Range Sensing Strategies

CS689
Robot Motion Planning
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Slides adopted from Siegwart and Nourbakhsh

Range Sensing strategies

- ***Active range sensors***
- ***Ultrasound***
- ***Laser range sensor***

Range Sensors (time of flight) (1)

- ***Large range distance measurement -> called range sensors***
- ***Range information:***
  - ***key element for localization and environment modeling***
- ***Ultrasonic sensors as well as laser range sensors make use of propagation speed of sound or electromagnetic waves respectively. The traveled distance of 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.***

Range Sensors (time of flight) (2)

- *It is important to point out*
  - *Propagation speed v of sound: 0.3 m/ms*
  - *Propagation speed v of electromagnetic signals: 0.3 m/ns,*
    - *one million times faster.*
  - *3 meters*
    - *is 10 ms ultrasonic system*
    - *only 10 ns for a laser range sensor*
    - *laser range sensors expensive and delicate*

- *The quality of time of flight range sensors manly depends on:*
  - *Uncertainties about the exact time of arrival of the reflected signal*
  - *Inaccuracies in the time of fight measure (laser range sensors)*
  - *Opening angle of transmitted beam (ultrasonic range sensors)*
  - *Interaction with the target (surface, specular reflections)*
  - *Variation of propagation speed*
  - *Speed of mobile robot and target (if not at stand still)*

Ultrasonic Sensor (time of flight, sound) (1)

- ***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 (340 m/s) in air is given by***

$$c = \sqrt{\gamma \cdot R \cdot T}$$

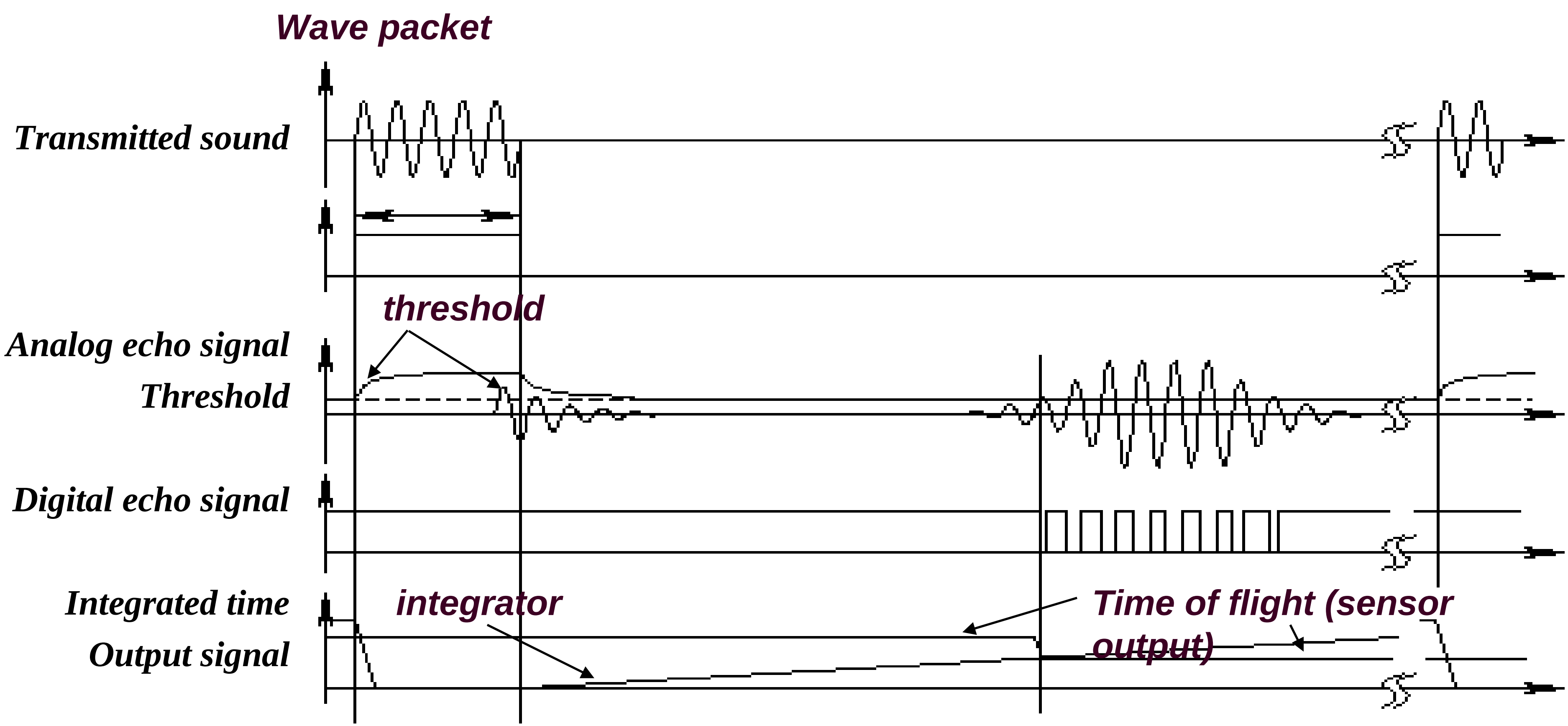
where

γ***: ration of specific heats***

R: gas constant

T: temperature in degree Kelvin

Ultrasonic Sensor (time of flight, sound) (2)

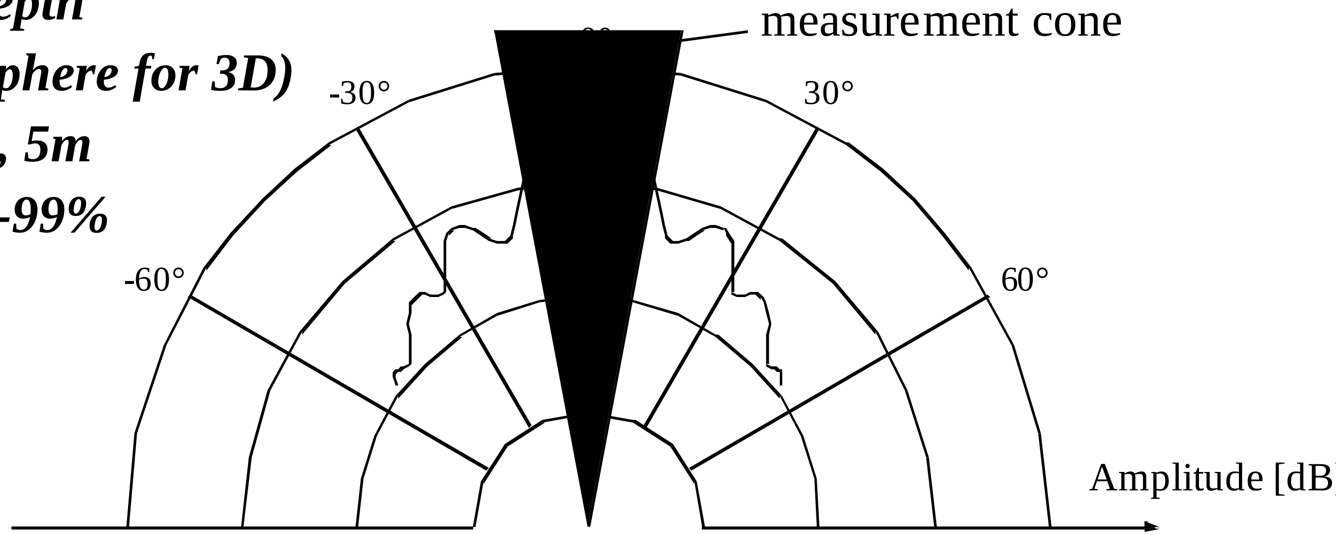


Signals of an ultrasonic sensor

- *Send a wave packet wait until in comes back*

Ultrasonic Sensor (time of flight, sound) (3)

