



上海科技大学
ShanghaiTech University

CS283: Robotics Spring 2026: Sensors II

Sören Schwertfeger

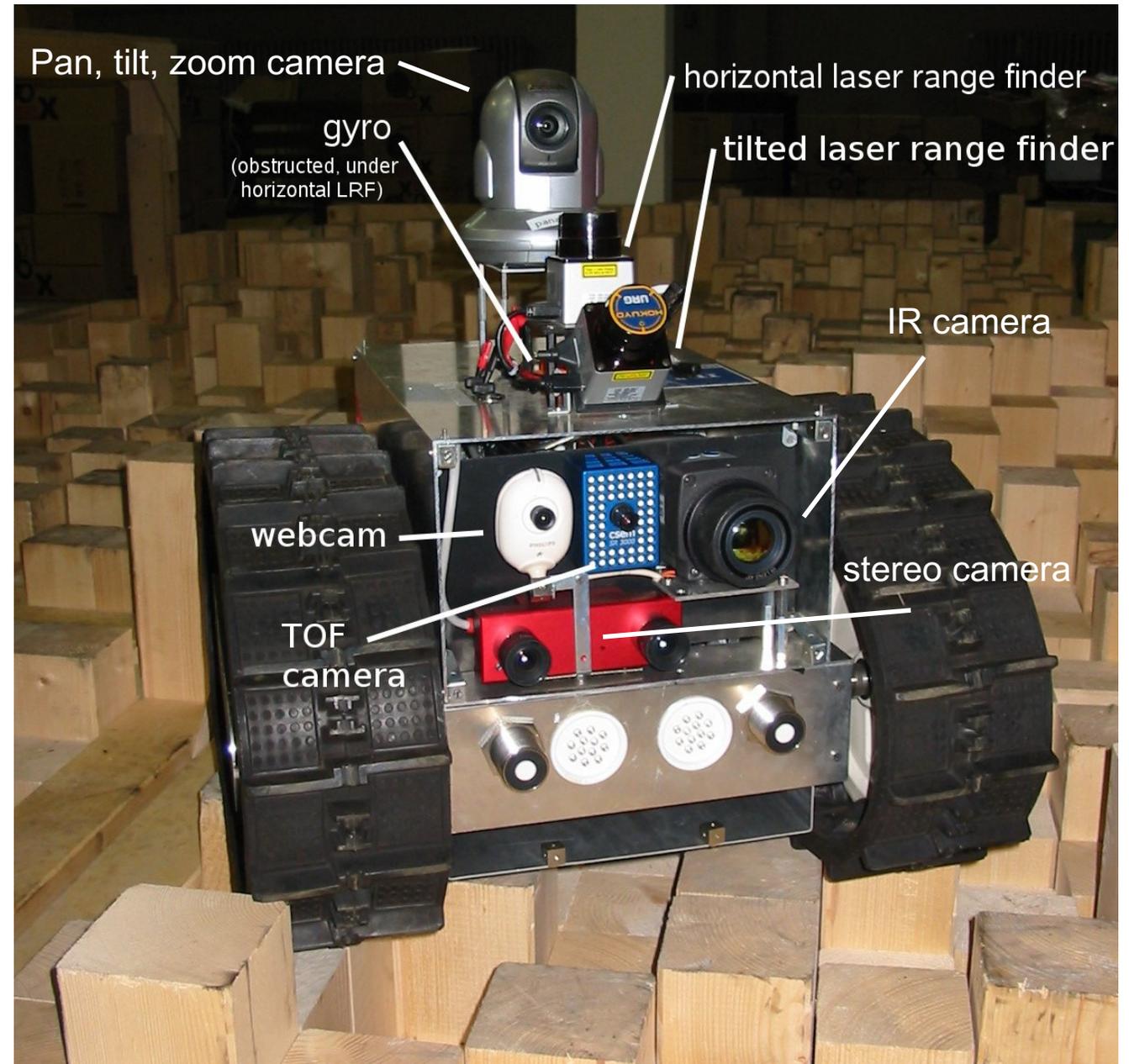
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SENSORS II

Introduction to Autonomous Mobile Robots page 102 ff

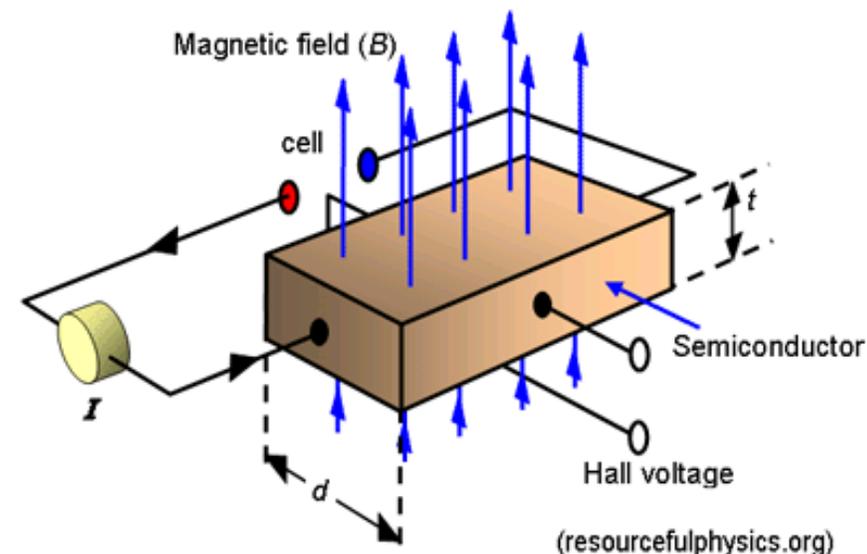
Sensors: outline

- Optical encoders
- Heading sensors
 - Compass
 - Gyroscopes
 - Accelerometer
 - IMU
- GPS
- Range sensors
 - Sonar
 - Laser
 - Structured light
- Vision sensors:
 - separate lectures later



Compass

- Magnetic field on earth
 - absolute measure for orientation
- Large variety of solutions to measure the earth magnetic field
 - mechanical magnetic compass
 - direct measure of the magnetic field (Hall-effect, magneto-resistive sensors)
- Major drawback
 - weakness of the earth field ($30 \mu\text{Tesla}$)
 - easily disturbed by magnetic objects or other sources
 - bandwidth limitations (0.5 Hz) and susceptible to vibrations
 - not feasible for indoor environments for absolute orientation
 - useful indoor (only locally)

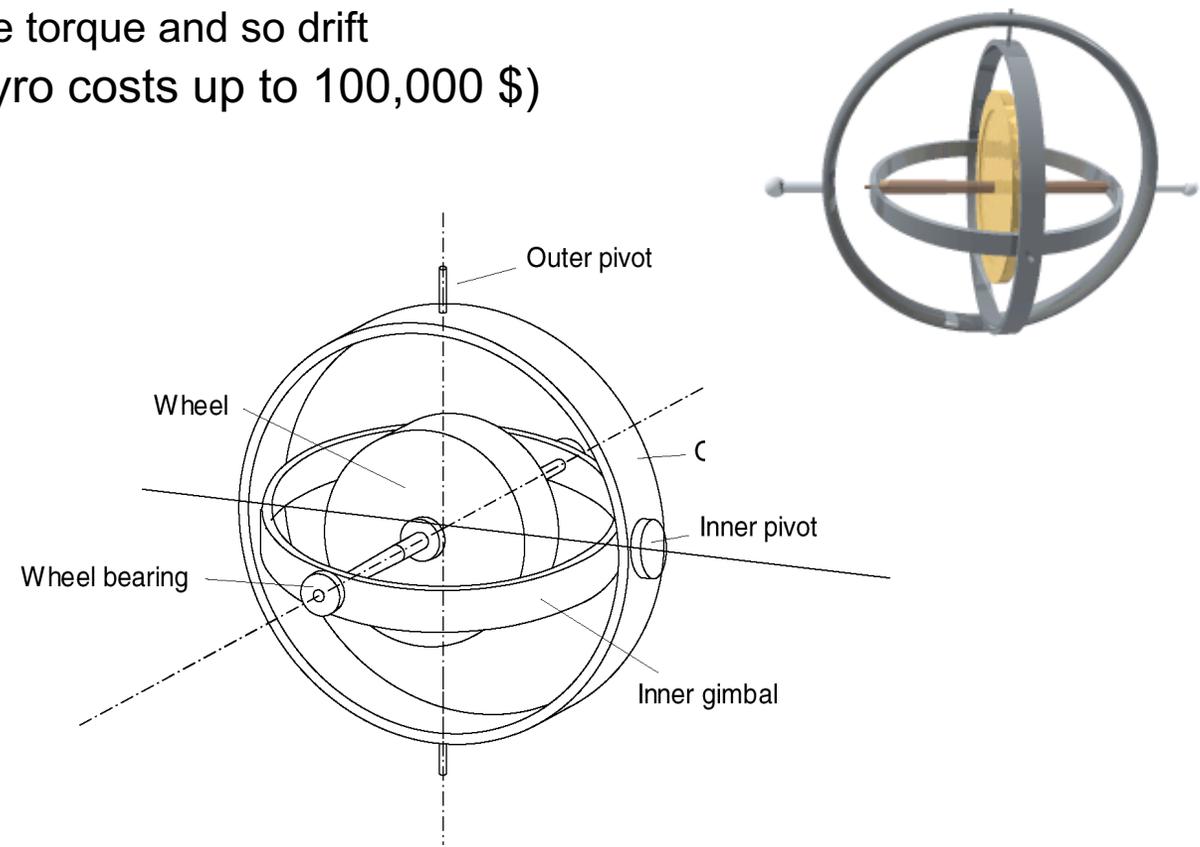


Gyroscope

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

Mechanical Gyroscopes

- Concept: inertial properties of a fast spinning rotor
- Angular momentum associated with a spinning wheel keeps the axis of the gyroscope inertially stable.
- No torque can be transmitted from the outer pivot to the wheel axis
 - spinning axis will therefore be space-stable
 - however friction in the axes bearings will introduce torque and so drift
- Quality: 0.1° in 6 hours (a high quality mech. gyro costs up to 100,000 \$)
- If the spinning axis is aligned with the north-south meridian, the earth's rotation has no effect on the gyro's horizontal axis
- If it points east-west, the horizontal axis reads the earth rotation



Optical Gyroscopes

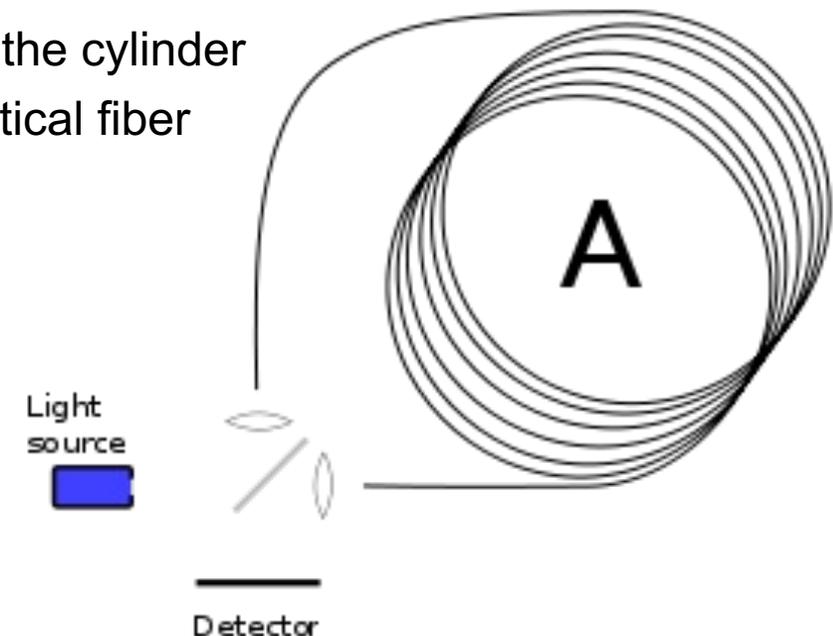
- First commercial use: early 1980 in airplanes
- Optical gyroscopes
 - angular speed (heading) sensors using two monochromatic light (or laser) beams from the same source.
- One is traveling in a fiber clockwise, the other counterclockwise around a cylinder
- Laser beam traveling in direction opposite to the rotation
 - 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 build using micro-fabrication technology.



