上海科技大学
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CS283: Robotics Fall 2016: Sensors III

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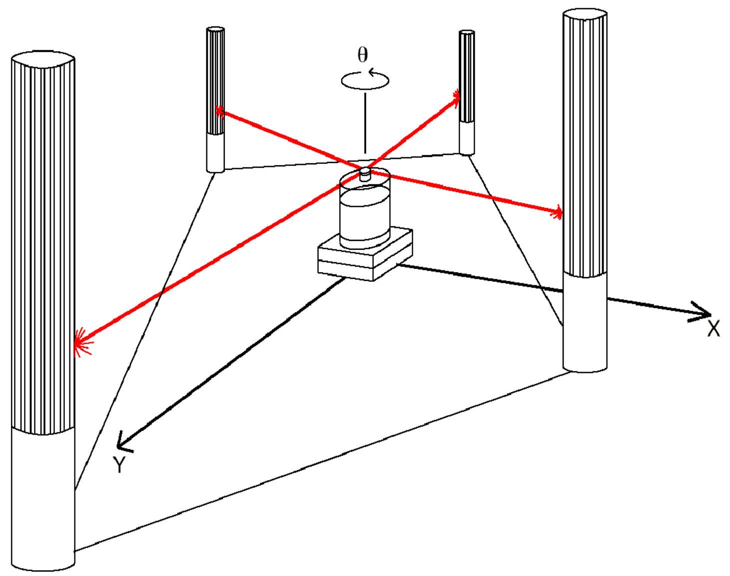
SENSORS FOR LOCALIZATION

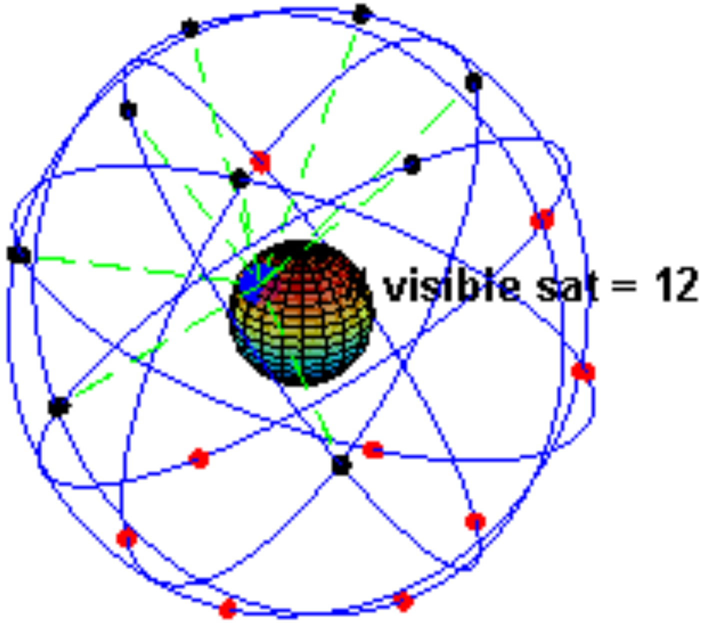
Ground-Based Active and Passive Beacons

- “Elegant” way to solve the localization problem in mobile robotics
- Beacons are signaling guiding devices with a precisely known position
- Beacon base navigation is used since the humans started to travel
  - Natural beacons (landmarks) like stars, mountains or the sun
  - Artificial beacons like lighthouses
- The recently introduced Global Positioning System (GPS) revolutionized modern navigation technology
  - Already one of the key sensors for outdoor mobile robotics
  - For indoor robots GPS is not applicable,
- Major drawback with the use of beacons in indoor:
  - Beacons require changes in the environment -> costly.
  - Limit flexibility and adaptability to changing environments.



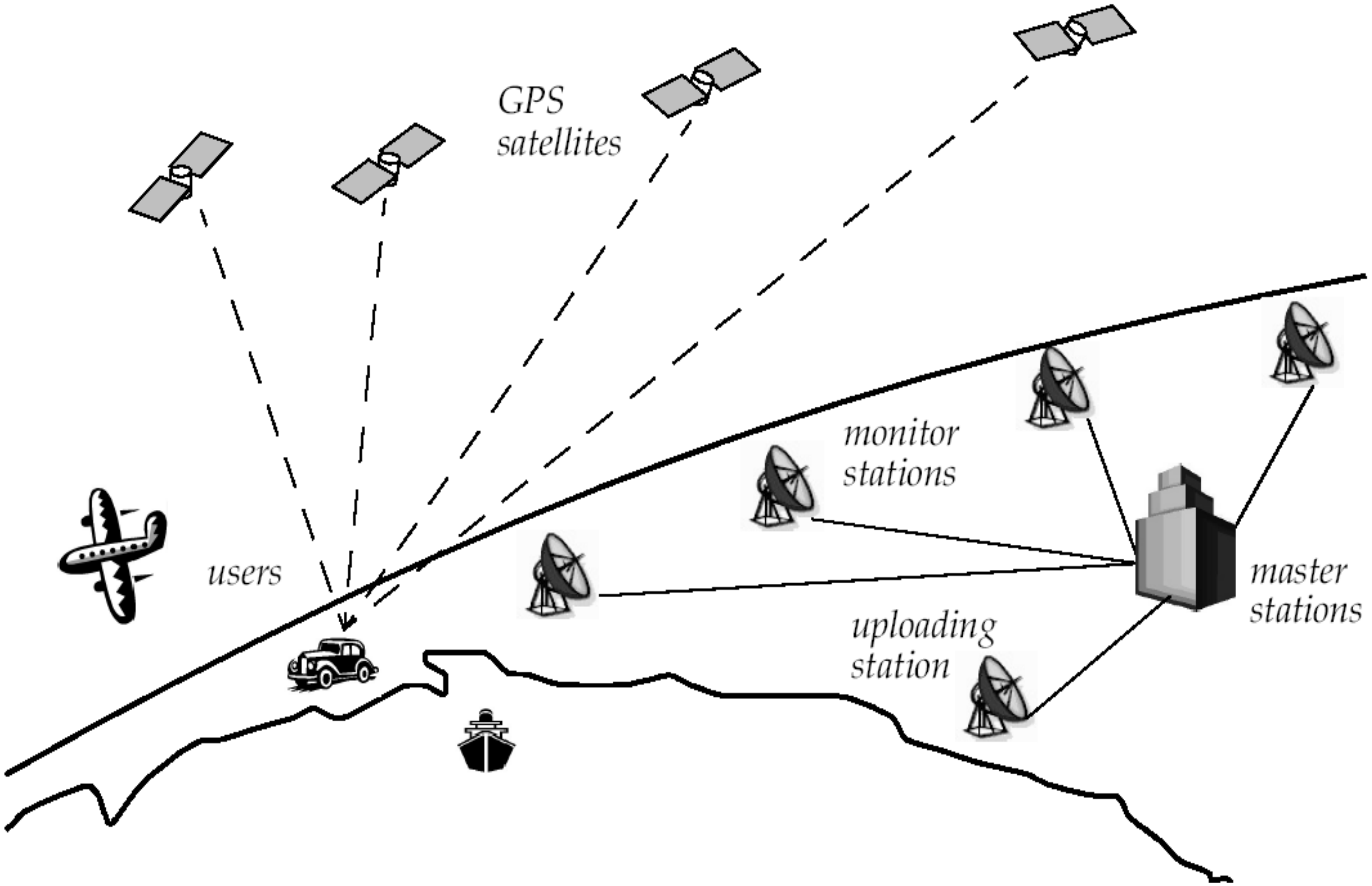
Global Positioning System (GPS) (1)

- Developed for military use
- 1995 it became accessible for commercial applications
- 24 satellites orbiting the earth every 12 hours at a height of 20.190 km.
- 4 satellites are located in each of 6 orbits with 60 degrees orientation between each other. The orbital planes do not rotate with respect to stars. Orbits arranged so that at least 6 satellites are always within line of sight from any point on Earth's surface.
- From 2008: 32 satellites to improve localization accuracy through redundancy
- Location of any GPS receiver is determined through a time of flight measurement (satellites send orbital location (*ephemeris*) plus time; the receiver computes its location through **trilateration** and **time correction**)



- 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
- Roughly 0.3 m per nanosecond
  - position accuracy proportional to precision of time measurement
- Real time update of the exact location of the satellites:
  - monitoring the satellites from a number of widely distributed ground stations
  - master station analyses all the measurements and transmits the actual position to each of the satellites
- Exact measurement of the time of flight
  - the receiver correlates a pseudocode with the same code coming from the satellite
  - The delay time for best correlation represents the time of flight.
  - quartz clock on the GPS receivers are not very precise
  - the range measurement with four satellite allows to identify the three values (x, y, z) for the position and the clock correction ΔT
- Recent commercial GPS receiver devices allows position accuracies down to a couple meters.

GPS Error Sources

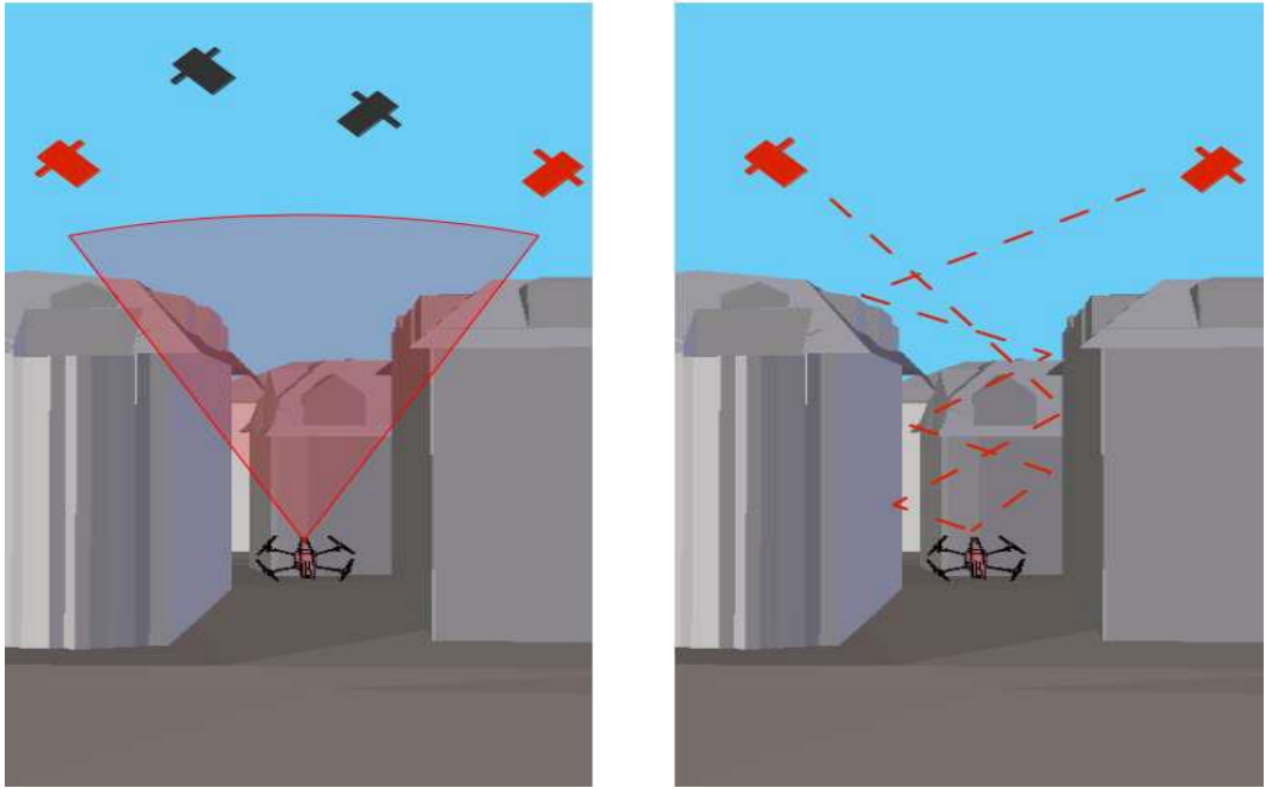
Satellite clock errors uncorrected by monitor stations may result in one meter errors:

