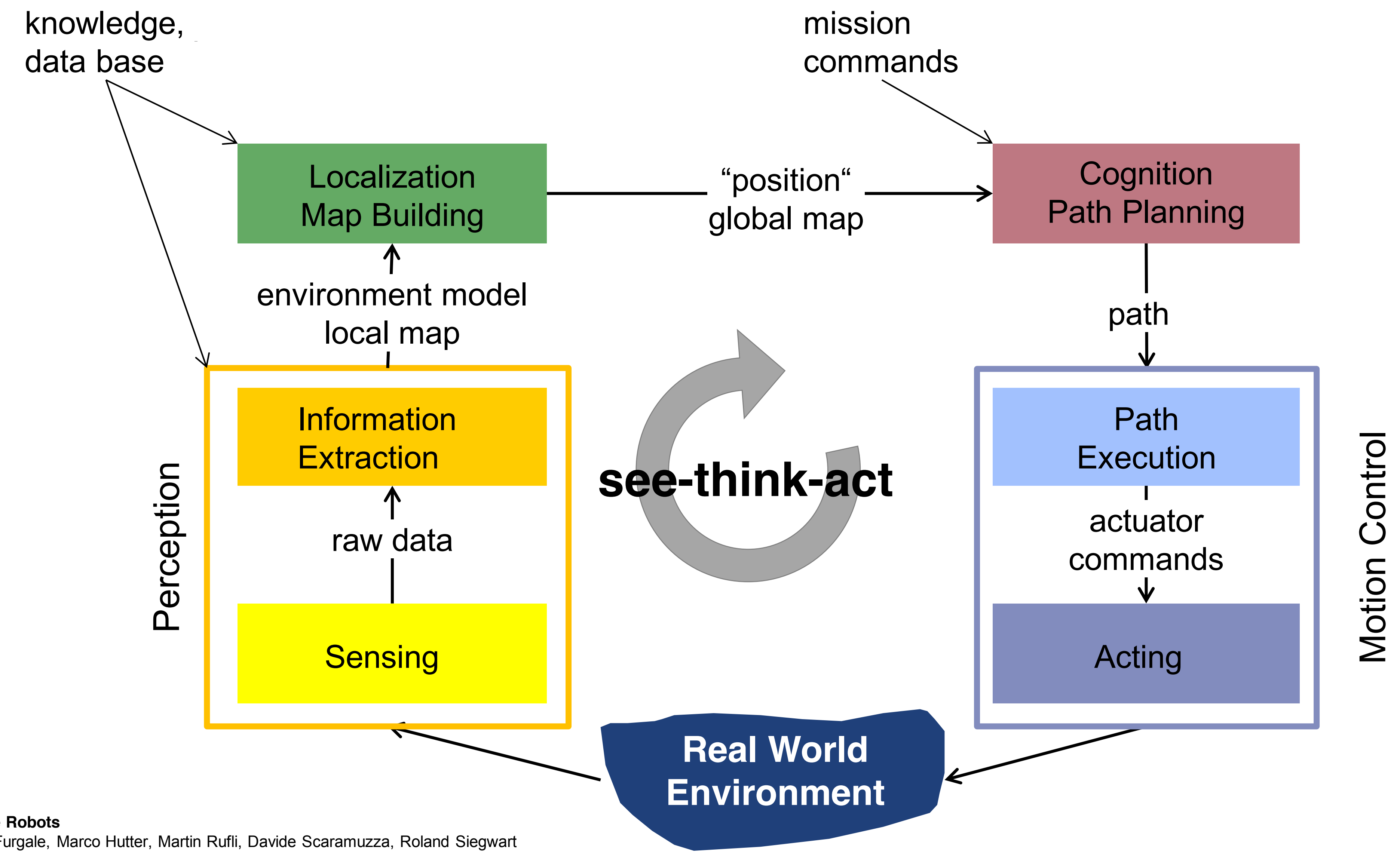
ETH zürich | University of Zurich[UZH] | ROBOTICS & PERCEPTION GROUP | ASL Autonomous Systems Lab

Perception: Sensors
Autonomous Mobile Robots

Davide Scaramuzza

Margarita Chli, Paul Furgale, Marco Hutter, Roland Siegwart

Mobile Robot Control Scheme



Sensors for Mobile Robots

- Robot = sensors + actuators
- **Sensors** are the **key components** for **perceiving** the environment
- Perception is the HOT research topic of the last years
- Sensors vary according to:
  - physical principle
  - resolution
  - bandwidth
  - price
  - energy needed

Perception is hard!

- **Understanding = raw data + (probabilistic) models + context**

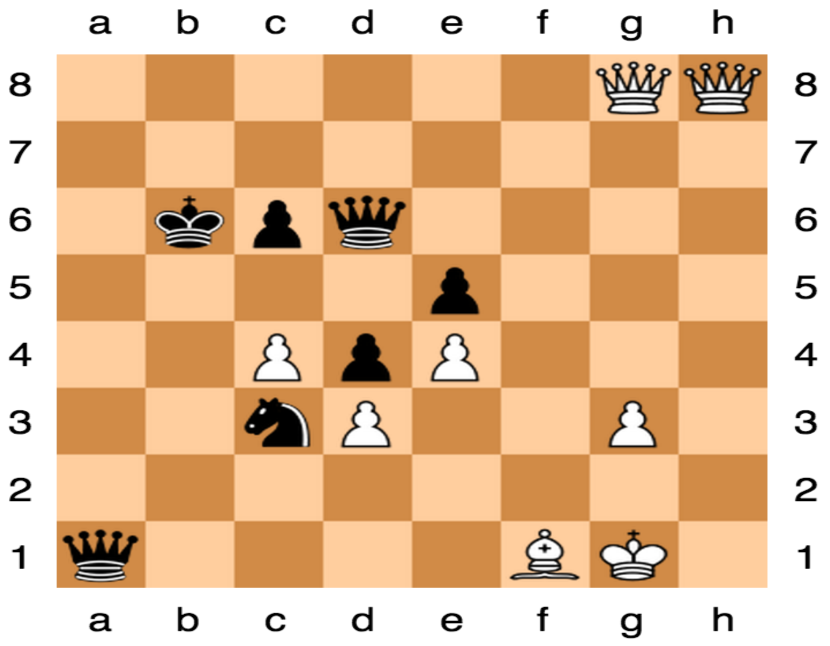
- Intelligent systems interpret **raw data** according to **probabilistic models** and using **contextual information** that gives meaning to the data.

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

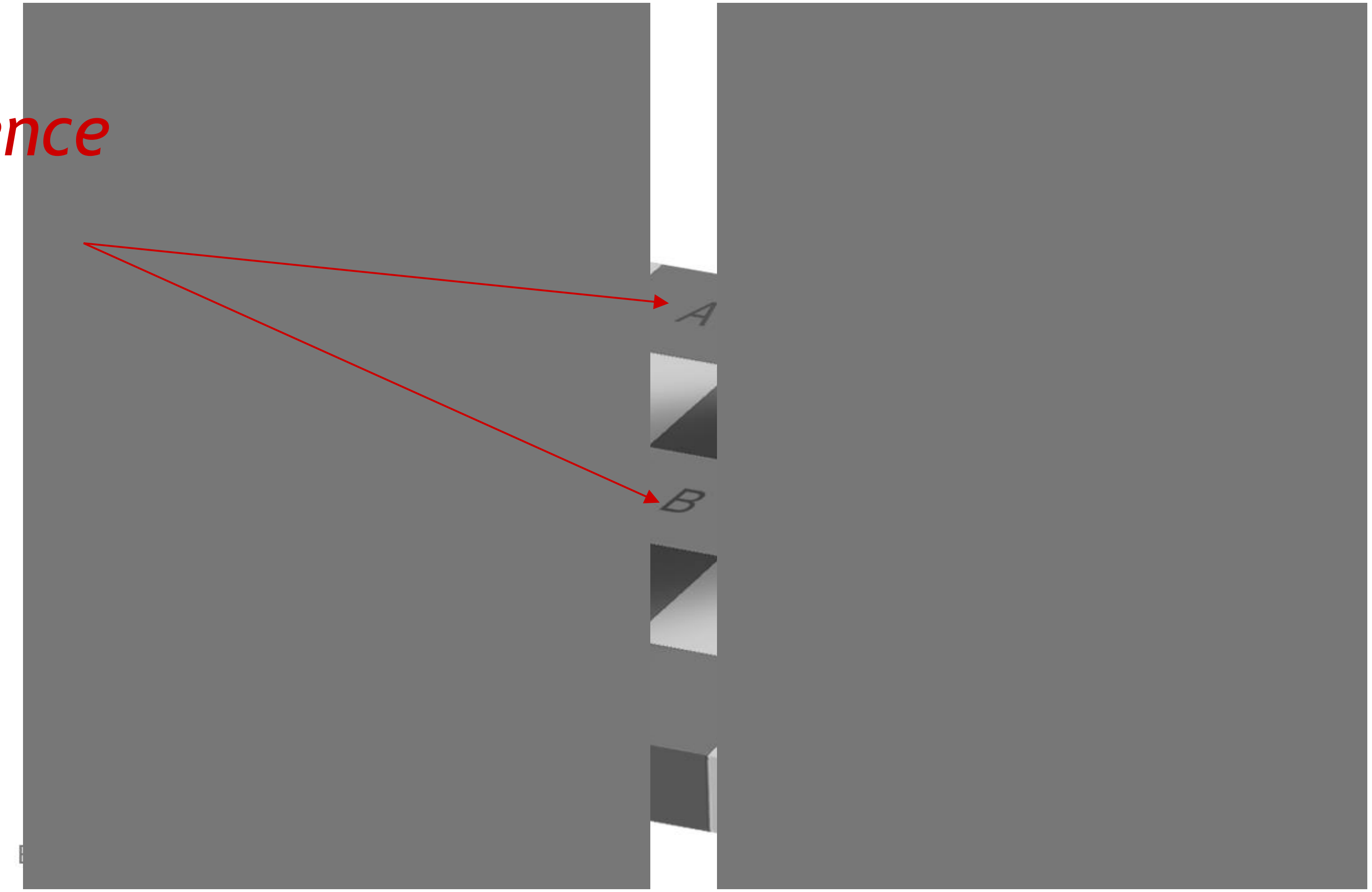
create a machine with some “common sense”: very HARD



The Challenge

- Perception and models are strongly linked

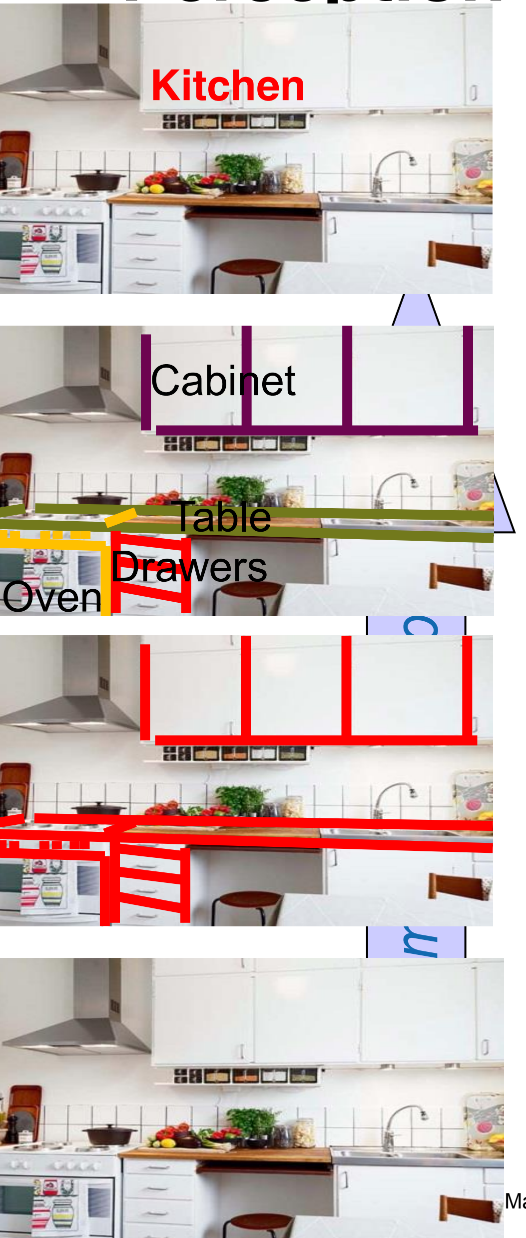
What is the difference in brightness?



Courtesy E. Adelson

http://web.mit.edu/persci/people/adelson/checkershadow_downloads.html

Perception for Mobile Robots



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

Servicing / Reasoning

Objects
Doors, Humans, Coke bottle, car , …

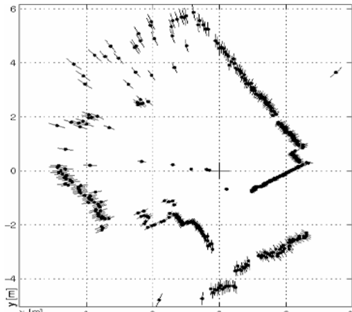
Interaction

Features
Corners, Lines, Colors, Phonemes, …

Navigation

Raw Data
Vision, Laser, Sound, Smell, …

Martin Rufli, Davide Scaramuzza, Roland Siegwart



Evolution of robotic sensors

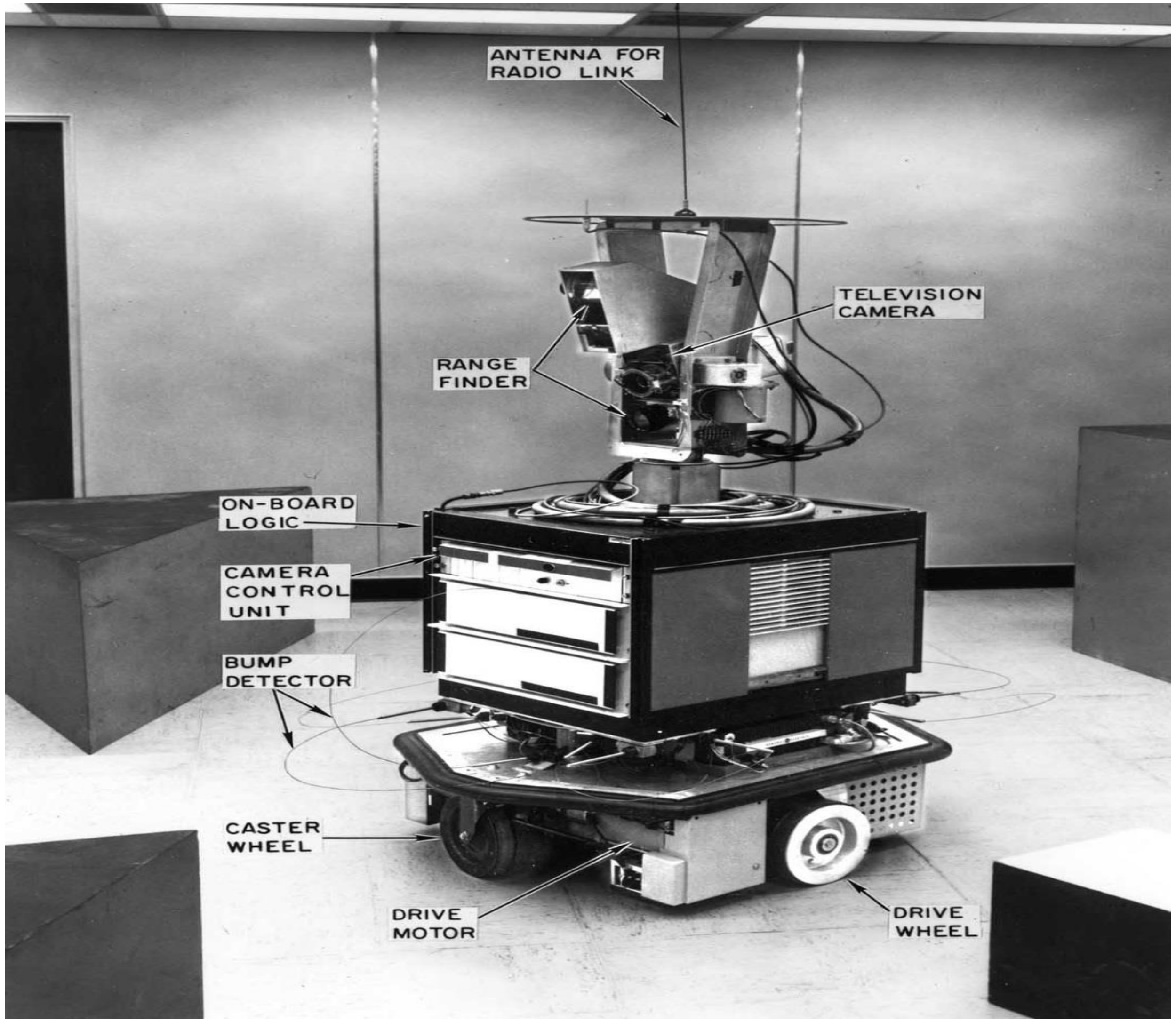
- Historically, robotic sensors have become richer and richer
  - 1960s: Shakey
  - 1990s: Tourguide robots
  - 2010s: Willow Garage PR2
  - 2010s: SmartTer – the autonomous car
  - 2011: Google autonomous car

richer sensors

unstructured environments

- Reasons:
  - **Commodization** of consumer electronics
  - **More computation** available to process the data