Single axis optical gyro

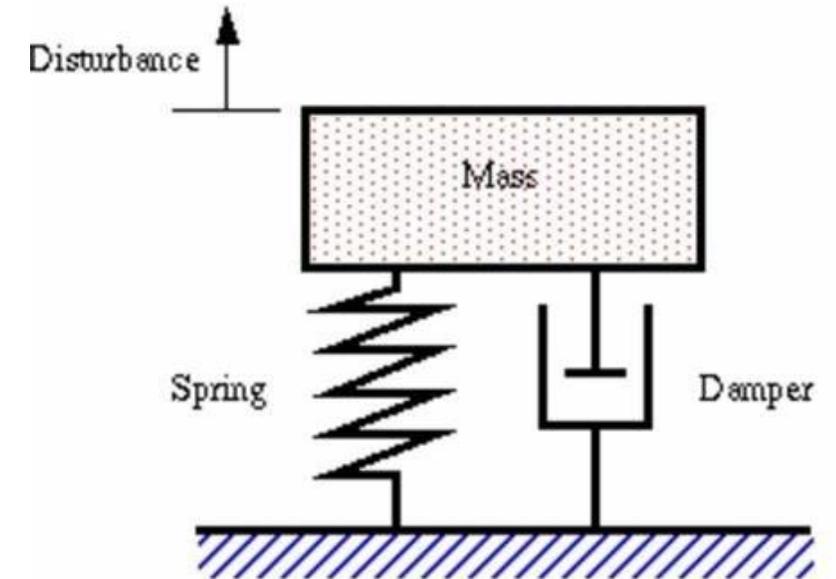


3-axis optical gyro

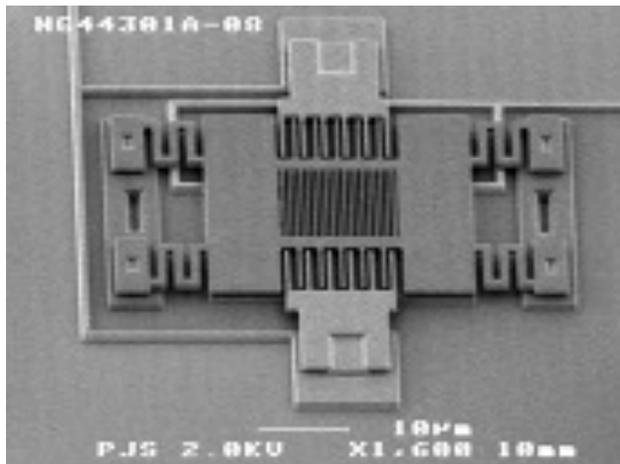
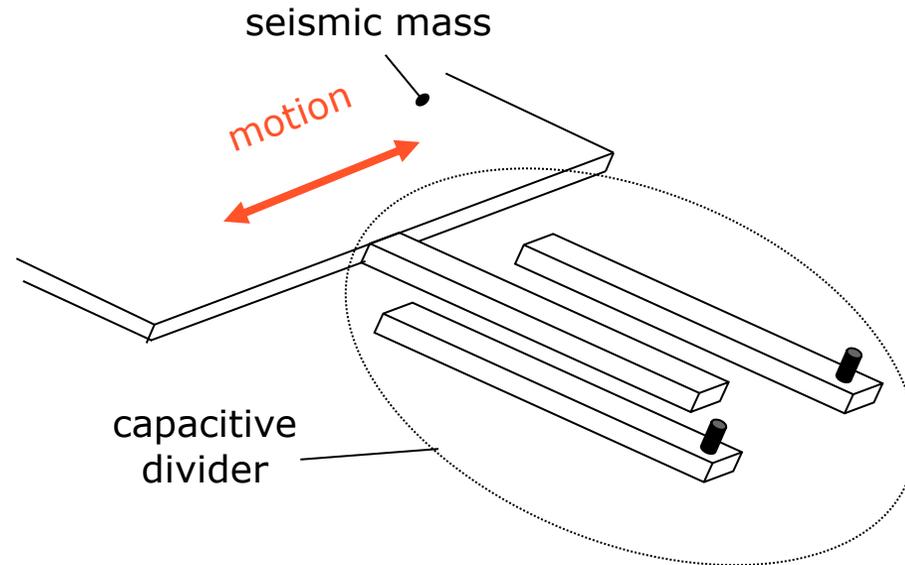


Mechanical Accelerometer

- Accelerometers measure all external forces acting upon them, including gravity
- Accelerometer acts like a spring–mass–damper system
- 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.
- Bandwidth up to 50 KHz
- An accelerometer measures acceleration only along a single axis
- => mount 3 accelerometers orthogonally => three-axis accelerometer



Factsheet: MEMS Accelerometer



<<http://www.mems.sandia.gov/>>

1. Operational Principle

The primary transducer is a vibrating mass that relates acceleration to displacement. The secondary transducer (a capacitive divider) converts the displacement of the seismic mass into an electric signal.

2. Main Characteristics

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

3. Applications

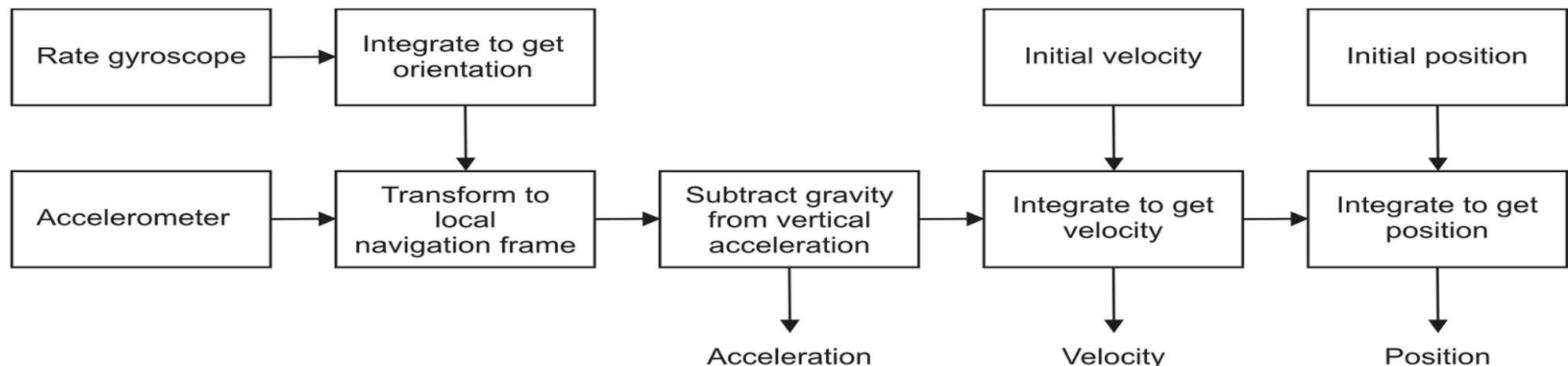
- Dynamic acceleration
- Static acceleration (inclinometer)
- Airbag sensors (± 35 g)
- Control of video games (Wii)

Inertial Measurement Unit (IMU)

- Device combining different measurement systems:
 - Gyroscopes, Accelerometers, Compass
- Estimate relative position (x, y, z), orientation (roll, pitch, yaw), velocity, and acceleration
- Gravity vector is subtracted to estimate motion
 - Initial velocity has to be known



Xsens MTI

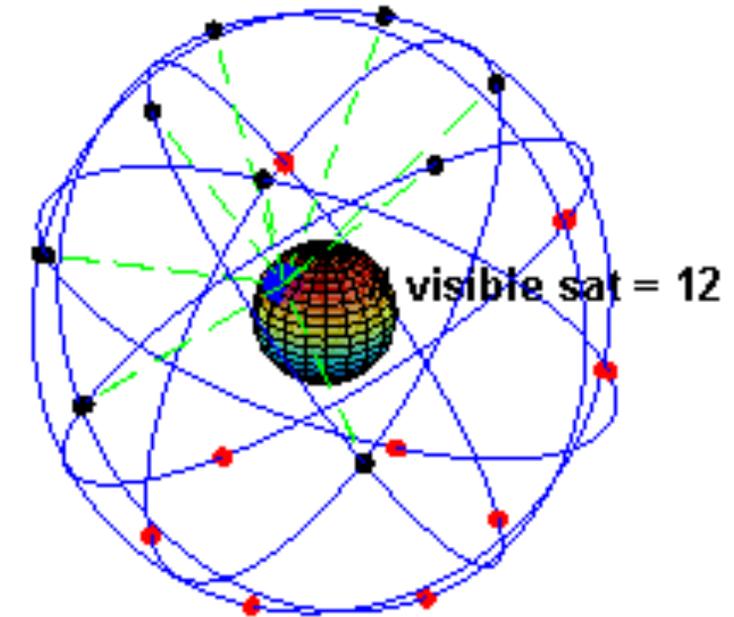


IMU Error and Drift

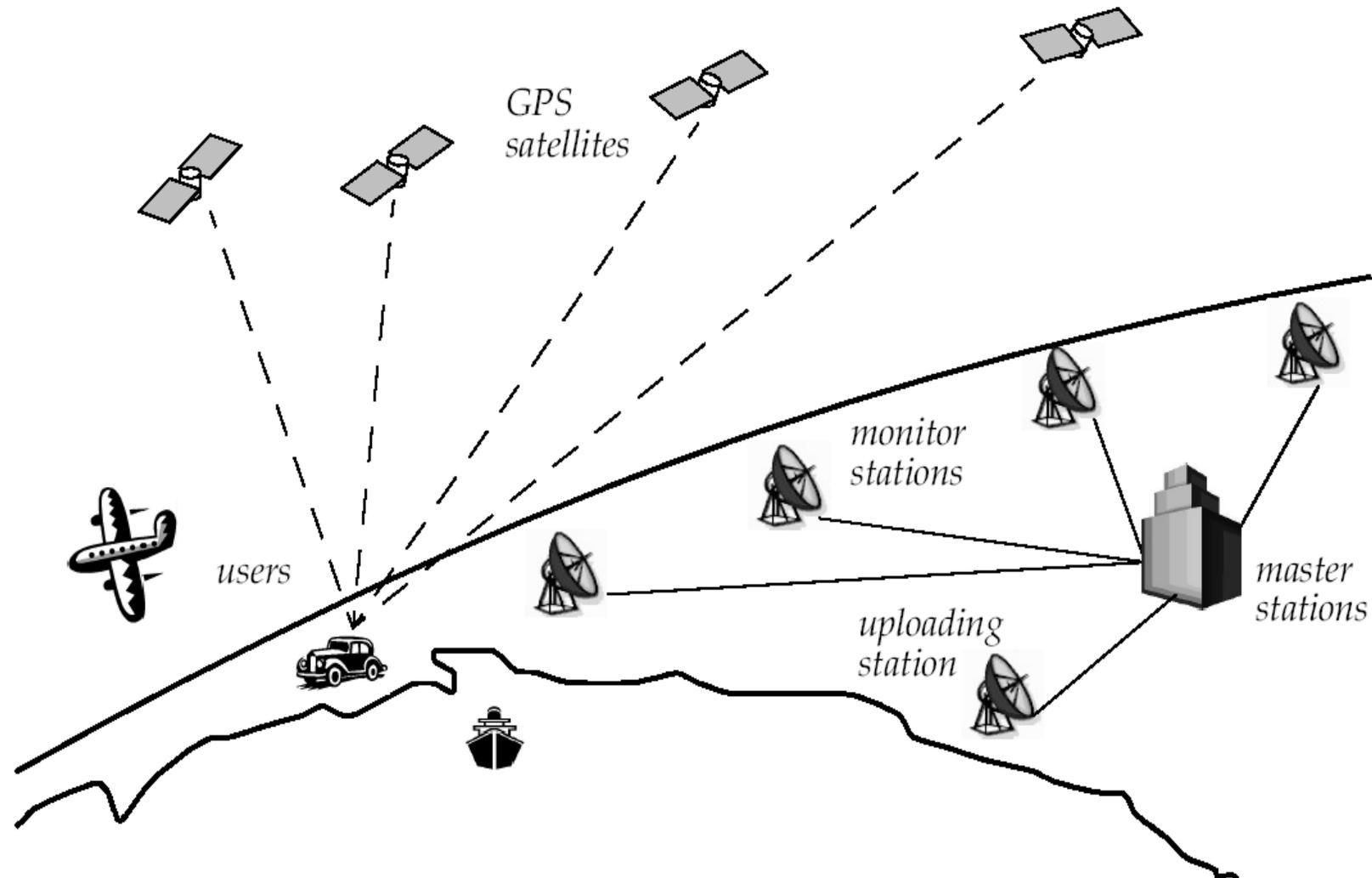
- Extremely sensitive to measurement errors in gyroscopes and accelerometers:
 - drift in the gyroscope unavoidably =>
 - error in orientation relative to gravity =>
 - incorrect cancellation of the gravity vector.
- Accelerometer data is integrated twice to obtain the position => gravity vector error leads to quadratic error in position.
- All IMUs drift after some time
 - Use of external reference for correction:
 - compass, GPS, cameras, localization

Global Positioning System (GPS)

- 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

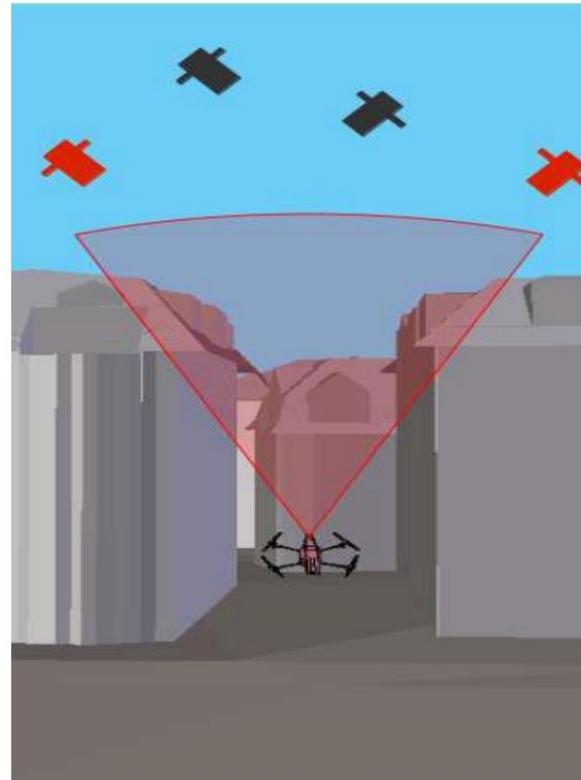
Satellite clock errors uncorrected by monitor stations may result in one meter errors:

- 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 unmodeled residual.
- Number of satellites under line of sight

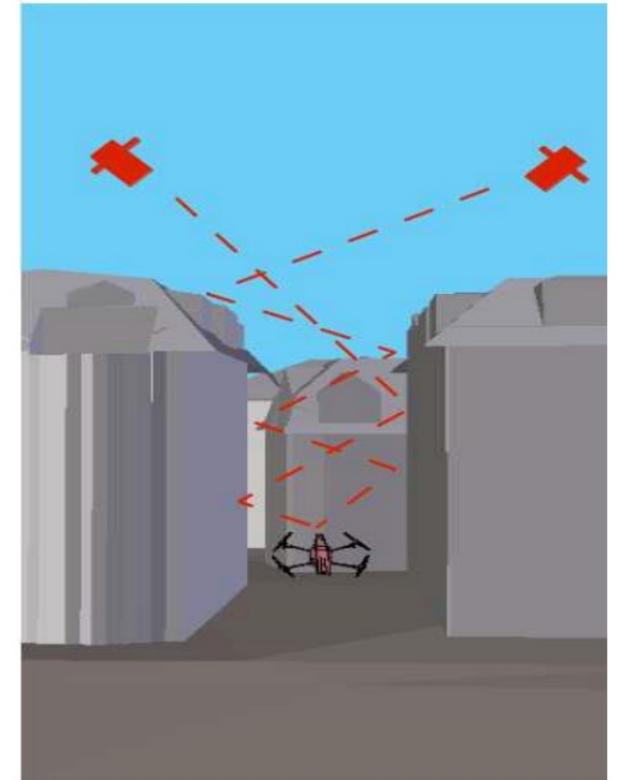
GPS Multipath

- 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

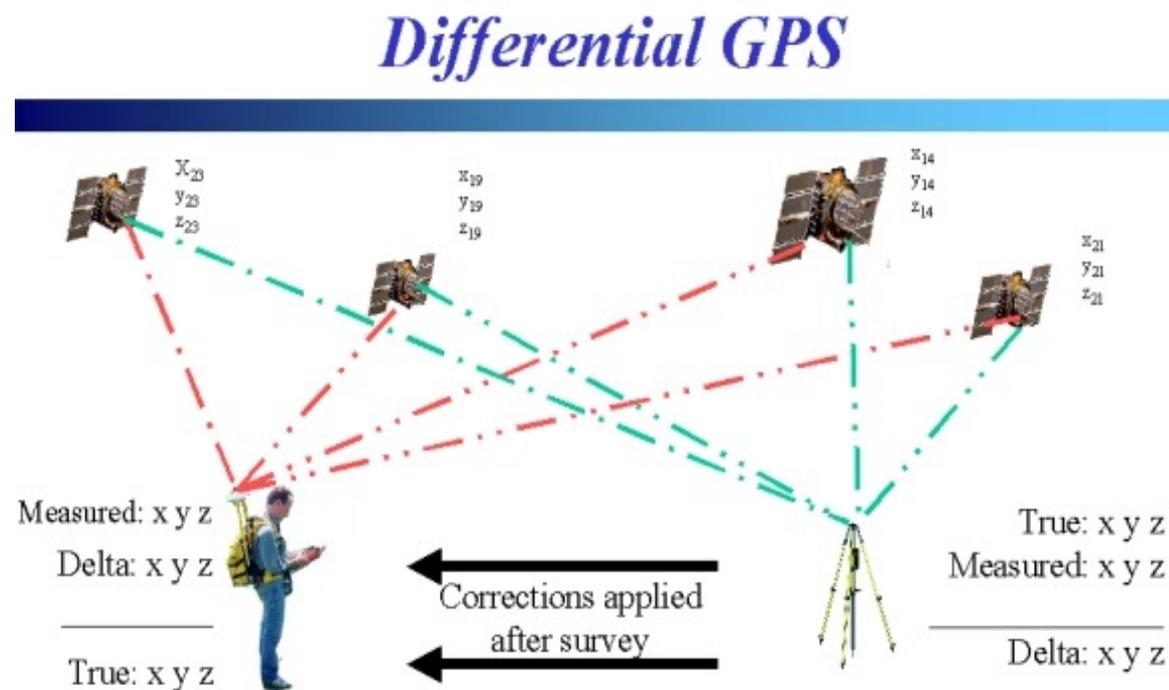


Multipath problem



Differential Global Positioning System (dGPS)

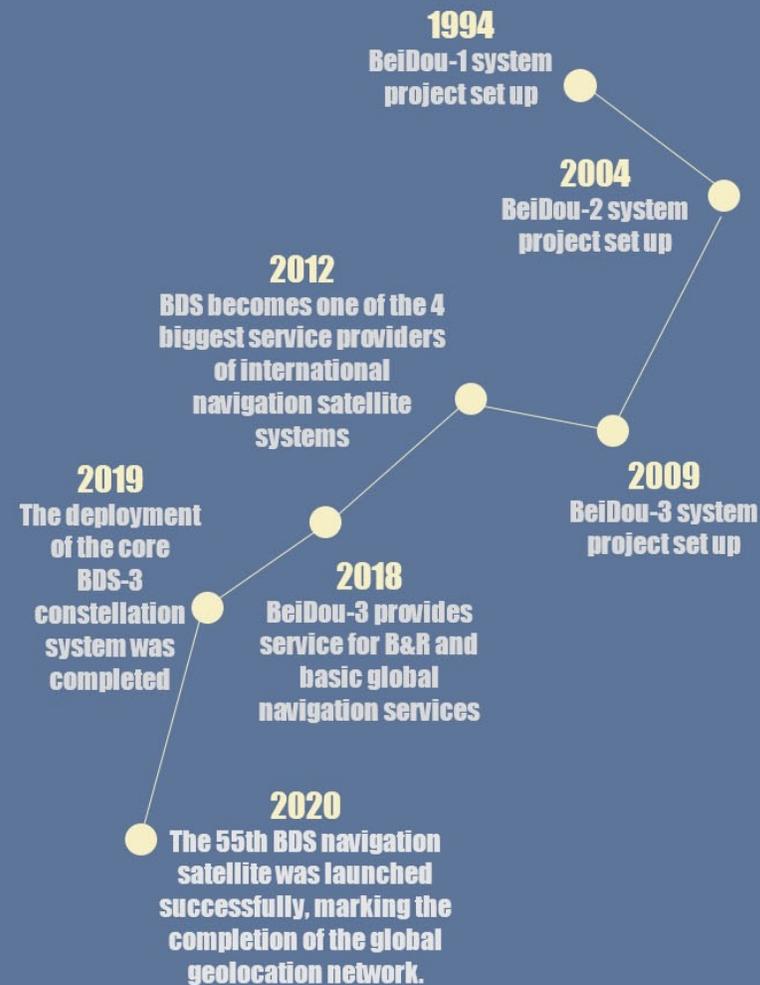
- Base station GPS receiver: set up on a precisely known location
- Base station receiver calculates its position based on satellite signals
- Compares this location to the known location
- Difference is applied to the GPS data recorded by the mobile GPS receivers
- Position accuracies in sub-meter to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



Other Global Positioning Systems

- **GLONASS**
 - Russian GPS – developed since 1976
 - Full global coverage as of 2011 (24 satellites)
- **Galileo**
 - European GPS – initiated 2003
 - 22 operational satellites in orbit
- **IRNSS (Indian Regional Navigation Satellite System)**
 - Initiated 2010
 - 8 satellites for Indian Coverage in orbit
 - Full operation
- **BeiDou Navigation Satellite System 北斗卫星导航系统**
 - Chinese GPS – developed since 1994
 - BeiDou Satellite Navigation System (BDS)
 - 2011 full China coverage – 2019 global coverage
 - 45 satellites system

Key Moments of BDS' Development



A more ubiquitous, mixable, intelligent national navigation system based on BDS is planned to be finished by **2035**.

GPS coordinate errors

- HD maps: save locations in coordinates (e.g. location of traffic light)
- Many sources of errors – e.g.:
 - Wrong survey (input data is wrong)
 - Human error and instrument error
 - Continental drift! (Australia: 7 cm per year!)
- China: GCJ-02: WGS 84 plus random offsets (about 300-500m) (for national safety) makes autonomous driving development difficult :/
地形图非线性保密处理算法
 - Called “Mars coordinate system”
 - Need special license to calculate correct position
 - afaik: 15-20 companies in China have this license
- Baidu: BD-09 further offsets (so competitors don't copy)

Australia Is Drifting So Fast GPS Can't Keep Up

A significant correction must be made by the end of the year for navigation technology to keep working smoothly.

BY BRIAN CLARK HOWARD

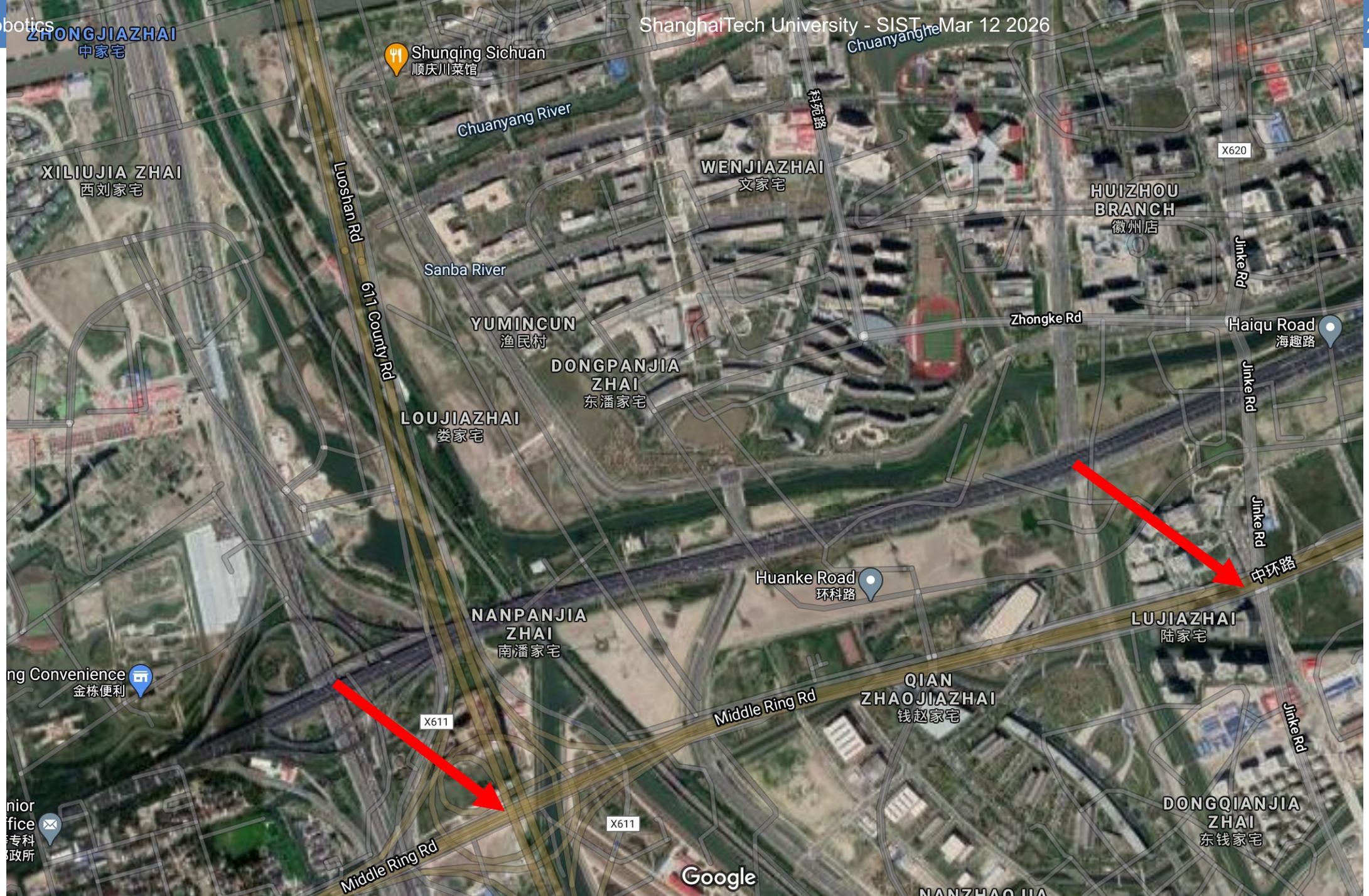


PUBLISHED SEPTEMBER 24, 2016 • 2 MIN READ

Australia is not quite where you think it is. The continent has shifted by 4.9 feet since the last adjustment was made to GPS coordinates in 1994, reports the *New York Times*.

All of the Earth's continents float on tectonic plates, which glide slowly over a plastic-like layer of the upper mantle. And the plate that Australia sits on has been moving relatively fast, about 2.7 inches a year (northward and with a slight clockwise rotation).

