上海科技大学
ShanghaiTech University

CS283: **Robotics Spring 2024: Sensors III**

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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

$$d = c \cdot t$$

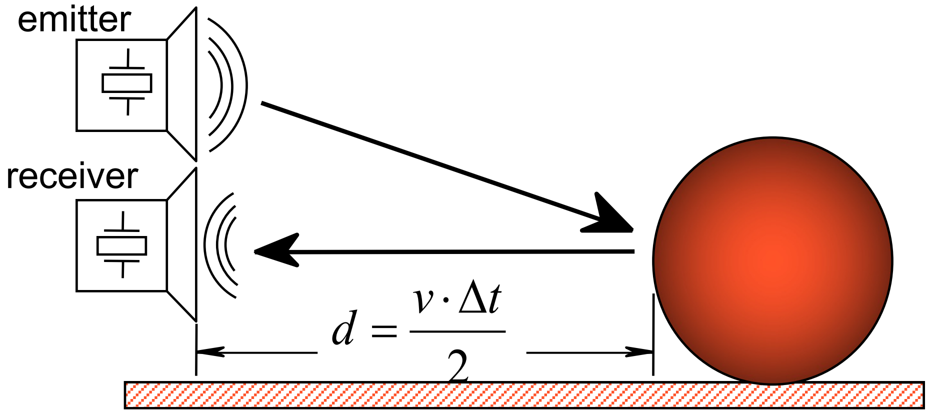
- Where
  - d = distance traveled (usually round-trip)
  - c = speed of wave propagation
  - t = time of flight.

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*.

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

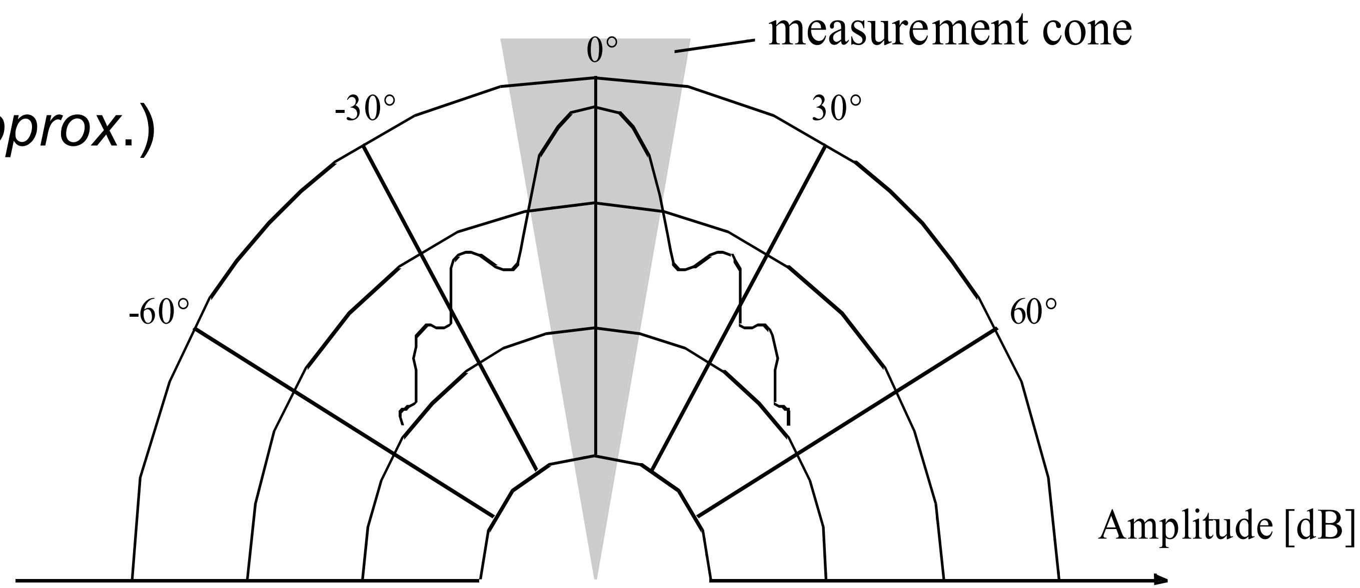
- The speed of sound *c* (340 m/s) in air is given by $\sqrt{\gamma \cdot R \cdot T}$

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)