- Ephemeris data errors: 1 meter
- Tropospheric delays: 1 meter.
  - The troposphere is the lower part (ground level to from 8 to 13 km) of the atmosphere that experiences the changes in temperature, pressure, and humidity associated with weather changes. Complex models of tropospheric delay require estimates or measurements of these parameters.
- Unmodeled ionosphere delays: 10 meters.
  - The ionosphere is the layer of the atmosphere from 50 to 500 km that consists of ionized air. The transmitted model can only remove about half of the possible 70 ns of delay leaving a ten meter un-modeled residual.
- Number of satellites under line of sight

GPS Multipath

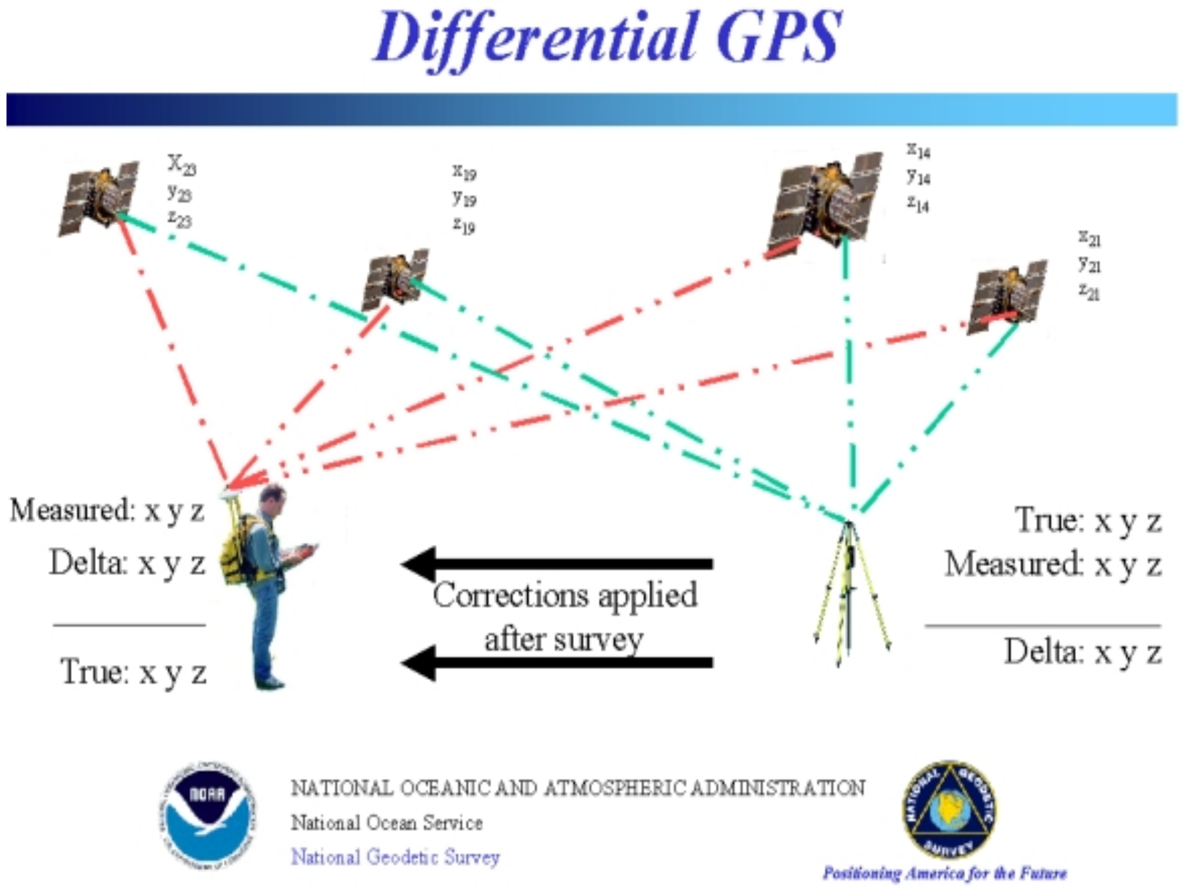
- Multipath: 0.5 meters
  - Multipath is caused by reflected signals from surfaces near the receiver that can either interfere with or be mistaken for the signal that follows the straight line path from the satellite. Multipath is difficult to detect and sometime hard to avoid.

Satellite coverage Multipath problem



Differential Global Positioning System (dGPS)

- Base station GPS receiver: set up on a precisely known location
- Base station receiver calculates its position based on satellite signals
- Compares this location to the known location
- Difference is applied to the GPS data recorded by the mobile GPS receivers
- Position accuracies in sub-meter to cm range



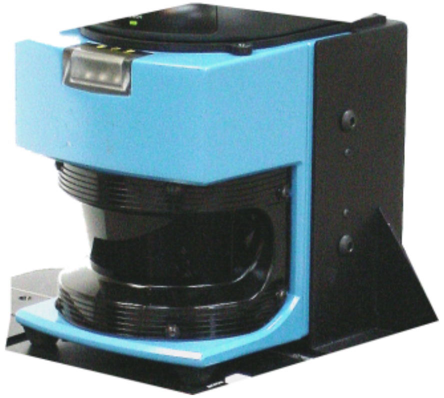
Other Global Positioning Systems

- GLONASS
  - Russian GPS – developed since 1976
  - Full global coverage as of 2011 (24 sattelites)
- Galileo
  - European GPS – initiated 2003
  - Six satellites in orbit
  - Expected completion: 2019
- IRNSS (Indian Regional Navigation Satellite System)
  - Initiated 2010
  - 7 satellites for Indian Coverage in orbit
  - Full operation soon
- BeiDou Navigation Satellite System 北斗卫星导航系统
  - Chinese GPS – developed since 2003
  - BeiDou Satellite Navigation System (BDS)
  - 2011 full China coverage – 2020 global coverage
  - 37 satellites system

Range sensors

- Sonar --->

- Laser range finder --->



- Time of Flight Camera -------------------------------------->

- Structured light ---------->

Range Sensors (time of flight) (1)

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

$$d = c \cdot t$$

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

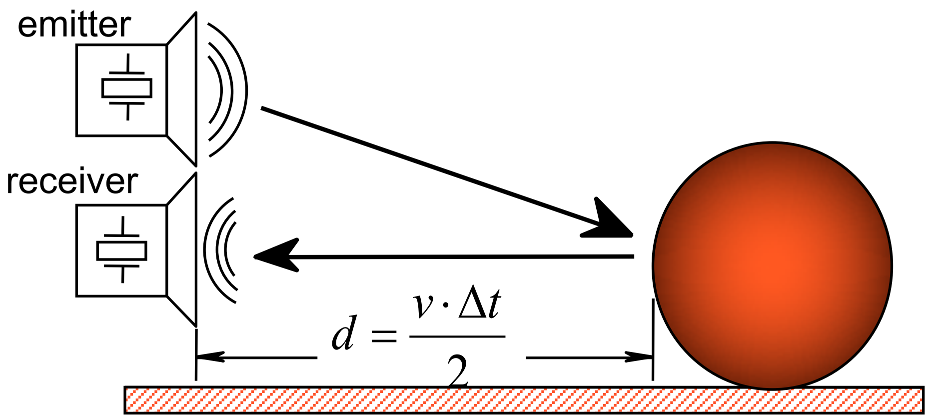
Range Sensors (time of flight) (2)

- It is important to point out
  - Propagation speed v of sound in air: 0.3 m/ms - 300 m/s
  - Propagation speed v of sound in water: 1.5 m/ms - 1,500 m/s

  - Propagation speed v of of electromagnetic signals: 0.3 m/ns,
    - one million times faster.
  - 3 meters
    - is 10 ms for an ultrasonic system
    - only 10 ns for a laser range sensor
    - 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 measure (laser range sensors)
  - Opening angle of transmitted beam (especially ultrasonic range sensors)
  - Interaction with the target (surface, specular reflections)
  - Variation of propagation speed (sound)
  - Speed of mobile robot and target (if not at stand still)

Factsheet: Ultrasonic Range Sensor (1)



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) (1)

- transmit a packet of (ultrasonic) pressure waves
- distance *d* of the echoing object can be calculated based on the propagation speed of sound *c* and the time of flight *t*.

$$d = \frac{c \cdot t}{2}$$

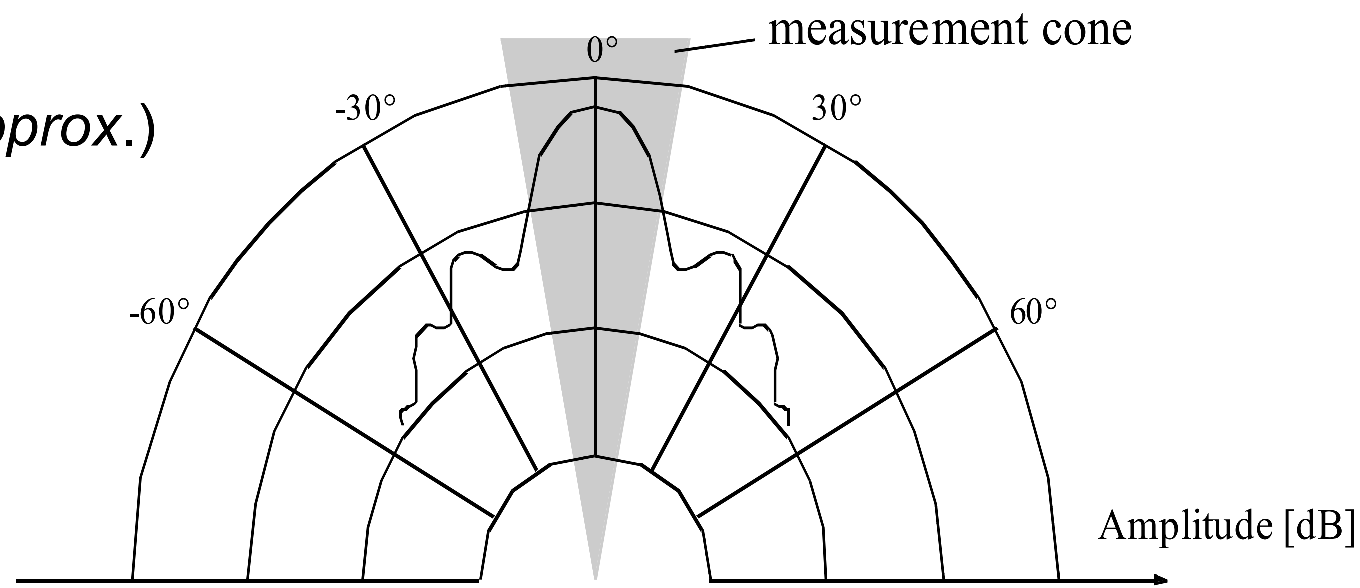
- The speed of sound *c* (340 m/s) in air is given by $\sqrt{\gamma \cdot R \cdot T}$

