Sensory robotics

Lecture 06.

i.) Sensors for localization and navigation

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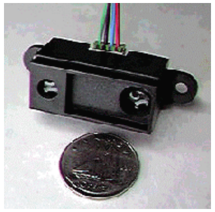
03.22.2021.

SLAM (simultanous localization and mapping)

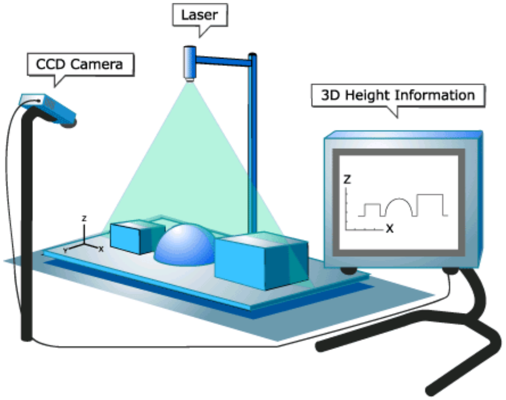
- DARPA Challenge 2004, 2005
- Odometry (odos~ „route” and metron~ „measure”): calculates the position using inner sensors (rotation of wheels, encoders, gyroscopes, compass, accelerometers, IMUs, etc.). Inaccurate because it accumulates the error of the measurements.
- SLAM: The robot updates (and corrects) its odometry calculated position with measuring its relative position to the environment using distance measurement sensors. The process builds a map and update the robot’s position simultanously.

Sensors for localization and navigation – **range sensors**



- Distance Measurement Sensors: infrared sensors (intensity based, modulated, ranging); ultrasound, laser rangefinders, measurement methods; the environment; principles of operation; resolution, operating range; limitations, advantages and disadvantages, comparisons; applications;

- Time of Flight Camera
- Structured light



Source: http://www.nanolinelaser.com/applications_3dimage.html

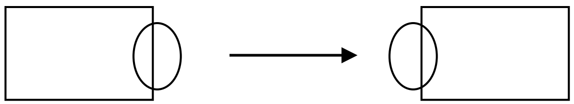
Infrared sensors

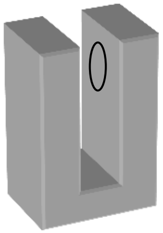
- Intensity based infrared
  - Reflective sensors
  - Easy to implement
  - Susceptible to ambient light

- Modulated Infrared
  - Proximity sensors
  - Requires modulated IR signal
  - Insensitive to ambient light

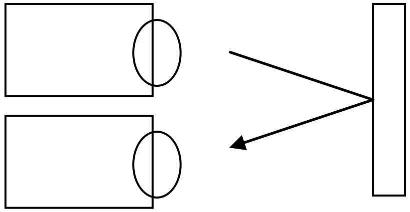
- Infrared Ranging
  - Distance sensors
  - Short range distance measurement
  - Impervious to ambient light, color and reflectivity of object

Intensity based infrared

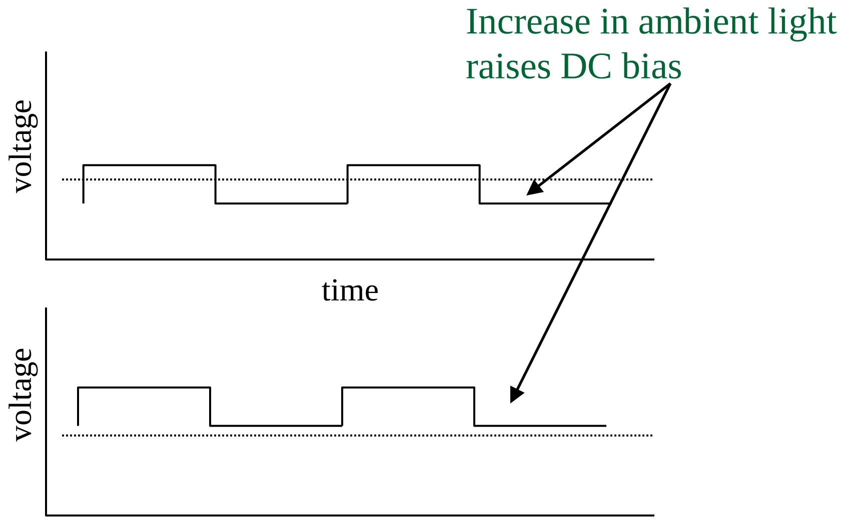




Break-Beam sensor



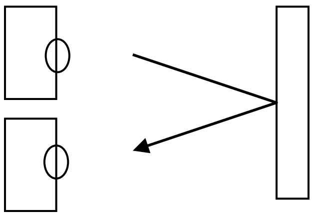
Reflective sensor



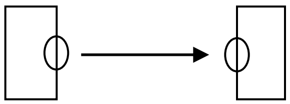
- Easy to implement (few components)
- Works very well in controlled environments
- Sensitive to ambient light

IR Reflective sensors

- Reflective Sensor:
  - Emitter (IR LED) + detector (phototransistor)
  - Phototransistor: the more light reaching the phototransistor, the more current passes through it
  - The light is reflected from the surface into a detector
  - Light is usually in infrared spectrum, IR light is invisible



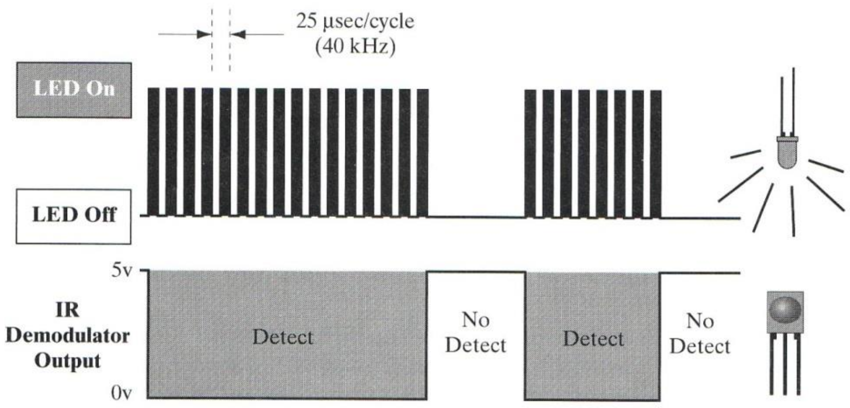
- Applications:
  - Object detection
  - Line following, Wall tracking
  - Optical encoder (Break-Beam sensor)



- Disadvantages:
  - Sensitive to ambient lighting, sensitive to reflectivity of the object, and sensitive to the distance between sensor and the object
    - Separate from outside lighting

Modulated IR – Proximity sensors

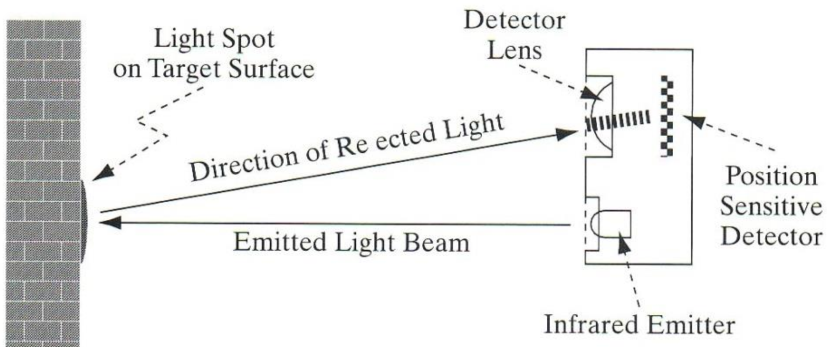
- Flashing a light source at a particular frequency – modulation (32kHz~45kHz)
- Flashes of light can be detected easier - demodulation
- Less sensitive to ambient lighting and reflectivity of objects
- Used in most IR remote control units, proximity sensors
- Detection range: varies with different objects (shiny white card vs. dull black object)
- Applications:
  - Rough distance measurement
  - Obstacle avoidance
  - Wall following, line following