Shakey the Robot (1966-1972), SRI International



C SRI International

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

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-), Willow Garage

C Willow Garage

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

The SmartTer Platform (2004-2007)

- Three navigation SICK laser scanners
  - Obstacle avoidance and local navigation
- Two rotating laser scanners (3D SICK)
  - 3D mapping of the environment
  - Scene interpretation
- Omnidirectional camera
  - Texture information for the 3D terrain maps
  - Scene interpretation
- Monocular camera
  - Scene interpretation

Motion Estimation / Localization

- Differential GPS system *(Omnistar 8300HP)*
- Inertial measurement unit *(Crossbow NAV420)*
- **Optical Gyro**
- Odometry (wheel speed, steering angle)
  - Motion estimation
  - Localization

Internal car state sensors

- Vehicle state flags (engine, door, etc.)
- Engine data, gas pedal value

Camera for life video streaming

- Transmission range up to 2 km

The SmartTer Platform (2004-2007)

- Three navigation SICK laser scanners
  - Obstacle avoidance and local navigation
- Two rotating laser scanners (3D SICK)
  - 3D mapping of the environment
  - Scene interpretation
- Omnidirectional camera
  - Texture information for the 3D terrain maps
  - Scene interpretation
- Monocular camera
  - Scene interpretation

Motion Estimation / Localization

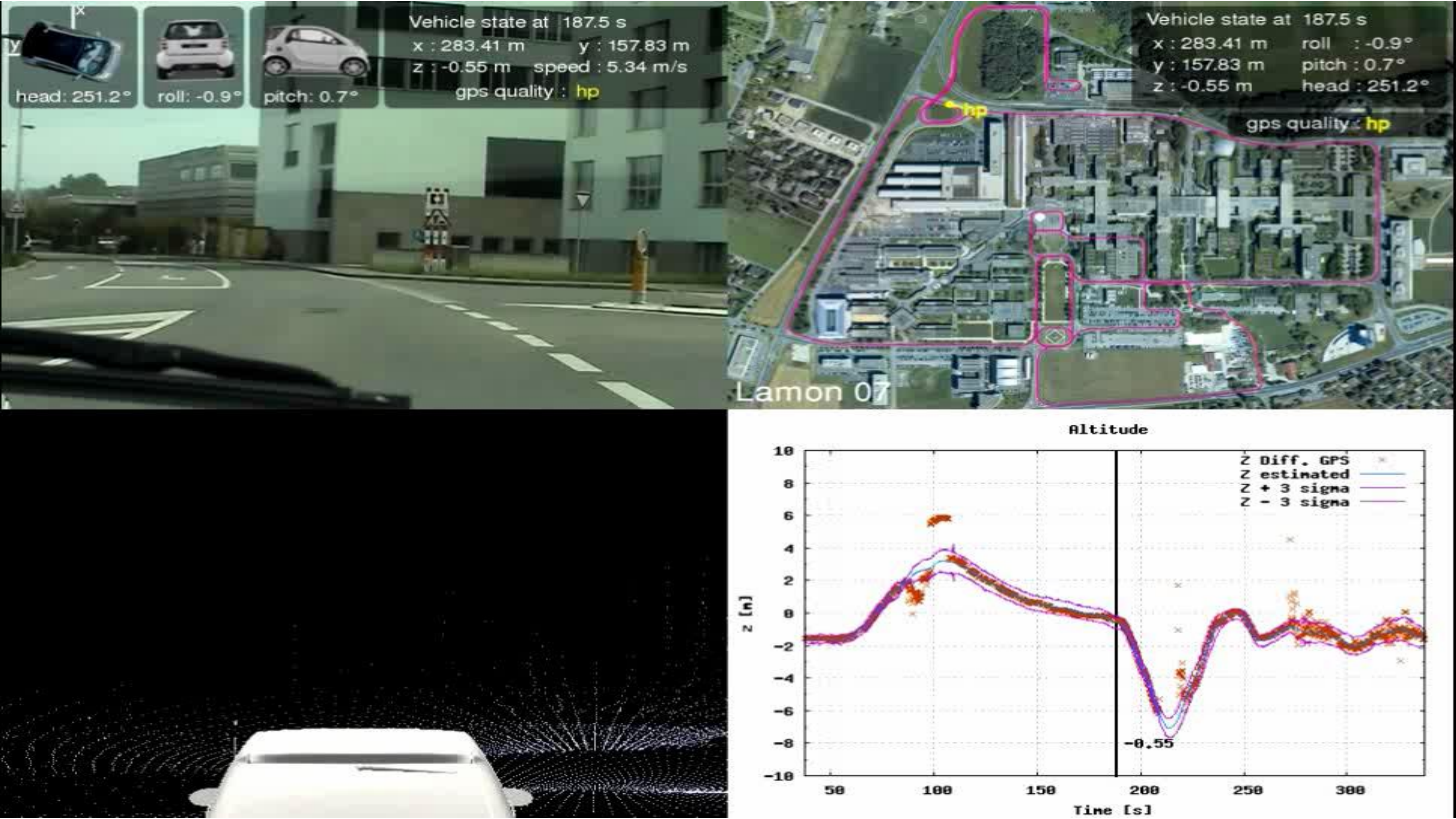
- Differential GPS system *(Omnistar 8300HP)*
- Inertial measurement unit *(Crossbow NAV420)*
- **Optical Gyro**
- Odometry (wheel speed, steering angle)
  - Motion estimation
  - Localization

Internal car state sensors

- Vehicle state flags (engine, door, etc.)
- Engine data, gas pedal value

Camera for life video streaming

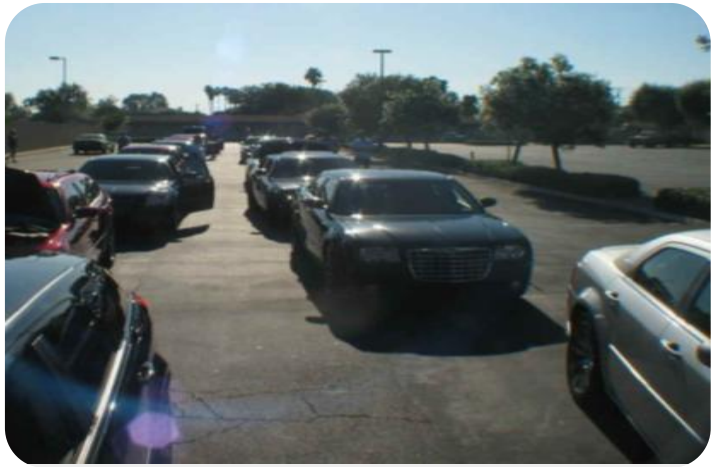
- Transmission range up to 2 km



head: 251.2°
roll: -0.9°
pitch: 0.7°
Vehicle state at 187.5 s
x : 283.41 m
y : 157.83 m
z : -0.55 m
speed : 5.34 m/s
gps quality : hp
Vehicle state at 187.5 s
x : 283.41 m
y : 157.83 m
z : -0.55 m
roll : -0.9°
pitch : 0.7°
head : 251.2°
gps quality : hp
hp
Lamon 07
Altitude
Z Diff. GPS
Z estimated
Z + 3 sigma
Z - 3 sigma
z [m]
Time [s]
-0.55
10
8
6
4
2
0
-2
-4
-6
-8
-10
50
100
150
200
250
300

Multimodal detection and tracking

Pedestrians



Cars

Rich info

Inexpensive

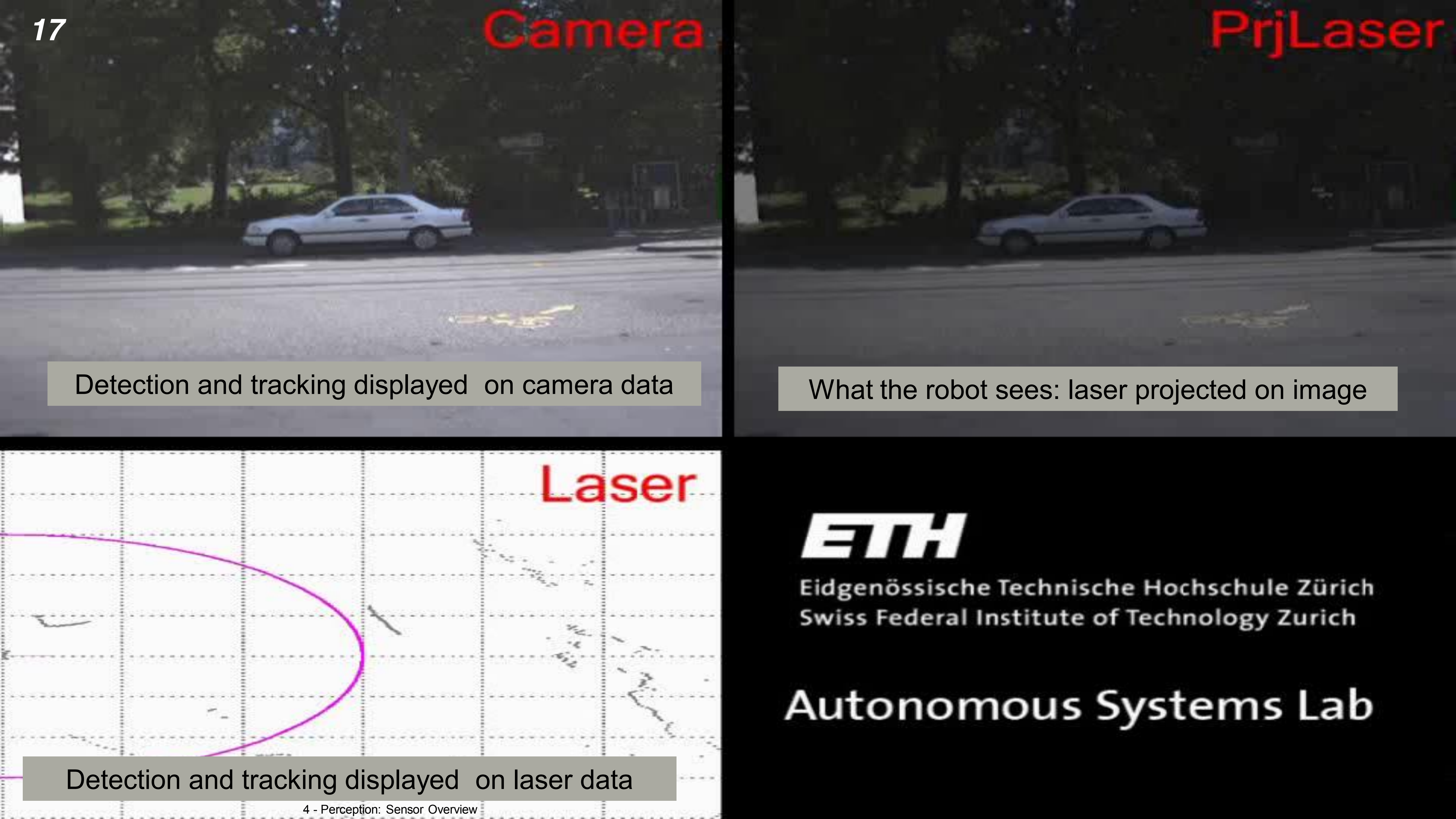
Noise

No distance

High prec

Light independent

Low info


Camera
Detection and tracking displayed on camera data
PrjLaser
What the robot sees: laser projected on image
Laser
Detection and tracking displayed on laser data
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Autonomous Systems Lab

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)

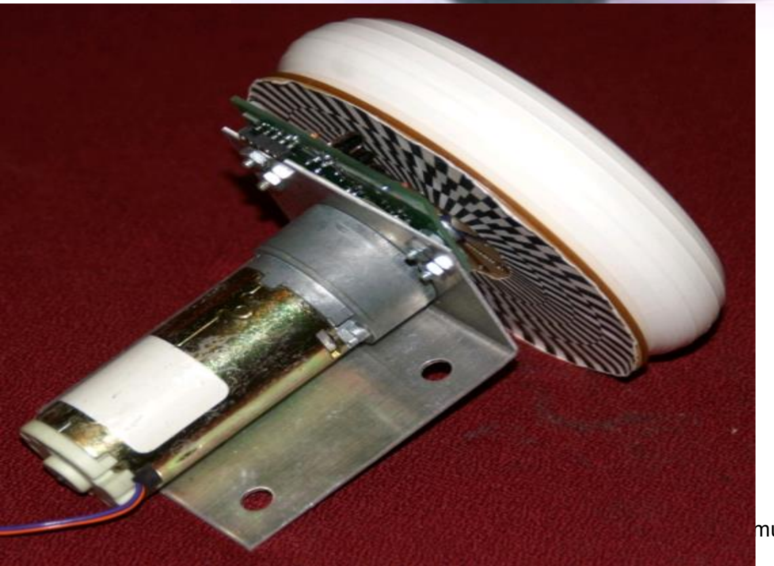
General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Ground-based beacons (localization in a fixed reference frame)	GPS Active optical or RF beacons Active ultrasonic beacons Reflective beacons	EC EC EC EC	A A A A
Active ranging (reflectivity, time-of-flight, and geometric triangulation)	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