Where

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

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

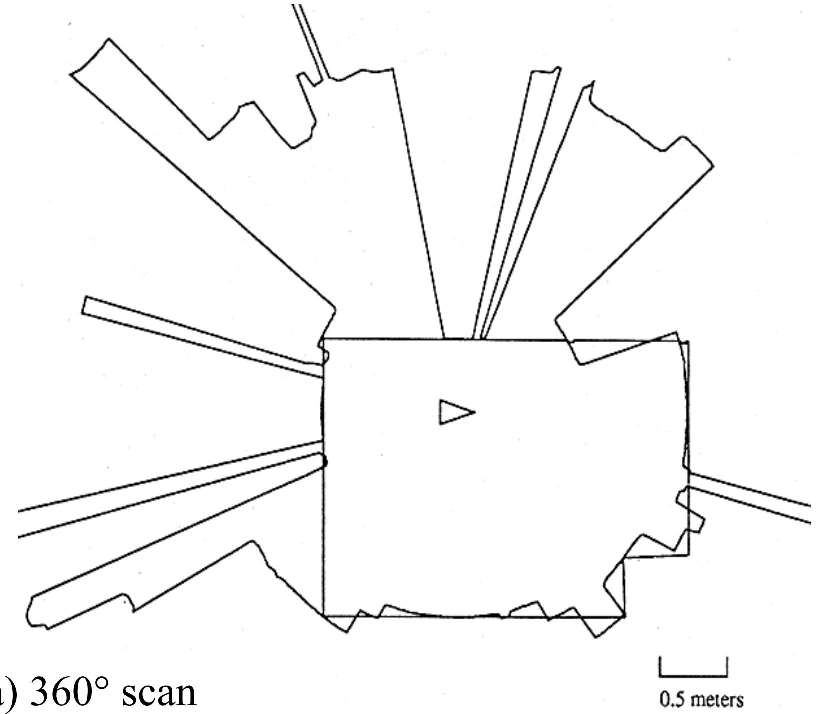
- typical frequency: 40kHz - 180 kHz
  - Lower frequencies correspond to longer range
- generation of sound wave: piezo transducer
  - transmitter and receiver separated or not separated
- Range between 12 cm up to 5 m
- Resolution of ~ 2 cm
- Accuracy 98% => relative error 2%
- sound beam propagates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



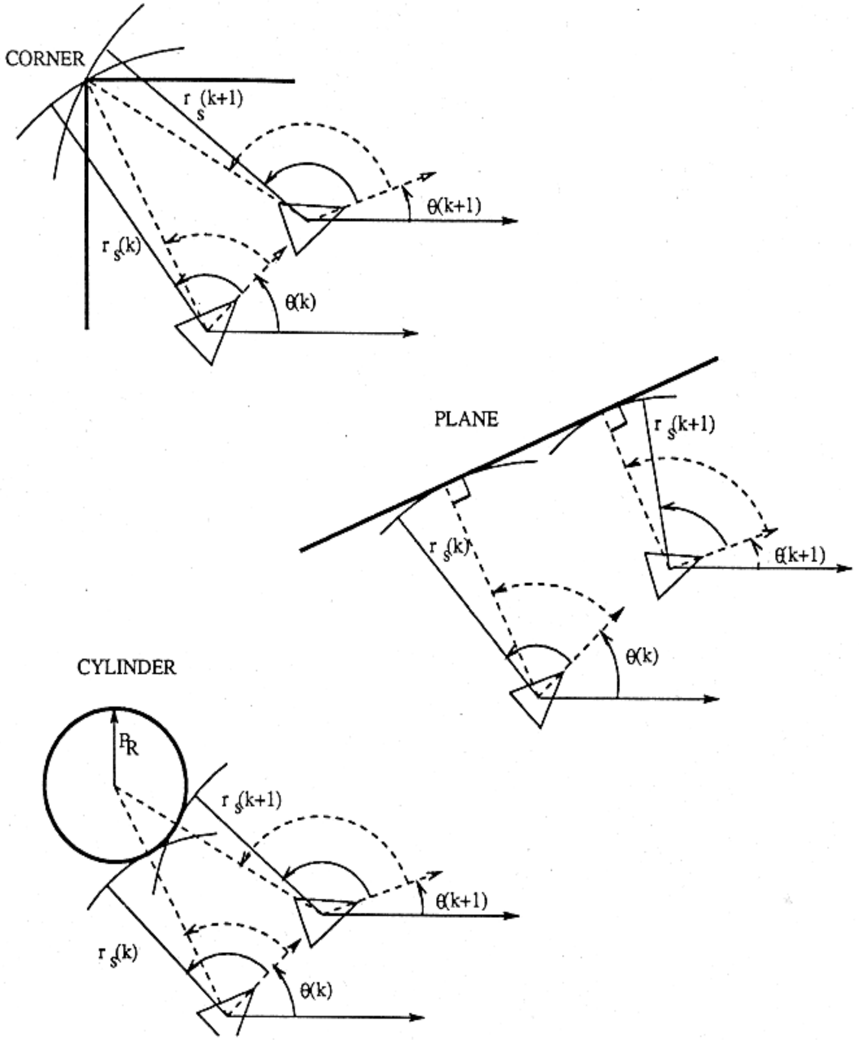
Typical intensity distribution of a ultrasonic sensor

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

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



a) 360° scan



b) results from different geometric primitives

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

- Bandwidth
  - measuring the distance to an object that is 3 m away will take such a sensor 20 ms, limiting its operating speed to 50 Hz. But if the robot has a ring of 20 ultrasonic sensors, each firing sequentially and measuring to minimize interference between the sensors, then the ring's cycle time becomes 0.4 seconds => frequency of each one sensor = 2.5 Hz.
  - This update rate can have a measurable impact on the maximum speed possible while still sensing and avoiding obstacles safely.

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

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

SICK

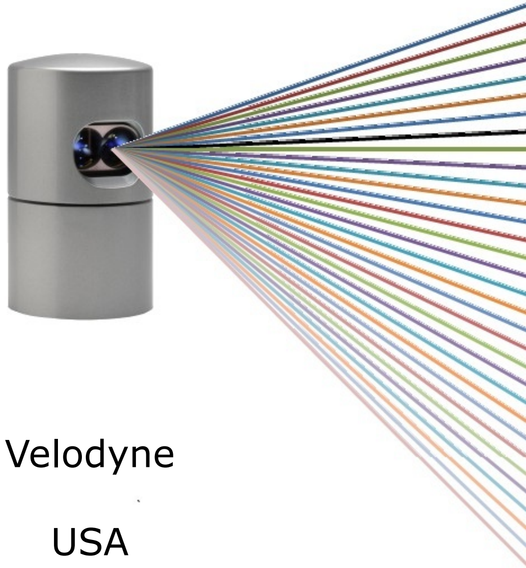
Germany

High Quality,
Safety Certification
Expensive

Hokuyo

Japan

Small sizes,
Popular for Robotics

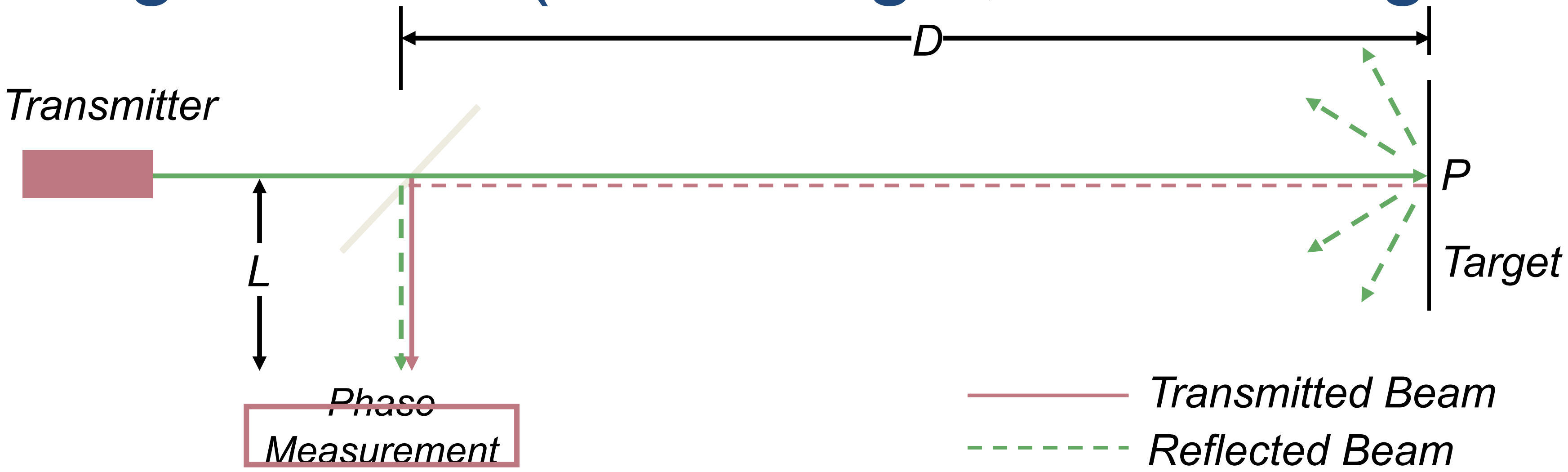


Velodyne

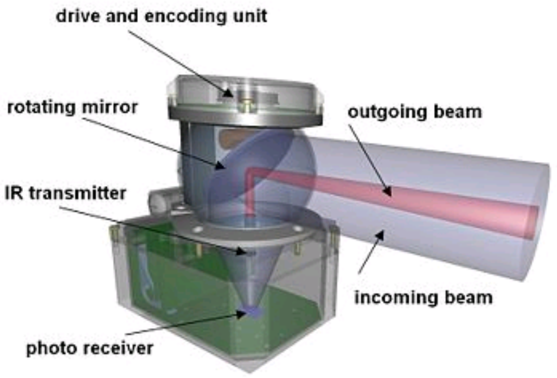
USA

3D Sensor (32 beams),
For autonomous cars,
Extremely Expensive

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



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



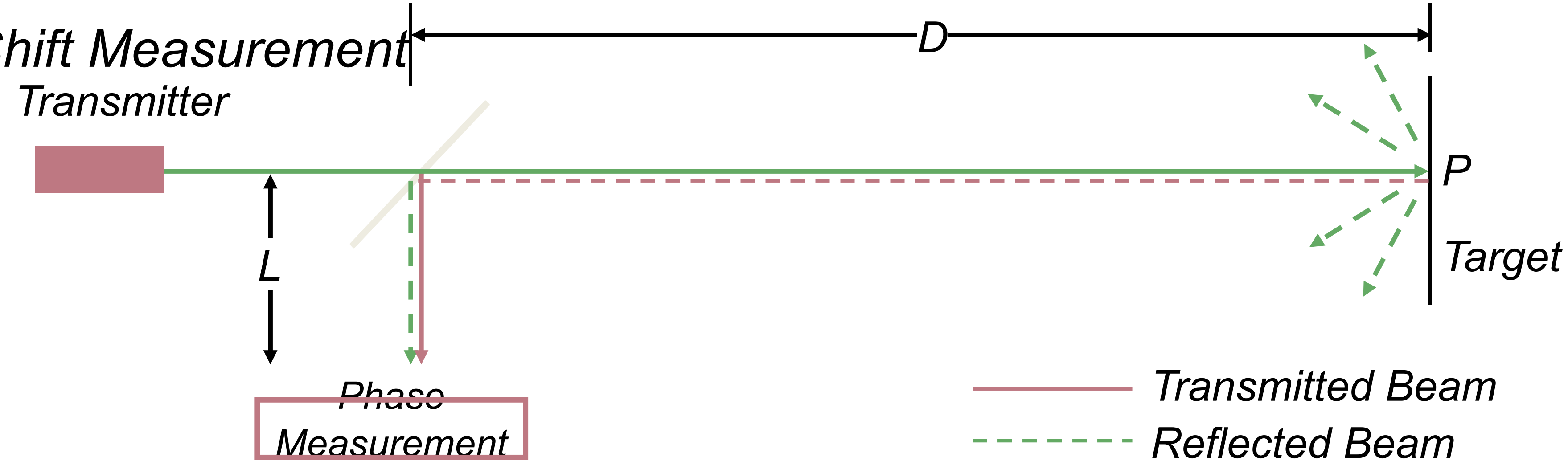
Laser Range Sensor (time of flight, electromagnetic) (2)