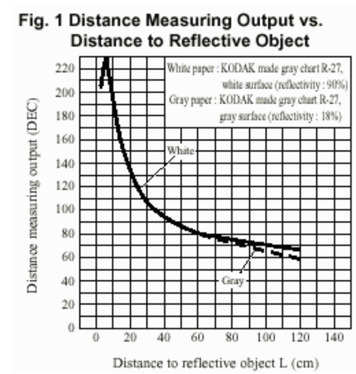


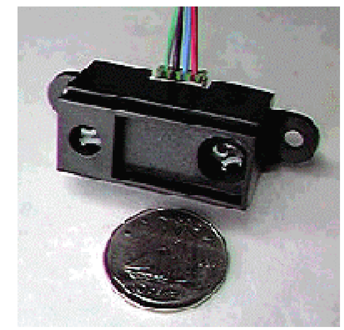
Source: https://ucilnica.fri.uni-lj.si/1617/pluginfile.php/30505/mod_resource/content/2/rins04sensors.pdf

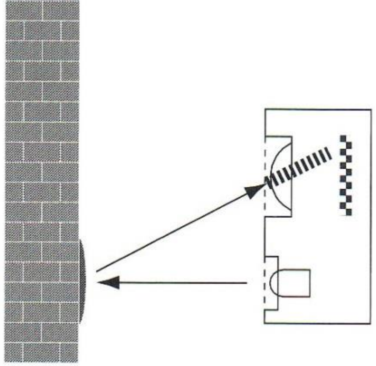
IR distance sensors

- Basic operation: IR emitter + focusing lens + position-sensitive detector









Location of the reflected light spot on the detector corresponds to the distance between the sensor and the target surface. This sensor converts the horizontal distance to vertical distance.

- Moderately reliable for distance measurement (10cm ~ 80cm), insensitive to ambient light, color and reflectivity of object

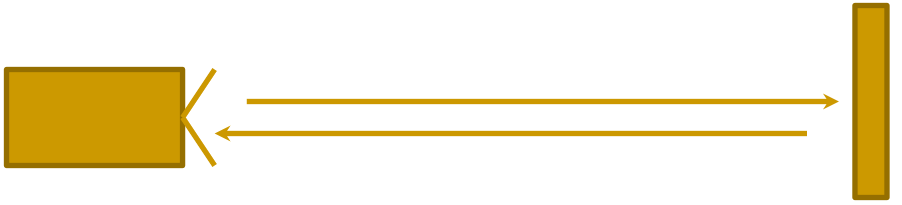
Source: https://ucilnica.fri.uni-lj.si/pluginfile.php/30505/mod_resource/content/4/rins04sensors.pdf

Range finder (time of flight)

- Time of flight: time measurement while a wave travels a distance in a medium
- The measurement process of ultrasound and laser range finders is based on the propagation speed of the sound or electromagnetic waves.
- The measured pulses reflect from the objects, therefore:

$$d = v \cdot t$$

  - *d* = round trip distance
  - *v* = speed of wave propagation
  - *t* = elapsed time



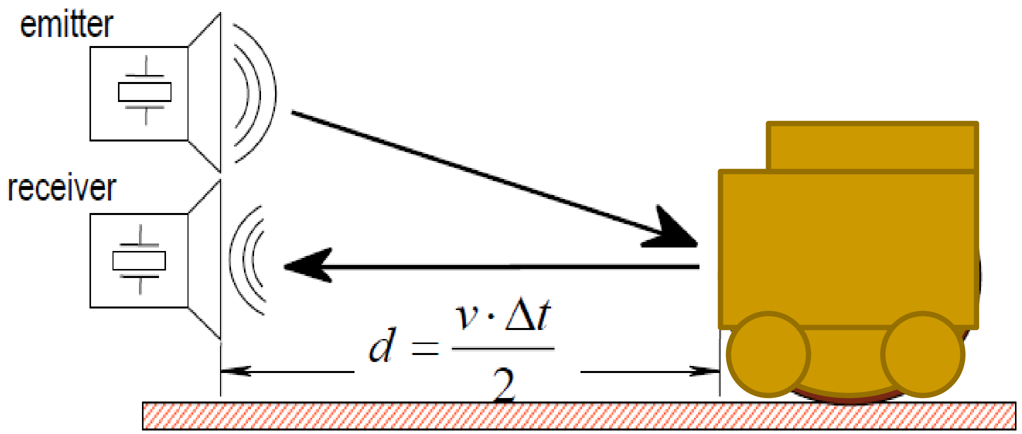
Range finder (time of flight)

- Please note that
  - Sound travels by 0.3 meters / ms
  - RF/light travels by 0.3 meters / ns (very difficult to measure short distances 1-100 meters)
  - The electromagnetic signals propagate million times faster
  - 3 meter
    - 10 ms for the ultrasound based systems
    - It is only 10 ns for a laser based system
    - In case of electromagnetic signals, the time measurement is not an easy issue
    - The laser range finders are still expensive and sensitive

Range finder (time of flight)

- The quality of time measurement of range finders depends on:
  - The inaccuracy and error of time measurement (laser range finder)
  - The angle of beam (especially in case of ultrasound sensor)
  - Interaction with objects (surface, reflections)
  - Variation of the propagation speed (sound)
  - The speed of the mobile robot and target point (in case they are not static)

Ultrasound sensor

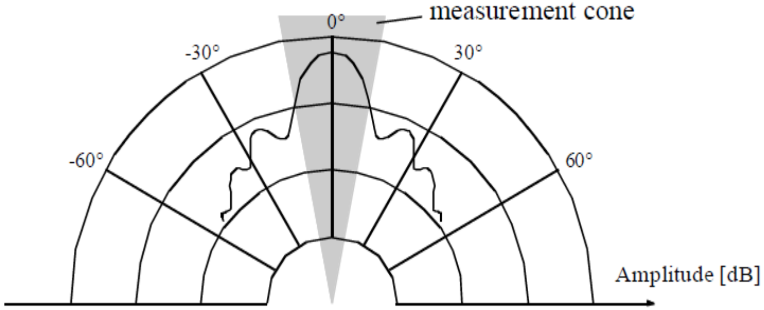


- The ultrasonic wave is usually generated by a piezo or electrostatic transducer. Often the same device is used to measure the reflected signal, although the required blanking interval can be reduced through the use of separate output and input devices. The distance of the sensor and the object can be calculated based on the propagation speed of the sound in air and the time of flight.

Source: Siegwart, R., at al. (2011). *Introduction to autonomous mobile robots.* MIT press.

Ultrasound sensor (time of flight, sound)

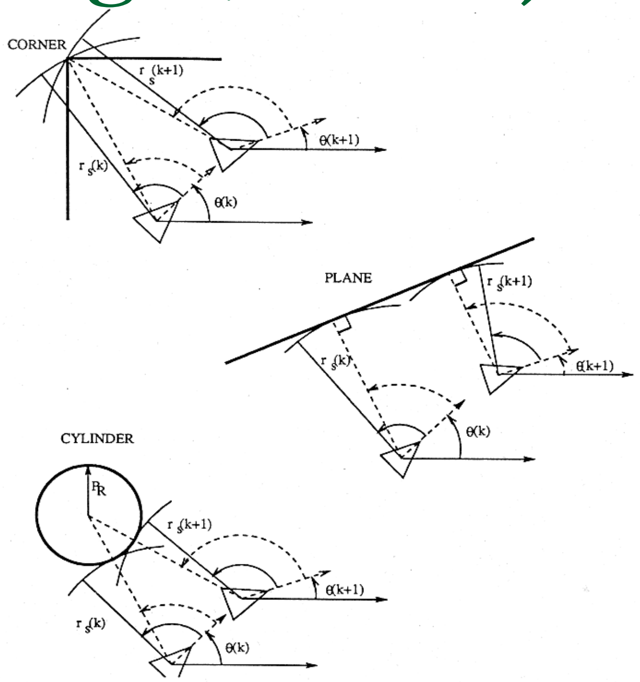
- Main properties
  - The accuracy depends on the relative angle towards to the object
  - **Relative cheap technology**
  - Tipical operational freqencies: 40kHz - 180 kHz
  - **Effectiv range is between 12 cm and 5 m**
  - **Resolution is approximately ~ 2 cm;** Relative error 2%
  - Sound propagates in a cone-like manner
  - **Opening angles around 20 to 40 degrees**