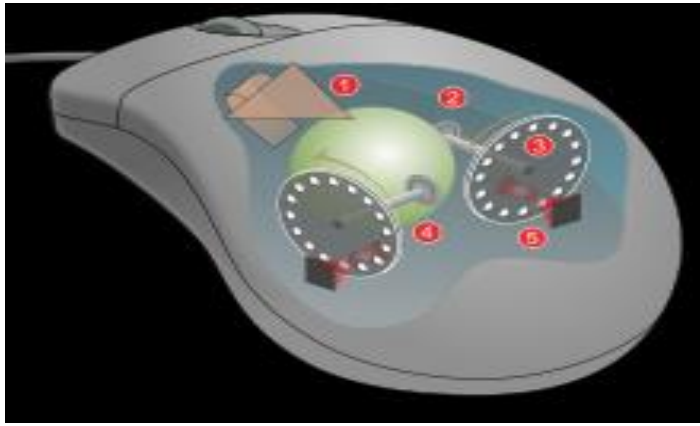
Sensors: outline

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

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

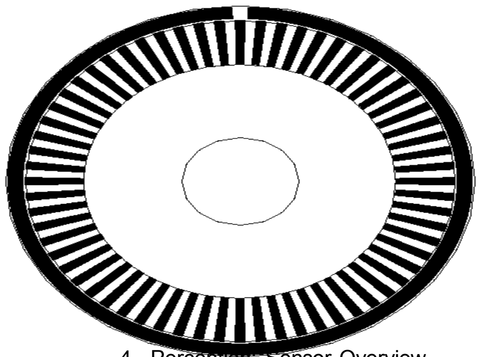


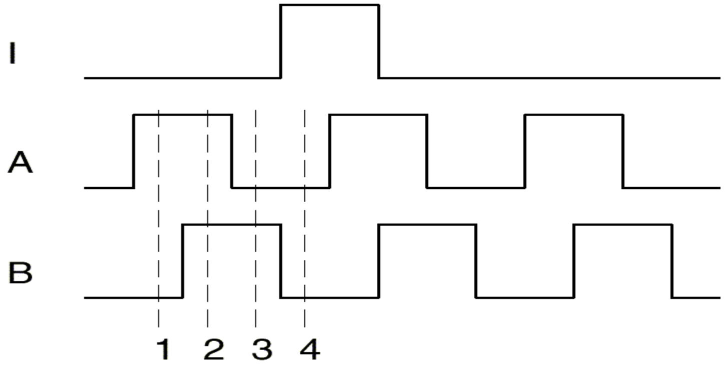


Wheel / Motor Encoders

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

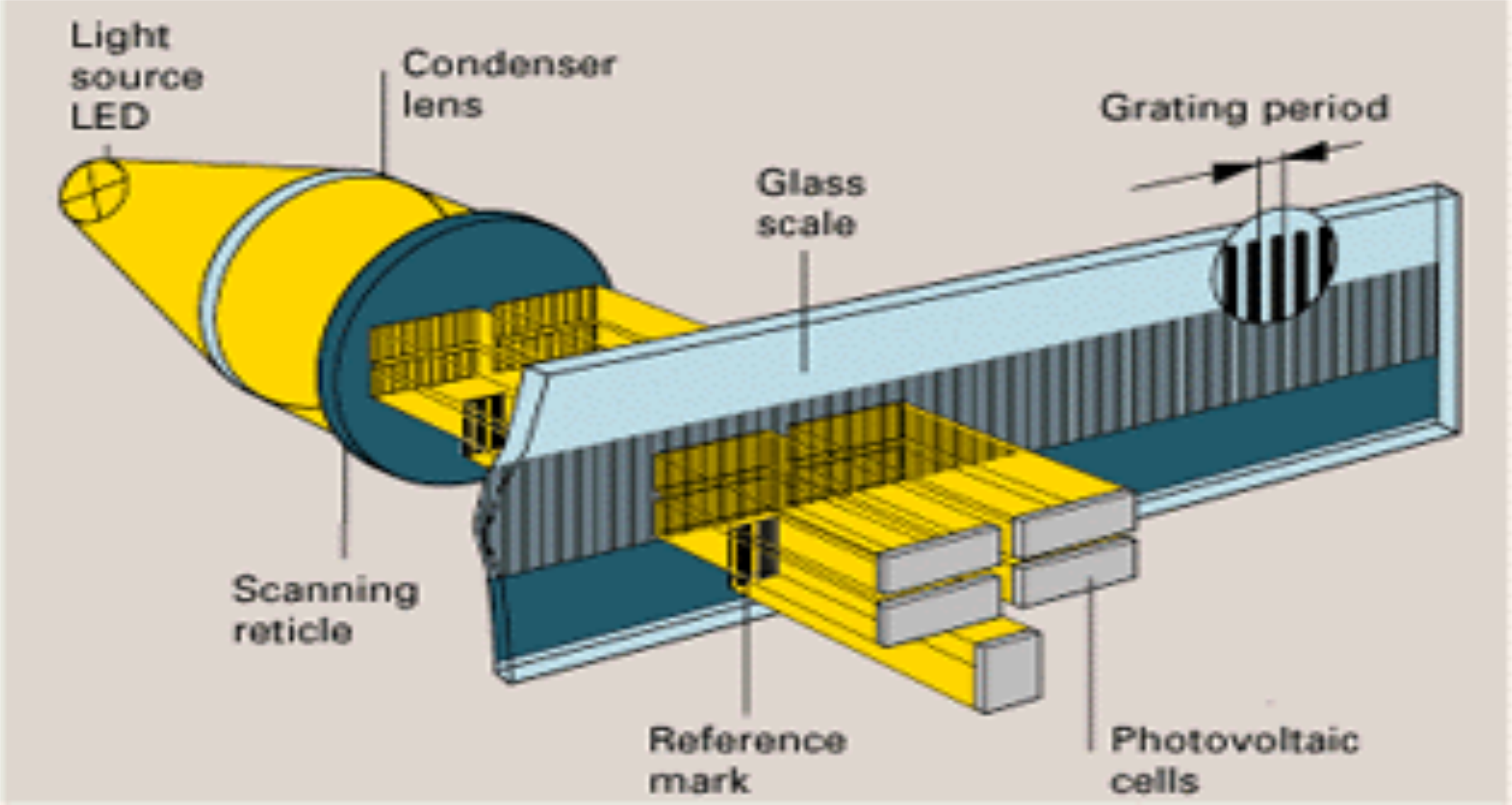
- Working principle of optical encoders
  - regular: counts the number of transitions but cannot tell the direction of motion
  - quadrature: uses two sensors in quadrature-phase shift. The ordering of which wave produces a rising edge first tells the direction of motion. Additionally, resolution is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





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

Wheel / Motor Encoders (2)



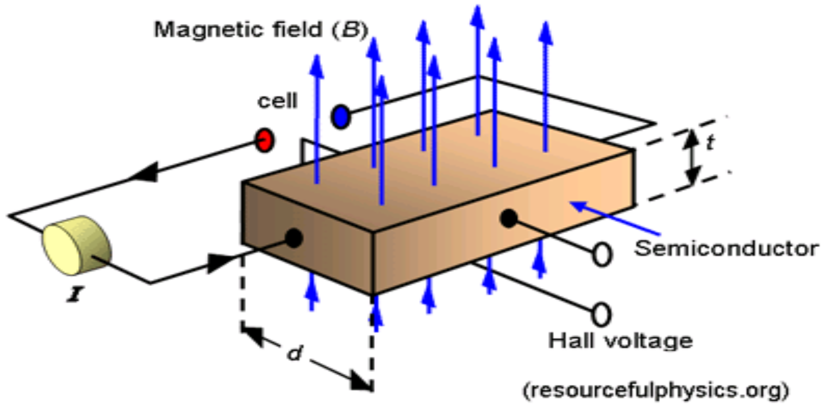
Heading Sensors

- 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)



(resourcefulphysics.org)

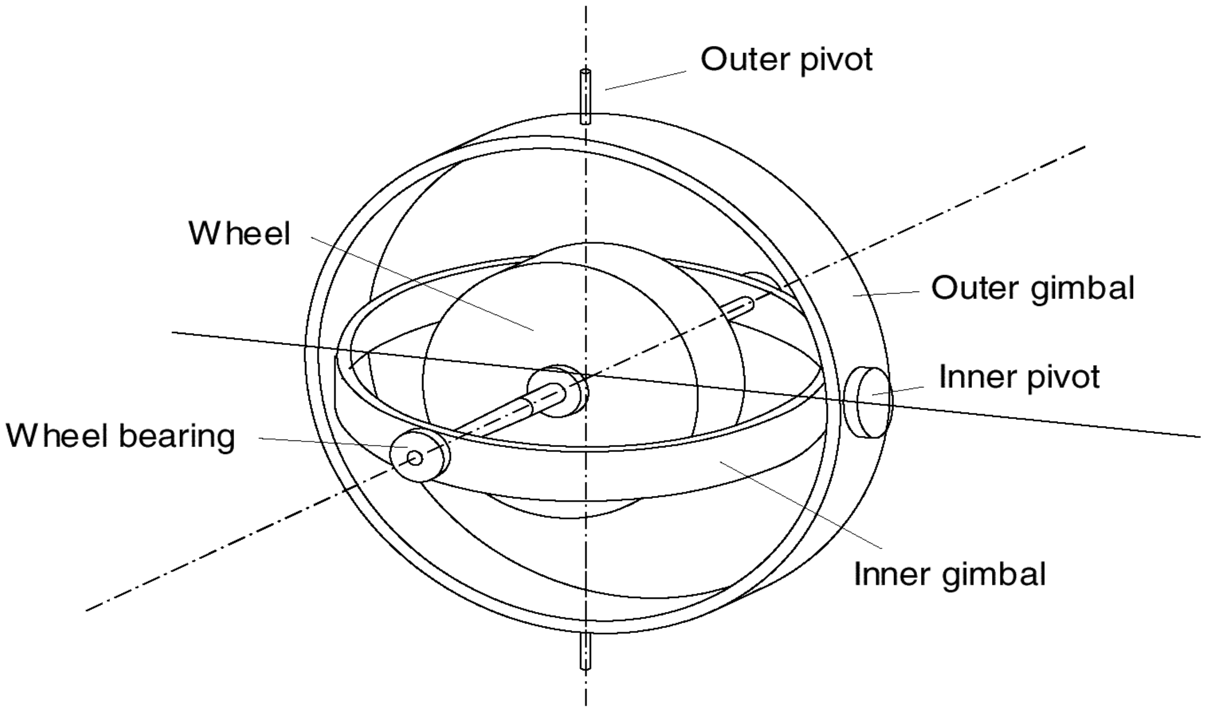
Example Magnetic Field Indoors

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)

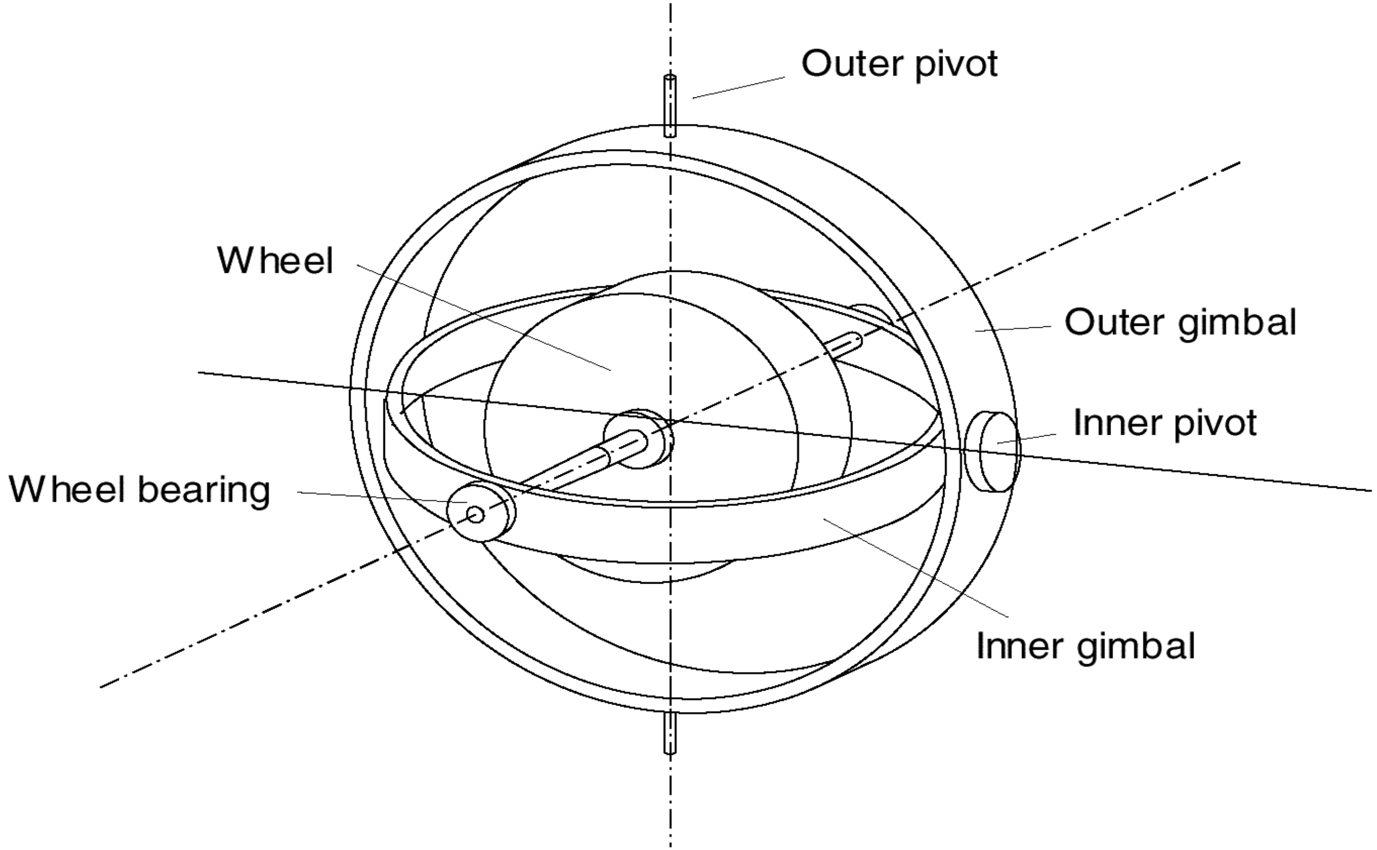
Mechanical Gyroscopes

- 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 $)



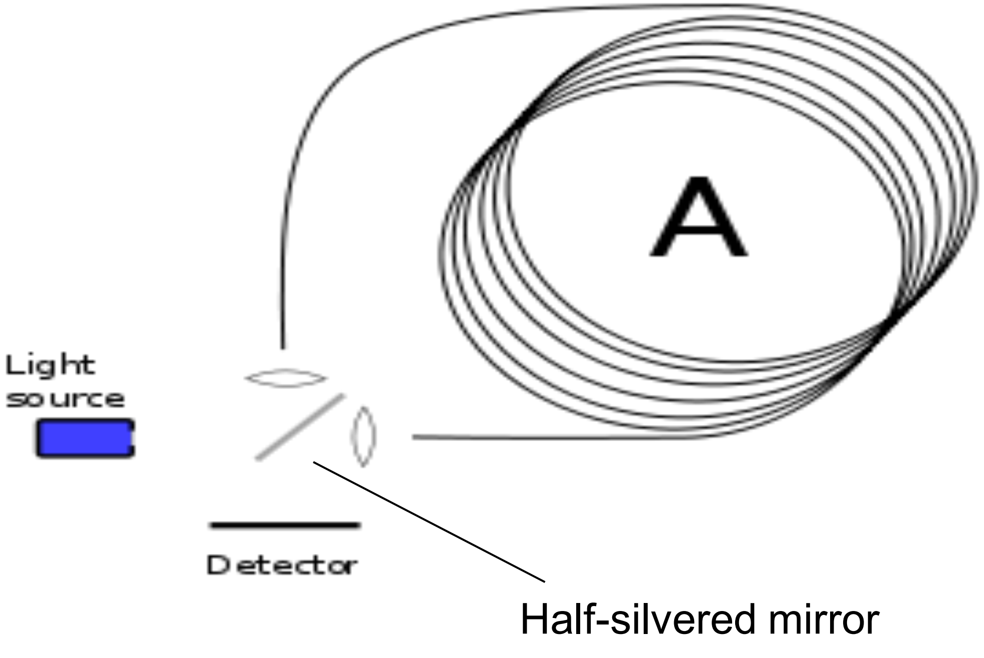
Rate gyros

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



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
  - expeiriences slightly shorter path
  - phase shift of the two beams is proportional to the angular velocity Ω of the cylinder
  - In order to measure the phase shift, coil consists of as much as 5Km optical fiber
- New solid-state optical gyroscopes based on the same principle are built using microfabrication technology.