Time of flight measurement

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

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

- *Phase-Shift Measurement*



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

Where:

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

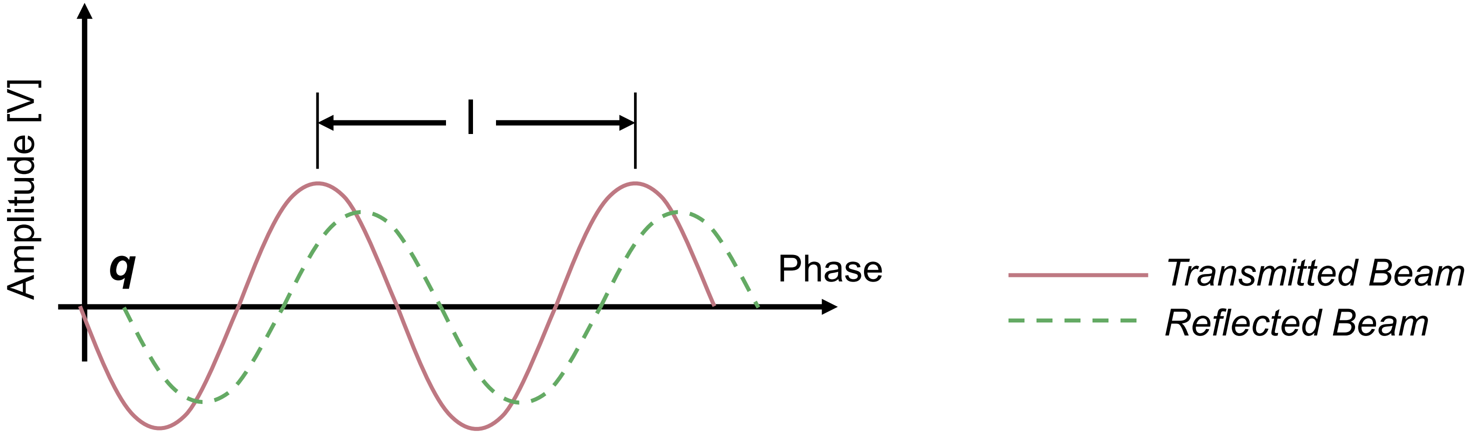
- for f = 5 MHz (as in the A.T&T. sensor), λ = 60 meters

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

- Distance D, between the beam splitter and the target

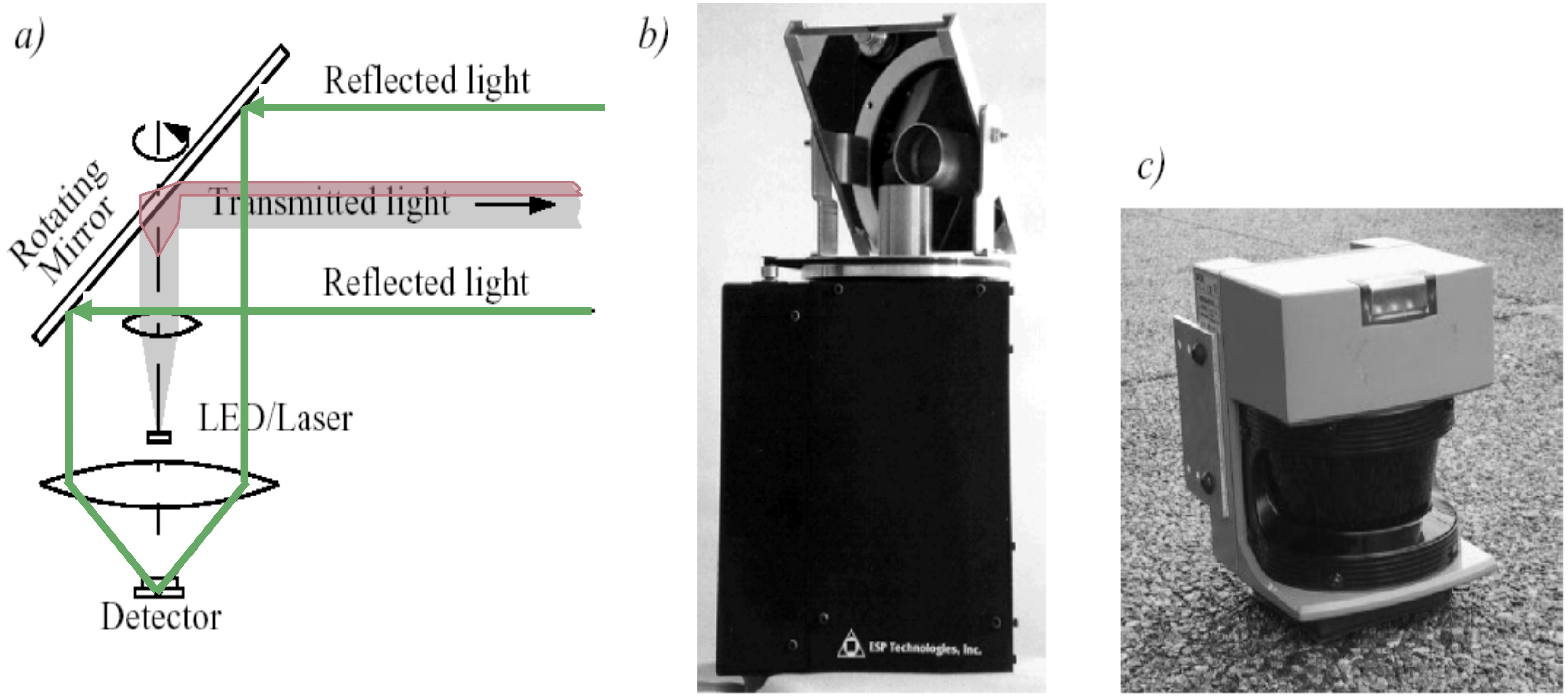
$$D = \frac{\lambda}{4\pi}\theta$$

- where
  - θ: phase difference between transmitted and reflected beam
- Theoretically ambiguous range estimates
  - since for example if λ = 60 meters, a target at a range of 5 meters = target at 35 meters



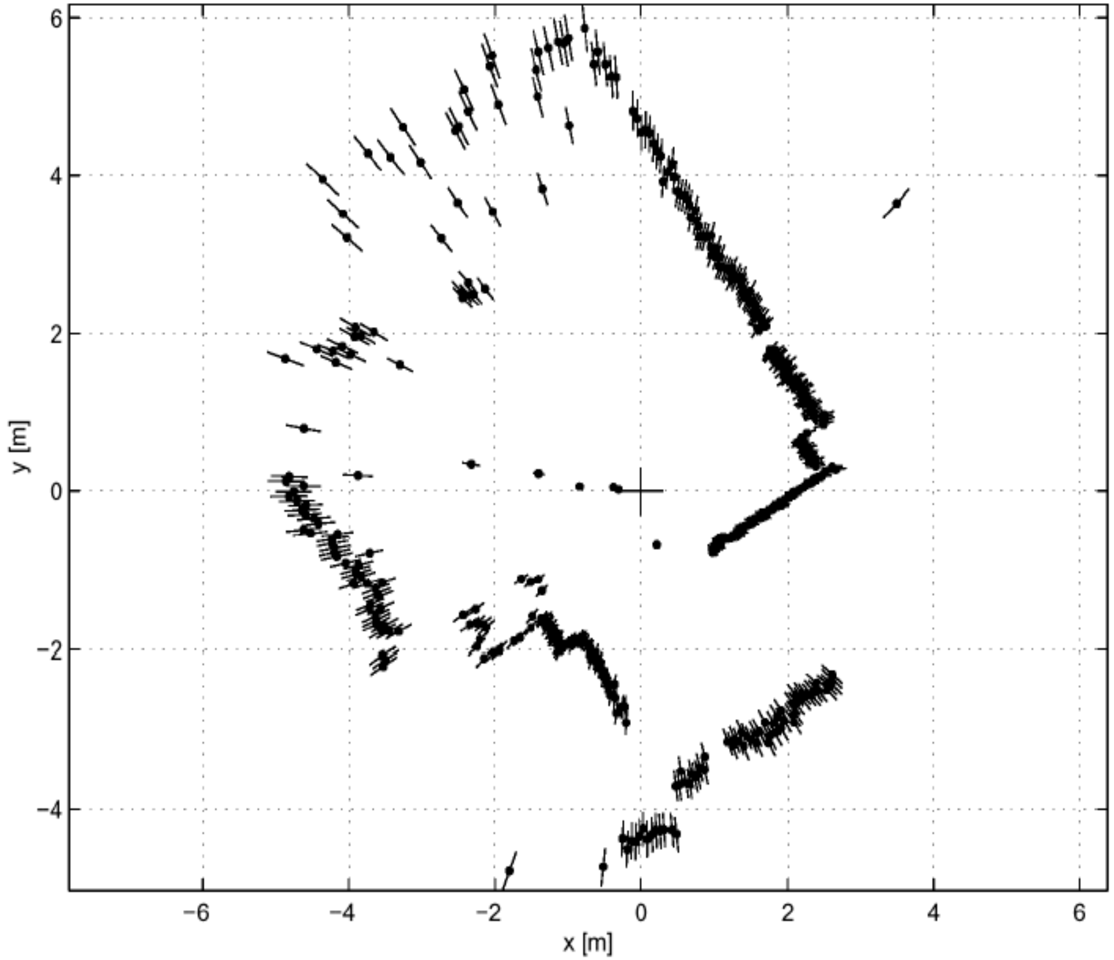
Laser Range Sensor (time of flight, electromagnetic) (5)

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



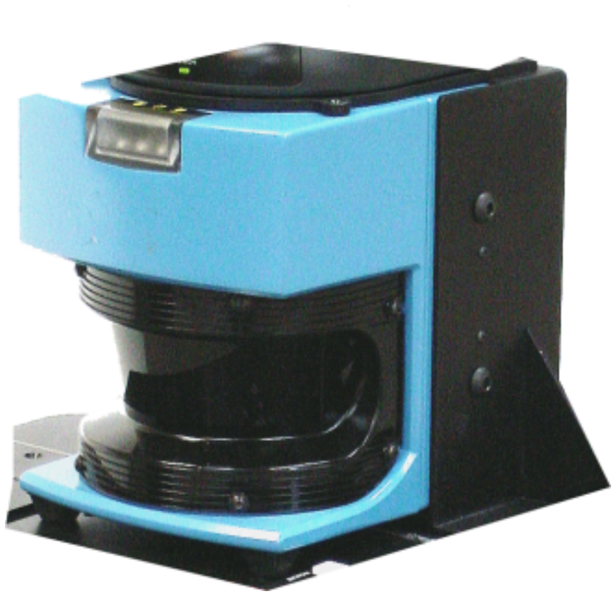
Laser Range Sensor (time of flight, electromagnetic)

- Typical range image of a 2D laser range sensor with a rotating mirror. The length of the lines through the measurement points indicate the uncertainties.