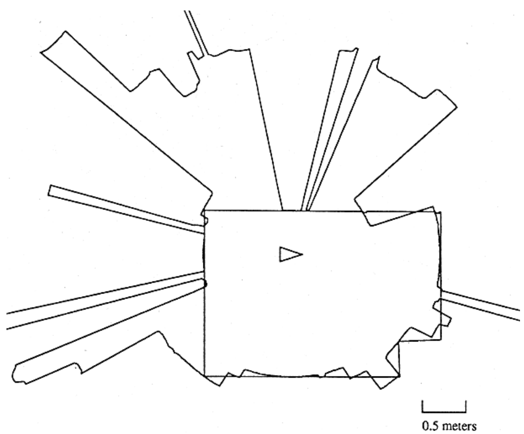
- Applications
  - Distance measurement (also at transparent surfaces)
  - Collision avoidance

Source: Siegwart, R., at al. (2011). *Introduction to autonomous mobile robots.* MIT press.

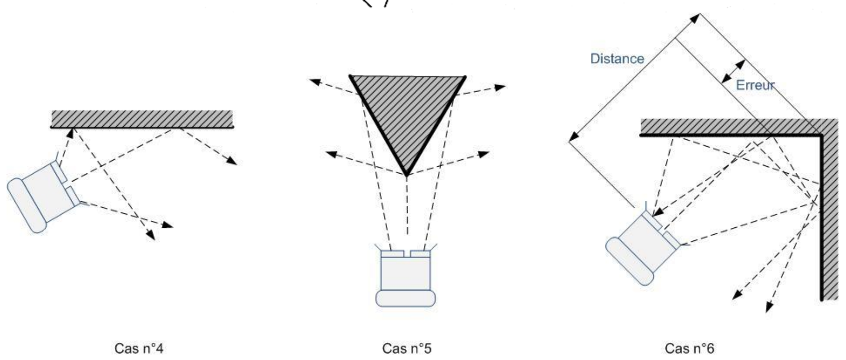
Ultrasound sensor (time of flight, sound)



- Ultrasonic sensors suffer from several additional drawbacks
  - Quality of the surface, soft surfaces can absorb much of the sound energy
  - Surfaces which are not perpendicular to the beam -> **reflections**



360° scan



results from different geometric primitives

Source: Siegwart, R., at al. (2011). *Introduction to autonomous mobile robots.* MIT press.

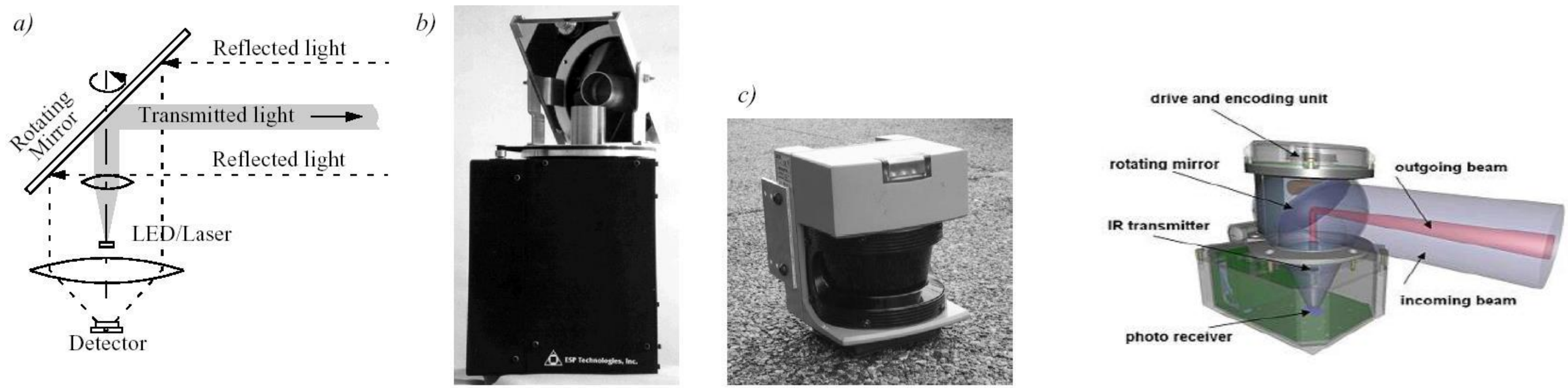
Laser rangefinder (time of flight, electromagnetic)

- Laser rangefinders are known called LIDAR as well (**L**ight **D**etection **A**nd **R**anging)

Source: https://news.voyage.auto/an-introduction-to-lidar-the-key-self-driving-car-sensor-a7e405590cff

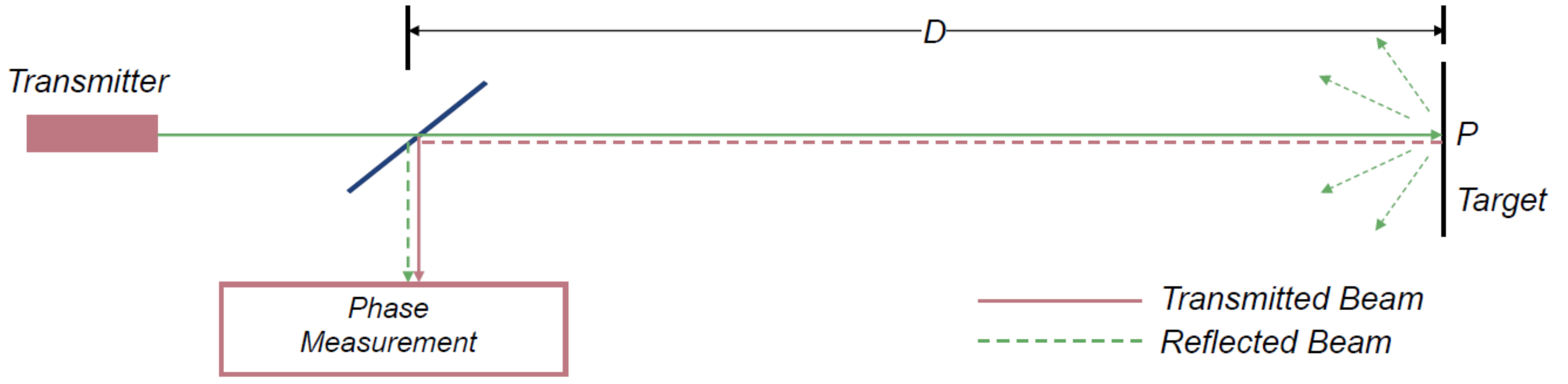
Laser rangefinder (time of flight, electromagnetic)

- Operational principles:
  - Pulsed laser (currently standard method)
    - measure the elapsed time directly
    - electronics capable of resolving picoseconds are required (expensive)
  - Phase-shift measurement
    - Technically easier



Laser rangefinder (time of flight, electromagnetic)