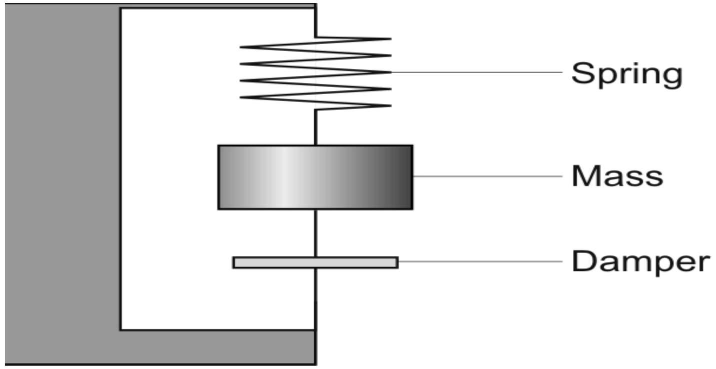


Single axis optical gyro

3-axis optical gyro

Mechanical Accelerometer

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



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

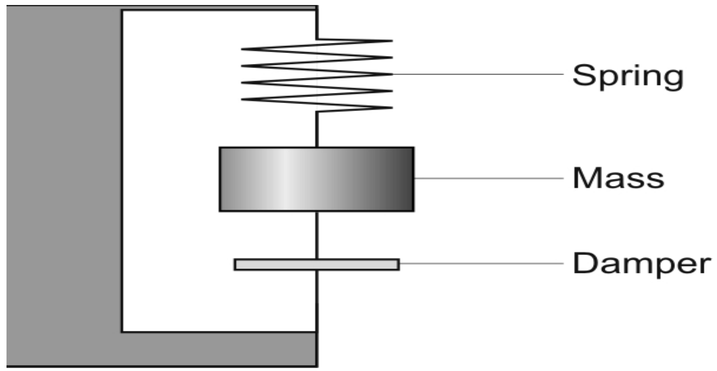
Where *m* is the proof mass, *c* the damping coefficient, *k* the spring constant

- at steady-state:

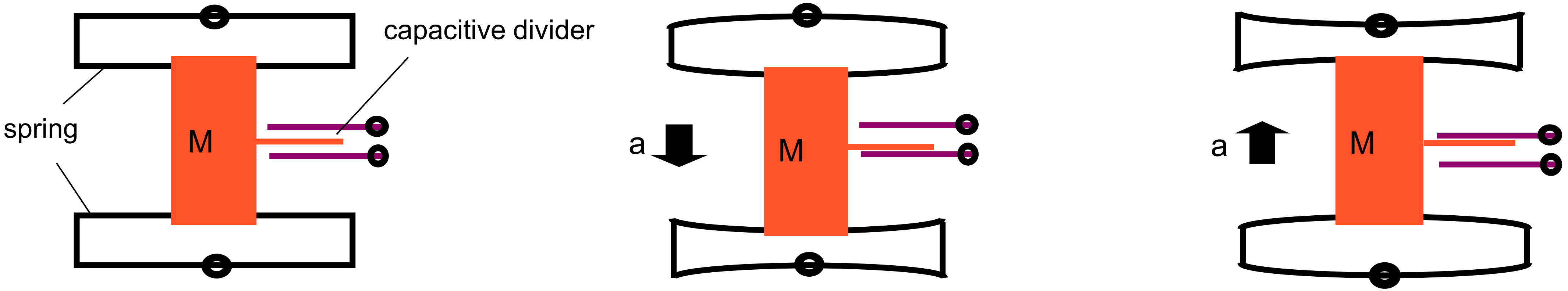
$$a_{applied} = \frac{kx}{m}$$

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)



Operational Principle

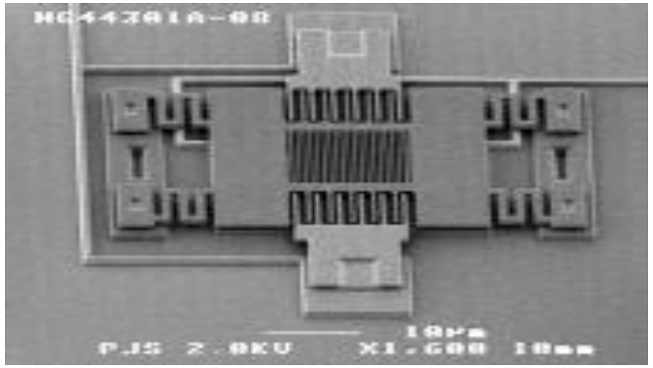
- A spring-like structure connects the device to a seismic mass vibrating in a capacity devider. A capacitive divider converts the displacement of the seismic mass into an electric signal. Damping is created by the gas sealed in the device.

Main Characteristics

- Can be multi-directional
- Can measure accelerations up to 50 g

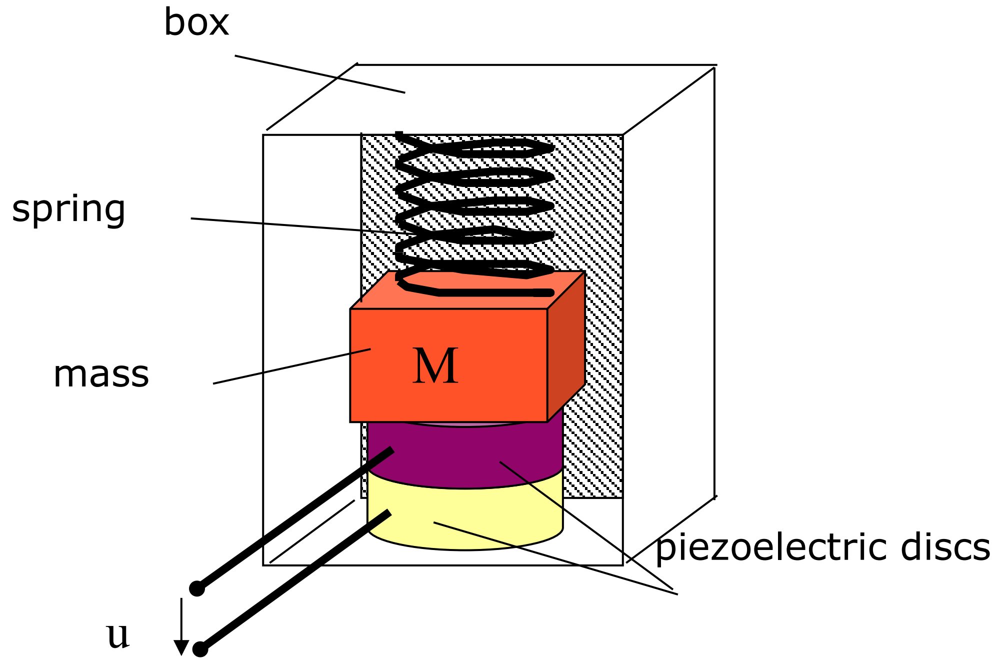
Applications

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



http://www.mems.sandia.gov

Factsheet: Piezoelectric Accelerometer



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

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

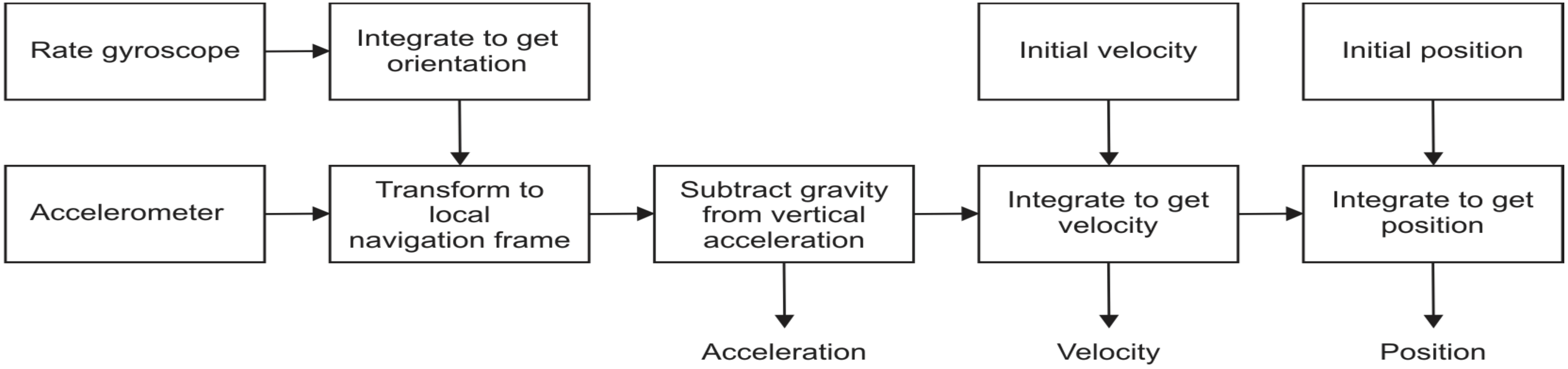
Applications

- 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

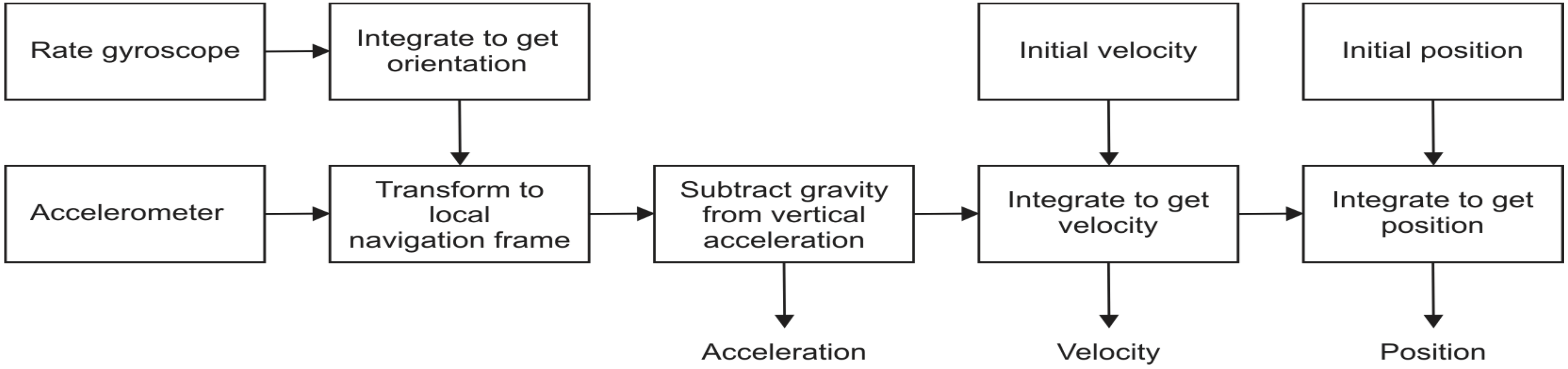
- In order to estimate motion, the gravity vector must be subtracted. Furthermore, initial velocity has to be known.



Inertial Measurement Unit (IMU)

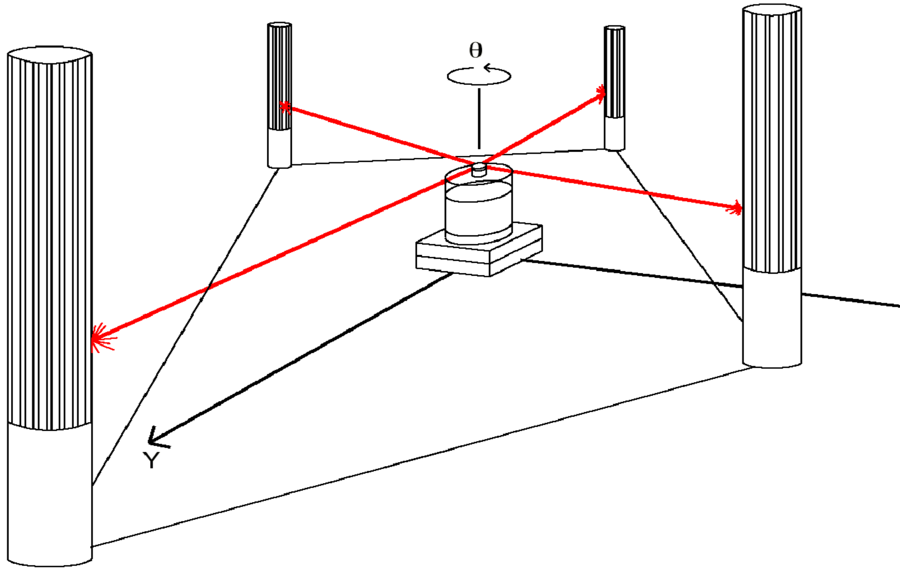
- **IMUs are extremely sensitive to measurement errors** in gyroscopes and accelerometers: **drift in the gyroscope** unavoidably undermines the estimation of the vehicle orientation relative to gravity, which results in incorrect cancellation of the gravity vector. Additionally observe that, because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



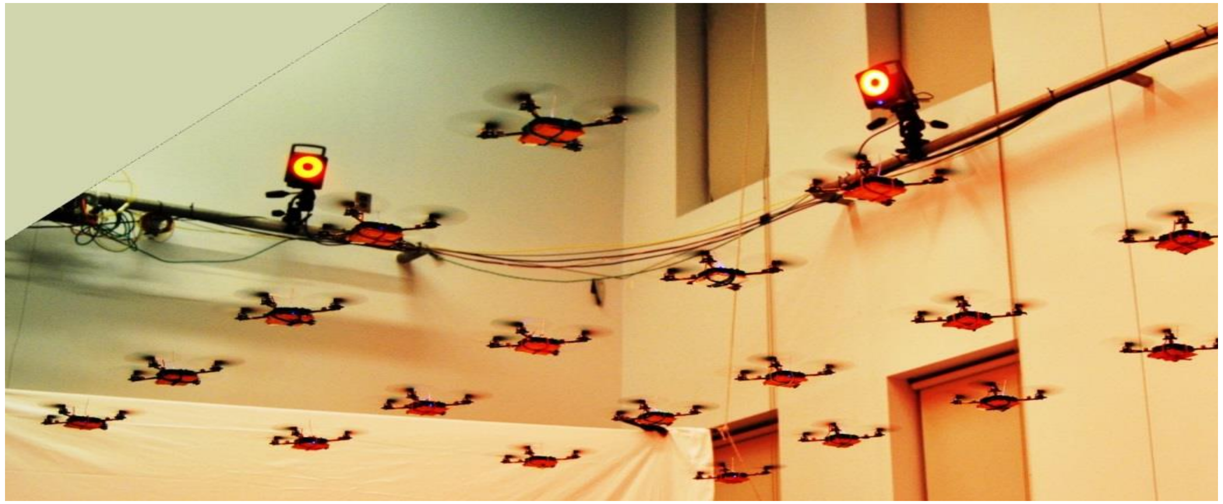
Ground-Based Active and Passive Beacons

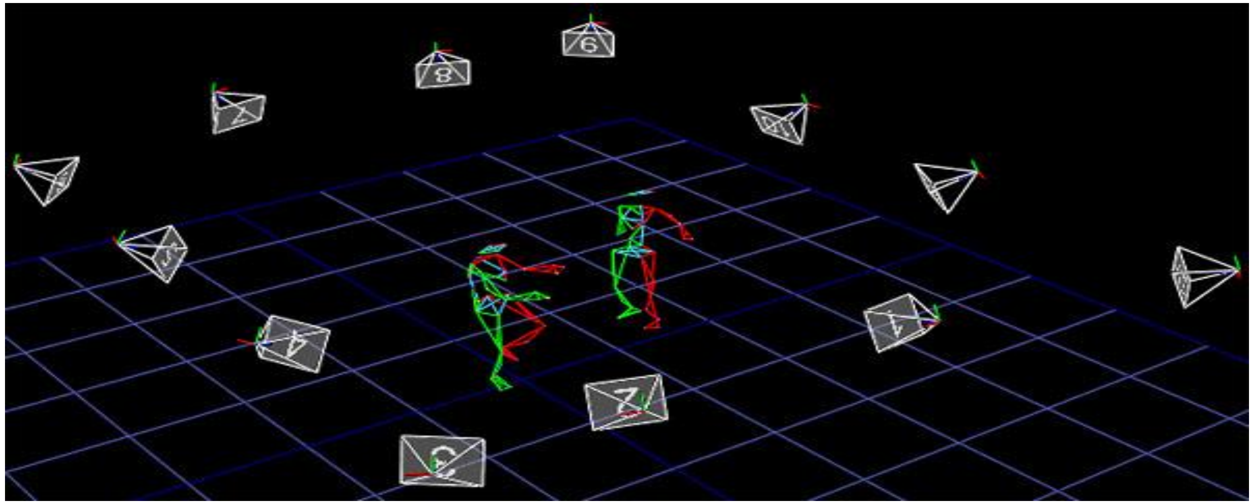
- “Elegant” way to solve the localization problem in mobile robotics
- **Beacons are signaling guiding devices with a precisely known position**
- Beacon base navigation is used since the humans started to travel
  - Natural beacons (landmarks) like **stars, mountains or the sun**
  - Artificial beacons 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)