The SICK LMS 200 Laser Scanner

- Angular resolution 0.25 deg
- Depth resolution ranges between 10 and 15 mm and the typical accuracy is 35 mm, over a range from 5 cm up to 20 m or more (up to 80 m)
  - depending on the reflectivity of the object being ranged.
- This device performs seventy five 180-degrees per sec.
- Dimensions: W155 x D155 x H210mm,
- Weight: 1,2 kg
- Cost: about RMB 22,000



Hokuyo UTM-30LX

- Long Detection range: 30m
- 0.1 to 10m: ± 30mm, 1
- 0 to 30m: ± 50mm*1
- Field of View: 270°
- 40Hz
- Outdoor Environment
- Dimensions: 60 x 60 x 87 mm
- Weight: 370g

- Cost: about 35,000 RMB

URG-04LX-UG01

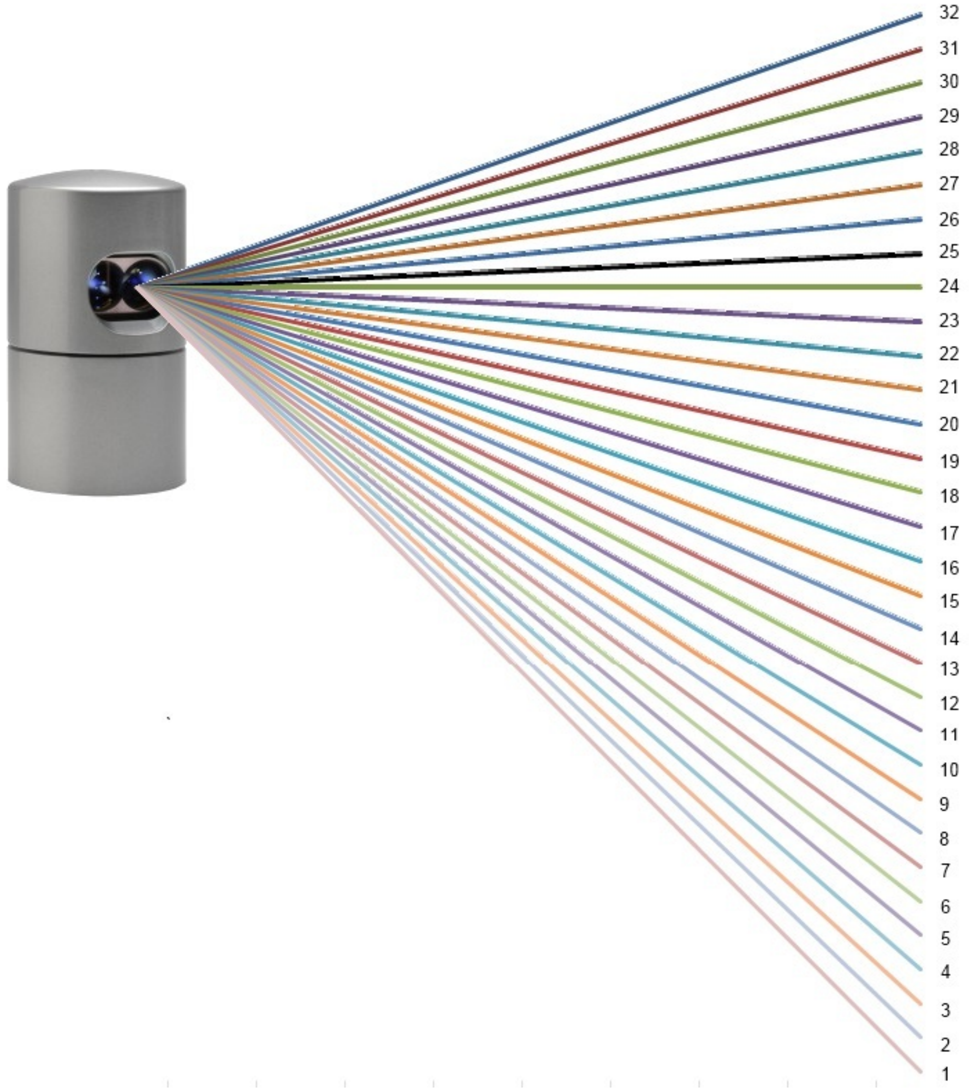
- Low-power consumption (2.5W)
- Wide-range (5600mm×240°).
- 60 to 1,000mm : ±30mm,
- 1,000 to 4,095mm : ±3% of measurement
- 10Hz
- Dimensions: 50 x 50 x 70 mm
- Weight: 160g

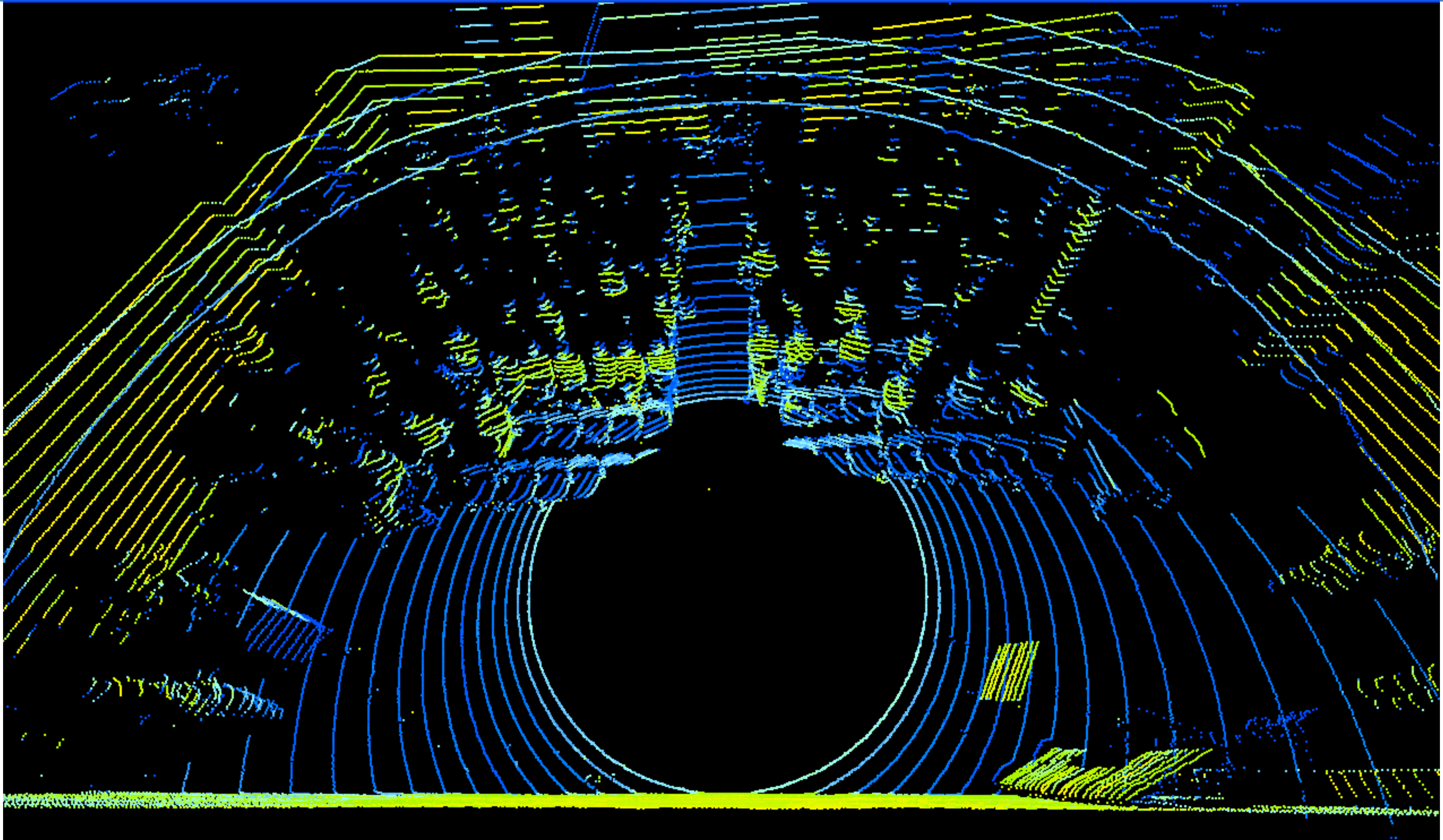
- Cost: about 6,500 RMB

Velodyne hdl-32e

- Range: up to 80 – 100 m
- +10.67 to -30.67 degrees field of view (vertical)
- 360° field of view (horizontal)
- 10 Hz frame rate
- Accuracy: <2 cm (one sigma at 25 m)
- Angular resolution (vertical) 1.33°
- 700,000 points per second
- internal MEMS accelerometers and gyros for six-axis motion correction

- Dimensions:
  - Diameter: 85mm,
  - Deight: 144 mm
- Weight: 1kg
- Cost: about 220,000 RMB





PROJECTS

Projects

- Three students per project
- Projects will be split into two distinct parts!
- The group will have to write a short project proposal (LaTeX, 2 pages, English)
- Other steps:
  - Coding/ building
  - Experiments
  - Evaluation
  - Documentation!
  - Write short project report
  - Create a webpage
  - Make videos
- After the 2nd part of the project: Presentation/ Demo