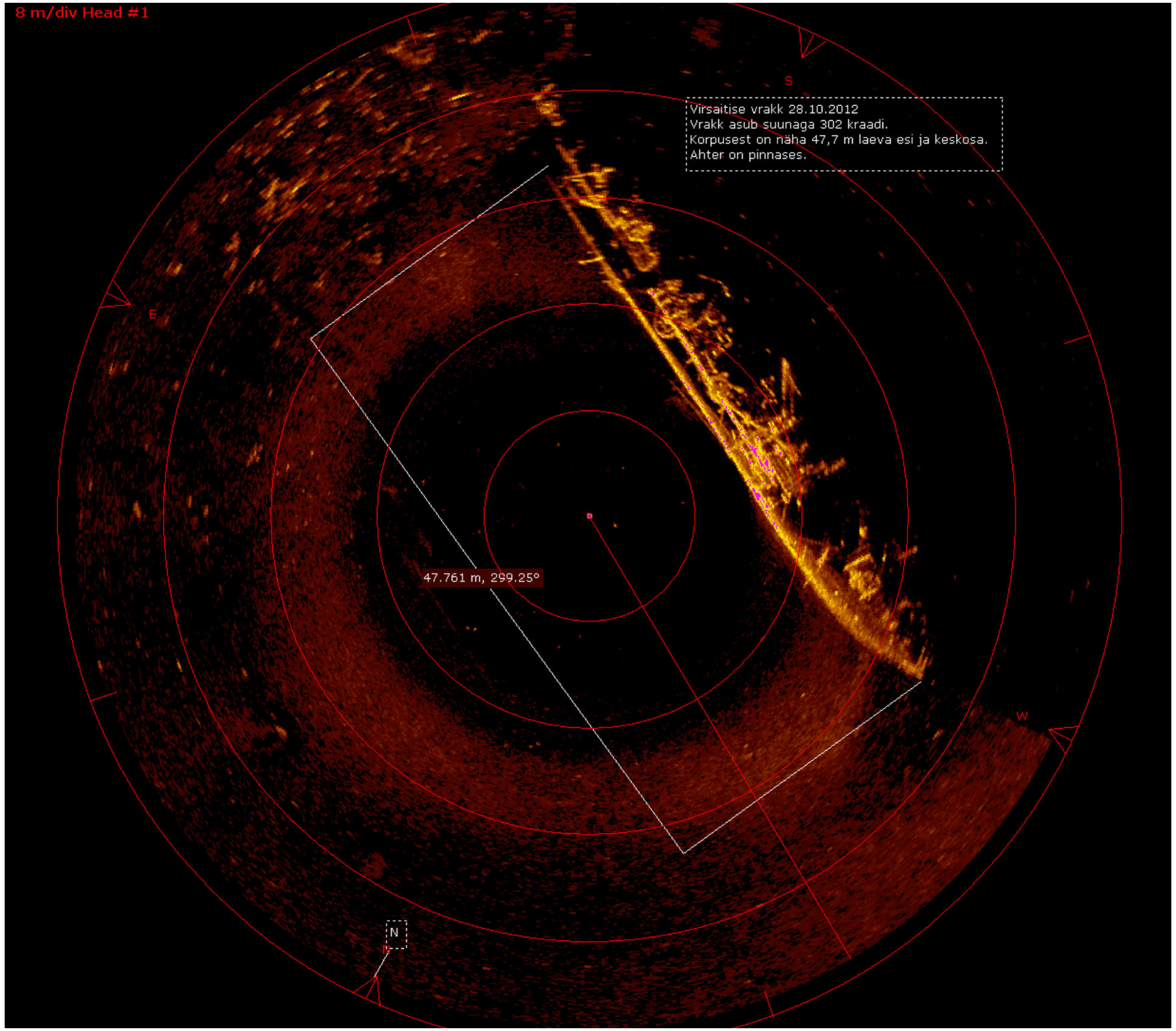
Typical intensity distribution of a ultrasonic sensor

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

- 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

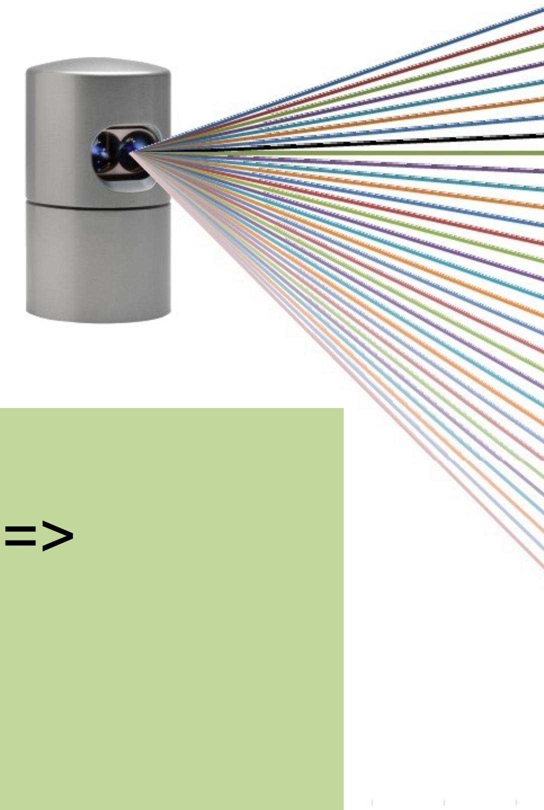
- Light visibility very low => often sonar the only/ best sensor available
- Types:
  - Sonar
  - Side-scanning
  - Synthetic aperture sonar
- Problems:
  - Absorption
  - Reflections:
    - Layers of different water temperature
    - Layers of different salinity
    - …