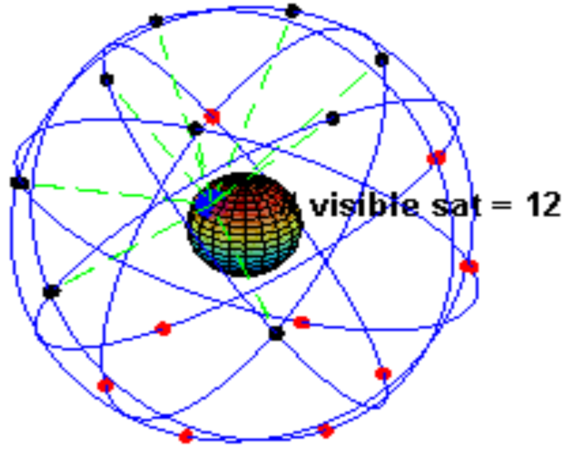




Augmented Reality Tag

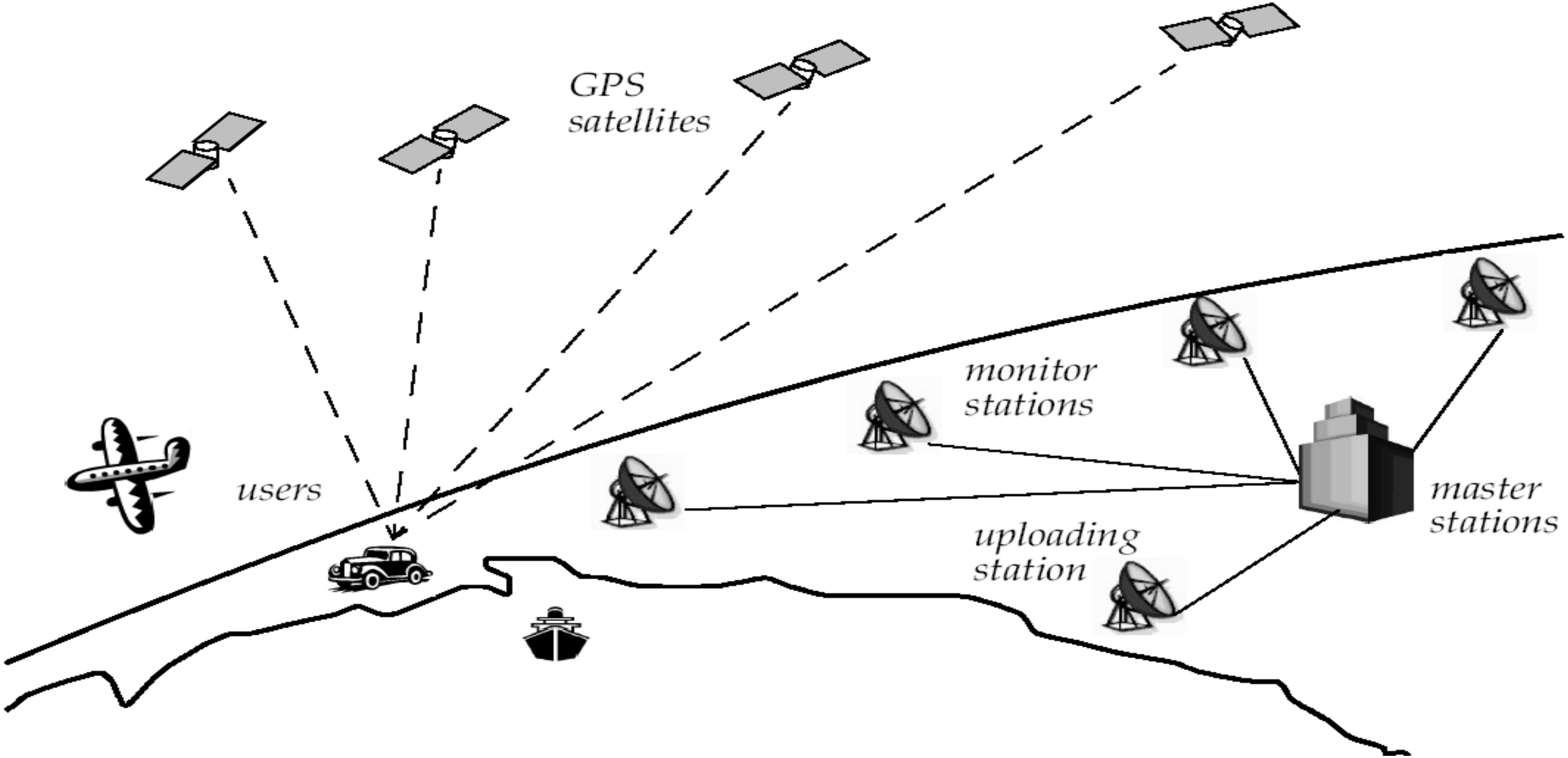
- Each tag carries a unique identifier
- Works only in combination with a camera
- Returns relative pose of the camera (x,y,z,roll,pitch,yaw) with respect to tag reference frame
- Accuracy depends on size and angle of sight of the tag (e.g., with a 10 cm tag and 2 meters distance -> 2 cm accuracy 5 deg precision)
- Good for rough localization

Global Positioning System (GPS) (1)



- 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 individual satellites and the GPS receiver
  - Real time update of the exact location of the satellites
  - Precise measurement of the time of flight
  - **Interferences** with other signals

Global Positioning System (GPS) (2)



Global Positioning System (GPS) (3)

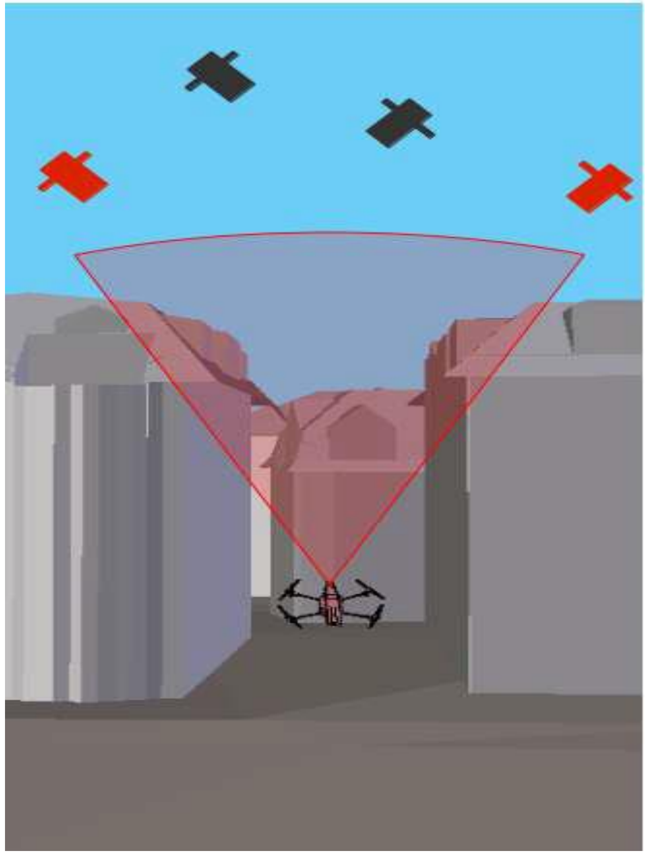
- **Time synchronization**:
  - **atomic clocks on each satellite**
  - monitoring them from different ground stations.
- Ultra-precision time synchronization is extremely important
  - electromagnetic radiation propagates at light speed
- **Light travels roughly 0.3 m per nanosecond**
  - position accuracy proportional to precision of time measurement
- **Real time update of the exact location of the satellites:**
  - monitoring the satellites from a number of widely distributed ground stations
  - master station analyses all the measurements and transmits the actual position to each of the satellites
- **Exact measurement of the time of flight**
  - **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

GPS Error Sources

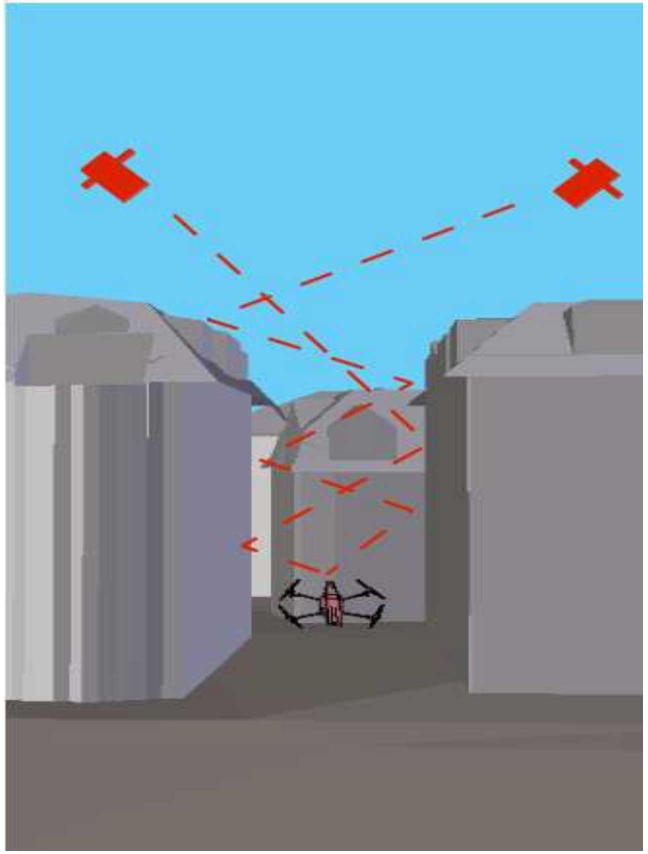
- Ephemeris data errors: **1 meter**
- Tropospheric delays: **1 meter**
  - The troposphere is the lower part (ground level to from 8 to 13 km) of the atmosphere that experiences the changes in temperature, pressure, and humidity associated with weather changes. Complex models of tropospheric delay require estimates or measurements of these parameters.
- Unmodeled ionosphere delays: **10 meters.**
  - The ionosphere is the layer of the atmosphere from 50 to 500 km that consists of ionized air. The transmitted model can only remove about half of the possible 70 ns of delay leaving a ten meter (30 ns) un-modeled residual.
- Multipath: **0.5 - 100 meters**
  - Multipath is caused by reflected signals from surfaces near the receiver that can either interfere with or be mistaken for the signal that follows the straight line path from the satellite. Multipath is difficult to detect and sometime hard to avoid.
- Coverage: Number of satellites under line of sight

Global Positioning System (GPS) (4)

Satellite coverage

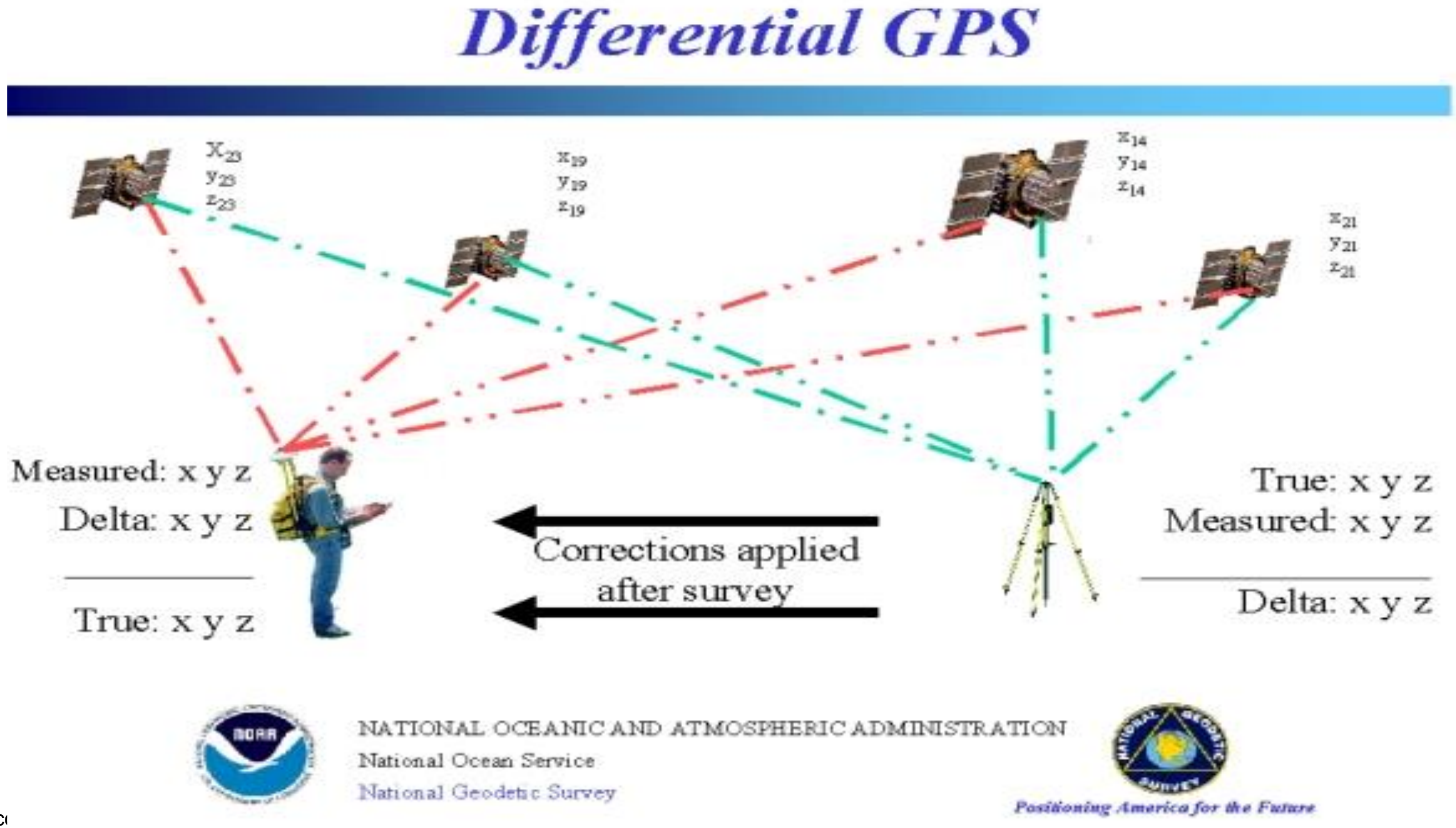


Multipath problem



Differential Global Positioning System (dGPS) (5)

