ETH zürich

ASL Autonomous Systems Lab

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Perception I: Sensors

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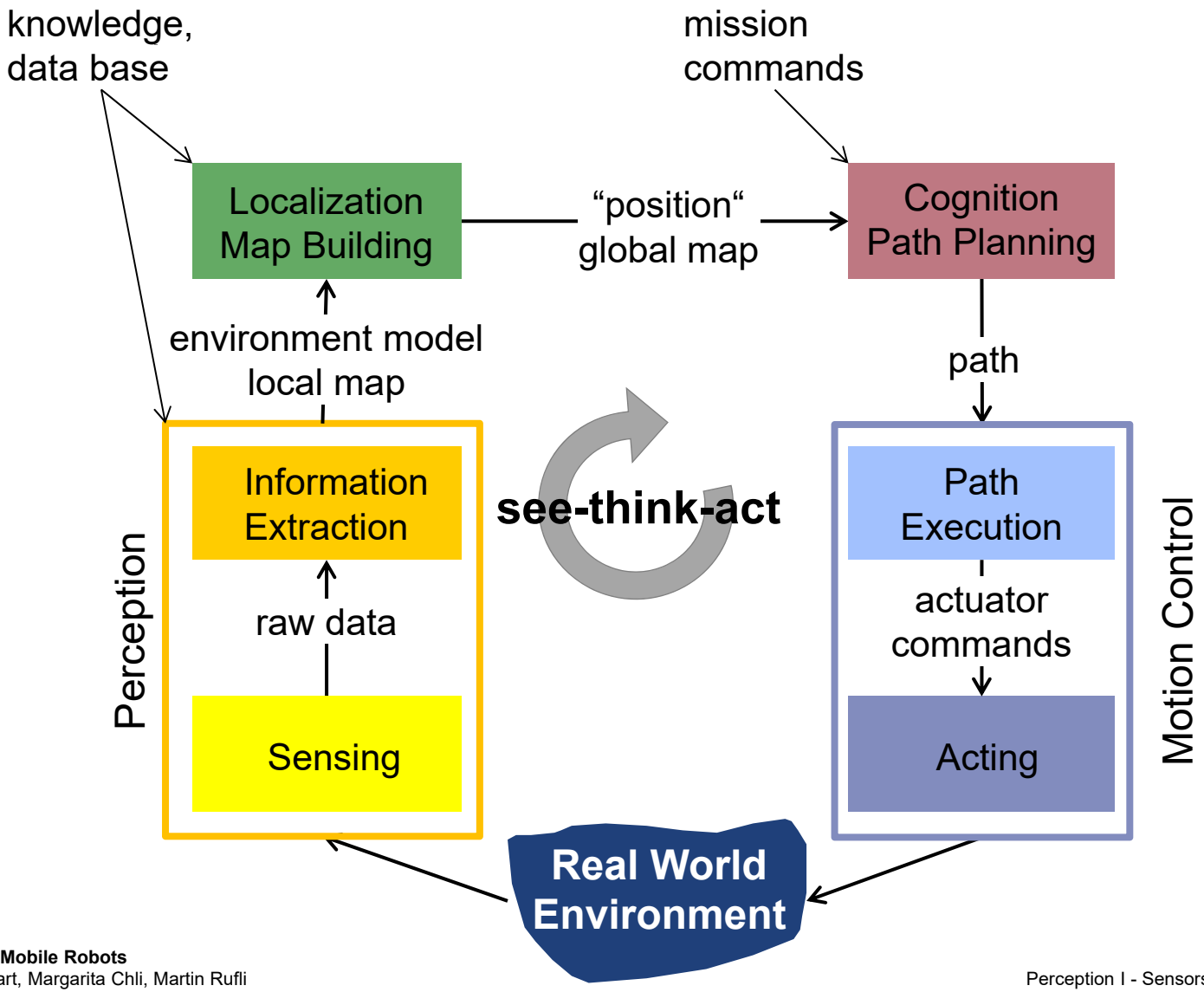
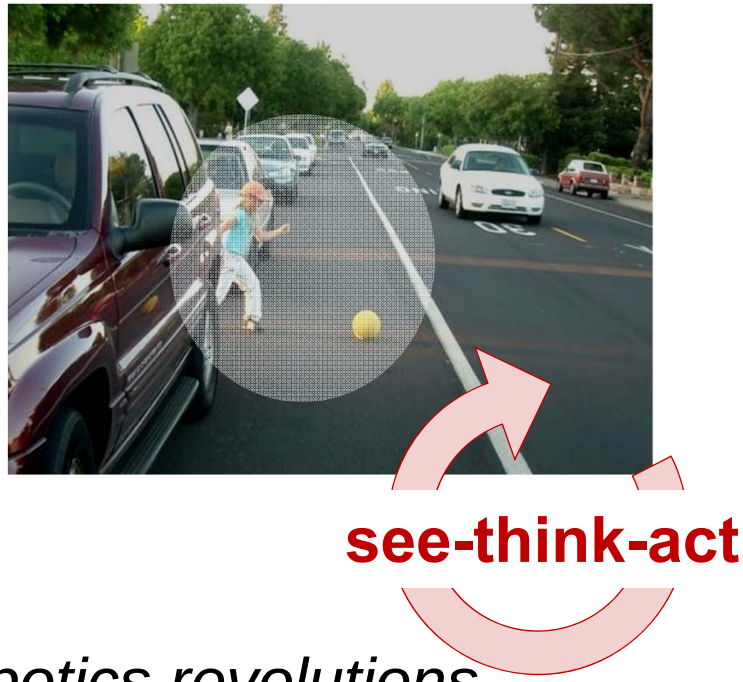
Mobile Robot Control Scheme



Robotics | challenges and technology drivers

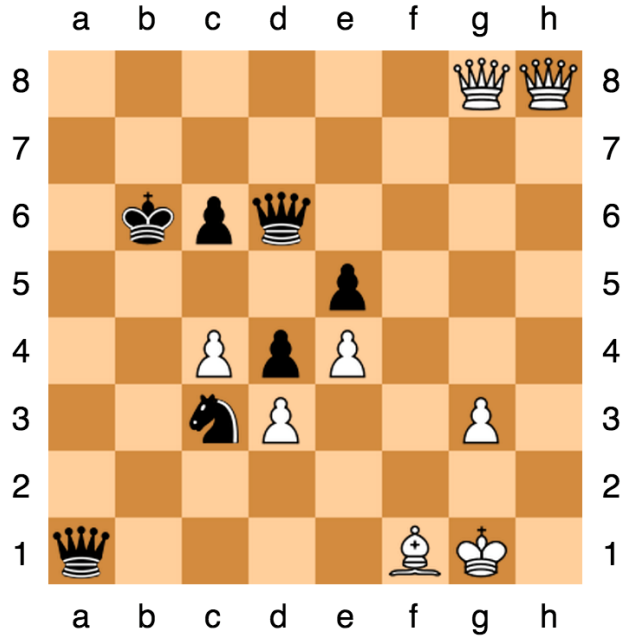
- The challenges
  - ***Seeing***, ***feeling*** and ***understanding*** the world
  - Dealing with ***uncertain*** and only ***partially available*** information
  - ***Act*** appropriately onto the environment



- Technology drivers
  | *technology evolutions enable robotics revolutions*
  - Laser time-of-flight sensors
  - Cameras and IMUs combined with required calculation power
  - Torque controlled motors, “soft” actuation
  - New materials

Perception is hard!

- **"In robotics, the *easy* problems are *hard* and the *hard* problems are *easy*"**
  - S. Pinker. The Language Instinct. New York: Harper Perennial Modern Classics, 1994



beating the world's chess master: EASY

create a machine with some "common sense": very HARD

Perception for Mobile Robots

Places / Situations
A specific room, a meeting situation, …

Servicing / Reasoning

Objects
Doors, Humans, Coke bottle, car , …

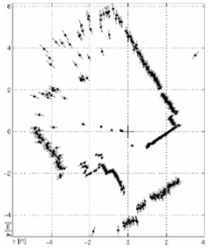
Interaction

Features
Corners, Lines, Colors, Phonemes, …

Navigation

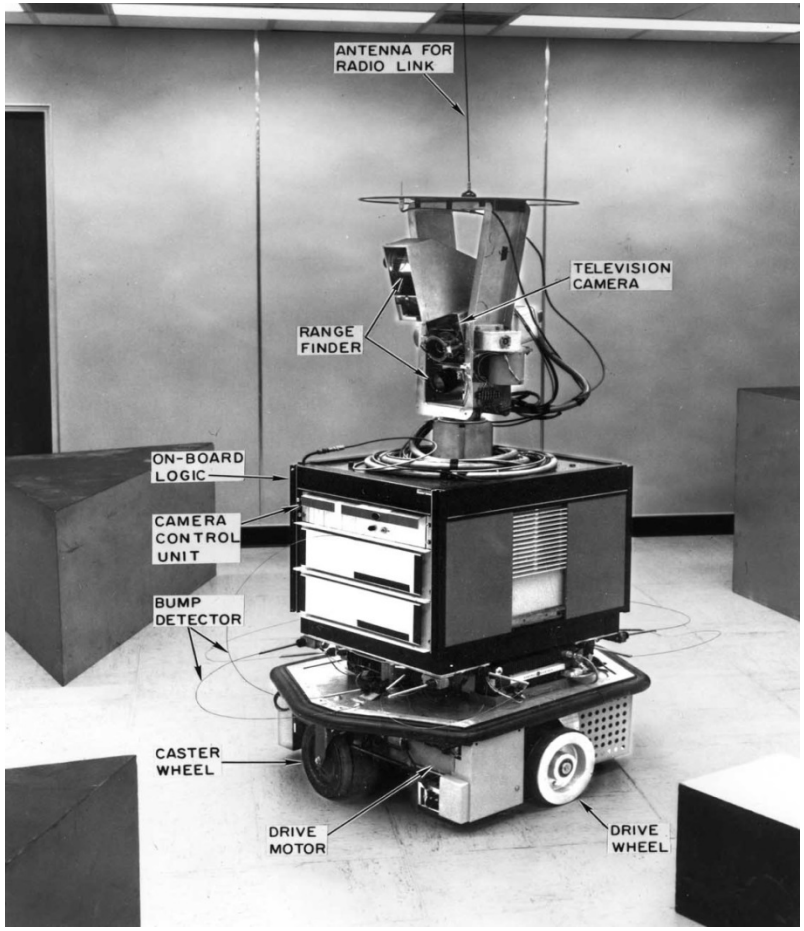
Raw Data
Vision, Laser, Sound, Smell, …

Compressing Information



Shakey the Robot (1966-1972), SRI International

- Operating environment
  - Indoors
  - Engineered
- Sensors
  - Wheel encoders
  - Bumb detector
  - Sonar range finder
  - Camera



C 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

PR2 (2010-)

https://www.youtube.com/watch?v=gy5g33S0Gzo

50x speed

C Willow Garage

- 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
  - ...

