ShanghaiTech University
上海科技大学
School of Information Science and Technology
信息科学与技术学院

Introduction to Information Science and Technology (EE 100)
Part II: Intelligent Machines and Robotics
Perception / Sensors

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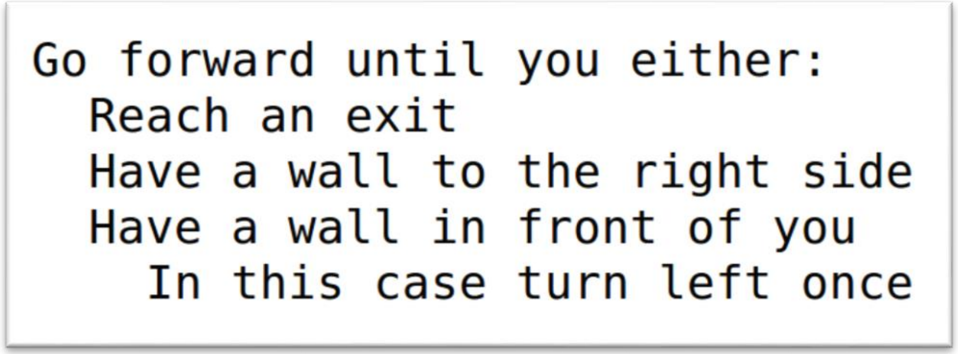
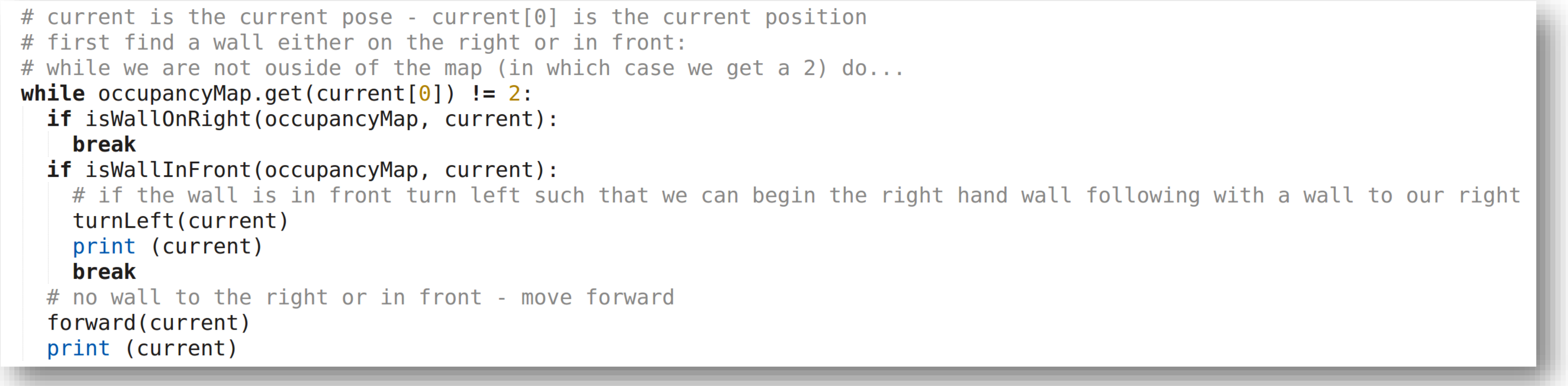
Homework



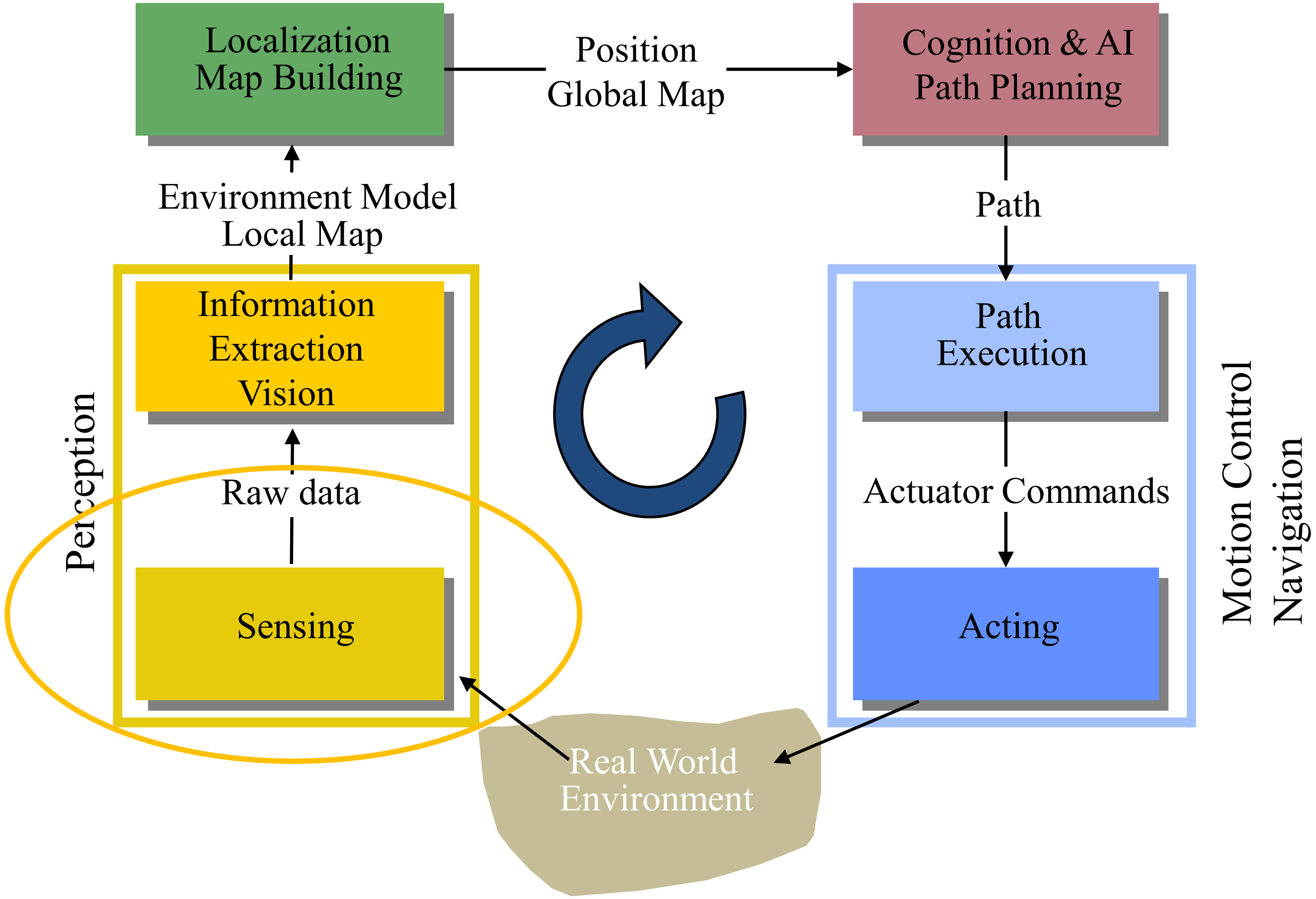
```
Go forward until you either:
  Reach an exit
  Have a wall to the right side
  Have a wall in front of you
    In this case turn left once
```

- You can and should program VERY close to the pseudo code:
  - Below is part of my code for finding the wall: 9 lines!
  - My code for following the wall, including step counter is 15 lines!
  - Map code including parsing less than 40 lines;
  - 5 helper functions (turnLeft, turnRight, forward, isWallOnRight, isWallOnLeft): total 24 lines



```
# current is the current pose - current[0] is the current position
# first find a wall either on the right or in front:
# while we are not ouside of the map (in which case we get a 2) do...
while occupancyMap.get(current[0]) != 2:
  if isWallOnRight(occupancyMap, current):
    break
  if isWallInFront(occupancyMap, current):
    # if the wall is in front turn left such that we can begin the right hand wall following with a wall to our right
    turnLeft(current)
    print (current)
    break
  # no wall to the right or in front - move forward
  forward(current)
  print (current)
```

General Control Scheme for Mobile Robot Systems



Lecture 4:
Perception

With material from Roland Siegwart and Davide Scaramuzza, ETH Zurich

SENSORS

Sensors for Mobile Robots

- Why should a robotics engineer know about sensors?
  - Is the **key technology** for perceiving the environment
  - **Understanding the physical principle** enables appropriate use

- Understanding the physical principle behind sensors enables us:
  - To **properly select** the sensors for a given application
  - To **properly model** the sensor system, e.g. resolution, bandwidth, **uncertainties**

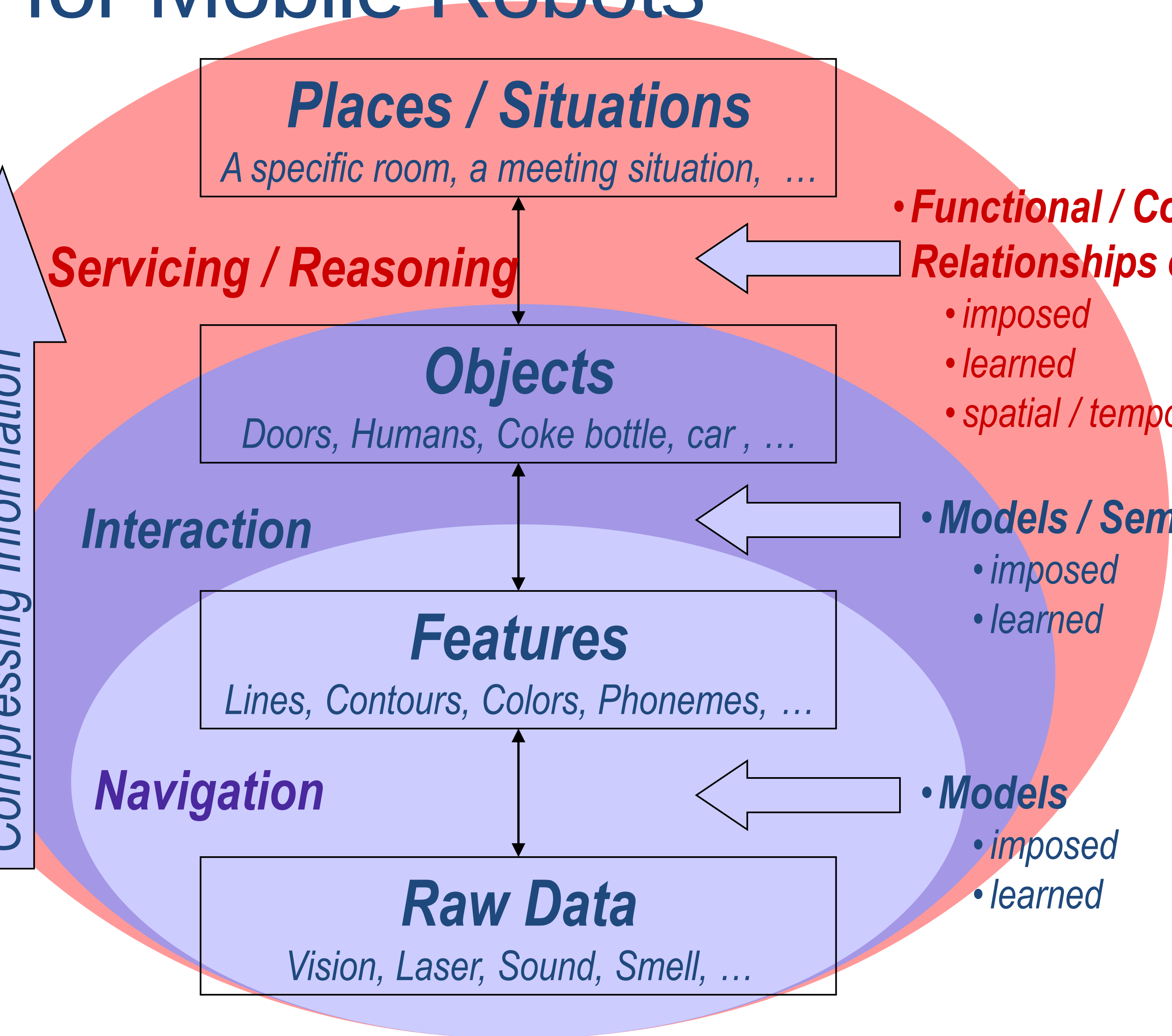
Dealing with Real World Situations

- Reasoning about a situation

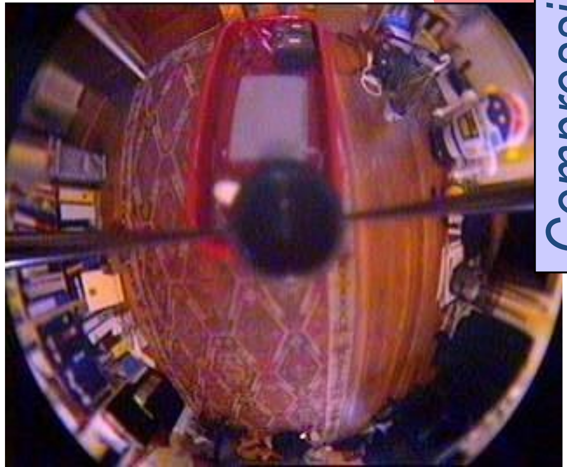
- Have to interpret situations based on uncertain and only partially available information
- Need ways to learn functional and contextual information (semantics / understanding)

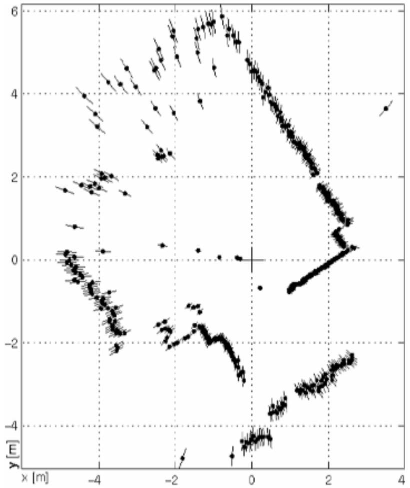
⇒ **Probabilistic Reasoning**

Perception for Mobile Robots



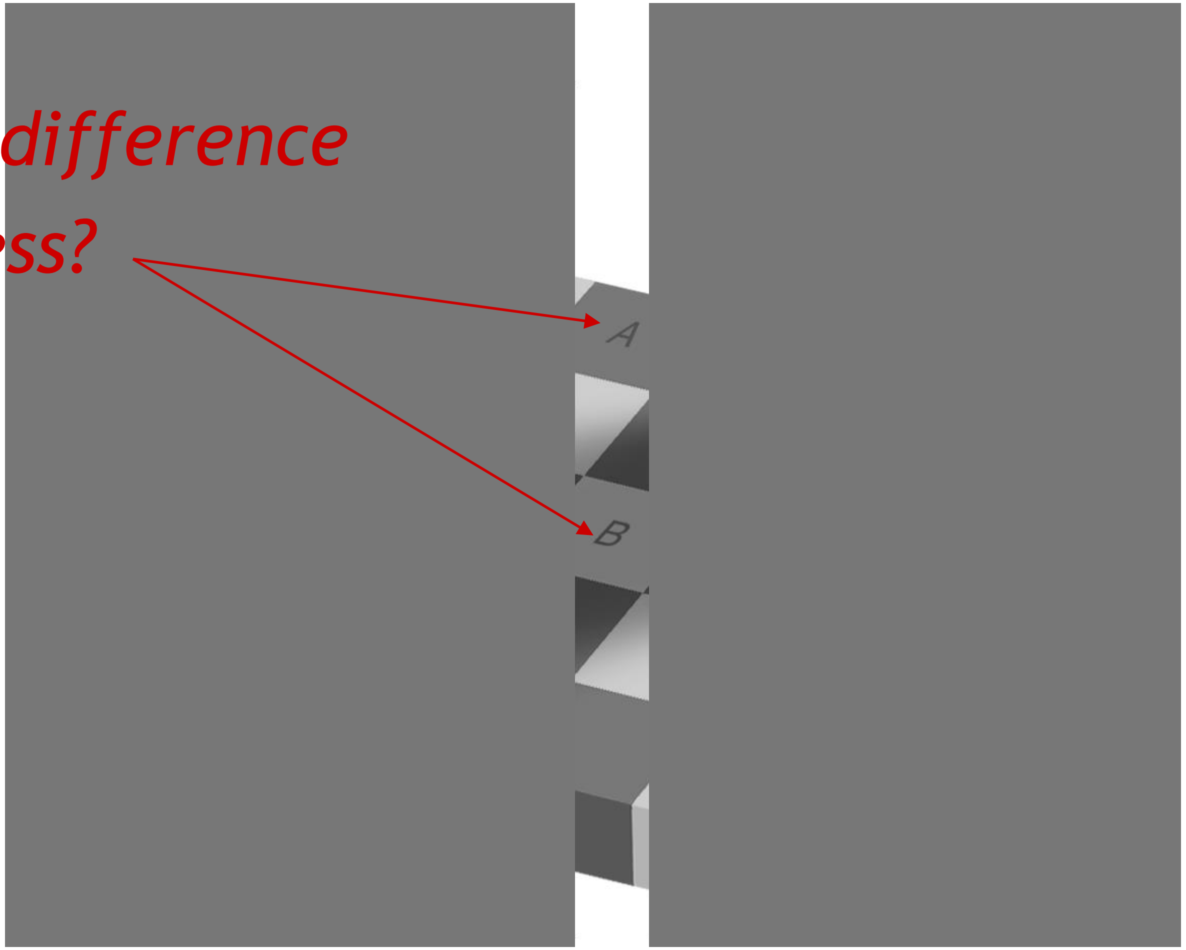
- ***Functional / Contextual Relationships of Objects***
  - *imposed*
  - *learned*
  - *spatial / temporal/semantic*
- ***Models / Semantics***
  - *imposed*
  - *learned*
- ***Models***
  - *imposed*
  - *learned*





The Challenge

- Perception and models are strongly linked



What is the difference in brightness?