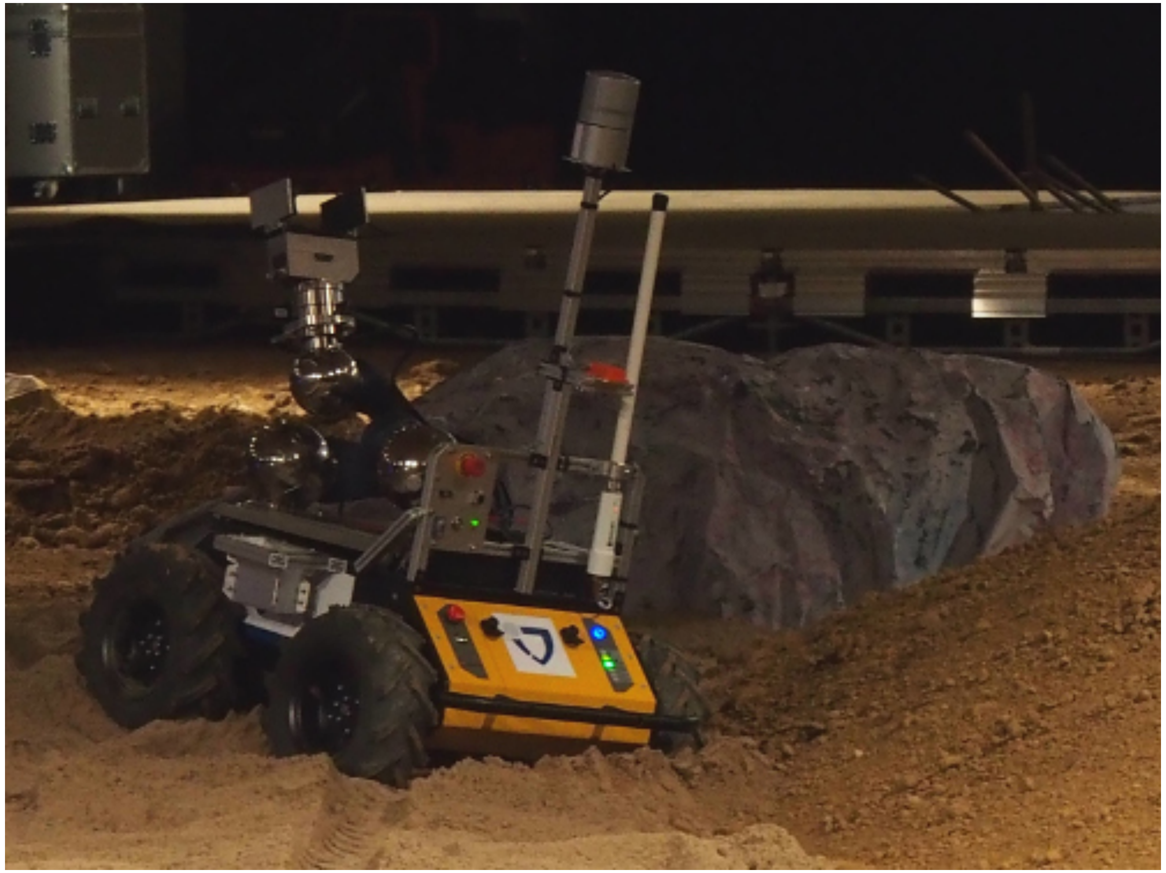
Project Ideas:

- 3D mapping robot
- "RoboCup Project Smartphone Robot"
- Schunk arm programming
- Omni-directional robot
- Car mapping (put sensors on my car and collect data)
- Full Speed Jackal
- Work with the FARO data (e.g. registration, extract planes, "terrain classification", path planning for ground robots)
- Some aerial project (I’m not a big fan)
- …

HW2 QUESTIONS?

Laser Range Finder: Applications

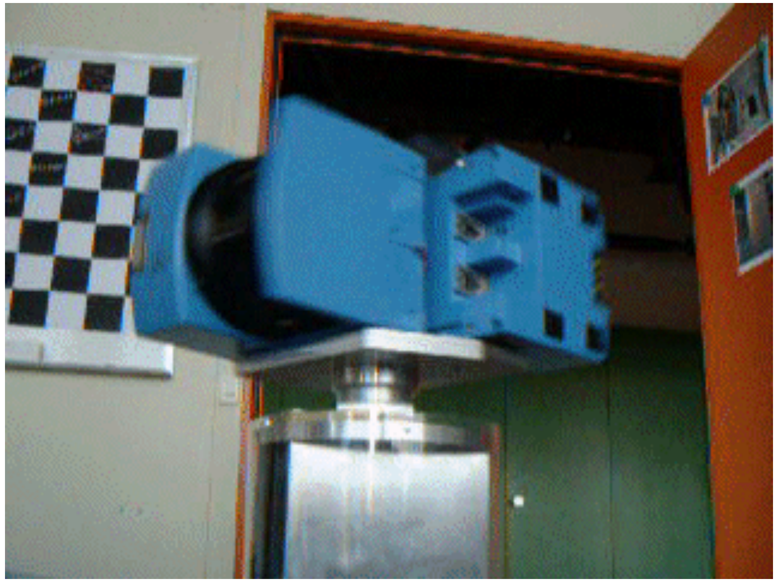
Stanley: Stanford
(winner of the 2005 Darpa Grand Challenge)



Jack the Gripper
Jacobs University – DLR SpaceBot Cup

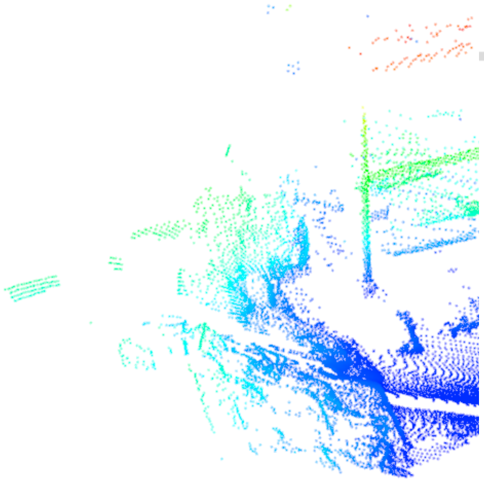
3D Laser Range Finder (LRF) (1)

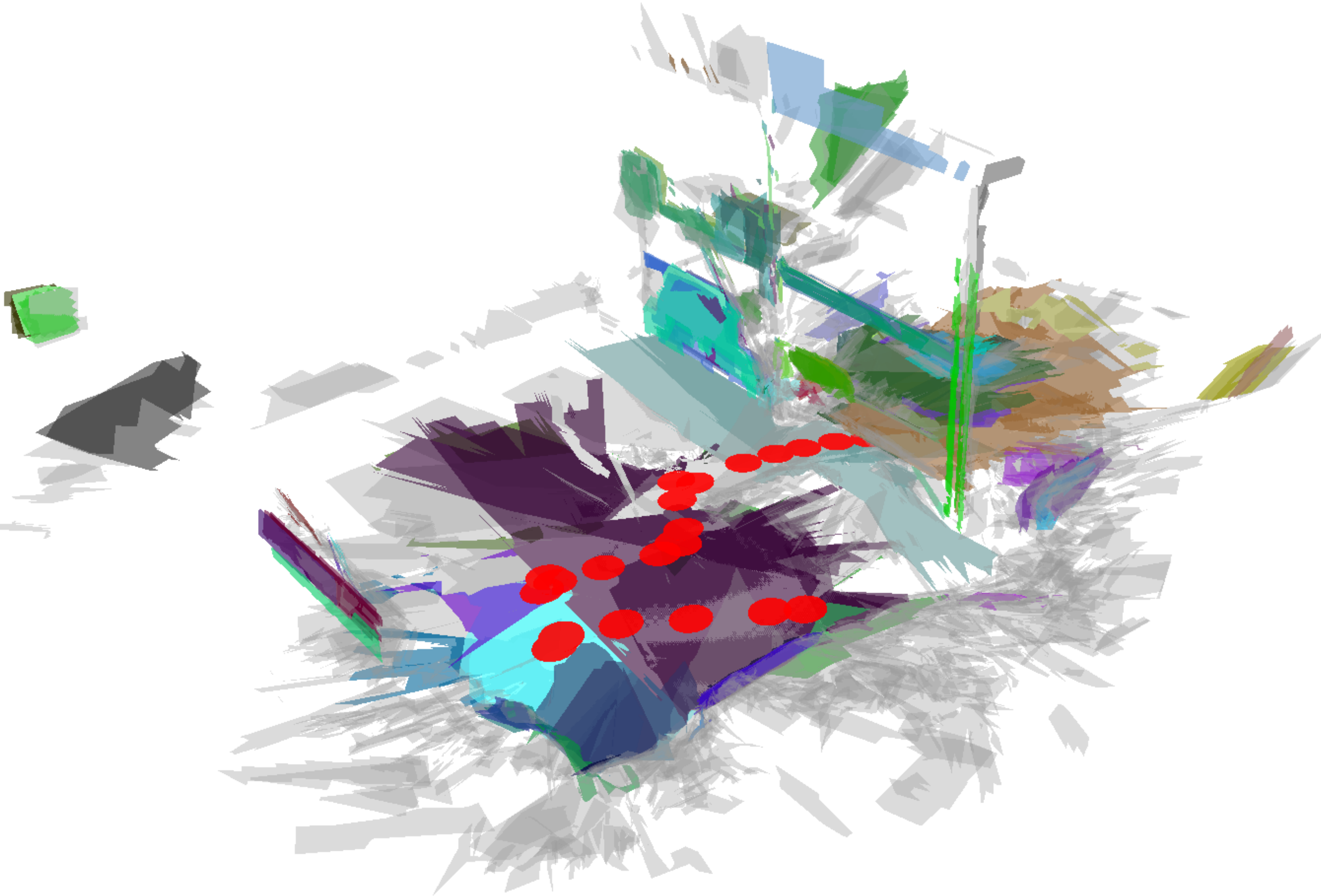
- A 3D laser range finder is a laser scanner that acquires scan data in more than a single plane.
- Custom-made 3D scanners are typically built by nodding or rotating a 2D scanner in a stepwise or continuous manner around an axis parallel to the scanning plane.
- By lowering the rotational speed of the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