<https://www.nationalgeographic.com/science/article/australia-moves-gps-coordinates-adjusted-continental-drift>



RANGE SENSING

Range Sensing

- Color/ gray scale cameras: do NOT measure the distance to the object
- Range sensing: get the distance to the object
- Basic principles:
 - Time of flight
 - Sound/ Ultrasound (in air, underwater)
 - Light (Based on Phase or based on time)
 - Single rotating laser beam (LRF; e.g. Sick)
 - Multiple rotating laser beams (3D LRF; e.g. Velodyne)
 - Solid state laser (e.g. Intel RealSense L515)
 - LED light & imager (ToF camera, e.g. Kinect 2)
 - Radio Waves (Radar)
 - Projected Pattern
 - Single laser (Triangulation)
 - 2D pattern (e.g. Kinect 1)
 - Stereo Vision
 - Passive
 - Active with pattern (e.g. Intel RealSense D435)

RANGE SENSING: TIME OF FLIGHT

Range Sensors (time of flight) (1)

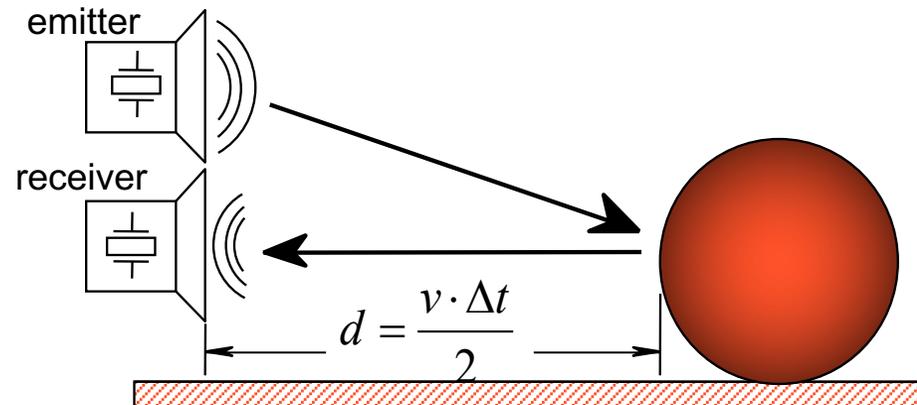
- Large range distance measurement -> called range sensors
 - Range information:
 - key element for localization and environment modeling
 - Ultrasonic sensors as well as laser range sensors make use of propagation speed of sound or electromagnetic waves respectively. The traveled distance of a sound or electromagnetic wave is given by
-
- Where
 - d = distance traveled (usually round-trip)
 - c = speed of wave propagation
 - t = time of flight.

$$d = c \cdot t$$

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 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 flight 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

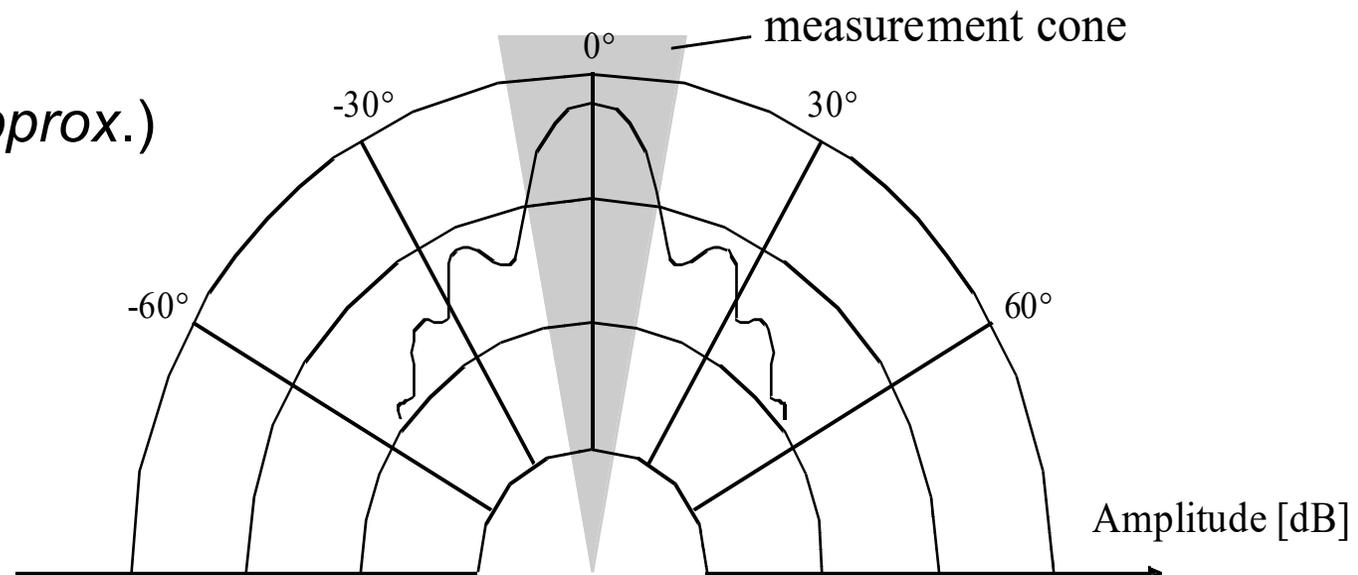
γ : adiabatic index (isentropic expansion factor) - ratio of specific heats of a gas

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% \Rightarrow 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

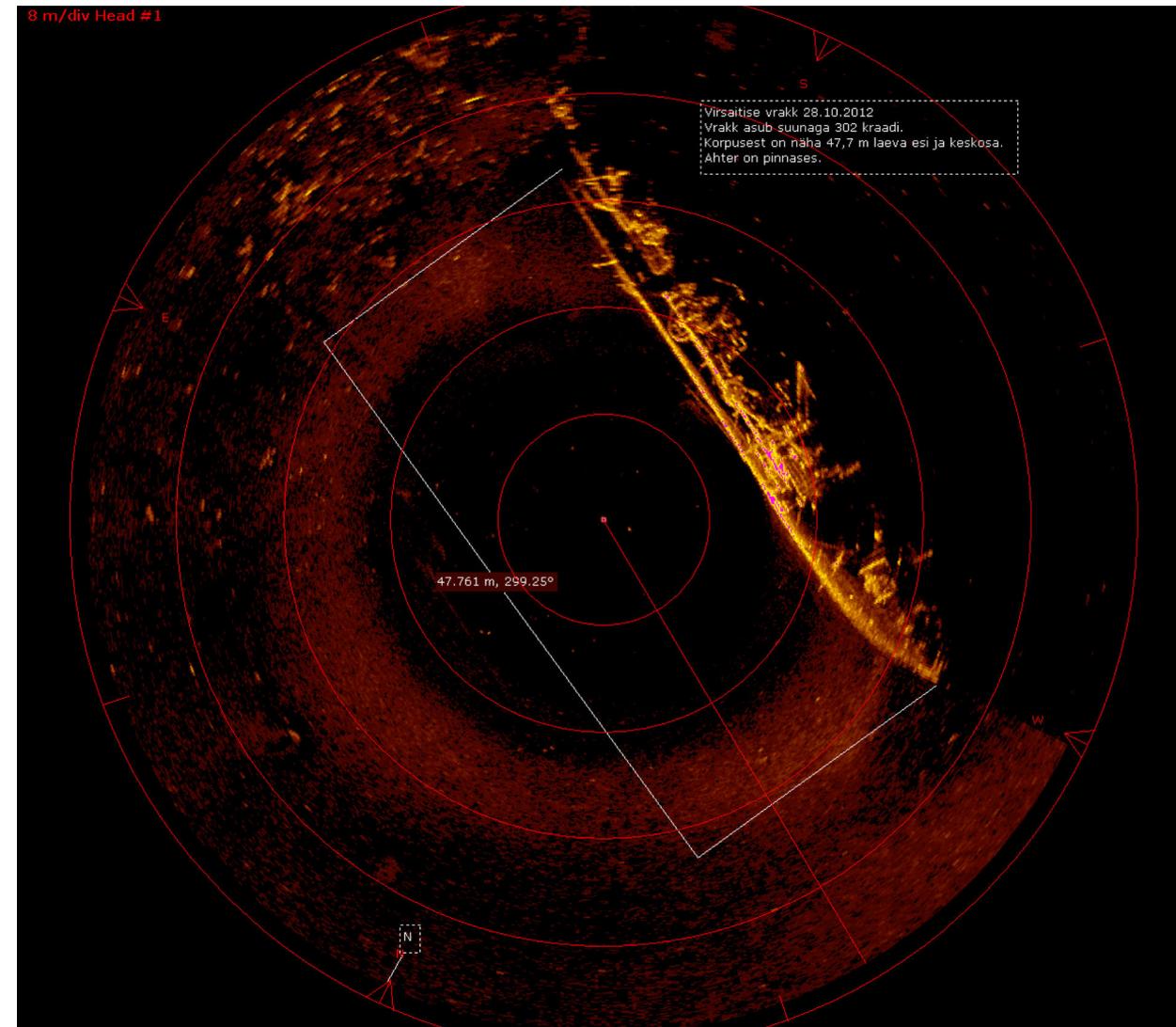
Ultrasonic Sensor (time of flight, sound) (3)

- 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.

Underwater Sonar

- Light visibility very low => often sonar the only/ best sensor available
- Types:
 - Sonar
 - Side-scanning
 - Synthetic aperture sonar
- Problems:
 - Absorption
 - Reflections:
 - Layers of different water temperature
 - Layers of different salinity
 - ...



Laser Range Sensor (time of flight, electromagnetic)

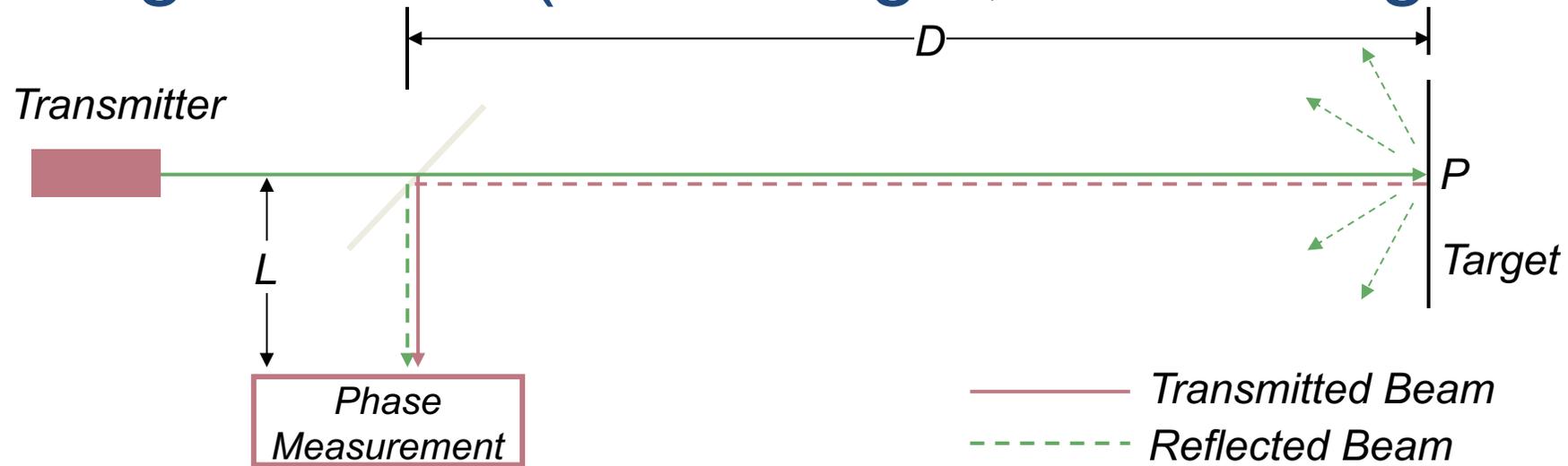
- Is called Laser range finder or Lidar (Light Detection And Ranging)



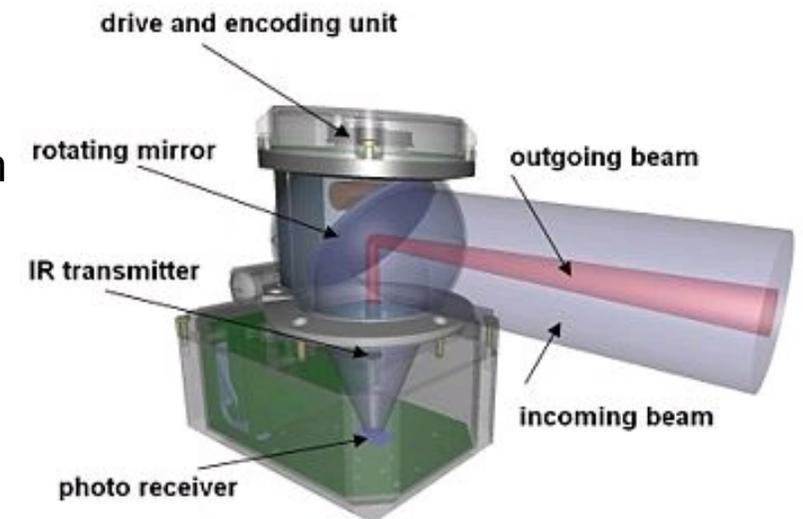
Autonomous Driving will rely heavily on range sensing =>
Many 3D range sensing companies emerge!