- 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**

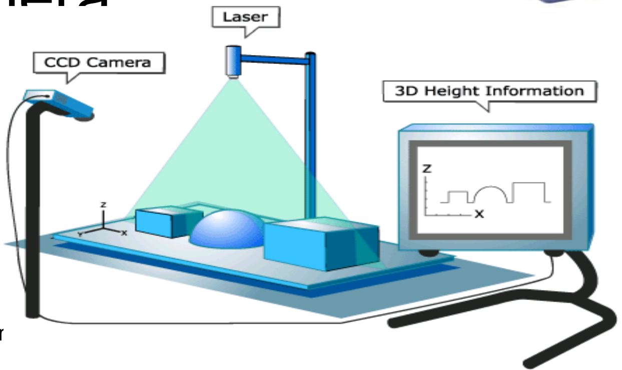


Range sensors

- Sonar

- Laser range finder

- Time of Flight Camera



- Structured light

Range Sensors (time of flight) (1)

- Large range distance measurement → thus called range sensors
- Range information:
  - key element for localization and environment modeling
- Ultrasonic sensors as well as laser range sensors make use of propagation speed of sound or electromagnetic waves respectively.
- The traveled distance of a sound or electromagnetic wave is given by

$$d = c \cdot t$$

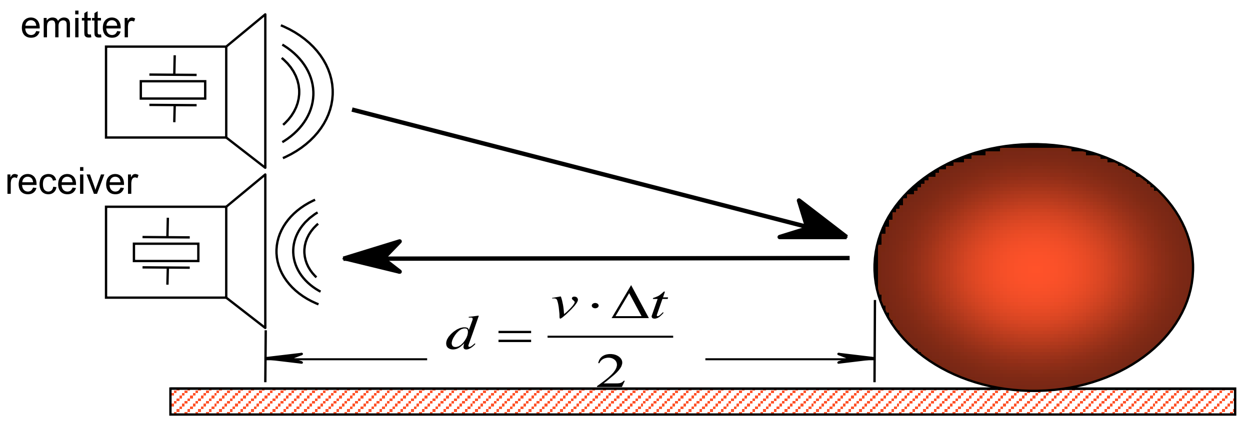
  - d = distance traveled (usually round-trip)
  - c = speed of wave propagation
  - t = time of flight.

Range Sensors (time of flight) (2)

- It is important to point out
  - **Propagation speed 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

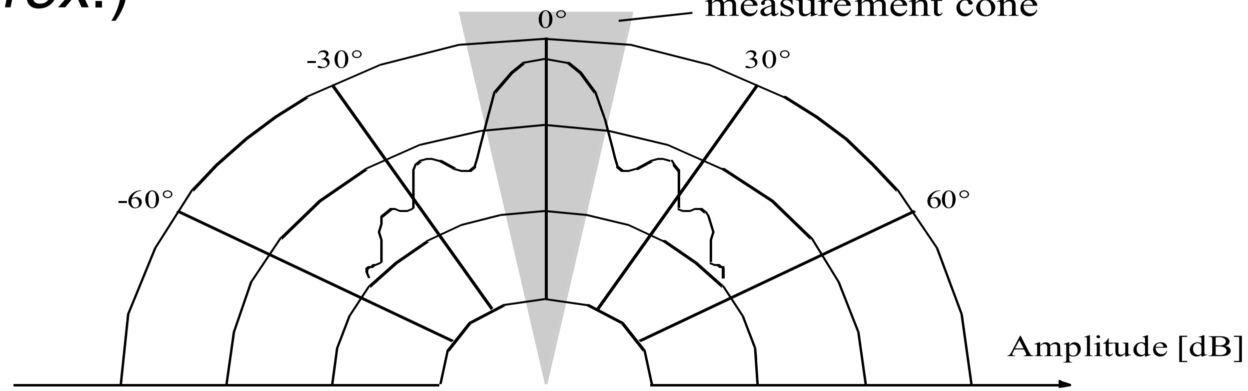
- Precision influenced by angle to object (as illustrated on the next slide)
- Useful in ranges from several cm to several meters
- **Typically relatively inexpensive**

3. Applications

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

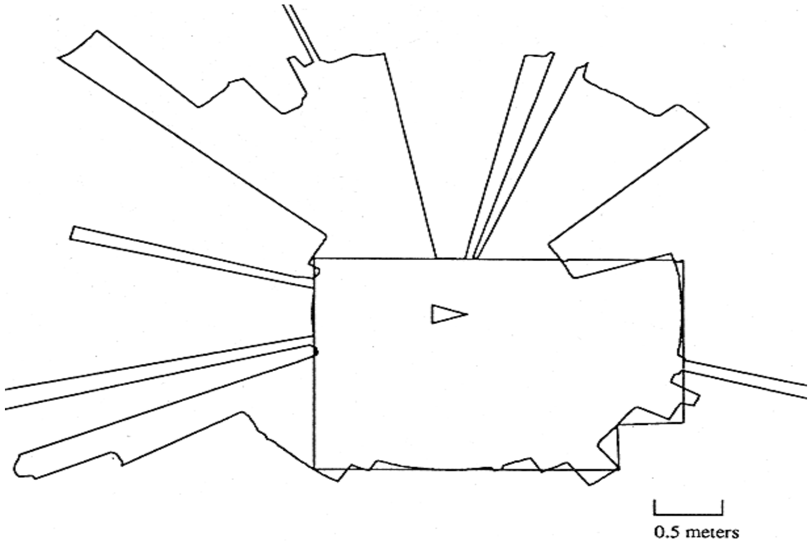
Ultrasonic Sensor (time of flight, sound) (2)

- 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)

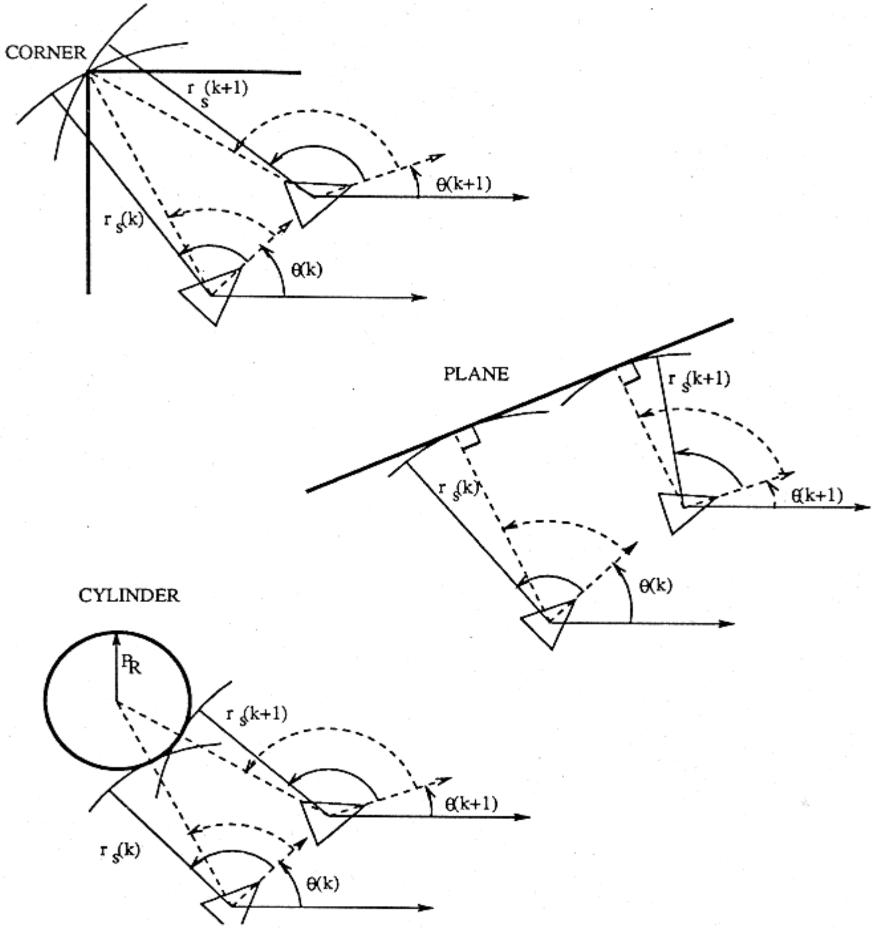


Ultrasonic Sensor (time of flight, sound) (3)

- 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

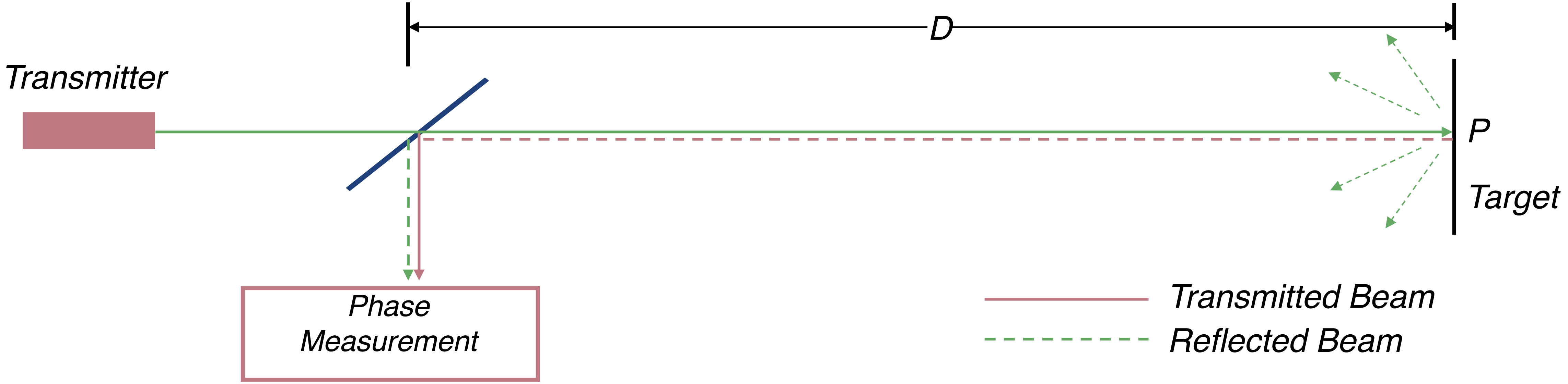
Laser Range Sensor (time of flight, electromagnetic) (1)

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

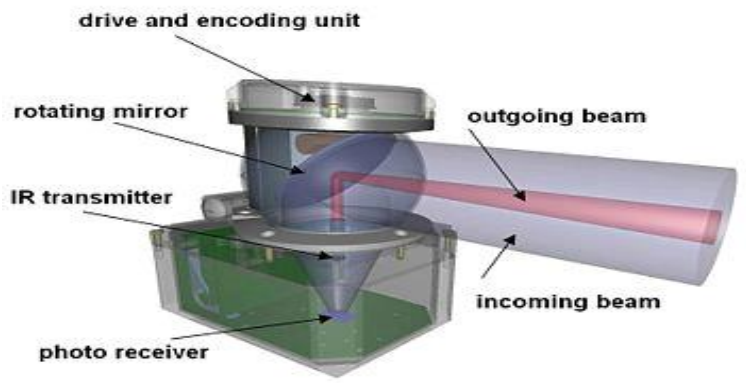
SICK

Hokuyo

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



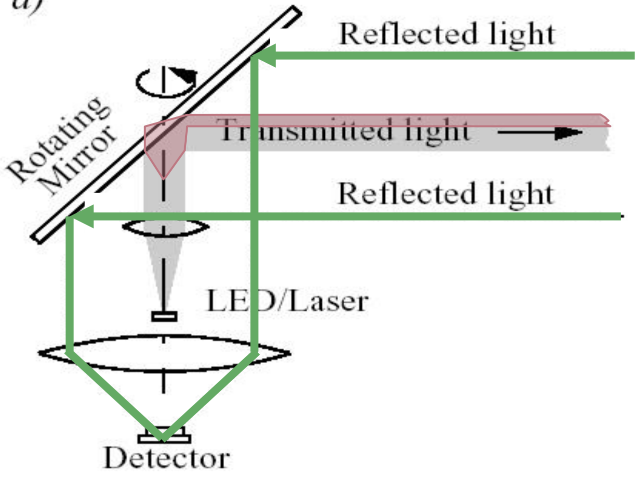
- Transmitted and received beams coaxial
- Transmitter illuminates a target with a collimated laser beam
- Receiver detects the time needed for round-trip
- A mechanical mechanism with a mirror sweeps
  - 2D or 3D measurement



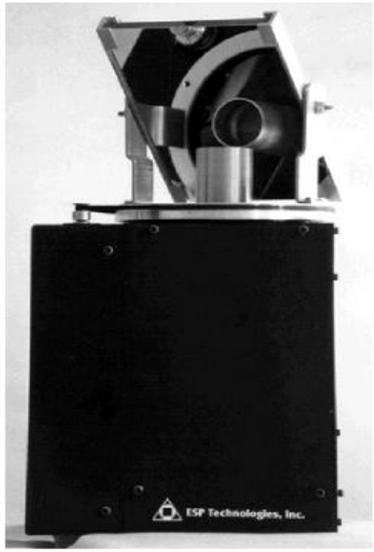
Laser Range Sensor (time of flight, electromagnetic) (2)

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

a)



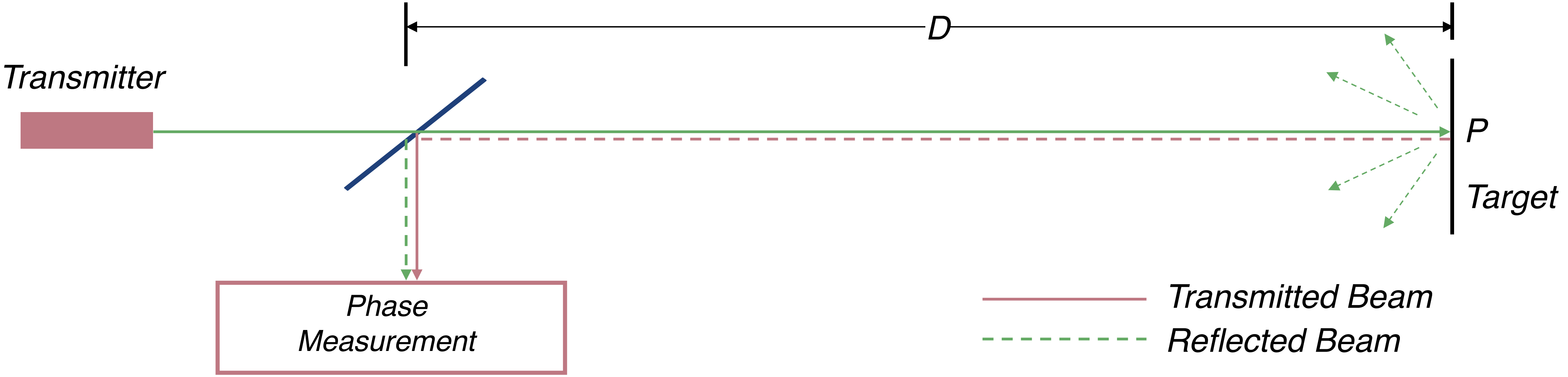
b)



c)

