Perception

Sensors

Vision

Uncertainties, Fusion

Features

4a

2 Perception – *Sensors*

- **4a - Sensors**
  - **case studies**
  - **classification, performance**
  - **technology overview**
- 4b - Vision
- 4c – Uncertainties, Fusion
- 4d - Features
  - Edges
  - Histograms
  - Fingerprints
  - Lines
  - Planes

3 Sensors for Mobile Robots

- Why should a robotics engineer know about sensors?
    - They are the **key components** for perceiving the environment
    - **Understanding the physical principles** enables appropriate use

- Understanding the physical principle behind sensors enables us:
    - To **properly select** the sensors for a given application
    - To **properly model** the sensor system, e.g. resolution, bandwidth, **uncertainties**

4 Example of "Simple" Real World Situations

- A typical play in robocup

- What the robot sees

Curtesy of Manuela Veloso <veloso@cs.cmu.edu >
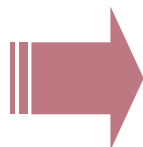*Carnegie Mellon University, veloso@cs.cmu.edu*

5 Dealing with Real World Situations
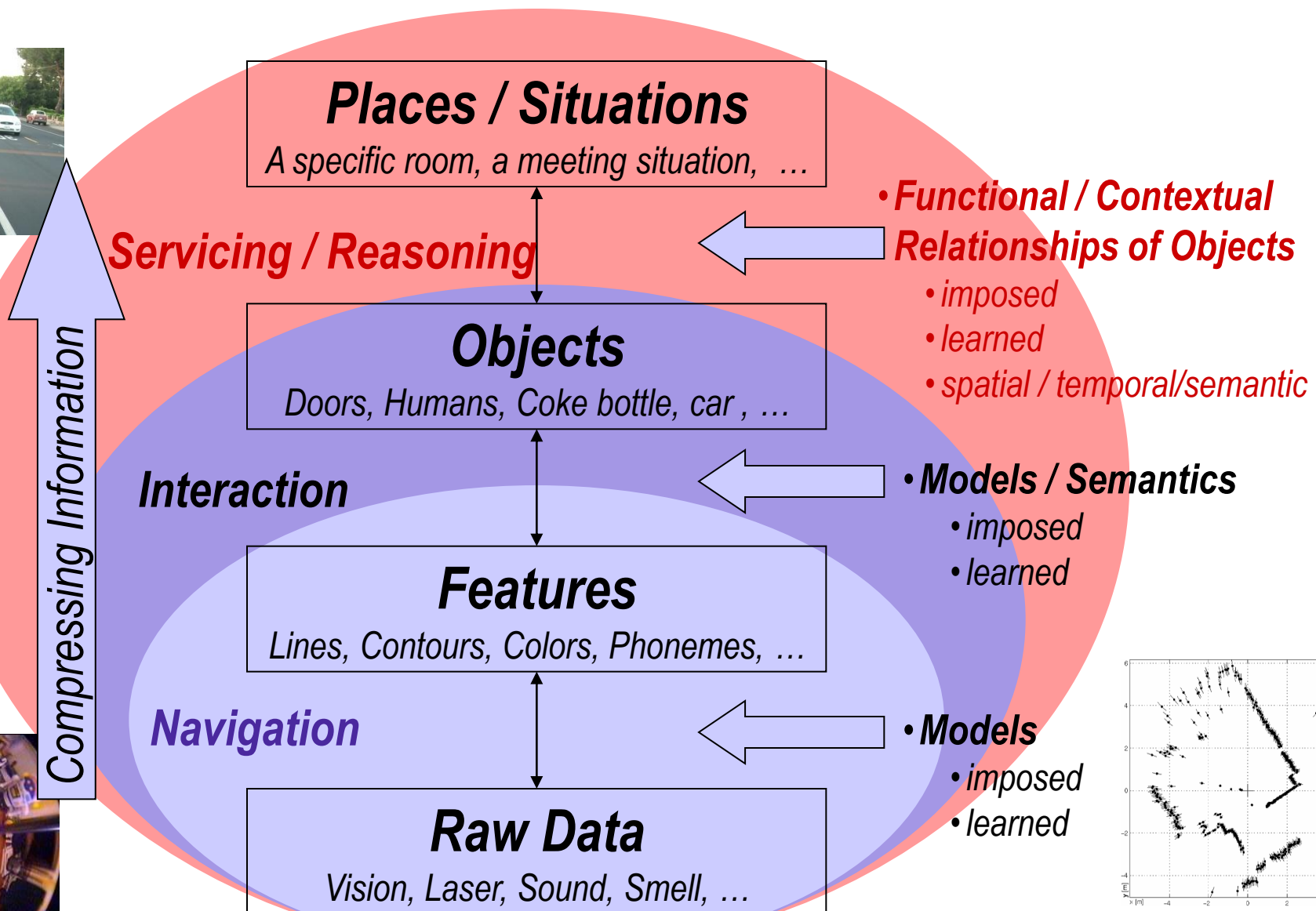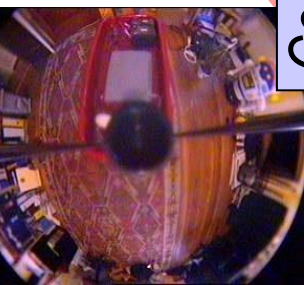
- Reasoning about a situation

- Cognitive systems have to interpret situations based on uncertain and only partially available information
- They need ways to learn functional and contextual information (semantics / understanding)
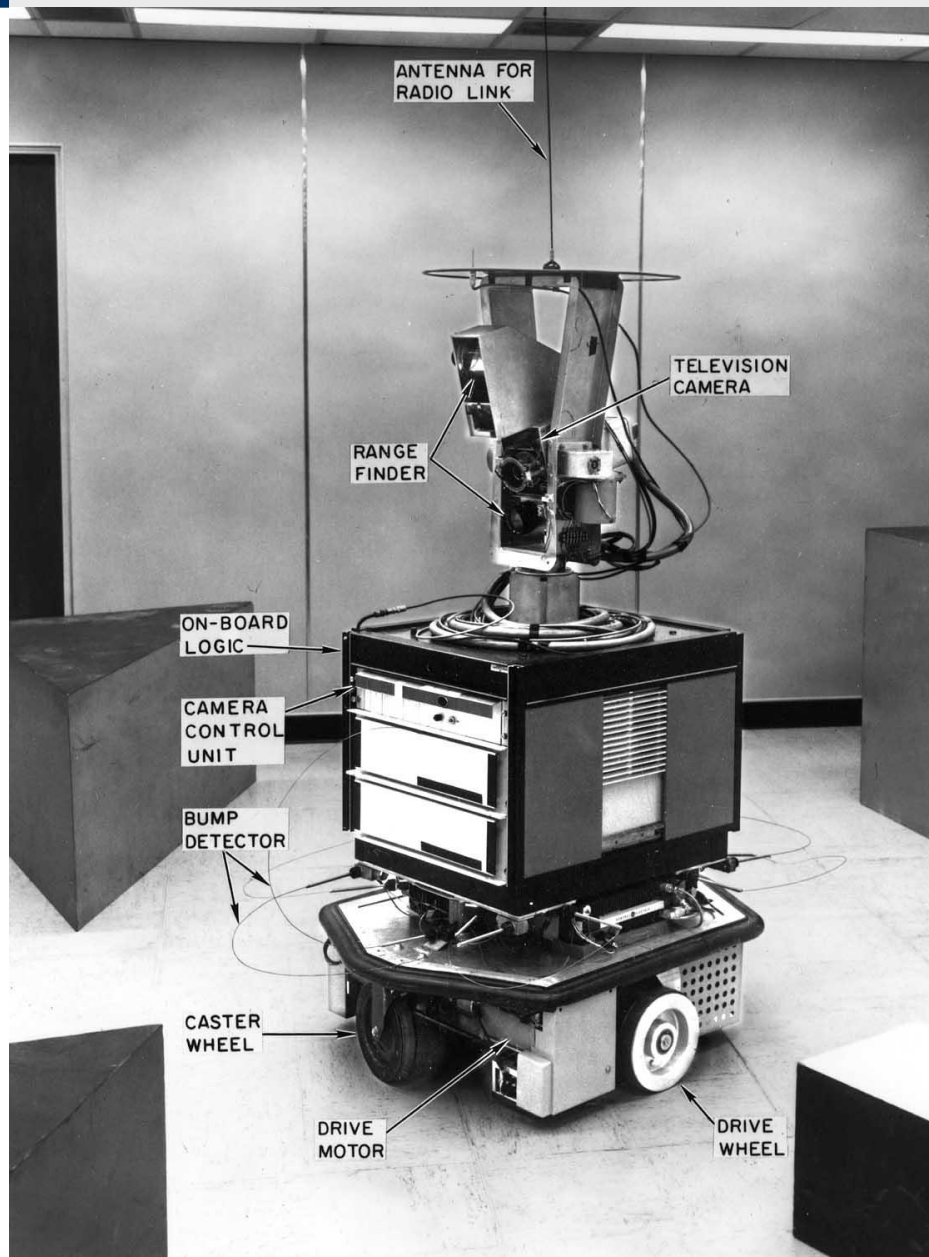
➡ **Probabilistic Reasoning**

Perception for Mobile Robots

Places / Situations

A specific room, a meeting situation, …

Servicing / Reasoning

• Functional / Contextual Relationships of Objects
- *imposed*
- *learned*
- *spatial / temporal/semantic*

Objects

Doors, Humans, Coke bottle, car , …

Interaction

• Models / Semantics
- *imposed*
- *learned*

Compressing Information

Features

Lines, Contours, Colors, Phonemes, …

Navigation

• Models
- *imposed*
- *learned*

Raw Data

Vision, Laser, Sound, Smell, …

Shakey the Robot (1966-1972), SRI International

- Operating environment
  - Indoors
  - Engineered

- Sensors
  - Wheel encoders
  - Bump detector
  - Range finder
  - Camera

© SRI International

Rhino Tourguide Robot (1995-1998), University of Bonn

- **Operating environment**
  - Indoors (Museum: unstructured and dynamic)

- **Sensors**
  - Wheel encoders
  - Ring of sonar sensors
  - Pan-tilt camera

C University of Bonn

11 | BibaBot (2002), BlueBotics SA

- **Operating environment**
  - Indoors and outdoors
  - Onroad only

- **Sensors**
  - Wheel encoders
  - Bumper
  - Sonar sensors
  - Laser range finder
  - Inertial measurement unit
  - Omnidirectional camera
  - Pan-tilt camera

C Bluebotics SA

PR2 (2010-), Willow Garage

- **Operating environment**
  - Indoors and outdoors
  - Onroad only

- **Sensors**
  - Wheel encoders
  - Bumper
  - IR sensors
  - Laser range finder
  - 3D nodding laser range finder
  - Inertial measurement unit
  - Pan-tilt stereo camera with texture projector (active)
  - Pressure sensor and accelerometer inside hands
  - ...

C Willow Garage

© R. Siegwart & D. Scaramuzza, ETH Zurich - ASL

13 Classification of Sensors

- What:
  - 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.
- How:
  - Passive sensors
    - Measure energy coming from the environment
  - Active sensors
    - emit their proper energy and measure the reaction
    - better performance, but some influence on environment

4a

14 General Classification (1)

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	EC	P
	Optical barriers	EC	A
	Noncontact proximity sensors	EC	A
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders	PC	P
	Potentiometers	PC	P
	Synchros, resolvers	PC	A
	Optical encoders	PC	A
	Magnetic encoders	PC	A
	Inductive encoders	PC	A
	Capacitive encoders	PC	A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass	EC	P
	Gyroscopes	PC	P
	Inclinometers	EC	A/P

A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

4a

15 General Classification (2)

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
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 geo- metric 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 analy- sis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

16 Characterizing Sensor Performance (1)

- Basic sensor response ratings

  - Dynamic range
    - **ratio between upper and lower limits**, usually in decibels (dB, power)
    - e.g. power measurement from 1 mW to 20 W

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

    - e.g. voltage measurement from 1 mV to 20 V

$$20 \cdot \log\left[\frac{20}{0.001}\right] = 86 dB \qquad P = U \cdot I = \frac{1}{R}U^2$$

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

17 Characterizing Sensor Performance (2)

- Basic sensor response ratings (cont.)

  - Range
    - **upper limit - lower limit**

  - 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 treated with a computer

$$x \rightarrow f(x)$$
$$y \rightarrow f(y)$$

$$\alpha \cdot x + \beta \cdot y \rightarrow f(\alpha \cdot x + \beta \cdot y) = \alpha \cdot f(x) + \beta \cdot f(y)$$

18 Characterizing Sensor Performance (3)

- Basic sensor response ratings (cont.)