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

Characterizing Sensor Performance

- Basic sensor response ratings
  - Range
    - upper limit; lower limit

  - Resolution
    - minimum difference between two values
    - usually: lower limit of dynamic range = resolution
    - for digital sensors it is usually the A/D resolution.
      - e.g. 5V / 255 (8 bit)

  - Linearity
    - variation of output signal as function of the input signal
    - linearity is less important when signal is treated with a computer

$$x \rightarrow f(x)$$

$$y \rightarrow f(y)$$

$$\alpha \cdot x + \beta \cdot y \rightarrow f(\alpha \cdot x + \beta \cdot y) = \alpha \cdot f(x) + \beta \cdot f(y)$$

Characterizing Sensor Performance

- Bandwidth or Frequency
  - the speed with which a sensor can provide a stream of readings
  - usually there is an upper limit depending on the sensor and the sampling rate
  - lower limit is also possible, e.g. acceleration sensor
  - one has also to consider phase (delay) of the signal

- Sensitivity
  - ratio of output change to input change

$$\frac{dy}{dx}$$

- Cross-sensitivity (and cross-talk)
  - sensitivity to other environmental parameters (e.g. temperature, magnetic field)
  - influence of other active sensors

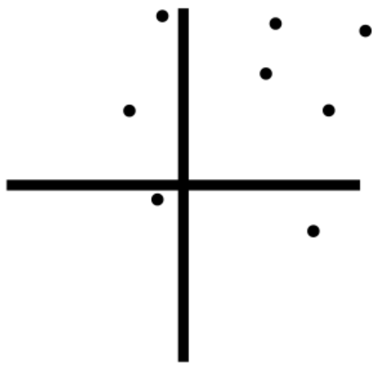
In Situ Sensor Performance

- In Situ: Latin for “in place”

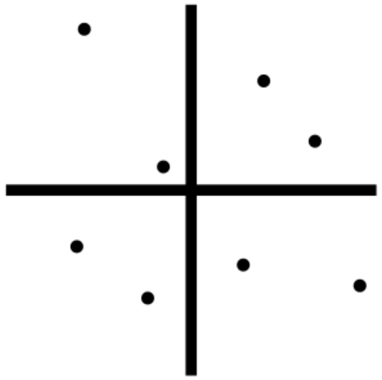
- Error / Accuracy
  - How close to true value
- Precision
  - Reproducibility

$$\left(accuracy = 1 - \frac{\overset{\text{error}}{|m-v|}}{v}\right)$$

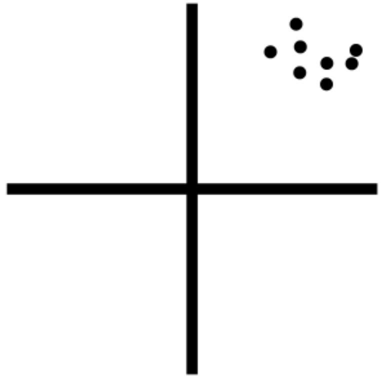
m = measured value
v = true value



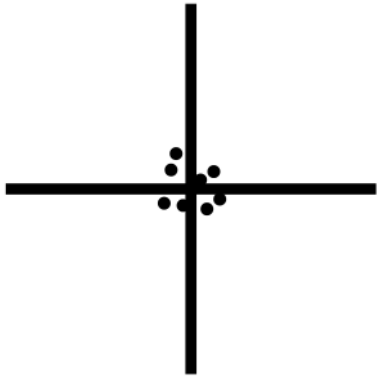
(a) Low precision and low accuracy



(b) Low precision and high accuracy



(c) High precision and low accuracy



(d) High precision and high accuracy

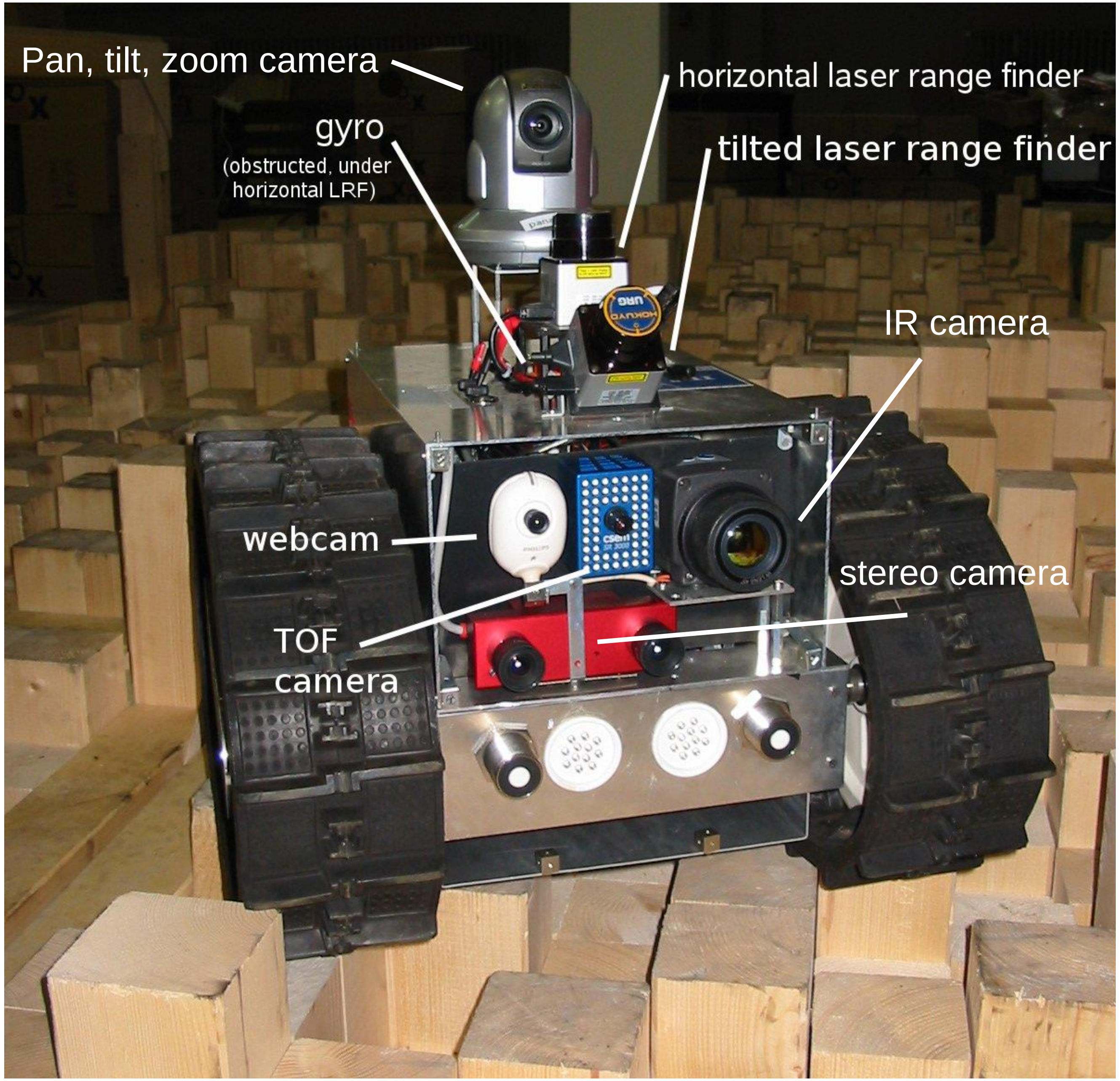
Types of error

- Systematic error -> deterministic errors
  - caused by factors that can (in theory) be modeled -> prediction
  - e.g. calibration of a laser sensor or of the distortion caused by the optic of a camera

- Random error -> non-deterministic
  - no prediction possible
  - however, they can be described probabilistically
  - e.g. Hue instability of camera, black level noise of camera ..

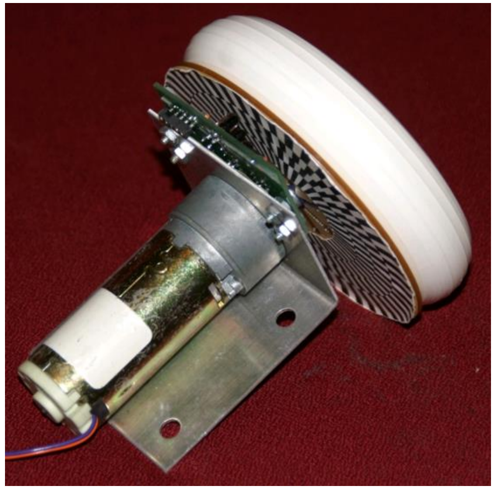
Sensors: outline

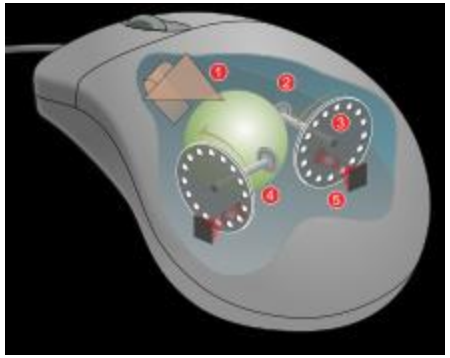
- Optical encoders
- Heading sensors
  - Compass
  - Gyroscopes
- Accelerometer
- IMU
- GPS
- Range sensors
  - Sonar
  - Laser
  - Structured light
- Vision



Encoders

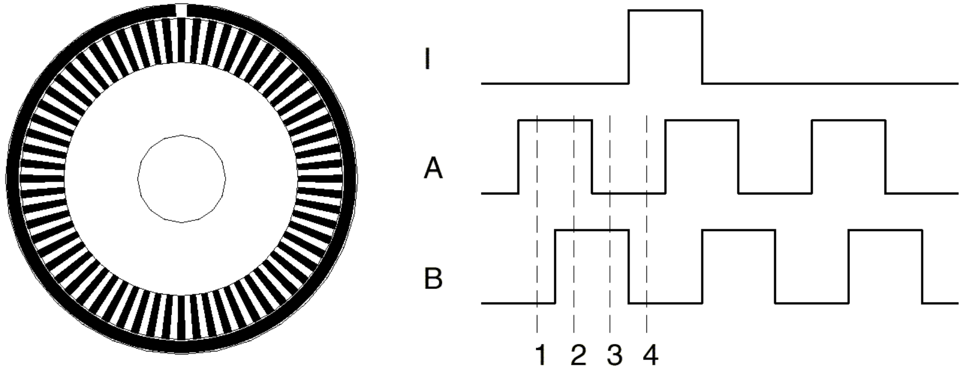
An encoder is an electro-mechanical device that converts the angular position of a shaft to an analog or digital signal, making it an angle transducer





Wheel / Motor Encoders

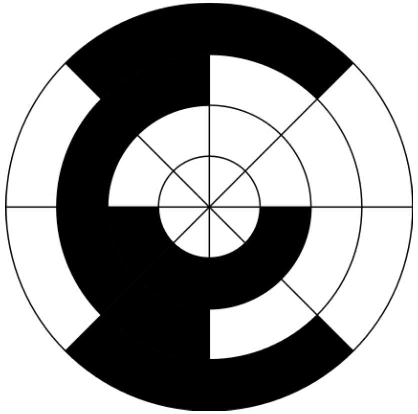
- Measure position or speed of the wheels or steering
- Integrate wheel movements to get an estimate of the position -> odometry
- typical resolutions: 64 - 2048 increments per revolution.
  - for high resolution: interpolation
- optical encoders
  - regular: counts the number of transitions but cannot 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

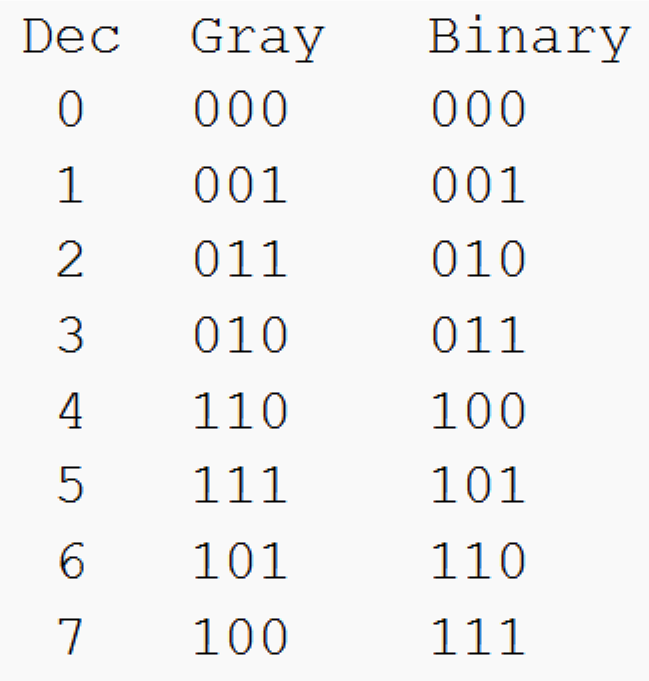
Gray Encoder

http://en.wikipedia.org/wiki/Gray_code

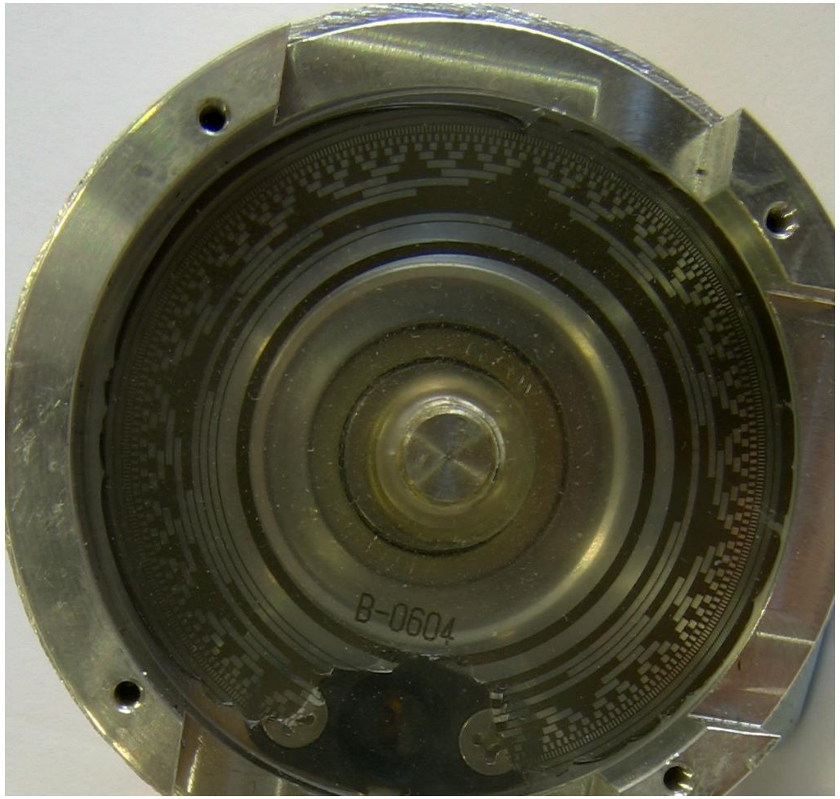


- Aka: reflected binary code, Gray Code
  - Binary numeral system where two successive values differ in only one bit
  - Also used for error correction in digital communications

- Absolute position encoder
  - Normal binary => change from 011 to 100
  - 2 bits change – NEVER simultaneously =>
  - 011 -> 111 -> 101 -> 100 or
  - 011 -> 010 -> 110 -> 100 ….
  - => wrong encoder positions might be read
  - Gray encoding: only one bit change!



Dec	Gray	Binary
0	000	000
1	001	001
2	011	010
3	010	011
4	110	100
5	111	101
6	101	110
7	100	111



Heading Sensors

- Used to determine the robots orientation and inclination.
- Together with an vehicle velocity information:
  - Integrate movement to a position and orientation (pose) estimate.
  - Called **deduced reckoning** (ship navigation)

- Gyroscope: measures acceleration
- Accelerometer : measures acceleration
- Compass: measures magnetic field

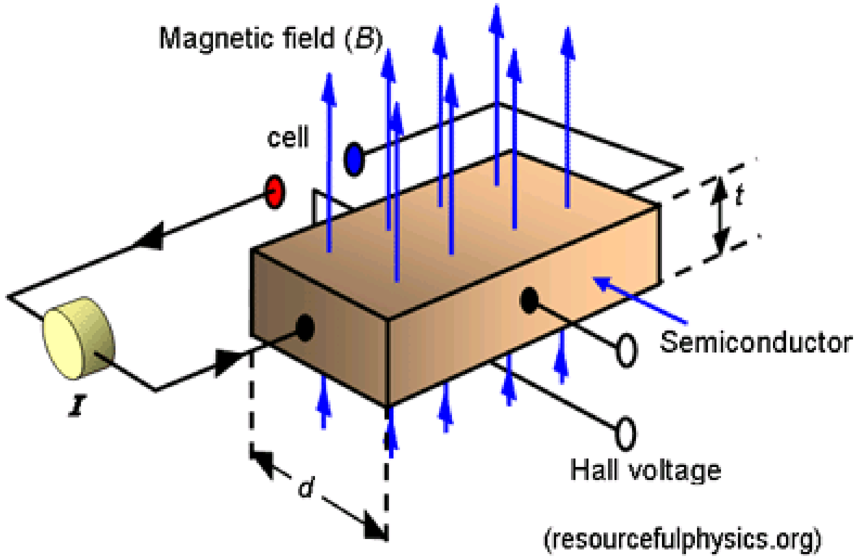
Compass

- Since over 2000 B.C.
  - China: suspended a piece of naturally magnetite from a silk thread 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 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 μTesla)
  - 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)



(resourcefulphysics.org)

Gyroscope

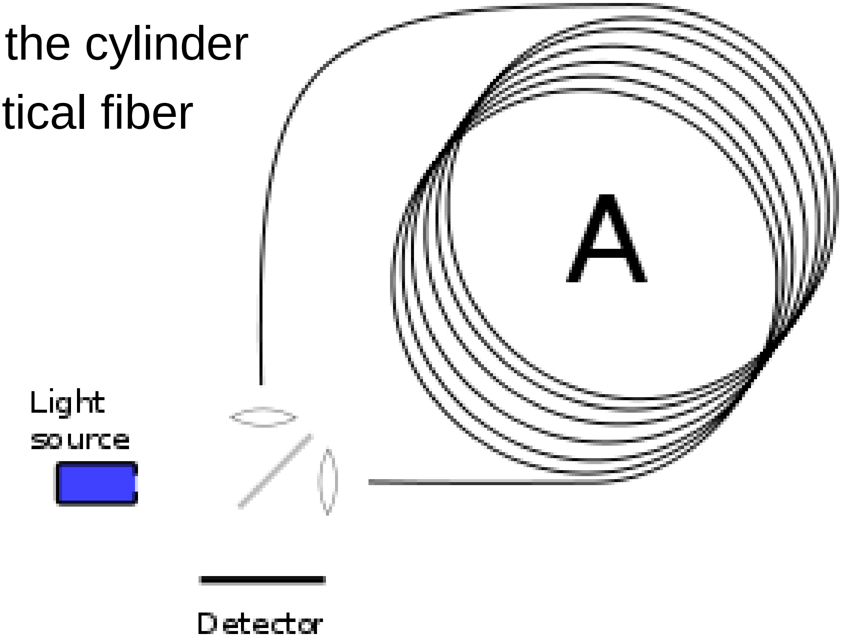
- Heading sensors that preserve their orientation in relation to a fixed reference frame
  - absolute measure for the heading of a mobile system.
- Two categories, the mechanical and the optical gyroscopes
  - Mechanical Gyroscopes
    - Standard gyro (angle)
    - Rate gyro (speed)
  - Optical Gyroscopes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

Optical Gyroscopes

- First commercial use: early 1980 in airplanes
- Optical gyroscopes
  - 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
  - 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.