- *Phase-shift measurement*



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

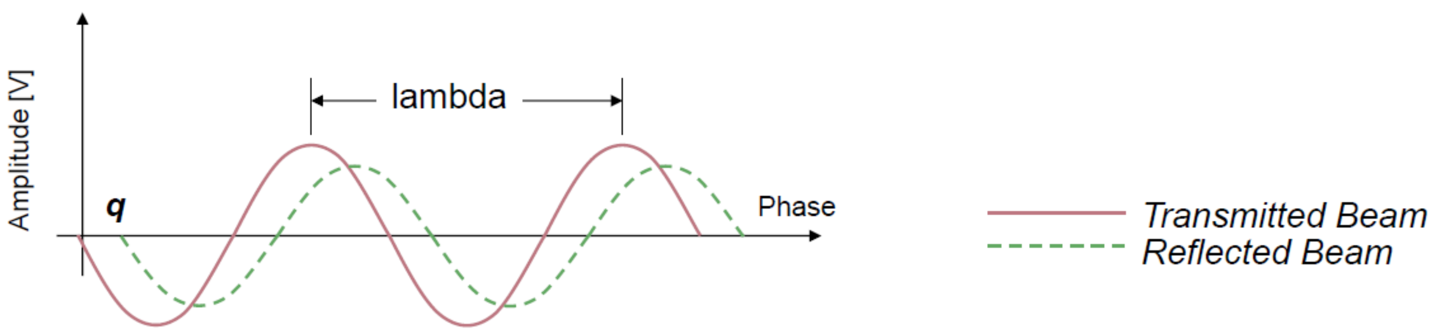
- Where:
  - *c*: the speed of light; *f* the modulating frequency; *D'* total distance.
  - For f = 5 MHz, λ = 60 meters

Laser rangefinder (time of flight, electromagnetic)

- D is the distance between the target and the receiver

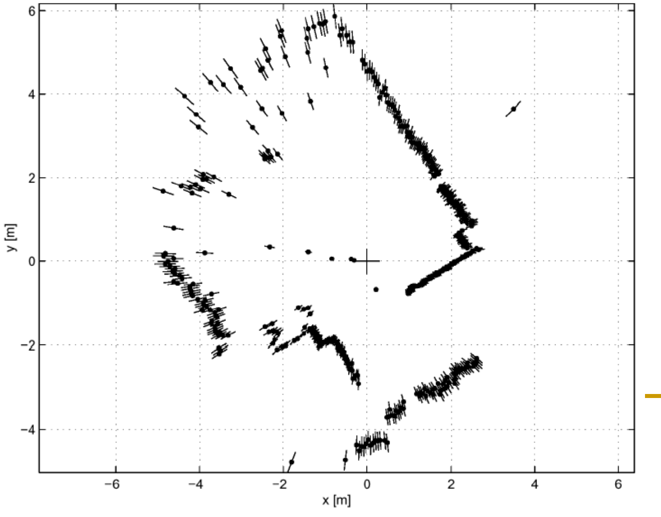
$$D = \frac{\lambda}{4\pi}\theta$$

- where
  - θ: is the electronically measured phase difference between the transmitted and reflected light beams
  - Max. measurable distance = $\lambda/2 \Rightarrow$ ambiguity interval
  - E.g. if f=5MHz (therefore λ = 60 meters) ⇒ max distance = 30 m ⇒ target is by 35 meters = the target is by 5 meters



Laser rangefinder (time of flight, electromagnetic)

- The confidence in the range (phase estimate) is inversely proportional to the square of the received signal amplitude, directly affecting the sensor's accuracy.
  - Hence dark, distant objects will not produce as good range estimates as close, bright objects.
- Typical 2D range image of a 360 degrees scan taken with a laser range sensor using a rotating mirror. The length of the lines corresponds to the measurement uncertainty of the measured points.

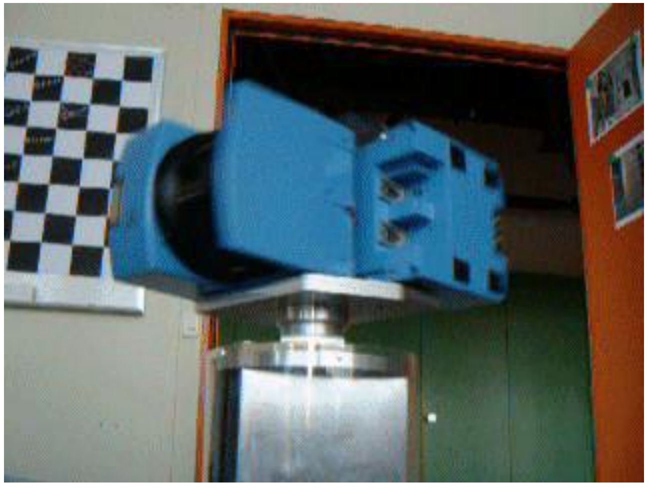


The SICK LMS 200 Laser Scanner

- Angular resolution 0.25 degrees
- Resolution ~10 mm typically with 35mm accuracy where the sensing range 5 cm and 20 m (or more, 80m) based on the reflections of the object.
- In every second it has 75 sweeps in 180 degrees

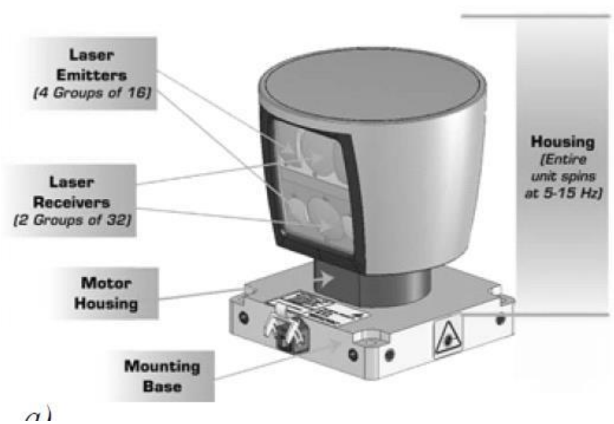
3D laser rengefinder

- **The 3D laser distance sensor is essentially a 2D scanner which collects data on more planes**
- 3D scanners are typically measure by moving or rotating a 2D sensor plane up and down with a stepwise or continuous shaft.
- You can set the desired extent of the angular resolution in the horizontal direction by reducing the rotation speed
- The whole a spherical field of view (360 ° incidence, and +/- 90 ° tilt) can be covered.



3D laser rengefinder

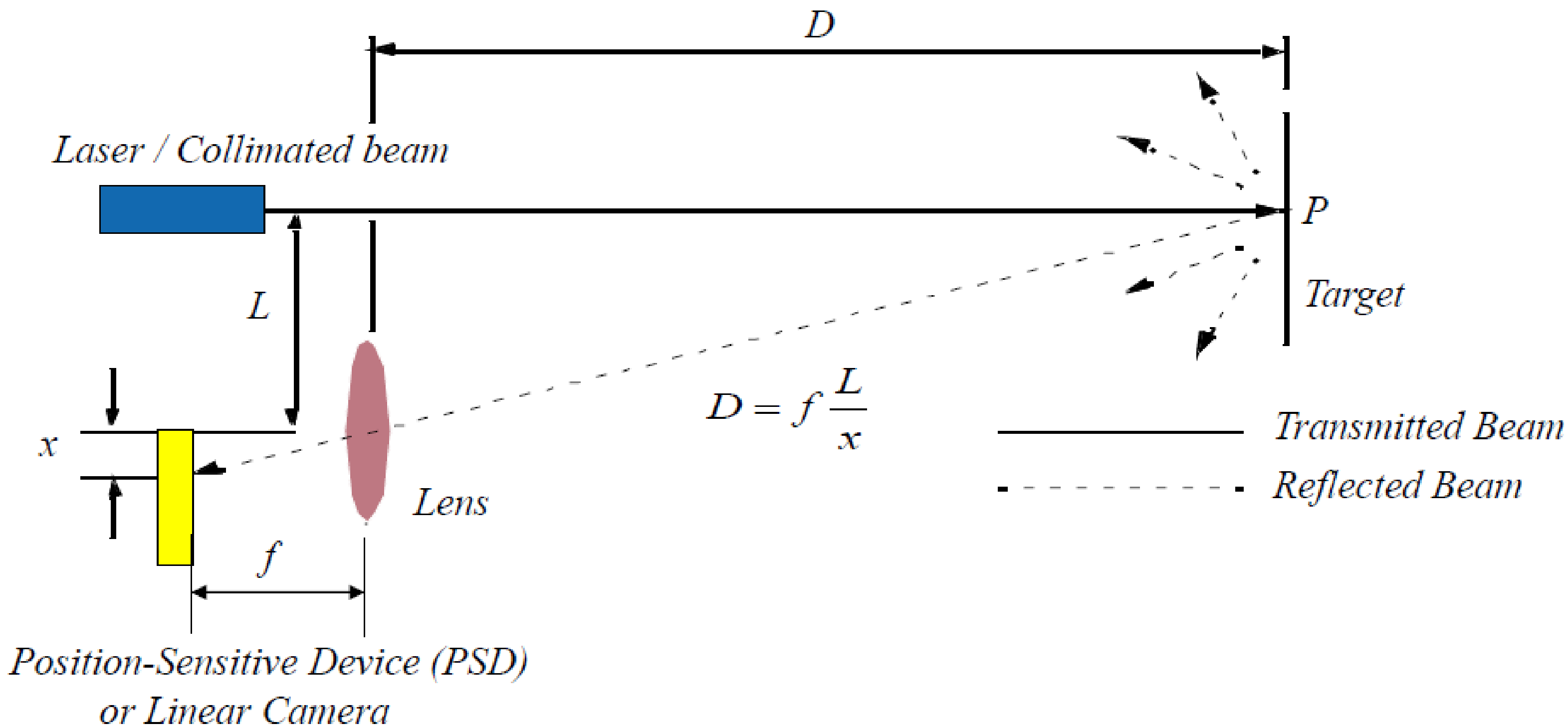
- The Velodyne HDL-64E 64 laser rangefinder
  - Rotating frequency can reach 15 Hz
  - The view is 360° all around and 26.8° in vertical direction
  - The angular resolution is correspondingly 0.09° and 0.4°
  - **Measures 1.3 million data points per second**
  - Distance accuracy is between 2 cm and measurement range is up to 50 m
  - This sensor was used in the urban challenge of DARPA 2007, it is mainly used for 3D terrain surface building and detecting obstacles. The Velodyne is 10-times more expensive than Sick sensor (SICK ~ 4000 $, Velodyne ~40,000 $)