    - 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
        - one has also to consider phase (delay) of the signal

4a

19 *In Situ* Sensor Performance (1)

Characteristics that are especially relevant for real world environments

- Sensitivity
  - ratio of output change to input change $\dfrac{dy}{dx}$

  - however, in real world environment, the sensor has very often high sensitivity to other environmental changes, e.g. illumination

- Cross-sensitivity (and cross-talk)
  - sensitivity to other environmental parameters (e.g. temperature, magnetic field)
  - influence of other active sensors

- Error / Accuracy
  - difference between the sensor's output and the true value

error

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

m = measured value
v = true value

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 caused by the optics of a camera

- Random error -> non-deterministic
    - **no prediction possible with given sensors**
    - however, they can be described probabilistically

- Precision
    - ***reproducibility* of sensor results:** $precision = \dfrac{range}{\sigma}$

Sensors: outline

- Optical encoders
- Heading sensors
  - Compass
  - Gyroscopes
- Accelerometer
- IMU
- GPS
- Range sensors
  - Sonar
  - Laser
  - Structured light
- Vision (next lecture)

Encoders

- Definition:
  - **electro-mechanical device** that converts linear or angular position of a shaft to an analog or digital signal, making it an linear/anglular transducer

Scaramuzza, ETH Zurich - ASL
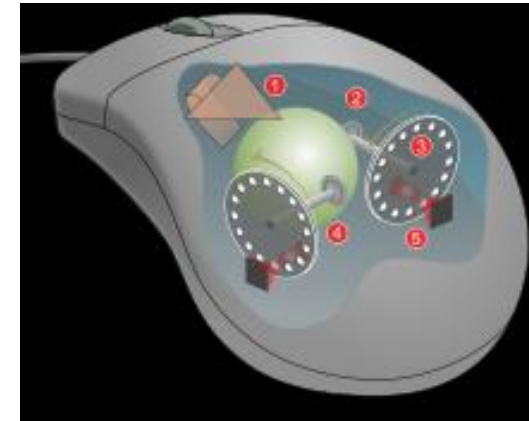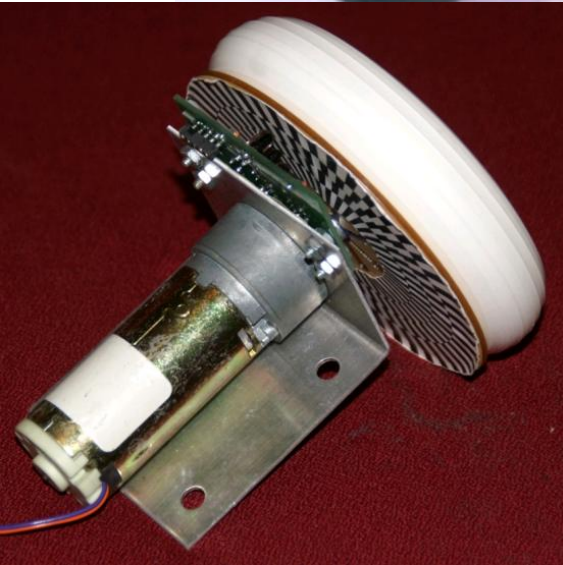
23 | Wheel / Motor Encoders

- Use cases
    - **measure position** or speed of the wheels or steering
    - **integrate wheel movements** to get an estimate of the position -> odometry
    - optical encoders are proprioceptive sensors
    - typical resolutions: 64 - 2048 increments per revolution.
    - for high resolution: interpolation

- Working principle of optical encoders
    - regular: counts the number of transitions but cannot tell the direction of motion
    - quadrature: uses two sensors in quadrature-phase shift. The ordering of which wave produces a rising edge first tells the direction of motion. Additionally, resolution is 4 times bigger
    - a single slot in the outer track generates a reference pulse per revolution
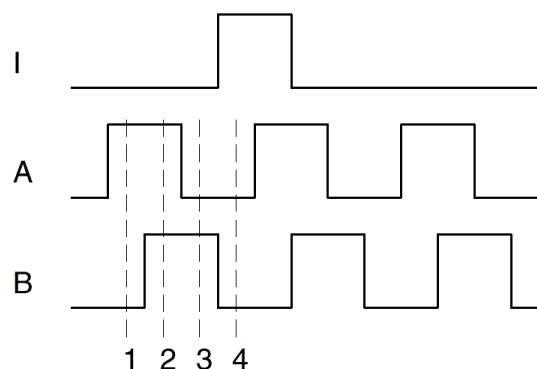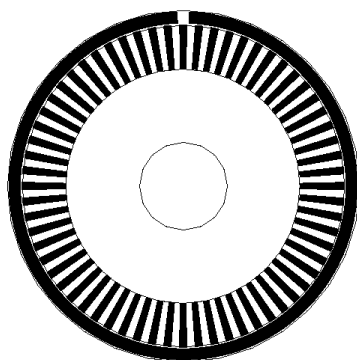
State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

Wheel / Motor Encoders (2)

Wheel / Motor Encoders (3)

scanning
reticle fields

scale
slits
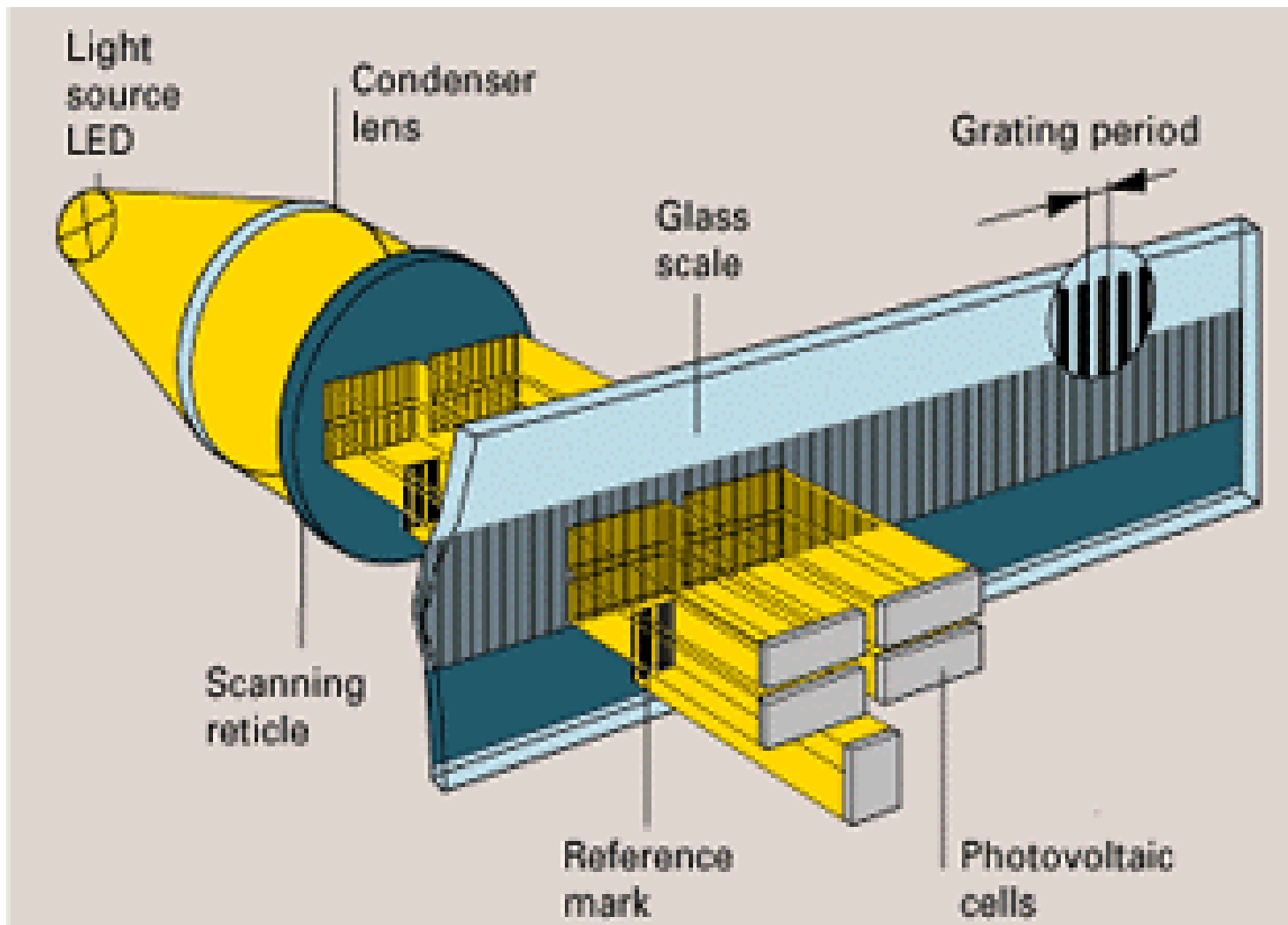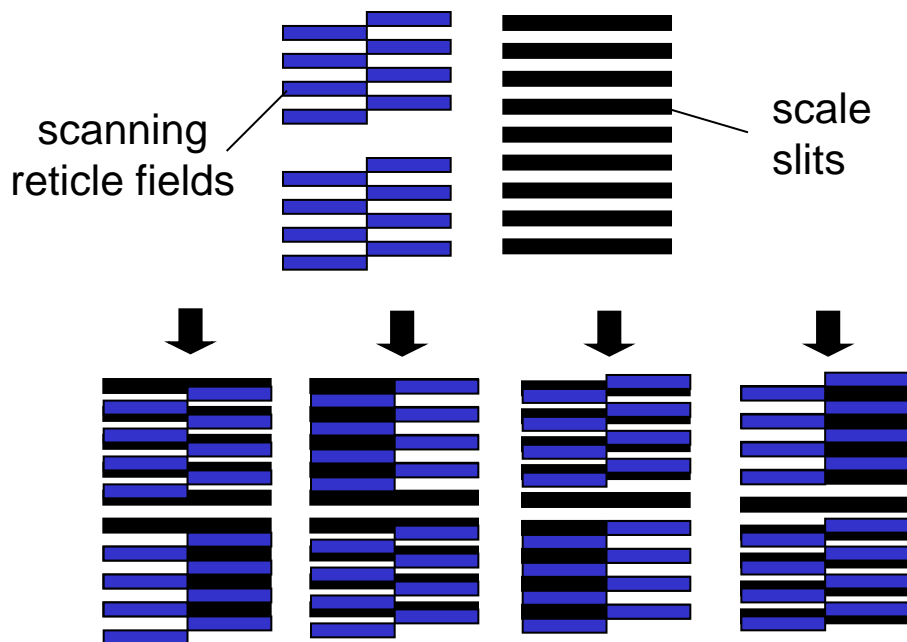
Notice what happens when the direction changes:
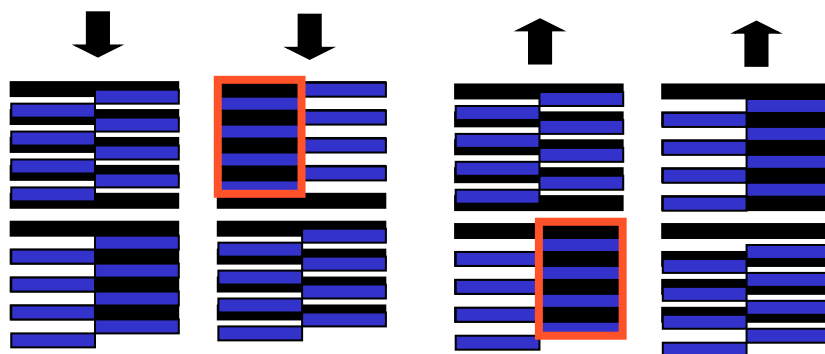
2. Main Characteristics
- The four fields on the scanning reticle are shifted in phase relative to each other by one quarter of the grating period, which equals 360°/(number of lines)
- This configuration allows the detection of a change in direction
- Easy to interface with a micro-controller

26 Heading Sensors

- Definition:
  - Heading sensors are sensors that determine the robot's orientation and inclination.

- Heading sensors can be proprioceptive (gyroscope, accelerometer) or exteroceptive (compass, inclinometer).
- Allows, together with an appropriate velocity information, to integrate the movement to a position estimate.
  - This procedure is called **deduced reckoning** (ship navigation)

27 Compass

- Used since before 2000 B.C.
  - when Chinese suspended a piece of natural magnetite from a silk thread and used it to guide a chariot over land.

