EE-381 Robotics-1
UG ELECTIVE

Lecture 12

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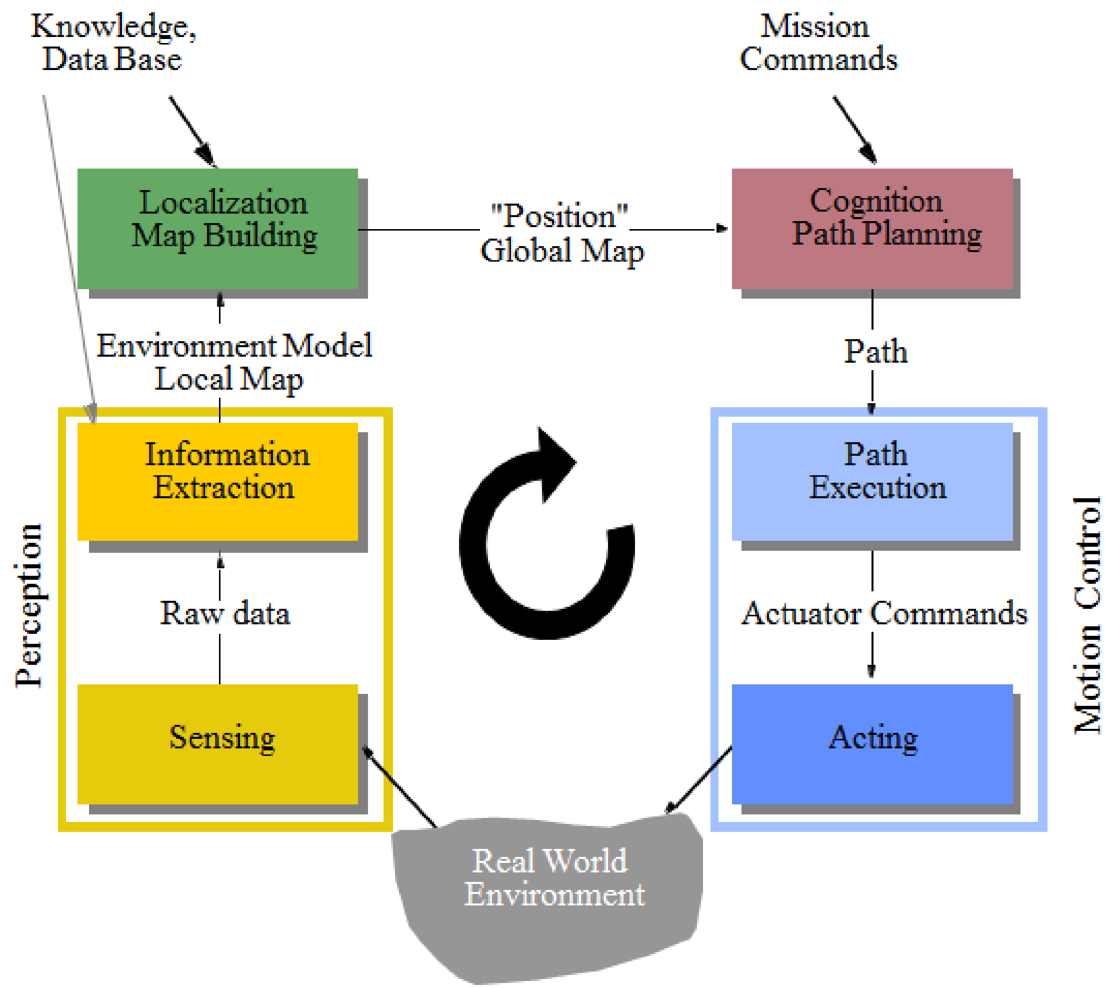
Introduction

- The three key questions in Mobile Robotics
  - Where I am?
  - Where am I going?
  - How do I get there?

- To answer these questions the robot has to
  - Have a model of the environment (given or autonomously built)
  - Perceive and analyze the environment
  - Find its position/situation within the environment
  - Plan and execute the movement

Autonomous Robotics (Mobile)

See, think and act cycle



Perception- sensors

Outlines

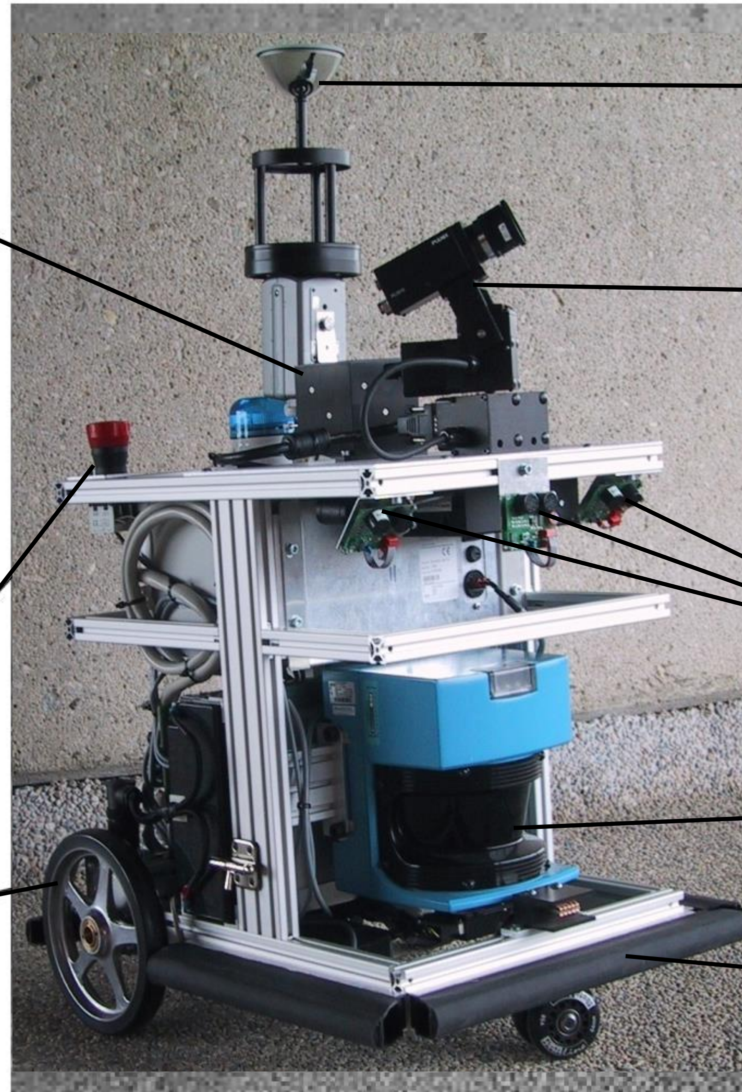
- Optical encoders
- Heading sensors
  - Compass
  - Gyroscopes
- Accelerometer
- IMU
- GPS
- Range sensors
  - Sonar
  - Laser
  - Structured light
- Camera

Sensors

- Why should a robotics engineer know about sensors?
  - Is the **key technology** for perceiving the environment
  - **Understanding the physical principle** 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**

BIBA Robot, BlueBotics SA



Classification of Sensors

What:

- **Proprioceptive sensors**
  - measure values internal 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 (microphones, cameras, temperature probes etc)
- **Active sensors**
  - emit their proper energy and measure the reaction (ultrasonic sensors and rangefinders etc)
  - better performance, but some influence on environment

General Classification

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.

General Classification

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 geometric 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 analysis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

Characterizing Sensor Performance

Measurement in real world environment is error prone

- 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

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

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

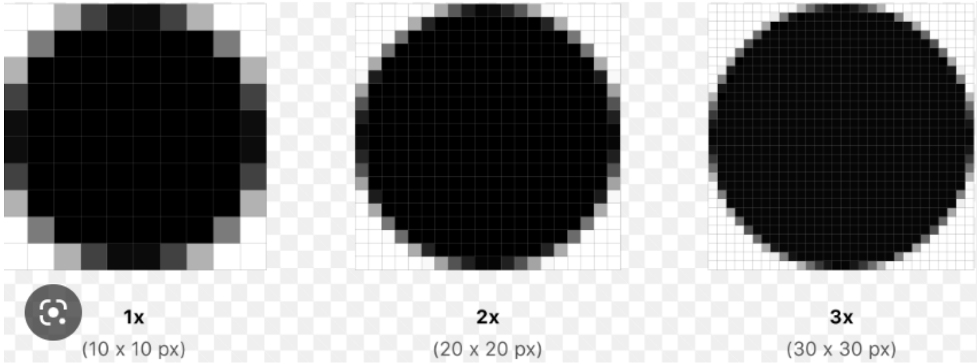
$$20 \cdot \log\left[\frac{20}{0.001}\right] = 86dB$$

$$P = U \cdot I = \frac{1}{R}U^2$$

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

Characterizing Sensor Performance

- Basic sensor response ratings (cont.)
  - Range
    - upper 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)



Characterizing Sensor Performance

- Basic sensor response ratings (cont.)
  - Linearity
    - variation of output signal as function of the input signal

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

  - Bandwidth or Frequency
    - the speed with which a sensor can provide a stream of readings (formally the number of measurements per second)
    - 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

In Situ Sensor Performance

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

error

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

m = measured value
v = true value

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

In Situ Sensor Performance

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 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

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

σ is the standard deviation

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 sensor, robot-environment dynamics
    - rarely possible to model -> *error blurring*: appear as "random" errors but are neither systematic nor random.
    - 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 …

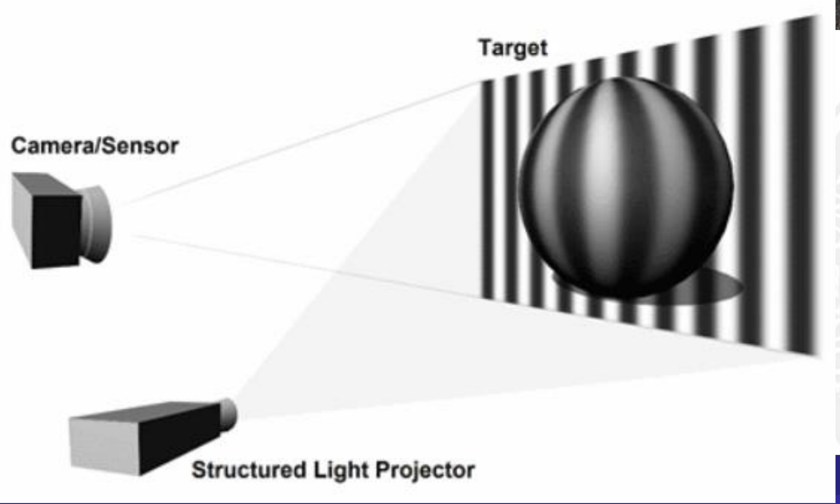
- Sensors modeled by probability distribution (random errors)
  - usually very little knowledge about the causes of random errors
  - often assumed to be symmetric or even Gaussian
  - however, it is important to realize how wrong this can be!