Triangulation Sensor

- 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 us to establish a distance.
- If size of a captured object is precisely known
  - triangulation without light projecting

Laser Triangulation (1D)

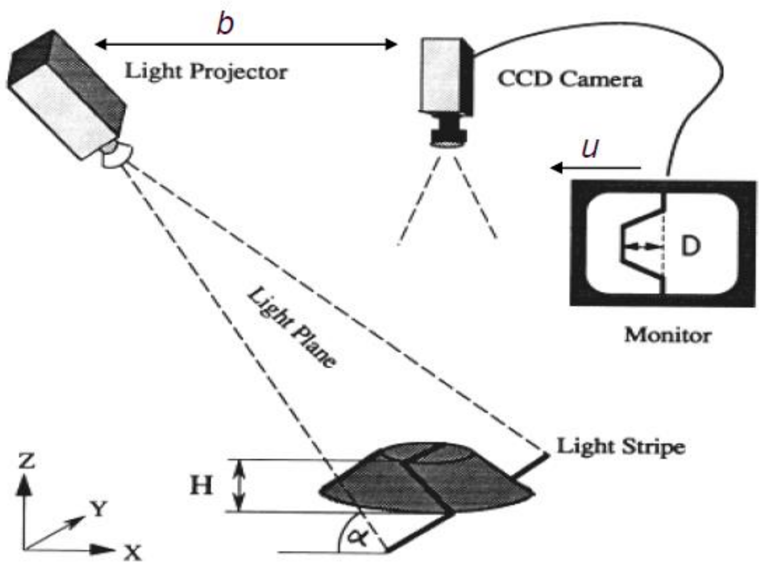


- Principle of 1D laser triangulation:

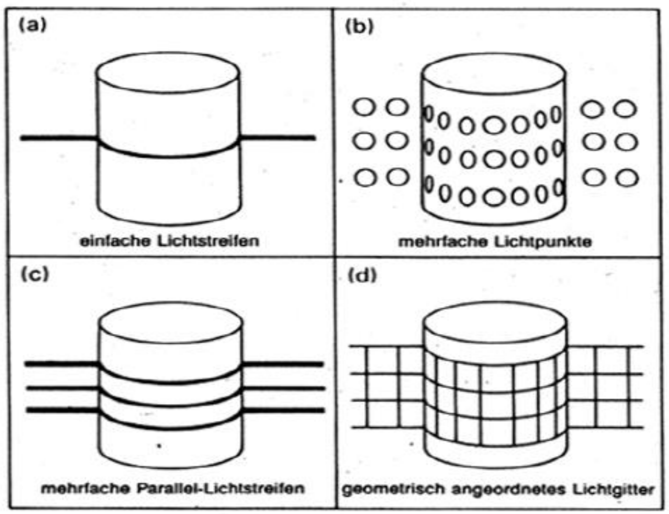
$$D = f\,\frac{L}{x}$$

Structured light (2D or 3D)

a



b

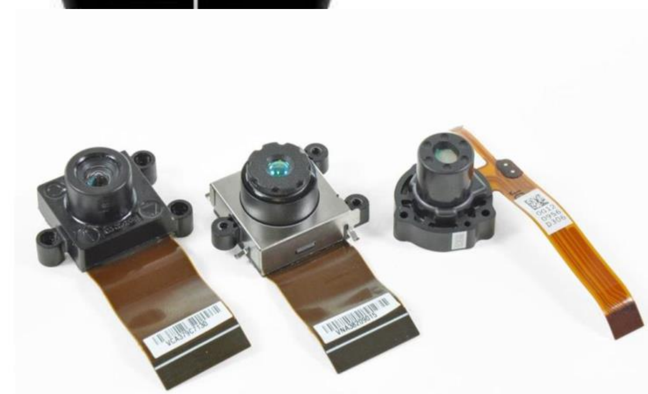


- Eliminate the correspondence problem by projecting structured light on the scene.
- Slits of light or emit collimated light (possibly laser) by means of a rotating mirror.
- Light perceived by camera
- Range to an illuminated point can then be determined from simple geometry.

Microsoft Kinect

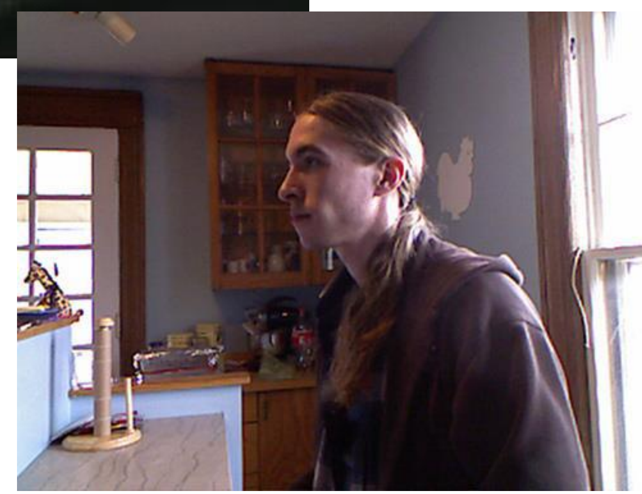
- Developed by the company PrimeSense in 2010

- Major components
  - IR Projector
  - IR Camera
  - VGA Camera
  - Microphone Array
  - Motorized Tilt
  - Field of view: 57.5 deg (horizontal) – 43.5 (vertical)
  - Camera resolution: 640x480 pixels