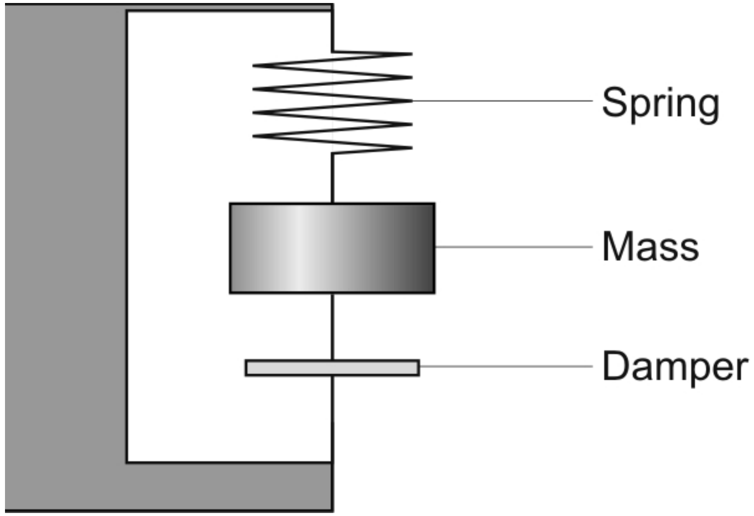

Single axis optical gyro


3-axis optical gyro

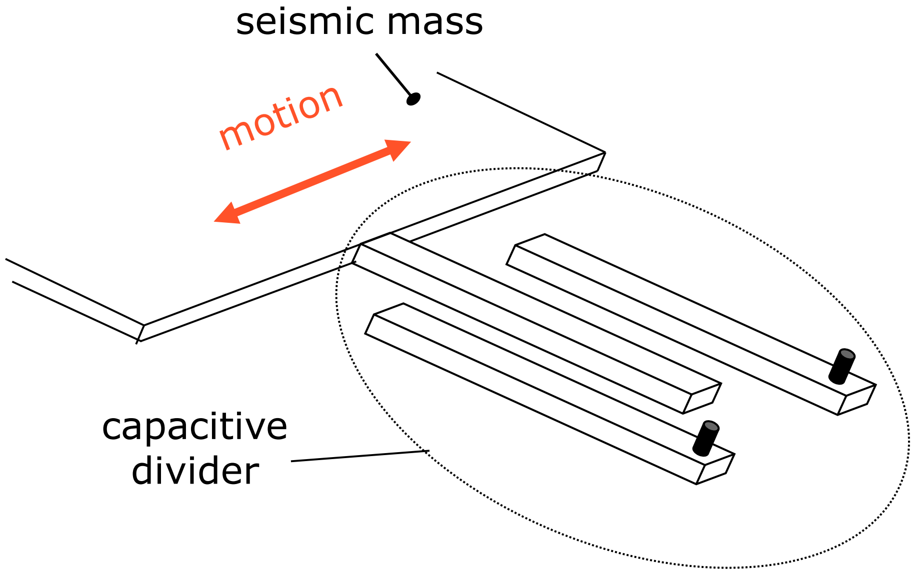


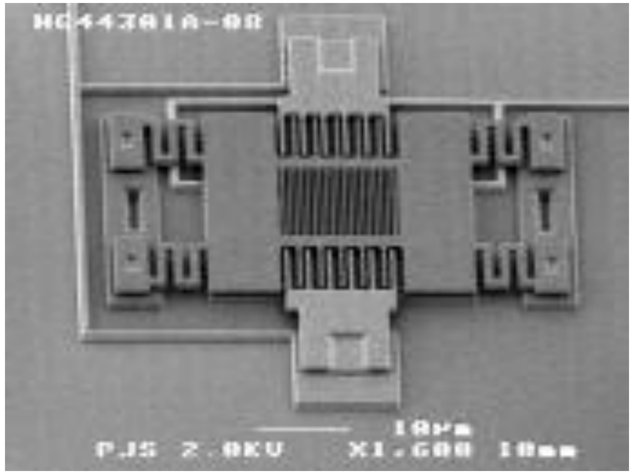
Mechanical Accelerometer

- 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

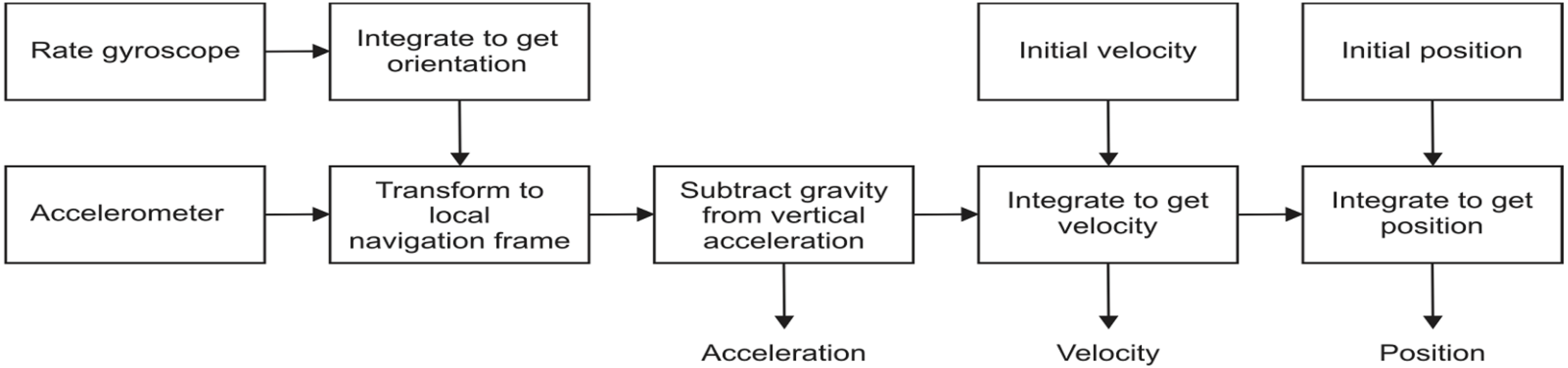
3. Applications

- 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



Rate gyroscope

Integrate to get orientation

Initial velocity

Initial position

Accelerometer

Transform to local navigation frame

Subtract gravity from vertical acceleration

Integrate to get velocity

Integrate to get position

Acceleration

Velocity

Position

IMU Error and Drift

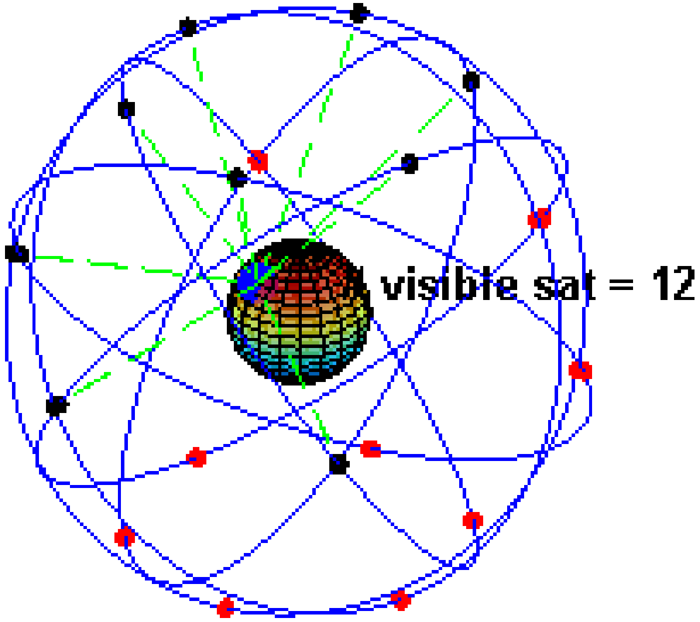
- Extremely sensitive to measurement errors in gyroscopes and accelerometers:
  - drift in the gyroscope unavoidably =>
  - error in orientation relative to gravity =>
  - incorrect cancellation of the gravity vector.

- 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)

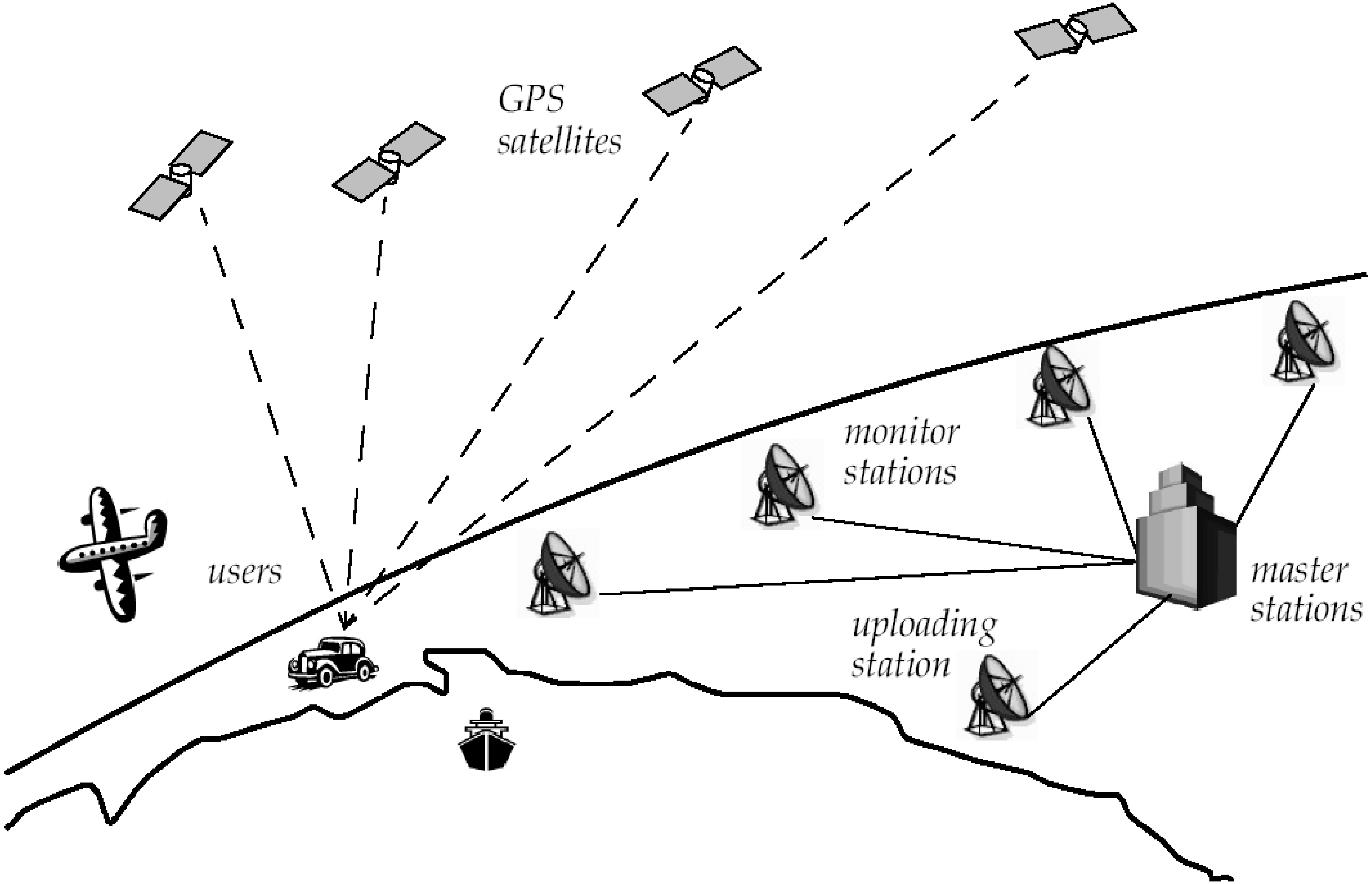
- Developed for military use
- 1995: accessible for commercial applications
- 32 satellites orbiting the earth every 12 hours at a height of 20.190 km.



- Method:
  - Position and motion vector of satellites orbital location (*ephemeris*) plus time transmitted to receiver
  - time of flight measurement => distance
  - **Trilateration** and **time correction** to compute location
  - Trilateration: use three **distances** to calculate position
  - (Triangulation: use three **angles** to calculate position)

Global Positioning System (GPS)

- 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)

- 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.

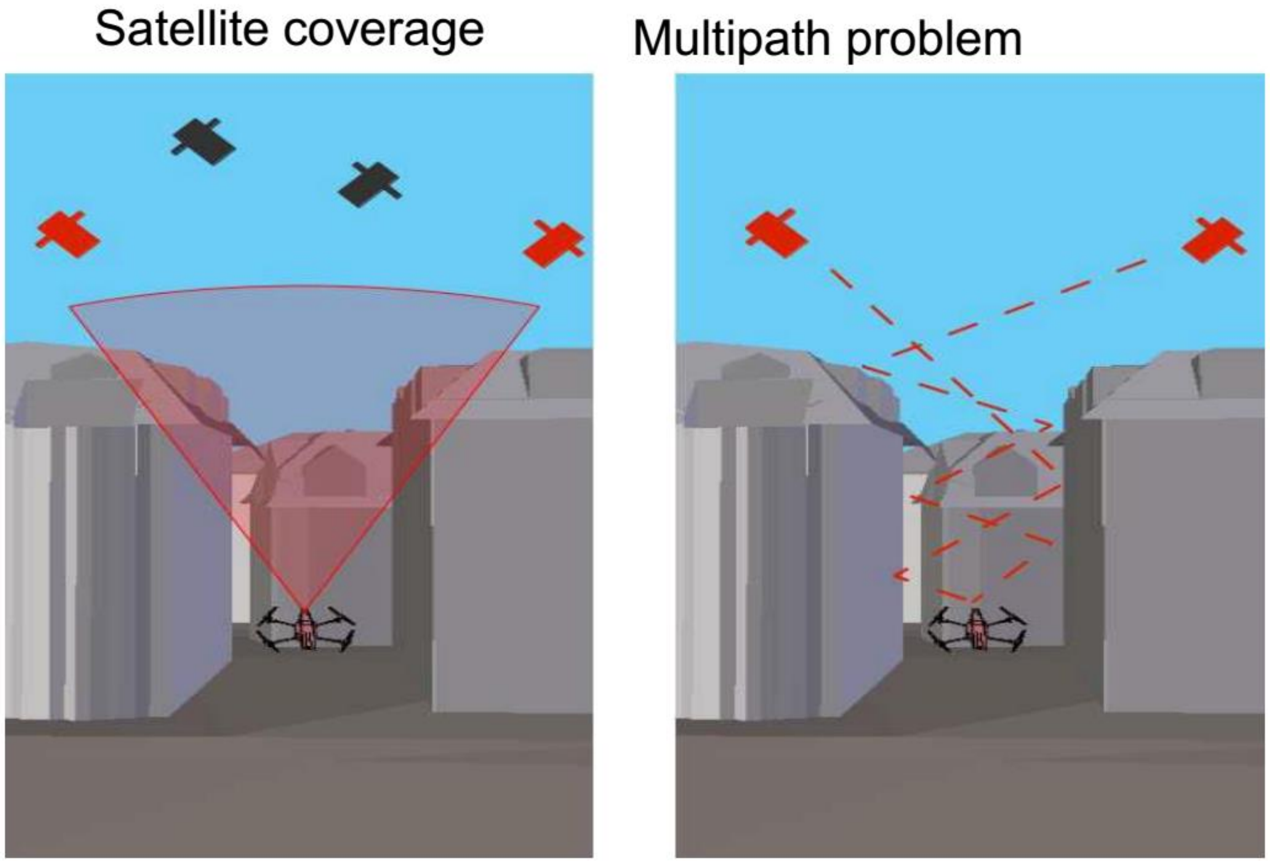
GPS Error Sources

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

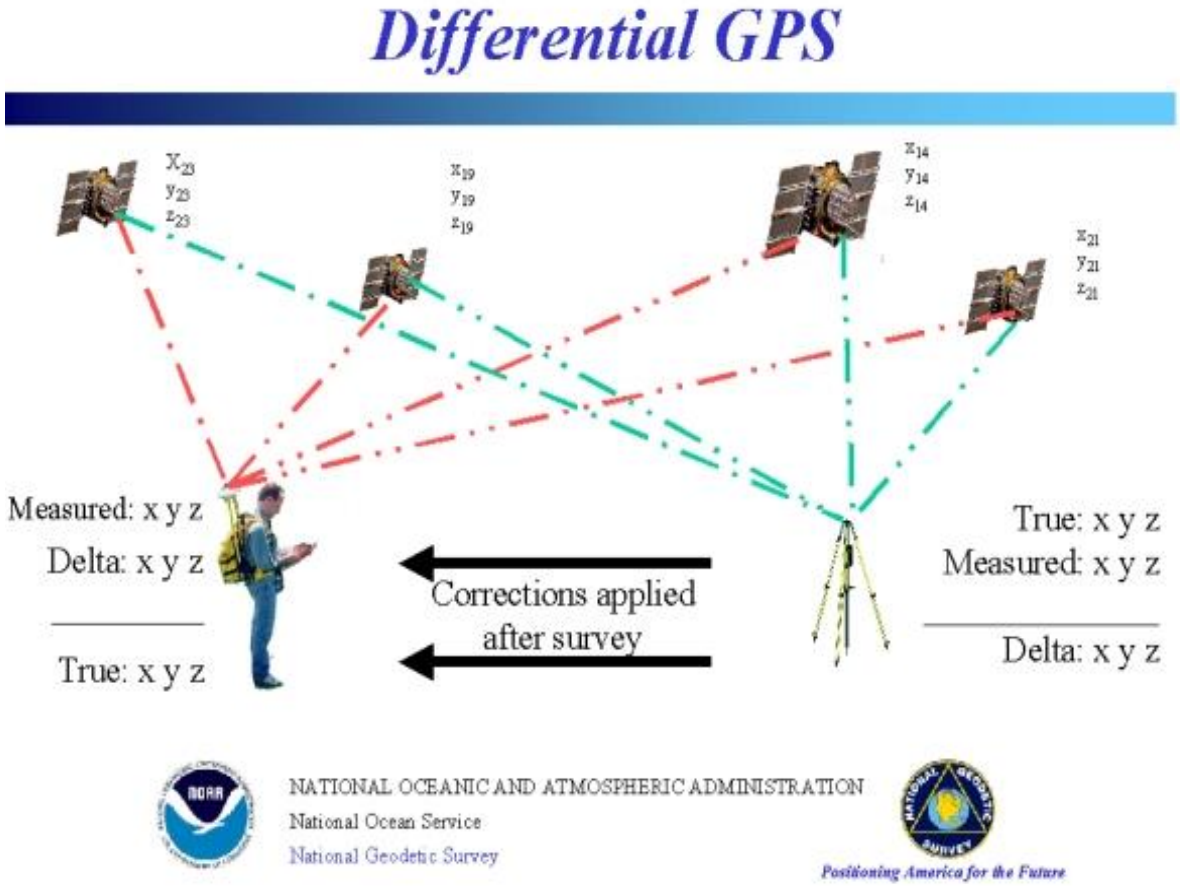
GPS Multipath

- 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.