  - 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

Section 4.2 (Representing Uncertainty) is just basics of probability theory. Read it yourself.

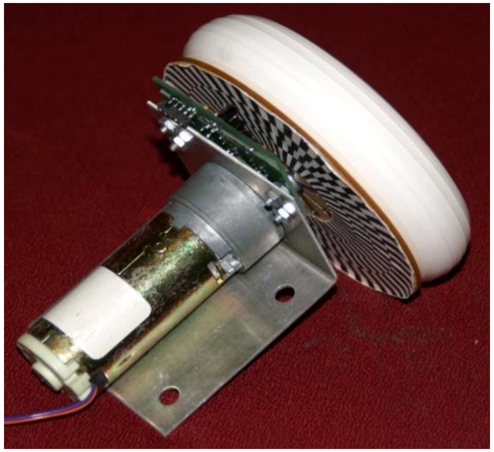
Sensors: outline

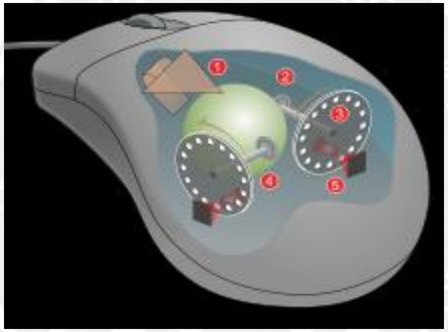
- Optical encoders
- Heading sensors
  - Compass
  - Gyroscopes
- Accelerometer
  - IMU
  - GPS
- Range sensors
  - Sonar
  - Laser
  - Structured light
- Vision Cameras



Encoders

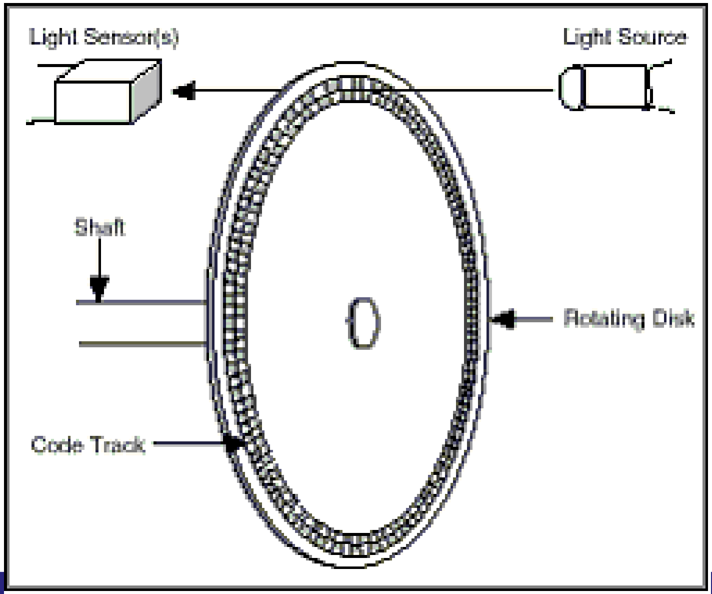
- An encoder is an electro-mechanical device that converts the angular position of a shaft to an analog or digital signal, making it an angle transducer

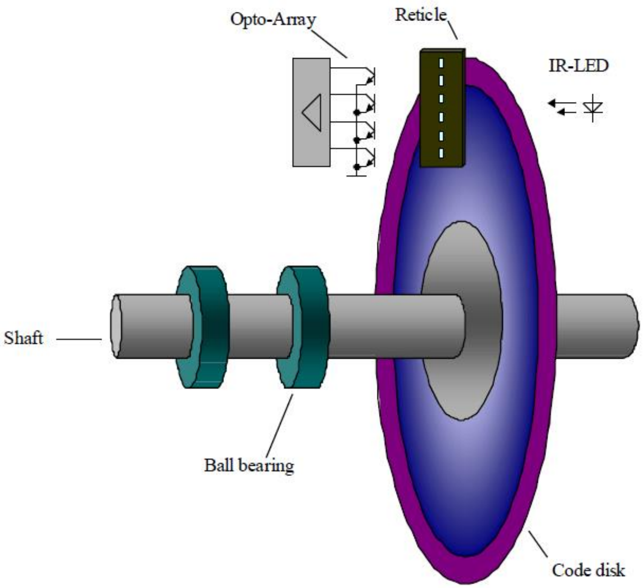




Wheel / Motor Encoders

- 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
- Optical encoders
  - regular: counts the number of transitions but cannot tell the direction of motion

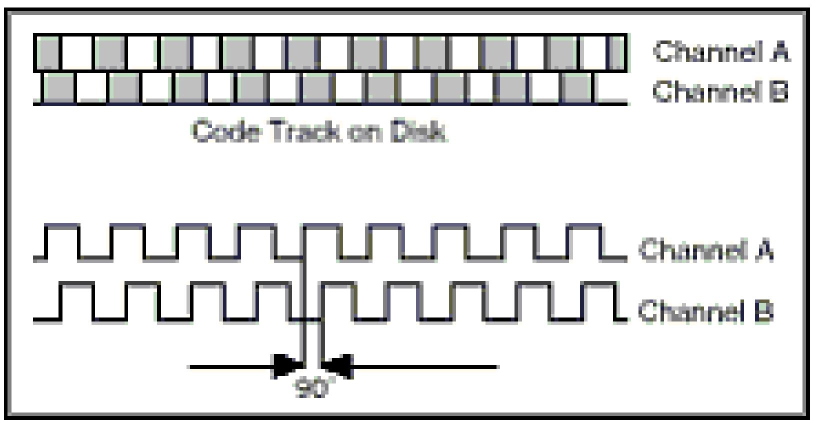


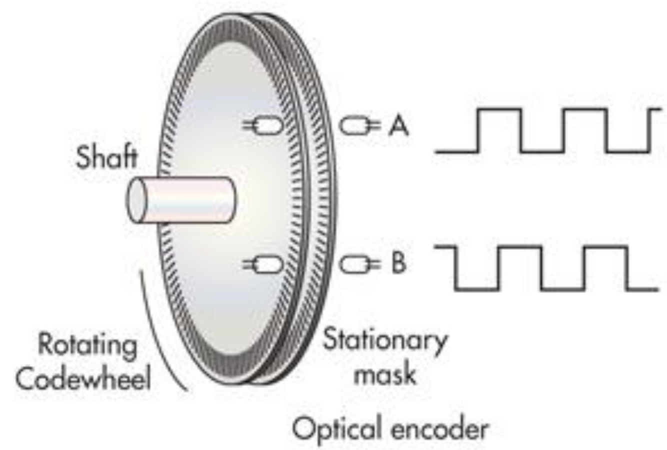


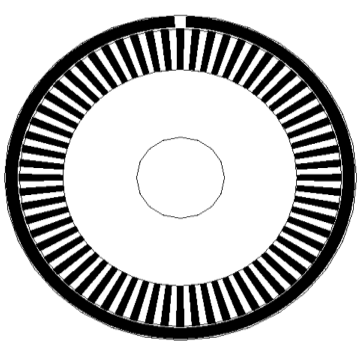
Wheel / Motor Encoders

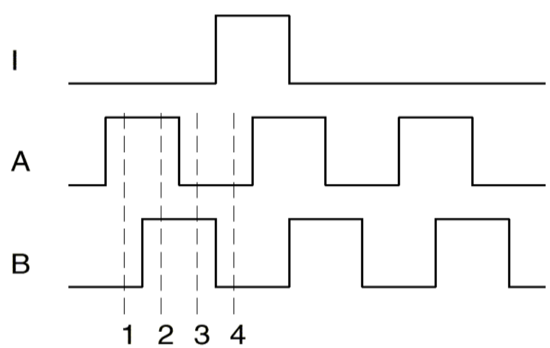
Right to left
- A will detect pulse
- B will have black strip

- Optical encoders
  - 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









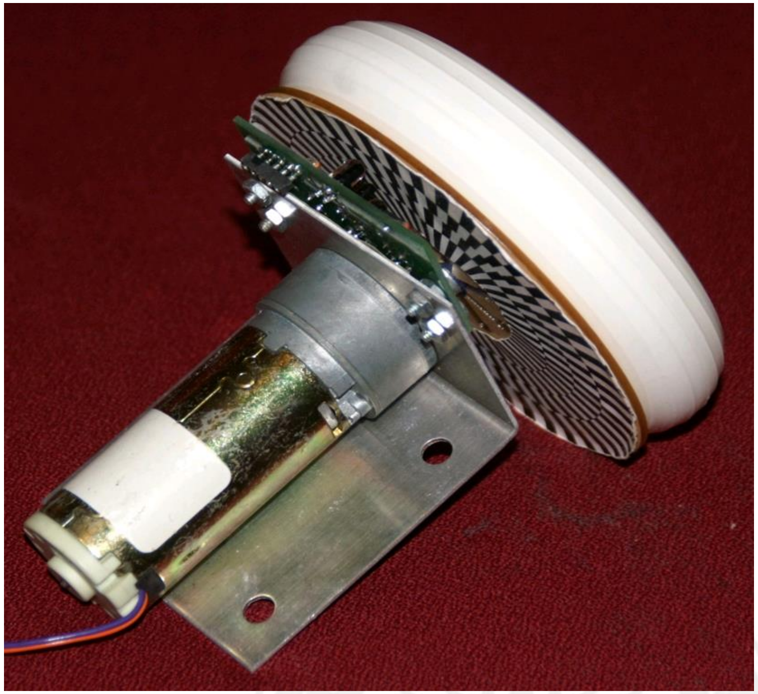
State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

A custom made optical encoder

- *Cycles per Revolution* (CPR) ratings

✓ Typical encoders in mobile robotics 2,000 CPR

✓ 10,000 CPR also available



- *Bandwidth* (speed of measurement)