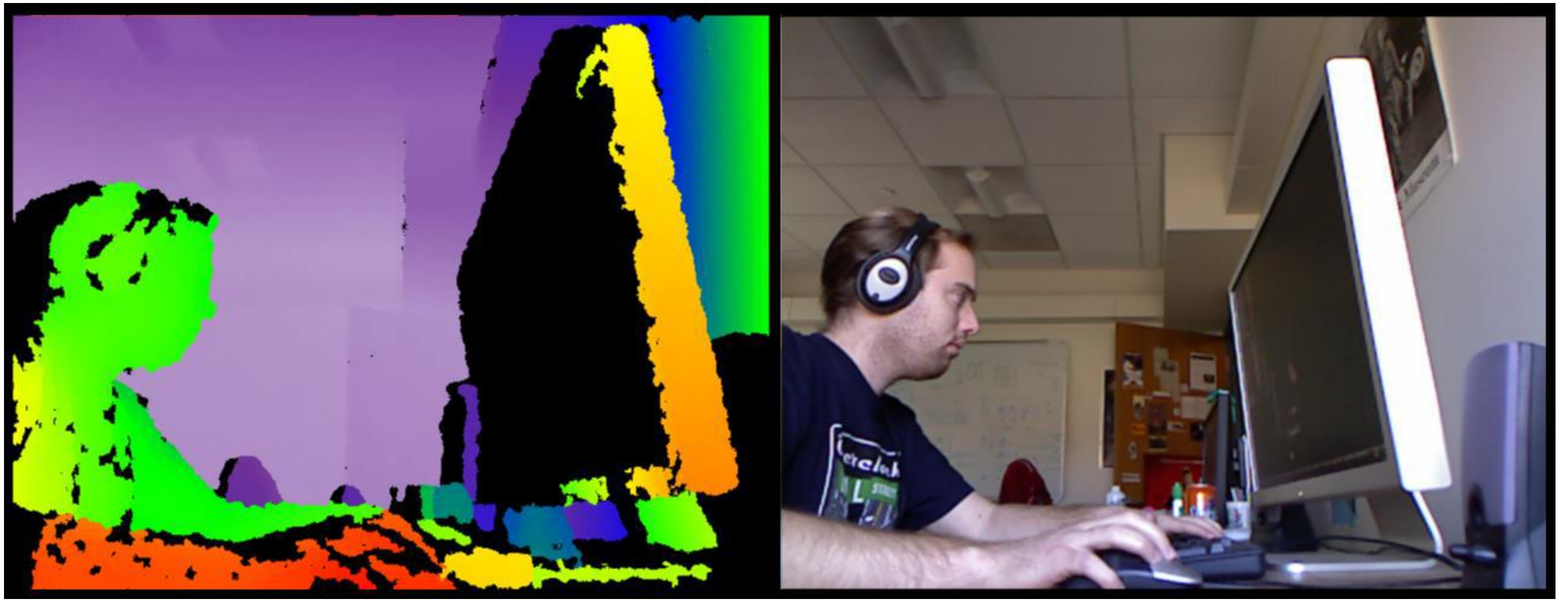
IR pattern

Depth map



Video Out

- 30 fps
- 57 degree
- 8 bit VGA RGB 640x480

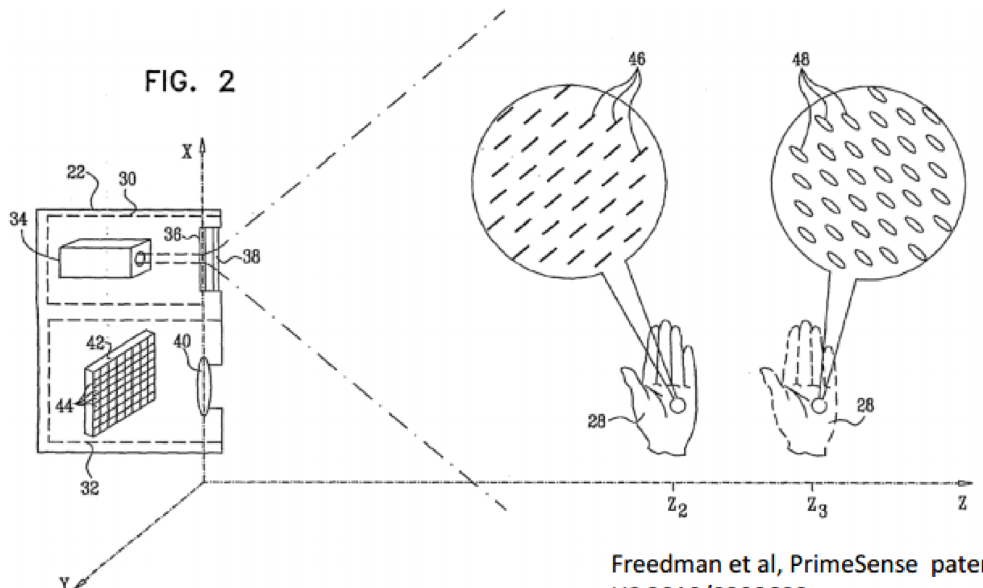


Microsoft Kinect: Depth Computation

- The Kinect uses an infrared projector and an infrared sensor; it does not use its RGB camera for depth computation
- The technique of analyzing a known pattern is “structured light
- The IR projector projects a pseudo-random pattern across the surface of the room.
- The direction of each speckle of the pattern is known (from pre calibration during manufacturing) and is hardcoded into the memory of the Kinect
- By measuring the position of each speckle in the IR image, its depth can be computed

Microsoft Kinect: Astigmatic lens

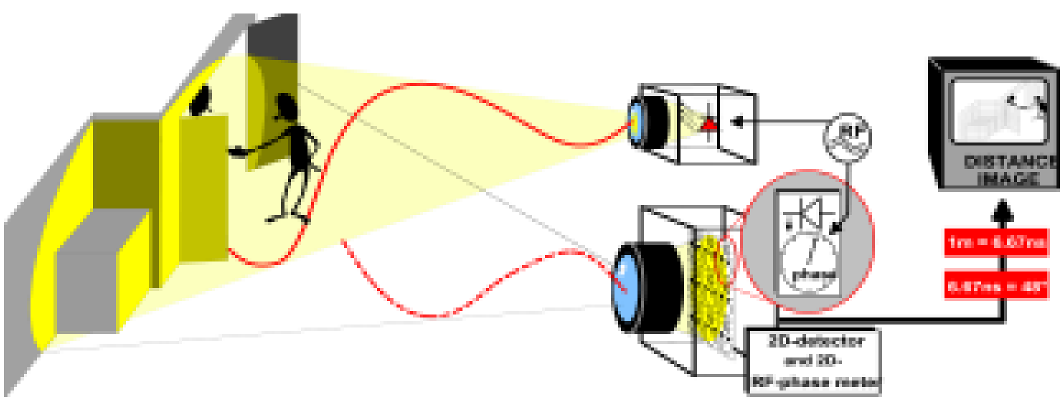
- The Kinect uses a special ("astigmatic") lens with different focal length in x- and y directions
- A projected circle then becomes an ellipse whose orientation depends on depth



Freedman et al, PrimeSense patent application
US 2010/0290698

3D Range Sensor - 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 an infrared lighting source to determine the distance for each pixel of a Photonic Mixer Device (PMD) sensor.



A MESA Swiss Ranger

- 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)

Kinect 2.0 – Time of Flight

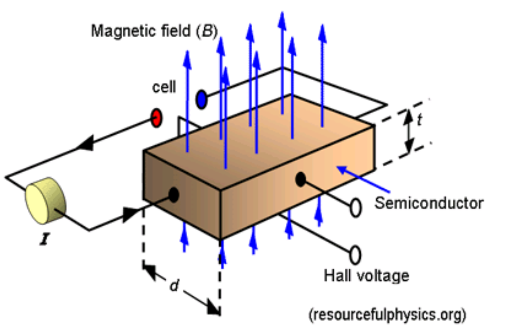
- Resolution 1920x1080 pixels
- Field of view: 70 deg (H), 60 deg (V)
- Claimed accuracy: 1 mm
- Claimed max range: 6 meters

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 magnetic or true north
  - mechanical magnetic compass
  - direct measure of the magnetic field (**Hall-effect**, magneto-resistive sensors)
  - Gyrocompass (**non-magnetic**, finds **true north** by using fast-spinning wheel and friction forces in order to exploit the rotation of the Earth) -> **used on ships**

Compass

- Major drawback of magnetic solutions
  - 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)