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
  - 3 out of 7 satellites for Indian Coverage in orbit
  - Completion by 2015
- 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)

- Large range distance measurement -> called range sensors
- Range information:
  - key element for localization and environment modeling
- Ultrasonic sensors: propagate sound wave: speed of sound (in air or water)
- Laser range sensors: propagate light: speed of light
- Traveled distance:

$$d = c \cdot t$$

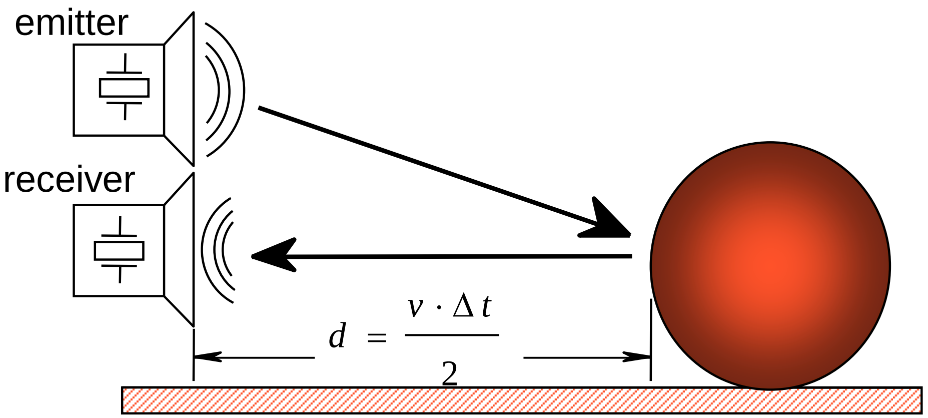
- Where
  - d = distance traveled (usually round-trip)
  - c = speed of wave propagation
  - t = time of flight.

Range Sensors (time of flight)

- It is important to point out
  - Propagation speed v of sound in air: 300 m/s
  - Propagation speed v of sound in water: 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

Factsheet: Ultrasonic Range Sensor



$$d = \frac{v \cdot \Delta t}{2}$$

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)

- 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*.

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

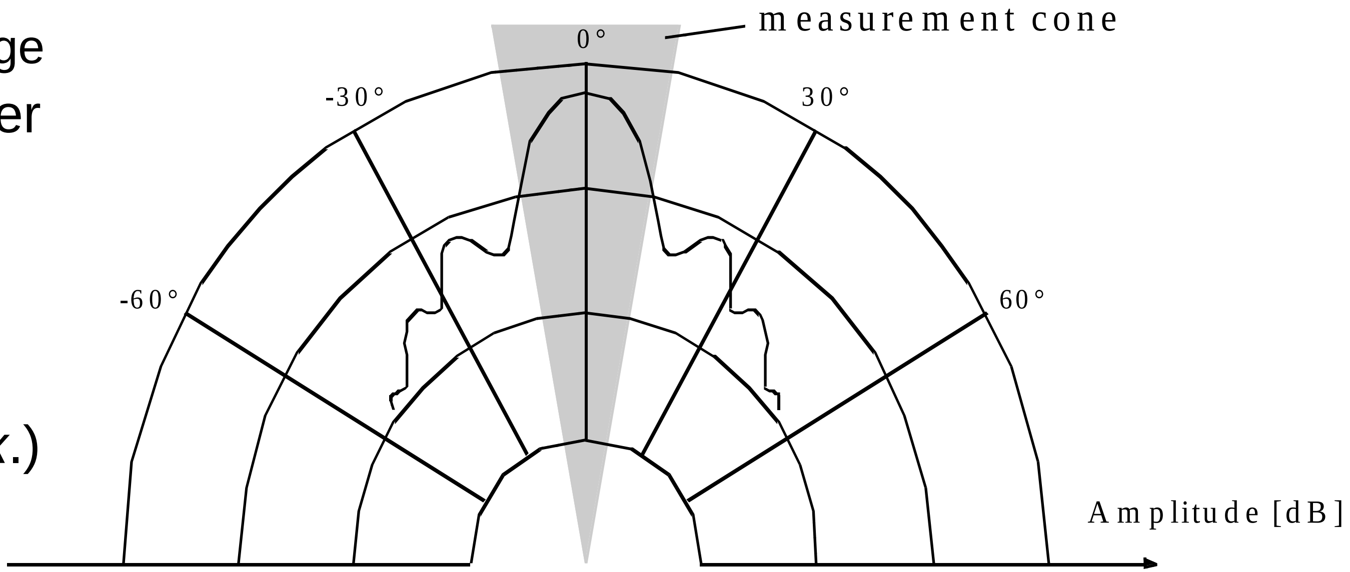
- The speed of sound *c* (340 m/s) in air is given by $\sqrt{\gamma \cdot R \cdot T}$

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)

- 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
- Problems:
  - soft surfaces that absorb most of the sound energy
  - surfaces that are far from being perpendicular to the direction of the sound -> specular reflection



Typical intensity distribution of a ultrasonic sensor

Laser Range Sensor (time of flight, electromagnetic)

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

SICK

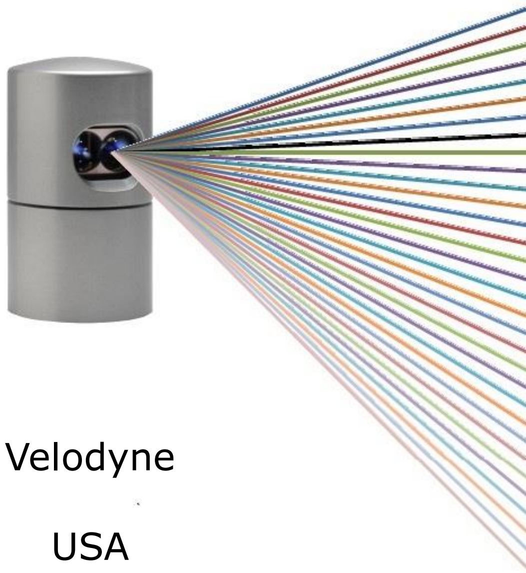
Germany

High Quality,
Safety Certification
Expensive

Hokuyo

Japan

Small sizes,
Popular for Robotics

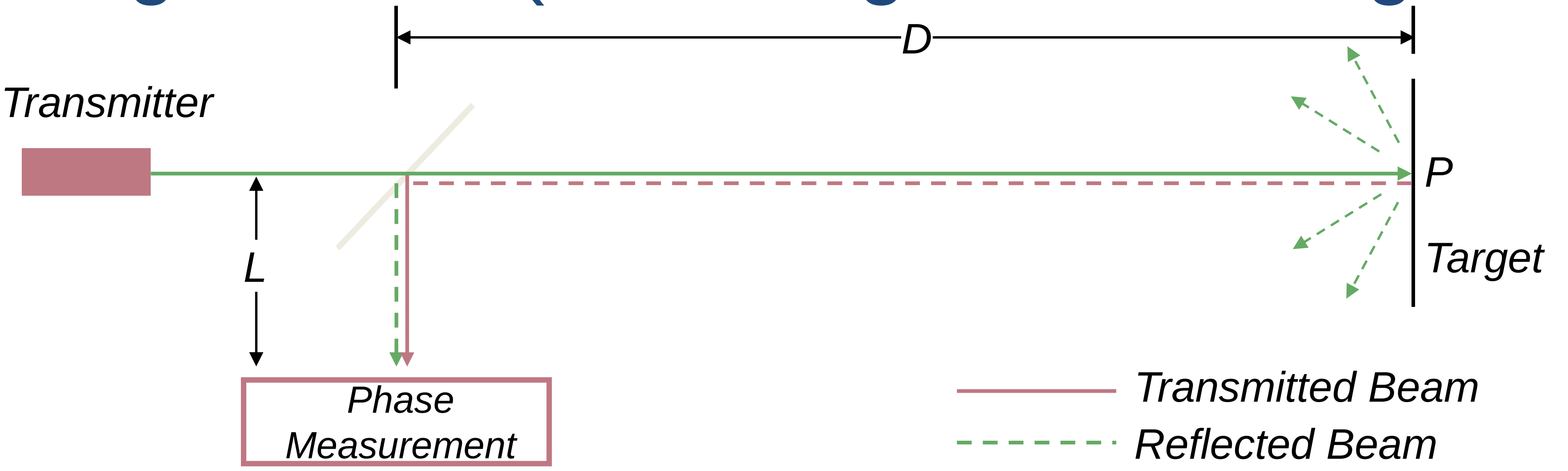


Velodyne

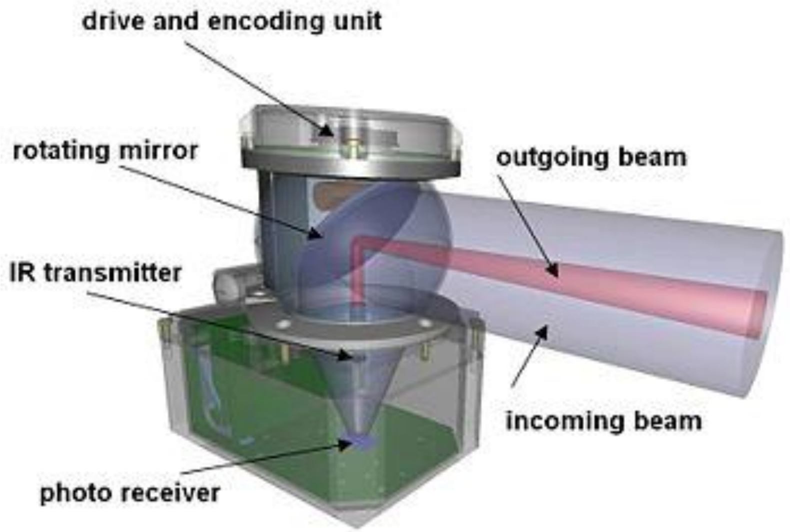
USA

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

Laser Range Sensor (time of flight, electromagnetic)

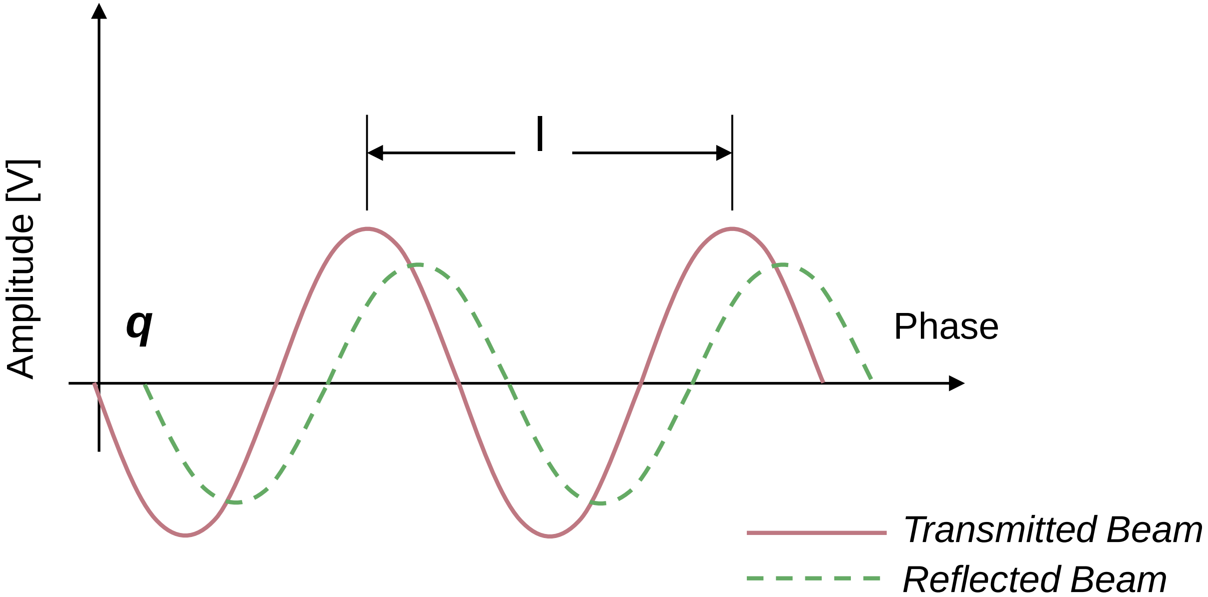


- Transmitted and received beams coaxial
- Transmitter illuminates a target with a collimated laser beam
- Received detects the time needed for round-trip
- Mechanical mirror mechanism to measure different points
  - 2D or 3D measurement



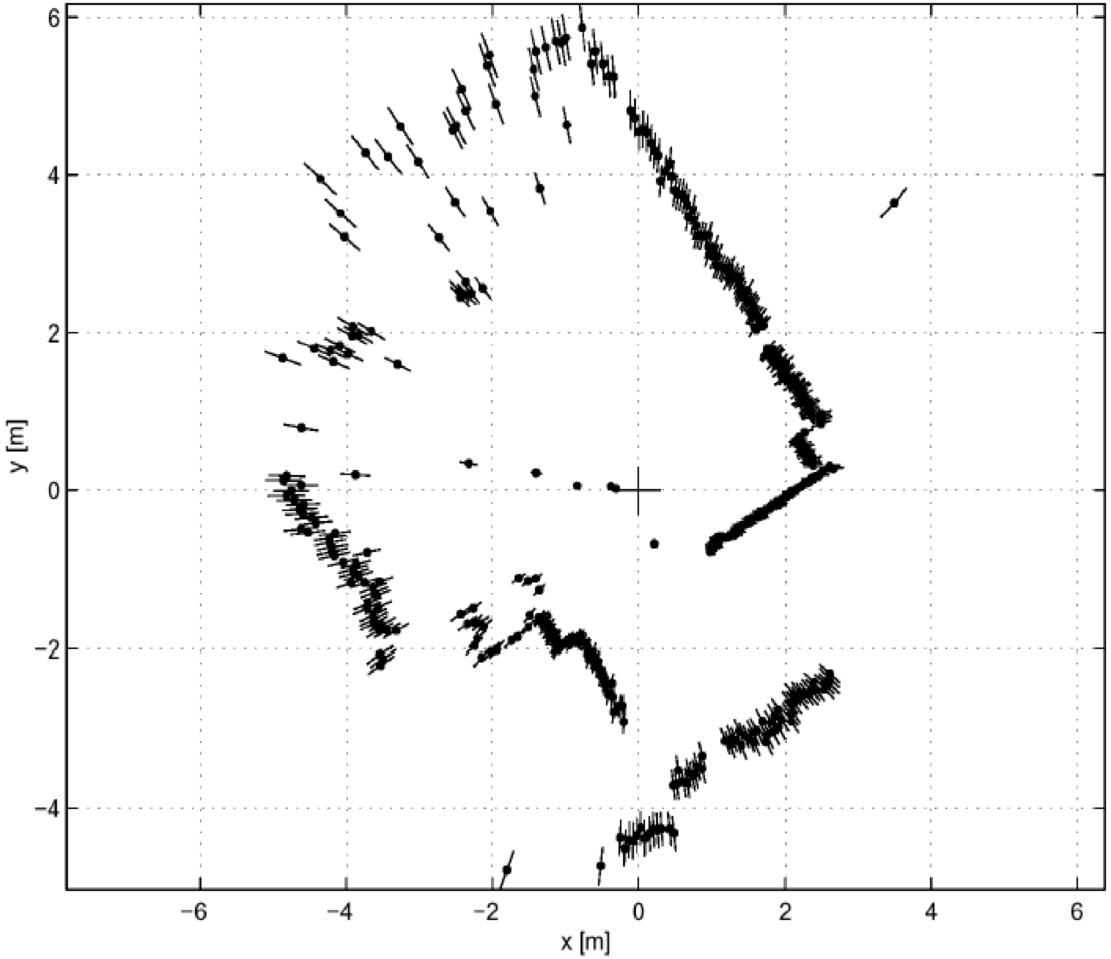
Laser Range Sensor (time of flight, electromagnetic)

- Time of flight measurement
- Pulsed laser
  - 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)

- 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.