✓ Encoders are sufficiently fast for robotics tasks

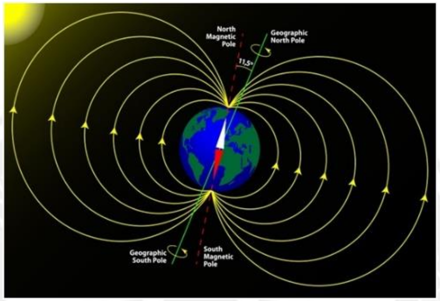
✓ Accuracy is often assumed to be 100%

Heading Sensors

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

Compass

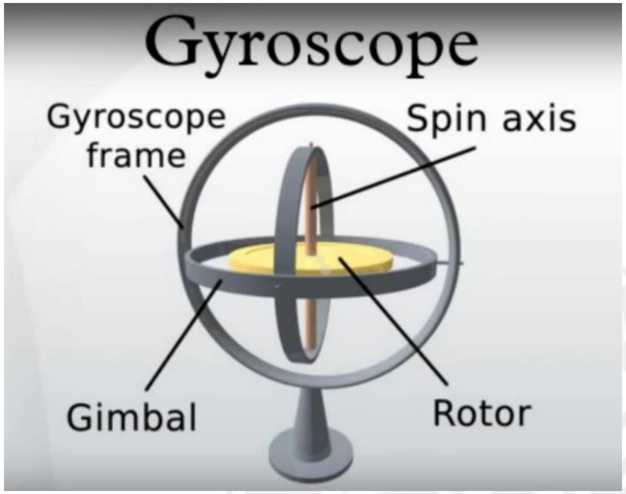
- Since over 2000 B.C.
  - when Chinese suspended a piece of natural magnetite from a silk thread and used it to guide a chariot over land.
- Magnetic field on earth
  - absolute measure for orientation (even birds use it for migrations (2001 discovery)
- Large variety of solutions to measure the earth magnetic field
  - mechanical magnetic compass
  - 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 feasible for indoor environments for absolute orientation
  - useful for local orientation



Gyroscope

- Heading sensors that preserve their orientation in relation to a fixed reference frame
  - 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)



- Gyroscope: https://www.youtube.com/watch?v=cquvA_IpEsA
- Gyro Precession: https://www.youtube.com/watch?v=ty9QSiVC2go

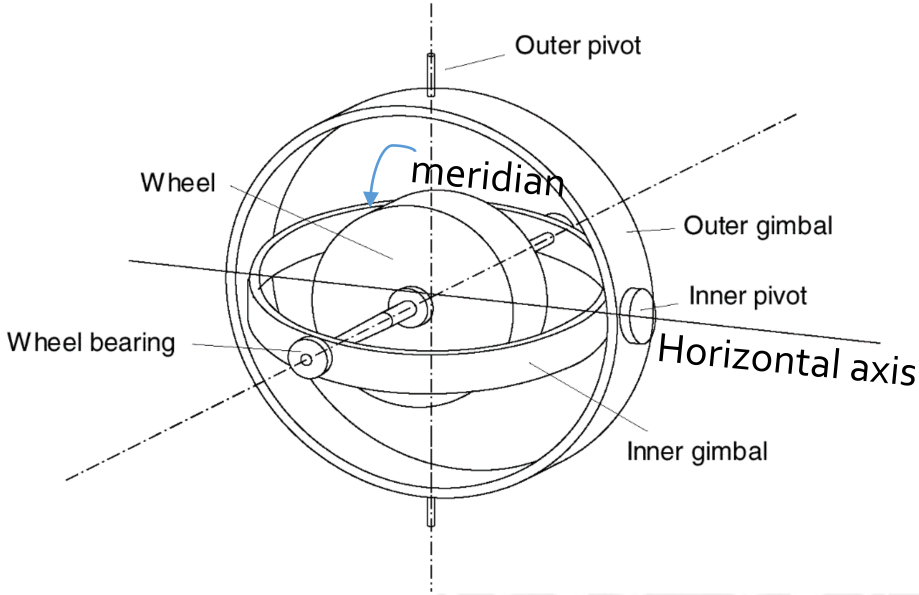
Mechanical Gyroscopes

- 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
- Quality: 0.1° in 6 hours (a high quality mech. gyro costs up to 100,000 $)

Mechanical Gyroscopes

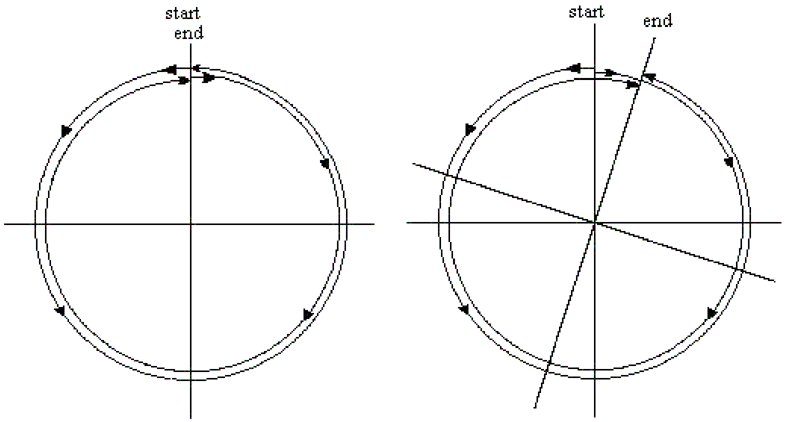
- If the spinning axis is aligned with the north-south meridian, the earth's rotation has no effect on the gyro's horizontal axis
- If it points east-west, the horizontal axis reads the earth rotation

Example: orientation of the airplanes independent of its position

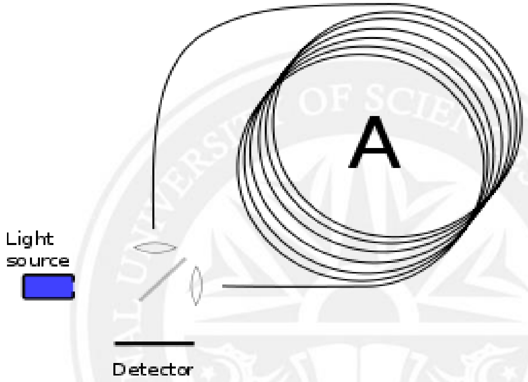


Optical Gyroscopes (Sagnac Interferometer)

- First commercial use started only in the early 1980 when they were first installed in airplanes.



- 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



$$\Delta f \propto \Omega$$

(angular velocity)

Optical Gyroscopes

- Laser beam traveling in direction of the rotation
  - slightly shorter path and have high frequency
  - 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 built using microfabrication technology.

Single axis optical gyro

3-axis optical gyro

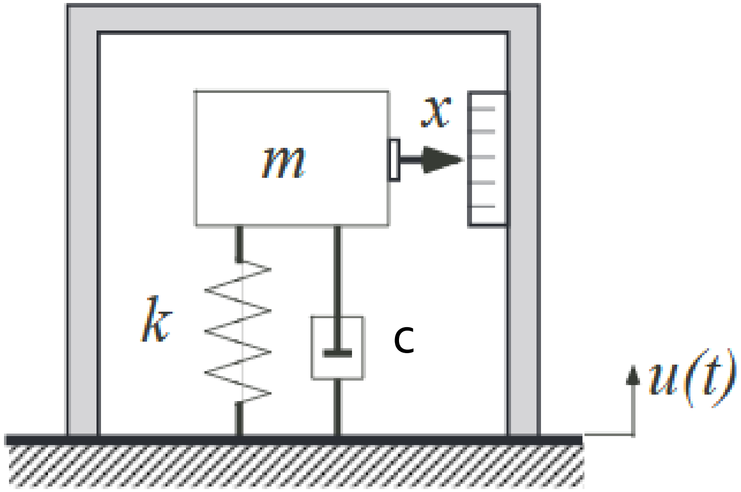
Mechanical Accelerometer

- Accelerometers measure all external forces acting upon them, including gravity
- Accelerometer acts like a spring–mass–damper system

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

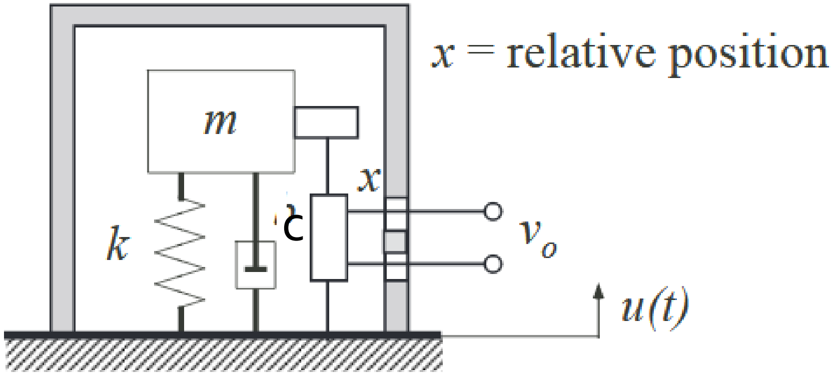
where *m* is the proof mass, *c* the damping coefficient, *k* the spring constant

at convergence: $$a_{applied} = \frac{kx}{m}$$



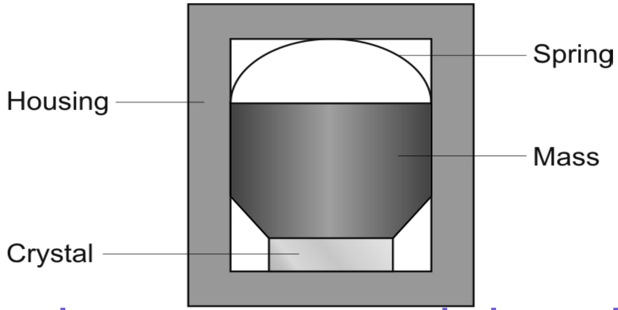
Mechanical Accelerometer

- 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

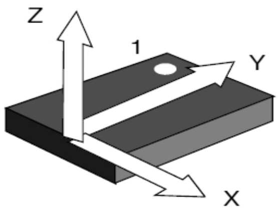


Other Accelerometers

- In capacitive accelerometers the capacitance between a fixed structure and the proof mass is measured

