almost all models assume that the noise is white with Gaussian distribution

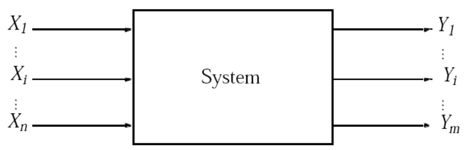
$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

- Error modelling is a basic part of robotics
- Understanding of the physical principles guide the work
- Example: uncertainty of SICK LMS 200



Error propagation

- Error propagation in a system with inputs $X_1, \ldots, X_n$ and outputs $Y_1, \ldots, Y_m$



- $Y_j = f_j(X_1, \ldots, X_n), \; j = 1, \ldots, m$
- Given covariance matrix for inputs C_X
- Covariance for output is $C_Y = F_X C_X F_X^T$ where $F_X = \nabla F$