Hokuyo UTM-30LX

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

- Cost: about 35,000 RMB

URG-04LX-UG01

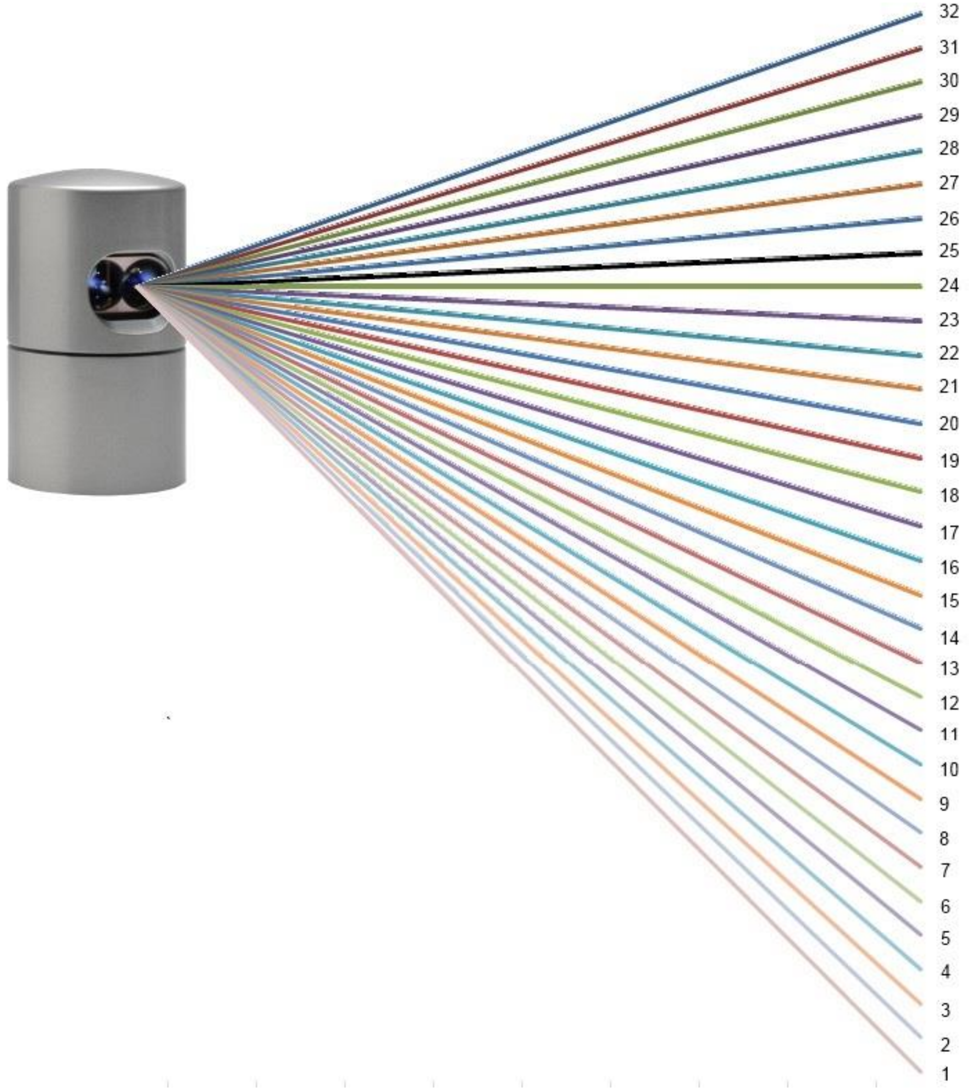
- Low-power consumption (2.5W)
- Wide-range (5600mm×240°)
- 60 to 1,000mm : ±30mm
- 1,000 to 4,095mm : ±3% of measurement
- 10Hz
- Dimensions: 50 x 50 x 70 mm
- Weight: 160g

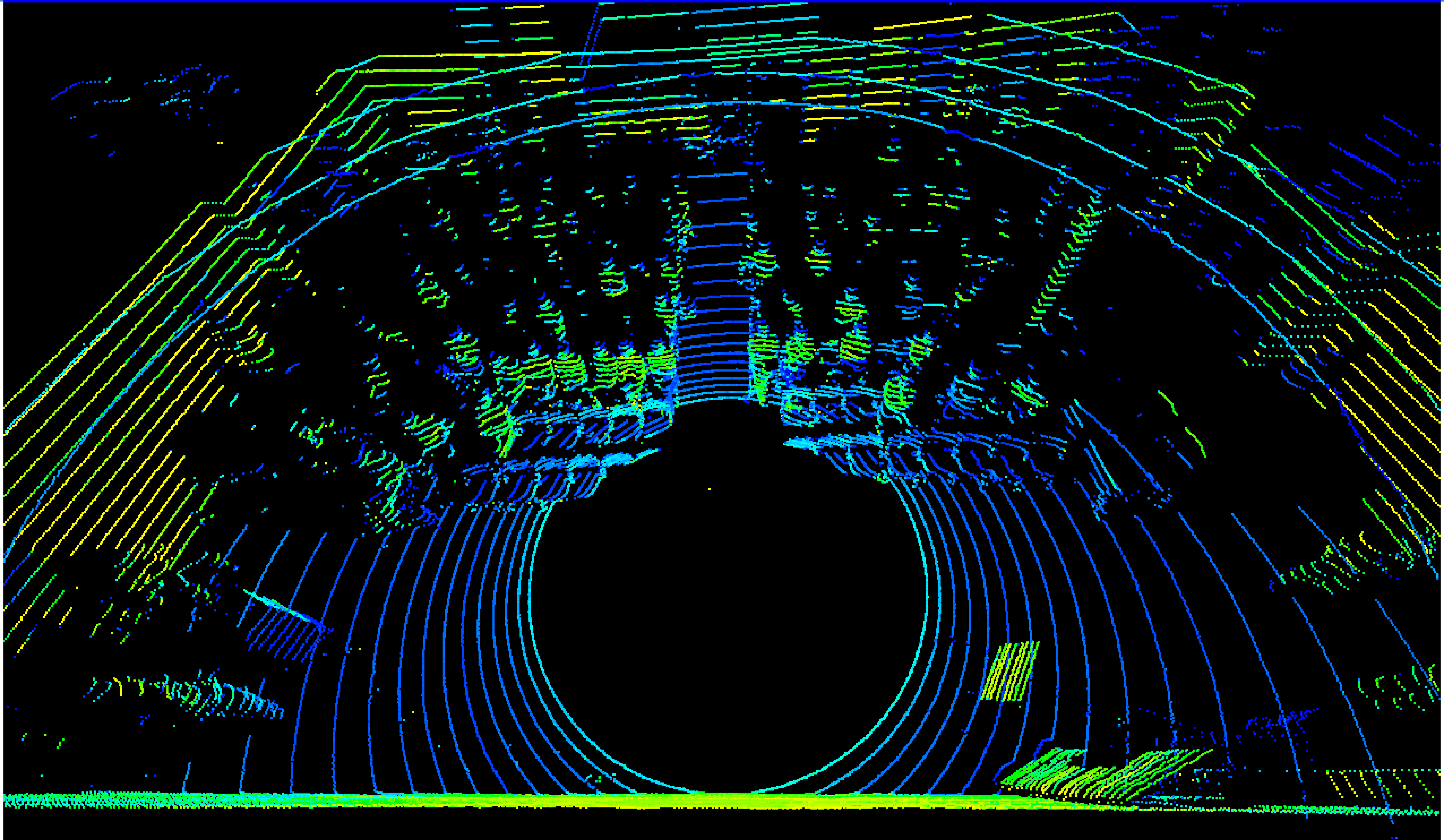
- Cost: about 6,500 RMB

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





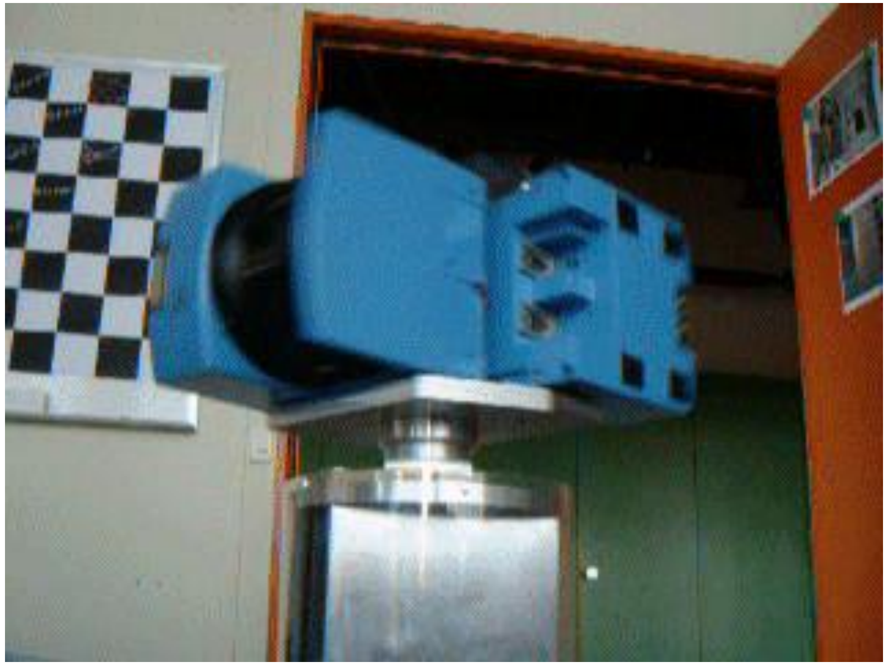
Laser Range Finder: Applications

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

Jack the Gripper
Jacobs University – DLR SpaceBot Cup

Actuated 2D LRF

- Acquire distance data in more than a single plane.
- Nodding or rotating stepwise or continuous
- A full spherical field of view can be covered (360° in azimuth and 90° in elevation).
- However, acquisition takes up to some seconds!



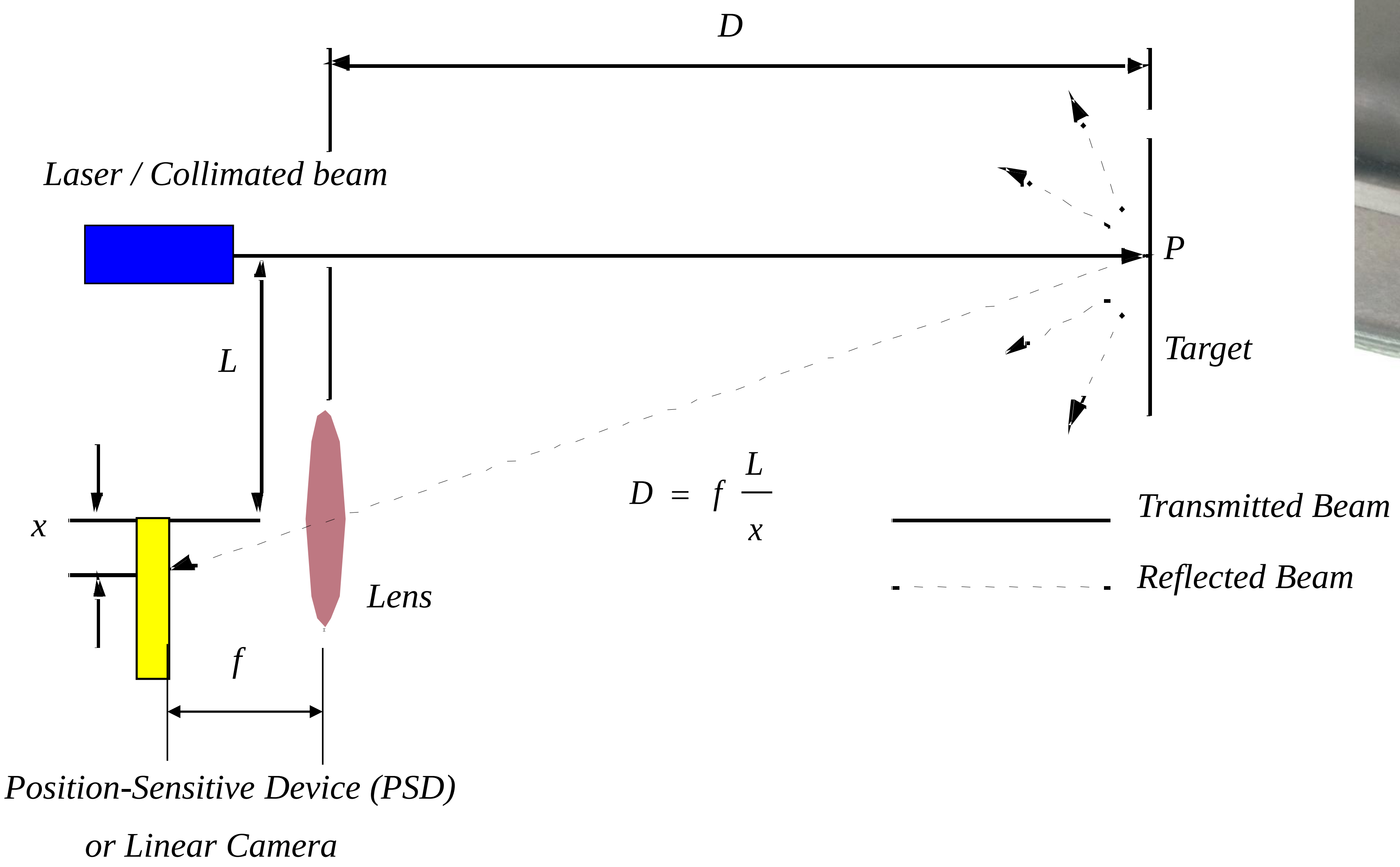
Triangulation Ranging

- 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)

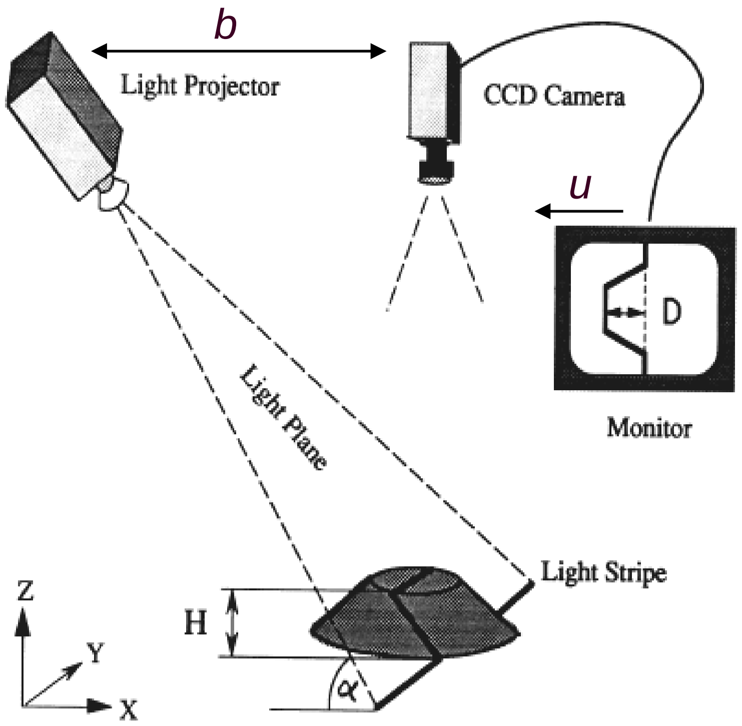


$$D = f\,\frac{L}{x}$$

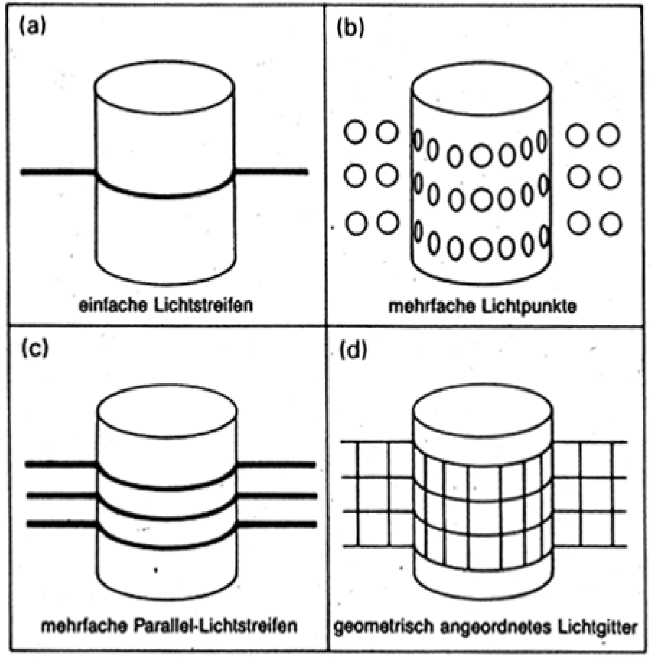
Cliff sensor on Turtle-bot

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

a



b

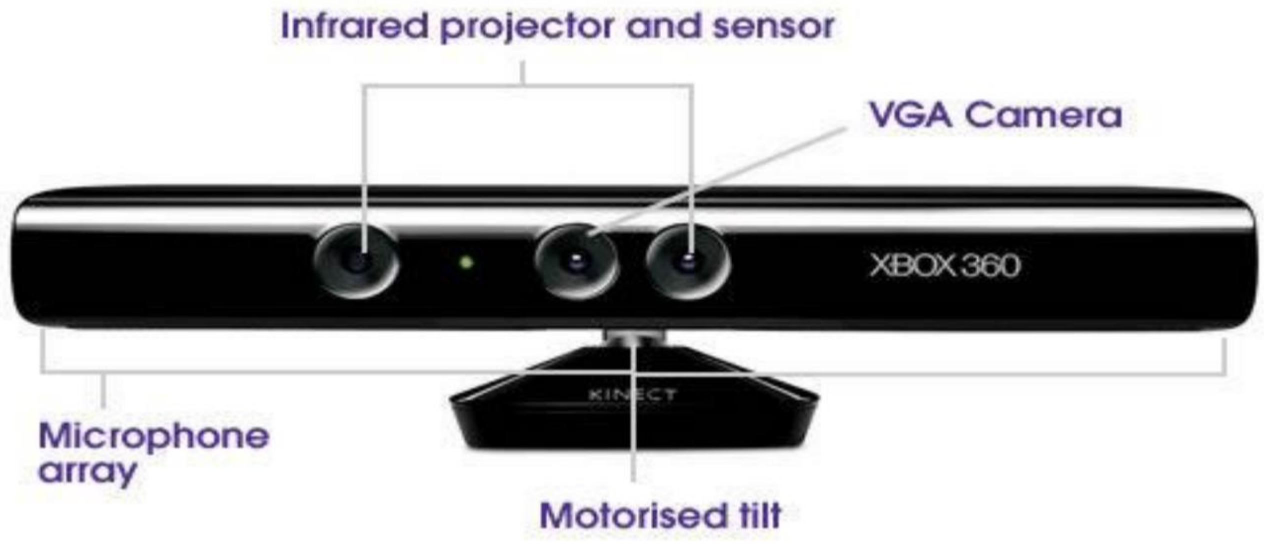


- Illuminate scene with a known pattern
- Light perceived by camera
- Range to an illuminated point can then be determined from simple geometry.