- Magnetic field on earth
  - absolute measure for orientation (even birds use it for migrations (2001 discovery))

- Large variety of solutions to measure the earth magnetic field
  - mechanical magnetic compass
  - Gyrocompass
  - direct measure of the magnetic field (Hall-effect, magneto-resistive sensors)

- Major drawback
  - weakness of the earth field (30 µTesla)
  - easily disturbed by magnetic objects or other sources
  - bandwidth limitations (0.5 Hz) and susceptible to vibrations
  - **not suitable for indoor environments for absolute orientation**
  - useful indoor (only locally)

Magnetic field (*B*)
cell
t
Semiconductor
I
Hall voltage
d
(resourcefulphysics.org)
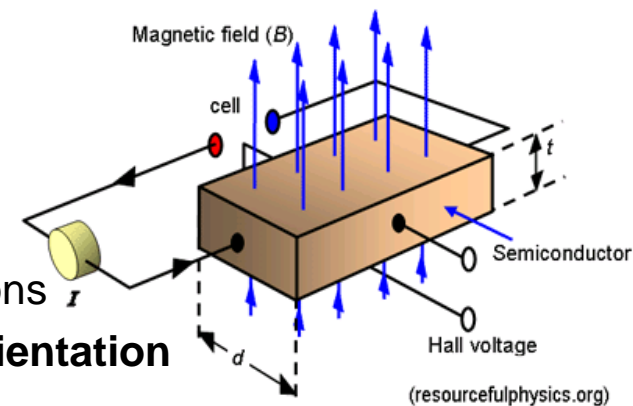
Gyroscope

- Definition:
  - Heading sensors that preserve their orientation in relation to a fixed reference frame
  - They provide an absolute measure for the heading of a mobile system.
- Two categories, the mechanical and the optical gyroscopes
  - Mechanical Gyroscopes
    - Standard gyro (angle)
    - Rate gyro (speed)
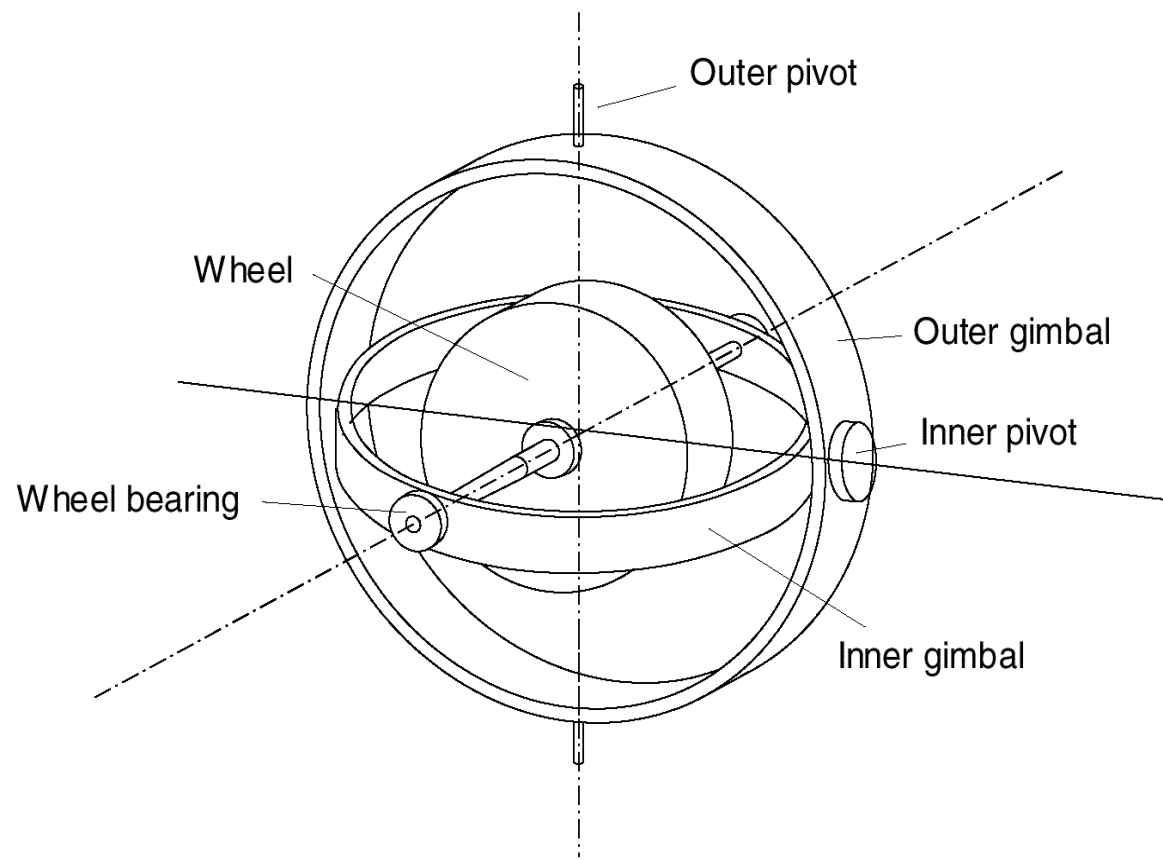 - Optical Gyroscopes
    - Rate gyro (speed)

29 Mechanical Gyroscopes

- Concept:
  - Inertial properties of a fast spinning rotor
  - Angular momentum associated with a spinning wheel keeps the axis of the gyroscope inertially stable.
- **No torque can be transmitted from the outer pivot to the wheel axis**
  - spinning axis will therefore be space-stable
  - however friction in the axes bearings will introduce torque and so drift ->precession
- Quality: 0.1° in 6 hours (a high quality mech. gyro costs up to 100,000 $)
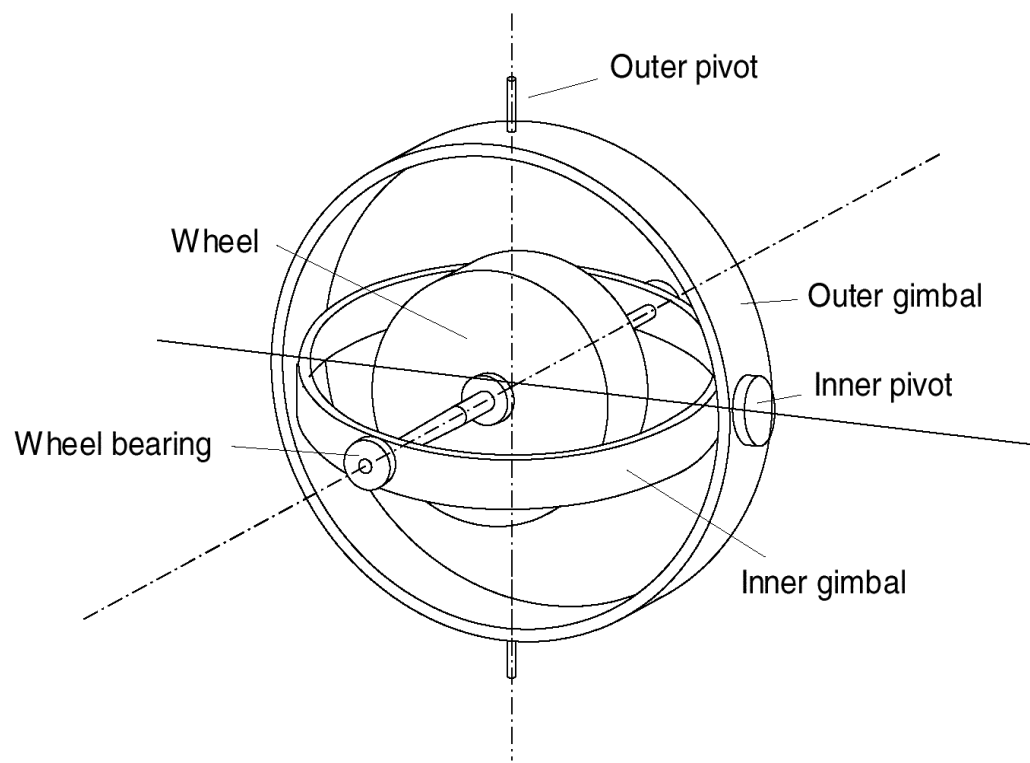
30 Rate gyros

- Same basic arrangement shown as regular mechanical gyros

- But: gimbals are restrained by torsional springs
  - enables to measure angular speeds instead of the orientation.

31 | Optical Gyroscopes

- Optical gyroscopes
  - angular speed (heading) sensors using two monochromic light (or laser) beams from the same source.
  - One is traveling in a fiber clockwise, the other counterclockwise around a cylinder
- Laser beam traveling in direction opposite to the rotation
  - slightly shorter path
  - phase shift of the two beams is proportional to the angular velocity Ω of the cylinder
  - In order to measure the phase shift, coil consists of as much as 5Km optical fiber
- New solid-state optical gyroscopes based on the same principle are build using microfabrication technology.
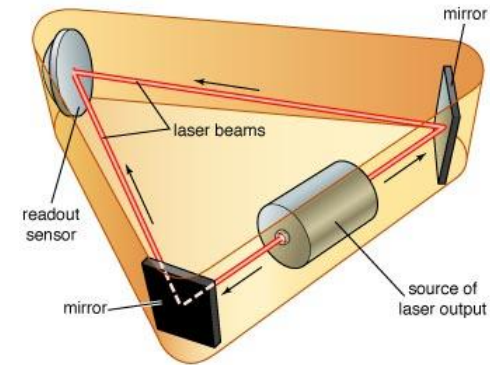
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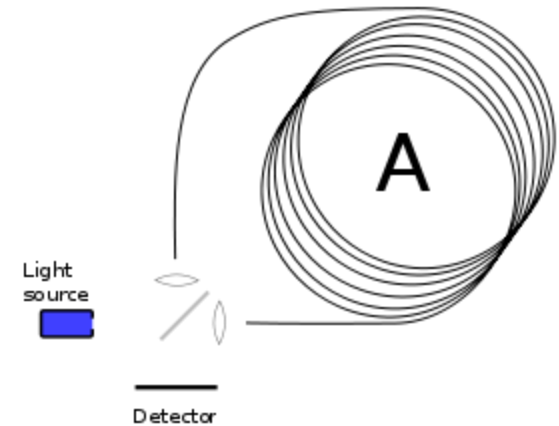
Single axis optical gyro   3-axis optical gyro

Mechanical Accelerometer

- Accelerometers measure all external forces acting upon them, including gravity

- accelerometer acts like a spring–mass–damper system

$$F_{applied} = F_{inertial} + F_{damping} + F_{spring} = m\ddot{x} + c\dot{x} + kx$$

  Where *m* is the proof mass, *c* the damping coefficient, *k* the spring constant

- at steady-state: $a_{applied} = \dfrac{kx}{m}$

Spring

Mass

Damper
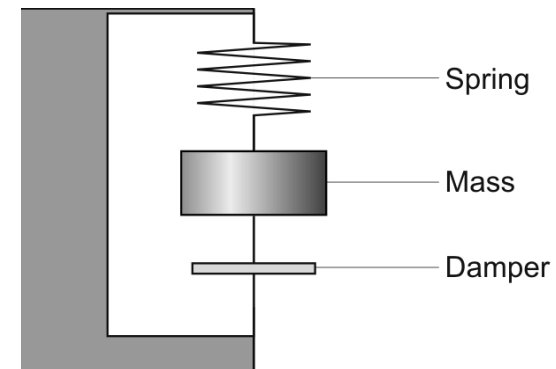
Mechanical Accelerometer

- On the Earth's surface, the accelerometer always indicates 1g along the vertical axis

- To obtain the inertial acceleration (due to motion alone), the gravity must be subtracted. Conversely, the device's output will be zero during free fall

- Bandwidth up to 50 KHz

- An accelerometer measures acceleration only along a single axis. By mounting three accelerometers orthogonally to one another, a three-axis accelerometer can be obtained

Factsheet: MEMS Accelerometer (1)