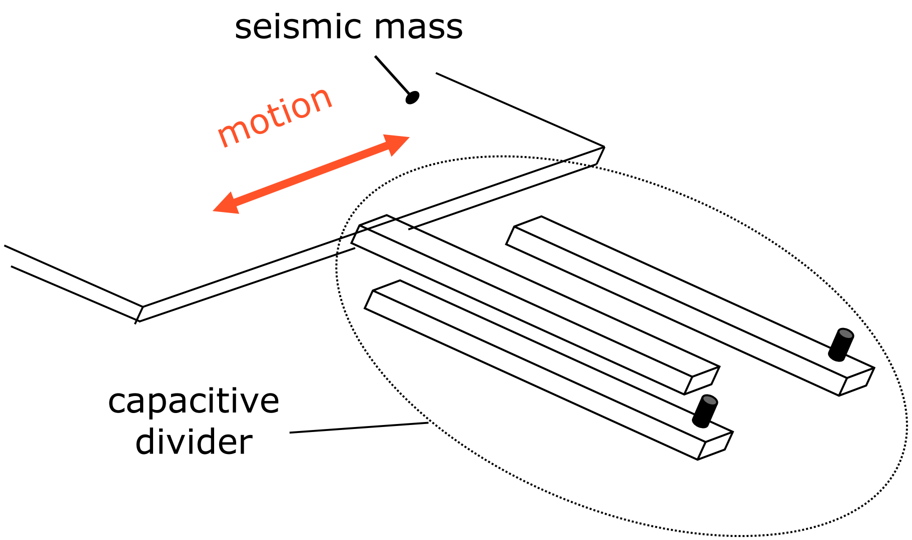


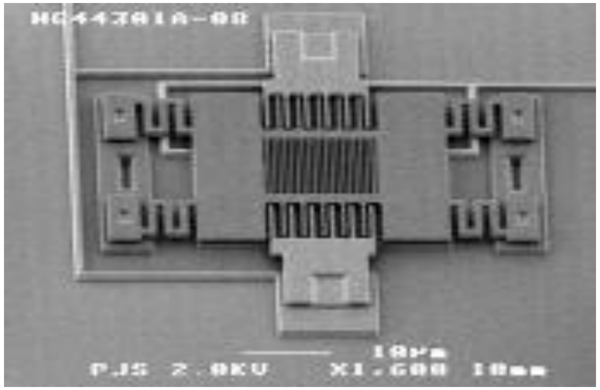
- Piezoelectric accelerometers are based on the property exhibited by certain crystals to generate a voltage when a mechanical stress is applied to them



- Modern accelerometers use Micro Electro-Mechanical Systems (MEMS) consisting of a spring-like structure with a proof mass. Damping results from the residual gas sealed in the device.

Factsheet: MEMS Accelerometer





<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.

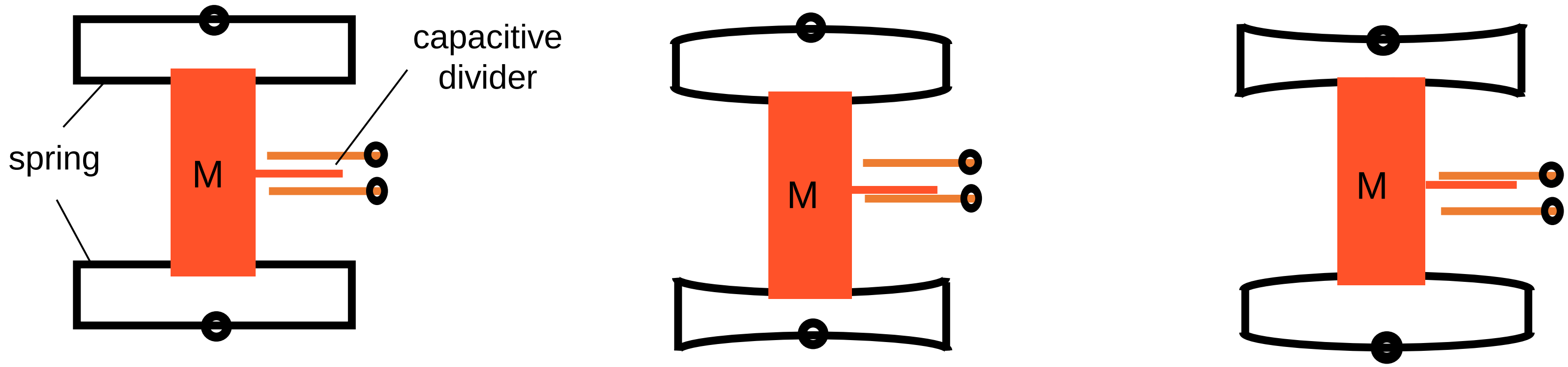
2. Main Characteristics

- Can be multi-directional
- Various sensing ranges from 1 to 50 g

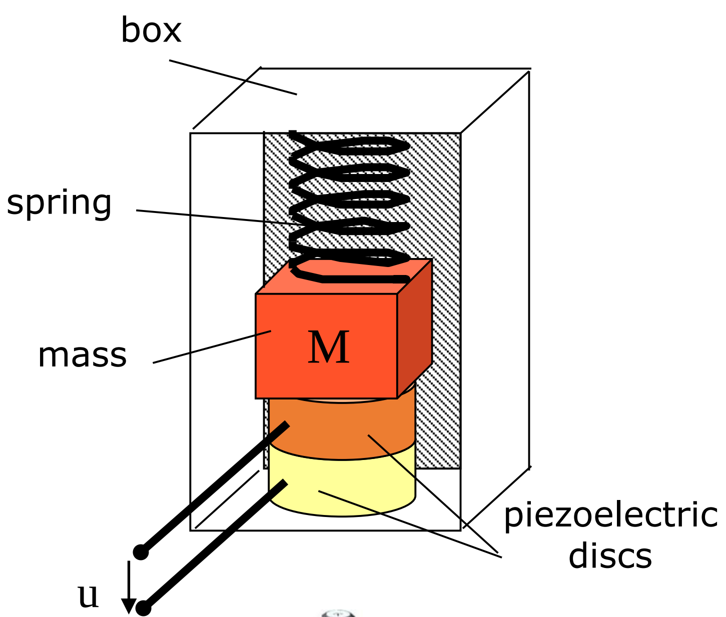
3. Applications

- Dynamic acceleration
- Static acceleration (inclinometer)
- Airbag sensors (+- 35 g)

Factsheet: MEMS Accelerometer



Factsheet: Piezoelectric Accelerometer



<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

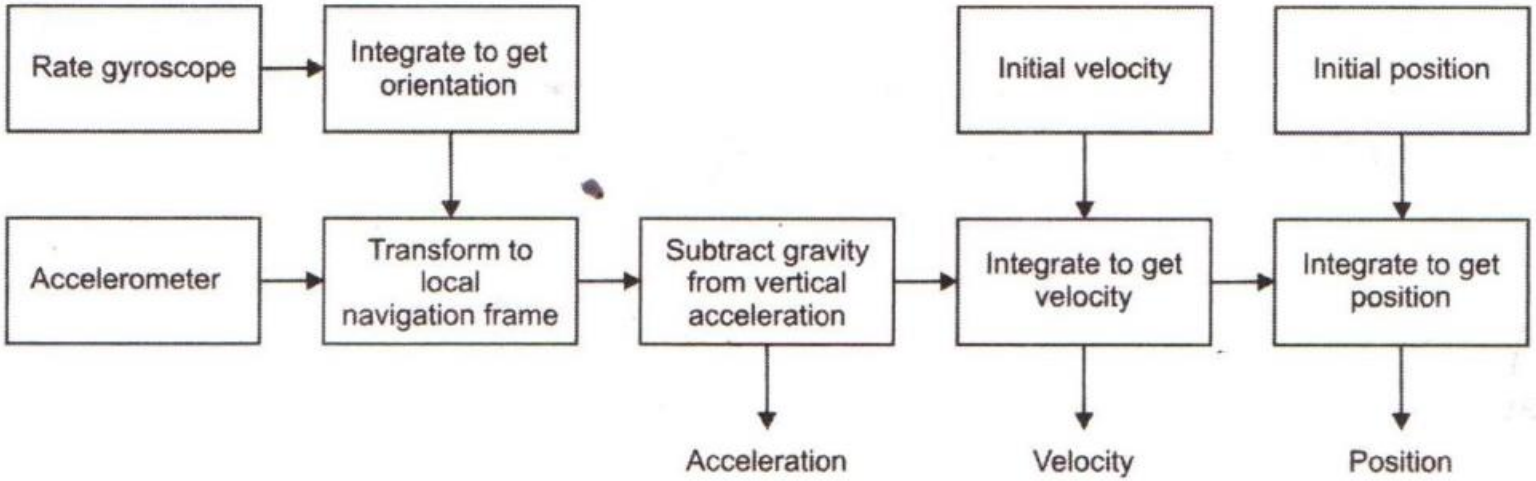
- Piezoelectric elements cannot produce a signal under constant acceleration (i.e., static) conditions
- 2-D and 3-D accelerometers can be created by combining 2 or 3 1-D modules

3. Applications

- Vibration analysis
- Machine diagnostics
- Active vehicle suspension
- Earthquake sensors

Inertial Measurement Unit (IMU)

- 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.



Inertial Measurement Unit (IMU)

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

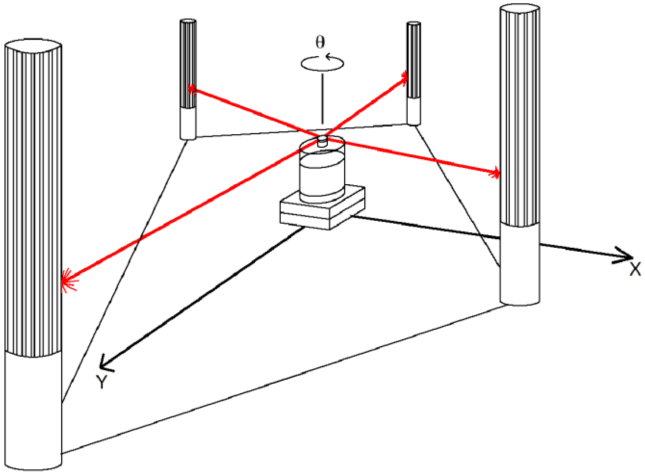
- IMUs are extremely sensitive to measurement errors in gyroscopes and accelerometers: drift in the gyroscope unavoidably undermines the estimation of the vehicle orientation relative to gravity, which results in incorrect cancellation of the gravity vector.

- 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.

Ground-Based Active and Passive Beacons

emit

- “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.