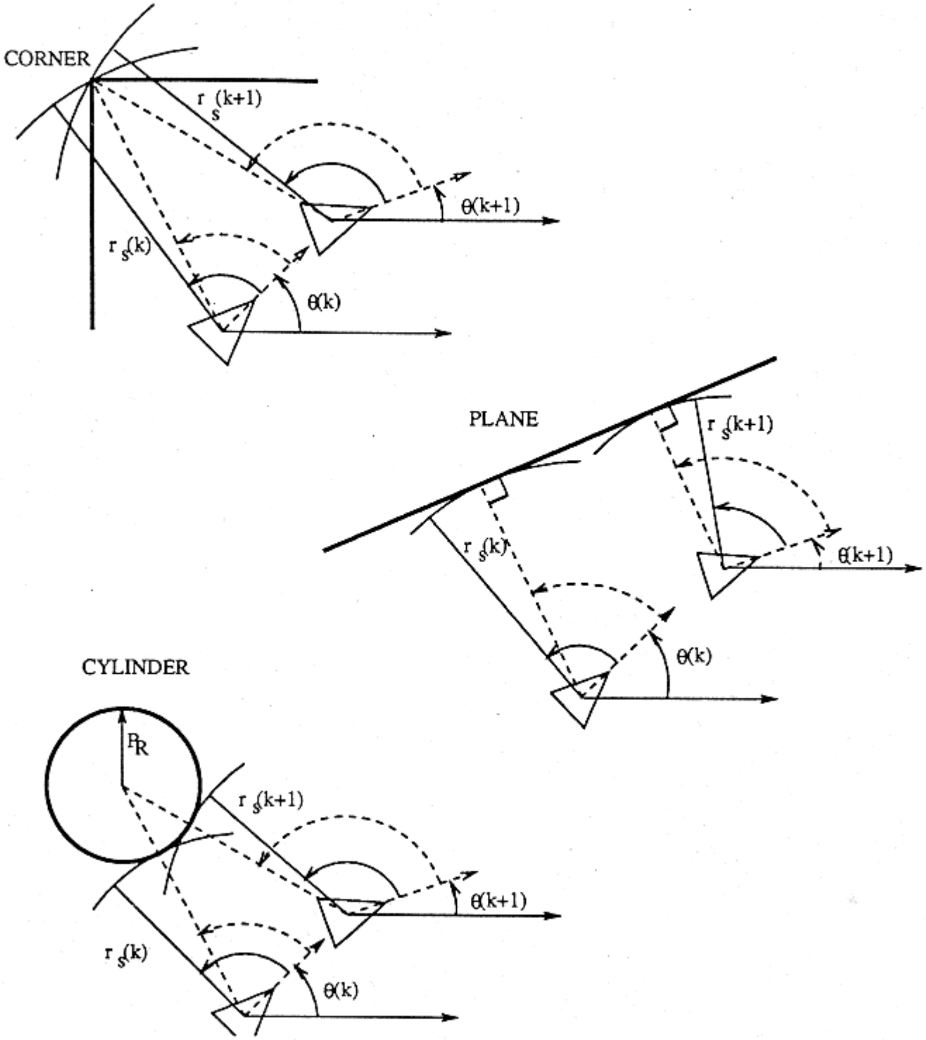
- ***typically a frequency: 40 - 180 kHz***
- ***generation of sound wave: piezo transducer***
  - ***transmitter and receiver separated or not separated***
- ***sound beam propagates in a cone like manner***
  - ***opening angles around 20 to 40 degrees***
  - ***regions of constant depth***
  - ***segments of an arc (sphere for 3D)***
  - ***Effective range 12cm, 5m***
  - ***Accuracy between 98-99%***



Typical intensity distribution of a ultrasonic sensor

Ultrasonic Sensor (time of flight, sound) (4)

- ***Other problems for ultrasonic sensors***
  - ***soft surfaces that absorb most of the sound energy***
  - ***surfaces that are far from being perpendicular to the direction of the sound -> specular reflection***