seismic mass

motion

capacitive
divider

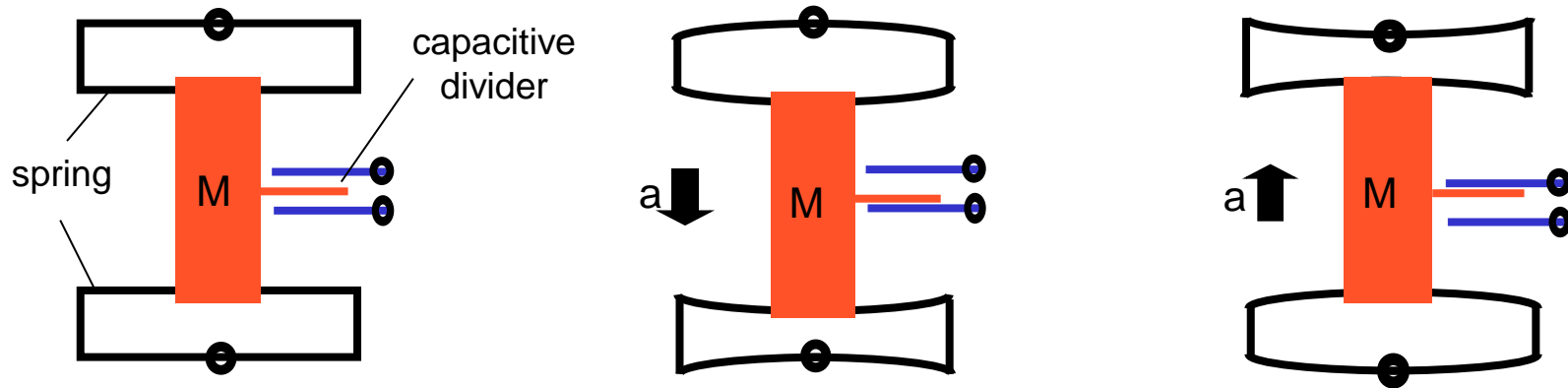<http://www.mems.sandia.gov/>
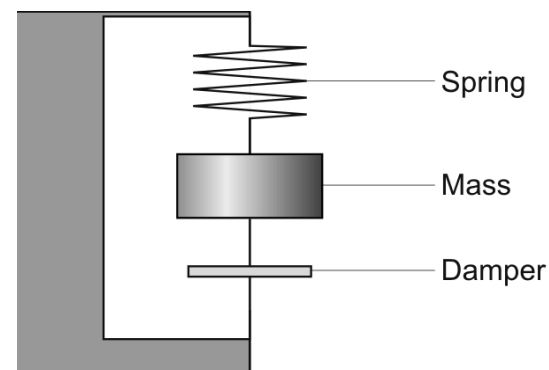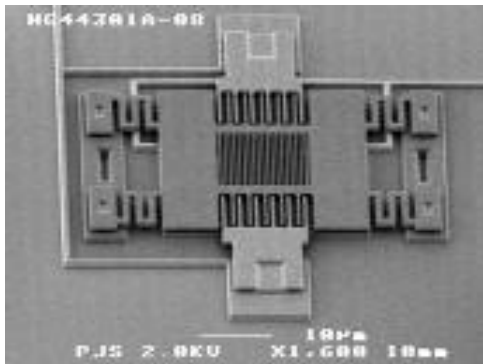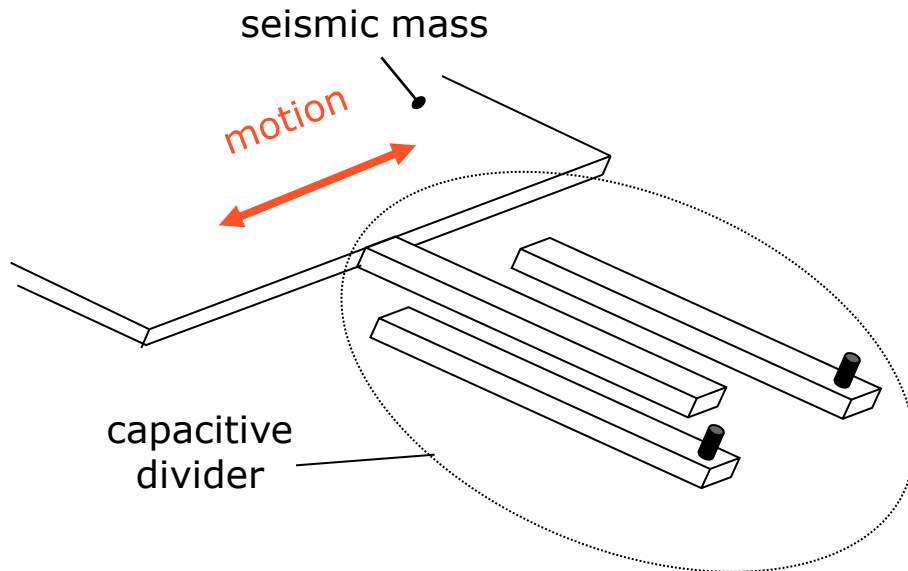
1. Operational Principle

The primary transducer is a vibrating mass that relates acceleration to displacement. The secondary transducer (a capacitive divider) converts the displacement of the seismic mass into an electric signal.
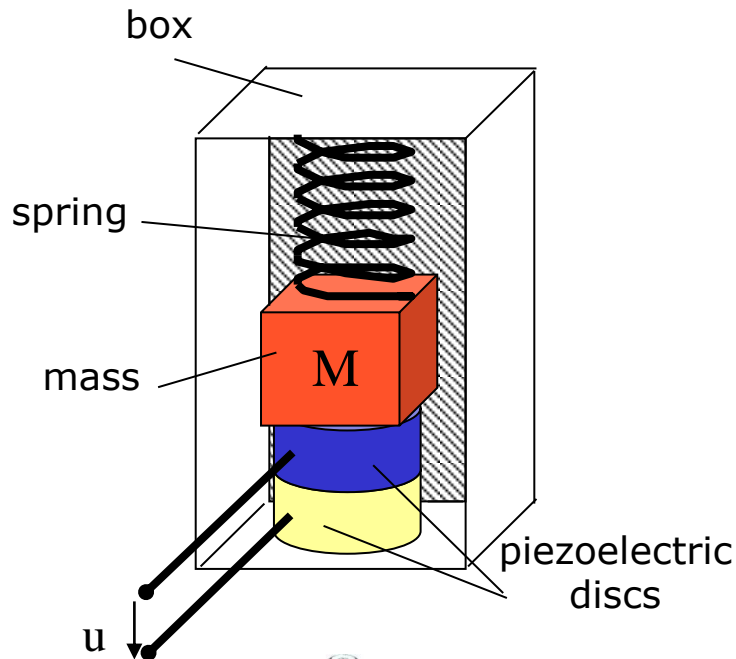
2. Main Characteristics
- Can be multi-directional
- Various sensing ranges from 1 to 50 g

3. Applications
- Dynamic acceleration
- Static acceleration (inclinometer)
- Airbag sensors (+- 35 g)
- Control of video games (Wii)

Factsheet: MEMS Accelerometer (2)

capacitive
divider

spring

M   M   M

a   a

Factsheet: Piezoelectric Accelerometer

box

spring

mass

M

u

piezoelectric discs

<http://www.pcb.com/>

1. Operational Principle

Primary transducer is typically a single-degree-of-freedom spring-mass system that relates acceleration to displacement. Secondary transducer (piezoelectric discs) converts displacement of the seismic mass into an electrical signal (voltage).

2. Main Characteristics

- Piezoelectric elements cannot produce a signal under constant acceleration (i.e., static) conditions
- 2-D and 3-D accelerometers can be created by combining 2 or 3 1-D modules

3. Applications

- Vibration analysis
- Machine diagnostics
- Active vehicle suspension
- Autonomously guided vehicles
- Earthquake sensors
- Modal analysis

Inertial Measurement Unit (IMU)

- **Definition**
  - **An inertial measurement unit (IMU) is a device that uses** measurement systems such as **gyroscopes and accelerometers** to estimate the relative position (x, y, z), orientation (roll, pitch, yaw), velocity, and acceleration of a moving vehicle.

- In order to estimate motion, the gravity vector must be subtracted. Furthermore, initial velocity has to be known.

- i**IMUs are extremely sensitive to measurement errors i**n gyroscopes and accelerometers: **drift in the gyroscope** unavoidably undermines the estimation of the vehicle orientation relative to gravity, which results in incorrect cancellation of the gravity vector. Additionally observe that, because the **accelerometer data is integrated twice** to obtain the position, any residual gravity vector results in a quadratic error in position.

- After long period of operation, **all IMUs drift.** To cancel it, some external reference like GPS or cameras has to be used.

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.

© R.
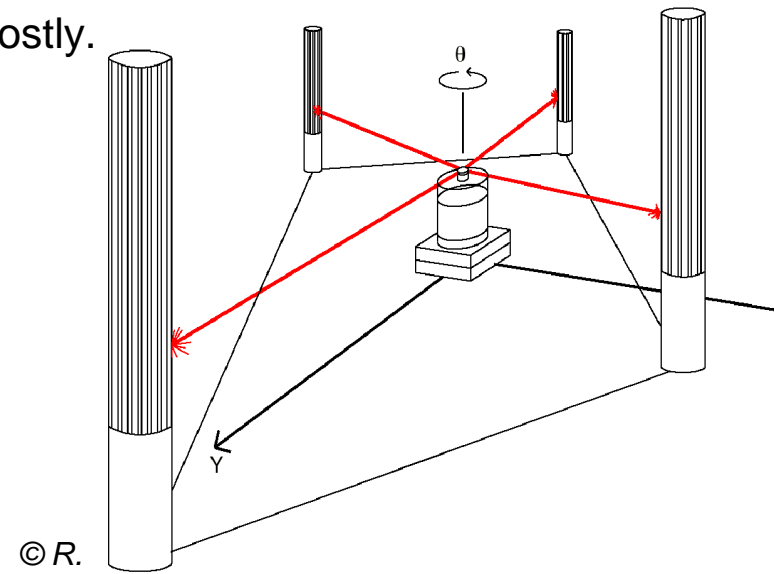
Global Positioning System (GPS) (1)

- Facts
  - Recently it became accessible for commercial applications (1995)
  - 24+ satellites orbiting the earth every 12 hours at a height of 20.190 km.
  - 4 satellites are located in each of 6 orbits with 60 degrees orientation between each other.
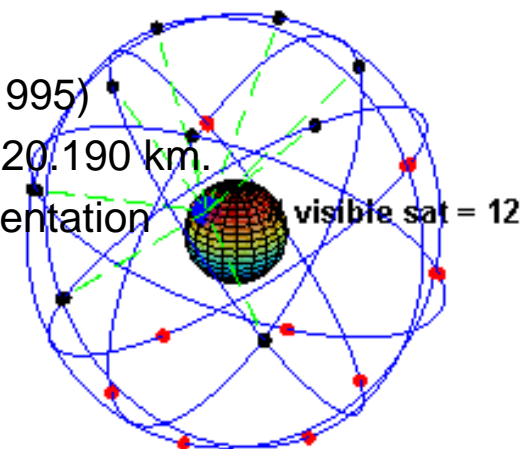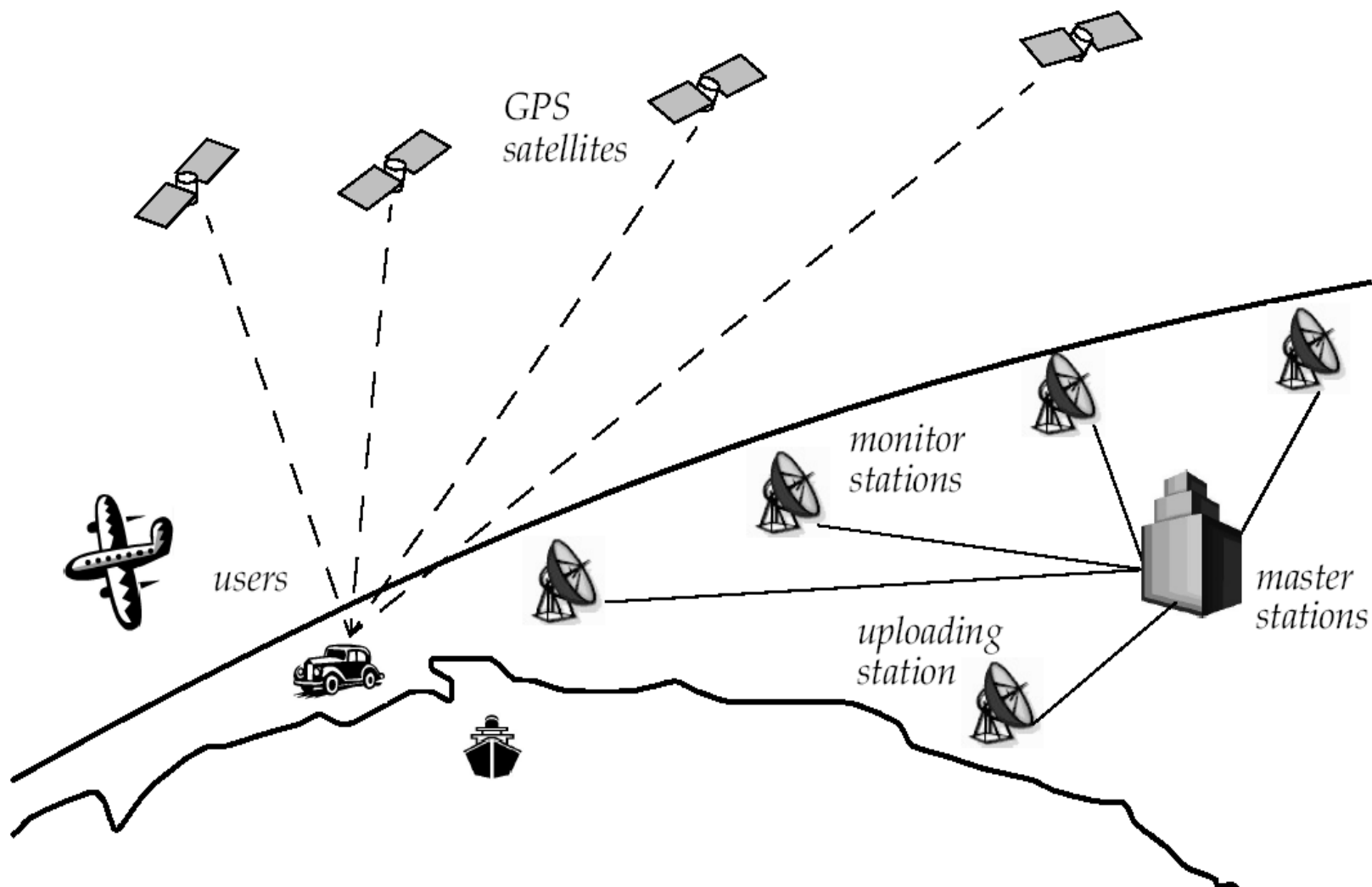
- Working Principle
  - Location of any GPS receiver is determined through a time of flight measurement (satellites send orbital location (*ephemeris*) plus time; the receiver computes its location through **trilateration** and **time correction**)

- 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)

Global Positioning System (GPS) (3)