E.g. RoboSense (China)

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



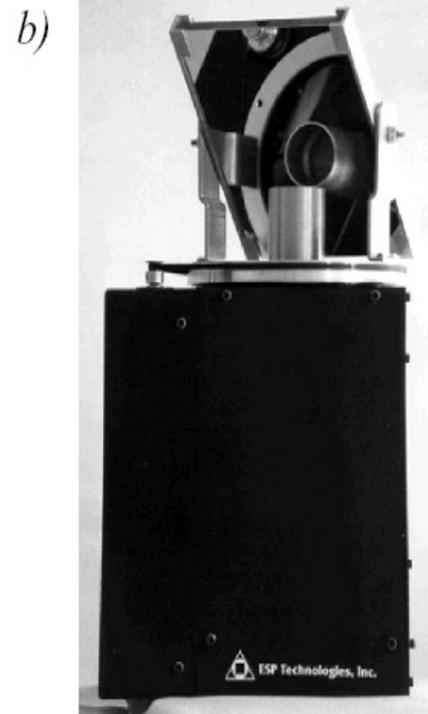
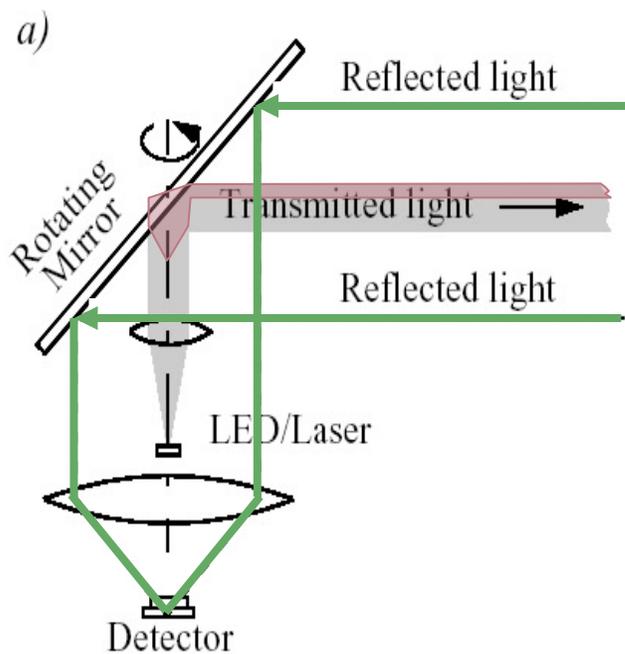
Laser Range Sensor (time of flight, electromagnetic) (2)

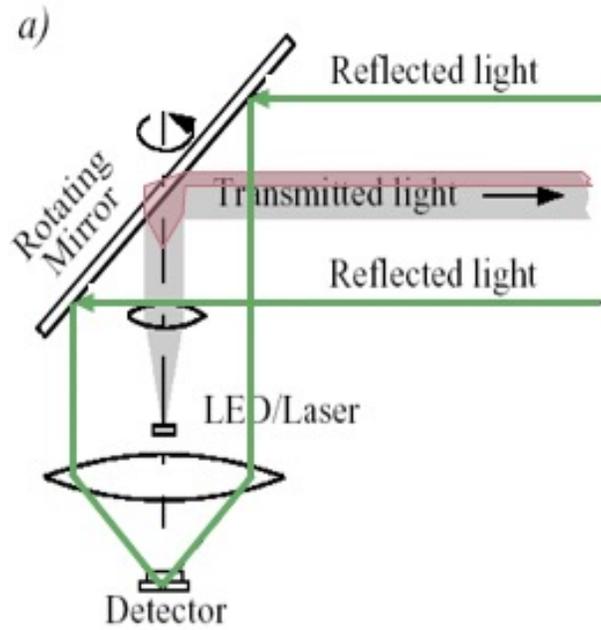
Time of flight measurement

- 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
- (3D) Laser Scanner == Lidar (Light detection and ranging)

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

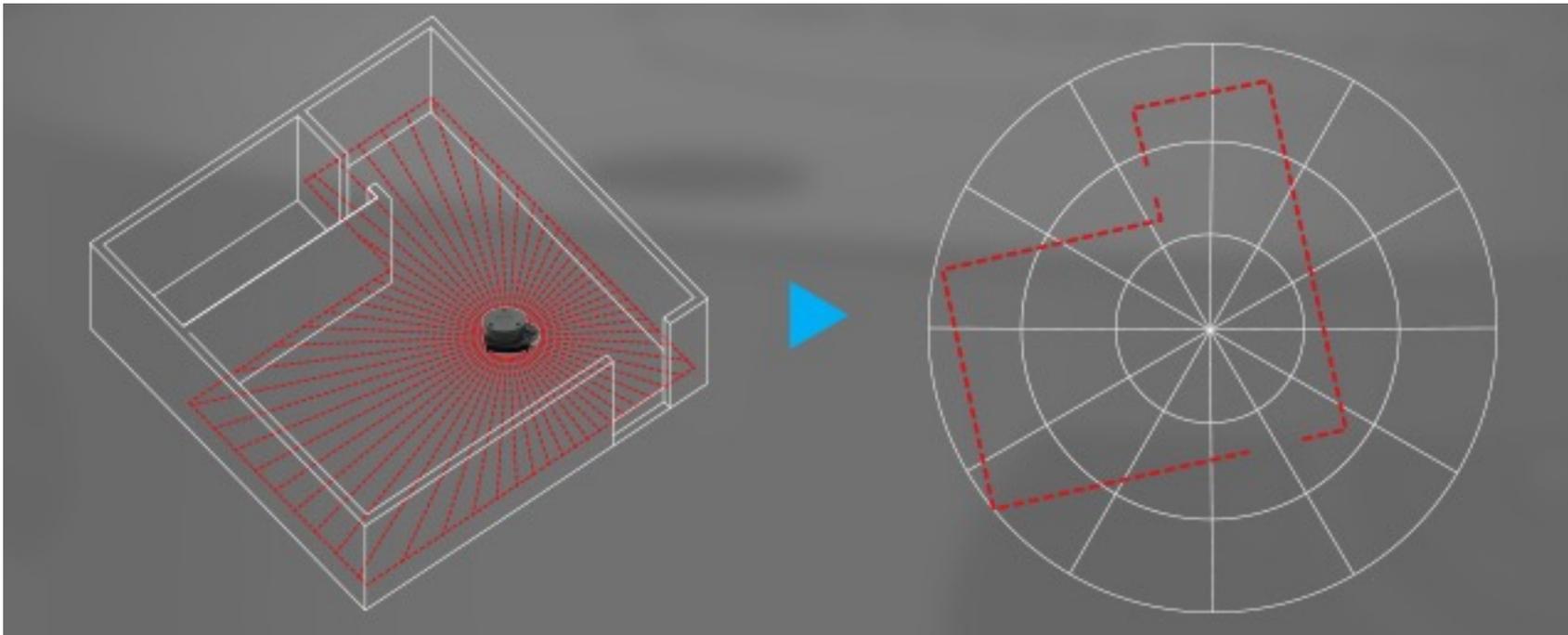
- Uncertainty of the range (phase/time estimate) is inversely proportional to the square of the received signal amplitude.
 - Hence dark, distant objects will not produce such good range estimated as closer brighter objects ...





Laser Range Sensor (time of flight, electromagnetic)

- Typical range image of a 2D laser range sensor with a rotating mirror



Hokuyo UTM-30LX

- Long Detection range: 30m
- 0.1 to 10m: $\pm 30\text{mm}$, 1
- 0 to 30m: $\pm 50\text{mm}^*1$
- 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 : ± 30 mm,
- 1,000 to 4,095mm : $\pm 3\%$ of measurement
- 10Hz
- Dimensions: 50 x 50 x 70 mm
- Weight: 160g

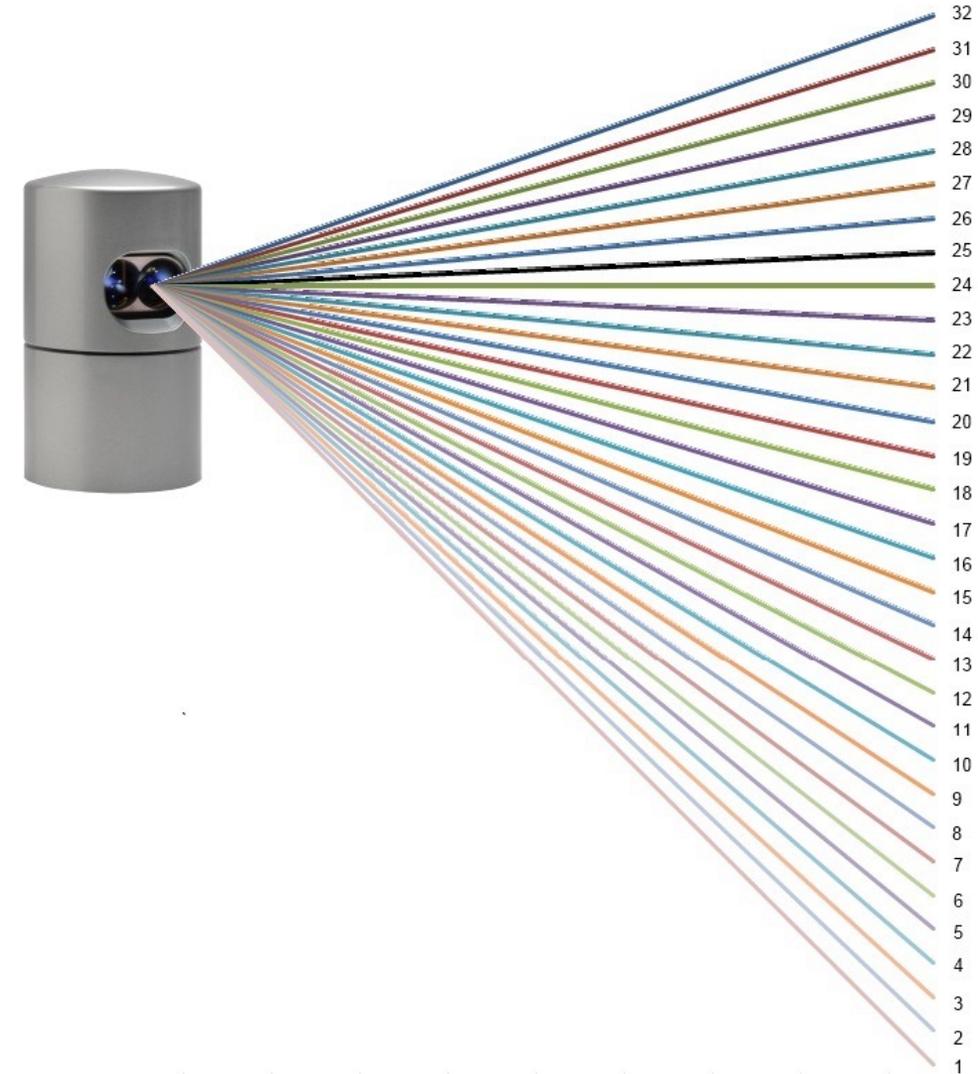
- Cost: about 6,500 RMB



Velodyne hdl-32e

- 32 beams
- 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,
 - Height: 144 mm
- Weight: 1kg
- Cost: about 220,000 RMB