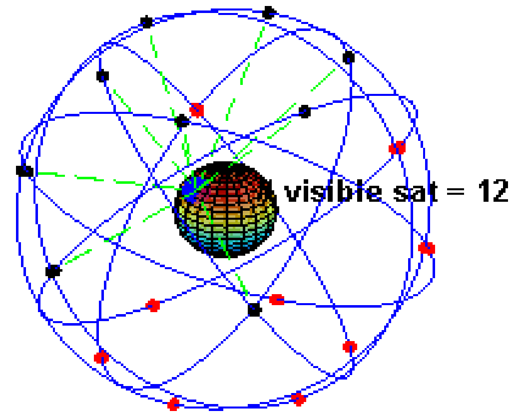
Global Positioning System (GPS)

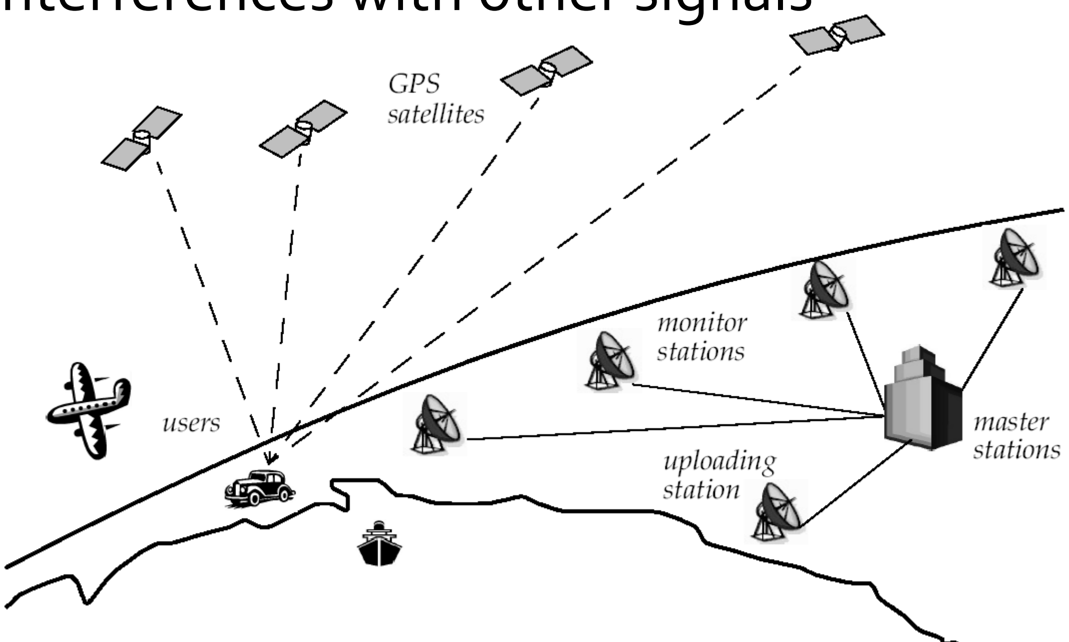
- Developed for military use (is based on ground-based radio navigation systems LORAN and DECCA Navigator built during Second World War (1940s)
- Recently it became accessible for commercial applications (1995)
- 24 satellites orbiting the earth every 12 hours at a height of 20.190 km.
- 4 satellites are located in each of 6 orbits with 60 degrees orientation between each other. The orbital planes do not rotate with respect to stars. Orbits arranged so that at least 6 satellites are always within line of sight from any point on Earth's surface.
- As from 2008 the satellites are 32 to improve localization accuracy through redundancy
- 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**)

Global Positioning System (GPS)

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)

- 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

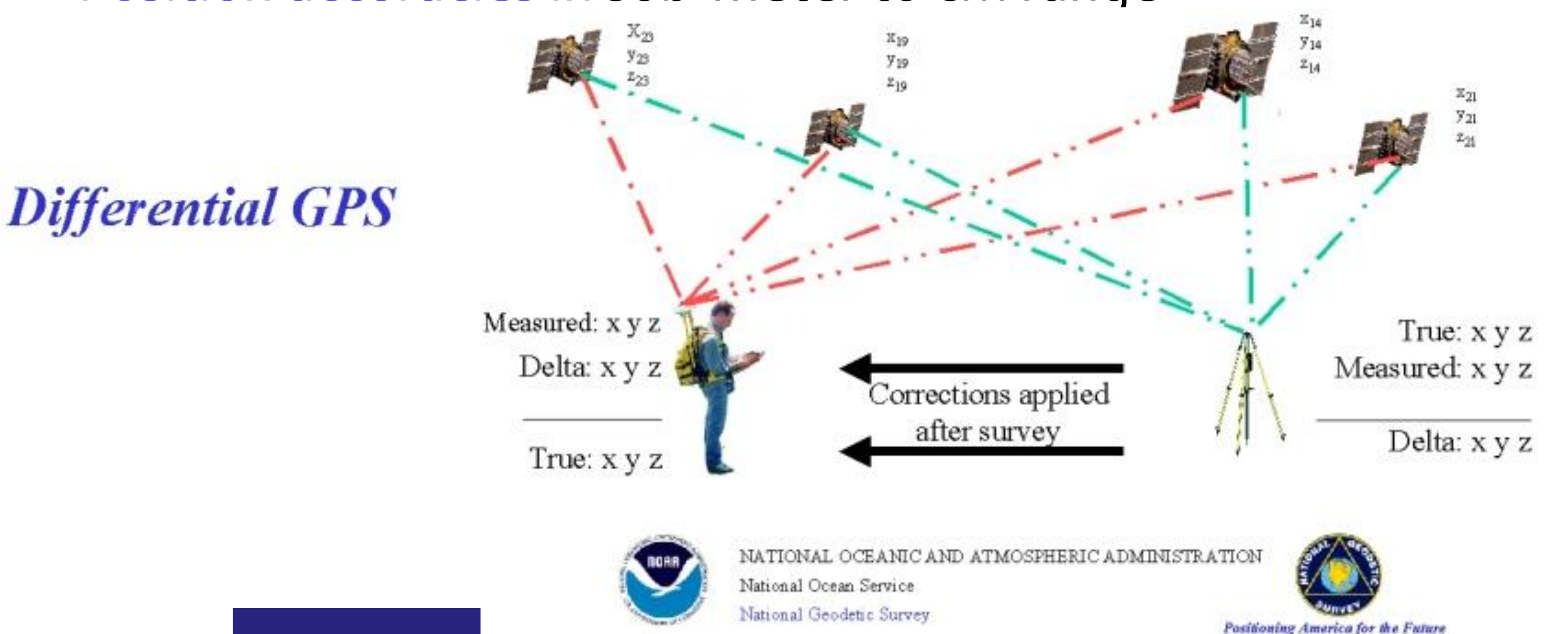
- Position accuracy proportional to precision of time measurement (roughly 0.3 m per nanosecond)

Global Positioning System (GPS)

- 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.

Differential Global Positioning System (dGPS)

- 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

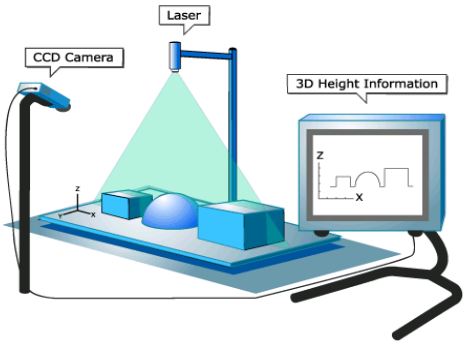


Range sensors

- Sonar

- Laser range finder

- Time of Flight Camera
- Structured light



Range Sensors (time of flight)

- 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)

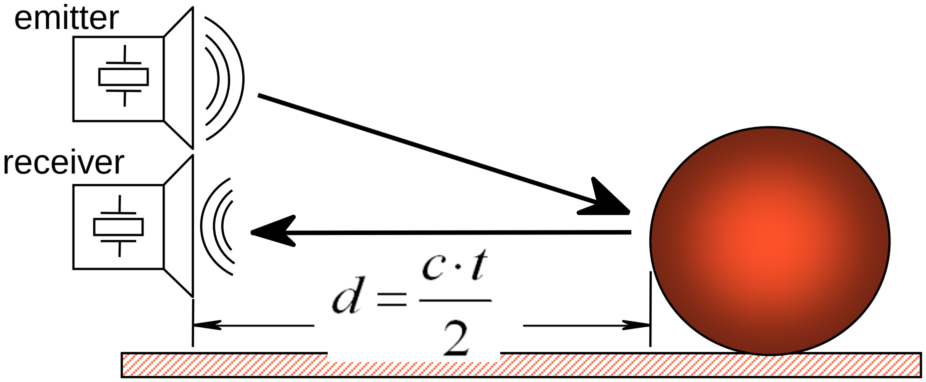
- It is important to point out
  - Propagation speed of sound: 0.3 m/ms
  - Propagation speed of electromagnetic signals: 0.3 m/ns,
    - one million times faster.

  - 3 meters
    - is 10 ms for an <u>ultrasonic system</u>
    - only 10 ns for a <u>laser range sensor</u>
    - <u>time of flight</u> with <u>electromagnetic signals</u> is not an easy task
    - laser range sensors <u>expensive and delicate</u>

Range Sensors (time of flight)

- The quality of time of flight range sensors mainly depends on:
  - Inaccuracies in the time of fight measure (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



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.