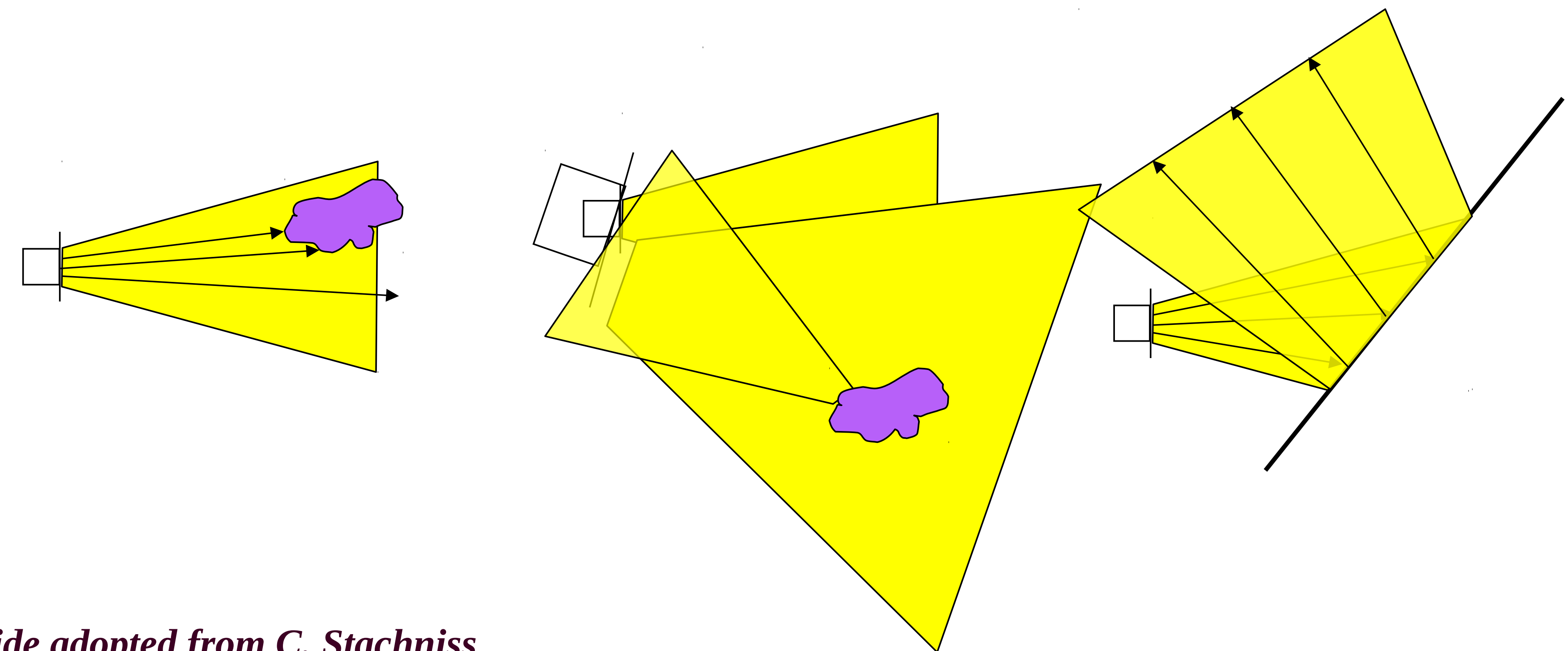


a) 360° scan

b) results from different geometric primitives

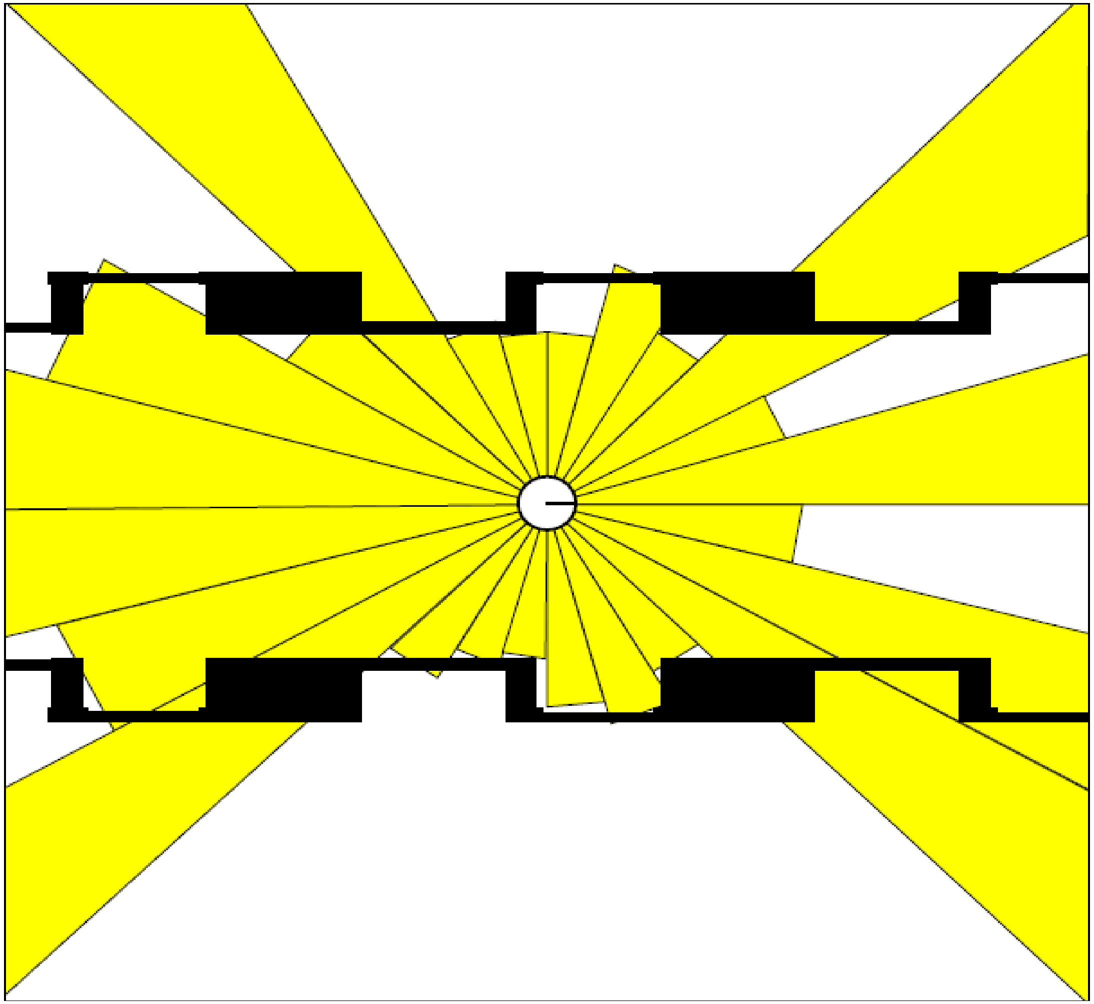
Sources of Error

- Opening angle
- Crosstalk
- Specular reflection



Slide adopted from C. Stachniss

Typical Ultrasound Scan



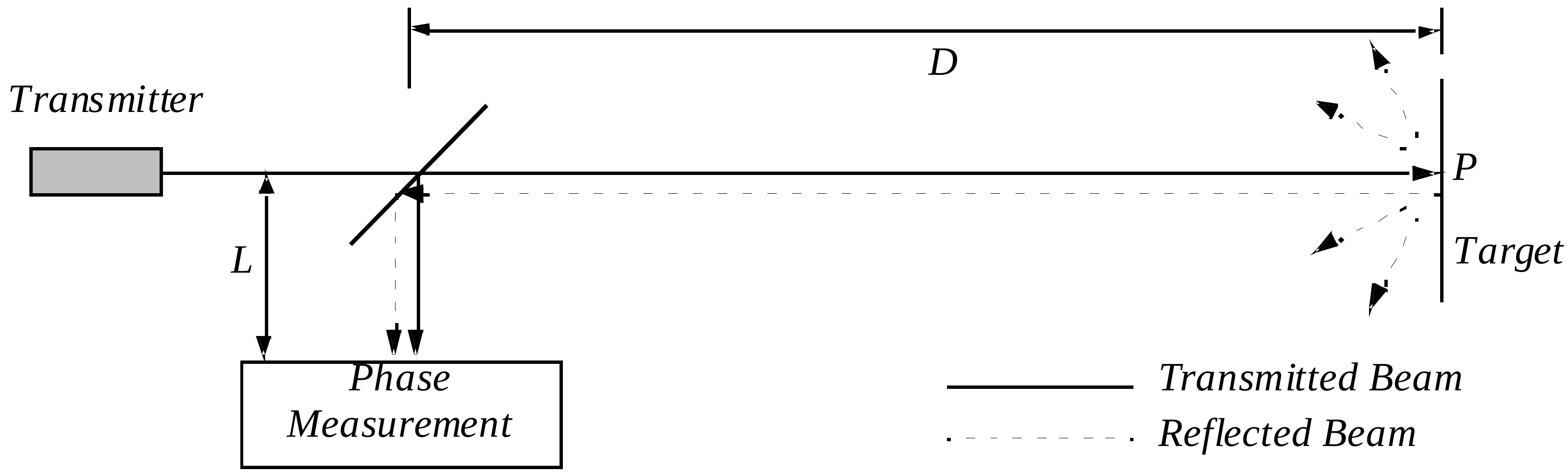
Slide adopted from C. Stachniss

Parallel Operation

- ***Given a 15 degrees opening angle, 24 sensors are needed to cover the whole 360 degrees area around the robot.***
- ***Let the maximum range we are interested in be 10m.***
- ***The time of flight then is 2*10/330 s=0.06 s***
- ***A complete scan requires 1.45 s***
- ***To allow frequent updates (necessary for high speed) the sensors have to be fired in parallel.***
- ***This increases the risk of crosstalk***

Slide adopted from C. Stachniss

Laser Range Sensor (time of flight, electromagnetic) (1)



- ***Laser light instead of sound***
- ***Transmitted and received beams coaxial***
- ***Transmitter illuminates a target with a collimated beam***
- ***Receiver detects the time needed for round-trip***
- ***Lidar (light detection and ranging)***