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

- *Phase-Shift Measurement*



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

Where:

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

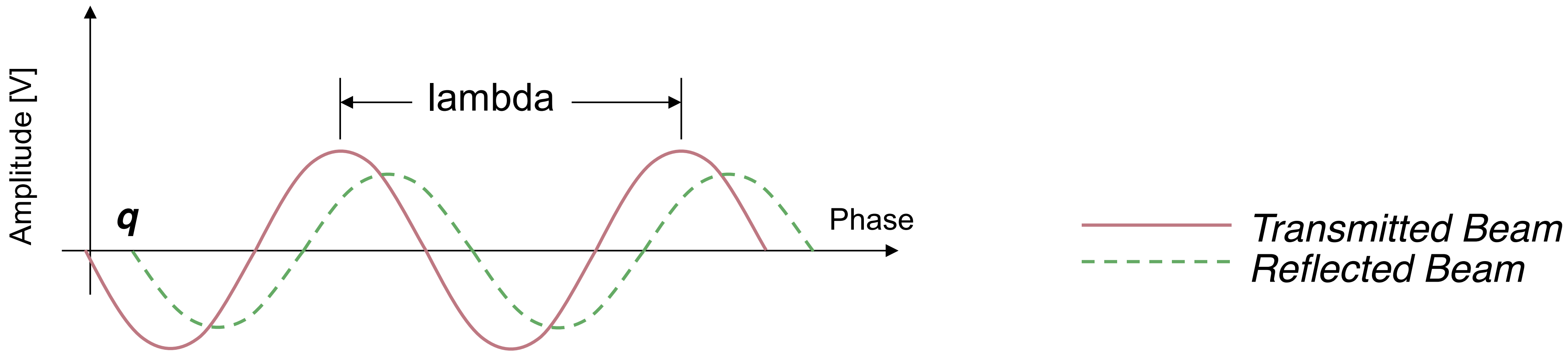
- for f = 5 MHz (as in the A.T&T. sensor), λ = 60 meters

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

- Distance D, between the beam splitter and the target

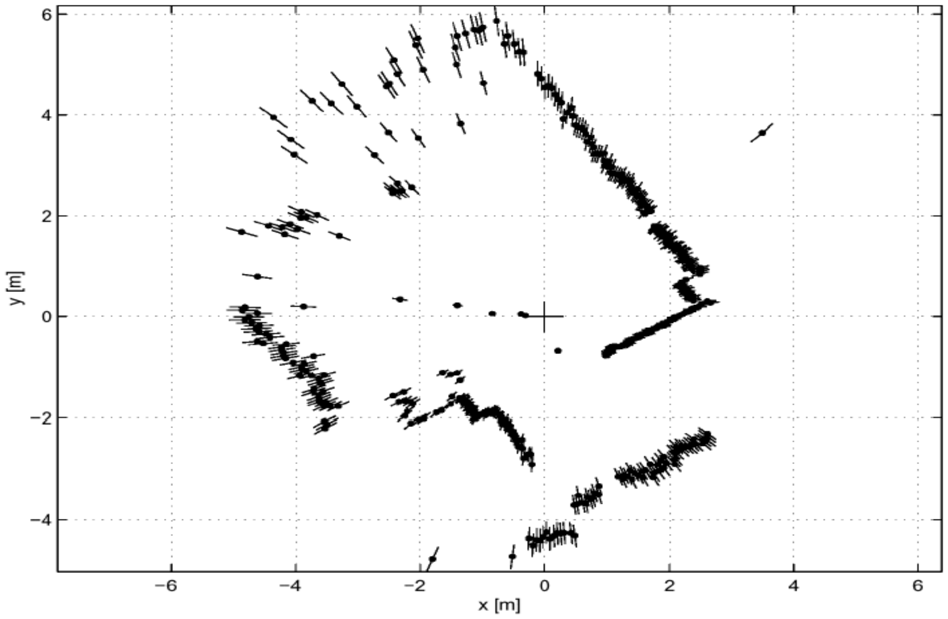
$$D = \frac{\lambda}{4\pi}\theta$$

- where
  - θ: phase difference between transmitted and reflected beam
  - Max measurable distance = $\boldsymbol{\lambda}/2 \Rightarrow$ ambiguous range estimates
  - E.g., if f=5Mh (i.e., λ = 60 meters) $\Rightarrow$ max distance = 30 m $\Rightarrow$ a target at a range of 35 meters = target at 5 meters



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

- Uncertainty of the range (phase/time estimate) is inversely proportional to the square of the received signal amplitude.
  - Hence dark, distant objects will not produce such good range estimated as closer brighter objects …
- Typical range image of a 2D laser range sensor with a rotating mirror. The length of the lines through the measurement points indicate the uncertainties.

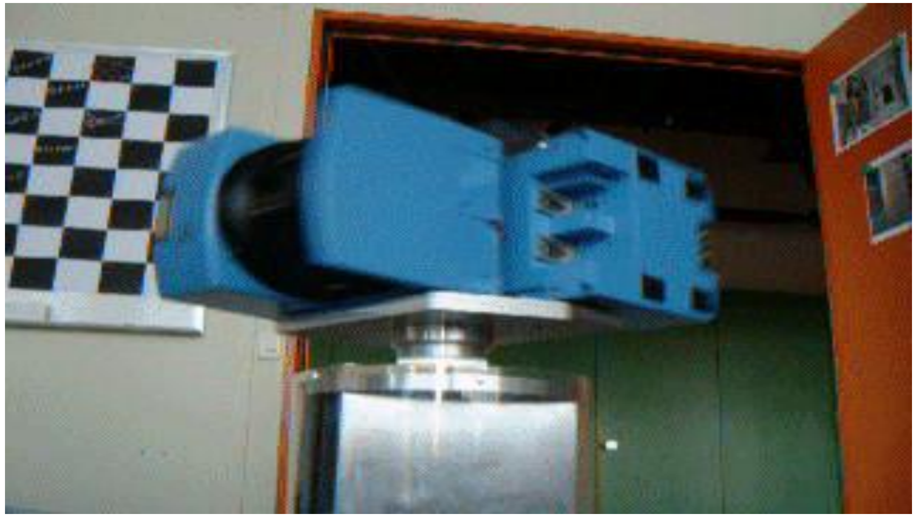


The SICK LMS 200 Laser Scanner

- Angular resolution 0.25 deg
- Depth resolution ranges between ~10 mm and the typical accuracy is 35 mm, over a range from 5 cm up to 20 m or more (up to 80 m), depending on the reflectivity of the object being ranged.
- This device performs 75 180-degrees scans per second

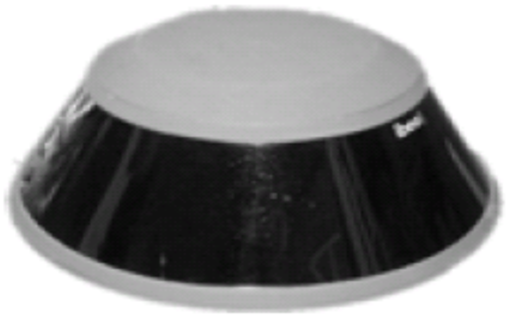
3D Laser Range Finder (1)

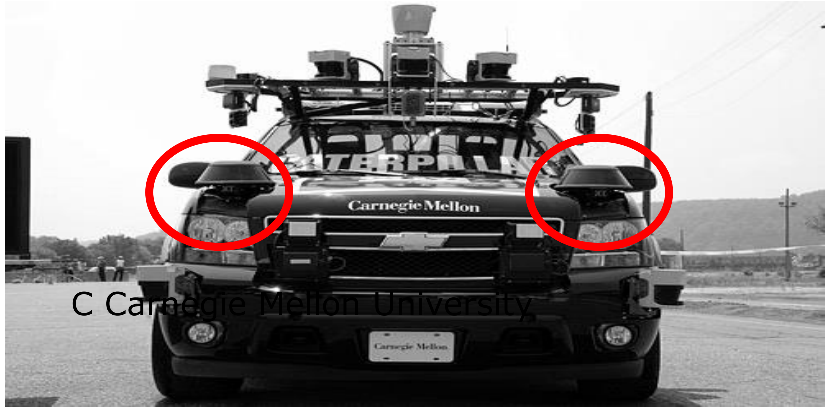
- **A 3D laser range finder is a laser scanner that acquires scan data in more than a single plane.**
- Custom-made 3D scanners are typically built by nodding or rotating a 2D scanner in a stepwise or continuous manner around an axis parallel to the scanning plane.
- By lowering the rotational speed of the turn-table, the angular resolution in the horizontal direction can be made as small as desired.
- A full spherical field of view can be covered (360° in azimuth and +/-90° in elevation).



3D Laser Range Finder (3)

- The **Alasca XT laser scanner** splits the laser beam into **four vertical layers** with an aperture angle of 3.2°.
- This sensor is typically used for obstacle and pedestrian detection on cars. Because of its multi-layer scanning principle, it allows us any pitching of the vehicle



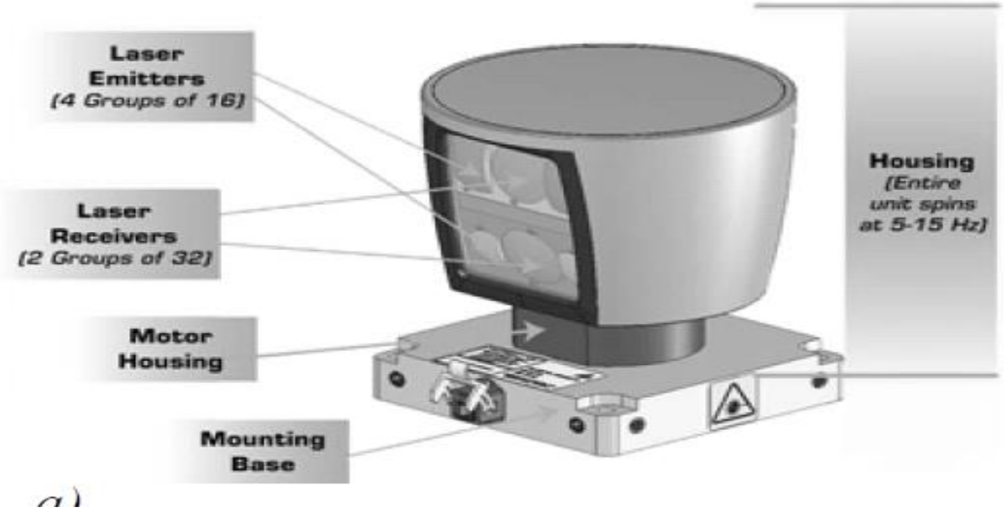


C Carnegie Mellon University

d)

3D Laser Range Finder (2)

- The Velodyne HDL-64E uses 64 laser emitters.
  - Turn-rate up to 15 Hz
  - The field of view is 360° in azimuth and 26.8° in elevation
  - Angular resolution is 0.09° and 0.4° respectively
  - **Delivers over 1.3 million data points per second**
  - The distance accuracy is 2 cm and can measure depth up to 50 m
  - This sensor was the primary means of terrain map construction and obstacle detection for all the top DARPA 2007 Urban Challenge teams. However, the Velodyne is currently still 10 times more expensive than a Sick laser range finder (SICK ~ 4000 $, Velodyne ~40,000 $)



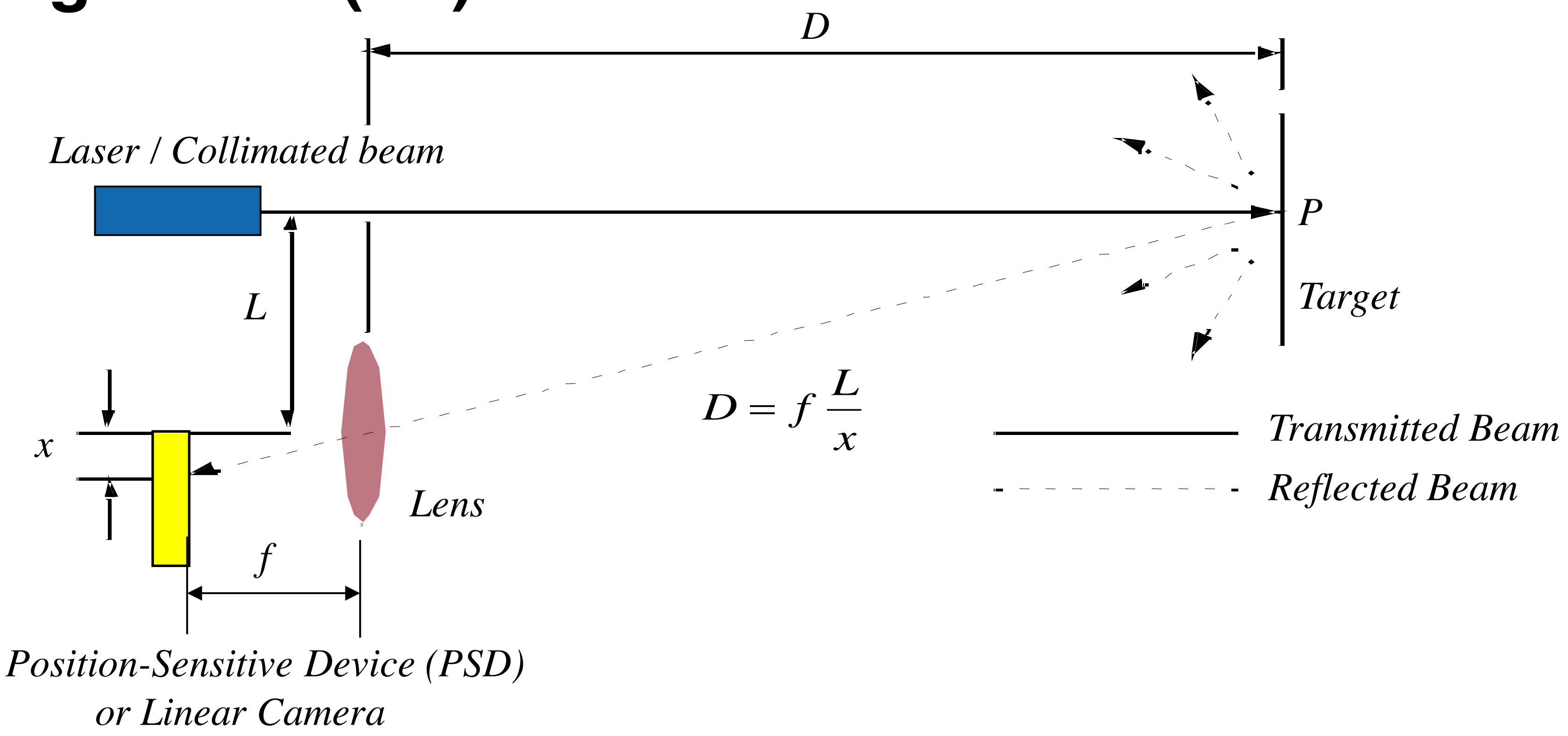
C Carnegie Mellon University

Google Self Driving Car

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)