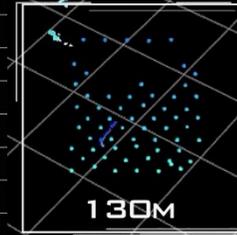
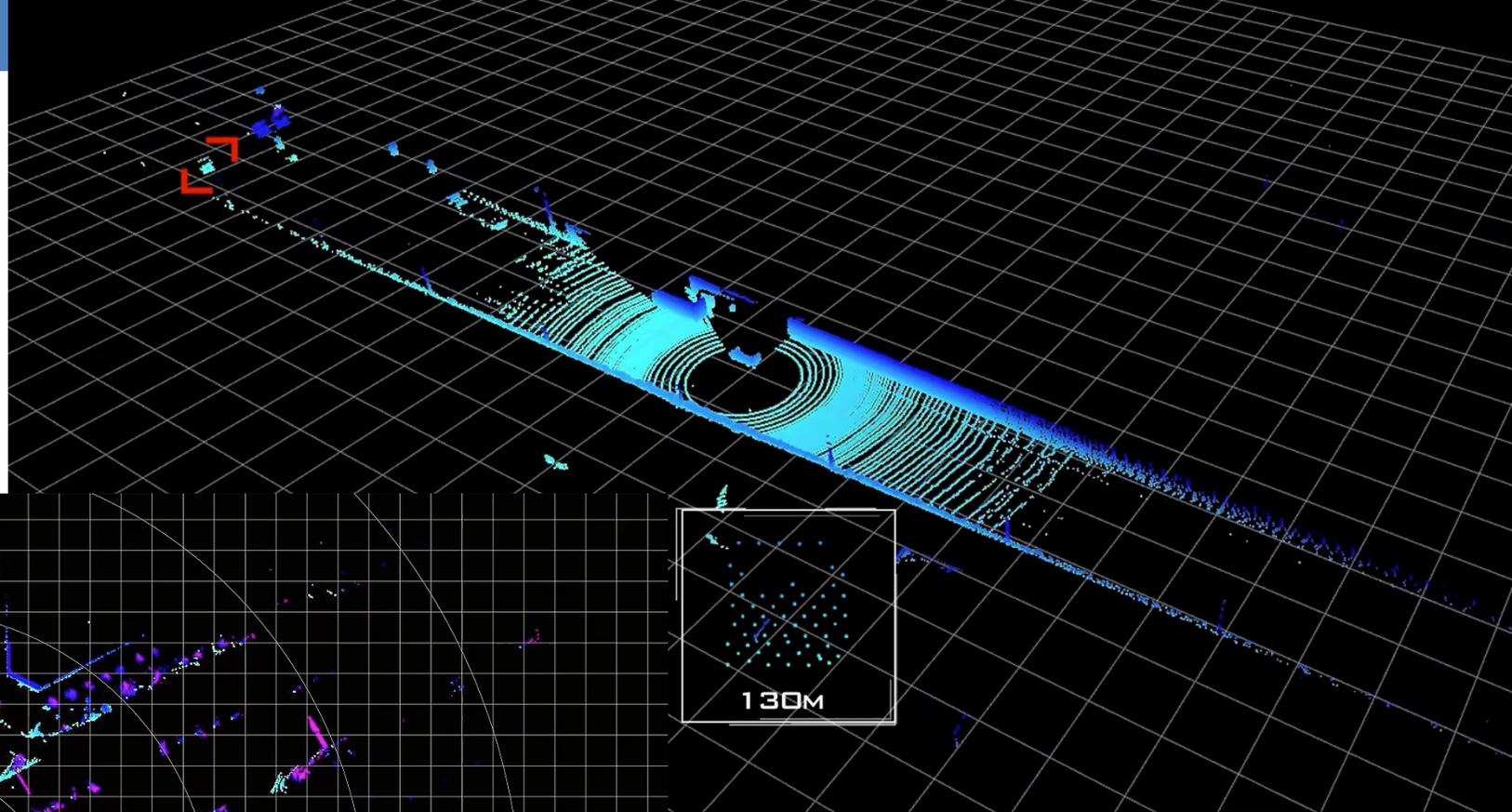
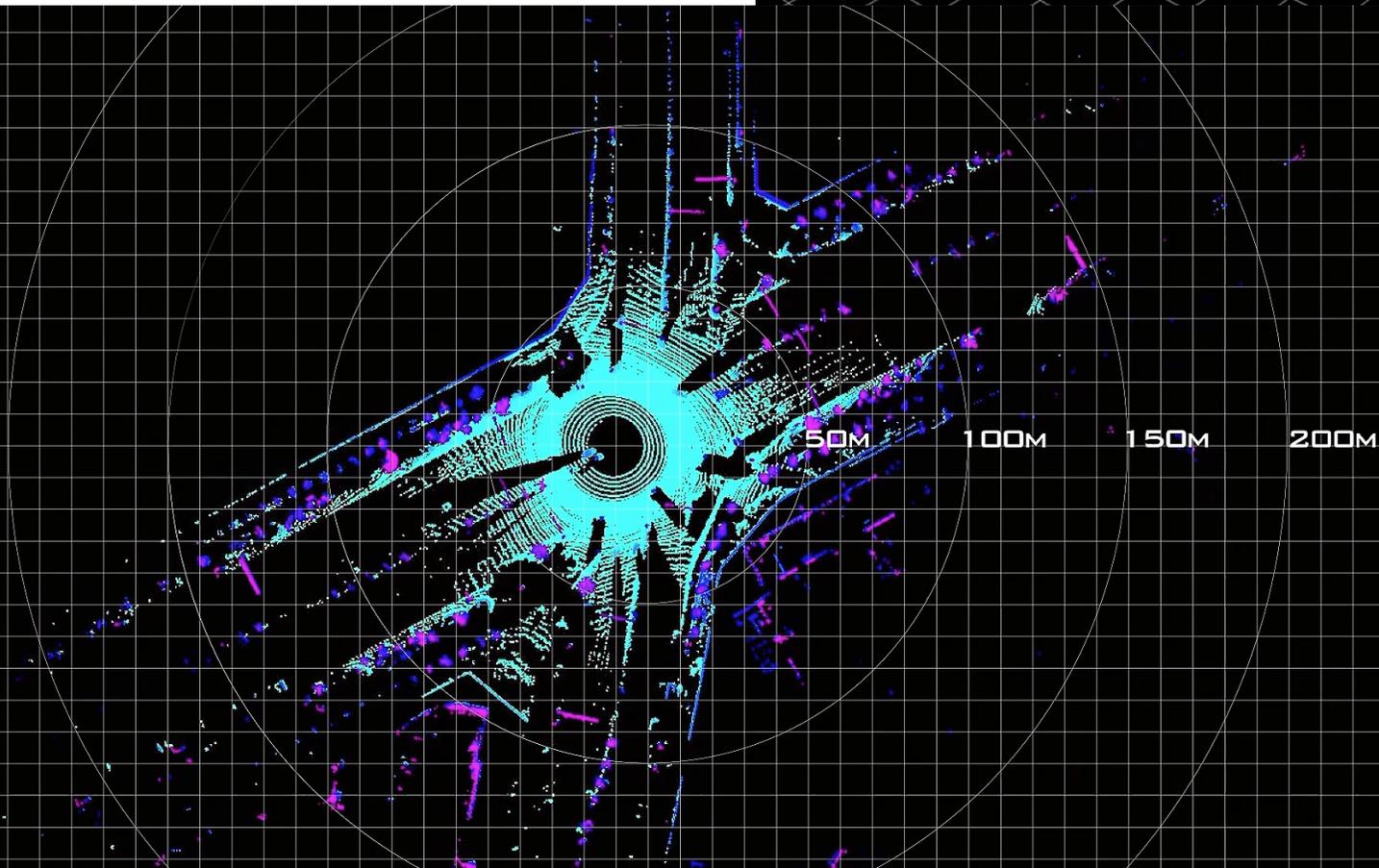
RoboSense Ruby

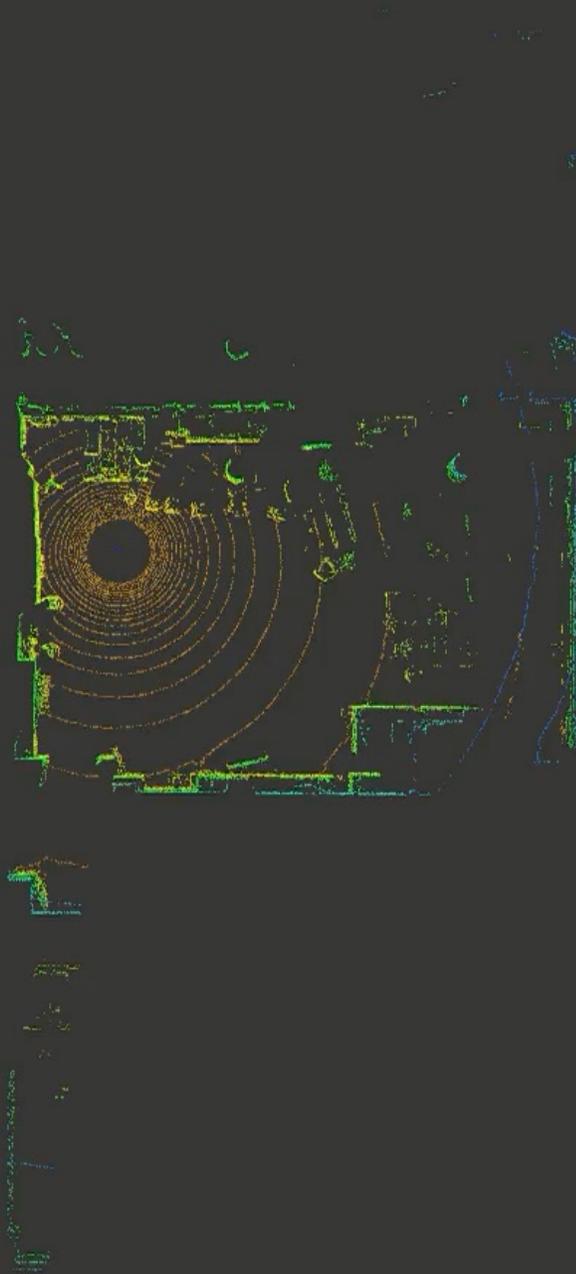
- 128 beams
- Range: 250m (200m@10% NIST)
- Range Accuracy (Typical): Up to $\pm 3\text{cm}$
- Vertical FOV: 40°
- Horizontal Resolution: $0.1^\circ / 0.2^\circ / 0.4^\circ$
- Vertical Resolution: Up to 0.1°
- Frame Rate: 5Hz/10Hz/20Hz
- Points Per Second: 2,304,000pts/s (Single return Mode)
- Points Per Second: 4,608,000pts/s (Dual return Mode)
- Operating Voltage: 19V - 32V
- Power Consumption: 45W
- Weight (without cabling): $\sim 3.75\text{ kg}$