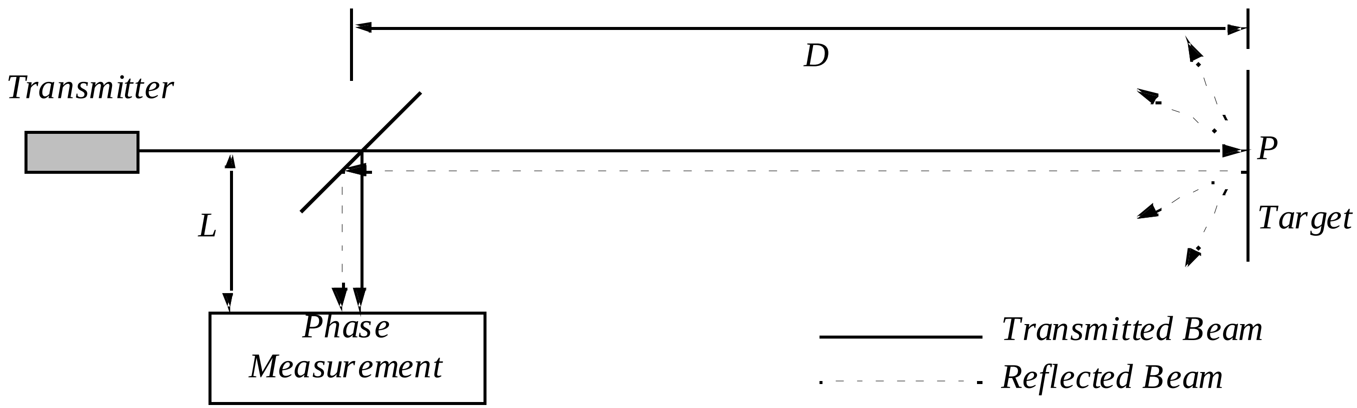
Laser Range Sensor (time of flight, electromagnetic) (2)

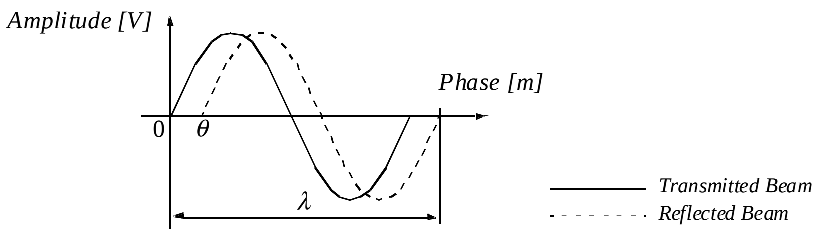
Time of flight measurement

- ***Pulsed laser***
  - ***measurement of elapsed time directly (as in ultrasound)***
- ***Beat frequency between a frequency modulated continuous wave and its received reflection***
- ***Phase shift measurement to produce range estimation***
  - ***technically easier than the above two methods.***

Laser Range Sensor (time of flight, electromagnetic) (3)

- ## Phase-Shift Measurement





Laser Range Sensor (time of flight, electromagnetic) (5)

- ***Confidence in the range (phase estimate) is inversely proportional to the square of the received signal amplitude.***

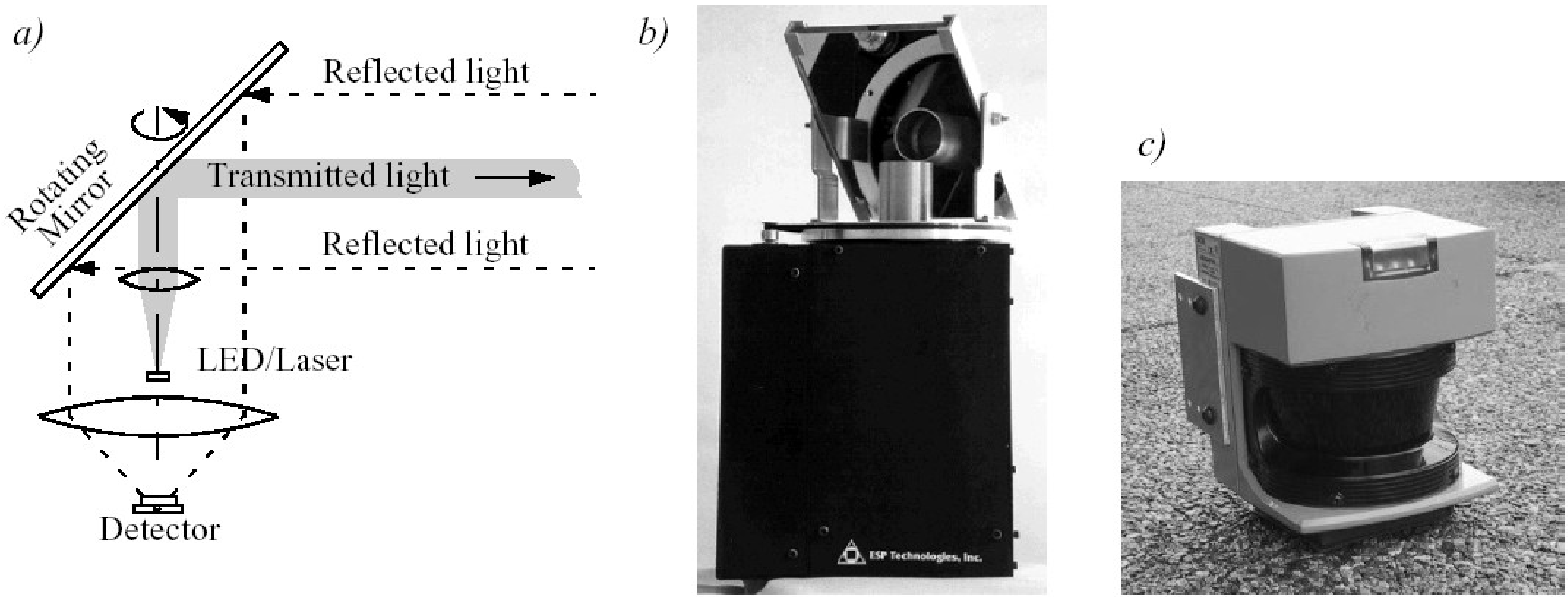
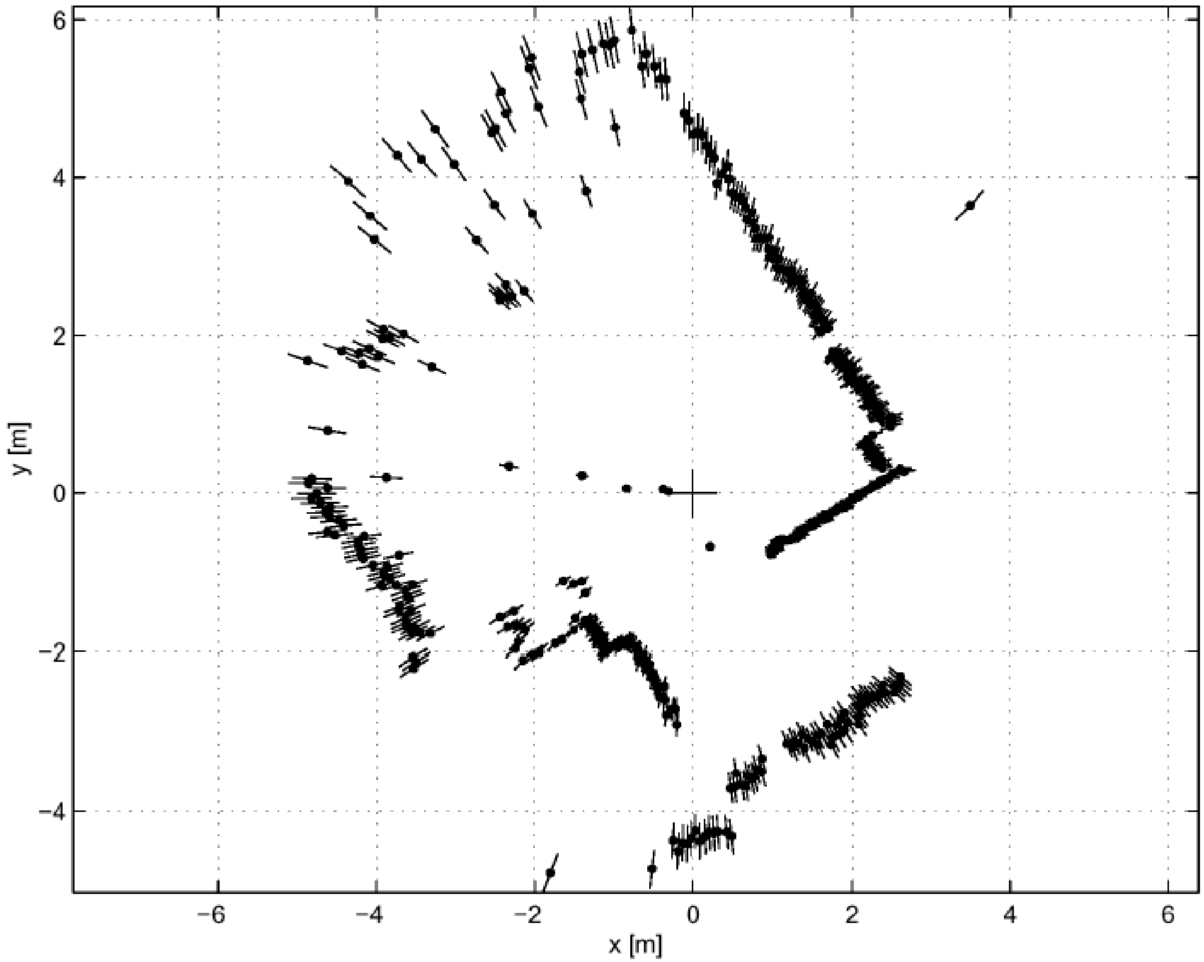