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; very much influenced by the environment
  - Active sensors
    - emit their proper energy and measure the reaction
    - better performance, but some influence on environment

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

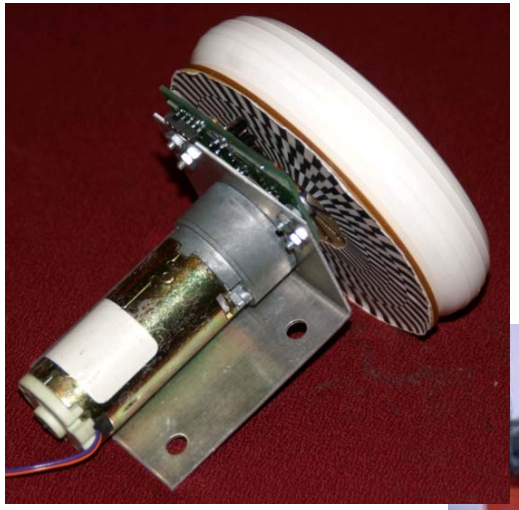
A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

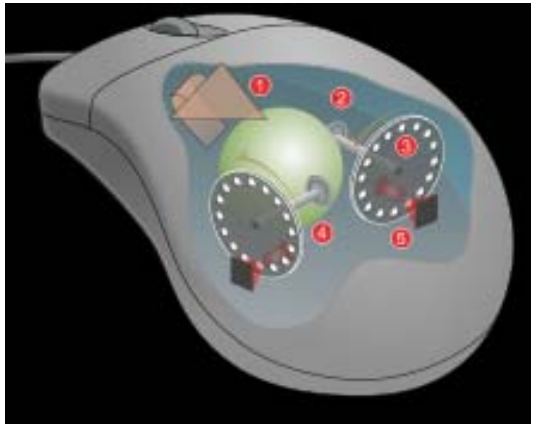
General Classification (2)

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 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

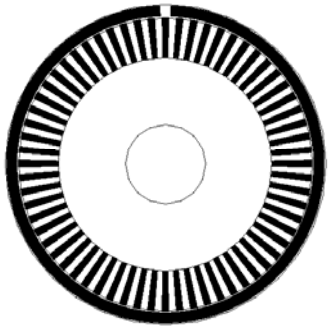
Encoders

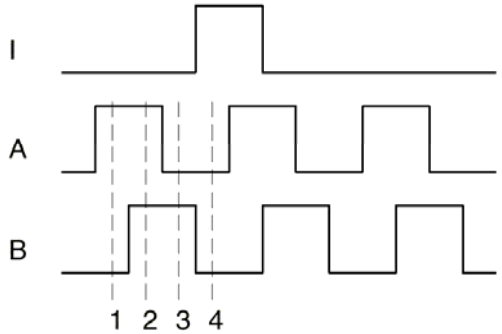
- Definition:
  - electro-mechanical device that converts linear or angular position of a shaft to an analog or digital signal, making it an linear/anglular transducer





Wheel / Motor Encoders

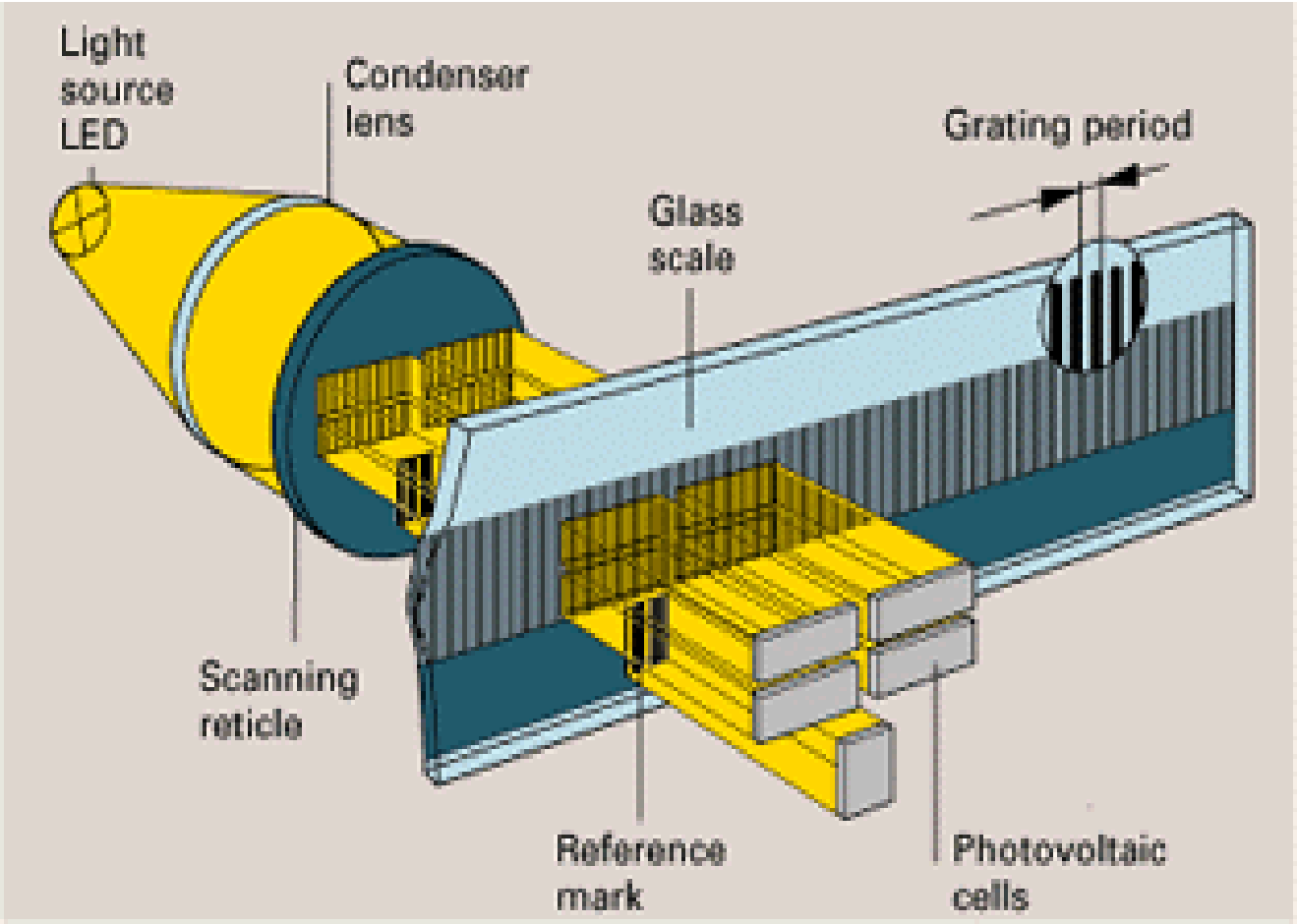




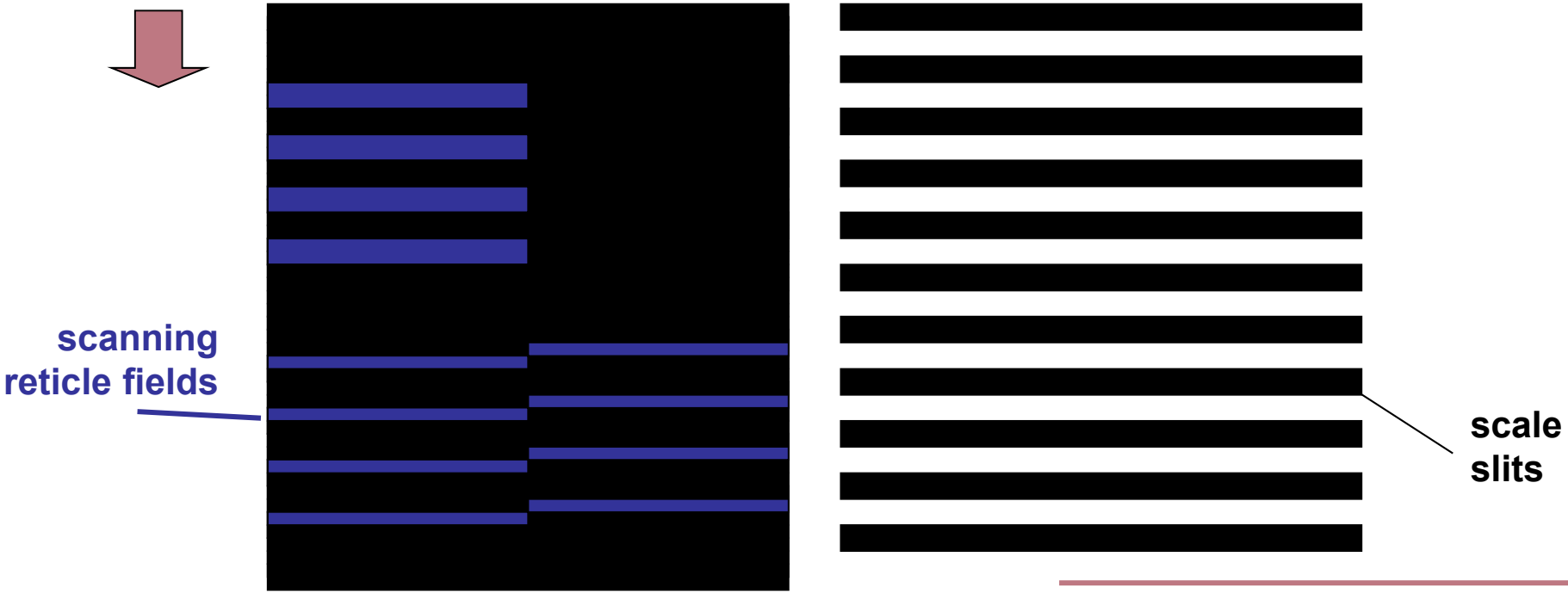
State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

- 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

Wheel / Motor Encoders (2)