- Cost: about RMB 500,000



RoboSense Ruby on Road

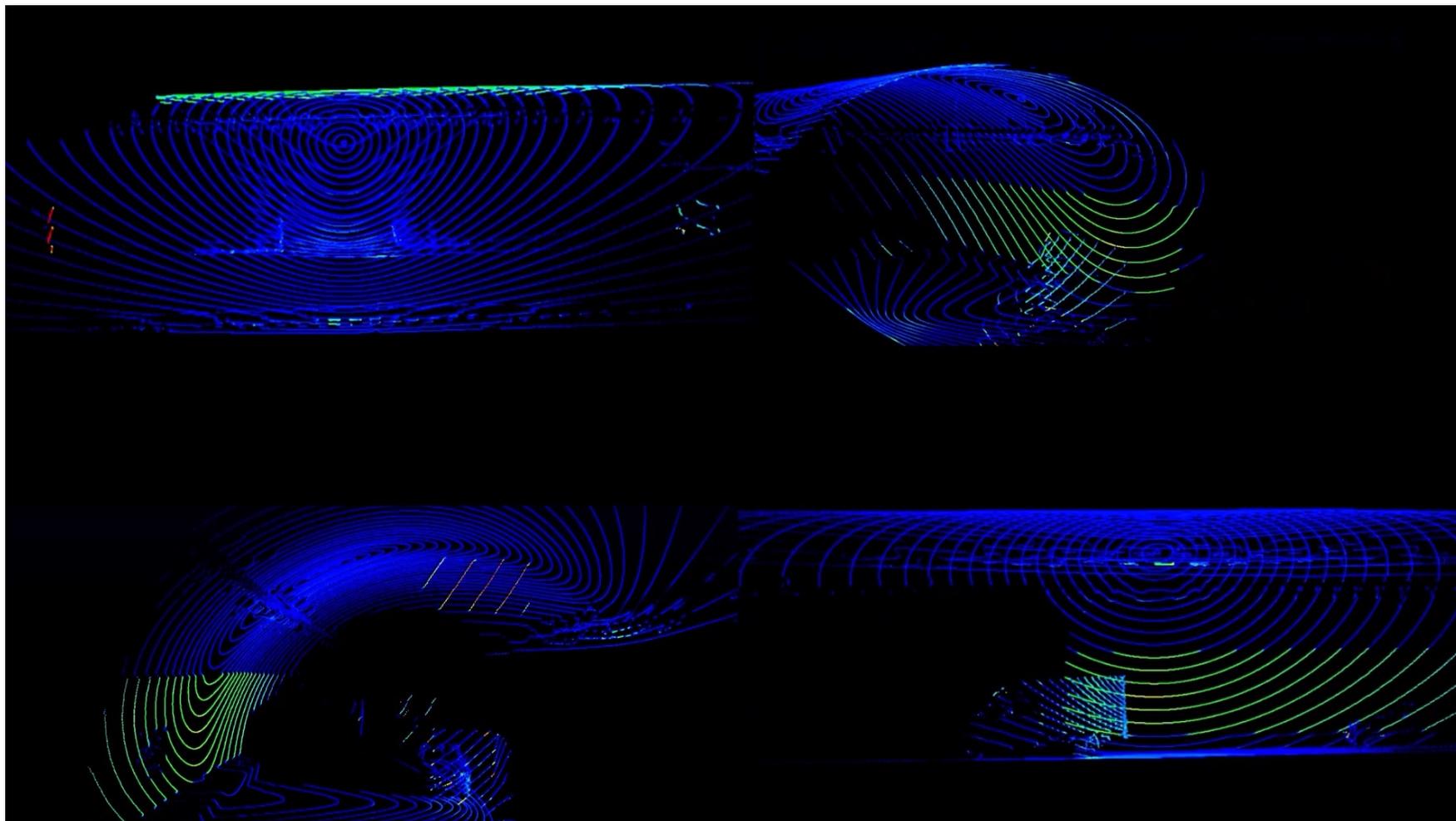






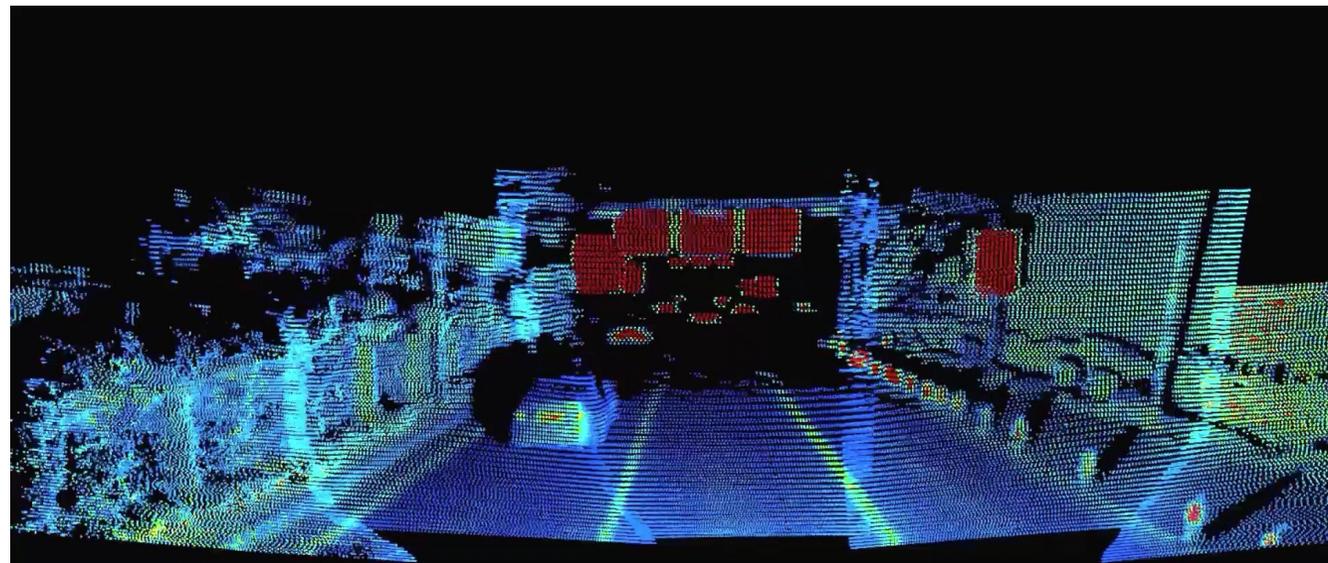
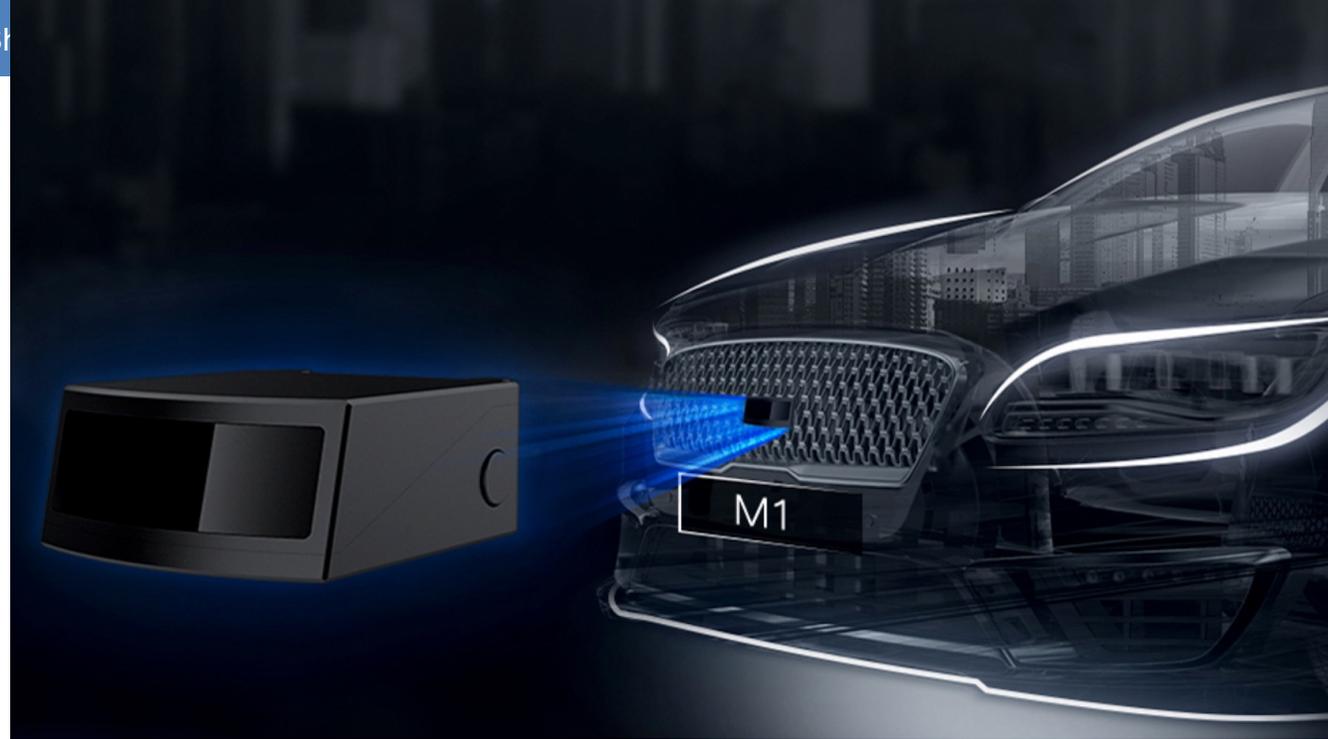
RoboSense Bpearl

- Hemispherical Lidar
- 32 beams
- Range: 100m (30m@10% NIST)
- Range Accuracy (Typical): Up to $\pm 3\text{cm}$
- Frame Rate: 10Hz/20Hz
- Points Per Second: 576,000pts/s (Single return Mode)
- Points Per Second: 1,152,000pts/s (Dual return Mode)
- Operating Voltage: 9V - 32V
- Power Consumption: 13W
- Weight: $\sim 0.92\text{ kg}$



RoboSense Lidar M1

- Solid state Lidar (300 x 125 pixel)
- Accuracy: Up to $\pm 5\text{cm}$
- Range: 150m on 10% NIST
- Vertical FOV: 25° ($-12.5^\circ \sim +12.5^\circ$)
- Vertical angular resolution: 0.2°
- Horizontal FOV: 120° ($-60.0^\circ \sim +60.0^\circ$)
- Horizontal angular resolution: 0.2°
- Refresh Rate: 15 Hz
- Data rate: 1,125,000pts/s (single return)
- Power consumption: 25w
- Weight: $\sim 800\text{g}$



Intel RealSense L515

- 9m distance
- Depth: 1024 x 786 pixel @ 30Hz => 23mill pts per second
- RGB: 1920 x 1080 @ 30Hz
- Depth FOV: 70° x 55° (±2°)
- Weight: 100g
- With IMU

- Solid state laser with RGB camera

- Sensitive to ambient infrared light =>
Does NOT work outdoors!



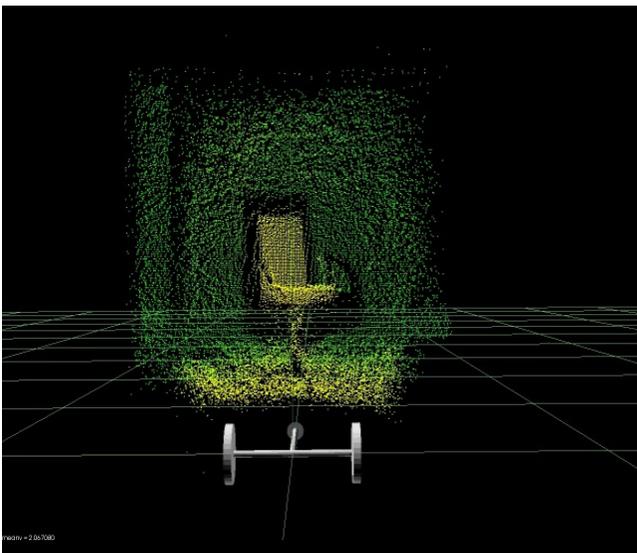
Cubemos skeletal tracking with
the Intel® RealSense™ LiDAR Camera L515

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

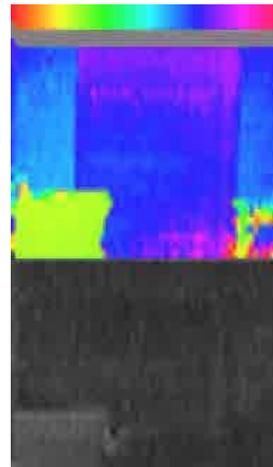
- 3D information with high data rate (100 Hz)
- Compact and easy to manage
- High, non-uniform measurement noise
- High outlier rate at jump edges
- Wrap-around error (phase ranging)
- Sensitive to ambient infrared light => Does NOT work outdoors!



- Kinect 2
- Resolution 1920x1080 pixels
- Field of view: 70 deg (H), 60 deg (V)
- Claimed accuracy: 1 mm
- Claimed max range: 6 meters

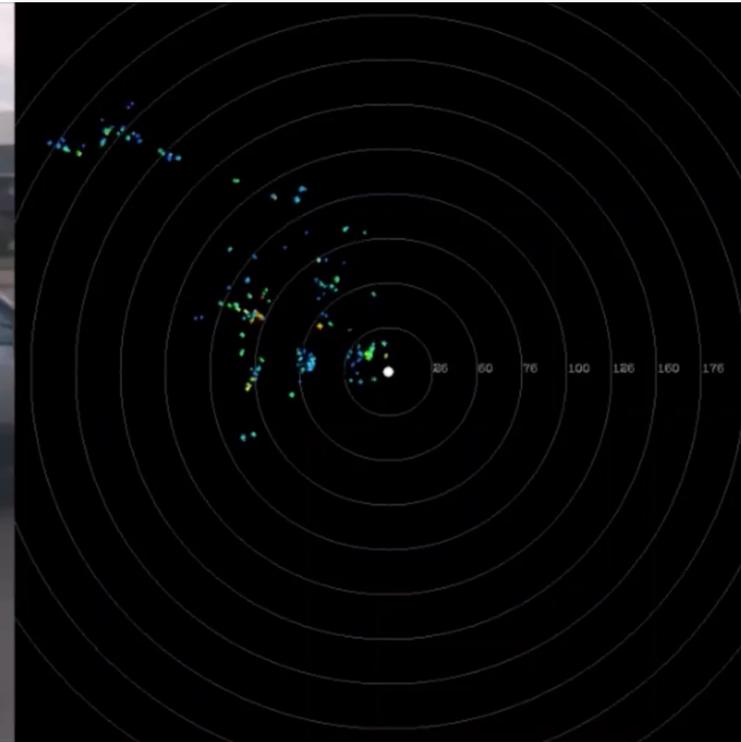


Swiss Ranger 3000
(produced by MESA)



Radar, 4D imaging radar (e.g. Oculii)

- Works in various weather and environment conditions:
 - fog, heavy rain, pitch darkness, air pollution
- High range (300+ meters)
- Capture doppler shifts (speed of other objects in a single scan) – this is the 4th dimension
- 250M+
- $<1^\circ$ Resolution
- 120° FOV