Figure 4.11

(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

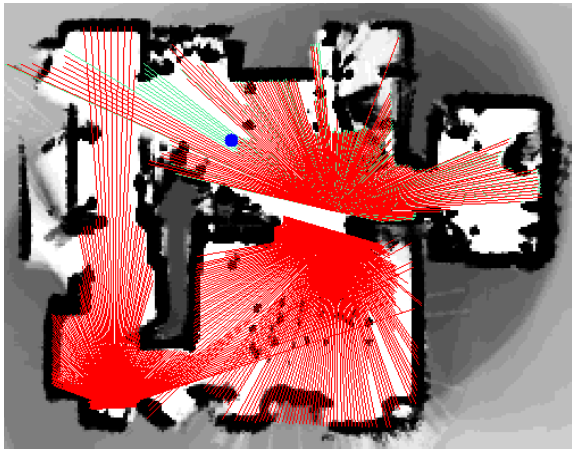
Laser Range Sensor (time of flight, electromagnetic)

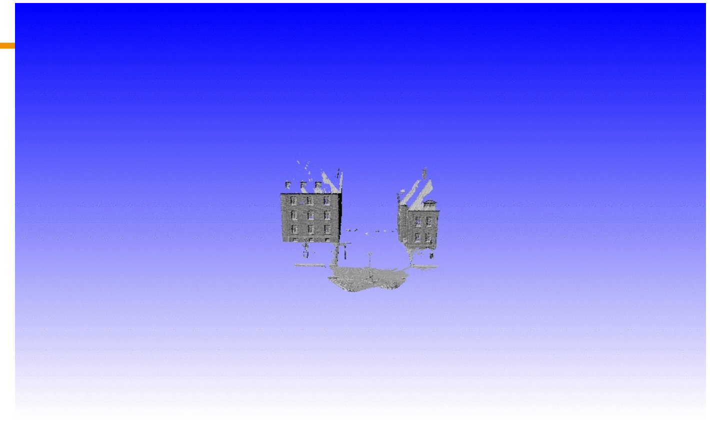
- ***Typical range image of a 2D laser range sensor with a rotating mirror. The length of the lines through the measurement points indicate the uncertainties.***