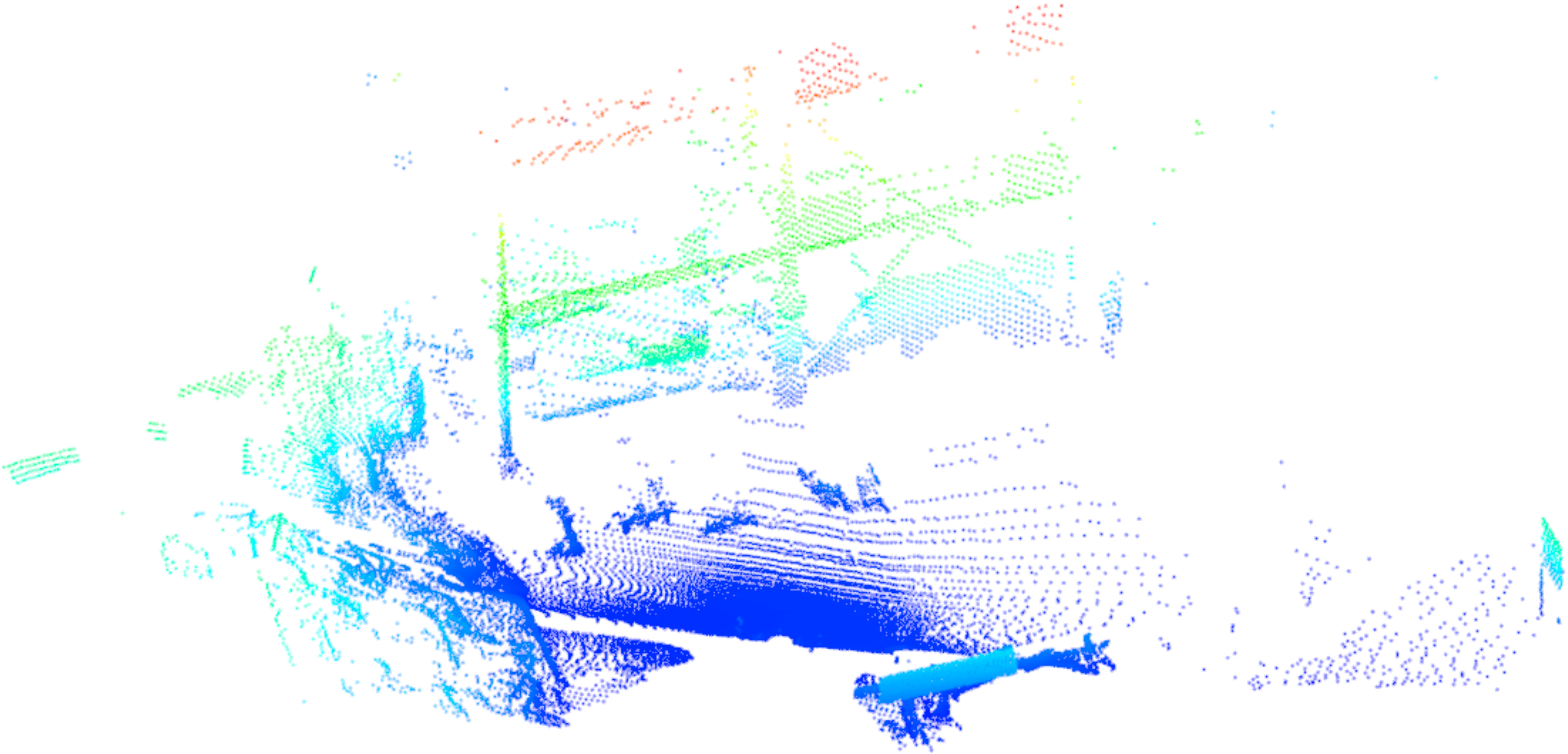


3D Point

- Points below
- Extracted pla



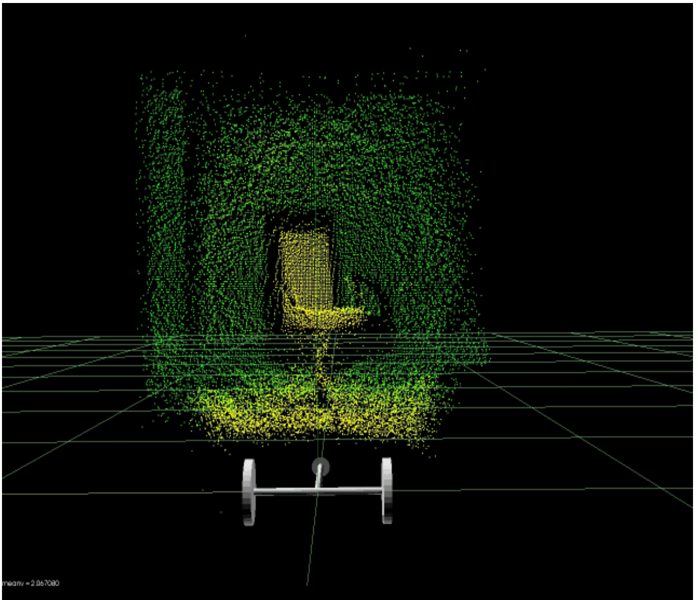




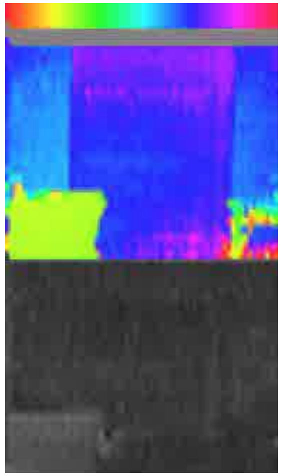
3D Range Sensor (4): Time Of Flight (TOF) camera

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

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



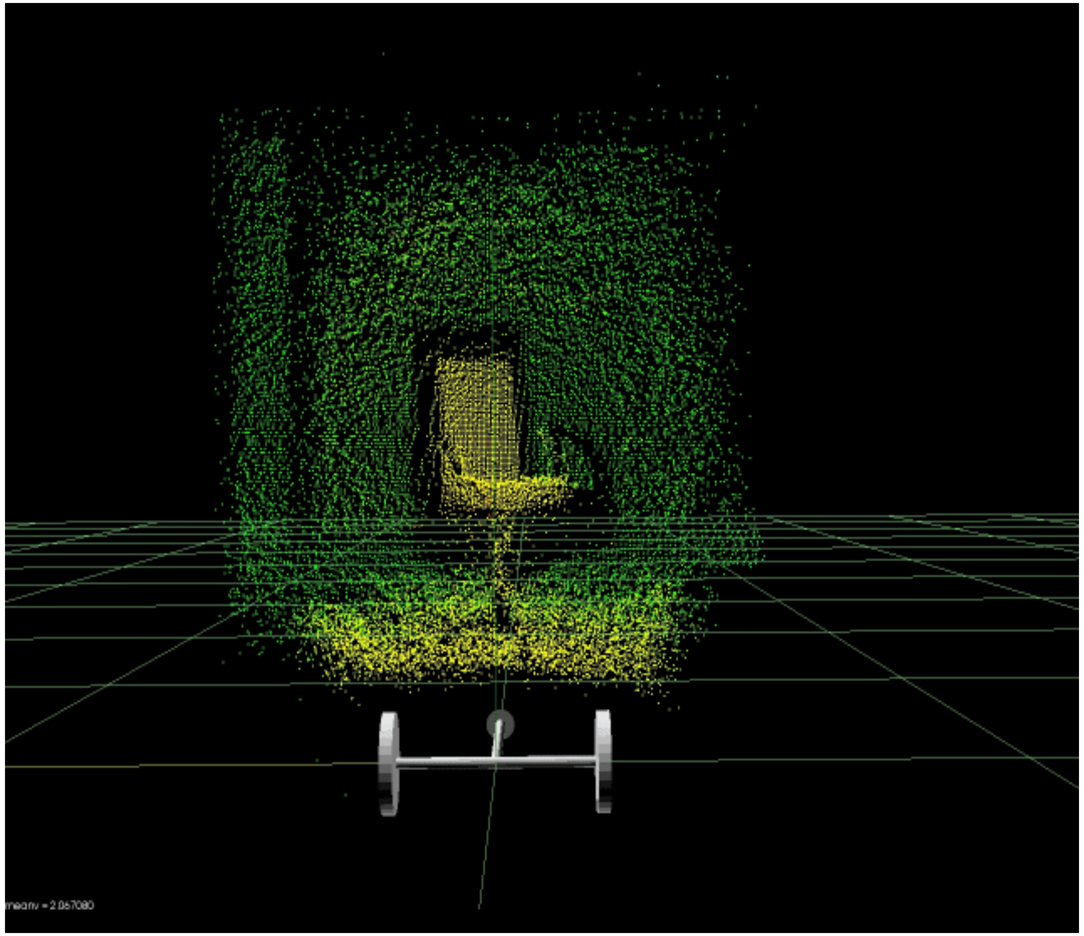
Swiss Ranger 3000
(produced by MESA)



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

- 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)
  - ZCAM achieves 320x240 pixels

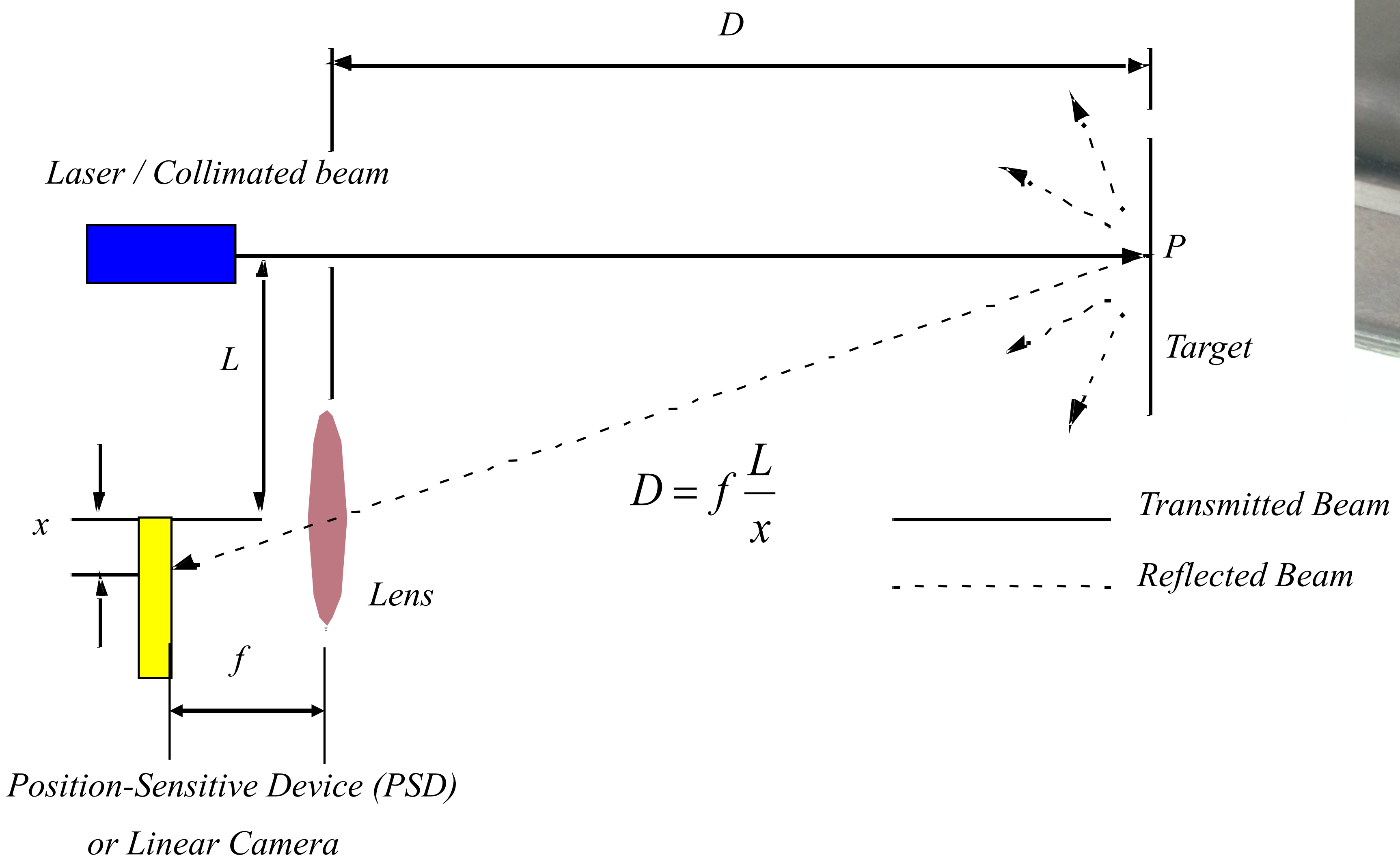
  - Sensitive to ambient infrared light!