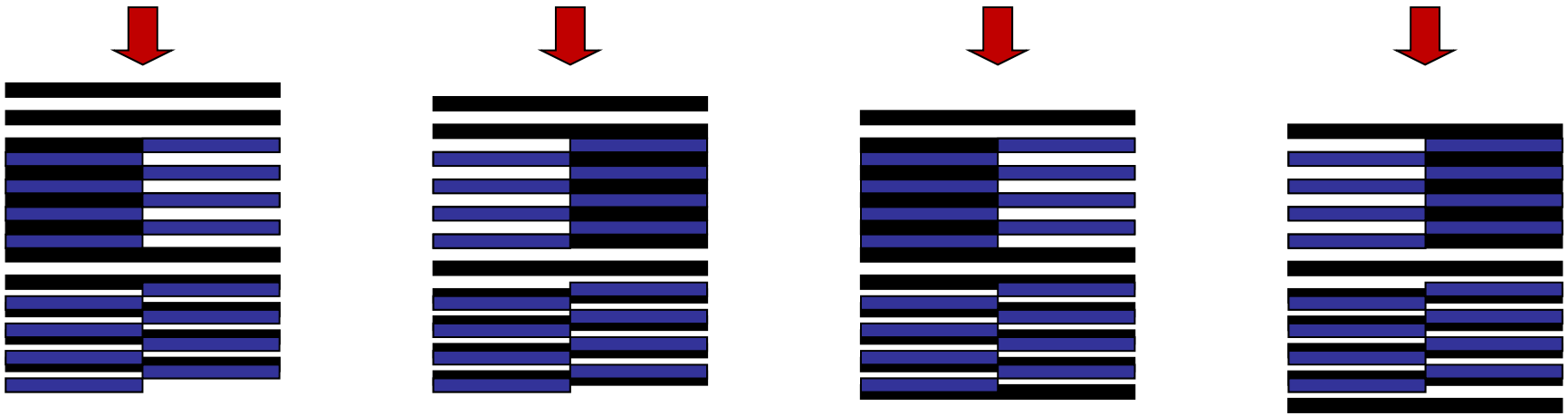
Wheel / Motor Encoders



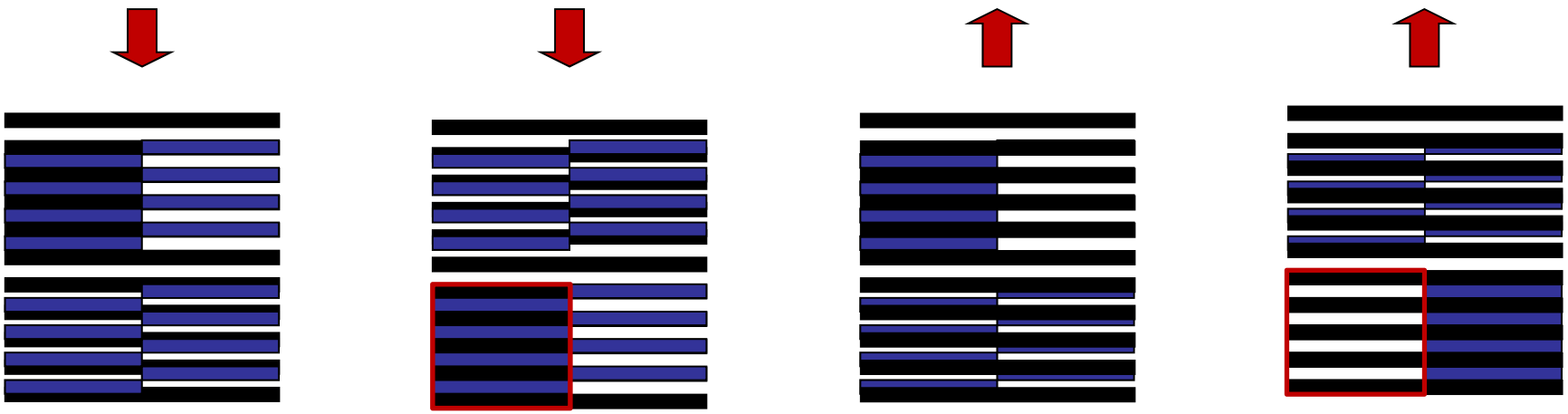
2. Main Characteristics

- 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

Wheel / Motor Encoders



Notice what happens when the direction changes:



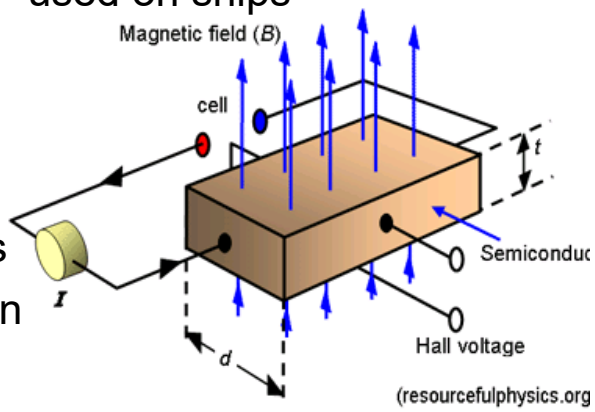
Heading Sensors

- Definition:
  - Heading sensors are sensors that determine the robot's orientation and inclination with respect to a given reference

- 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)

Compass

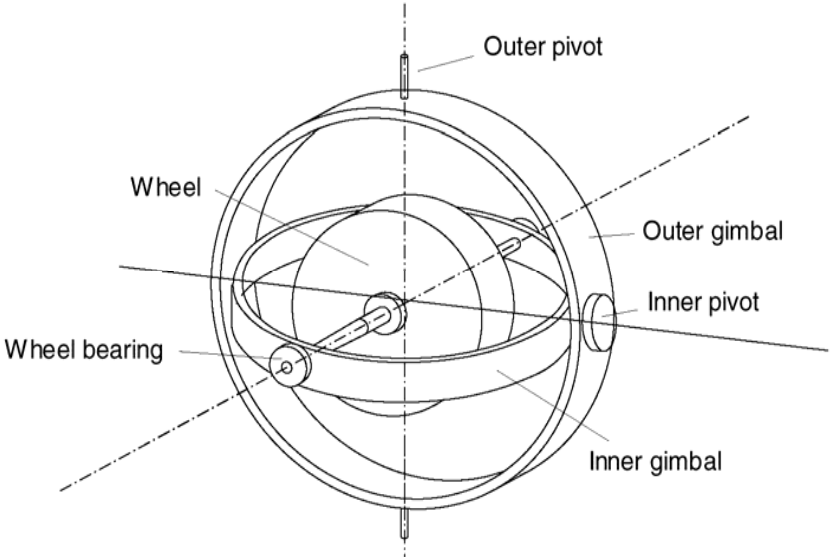
- Used since before 2000 B.C.
  - when Chinese suspended a piece of natural magnetite from a silk thread and used it to guide a chariot over land.
- Magnetic field on earth
  - absolute measure for orientation (even birds use it for migrations (2001 discovery))
- Large variety of solutions to measure 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
- 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

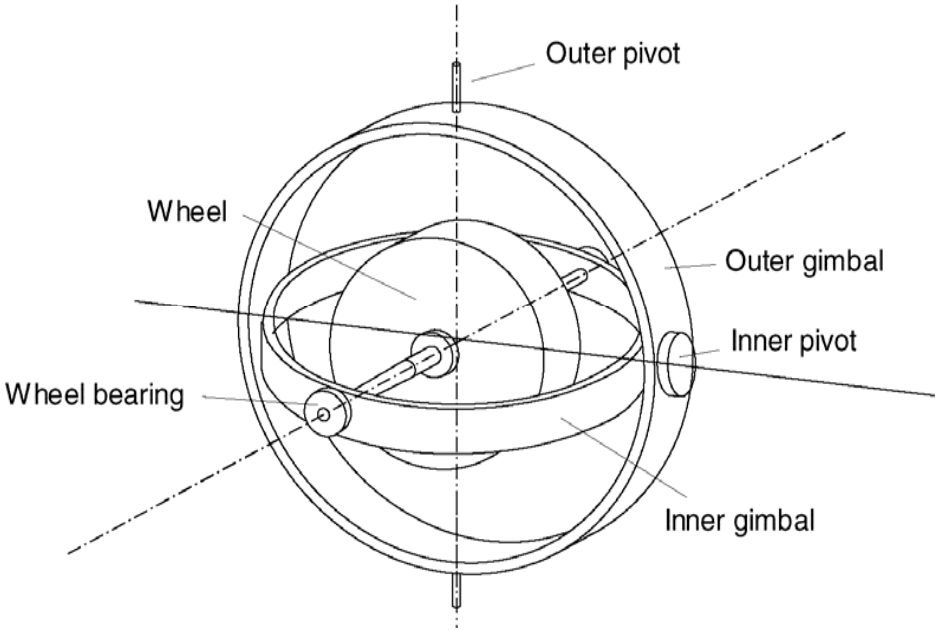
- Definition:
  - Heading sensors that preserve their orientation in relation to a fixed reference frame
  - They provide an absolute measure for the heading of a mobile system.
- Two categories, the mechanical and the optical gyroscopes
  - Mechanical Gyroscopes
    - Standard gyro (angle)
    - Rate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

Mechanical Gyroscopes



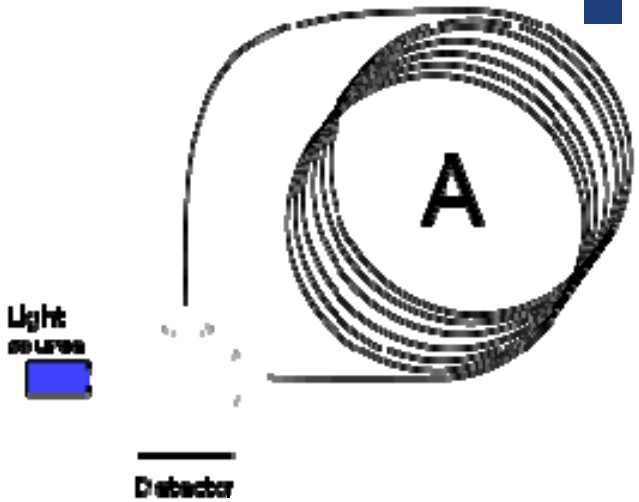
- Concept:
  - Inertial properties of a fast spinning rotor
  - Angular momentum associated with a spinning wheel keeps the axis of the gyroscope inertially stable.
- No torque can be transmitted from the outer pivot to the wheel axis
  - spinning axis will therefore be space-stable
  - however friction 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 instead of the orientation.

Optical Gyroscopes

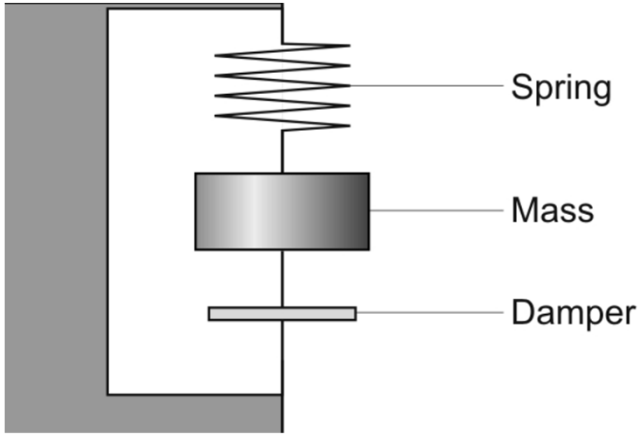


- Optical gyroscopes are based on the Sagnac effect
  - angular speed (heading) sensors using two monochromic light (or laser) beams from the same source.
  - One is traveling in a fiber clockwise, the other counterclockwise around a cylinder
- Laser beam traveling in direction opposite to the rotation
  - 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.