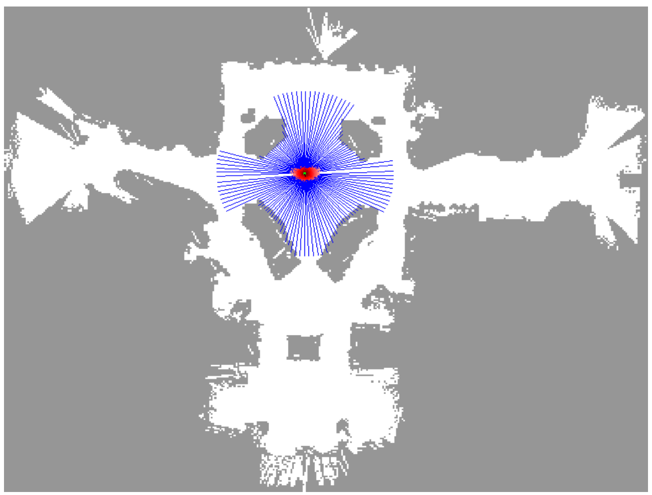


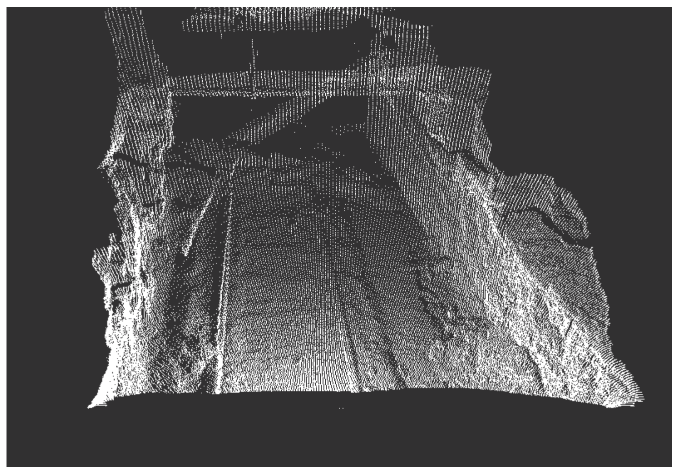
Robots Equipped with Laser Scanners

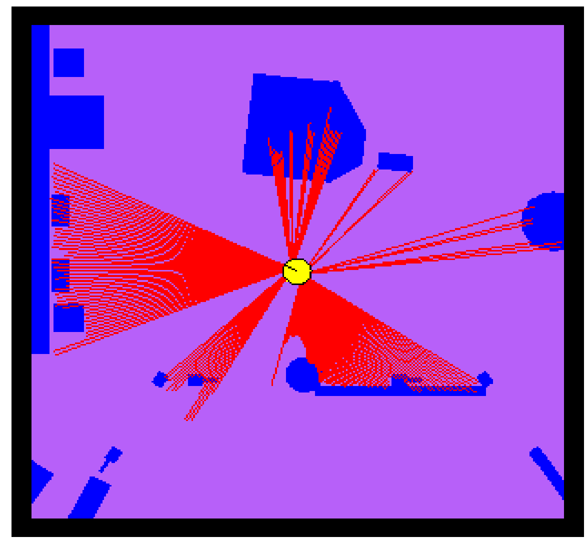
Typical Scans











Triangulation Ranging

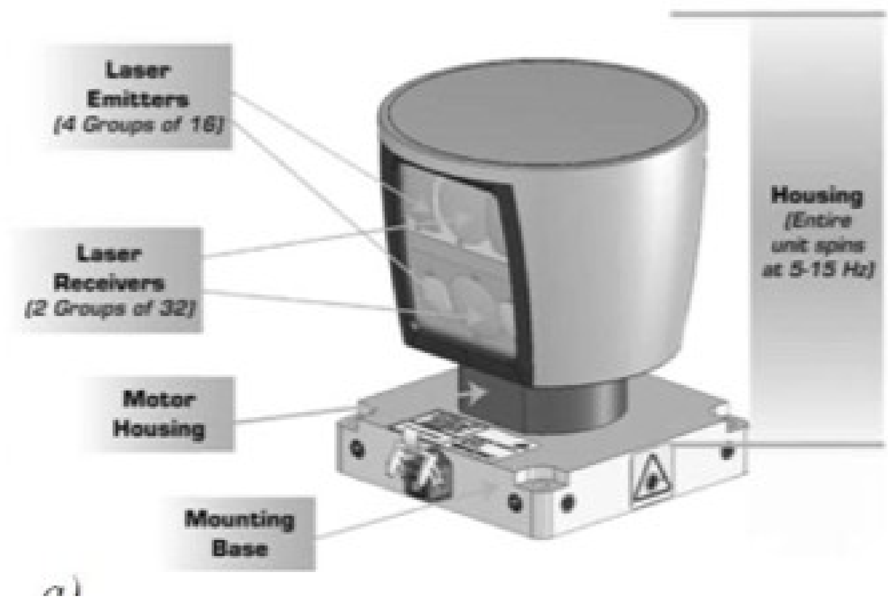
- ***geometrical properties of the image to establish a distance measurement***
- ***e.g. project a well defined light pattern (e.g. point, line) onto the environment.***
  - ***reflected light is than captured by a photo-sensitive line or matrix (camera) sensor device***
  - ***simple triangulation allows to establish a distance.***
- ***e.g. size of an captured object is precisely known***
  - ***triangulation without light projecting***

3D Laser

- **A 3D laser range finder is a laser scanner that acquires scan data in more than a single plane.**
- Custom-made 3D scanners are typically built by nodding or rotating a 2D scanner in a stepwise or continuous manner around an axis parallel to the scanning plane.
- By lowering the rotational speed of the turn-table, the angular resolution in the horizontal direction can be made as small as desired.
- A full spherical field of view can be covered (360° in azimuth and +/-90° in elevation).
- **However, acquisition takes up to some seconds!**
  For instance, if our laser takes 75 plane-scans/sec and we need an azimuthal angular resolution of 0.25 degrees, the period for a half rotation of the turn-table necessary to capture a spherical 3D scan with two Sicks is then 360 / 0.25 / 75 / 2 = 9.6 seconds. If one is satisfied with an azimuthal angular resolution of 1 degree, then the acquisition time drops down to 2.4 seconds, which is still too high for 3D mapping during motion!

3D Laser

- The Velodyne HDL-64E uses 64 laser emitters.
  - Turn-rate up to 15 Hz
  - The field of view is 360° in azimuth and 26.8° in elevation
  - Angular resolution is 0.09° and 0.4° respectively
  - **Delivers over 1.3 million data points per second**
  - The distance accuracy is better than 2 cm and can measure depth up to 50 m
  - This sensor was the primary means of terrain map construction and obstacle detection for all the top DARPA 2007 Urban Challenge teams. However, the Velodyne iscurrently still much more expensive than Sick laser range finders (SICK ~ 5000 Euros, Velodyne ~50,000 Euros!)



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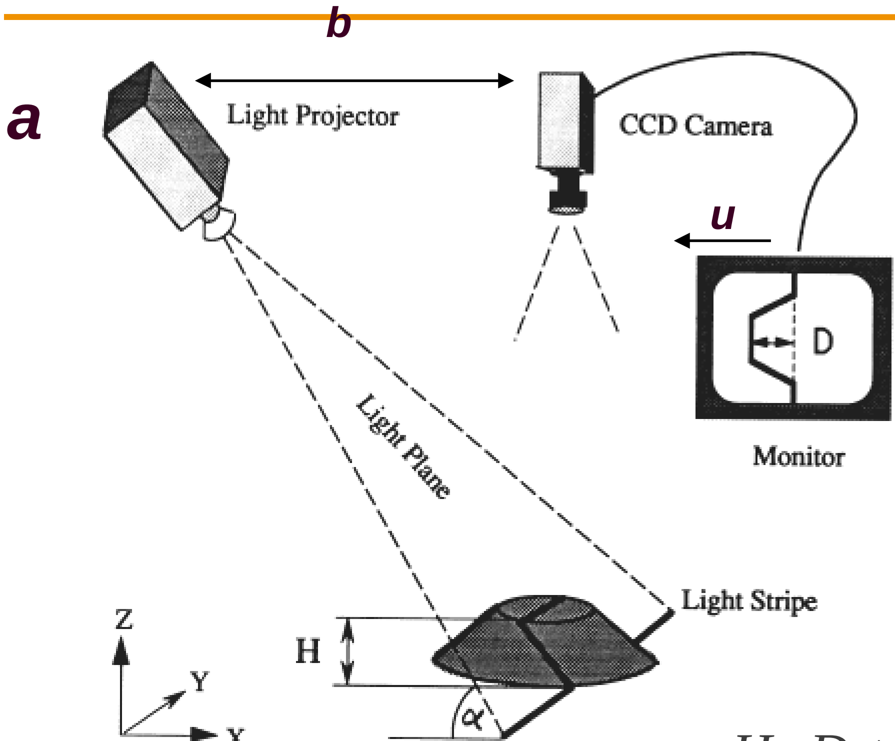
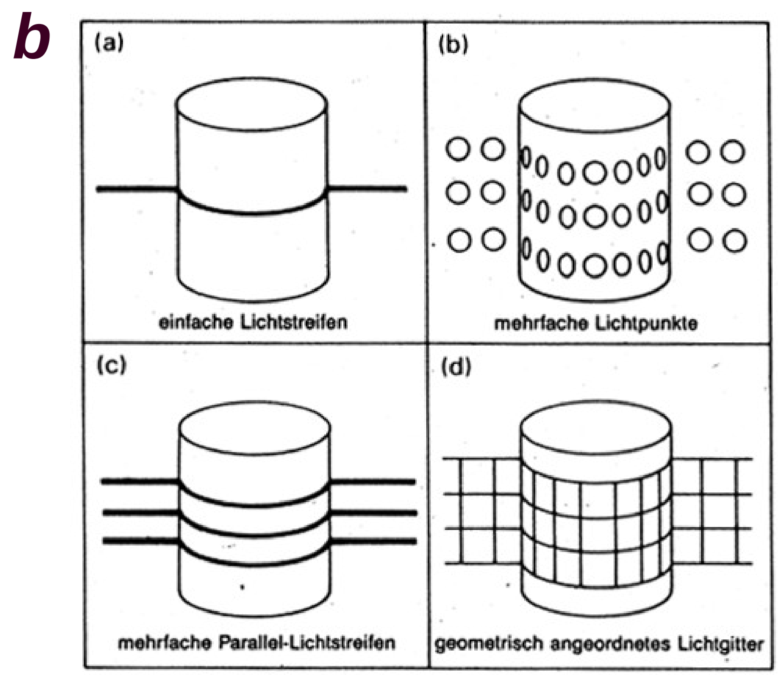
Structured Light (vision, 2 or 3D)