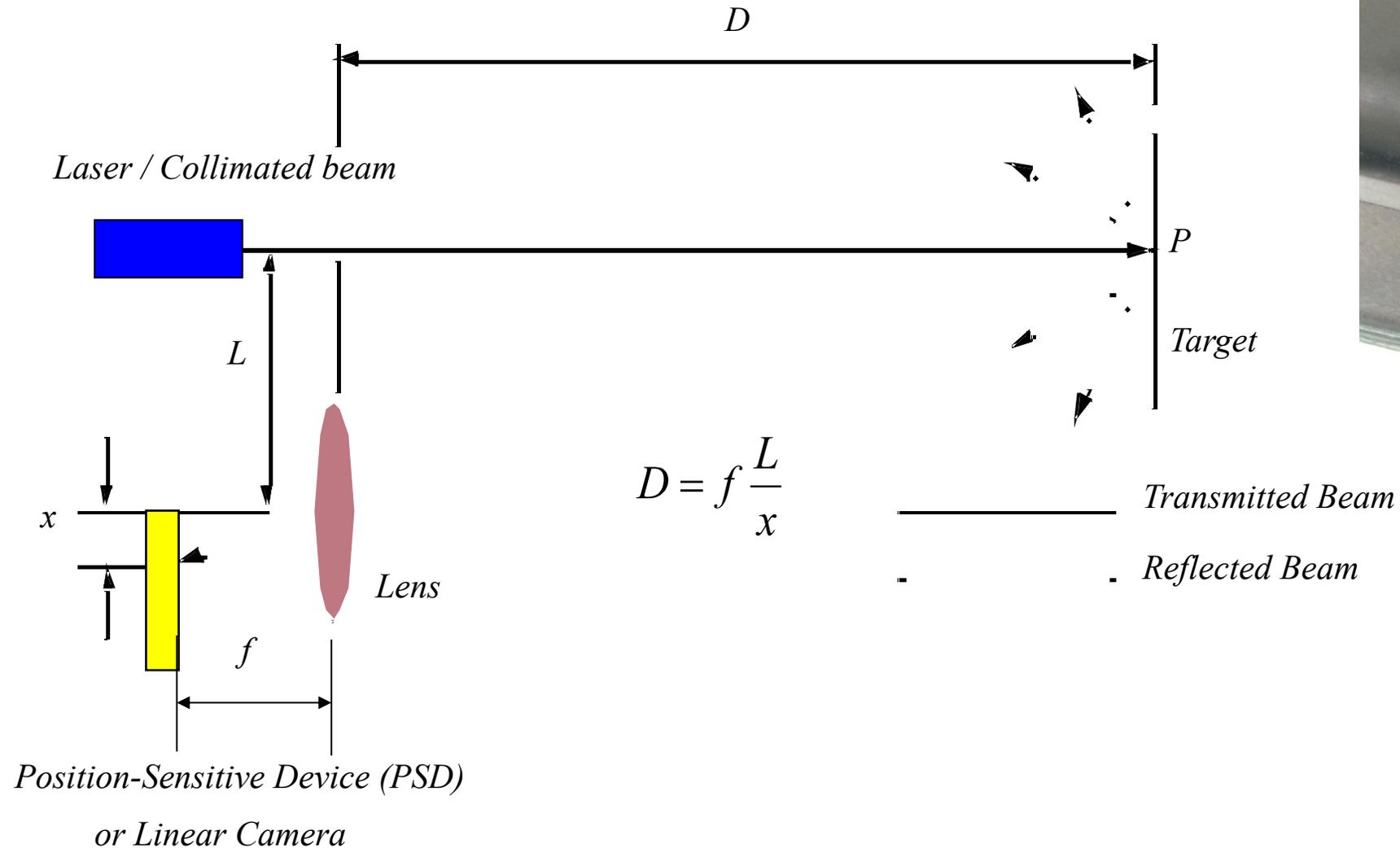


RANGE SENSING: PROJECTED PATTERN

Triangulation Ranging

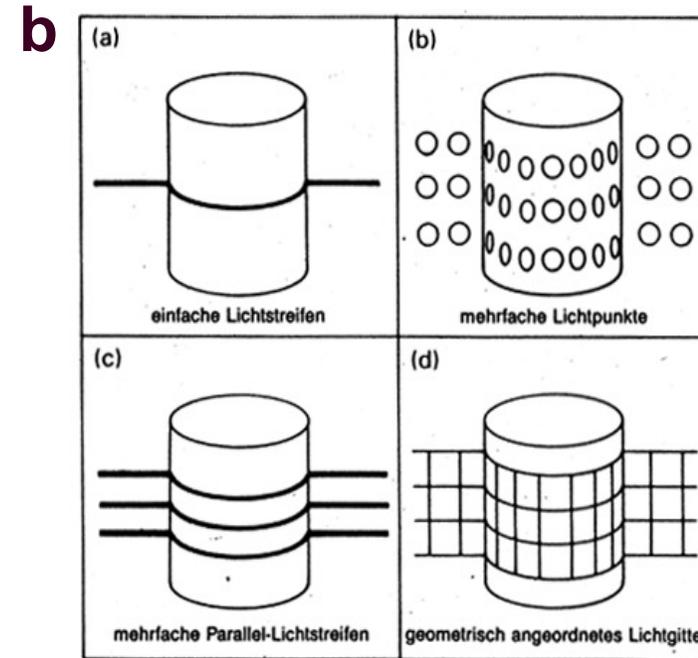
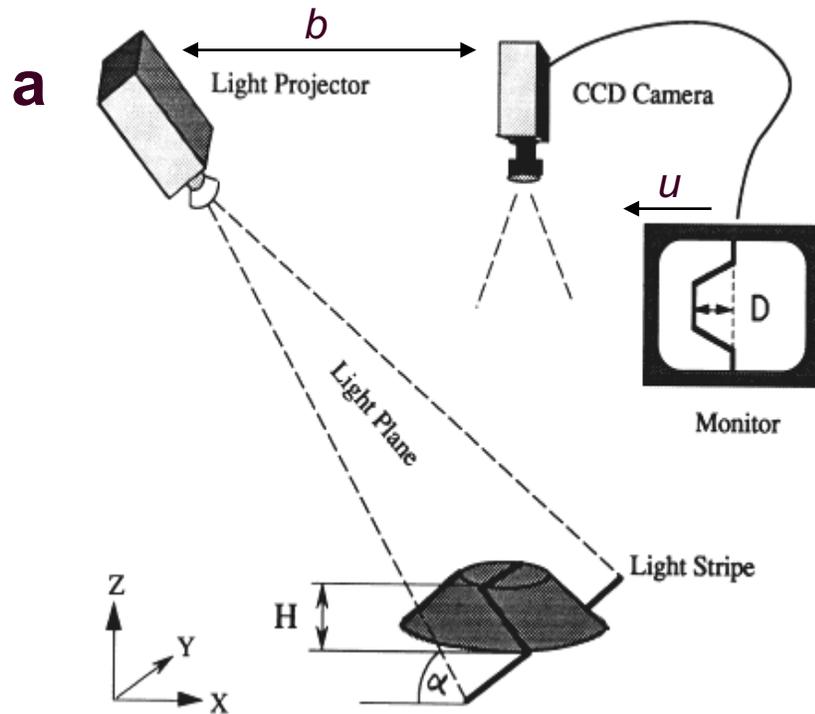
- Geometrical properties of the image to establish a distance measurement
- e.g. project a well defined light pattern (e.g. point, line) onto the environment.
 - reflected light is then captured by a photo-sensitive line or matrix (camera) sensor device
 - simple triangulation allows to establish a distance.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

Laser Triangulation (1D)



Cliff sensor on Turtle-bot

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



- 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)

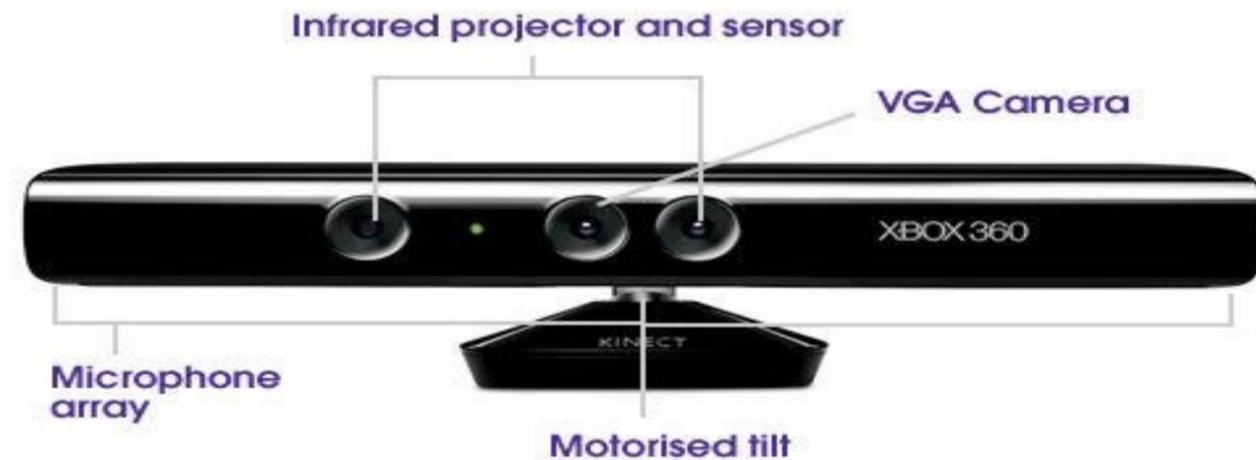
- Baseline length b :
 - the smaller b is the more compact the sensor can be.
 - the larger b is the better the range resolution is.

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

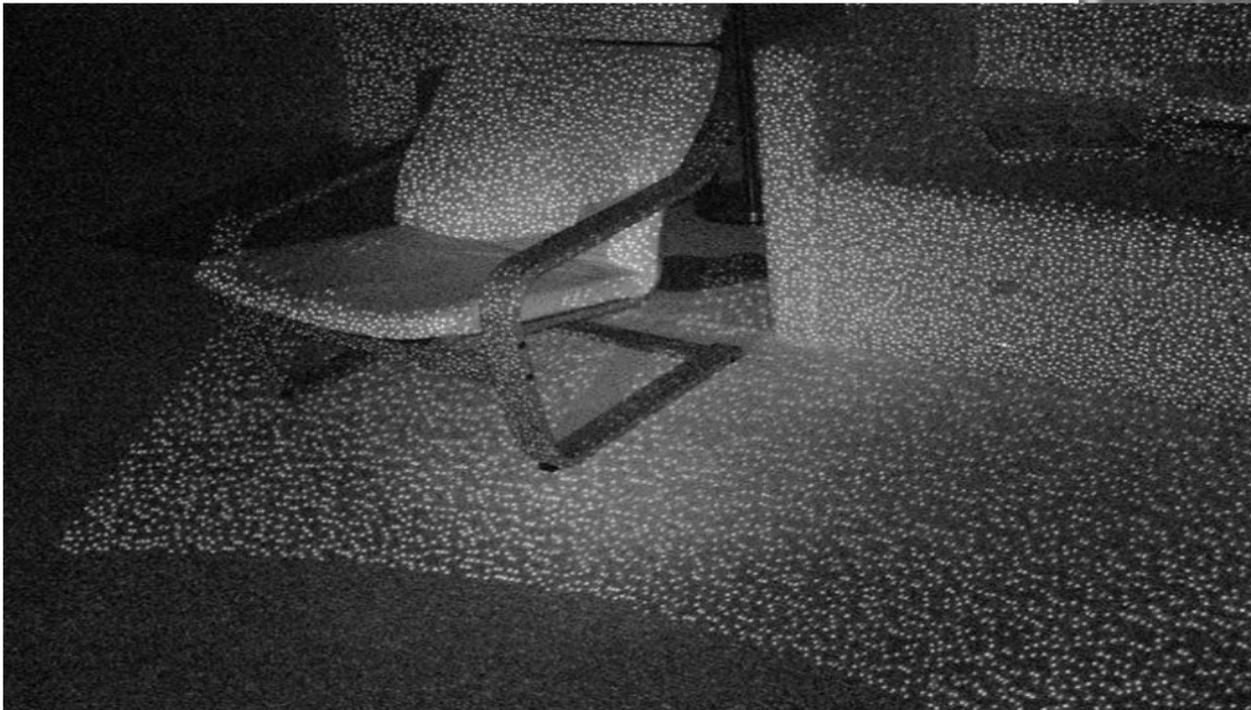


IR Pattern

Sensitive to infrared light

=>

Does NOT work outdoors!



Depth Map



Microsoft Kinect: Depth Computation (1)

• Depth from Stereo

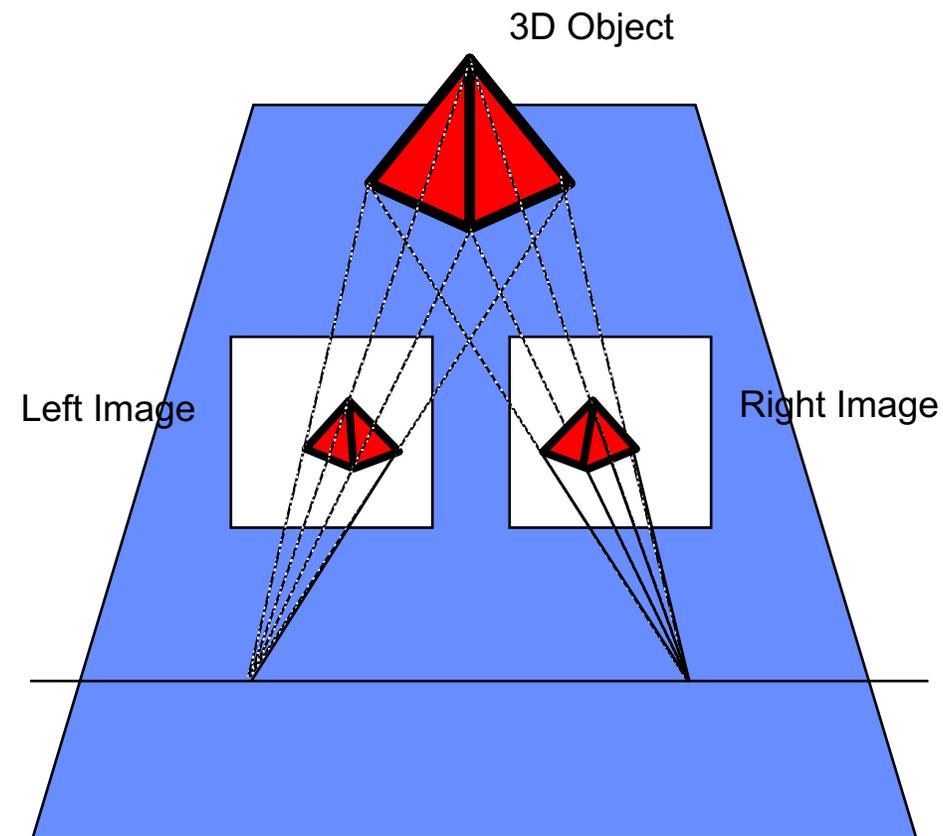
- The Kinect uses an infrared projector and an infrared sensor; it does not use its RGB camera for depth computation
- The technique of analyzing a known pattern is structured light
- The IR projector projects a pseudo-random pattern across the surface of the room.
- The direction of each speckle of 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



RANGE SENSING: STEREO VISION

Stereo Cameras

- Theory will be covered in detail in Vision Lecture
- Estimate depth by using 2 cameras



Stereo example: ZED camera



- Dual 4MP Camera @15Hz (lower resolution => higher fps)
- Up to 20m distance
- Passive Sensor
- Doesn't work on single color surfaces (e.g. white wall)!



Intel RealSense D435

- Stereo Infrared – works indoors and outdoors
- Active pattern (e.g. for white wall) – only works indoors!
- Depth resolution: 1280×720
- Depth Field of View (FOV): $86^\circ \times 57^\circ (\pm 3^\circ)$
- RGB: 1920×1080
- Small and lightweight
- With IMU