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

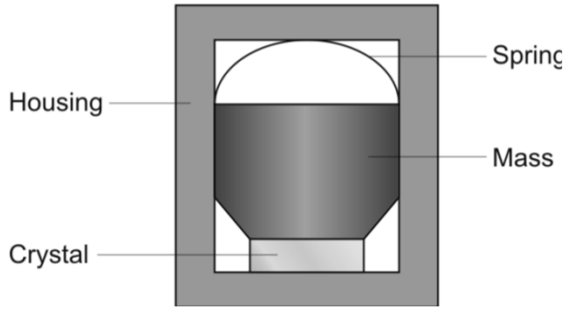
$$F_{applied} = F_{inertial} + F_{damping} + F_{spring} = m\ddot{x} + c\dot{x} + kx$$

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

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

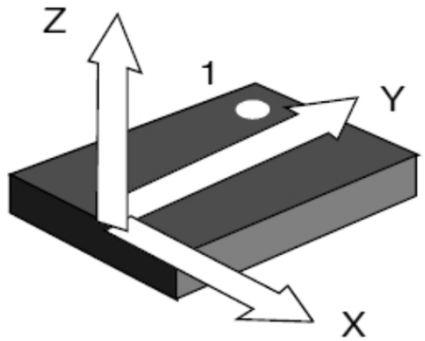
Other Accelerometers

- 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.

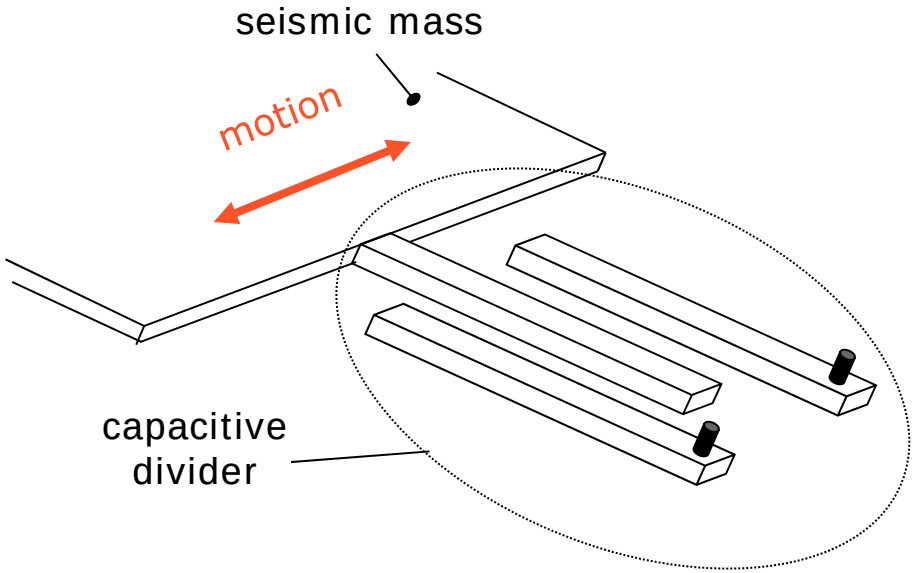


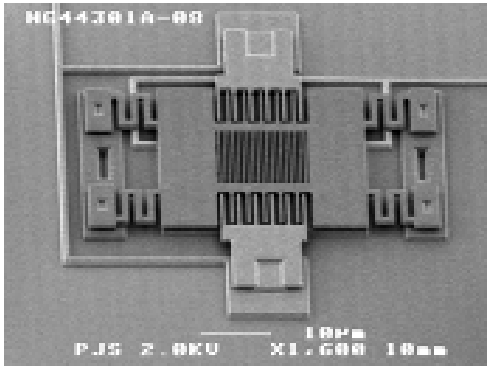
- In capacitive accelerometers the capacitance between a fixed structure and the proof mass is measured

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



Factsheet: MEMS Accelerometer (1)





<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

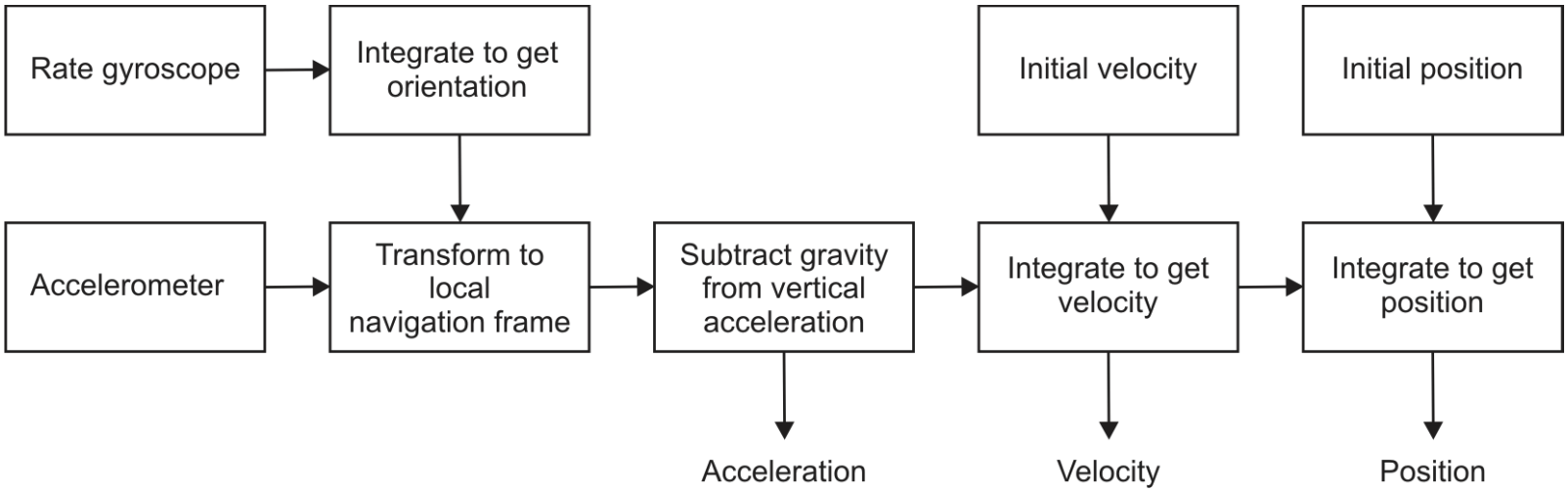
- Can be multi-directional
- Various sensing ranges from 1 to 50 g

3. Applications

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

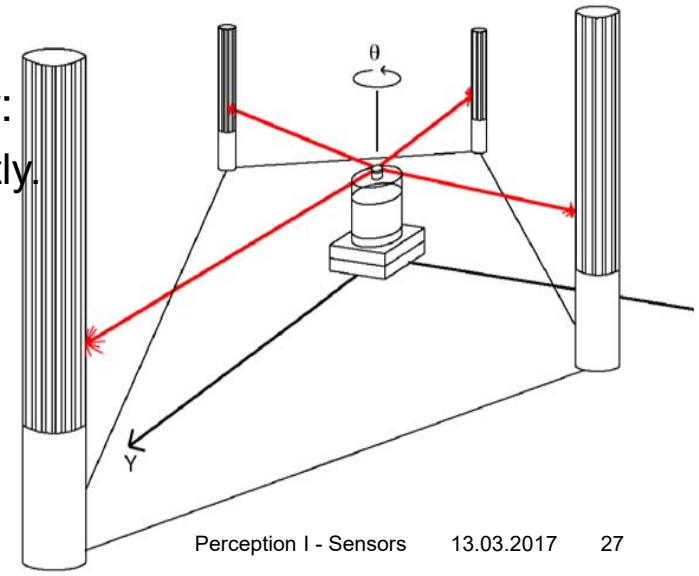
Inertial Measurement Unit (IMU)

- **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.



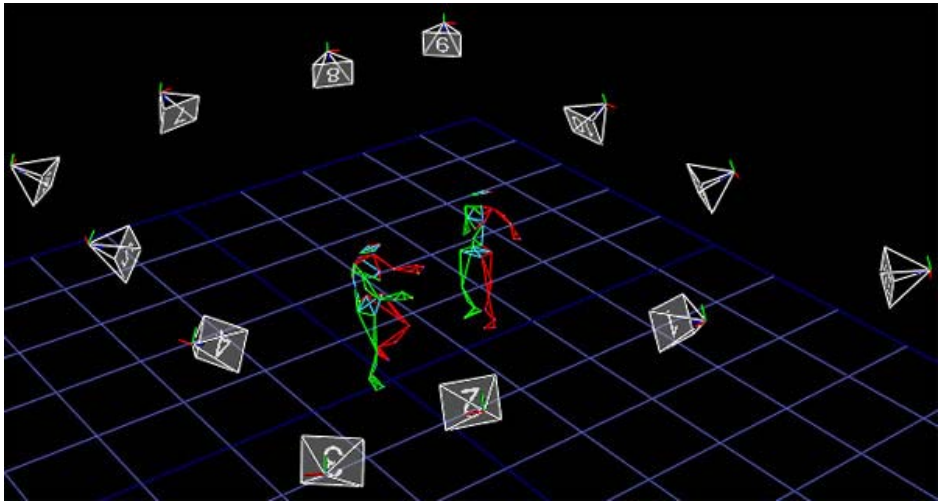
Ground-Based Active and Passive Beacons

- "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
  - 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.

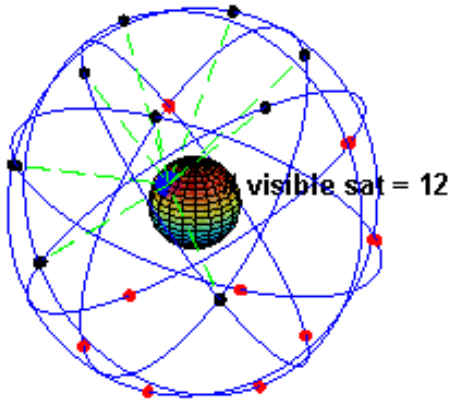


Motion-Capture Systems

- Vicon and Optitrack
  - System of several cameras that track the position of reflective markers
  - >300 fps
  - <1 mm precision
  - Suitable for ground-truth comparison, control stragies, (e.g., quadrotors)
  - Indoor or outdoor application
  - Require preinstallation and precalibration of the cameras (done with a special calibration rig moved by the user)