$$H = D \cdot \tan \alpha$$



- ***Eliminate the correspondence problem by projecting structured light on the scene.***
- ***Slits of light or emit collimated light (possibly laser) by means of a rotating mirror.***
- ***Light perceived by camera***
- ***Range to an illuminated point can then be determined from simple geometry.***

Heading Sensors

- ***Heading sensors can be proprioceptive (gyroscope, inclinometer) or exteroceptive (compass).***
- ***Used to determine the robots orientation and inclination.***
- ***Allow, together with an appropriate velocity information, to integrate the movement to an position estimate.***
  - ***This procedure is called dead reckoning (ship navigation)***

Compass

- ***Since over 2000 B.C.***
  - ***when 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***
  - ***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***

Gyroscope

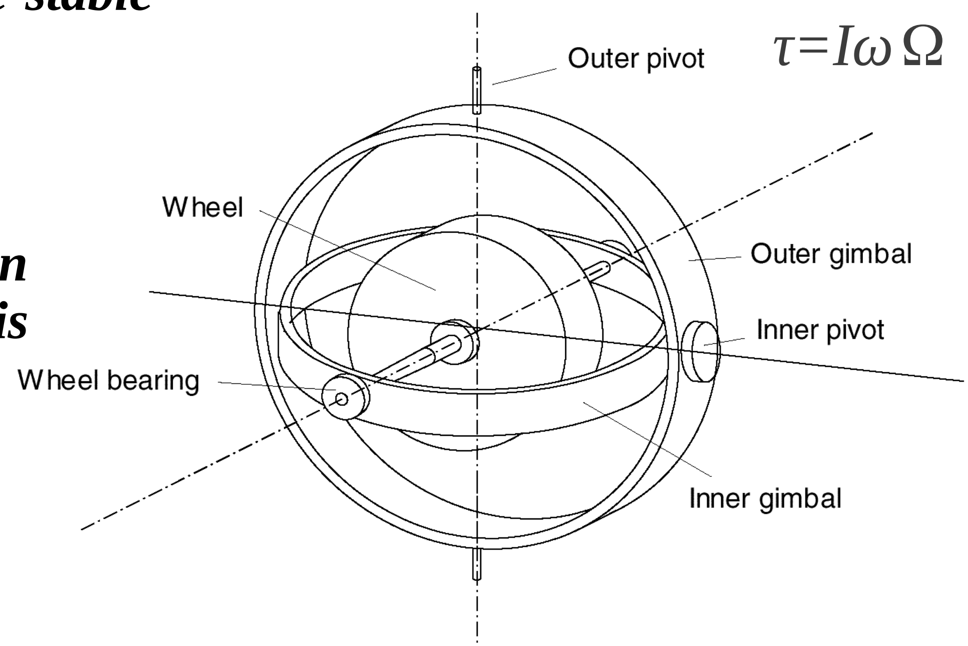
- Heading sensors, that keep the orientation to a fixed frame
  - absolute measure for the heading of a mobile system.
- Two categories, the mechanical and the optical gyroscopes
  - Mechanical Gyroscopes
    - Standard gyro
    - Rated gyro
  - Optical Gyroscopes
    - Rated gyro

Mechanical Gyroscopes

- *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 the spinning speed w, the precession speed W and the wheels inertia I.*
- *No torque can be transmitted from the outer pivot to the wheel axis*
  - *spinning axis will therefore be space-stable*
- *Quality: 0.1° in 6 hours*

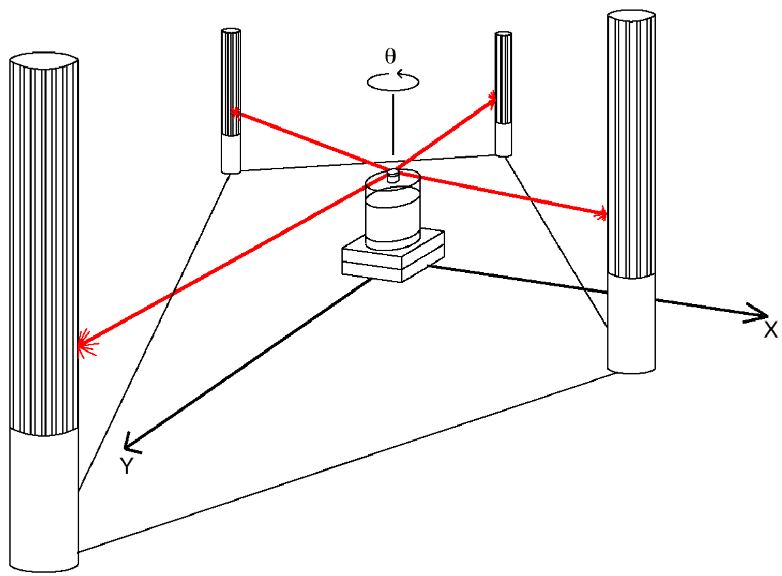
$$\tau = I\omega\Omega$$

- *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*



Ground-Based Active and Passive Beacons

- Elegant way to solve the localization problem in mobile robotics
- Beacons are signaling guiding devices with a precisely known position
- Beacon base navigation is used since the humans started to travel
  - Natural beacons (landmarks) like stars, mountains or the sun
  - Artificial beacons like lighthouses
- The recently introduced Global Positioning System (GPS) revolutionized modern navigation technology
  - Already one of the key sensors for outdoor mobile robotics
  - For indoor robots GPS is not applicable,
- Major drawback with the use of beacons in indoor:
  - Beacons require changes in the environment -> costly.
  - Limit flexibility and adaptability to changing environments.