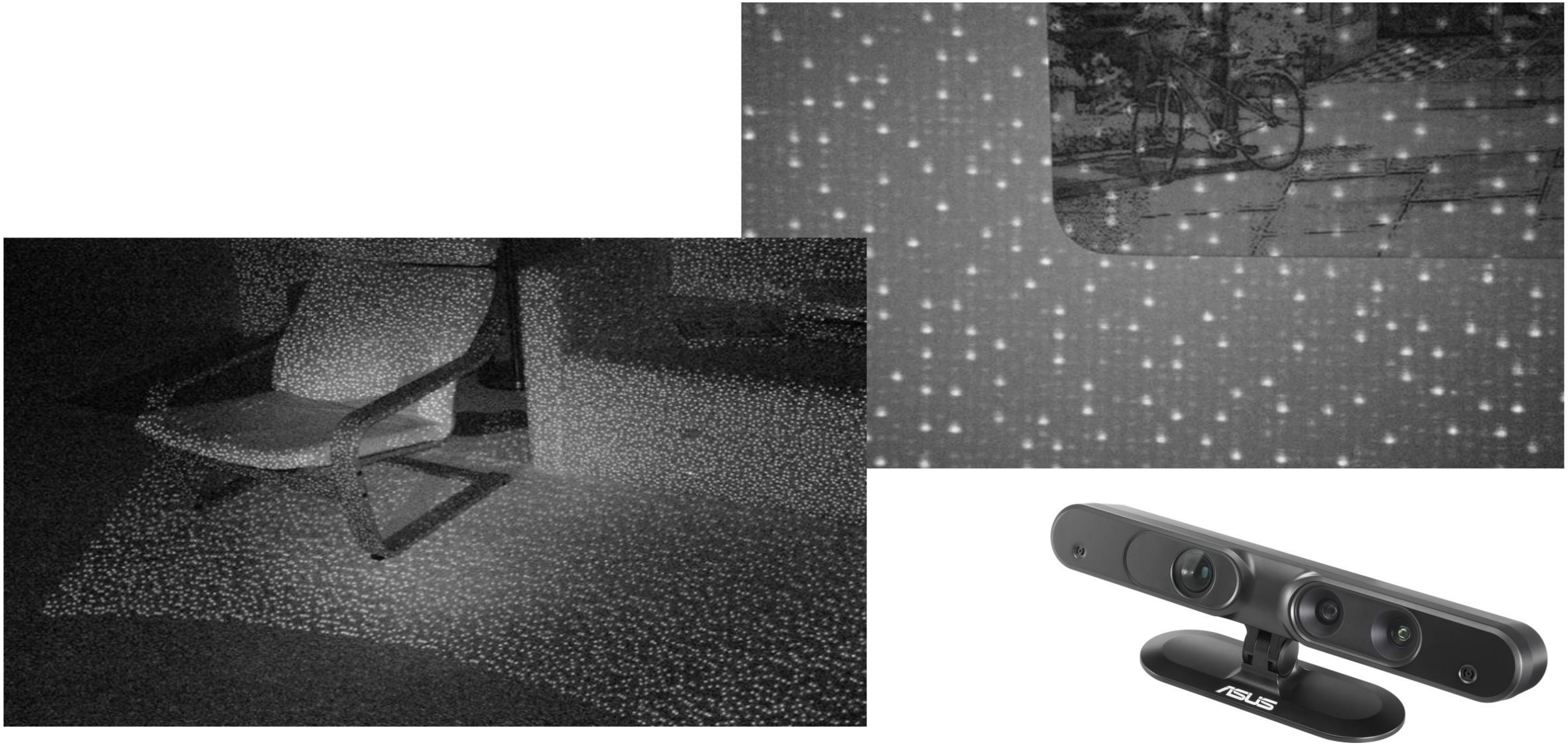
PrimeSense Cameras

- Devices: Microsoft Kinect and Asus Xtion (on TurtleBot)
- 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



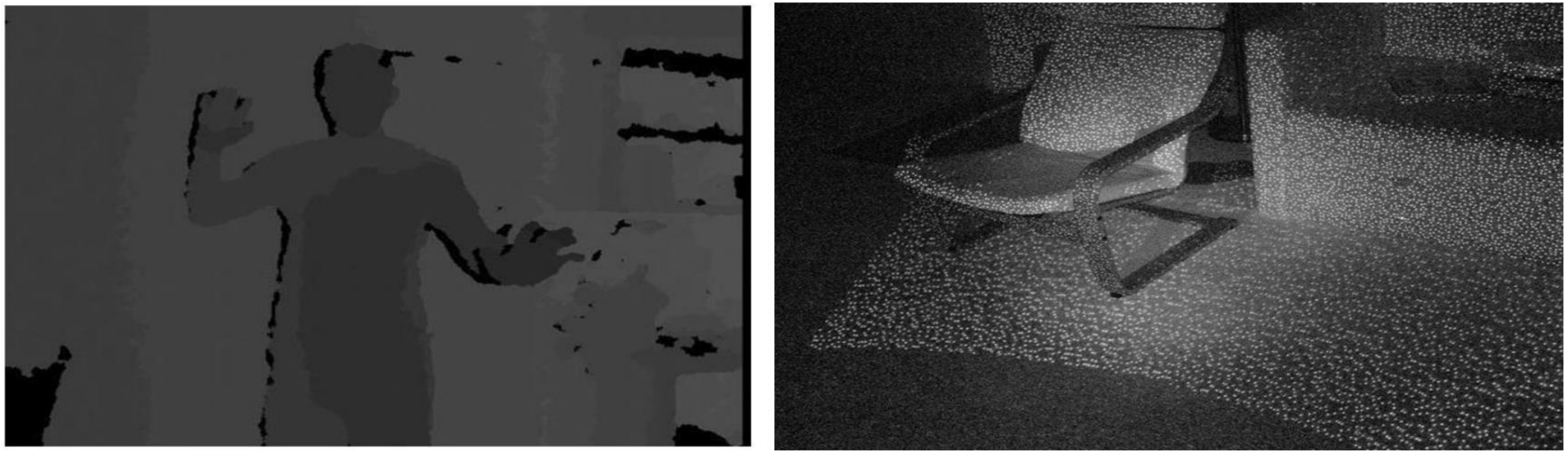
IR Pattern



Depth Map

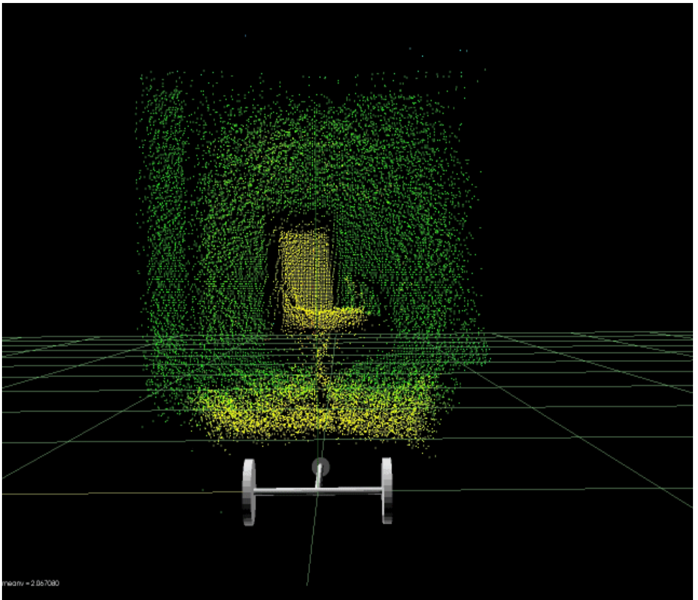
Kinect: Depth Computation

- **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

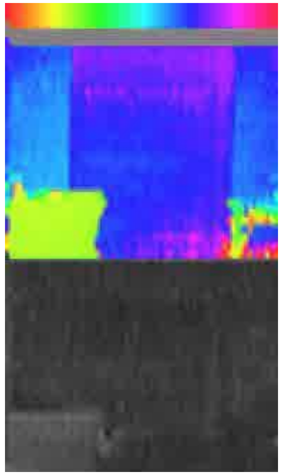


3D Range Sensor: Time Of Flight (TOF) camera

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



Swiss Ranger 3000
(produced by MESA)

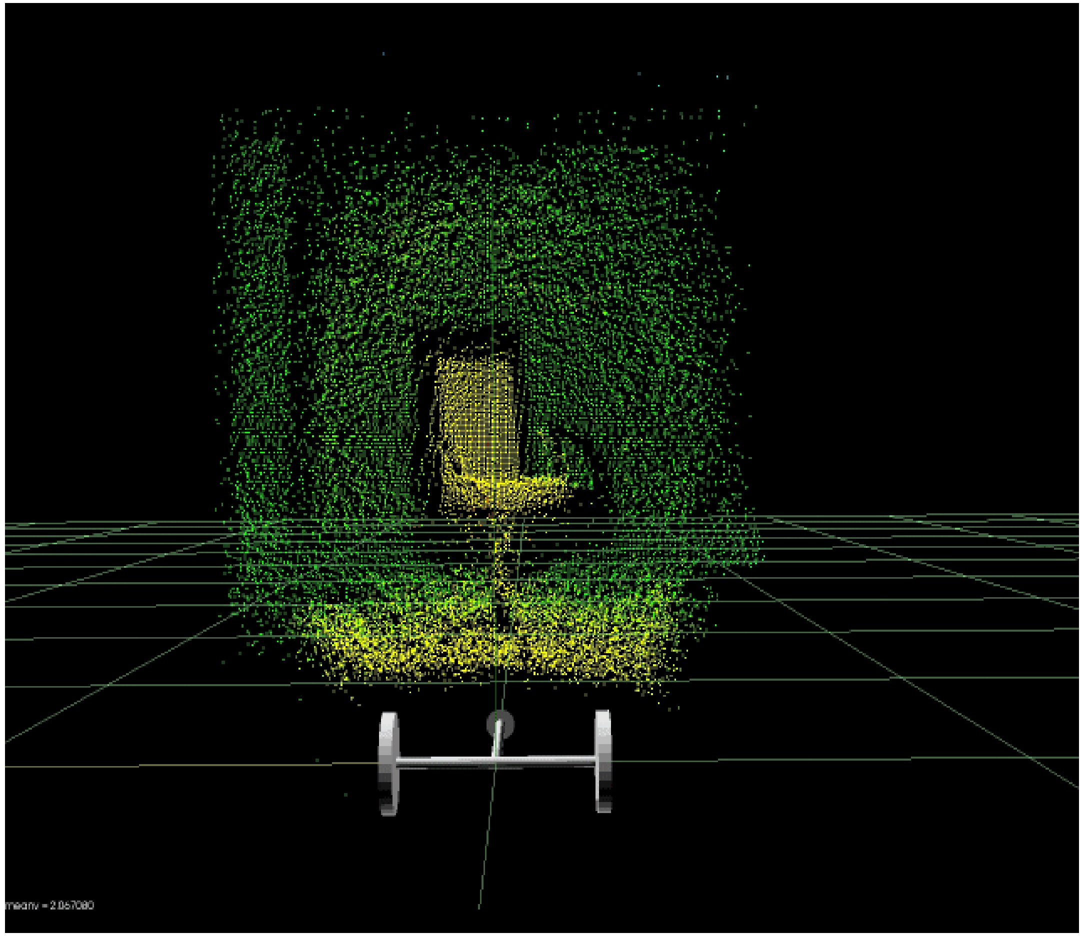


ZCAM
(from 3DV Systems now bought by
Microsoft for Project Natal)

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!



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

PERCEPTION EXAMPLE: LINE EXTRACTION

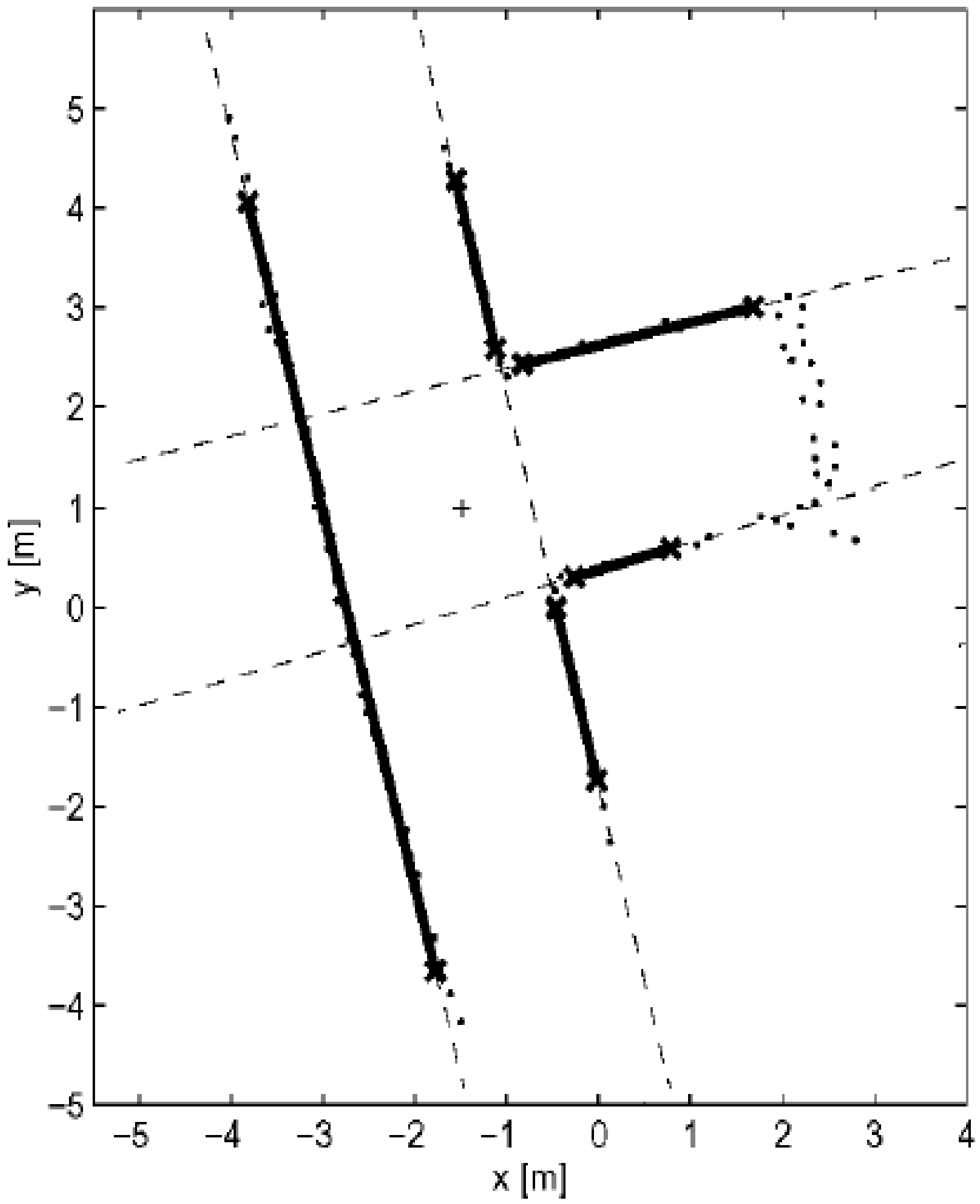
Line Extraction: Motivation

- Laser Range Scan
  - Example: 360 deg – black points
  - Example: dashed lines: desired line extractions

- Use detected lines for:
  - Scan registration (find out transform between frames of two consecutive LRF scans – change due to robot motion)