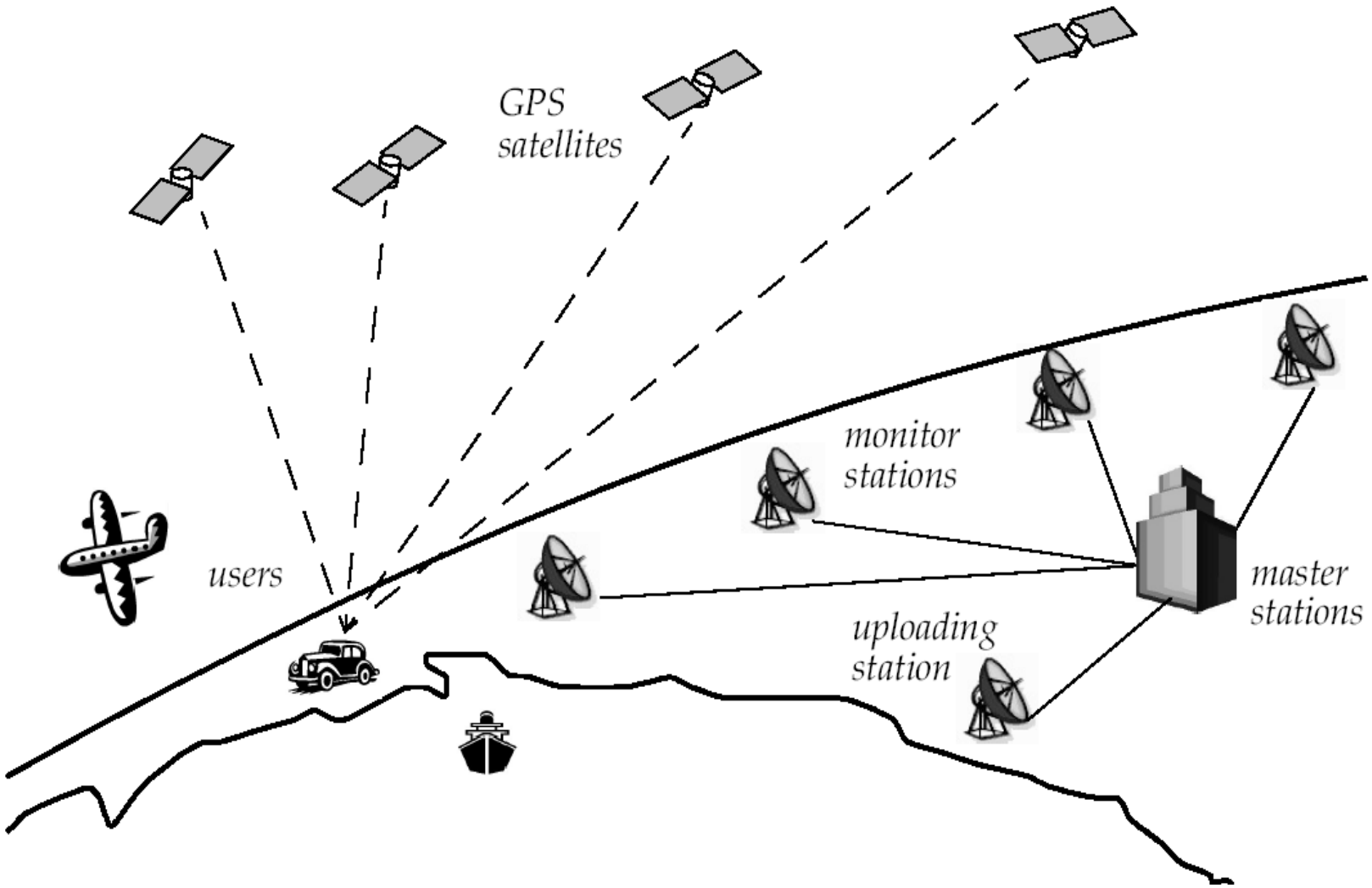


Global Positioning System (GPS)



- Facts
  - Became accessible for commercial applications in 1995
  - Initially there were 24 satellites orbiting the earth every 12 hours at a height of 20.190 km.
  - 4 satellites were 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 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)

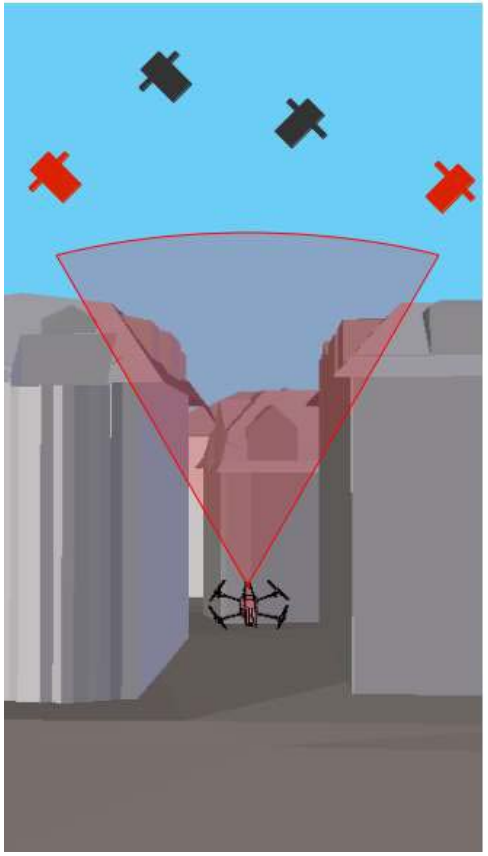


Global Positioning System (GPS)

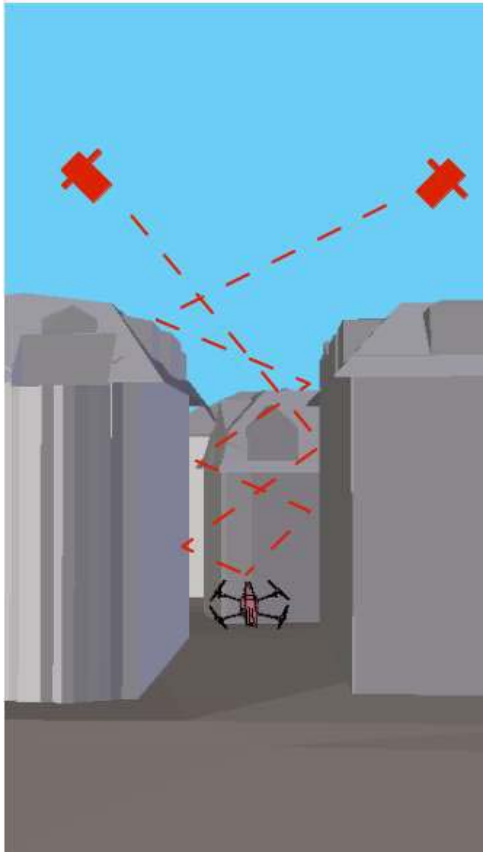
- **Time synchronization**:
  - **atomic clocks on each satellite**
  - monitoring them from different ground stations.
- Ultra-precision time synchronization is extremely important
  - electromagnetic radiation propagates at light speed
- **Light travels roughly 0.3 m per nanosecond**
  - position accuracy 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**
  - **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
- Commercial GPS receivers have nominal position accuracy of 3 meters

Global Positioning System (GPS)

Satellite coverage

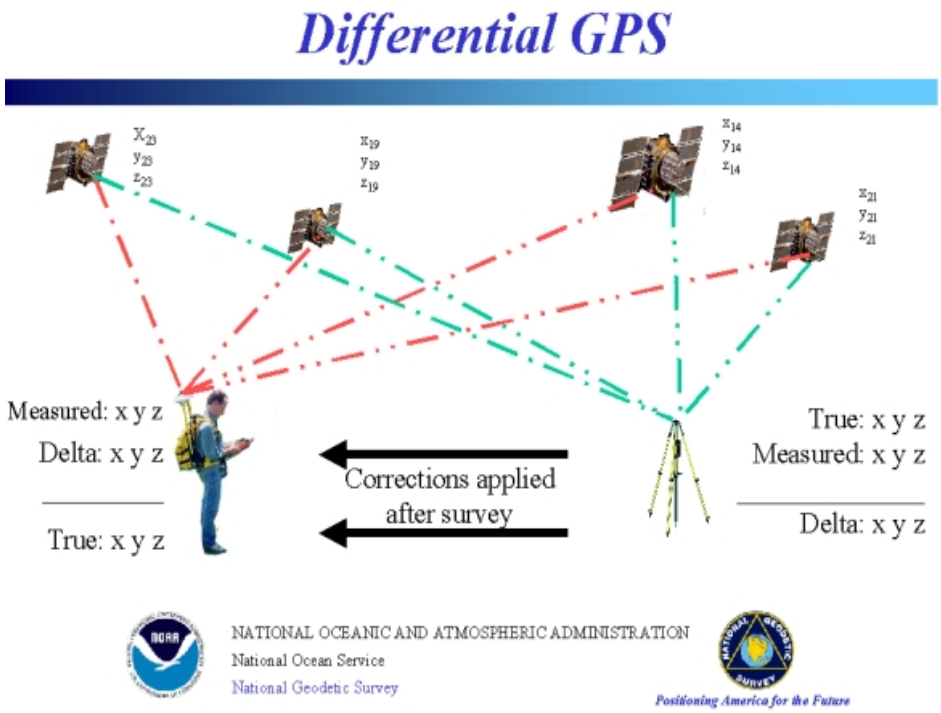


Multipath problem



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**



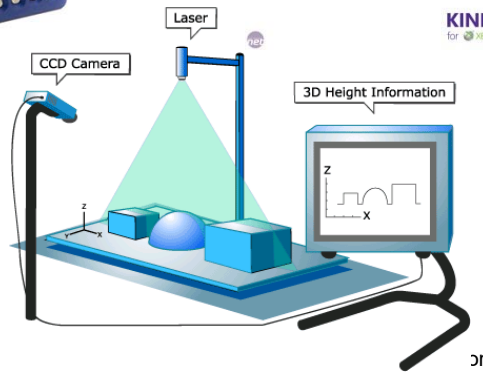
Range sensors

- Sonar

- Laser range finder

- Time of Flight Camera

- Structured light



Range Sensors (time of flight)

- Large range distance measurement → 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

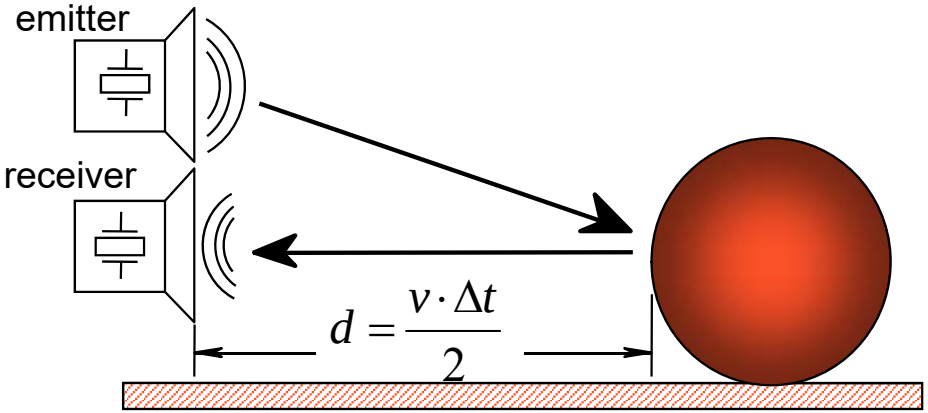
$$d = c \cdot t$$

  - d = distance traveled (usually round-trip)
  - c = speed of wave propagation
  - t = time of flight.