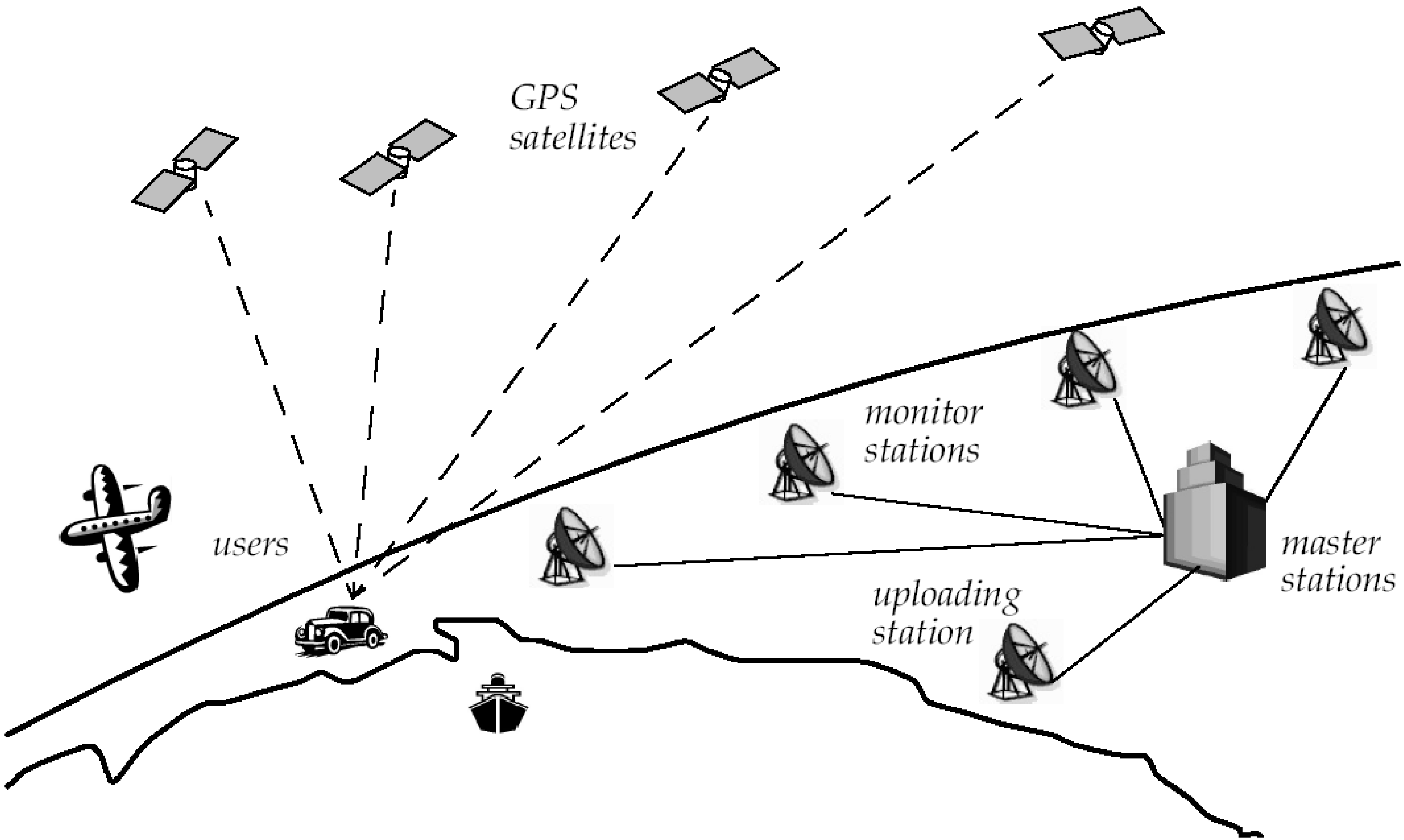


Global Positioning System (GPS) (1)

- *Developed for military use*
- *Recently it became accessible for commercial applications*
- *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 equators*
- *Location of any GPS receiver is determined through a time of flight measurement*

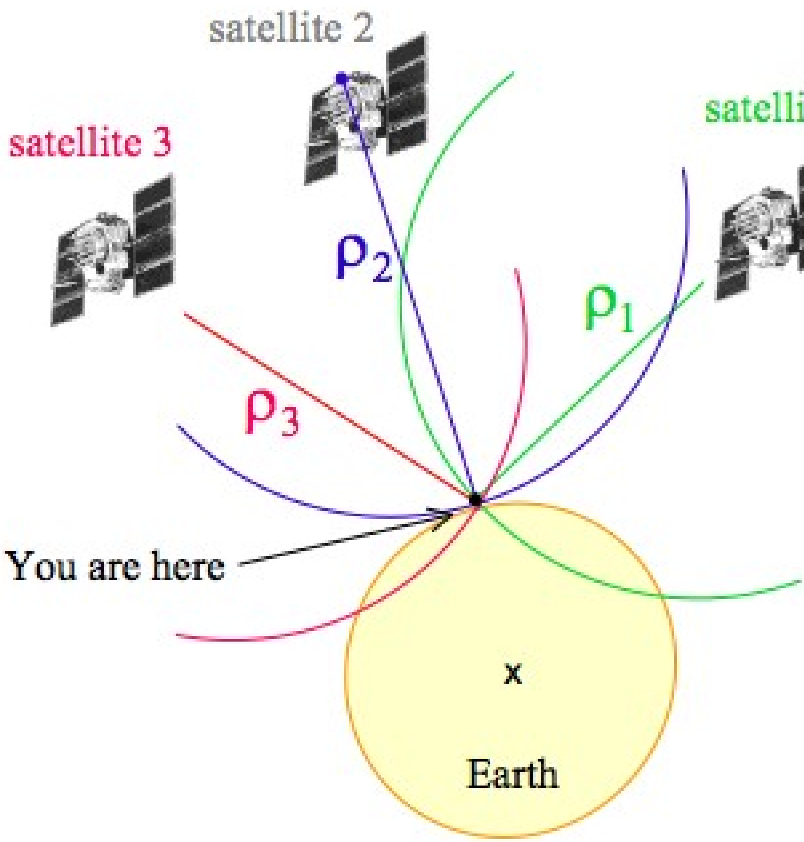
- *Technical challenges:*
  - *Time synchronization between the individual satellites and the GPS receiver*
  - *Real time update of the exact location of the satellites*
  - *Precise measurement of the time of flight*
  - *Interferences with other signals*

Global Positioning System (GPS) (2)



GPS positioning

- *Simple positioning principle*
- *Sattelites send signals, receivers received them with delay*



$$\rho = (t_r - t_e) ´ \text{speed of } light$$

$$\rho = \sqrt{(X_s - X_r)^2 + (Y_s - Y_r)^2 + (Z_s - Z_r)^2}$$

If we know at least three distance Measurements, we can solve for Postion on earth

Characterizing Sensor Performance

- ***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 A/D resolution.***

      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)

Characteristics that are especially relevant for real world environments

- ***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***
- ***Error / Accuracy***
  - ***difference between the sensor's output and the 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***
  - ***e.g. calibration of a laser sensor or of the distortion cause by the optic of a camera***
- ***Random error -> non-deterministic***
  - ***no prediction possible***
  - ***however, they can be described probabilistically***
  - ***e.g. Hue instability of camera, black level noise of camera ..***
- ***Precision***
  - ***reproducibility of sensor results***

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

Characterizing Error: The Challenges in Mobile Robotics

- ***Mobile Robot has to perceive, analyze and interpret the state of the surrounding***
- ***Measurements in real world environment 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 might be well defined in controlled environment. This is not the case for mobile robots !!***

Multi-Modal Error Distributions: The Challenges in …

- ***Behavior of sensors modeled by probability distribution (random errors)***
  - ***usually very little knowledge about the causes of random errors***
  - ***often probability distribution is assumed to be symmetric or even Gaussian***
  - ***however, it is important to realize how wrong this can be!***
  - ***Examples:***
    - ***Sonar (ultrasonic) sensor might overestimate the distance in real environment and is therefore not symmetric***

      Thus the sonar sensor might be best modeled by two modes:
      - mode for the case that the signal returns directly
      - mode for 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***