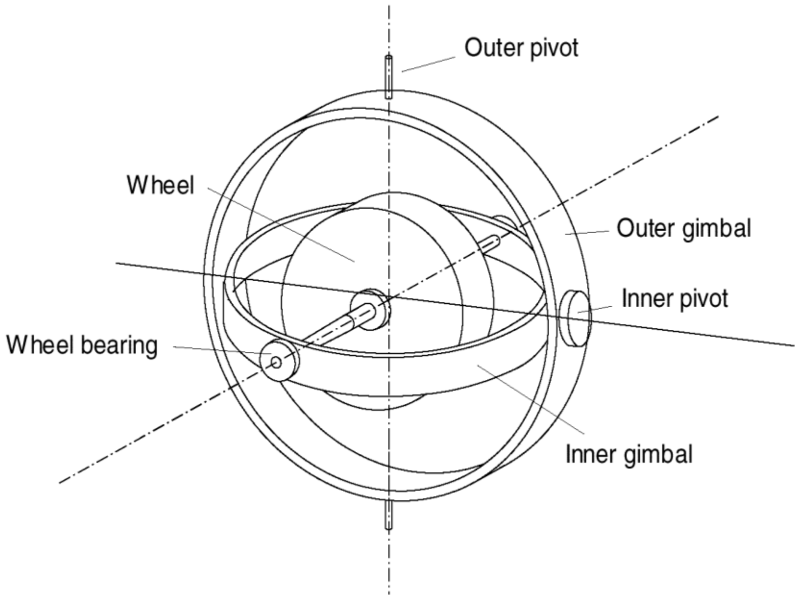


Gyroscope

- 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)

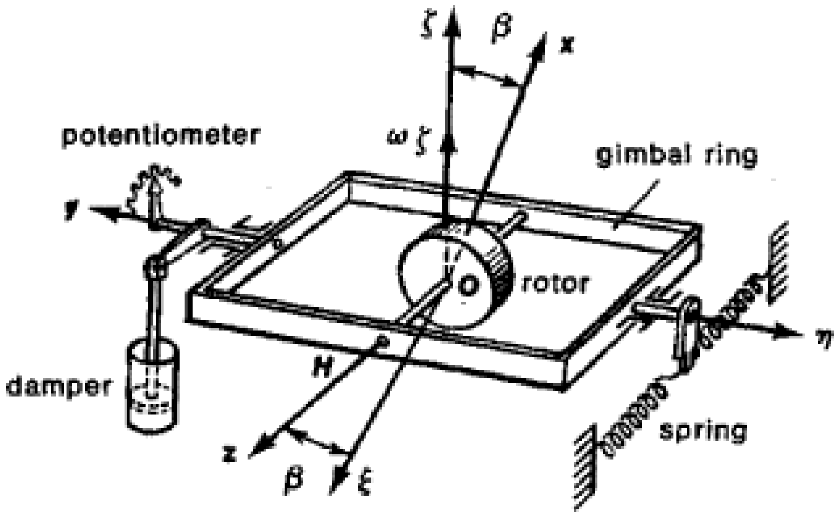
Mechanical Gyroscopes

- 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 $)



Rate gyros

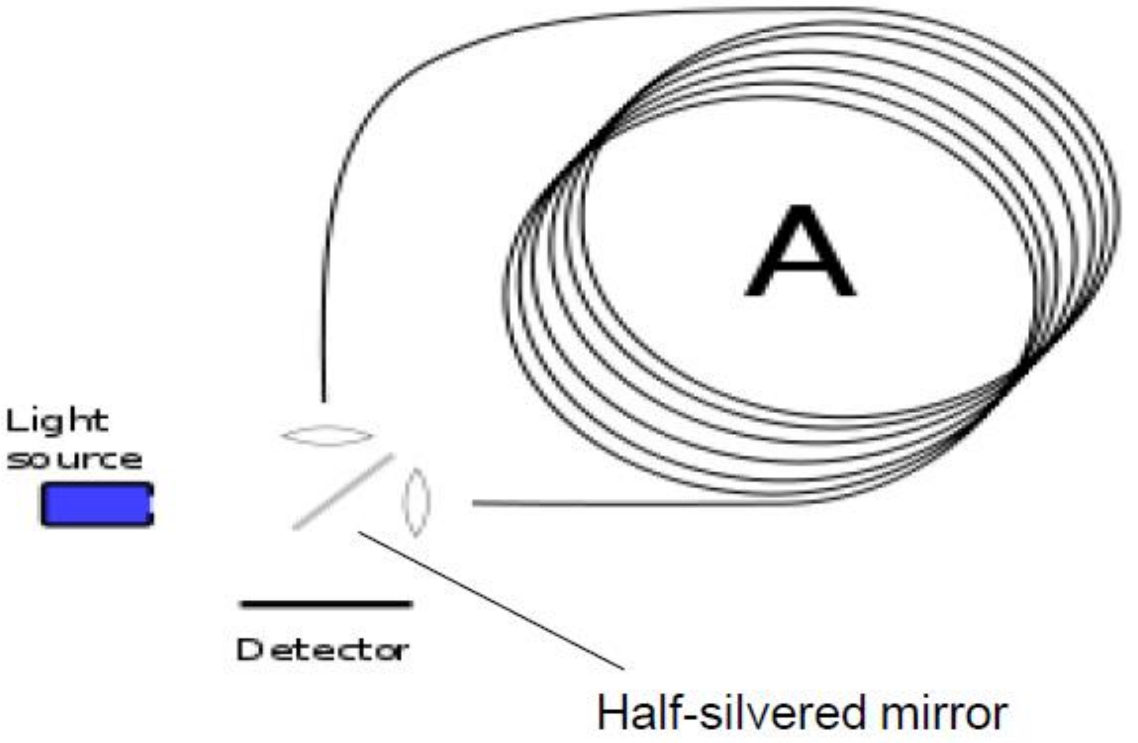
- Same basic arrangement shown as regular mechanical gyros
- But: gimbals are restrained by torsional springs
  - enables to measure angular speeds



Optical Gyroscopes

- Optical gyroscopes are based on the Sagnac effect
  - 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
  - experiences slightly shorter path
  - phase shift of the two beams is proportional to the angular velocity W 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.

Optical Gyroscopes



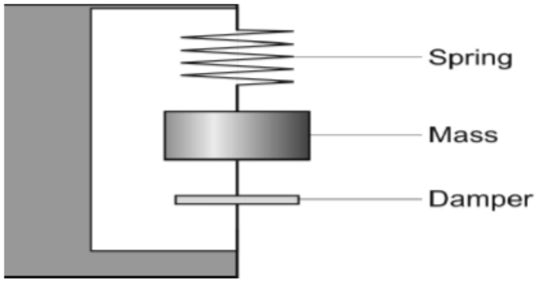
Mechanical Accelerometer

- 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:

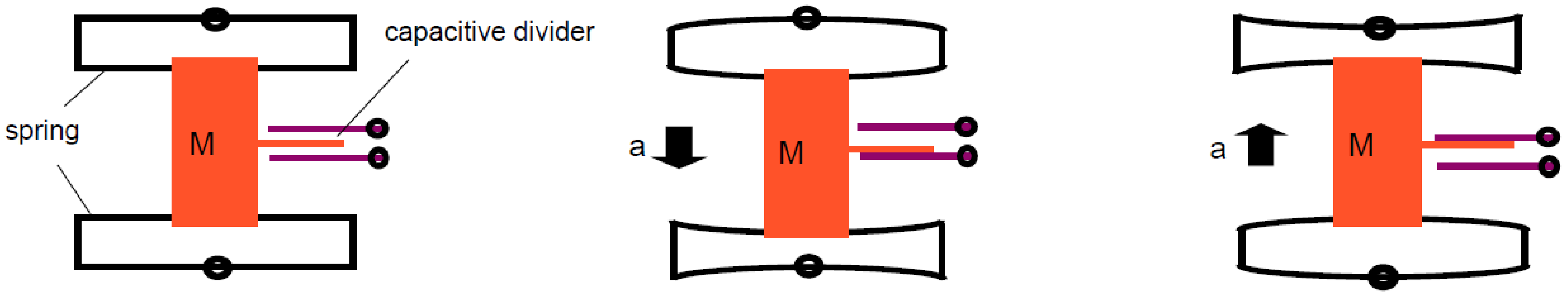
$$a_{applied} = \frac{kx}{m}$$

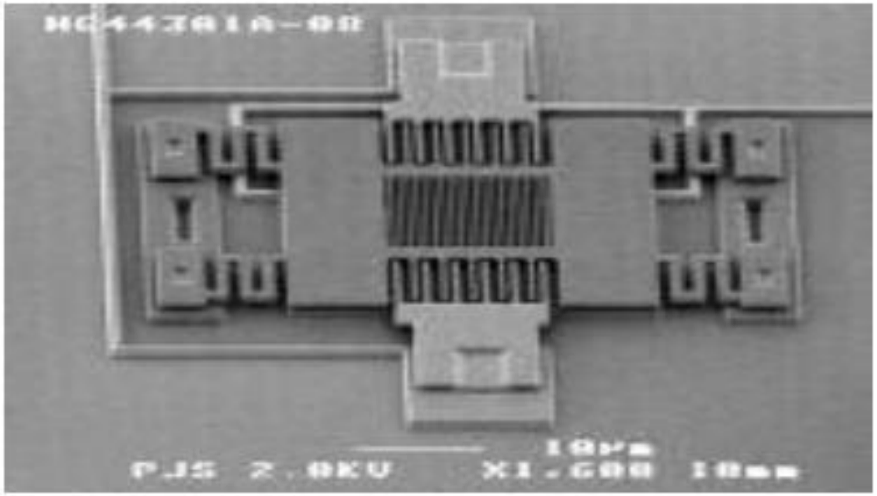


Mechanical Accelerometer

- 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

Factsheet: MEMS Accelerometer (2)



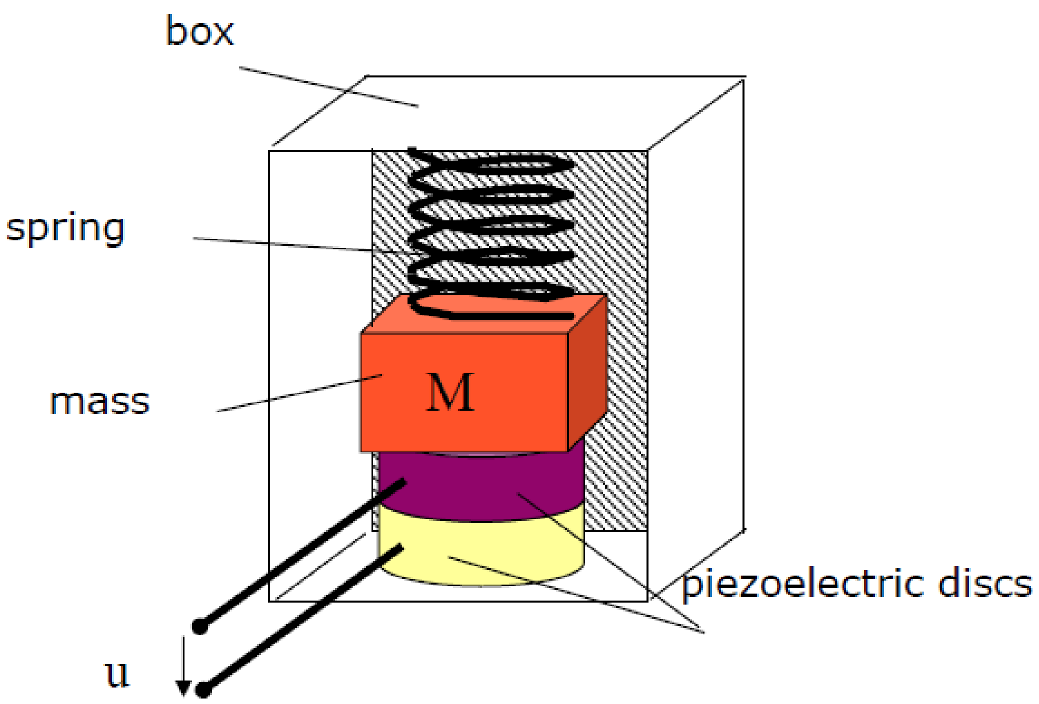


http://www.mems.sandia.gov

Factsheet: MEMS Accelerometer (2)

- **Operational Principle**
  - A spring-like structure connects the device to a seismic mass vibrating in a capacity devider. A capacitive divider converts the displacement of the seismic mass into an electric signal. Damping is created by the gas sealed in the device.
- **Main Characteristics**
  - Can be multi-directional
  - Can measure accelerations up to 50 g
- **Applications**
  - Dynamic acceleration
  - Static acceleration (inclinometer)
  - Airbag sensors (+- 35 g)
  - Control of video games (Wii)

Factsheet: Piezoelectric Accelerometer



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

Factsheet: Piezoelectric Accelerometer

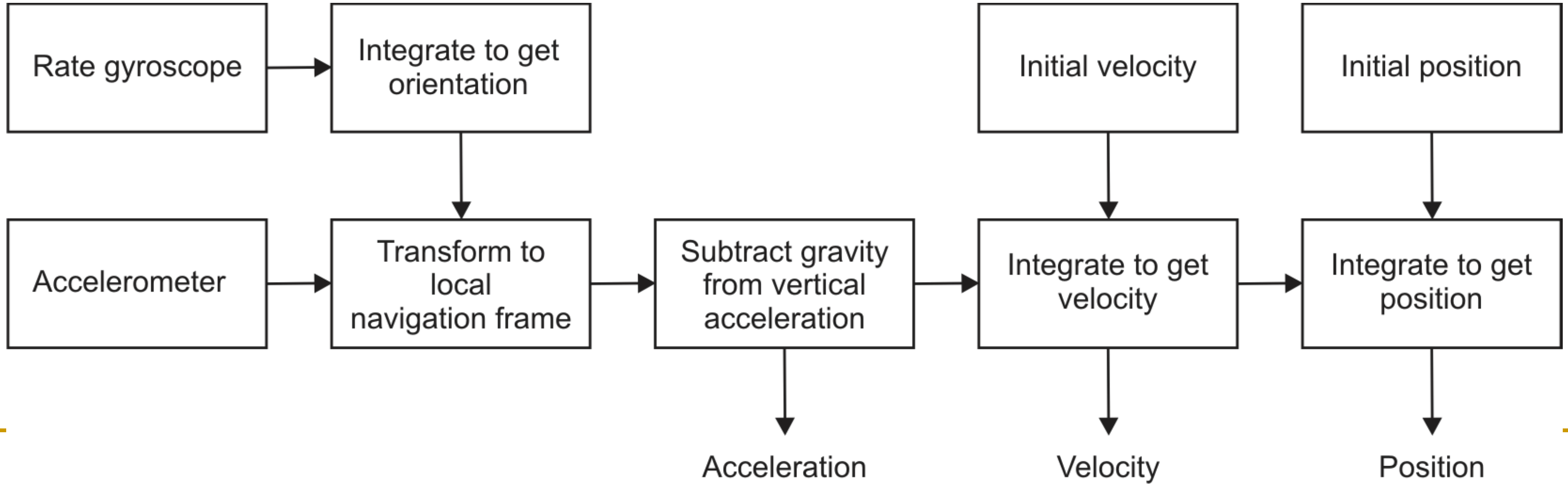
- **Operational Principle**
  - Primary transducer is typically a single-degree-of-freedom spring-mass system that relates acceleration to displacement. Secondary transducer (piezoelectric discs) converts displacement of the seismic mass into an electrical signal (voltage).
- **Main Characteristics**
  - 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
- **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 with respect to an inertial frame
- In order to estimate motion, the gravity vector must be subtracted. Furthermore, initial velocity has to be known.

Inertial Measurement Unit (IMU)

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



End of Lecture 06.

i.) Sensors for localization and navigation – range sensors

György Cserey
03.22.2021.