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

2. Main Characteristics

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

3. Applications

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

Ultrasonic Sensor (time of flight, sound)

- 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

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

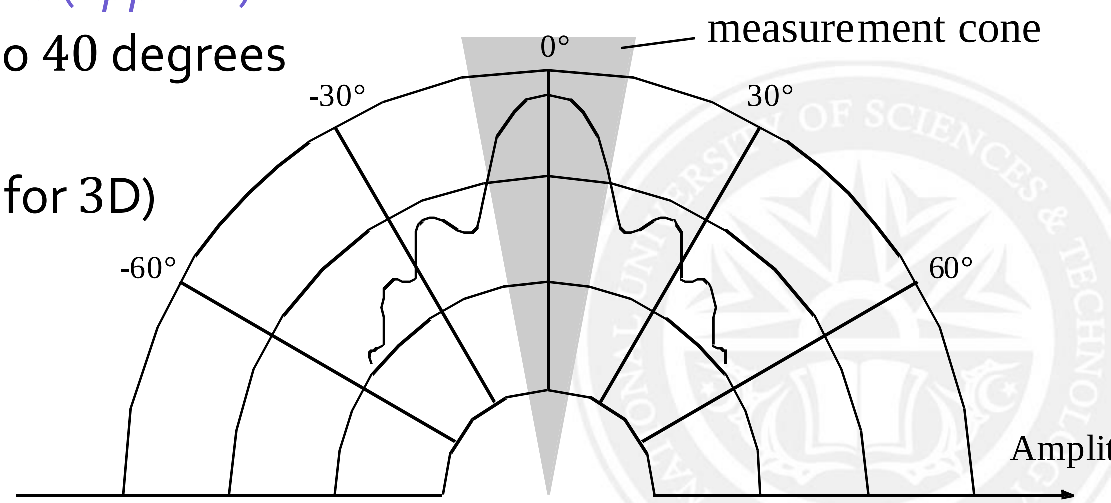
γ : adiabatic index (isentropic expansion factor) - ratio of specific heats of a gas ($\gamma = C_p / C_v$)

R: gas constant (8.3145 $J\ mol^{-1} K^{-1}$)

T: temperature in degree Kelvin

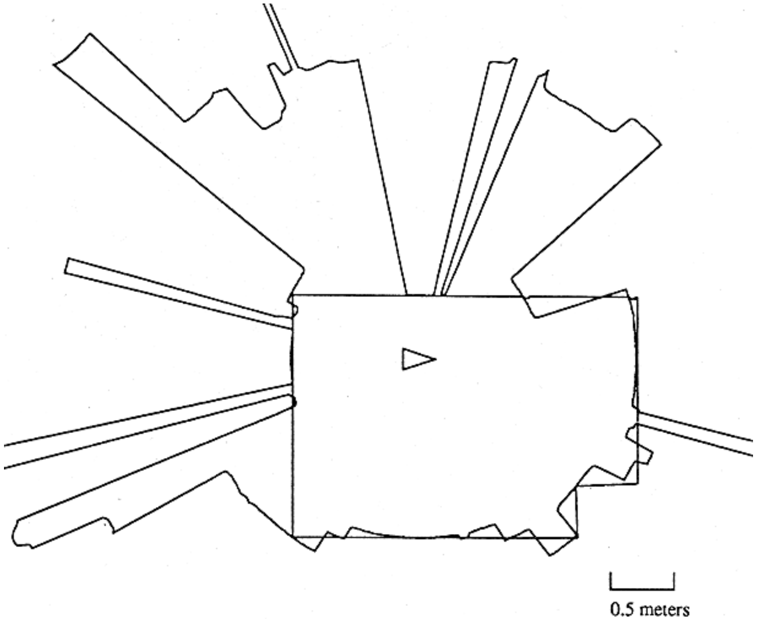
Ultrasonic Sensor (time of flight, sound)

- Typical frequency: $40kHz - 180\ kHz$
  - Lower frequencies correspond to longer range
- Generation of sound wave: piezo transducer
  - Transmitter and receiver 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)



Ultrasonic Sensor (time of flight, sound)

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

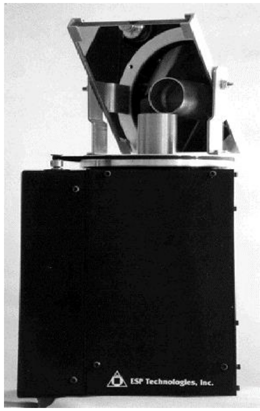


Ultrasonic Sensor (time of flight, sound)

- Bandwidth (A limitation for mobile robots)
  - 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.

Laser Range Sensor (time of flight, electromagnetic)

- Is called Laser range finder or LiDAR (LIght Detection And Ranging)

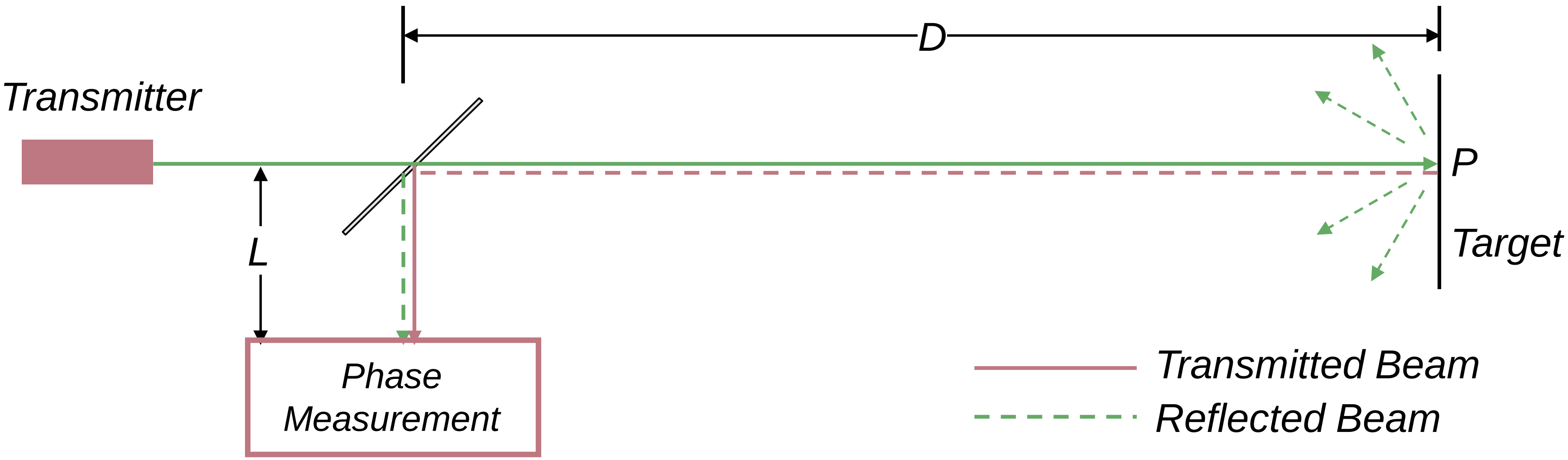


Alaska-IBEO

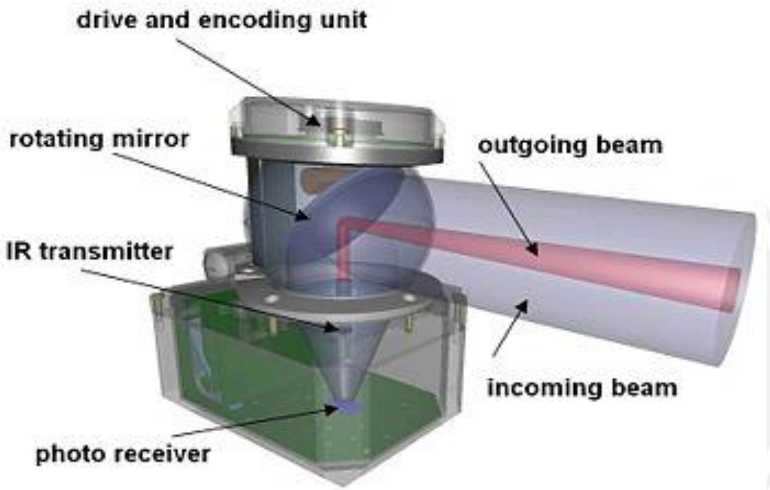
SICK

Hokuyo

Laser Range Sensor (time of flight, electromagnetic)



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



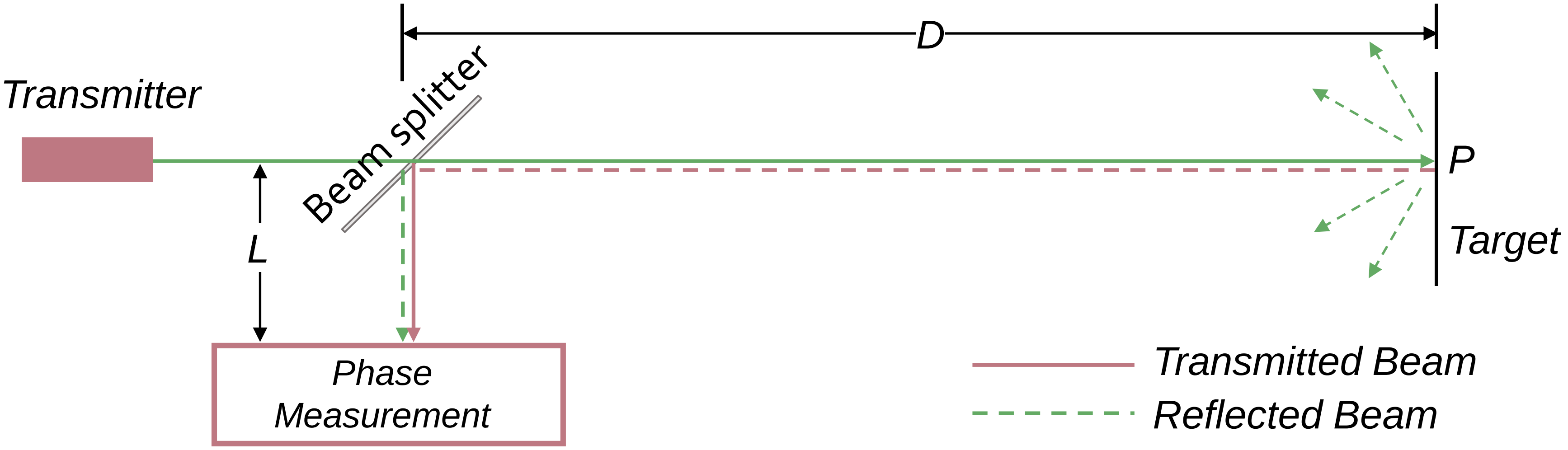
Laser Range Sensor (time of flight, electromagnetic)

Time of flight measurement

- Pulsed laser (today the standard)
  - measurement of elapsed time directly
  - resolving picoseconds
- Beat frequency
  - FMCW (frequency modulated continuous wave)
- Phase shift measurement to produce range estimation
  - technically easier than the above method

Laser Range Sensor (time of flight, electromagnetic)

- *Phase-Shift Measurement*



$$D' = L + 2D = L + \frac{\theta}{2\pi}\lambda \qquad \lambda = \frac{c}{f}$$

Where:

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

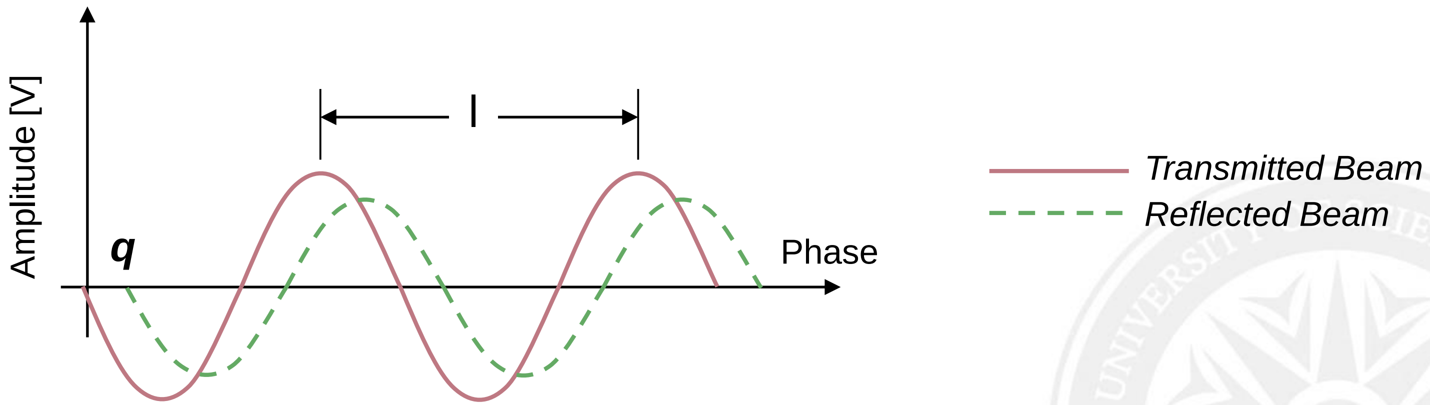
- for f = 5 MHz (as in the A.T&T. sensor), λ = 60 meters

Laser Range Sensor (time of flight, electromagnetic)

- Distance D, between the beam splitter and the target

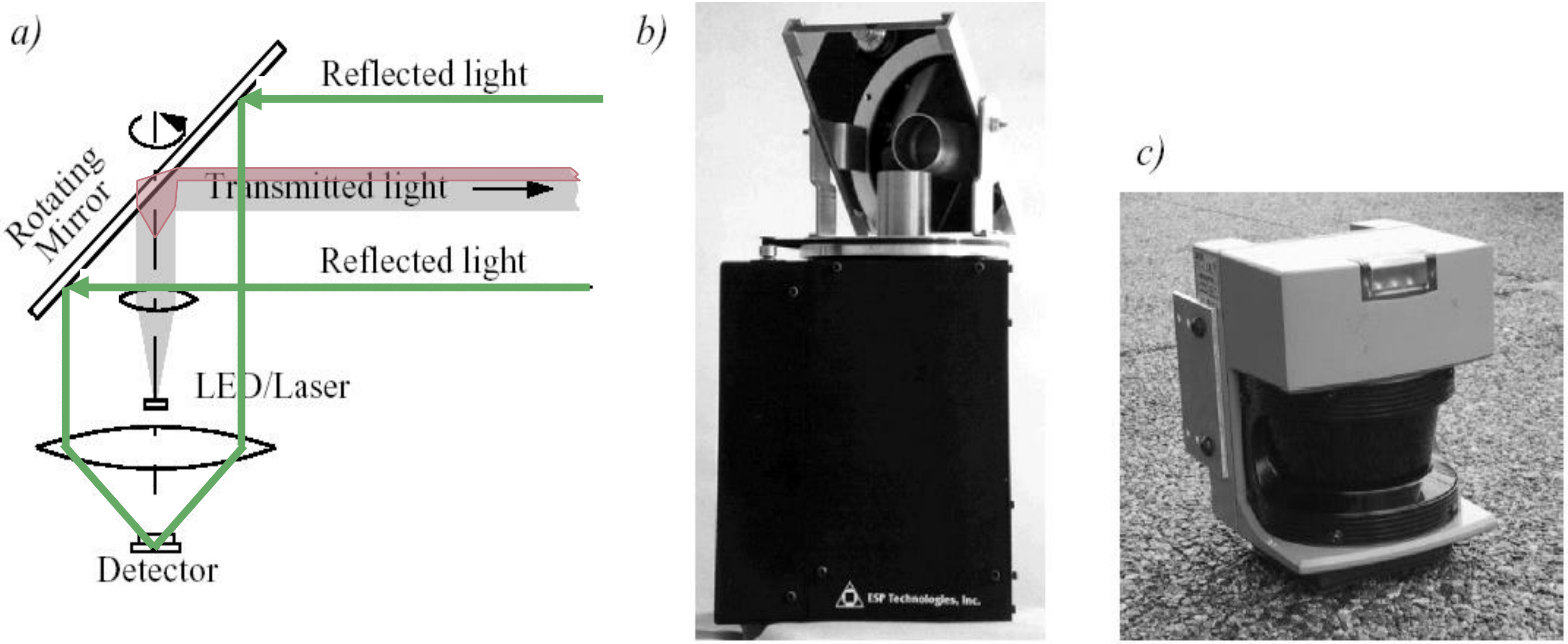
$$D = \frac{\lambda}{4\pi}\theta$$

- where
  - θ: phase difference between transmitted and reflected beam



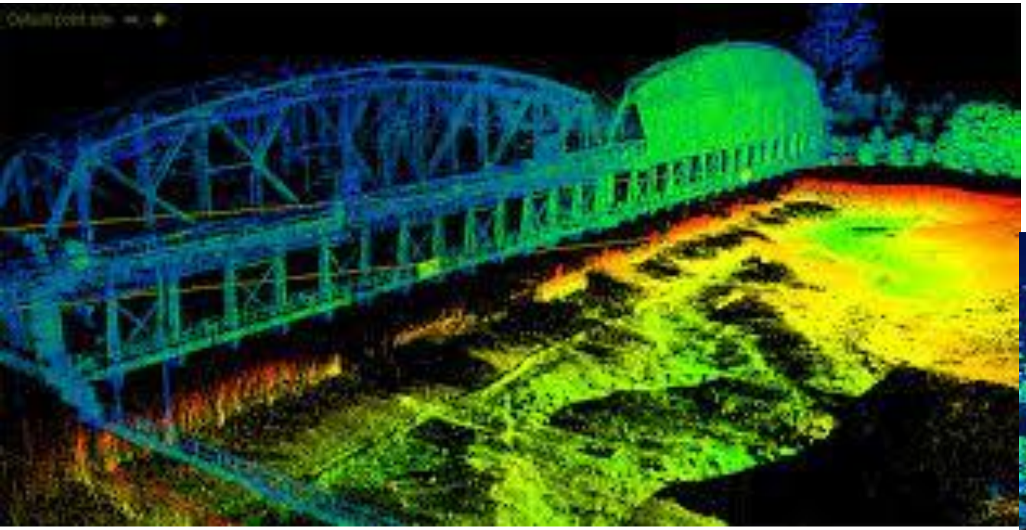
Laser Range Sensor (time of flight, electromagnetic)

- 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 <u>good range estimates</u> as closer brighter objects …



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.



Laser Range Finder: Applications

Stanley: Stanford
(winner of the 2005 Darpa Grand Challenge)

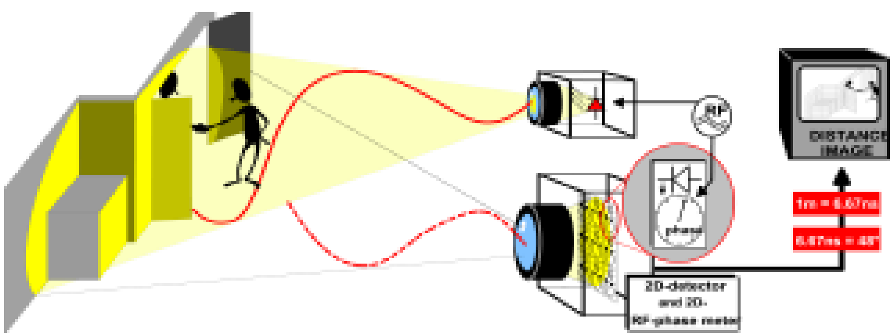
Autonomous Smart:
ASL ETH Zurich

3D Laser Range Finder

- 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).

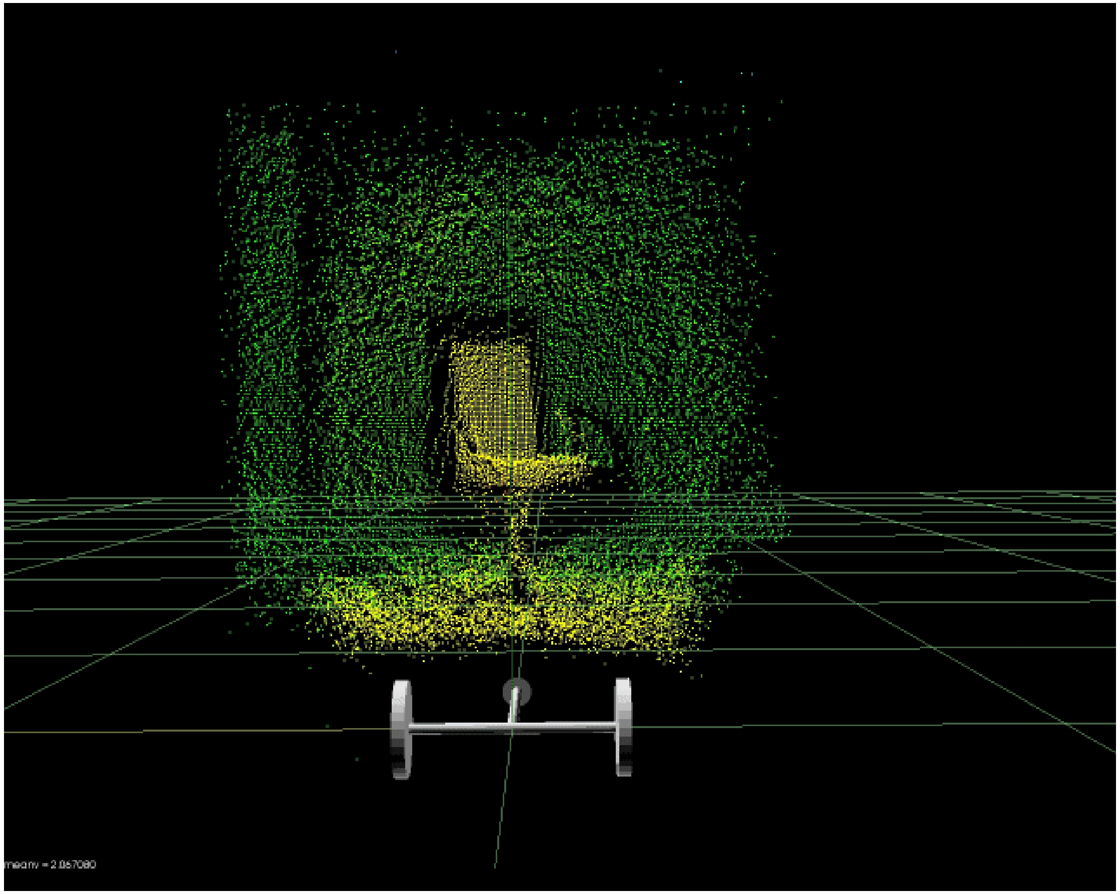
3D Range Sensor (4): Time Of Flight (TOF) camera

- 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.