- Time synchronization:
    - atomic clocks on each satellite
    - monitoring them from different ground stations.
- Ultra-precision time synchronization is extremely important
    - electromagnetic radiation propagates at light speed
- **Light travels roughly 0.3 m per nanosecond**
    - position accuracy proportional to precision of time measurement
- **Real time update of the exact location of the satellites:**
    - monitoring the satellites from a number of widely distributed ground stations
    - master station analyses all the measurements and transmits the actual position to each of the satellites
- **Exact measurement of the time of flight**
    - the receiver correlates a pseudocode with the same code coming from the satellite
    - The delay time for best correlation represents the time of flight.
    - **quartz clock on the GPS receivers are not very precise**
    - the range measurement with four satellite allows to identify the three values (x, y, z) for the position and the clock correction ΔT
- Recent commercial GPS receiver devices allows position accuracies down to a couple meters.
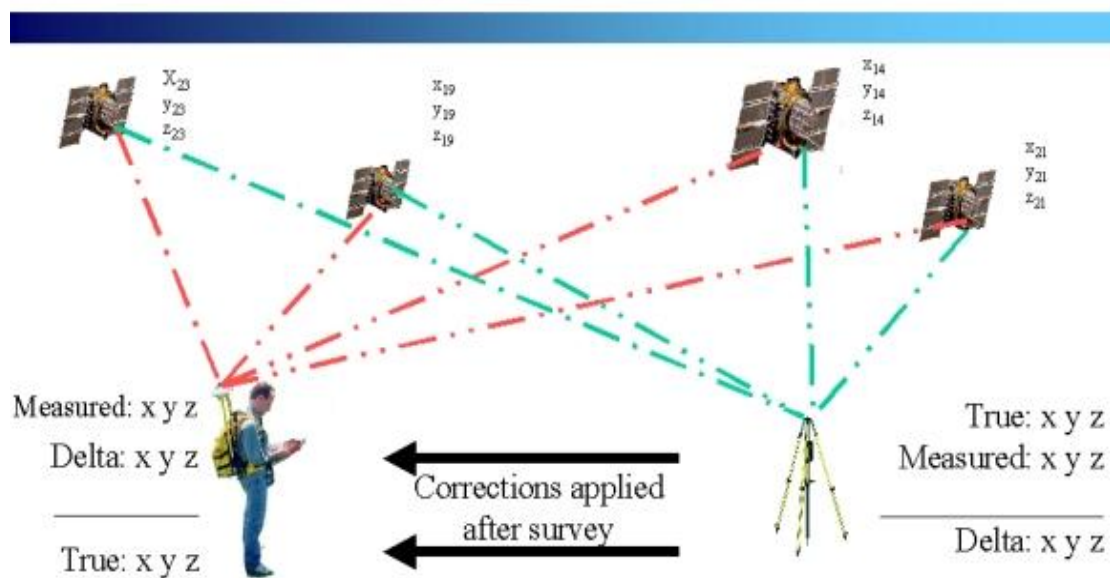
GPS Error Sources

- Ephemeris data errors: 1 meter
- Tropospheric delays: 1 meter.
  - The troposphere is the lower part (ground level to from 8 to 13 km) of the atmosphere that experiences the changes in temperature, pressure, and humidity associated with weather changes. Complex models of tropospheric delay require estimates or measurements of these parameters.
- Unmodeled ionosphere delays: 10 meters.
  - The ionosphere is the layer of the atmosphere from 50 to 500 km that consists of ionized air. The transmitted model can only remove about half of the possible 70 ns of delay leaving a ten meter un-modeled residual.
- Multipath: 0.5 - 100 meters.
  - Multipath is caused by reflected signals from surfaces near the receiver that can either interfere with or be mistaken for the signal that follows the straight line path from the satellite. Multipath is difficult to detect and sometime hard to avoid.
- Number of satellites under line of sight

Differential Global Positioning System (dGPS) (4)

- DGPS requires that a GPS receiver, known as the **base station**, be set up on a **precisely known location.** The base station receiver calculates its position based on satellite signals and compares this location to the known location. The difference is applied to the GPS data recorded by the roving GPS receiver
- **position accuracies in sub-meter to cm range**

Differential GPS

Measured: x y z
Delta: x y z
_____
True: x y z

Corrections applied after survey

True: x y z
Measured: x y z
_____
Delta: x y z

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
National Ocean Service
National Geodetic Survey

Positioning America for the Future

Range sensors

- Sonar

- Laser range finder

- Time of Flight Camera

- Structured light
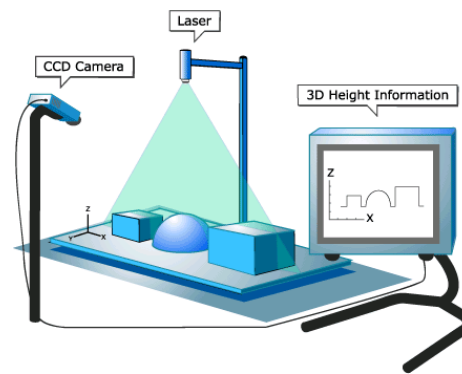
46 Range Sensors (time of flight) (1)

- Large range distance measurement → thus 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

$$d = c \cdot t$$

- 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 of electromagnetic signals: 0.3 m/ns,**
  - **Electromagnetic signals travel one million times faster.**
  - 3 meters
    - Equivalent to 10 ms for an ultrasonic system
    - Equivalent to only 10 ns for a laser range sensor
    - Measuring time of flight with electromagnetic signals is not an easy task
    - laser range sensors expensive and delicate

- The quality of time of flight range sensors mainly depends on:
  - **Inaccuracies** in the time of fight **measurement** (laser range sensors)
  - **Opening angle** of transmitted beam (especially ultrasonic range sensors)
  - Interaction with the target (surface, specular reflections)
  - **Variation of propagation speed (sound)**
  - **Speed of mobile robot and target (if not at stand still)**

Factsheet: Ultrasonic Range Sensor
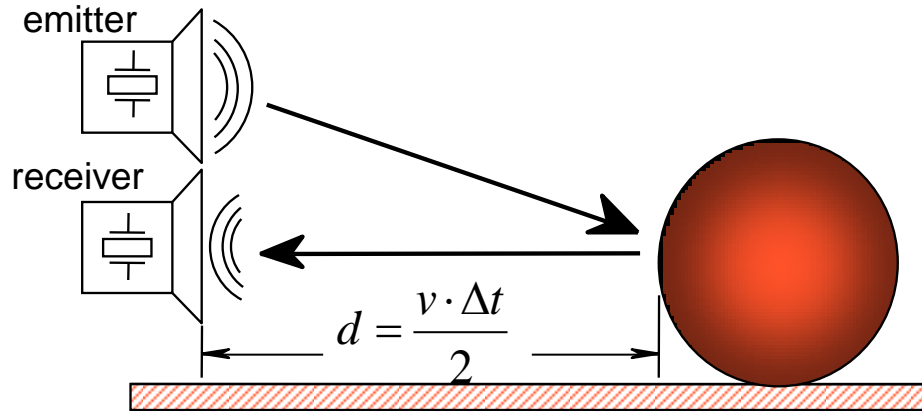
$$d = \frac{v \cdot \Delta t}{2}$$

<http://www.robot-electronics.co.uk/ shop/Ultrasonic_Rangers1999.htm>

1. Operational Principle

An ultrasonic pulse is generated by a piezo-electric emitter, reflected by an object in its path, and sensed by a piezo-electric receiver. Based on the speed of sound in air and the elapsed time from emission to reception, the distance between the sensor and the object is easily calculated.

2. Main Characteristics

- Precision influenced by angle to object (as illustrated on the next slide)
- Useful in ranges from several cm to several meters
- **Typically relatively inexpensive**

3. Applications

- Distance measurement (also for transparent surfaces)
- Collision detection

4a

49 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

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

  γ : adiabatic index (isentropic expansion factor) - ratio of specific heats of a gas
  R: gas constant
  T: temperature in degree Kelvin

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

- typical frequency: 40kHz - 180 kHz
  - Lower frequencies correspond to longer maximal sensor range
- generation of sound wave via piezo transducer
  - transmitter and receiver can be separated or not separated
- **Range between 12 cm up to 5 m**
- **Resolution of ~ 2 cm**
- Accuracy 98% → relative error 2%
- sound beam propagates in a cone (*approx.*)
 - **opening angles around 20 to 40 degrees**
  - regions of constant depth
  - segments of an arc (sphere for 3D)
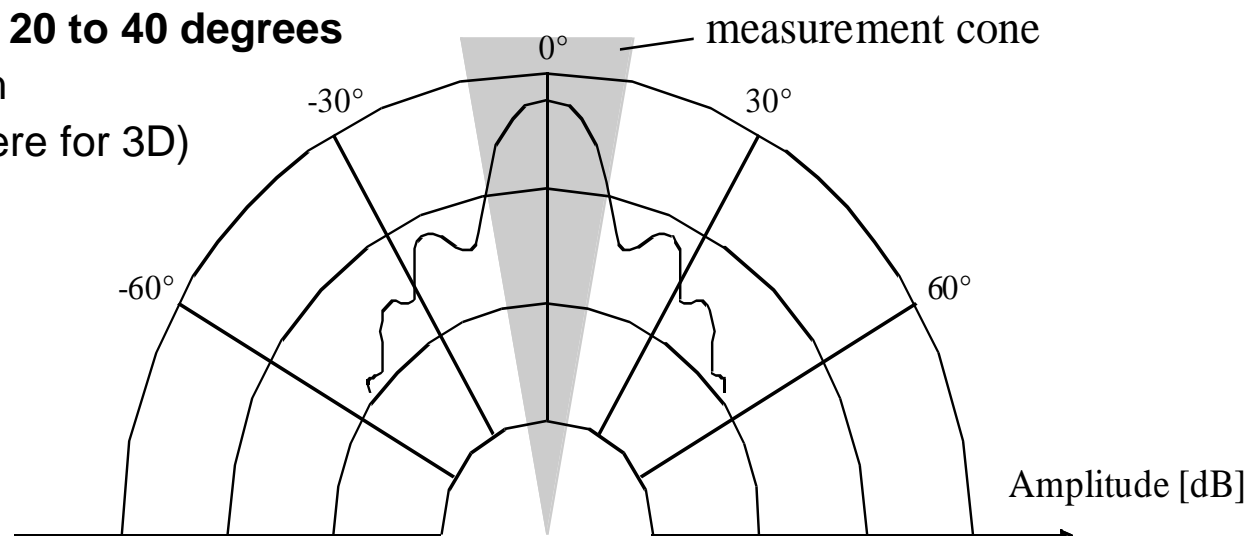
Typical intensity distribution of a ultrasonic sensor

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

- Other problems for ultrasonic sensors
  - soft surfaces that **absorb** most of the sound energy
  - surfaces that are fare from being perpendicular to the direction of the sound → **specular reflections**

CORNER

PLANE

CYLINDER

a) 360° scan

0.5 meters
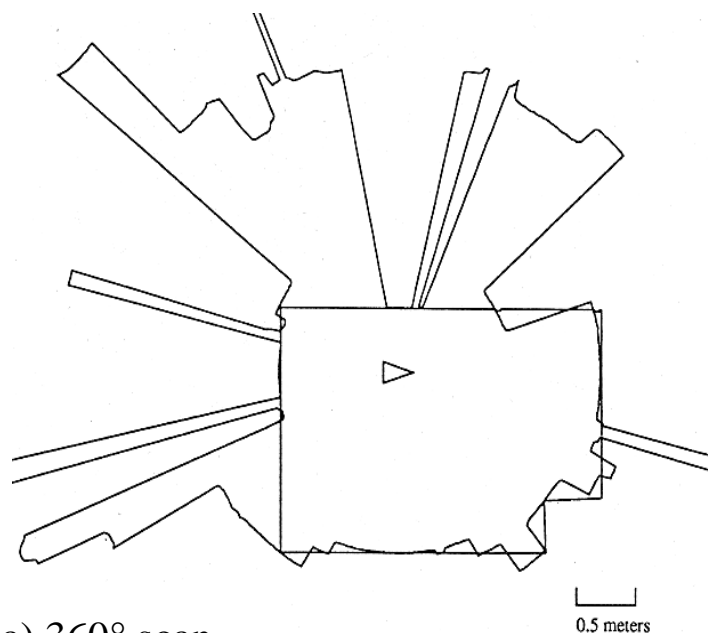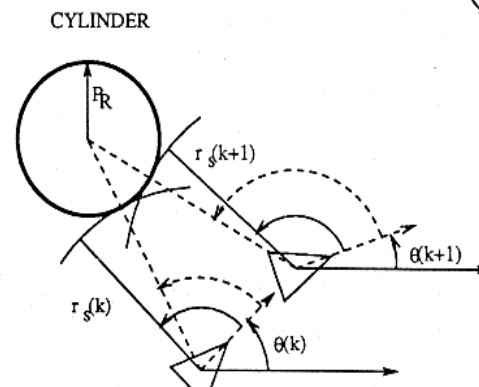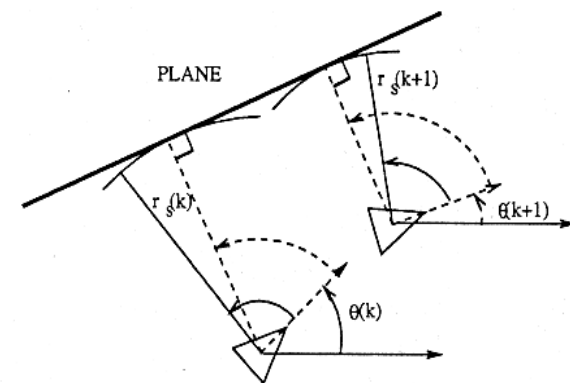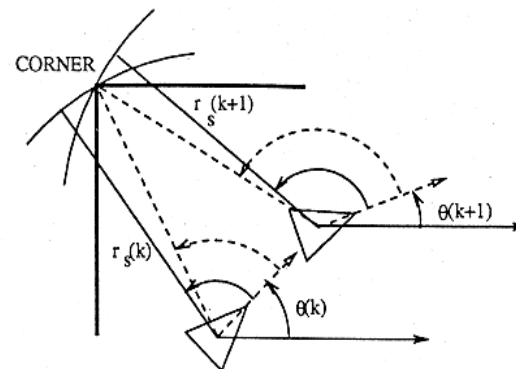
b) results from different geometric primitives

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

- Bandwidth

  - **measuring the distance to an object that is 3 m away will take such a sensor 20 ms, limiting its operating speed to 50 Hz**. But if the robot has a **ring of 20 ultrasonic sensors**, each firing sequentially and measuring to minimize interference between the sensors, then the ring's cycle time becomes 0.4 seconds => frequency of each one sensor = **2.5 Hz.**

  - This update rate can have a measurable impact on the maximum speed possible while still sensing and avoiding obstacles safely.