Range Sensors (time of flight)

- It is important to point out
  - Propagation speed of sound: 0.3 m/ms
  - Propagation speed 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



<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

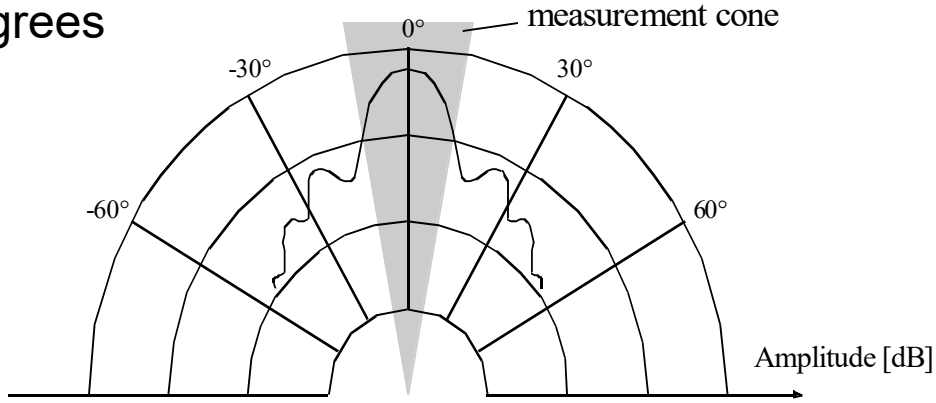
- Precision influenced by angle to object (as illustrated on the next slide)
- Useful in ranges from several cm to several meters
- **Typically relatively inexpensive**

3. Applications

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

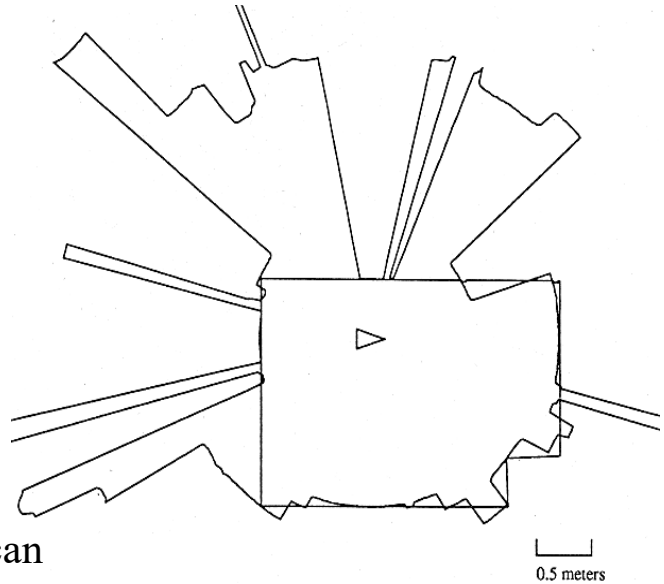
Ultrasonic Sensor (time of flight, sound) (2)

- 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 separate or integrated in the same unit
- Range between 12 cm up to 5 m
- Resolution of ~ 2 cm
- 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)

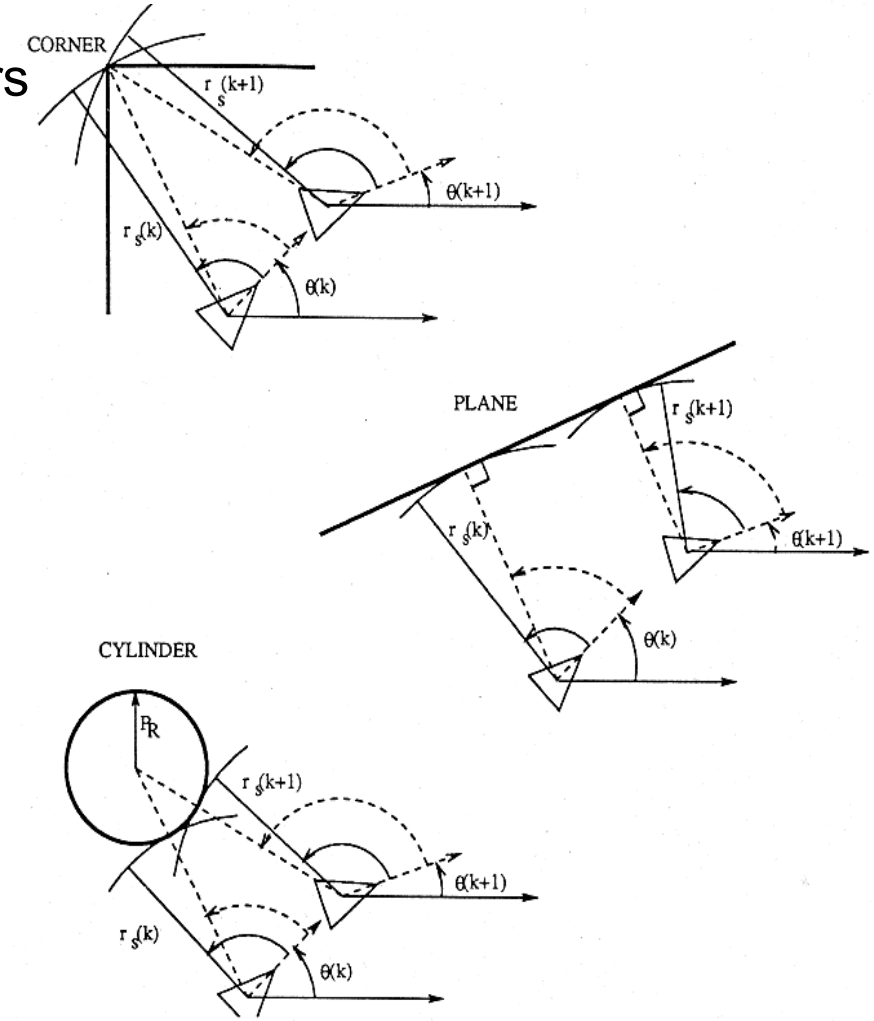


Ultrasonic Sensor (time of flight, sound) (3)

- 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



a) 360° scan



b) results from different geometric primitives

Laser Range Sensor (time of flight, electromagnetic)

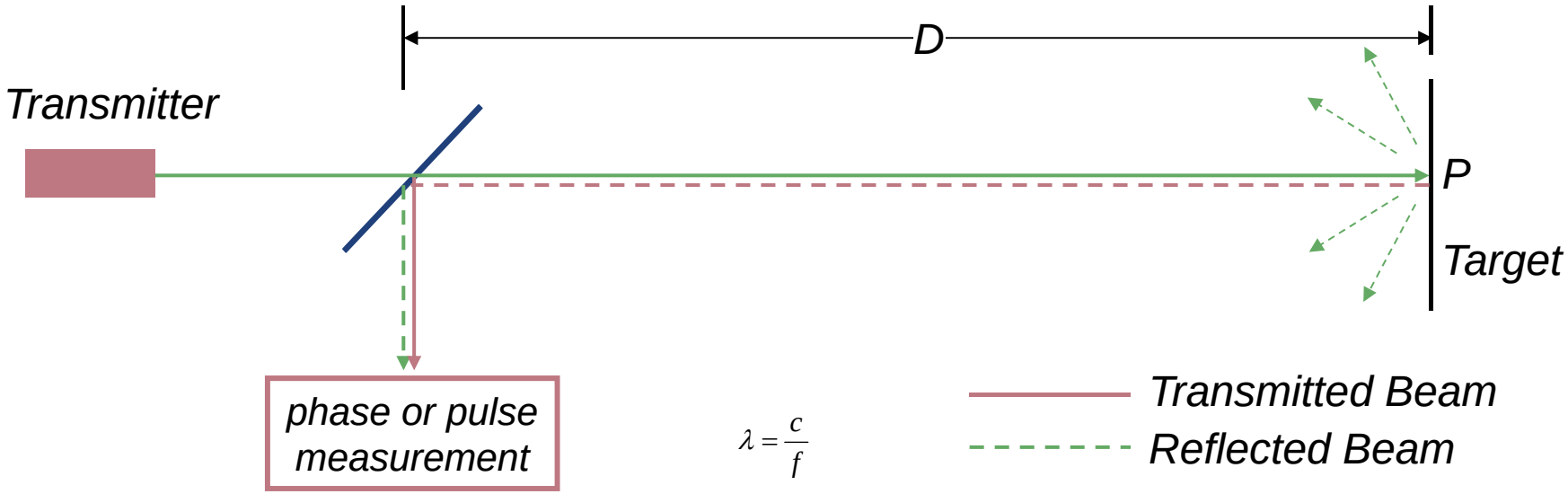
- Laser range finder are also known as Lidar (Light Detection And Ranging)

SICK

Hokuyo

Laser Range Sensor (time of flight, electromagnetic)

- *Phase-Shift Measurement*



$$\lambda = \frac{c}{f}$$

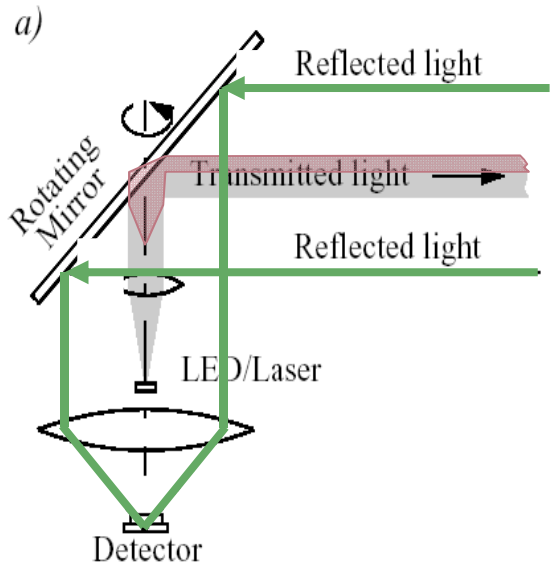
$$D' = 2D = \frac{\theta}{2\pi}\lambda$$

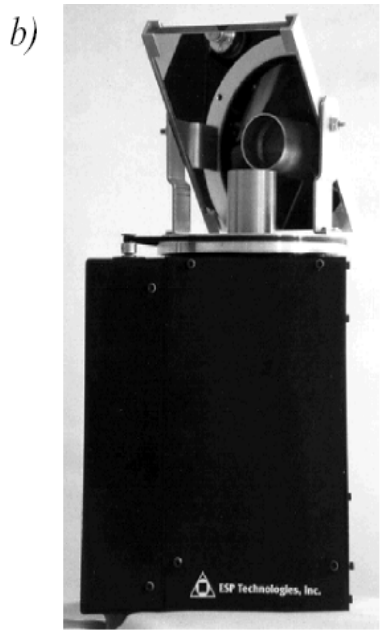
Where:

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

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

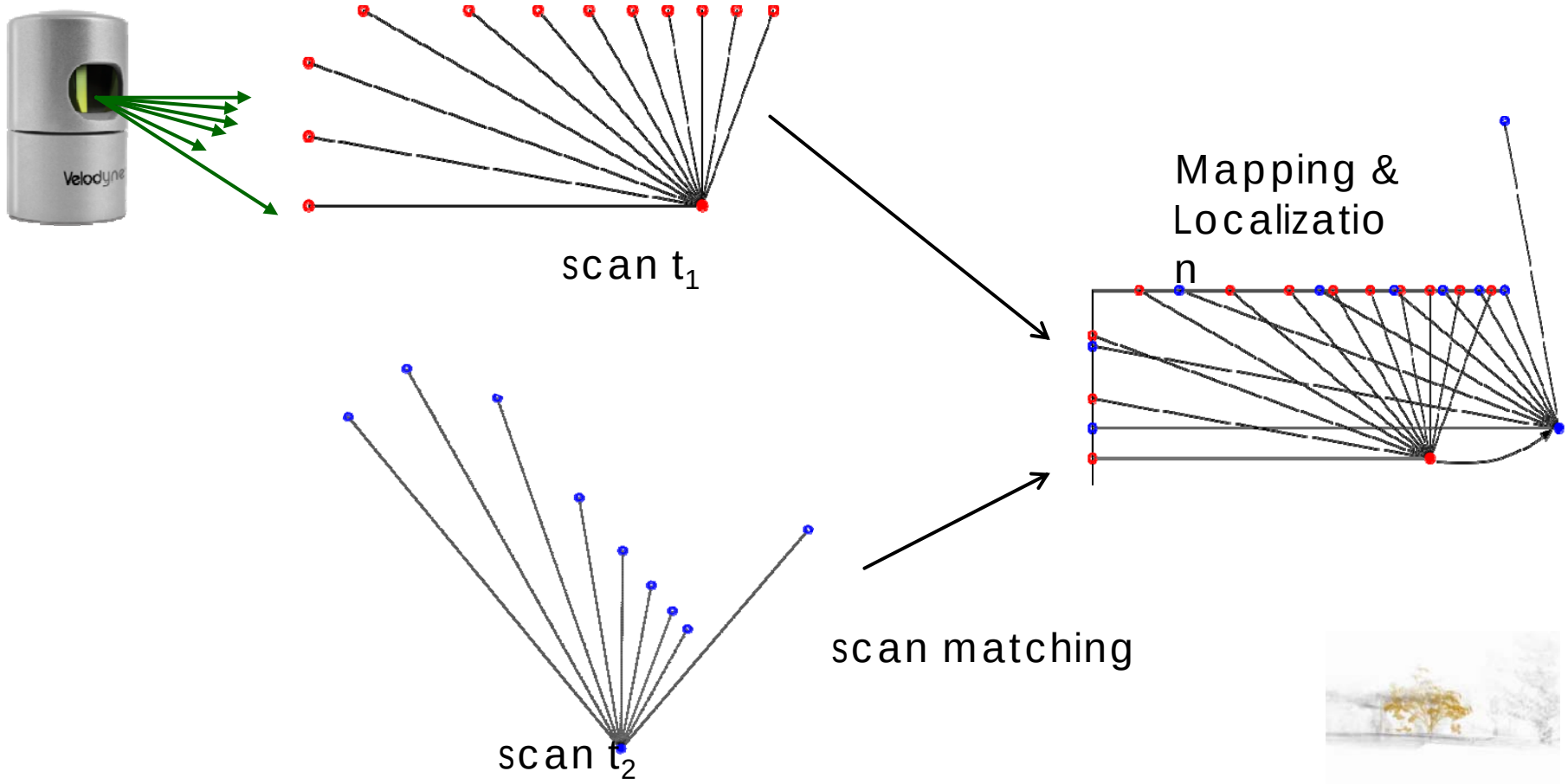
Laser Range Sensor (time of flight, electromagnetic)





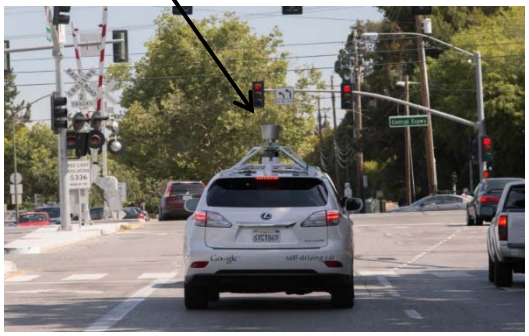
- Operating Principles:
  - Pulsed laser (today the standard)
    - measurement of elapsed time directly
    - resolving picoseconds
  - Phase shift measurement to produce range estimation
    - technically easier than the above method

"Seeing" | Laser-based 3D mapping

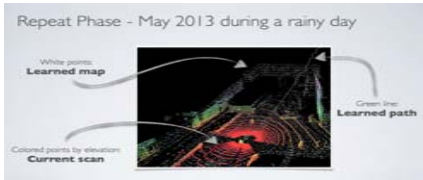


Today | 3D laser sensors → map based navigation

Expensive, complex and cumbersome



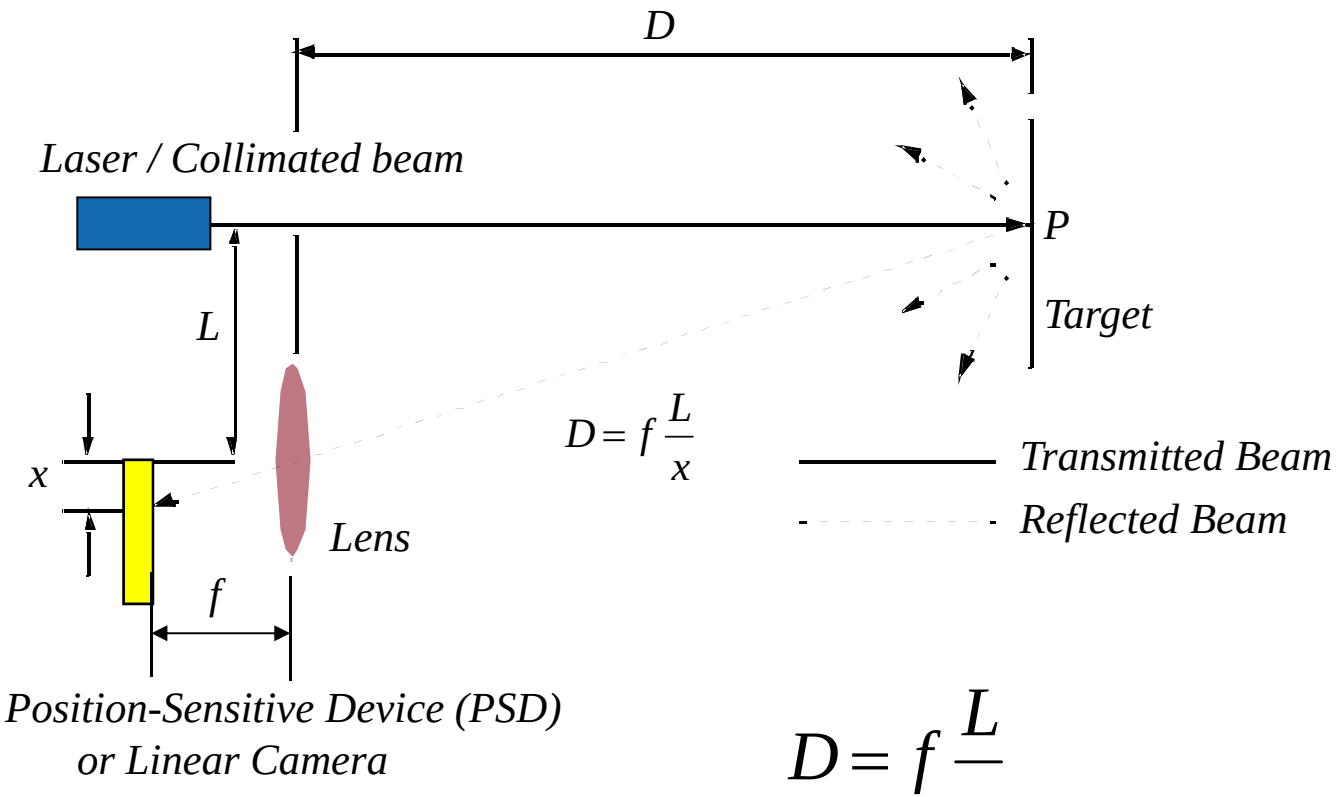
- Google Self-Driving Car Project (status summer 2015)
  - > 20 vehicles in use
  - > 2,7 mio km, 1.5 mio km in autonomous mode
  - > 11 accidents
    - No people insured
    - Non of them caused by car control algorithm



https://www.youtube.com/watch?v=eJCR2TaeSFc

Laser Triangulation (1D)

- Principle of 1D laser triangulation:

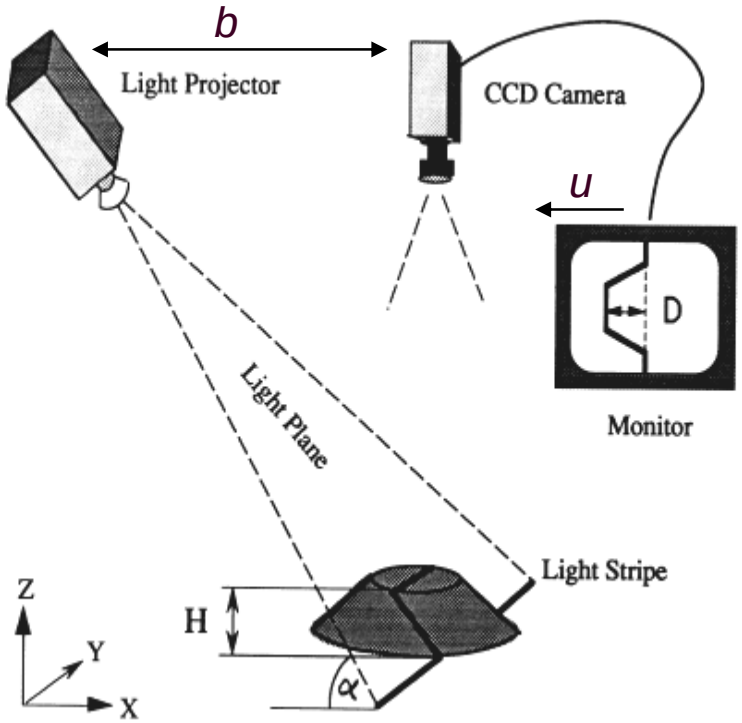


$$D = f\frac{L}{x}$$

Structured Light (vision, 2D or 3D)

- 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.

a



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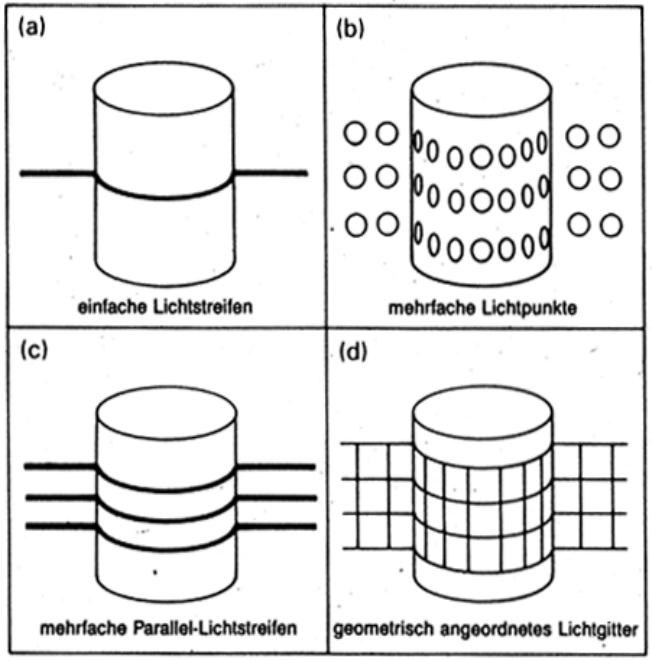
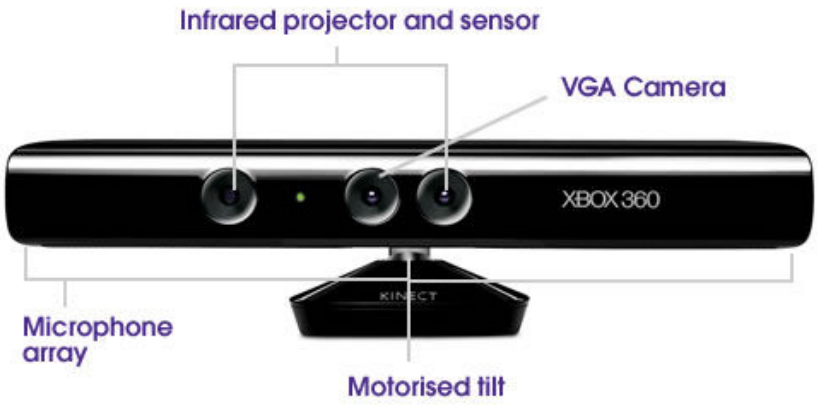