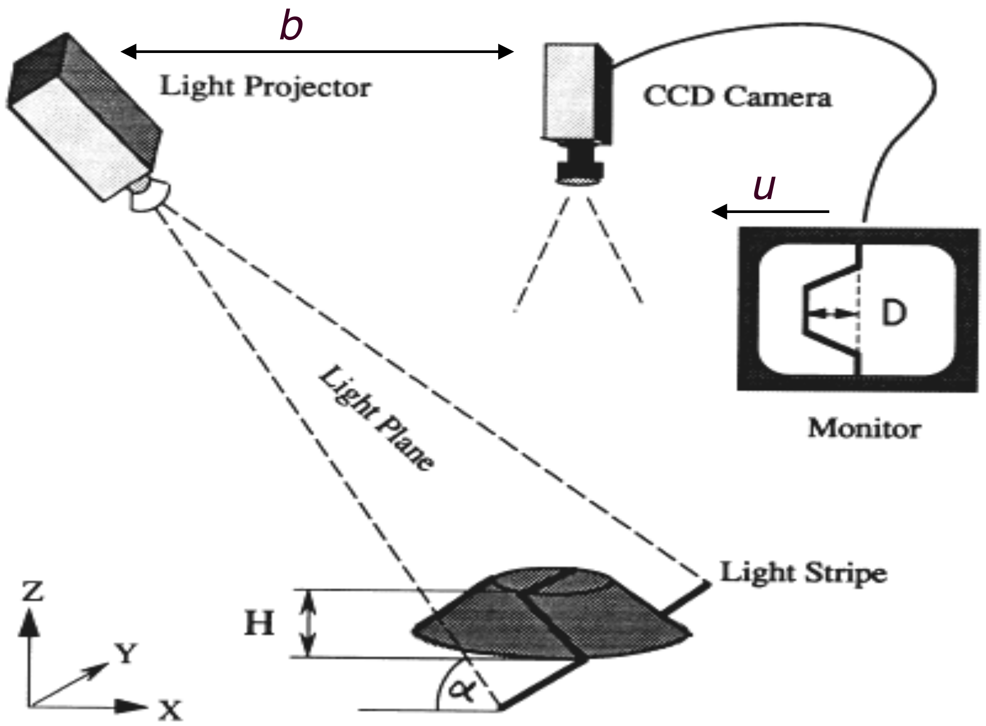


- Principle of 1D laser triangulation:

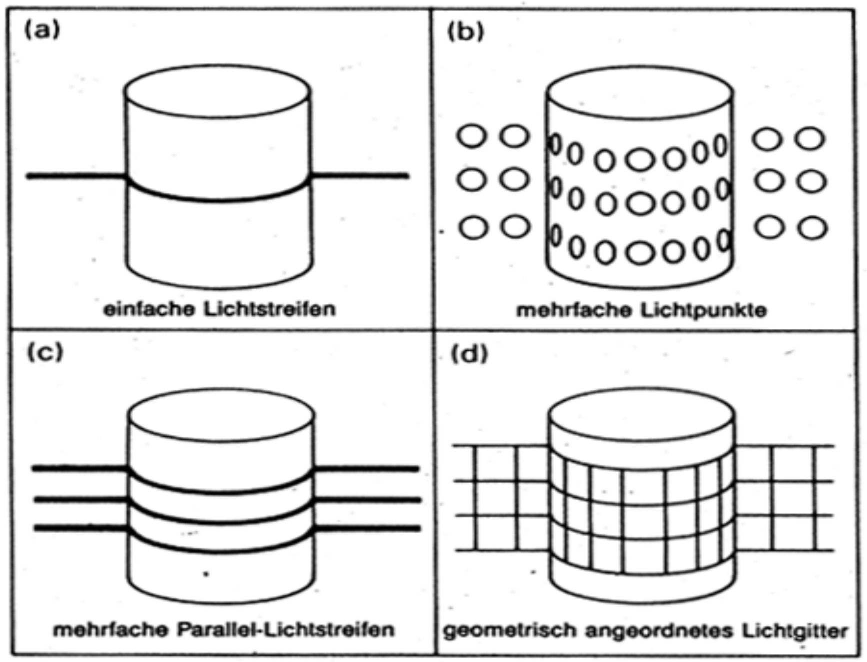
$$D = f\,\frac{L}{x}$$

Structured Light (vision, 2D or 3D): Structured Light

a



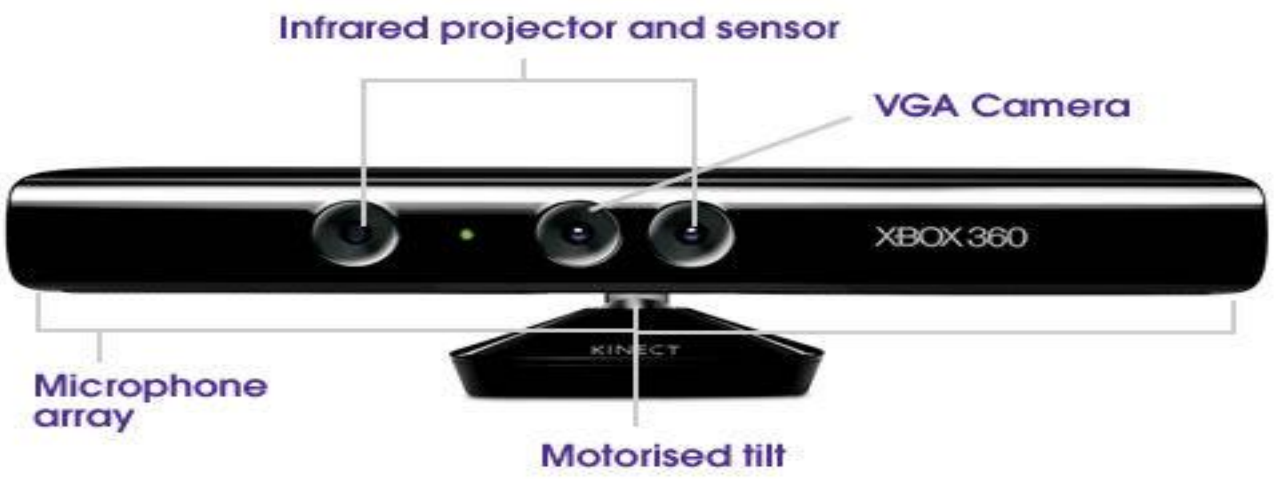
b



- 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.

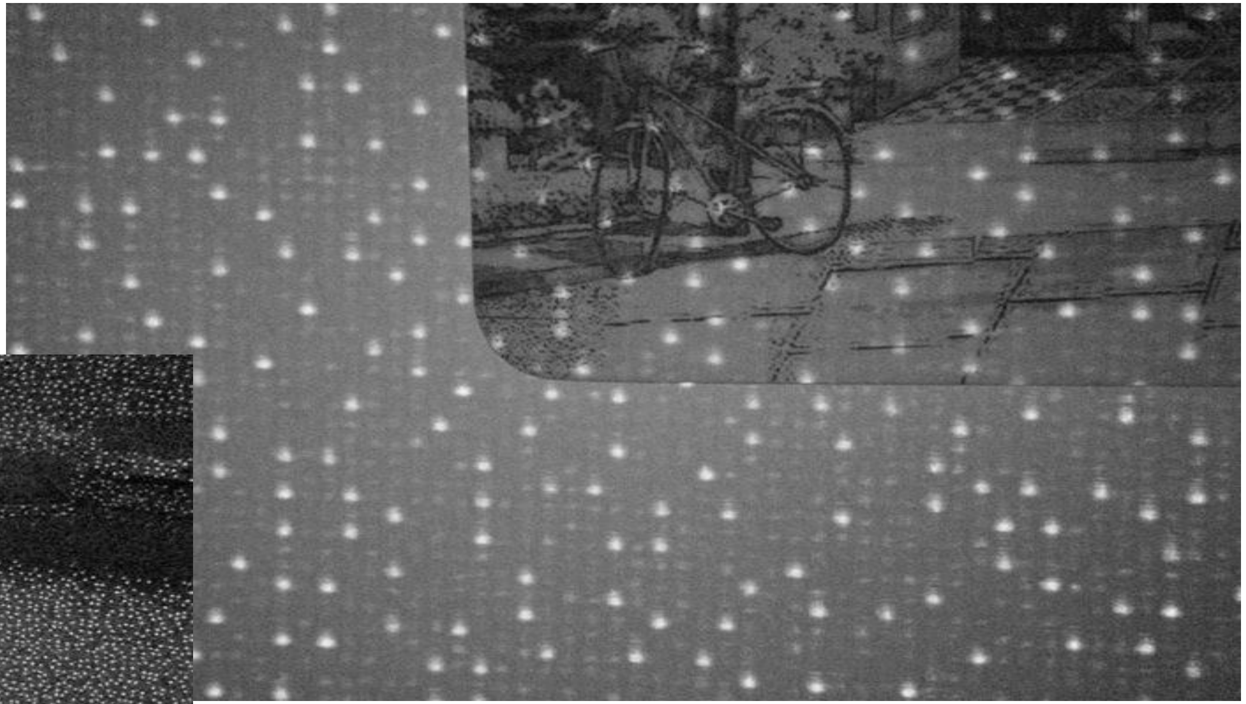
Microsoft Kinect

- Developed by 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

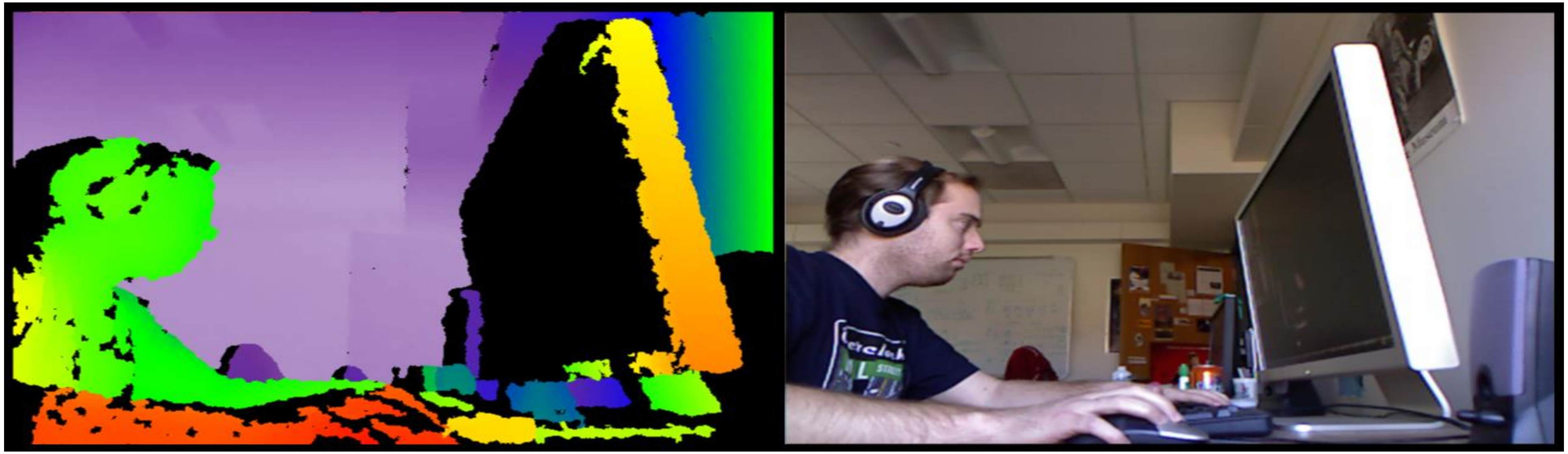
IR Pattern



Depth Map

Video Out

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



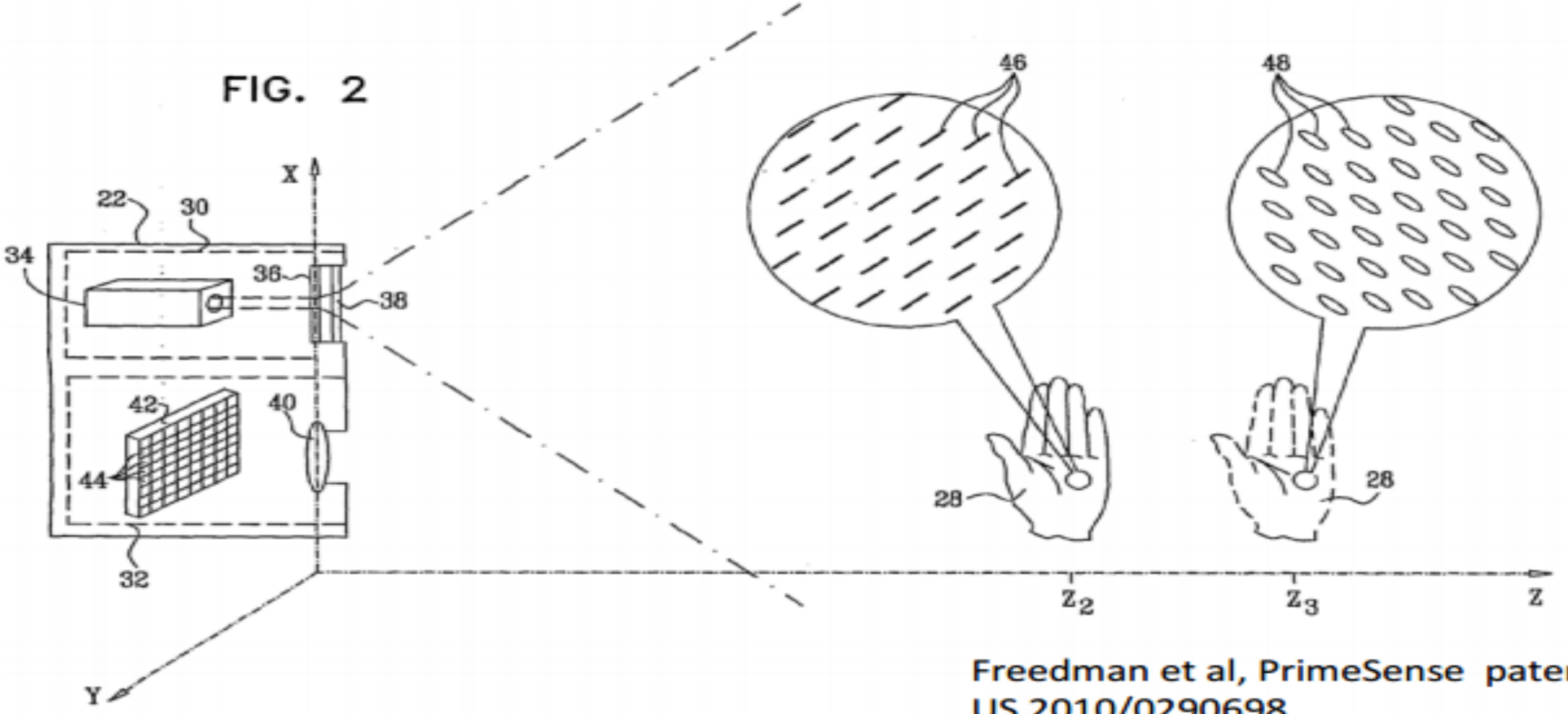
Microsoft Kinect: Depth Computation (1)
Depth from Stereo

- 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 patter 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: Depth Computation (2)
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

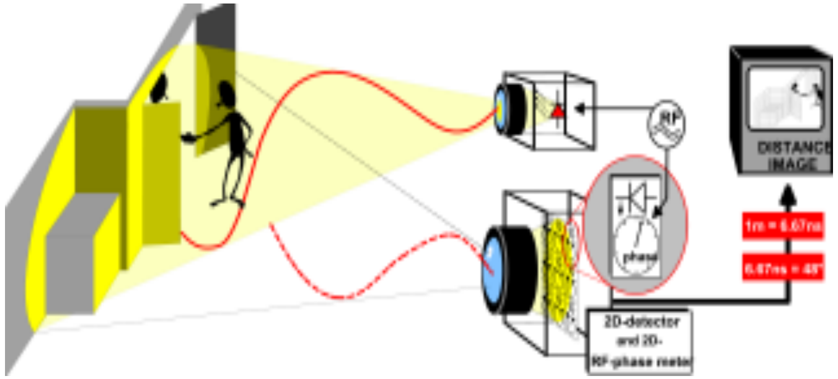
FIG. 2



Freedman et al, PrimeSense patent application
US 2010/0290698

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



Swiss Ranger 3000
(produced by MESA)

The 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)

Range Camera SR-3000

C MESA Imaging AG

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