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

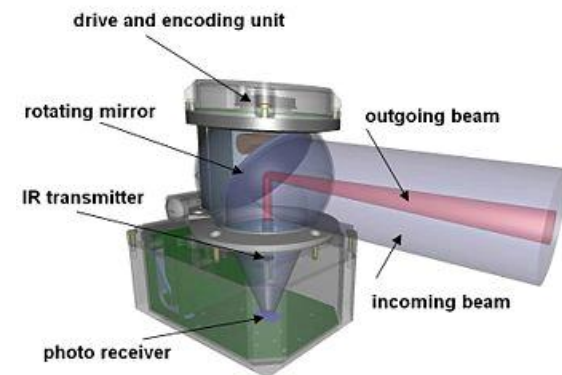- Laser range finder are also known as Lidar (LIght Detection And Ranging)

SICK

Alaska-IBEO

Hokuyo

Rotating lasers platform

Omnidirectional camera

Perspective camera

Static laser

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

Transmitter

D

L

Phase Measurement

P

Target

——— *Transmitted Beam*

– – – – *Reflected Beam*
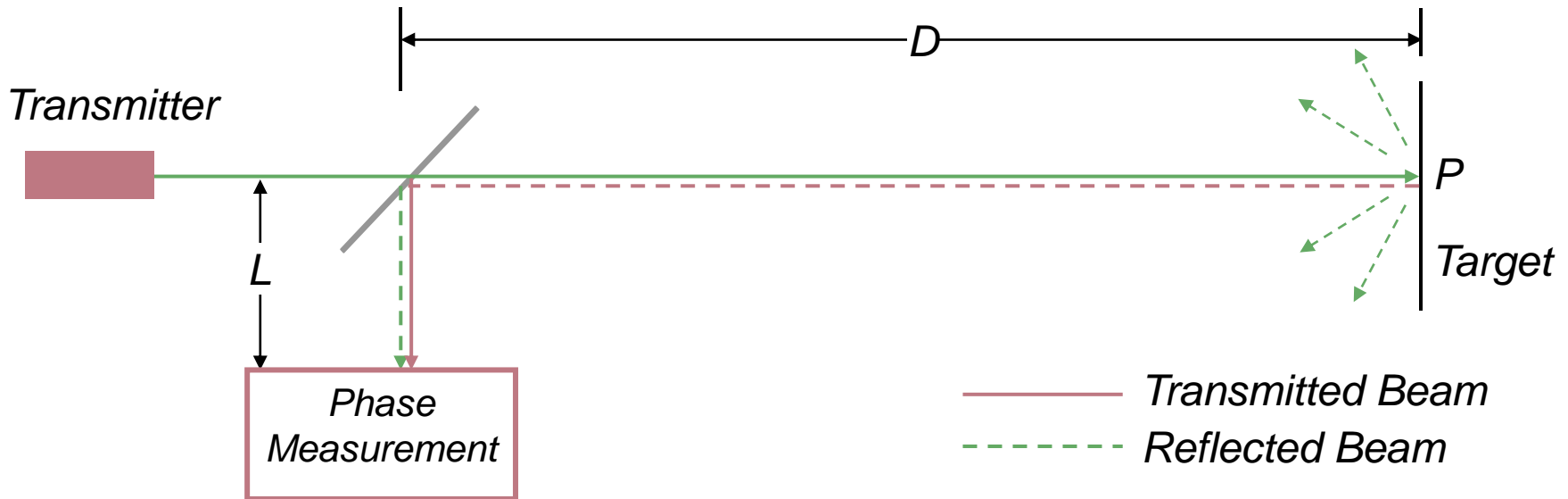
- Transmitted and received beams coaxial
- Transmitter illuminates a target with a collimated laser beam
- Receiver detects the time needed for round-trip
- A mechanical mechanism with a mirror sweeps
  - 2D or 3D measurement

drive and encoding unit

rotating mirror

outgoing beam

IR transmitter

incoming beam

photo receiver

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

- Operating Principles:
  - Pulsed laser (today the standard)
    - measurement of elapsed time directly
    - resolving picoseconds
  - Phase shift measurement to produce range estimation
    - technically easier than the above method

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

- *Phase-Shift Measurement*

Transmitter

D

L

Phase
Measurement

P

Target

——— Transmitted Beam
- - - - Reflected Beam
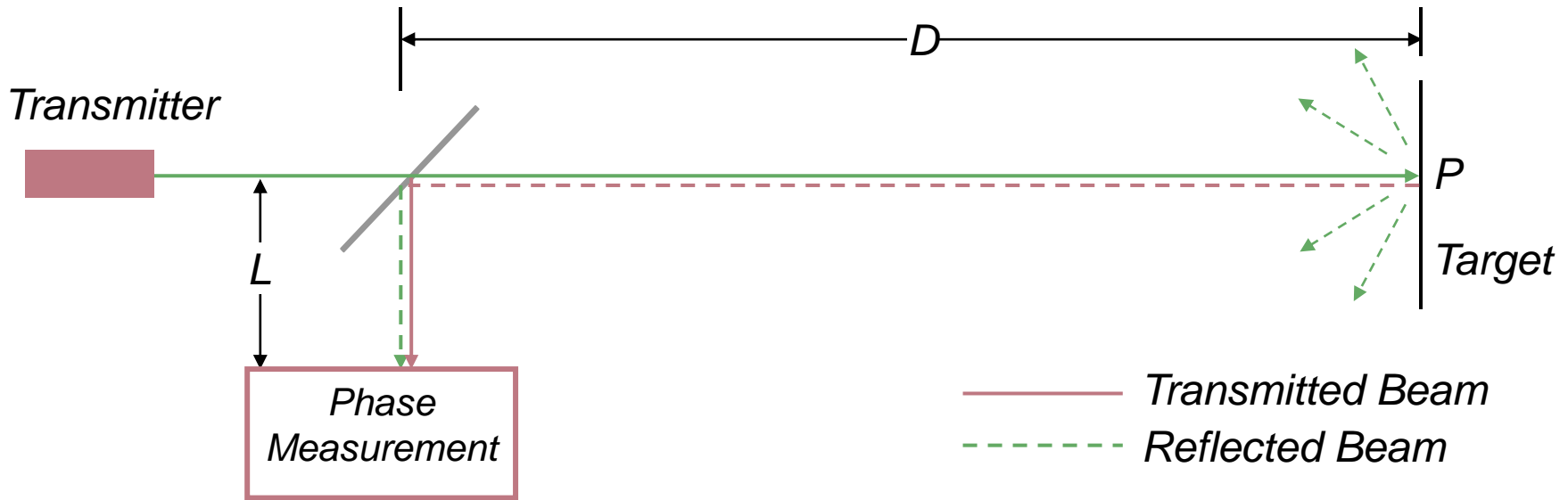
$$D' = L + 2D = L + \frac{\theta}{2\pi}\lambda \qquad \lambda = \frac{c}{f}$$

Where:

c: is the speed of light; f the modulating frequency; D' the distance covered by the emitted light is.

- for $f = 5$ MHz (as in the A.T&T. sensor), $\lambda = 60$ meters

58 Laser Range Sensor (time of flight, electromagnetic) (4)

- Distance D, between the beam splitter and the target

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

- where
 - θ: phase difference between transmitted and reflected beam
- Theoretically ambiguous range estimates
  - since for example if λ = 60 meters, a target at a range of 5 meters = target at 35 meters
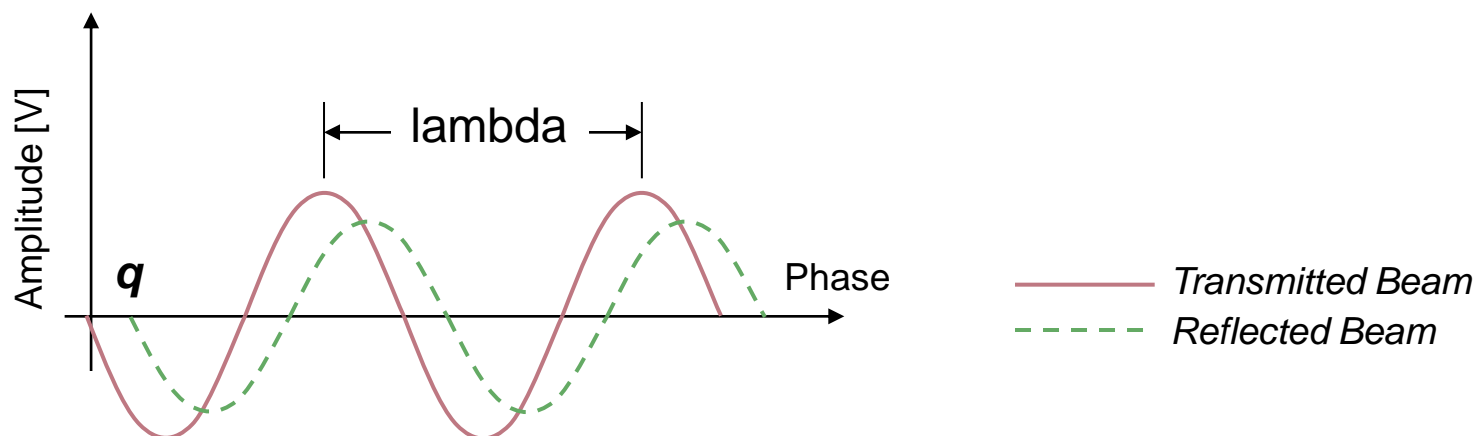
Laser Range Sensor (time of flight, electromagnetic) (5)

- Uncertainty of the range (phase/time estimate) is inversely proportional to the square of the received signal amplitude.
  - Hence dark, distant objects will not produce such good range estimated as closer brighter objects …
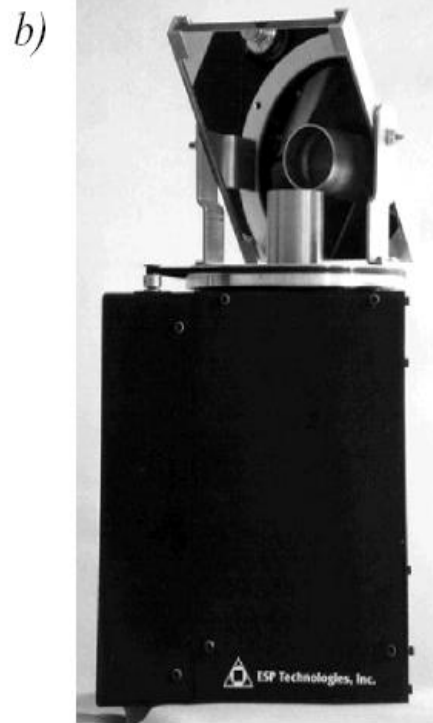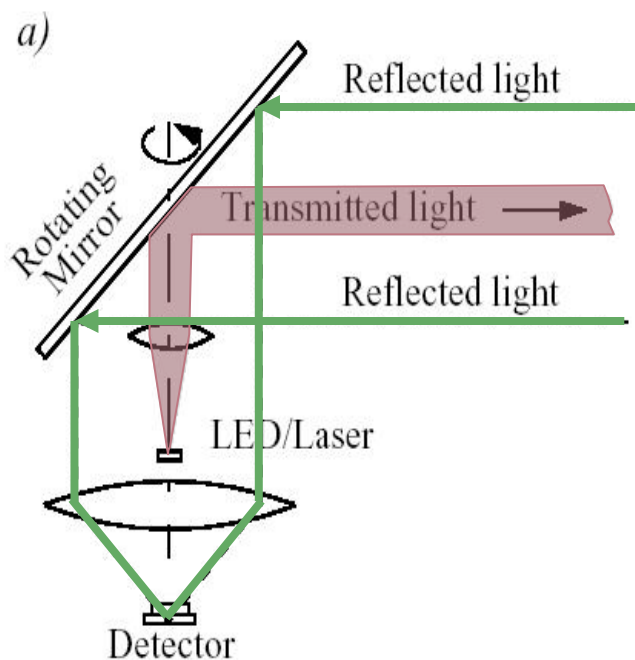
Laser Range Sensor (time of flight, electromagnetic)