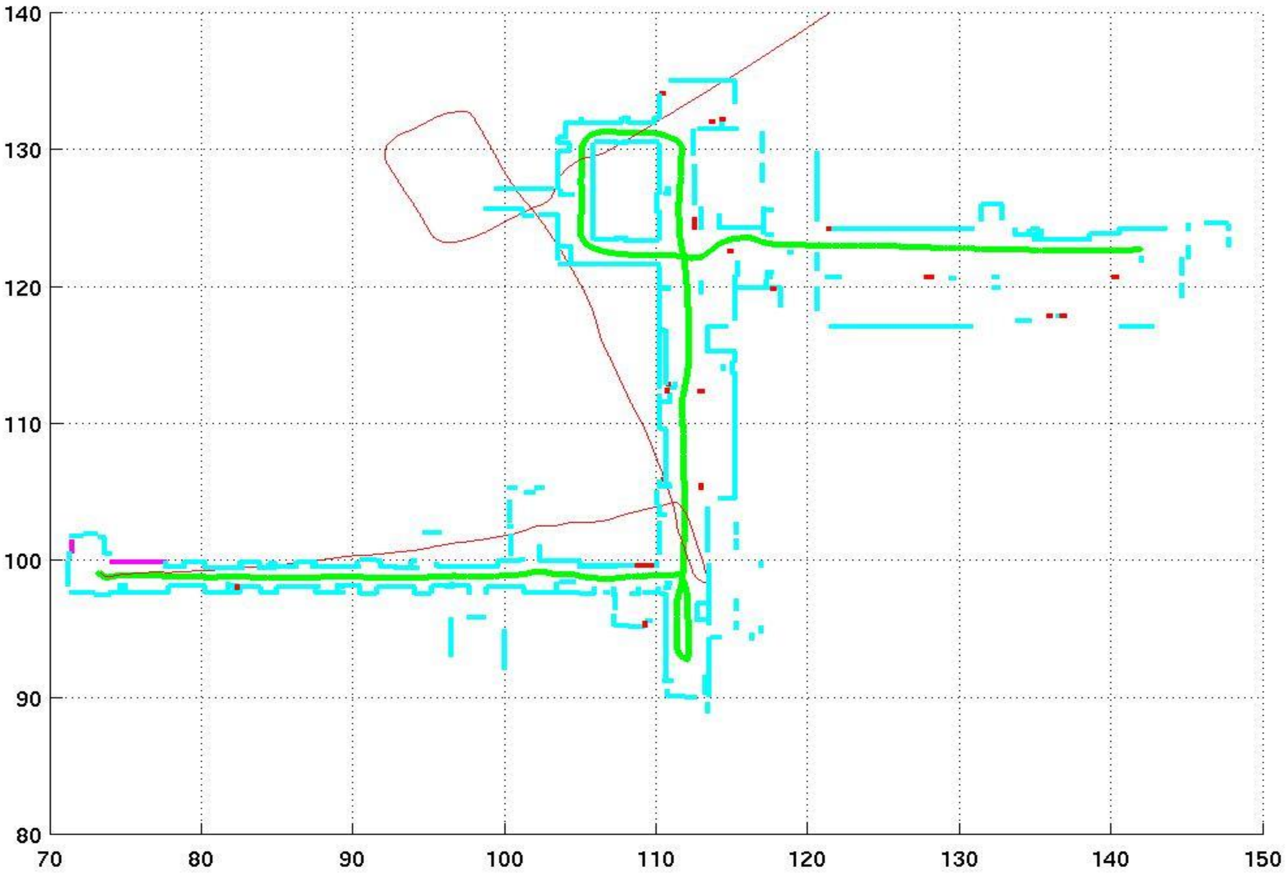
  OR

  - Mapping using line representation



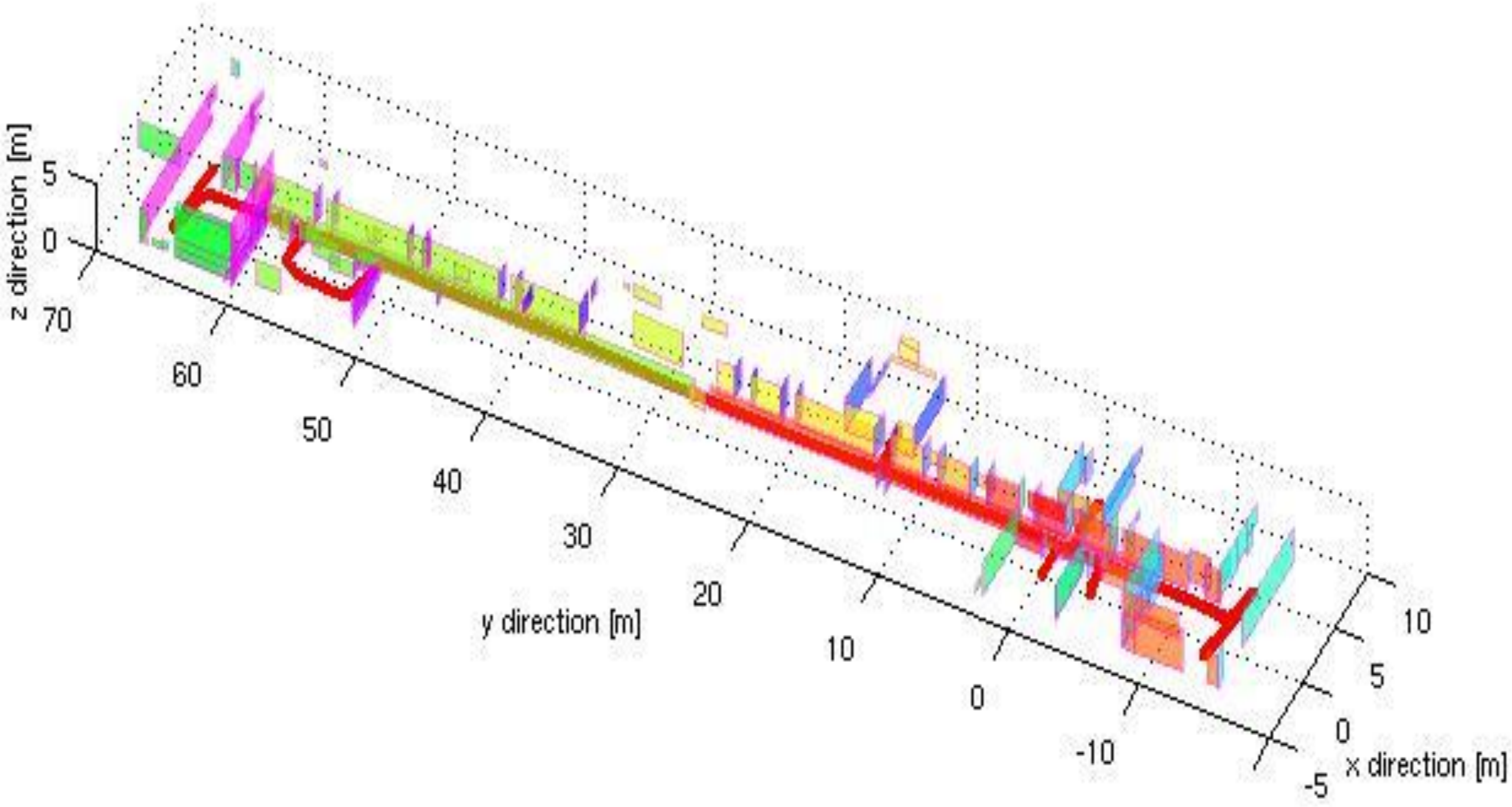
Line Extraction: Motivation

- Map of hallway built using line segments



Line Extraction: Motivation

- Map of the hallway built using orthogonal planes constructed from line segments

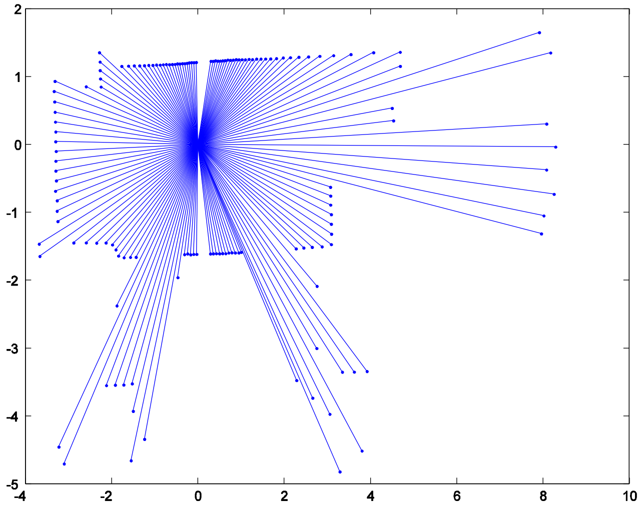


Line Extraction: Motivation

- Why laser scanner:
  - Dense and accurate range measurements
  - High sampling rate, high angular resolution
  - Good range distance and resolution.

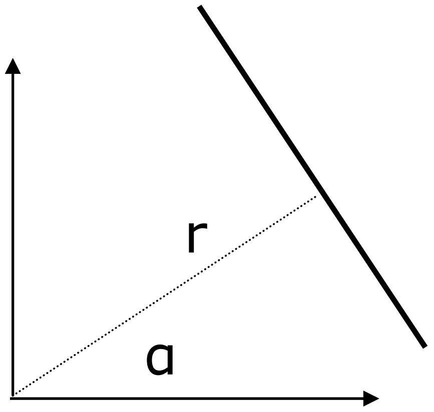
- Why line segment:
  - The simplest geometric primitive
  - Compact, requires less storage
  - Provides rich and accurate information
  - Represents most office-like environment.

Line Extraction: The Problem



- Scan point in polar form: (ρ_i, θ_i)

- Assumptions:
  - Gaussian noise
  - Negligible angular uncertainty



- Line model in polar form:
  - $x \cos \alpha + y \sin \alpha = r$
  - $-\pi < \alpha <= \pi$
  - $r >= 0$

Line Extraction: The Problem (2)

- Three main problems:
  - How many lines ?
  - Which points belong to which line ?
    - This problem is called SEGMENTATION
  - Given points that belong to a line, how to estimate the line parameters ?
    - This problem is called LINE FITTING

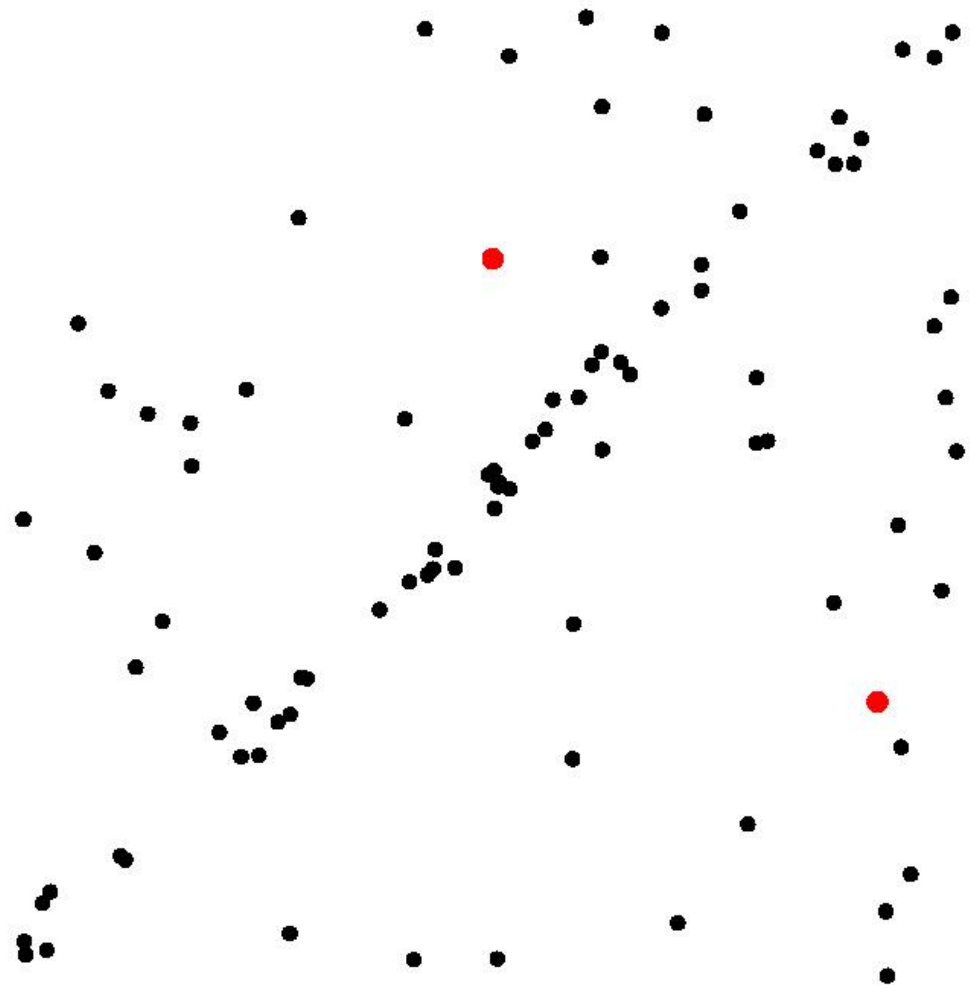
- One option: RANSAC

RANSAC: RANdom SAmple Consensus

- Generic and robust fitting algorithm of models with outliers
  - Outlier: point which does not satisfy a model
- RANSAC: many applications:
  - Goal: identify the inliers which satisfy a predefined mathematical model
- Typical robotics applications:
  - line extraction from 2D range data (sonar or laser);
  - plane extraction from 3D range data,
  - structure from motion
- RANSAC:
  - Iterative: runs in a loop over and over again
  - non-deterministic: outcome is different in every run (because of random component)
  - => more iterations likelihood to find good result increases
- <u>Drawback: A nondeterministic method, results are different between runs.</u>

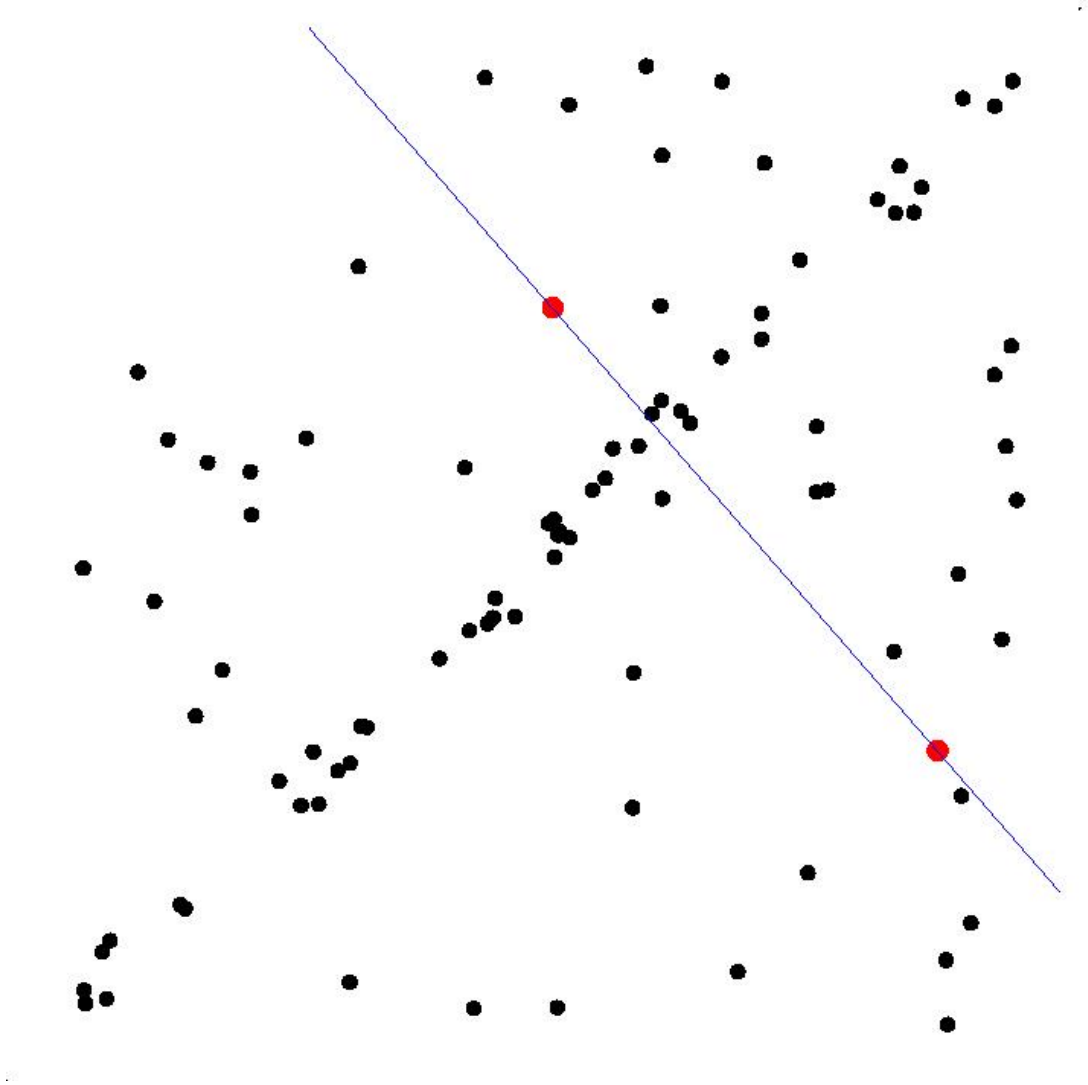
Algorithm 3: RANSAC

Algorithm 3: RANSAC



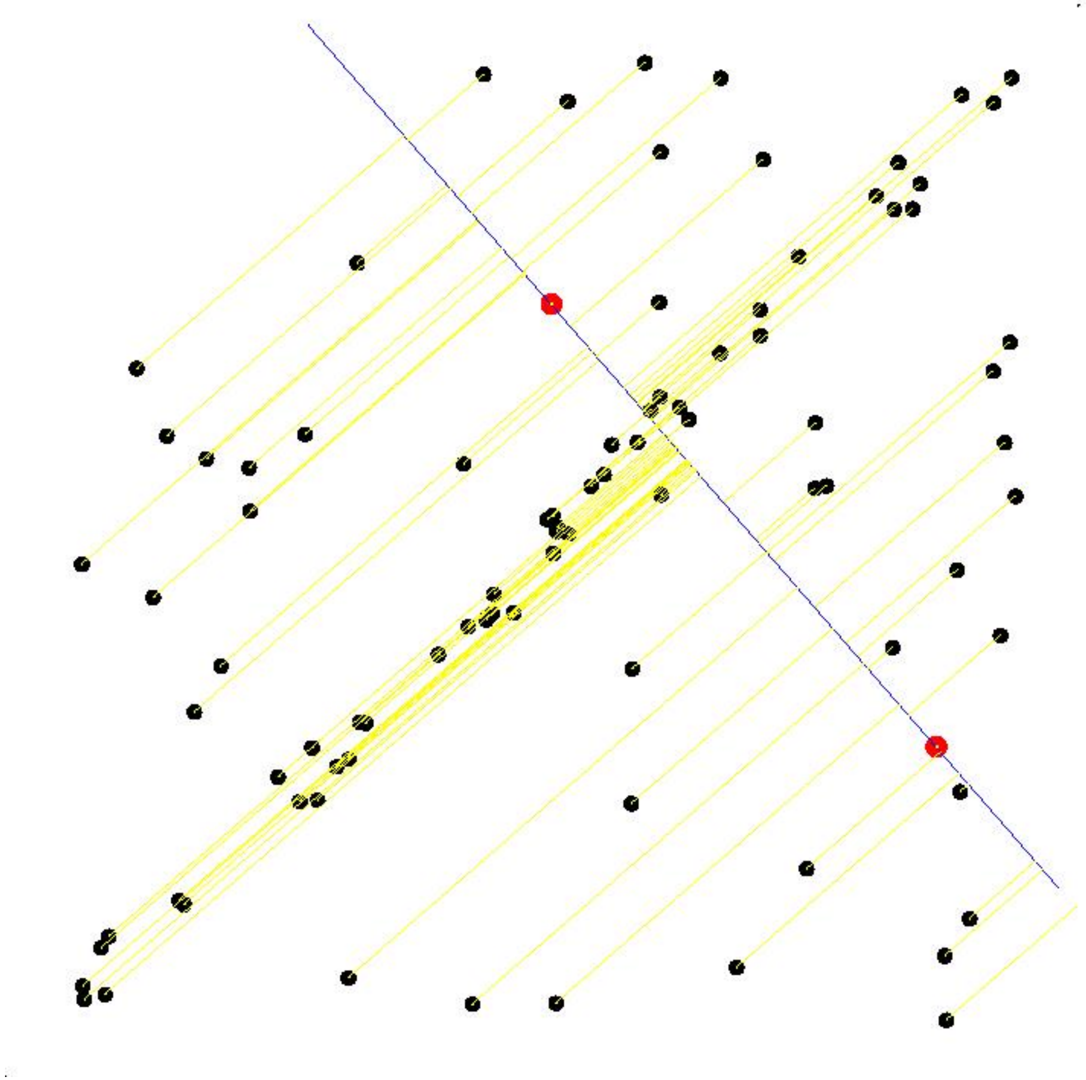
- **Select sample of 2 points at random**