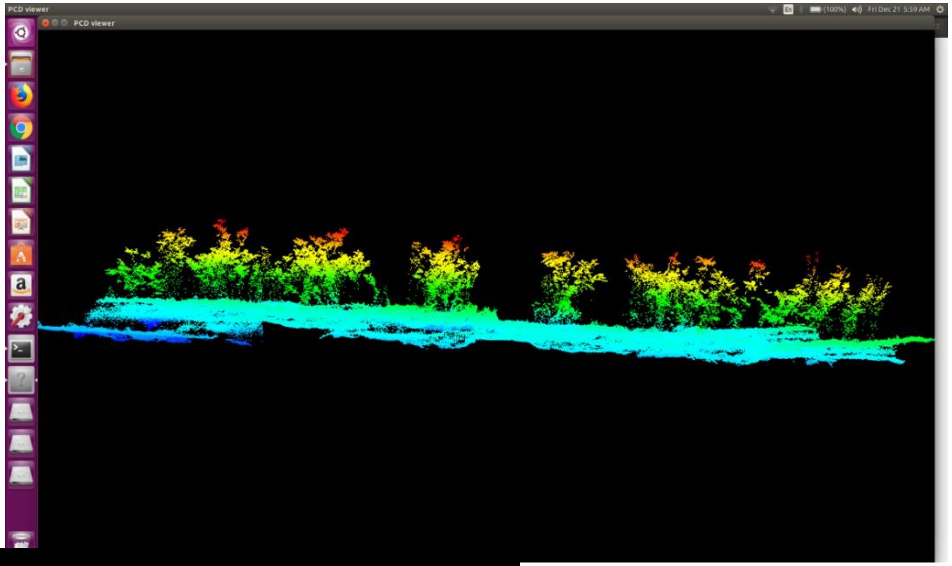
Swiss Ranger 3000
(produced by MESA)

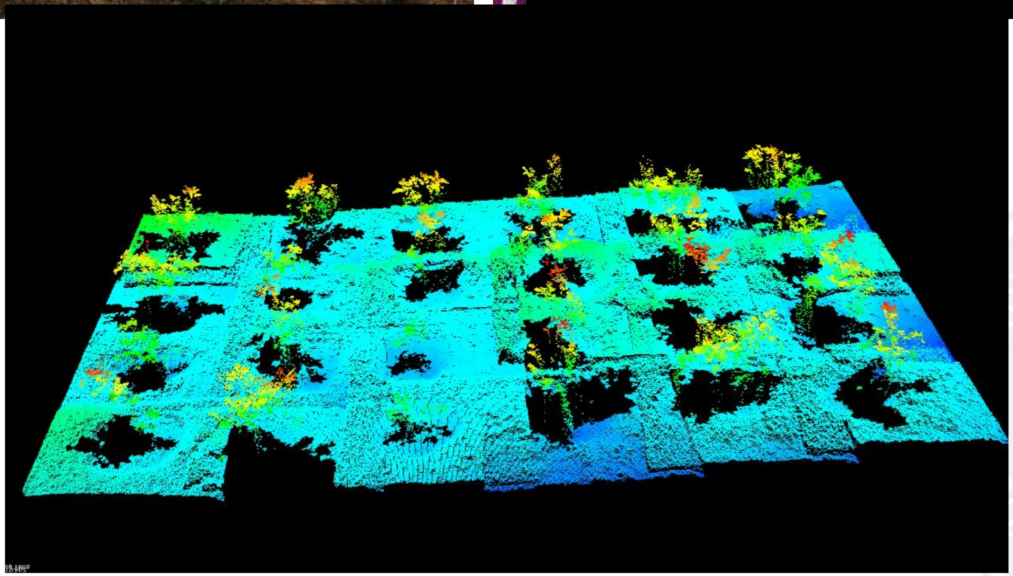
3D Range Sensor (4): Time Of Flight (TOF) camera



ZCAM (from 3DV Systems now bought by Microsoft for Project Natal)

Time Of Flight (TOF) camera: Kinect

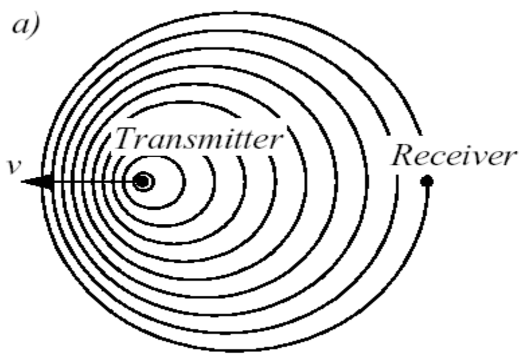


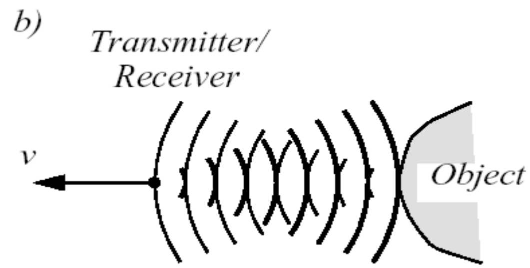


Doppler Effect Based (Radar or Sound): Speed Sensors

$f_t \rightarrow$ frequency of transmitted wave

$f_r \rightarrow$ frequency of received wave



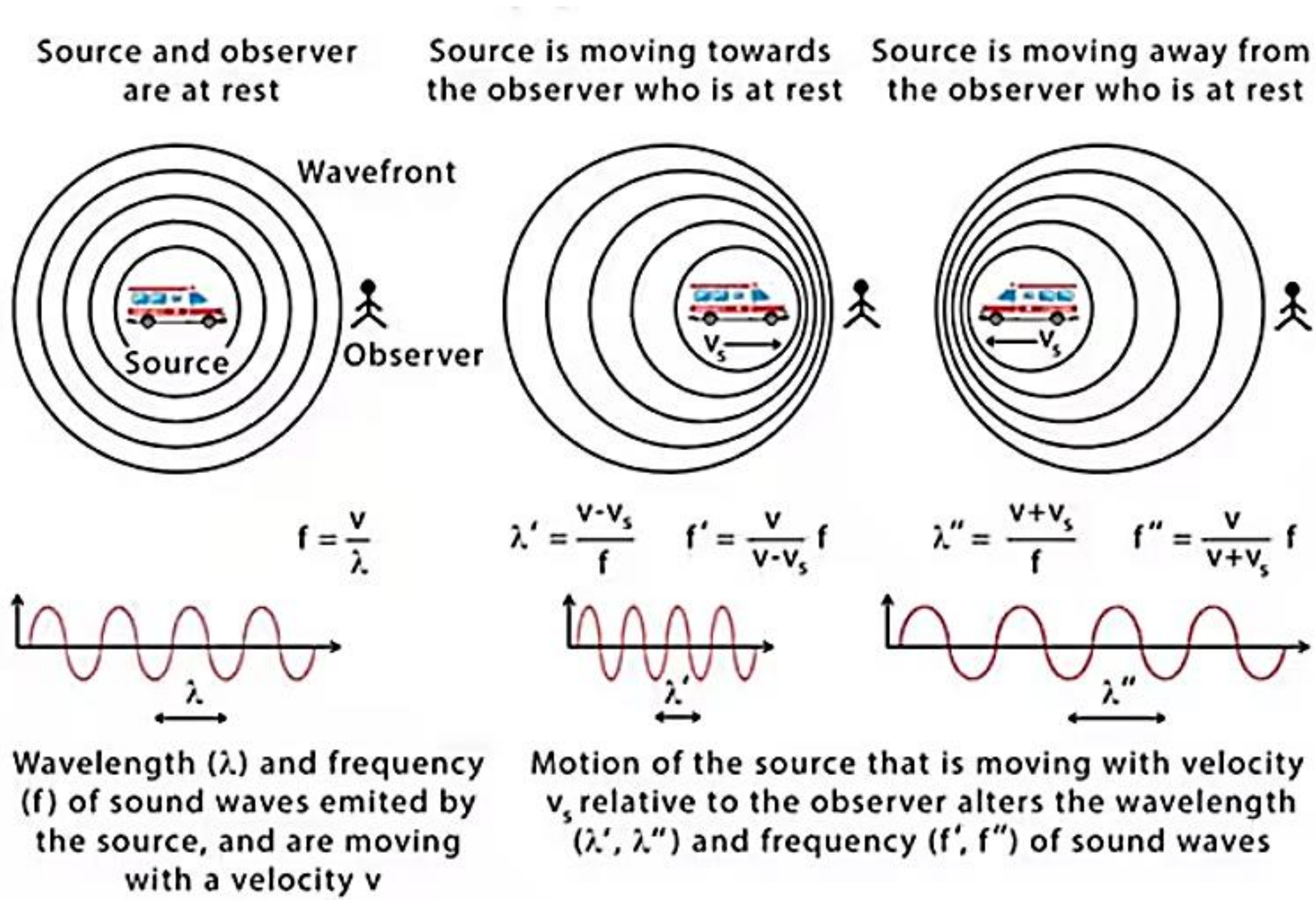


- a) Between two moving objects
- $f_r = f_t(1 + v/c)$ if transmitter is moving
- b) Between a moving and a stationary object
- $f_r = f_t \dfrac{1}{1 + v/c}$ if receiver is moving
- $\Delta f = f_t - f_r = \dfrac{2 f_t v \cos\theta}{c}$

for Doppler shift frequency

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

Doppler Effect Based (Radar or Sound): Speed Sensors



Doppler Effect Based (Radar or Sound): Speed Sensors

- θ = relative angle between direction of motion and beam axis.
- Sound waves: e.g. industrial process control, security, fish finding, measure of ground speed
- Electromagnetic waves: e.g. vibration measurement, radar systems, object tracking