Triangulation Ranging

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

Laser Triangulation (1D)

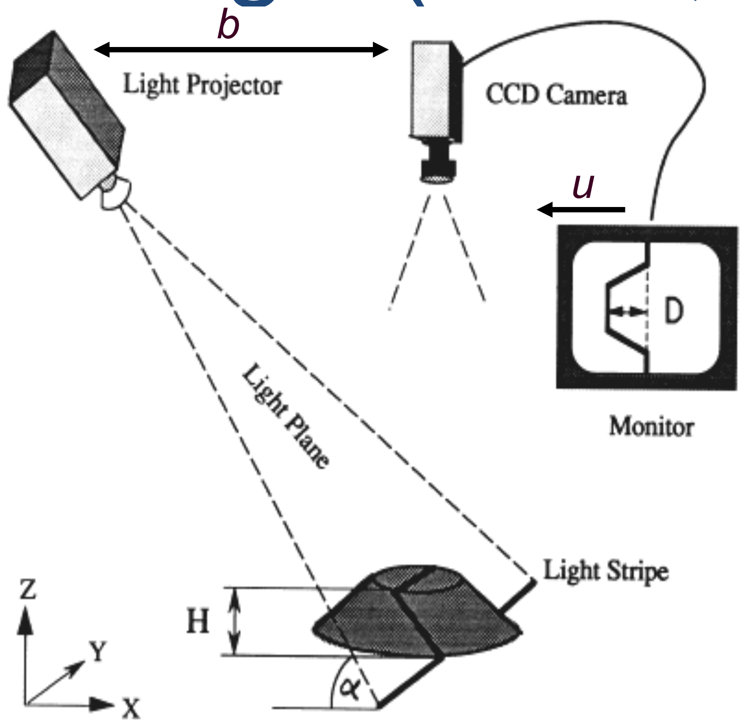


$$D = f\frac{L}{x}$$

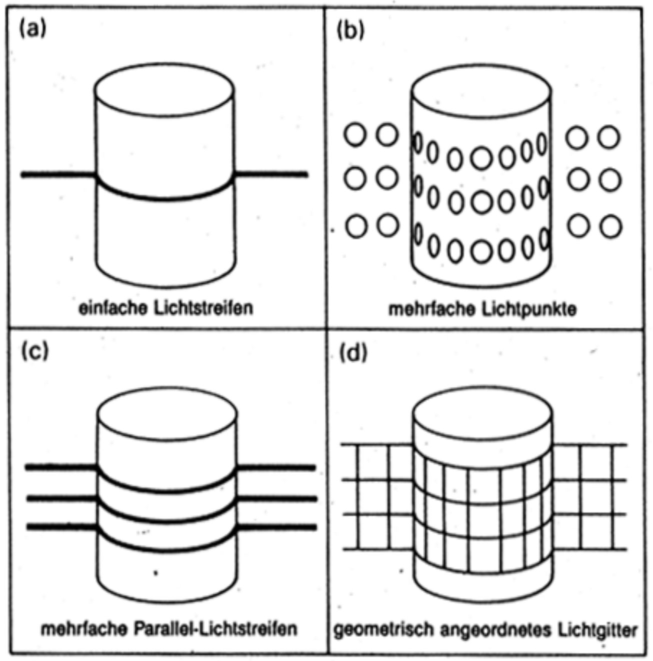
Cliff sensor on Turtle-bot

Structured Light (vision, 2 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.

Structured Light (vision, 2 or 3D)

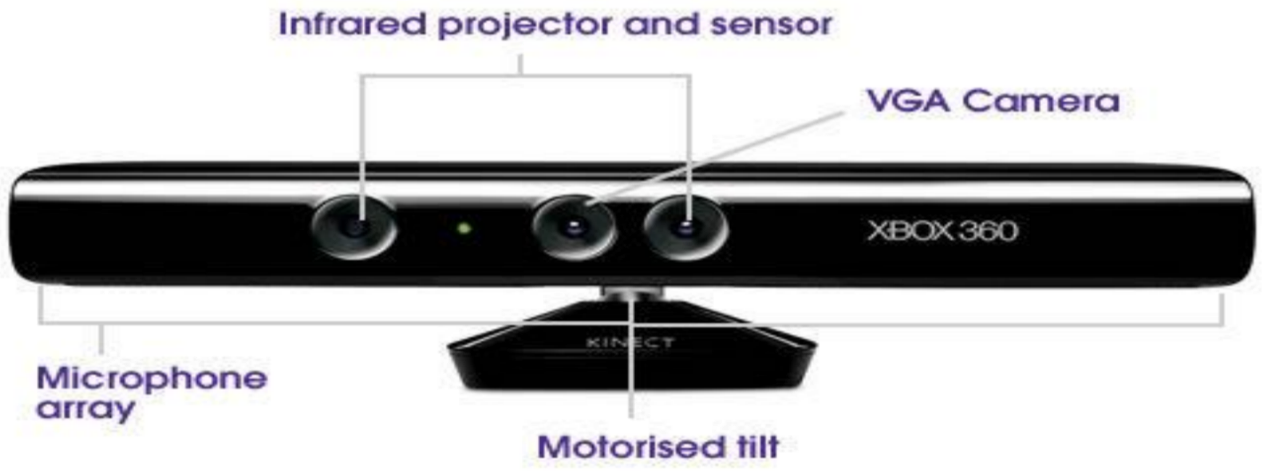
- Baseline length *b*:
  - the smaller b is the more compact the sensor can be.
  - the larger b is the better the range resolution is.

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

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

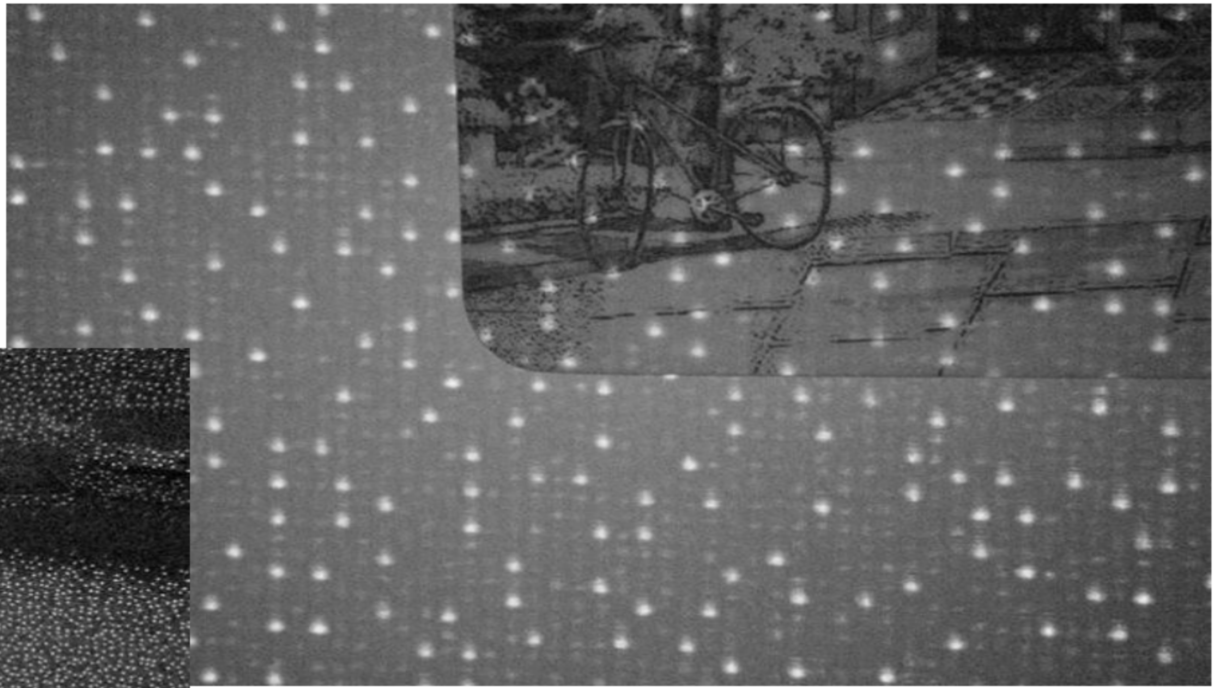
PrimeSense Cameras

- Devices: Microsoft Kinect and Asus Xtion
- Developed by Israeli company PrimeSense in 2010



- Components:
  - IR camera (640 x 480 pixel)
  - IR Laser projector
  - RGB camera (640 x 480 or 1280 x 1024)
  - Field of View (FoV):
    - 57.5 degrees horizontally,
    - 43.5 degrees vertically

IR Pattern



Depth Map

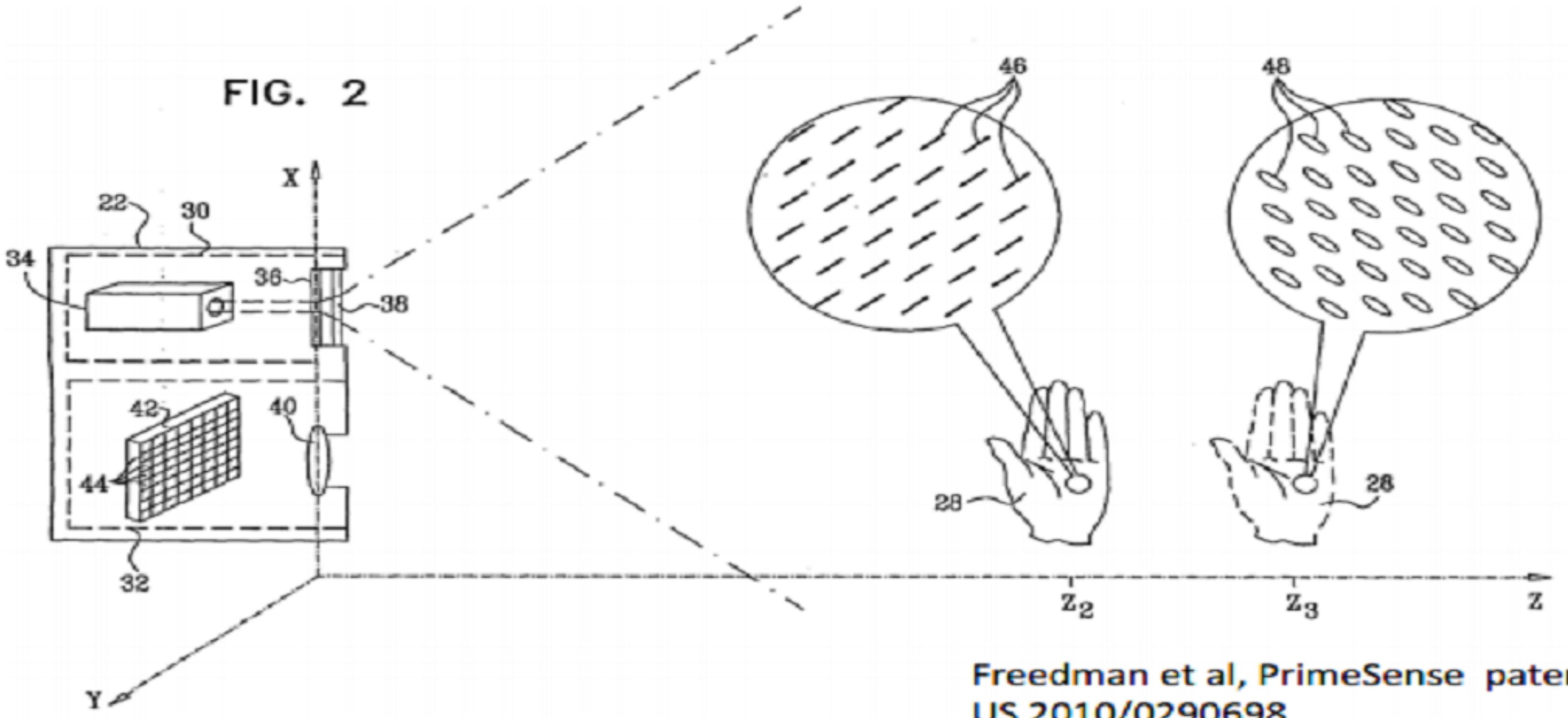
Microsoft Kinect: Depth Computation (1)

- **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

Kinect 2 – time of flight approach

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