- 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.
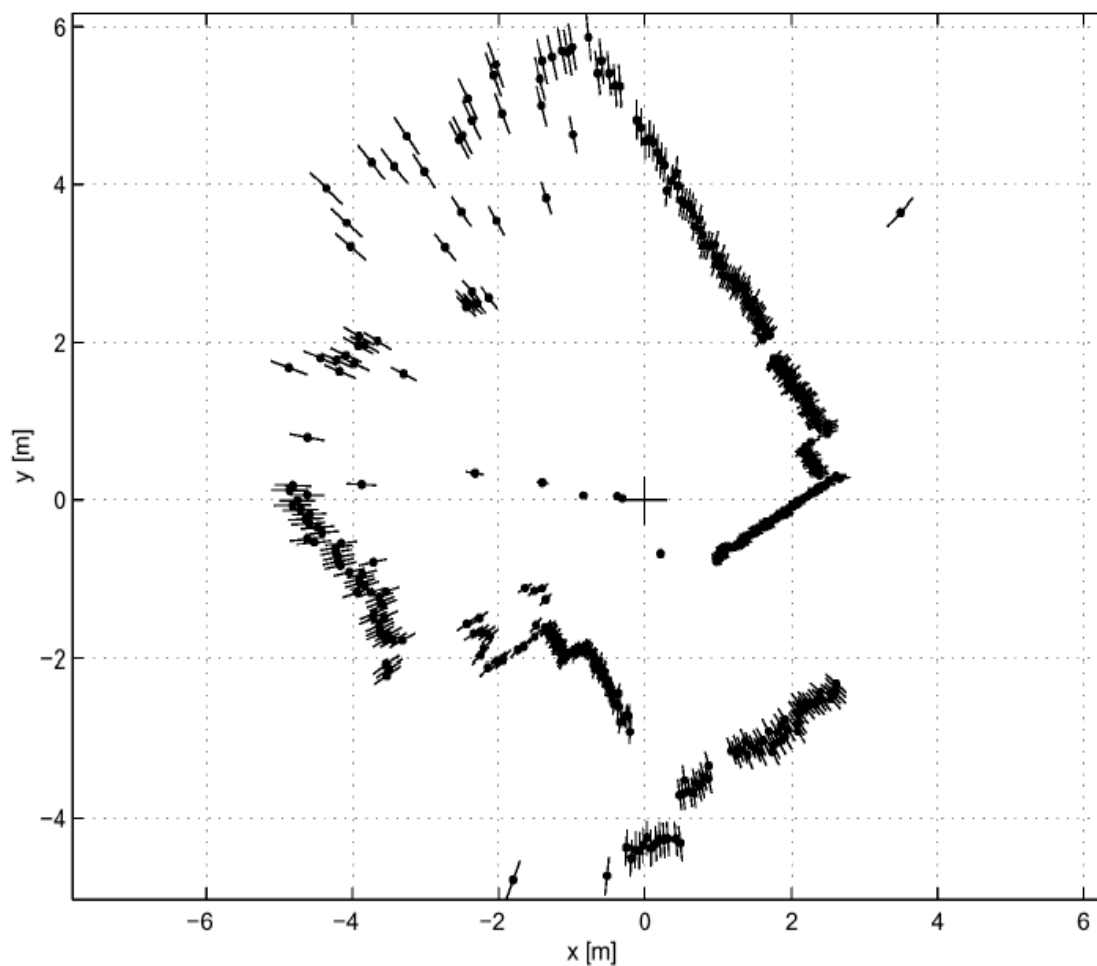
The SICK LMS 200 Laser Scanner

- Angular resolution 0.25 deg
- Depth resolution ranges between 10 and 15 mm and the typical accuracy is 35 mm, over a range from 5 cm up to 20 m or more (up to 80 m), depending on the reflectivity of the object being ranged.
- This device performs seventy five 180-degrees scans per second
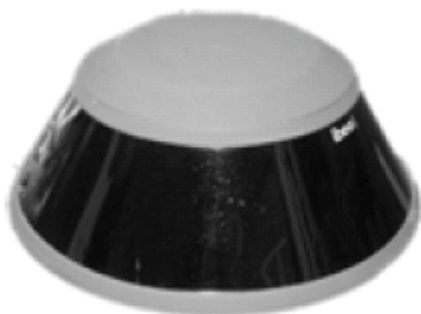
3D Laser Range Finder (1)

- **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 Range Finder (3)

- The **Alasca XT laser scanner** splits the laser beam into **four vertical layers** with an aperture angle of 3.2°.

- This sensor is typically used for obstacle and pedestrian detection on cars. Because of its multi-layer scanning principle, it allows us any pitching of the vehicle
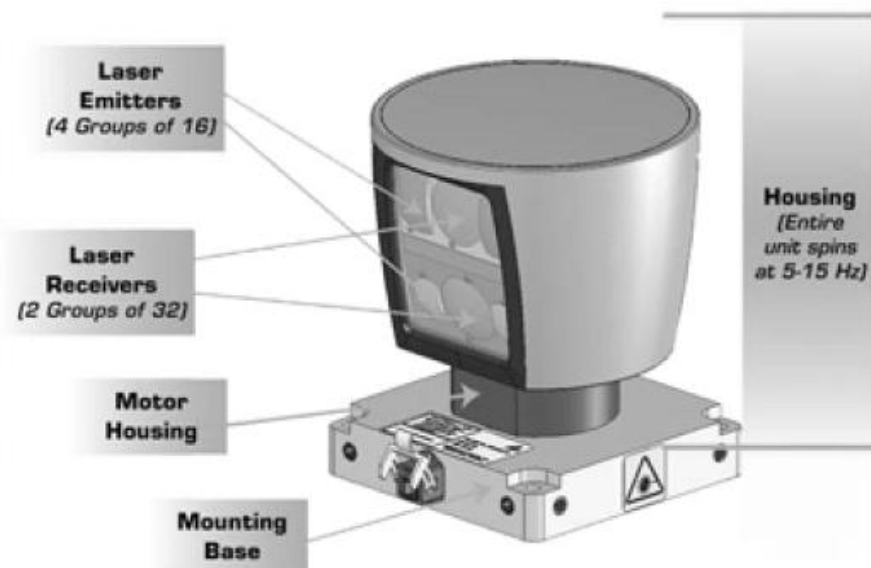

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d)

3D Laser Range Finder (2)

- 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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3D Range Sensor (4): Time Of Flight (TOF) camera

- A Time-of-Flight camera (TOF camera, figure) works similarly to a lidar with the advantage that **the whole 3D scene is captured at the same time and that there are no moving parts.** This device uses a modulated infrared lighting source to determine the distance for each pixel of a Photonic Mixer Device (PMD) sensor.
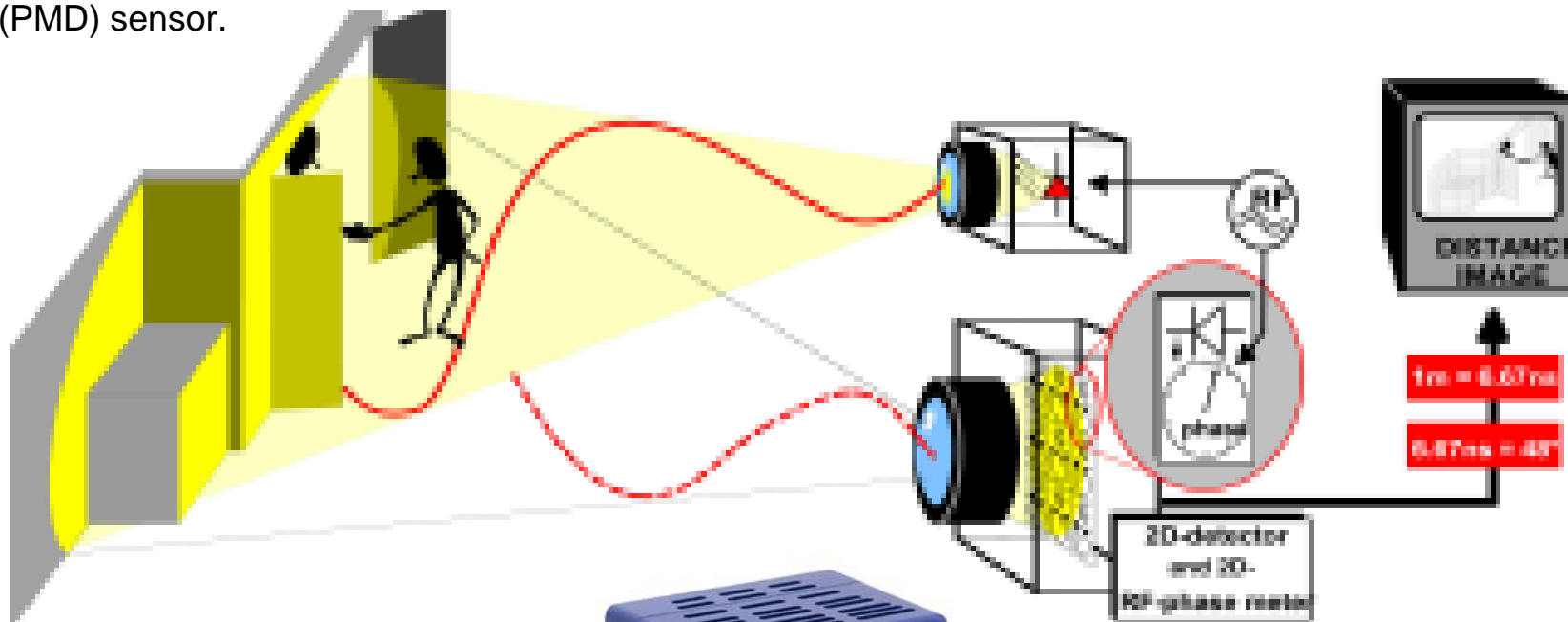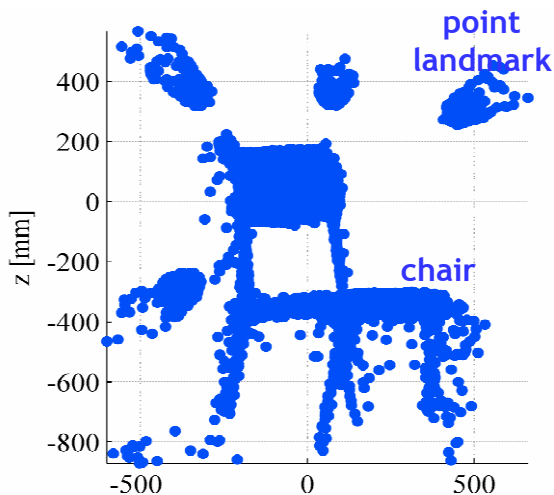
Swiss Ranger 3000
(produced by MESA)