Microsoft Kinect I

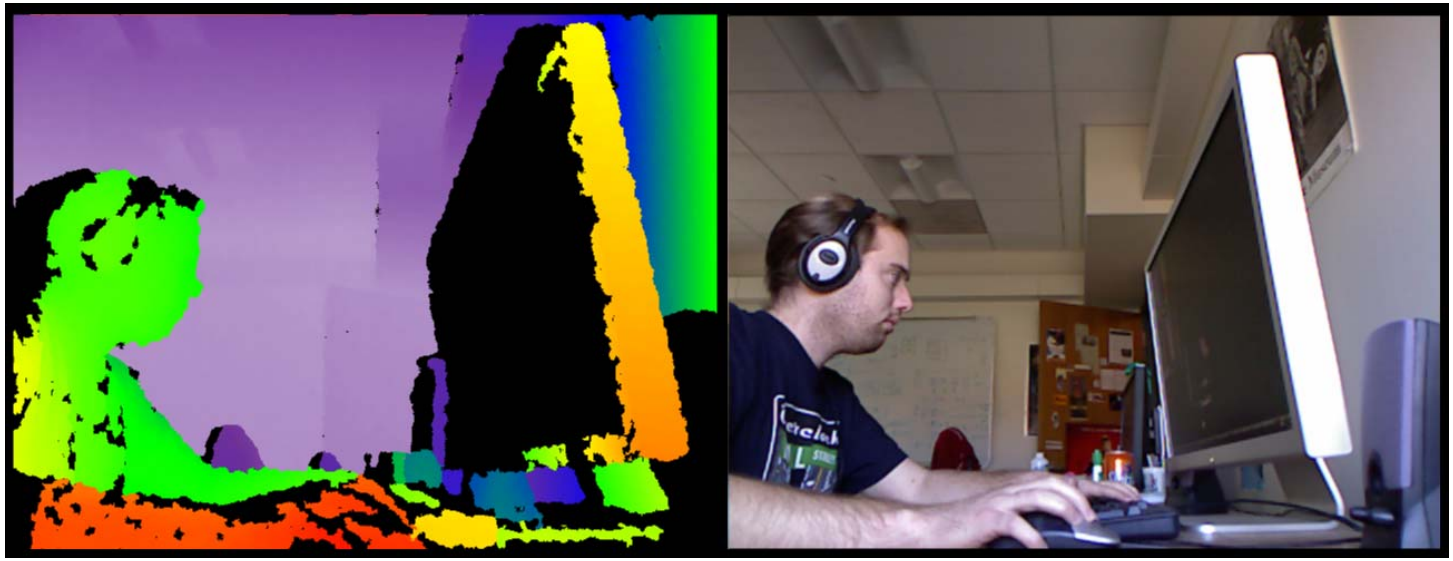
- Developed by Israeli company PrimeSense in 2010

- 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



Video Out

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

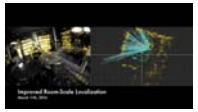


Time of Flight / Projected Light Patterns

e.g. Kinect 2.0 & Intel RealSense

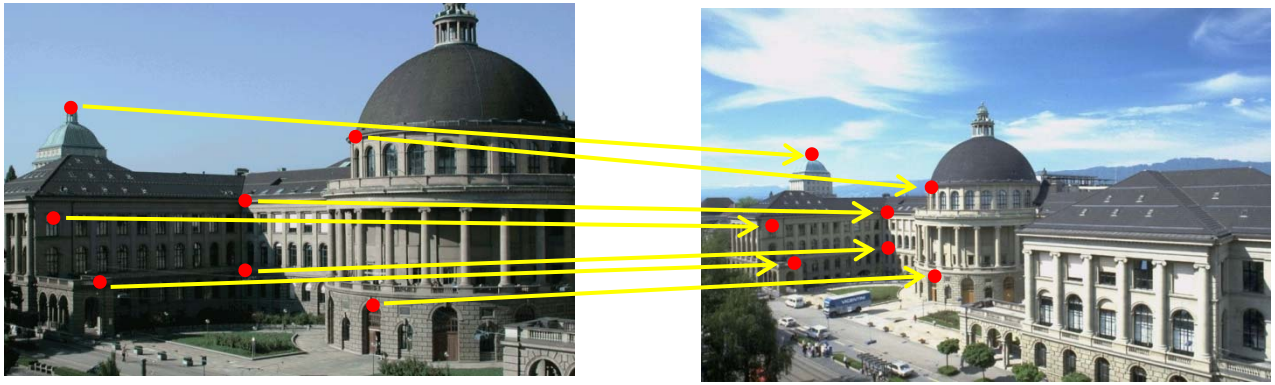
- Typical characteristic
  - Resolution 1920x1080 pixels
  - Field of view: 70 deg (H), 60 deg (V)
  - Claimed accuracy: 1 mm
  - Claimed max range: 6 meters

Google Project Tango

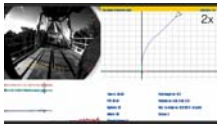


https://www.youtube.com/watch?v=yvgPrZNp4So

"Seeing" | Visual-Inertial Motion Estimation



Google
Project Tango



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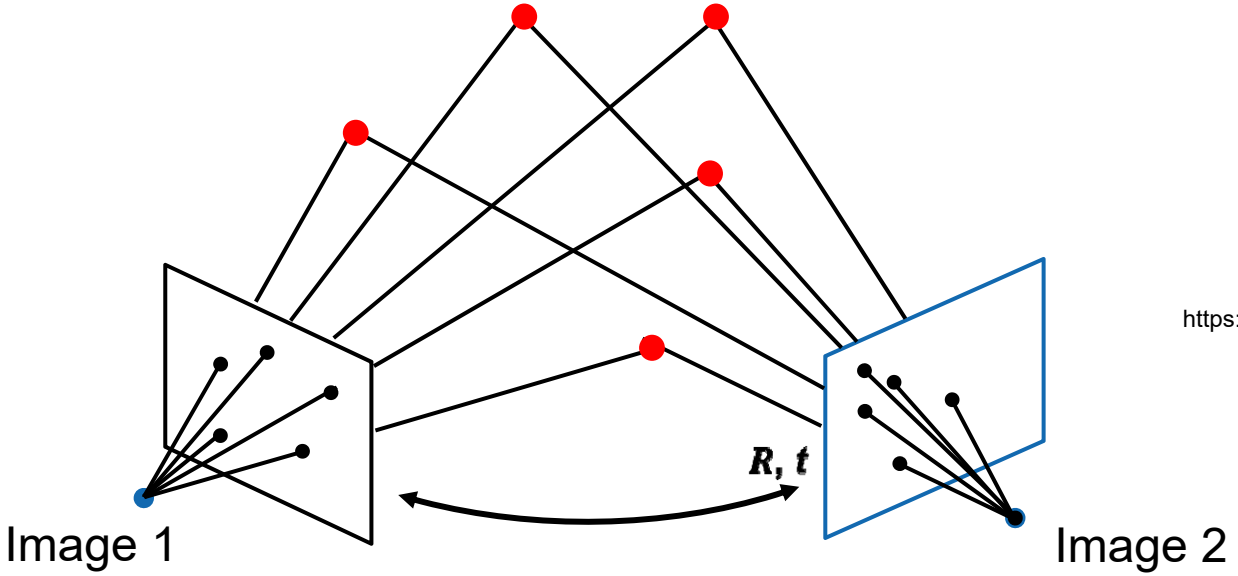


Autonomous Cars Today |

cameras (lane tracking, …) → no map

https://www.youtube.com/watch?v=aGW4nRzx8Iw

- Detection and tracking of …
  - Lanes,
  - street signs,
  - other cars,
  - …

Multimodal detection and tracking

Pedestrians

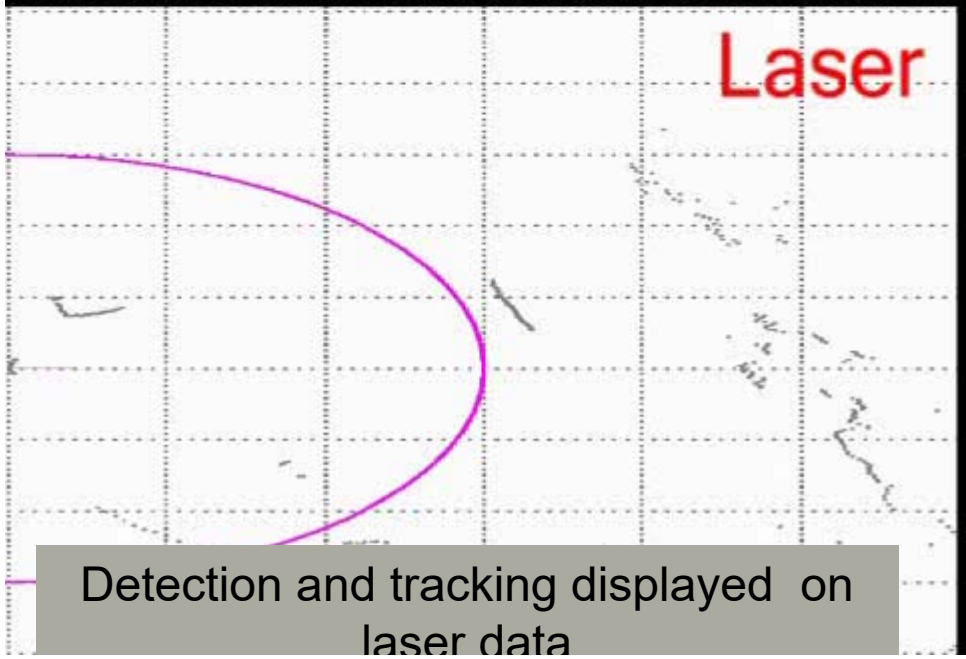
Cars

Rich info
Inexpensive
Noise
No distance

High prec
Light independent
Low info

Detection and tracking displayed on camera data

What the robot sees: laser projected on image



Detection and tracking displayed on laser data

ETH

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Autonomous Systems Lab