Algorithm 3: RANSAC



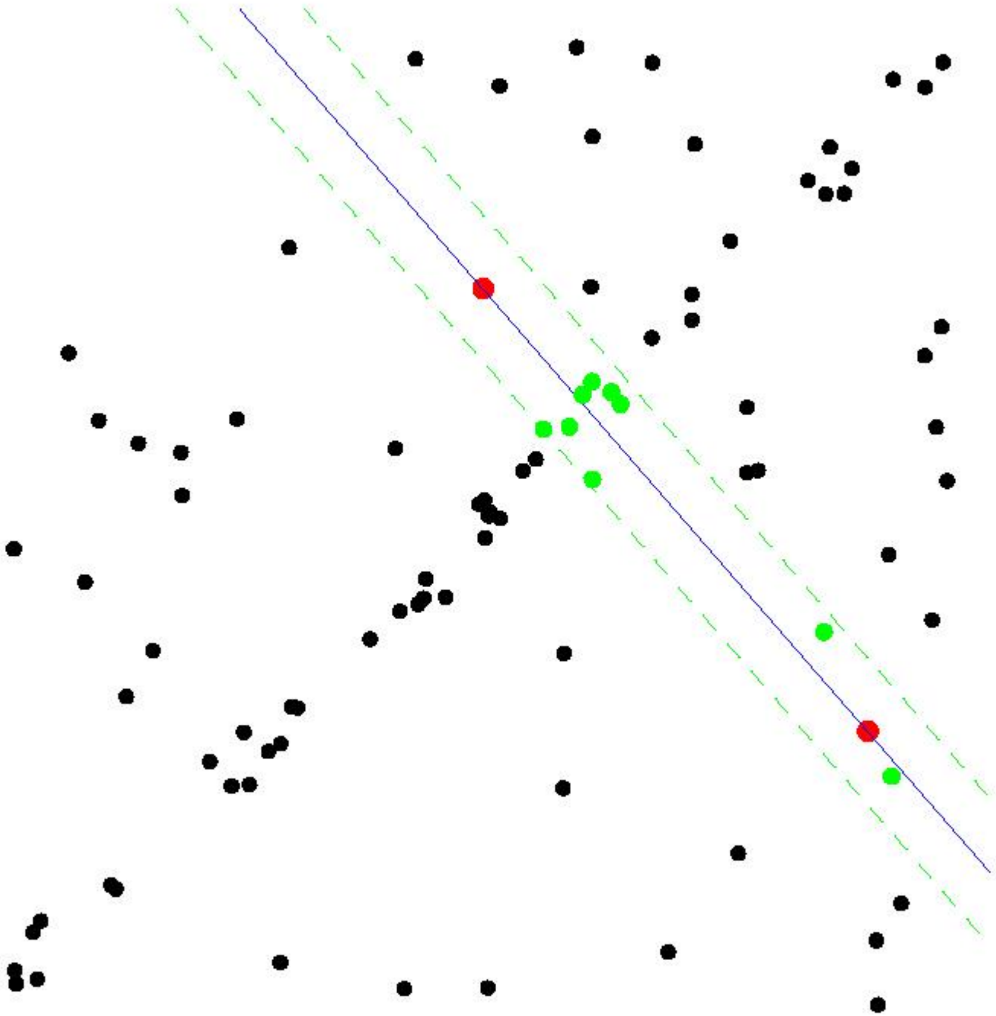
- Select sample of 2 points at random
- **Calculate model parameters that fit the data in the sample**

RANSAC



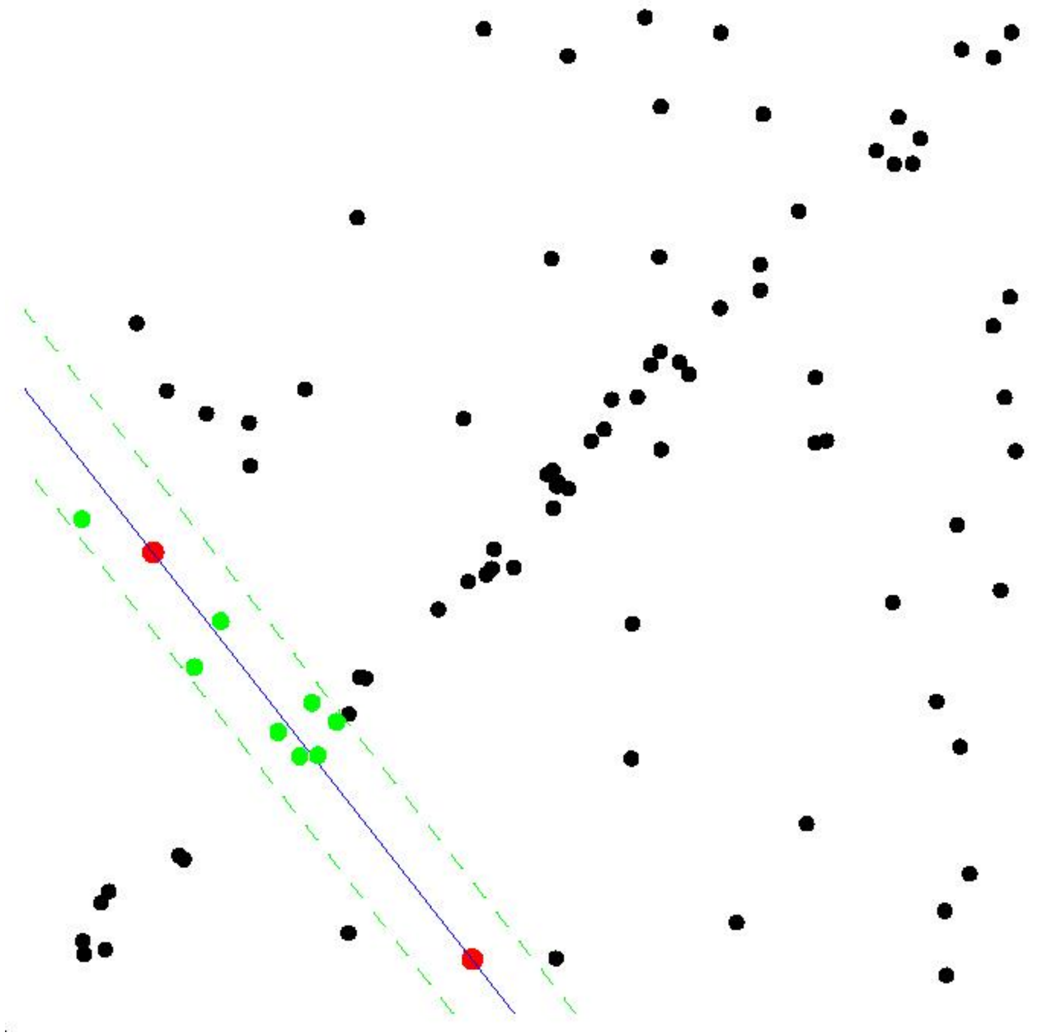
- Select sample of 2 points at random
- Calculate model parameters that fit the data in the sample
- **Calculate error function for each data point**

Algorithm 3: RANSAC



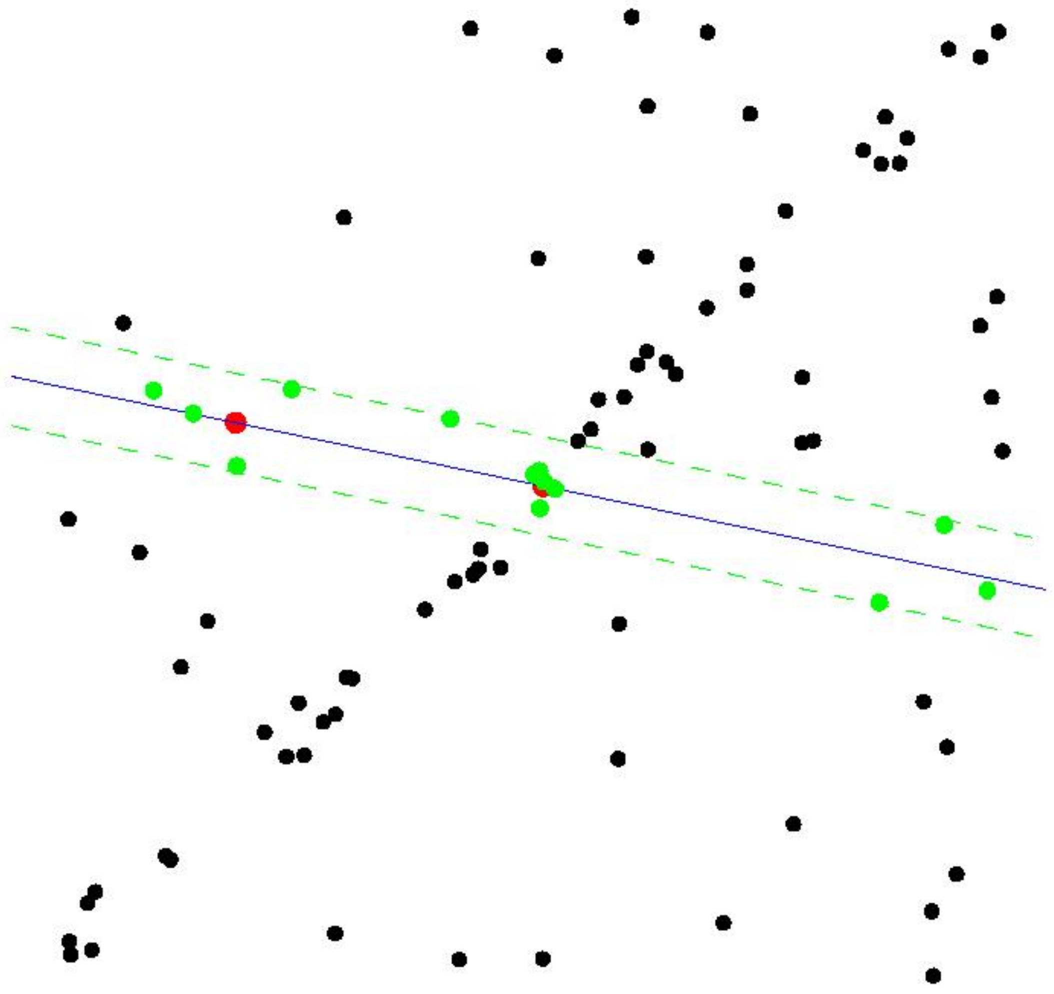
- Select sample of 2 points at random
- Calculate model parameters that fit the data in the sample
- Calculate error function for each data point
- **Select data that support current hypothesis**

Algorithm 3: RANSAC



- Select sample of 2 points at random
- Calculate model parameters that fit the data in the sample
- Calculate error function for each data point
- Select data that support current hypothesis
- **Repeat sampling**

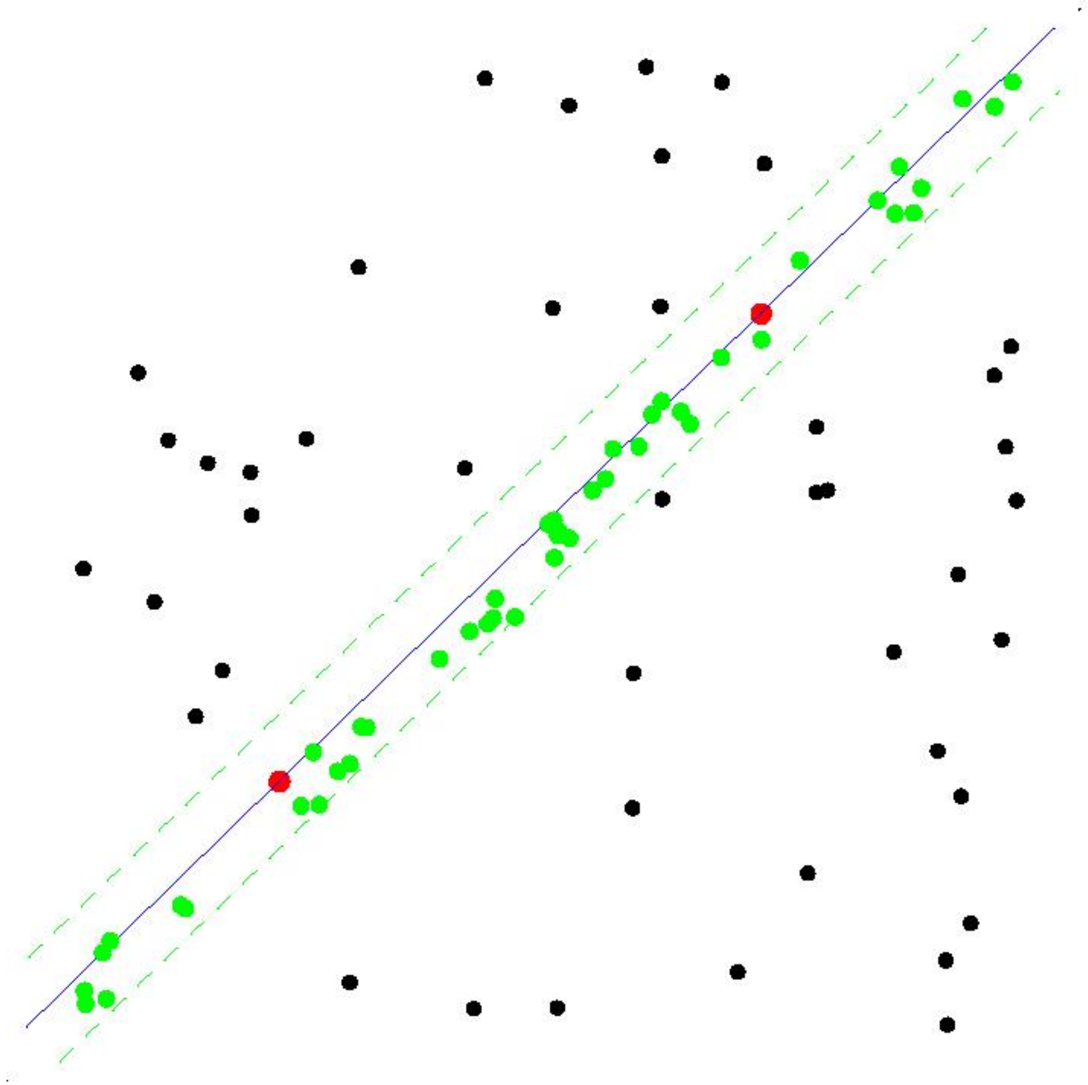
Algorithm 3: RANSAC



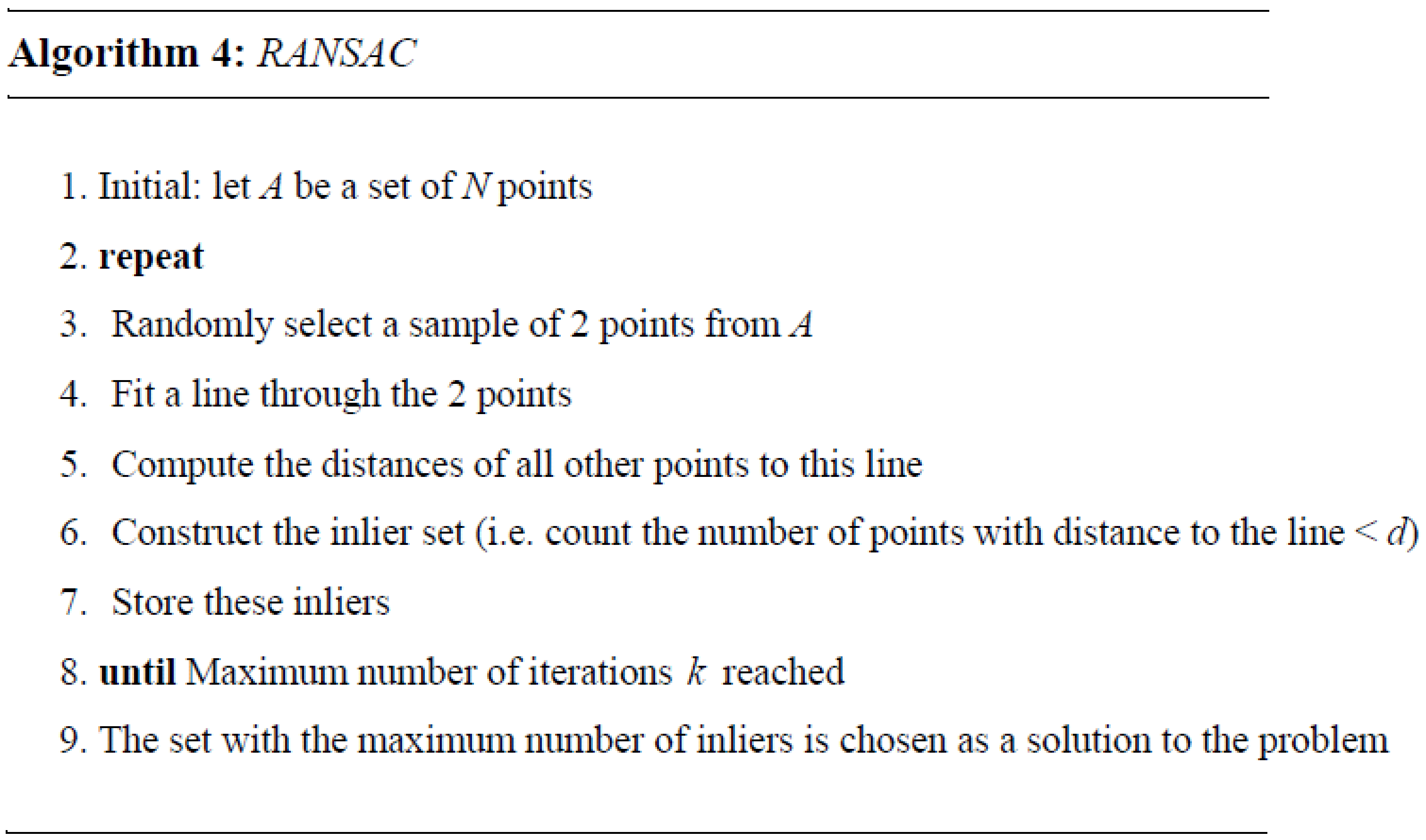
- Select sample of 2 points at random
- Calculate model parameters that fit the data in the sample
- Calculate error function for each data point
- Select data that support current hypothesis
- **Repeat sampling**

Algorithm 3: RANSAC

ALL-INLIER SAMPLE



Algorithm 3: RANSAC



Algorithm 4: *RANSAC*

```
Initial: let $A$ be a set of $N$ points
repeat
    Randomly select a sample of 2 points from $A$
    Fit a line through the 2 points
    Compute the distances of all other points to this line
    Construct the inlier set (i.e. count the number of points with distance to the line $< d$)
    Store these inliers
until Maximum number of iterations $k$ reached
The set with the maximum number of inliers is chosen as a solution to the problem
```

From Lines (2D) to 3D: Find planes

- 3D Point Cloud below
- Extracted planes on the right (NOT using RANSAC)