Incremental Object Part Detection
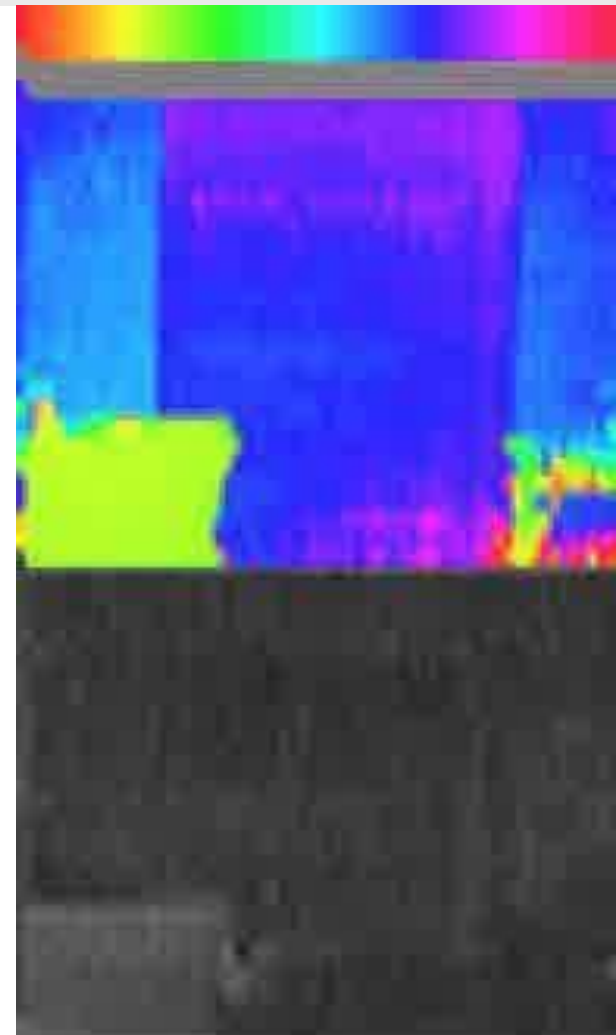
- Range Camera
    - 3D information with high data rate (100 Hz)
    - Compact and easy to manage
    - High, non-uniform measurement noise
    - High outlier rate at jump edges
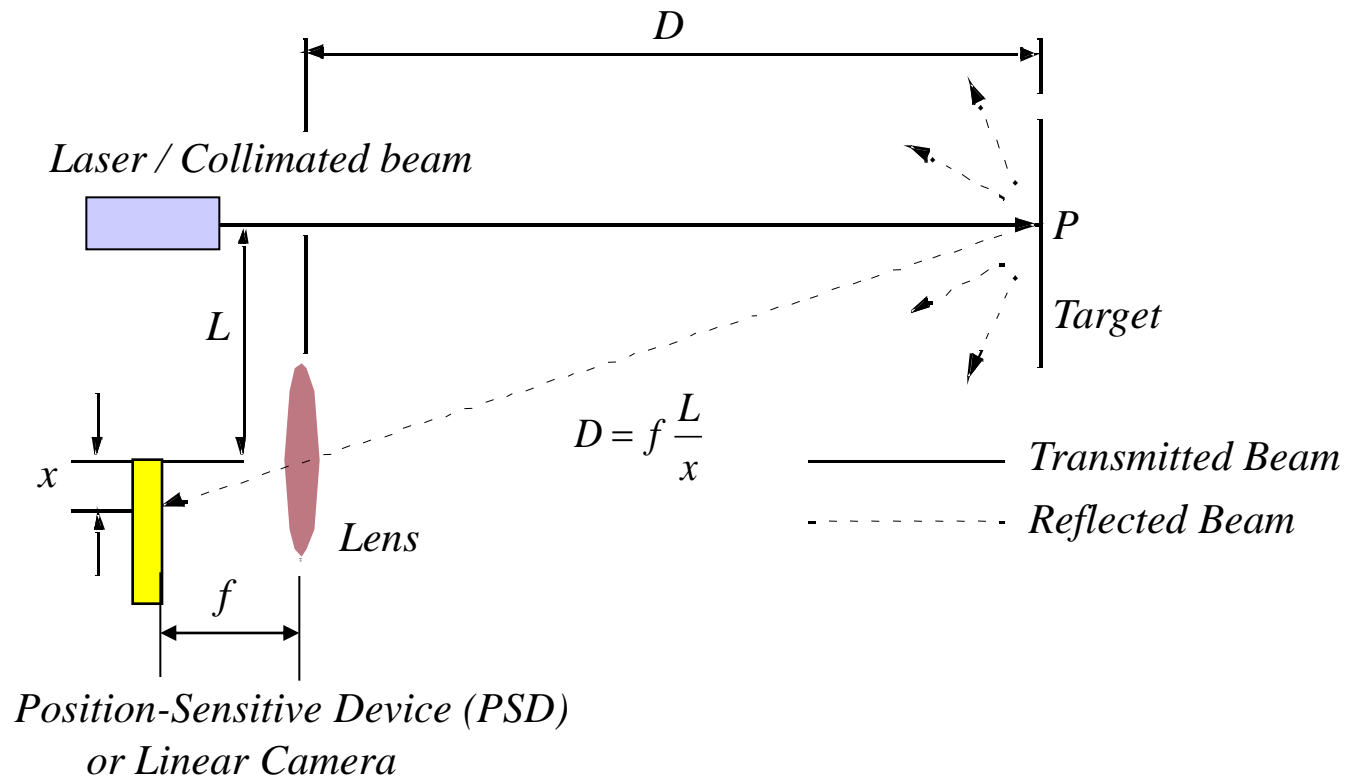   - However very low resolution (174x144 pixels)

3D Point Cloud

Range Camera SR-3000

67 Triangulation Ranging

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

Laser Triangulation (1D)

D

Laser / Collimated beam

L

$D = f\,\dfrac{L}{x}$

P

Target

x

Lens

f

Transmitted Beam

Reflected Beam

*Position-Sensitive Device (PSD)
or Linear Camera*

- Principle of 1D laser triangulation: $D = f\,\dfrac{L}{x}$

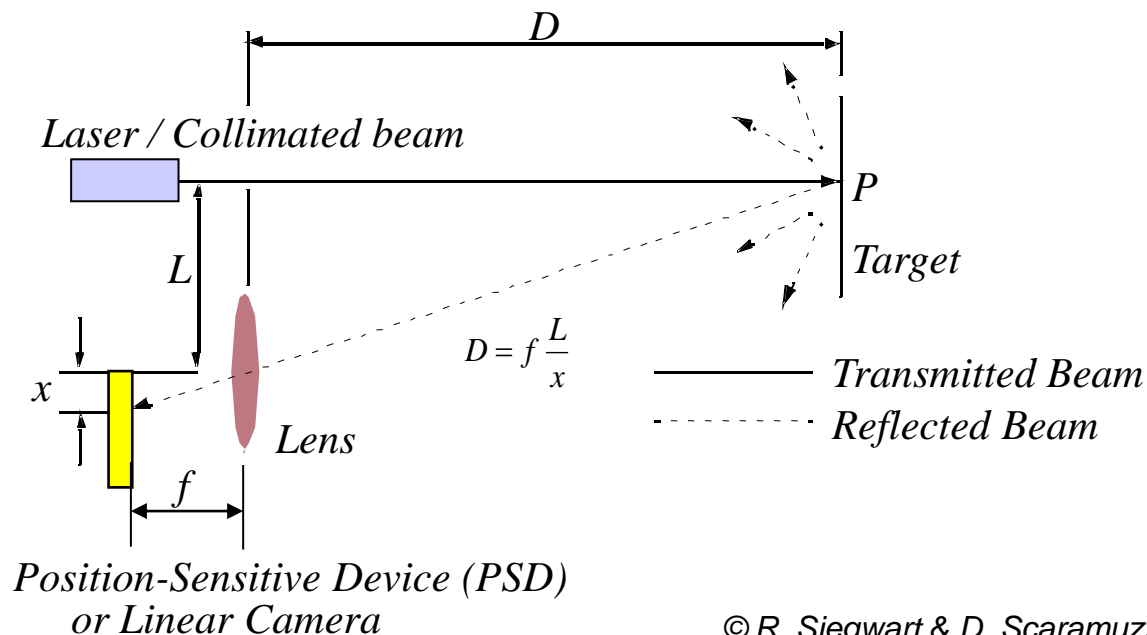# Structured Light (vision, 2D or 3D): Structured Light
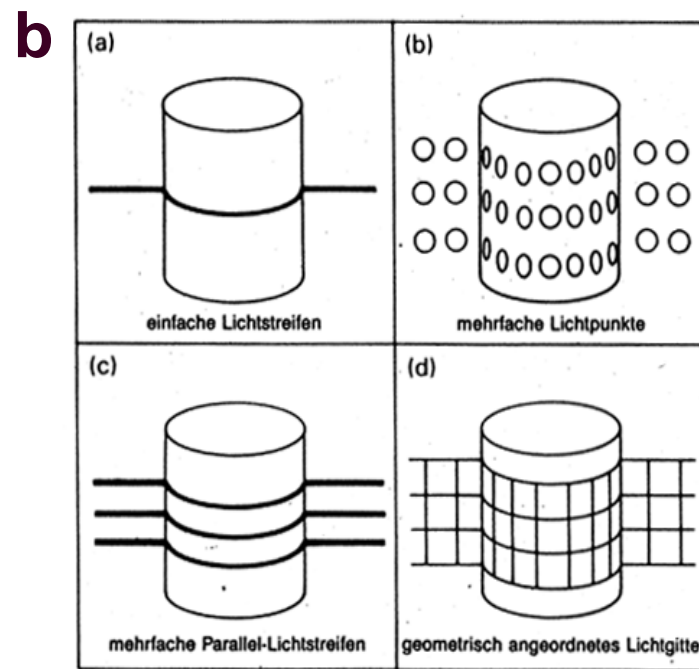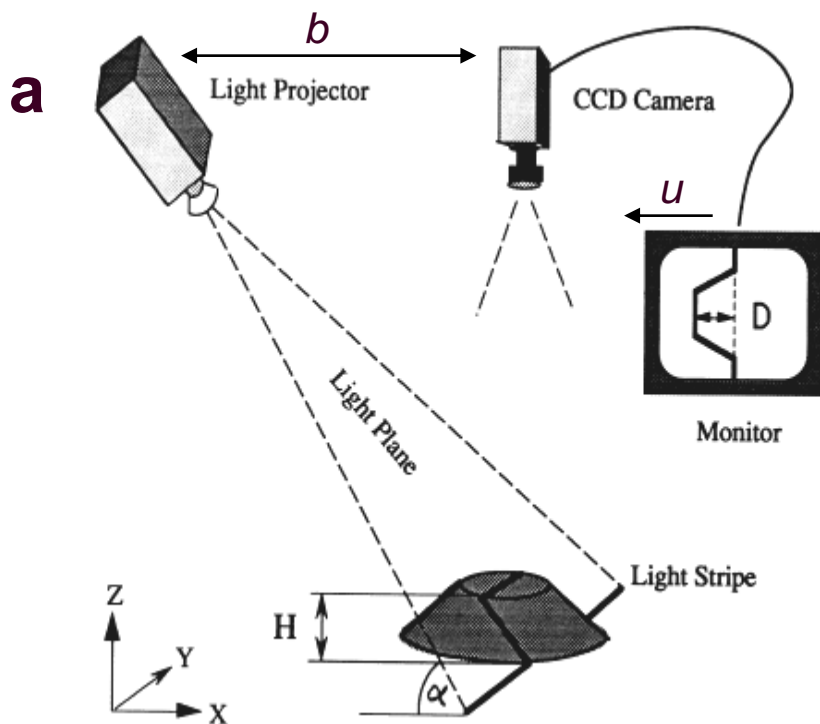
- Eliminate the correspondence problem by projecting structured light on the scene.
- Slits of light or emit collimated light (possibly laser) by means of a rotating mirror.
- Light perceived by camera
- Range to an illuminated point can then be determined from simple geometry.
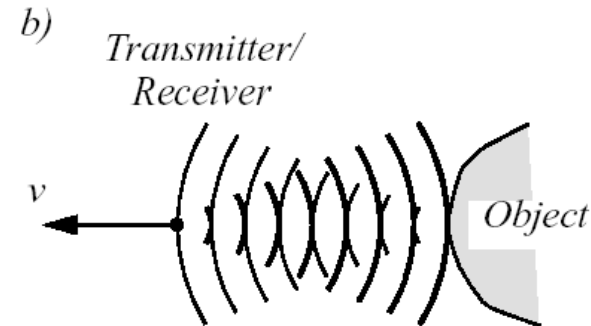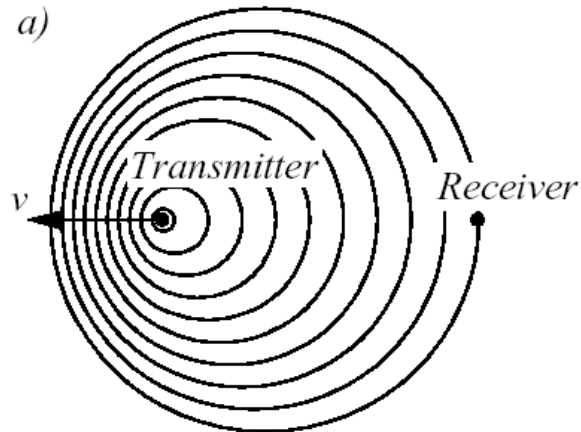
Structured Light (vision, 2 or 3D)

- Baseline length *L*:
  - the smaller L is the more compact the sensor can be.
  - the larger L is the better the range resolution is.

  Note: for large b, the chance that an illuminated point is not visible to the receiver increases.

- Focal length f:
  - larger focal length f can provide
    - either a larger field of view
    - or an improved range resolution
  - however, large focal length means a larger sensor head

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

——— *Transmitted Beam*

------- *Reflected Beam*

Laser / Collimated beam

Target

P

D

L

x

f

Lens

Position-Sensitive Device (PSD) or Linear Camera

Doppler Effect (Radar or Sound)

- a) between two moving objects   b) between a moving and a stationary object

- $f_r = f_t (1 + v/c)$ if transmitter is moving $f_r = f_t \dfrac{1}{1 + v/c}$ if receiver is moving

- $\Delta f = f_t - f_r = \dfrac{2 f_t v \cos\theta}{c}$ Doppler frequency shift $v = \dfrac{\Delta f \cdot c}{2 f_t \cos\theta}$ relative speed

- Usage
  - Sound waves: e.g. industrial process control, security, fish finding, measurement of ground speed
  - Electromagnetic waves: e.g. vibration measurement, radar systems, object tracking