Laser Range Sensor (time of flight, electromagnetic)

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

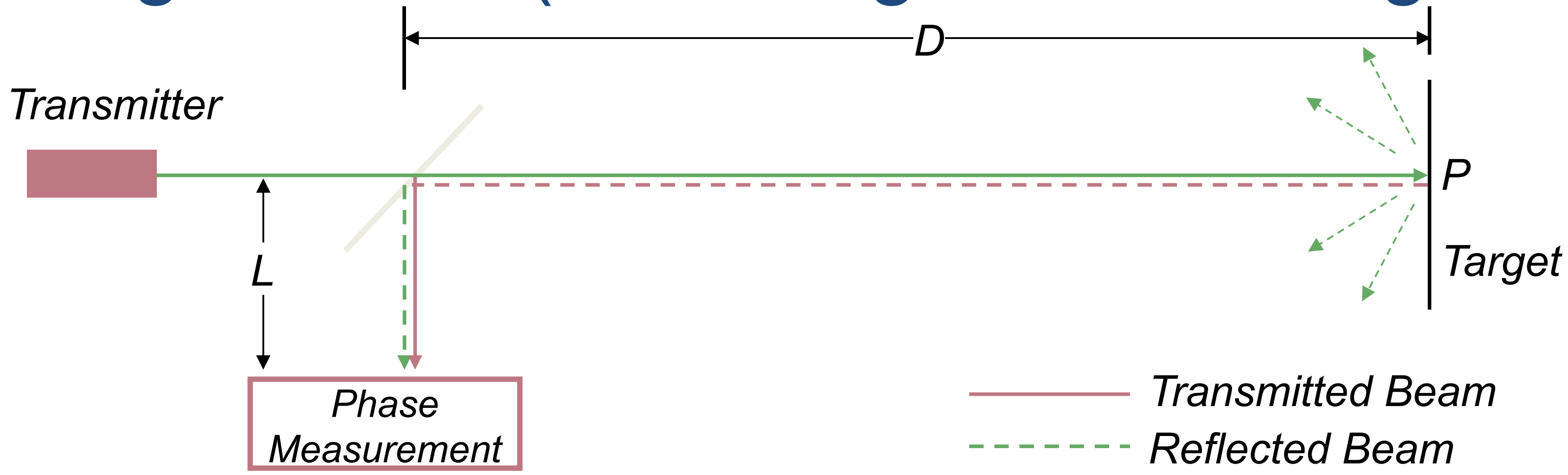




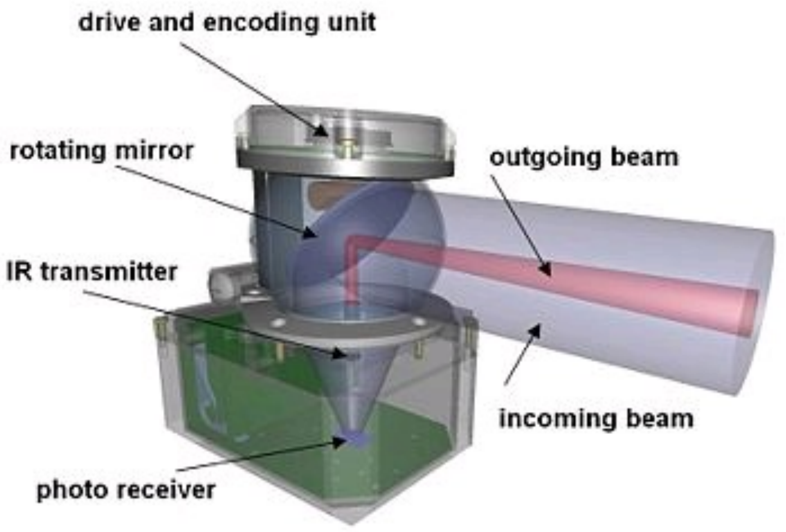
Autonomous Driving will rely heavily on range sensing =>
Many 3D range sensing companies emerge!

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
- 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)

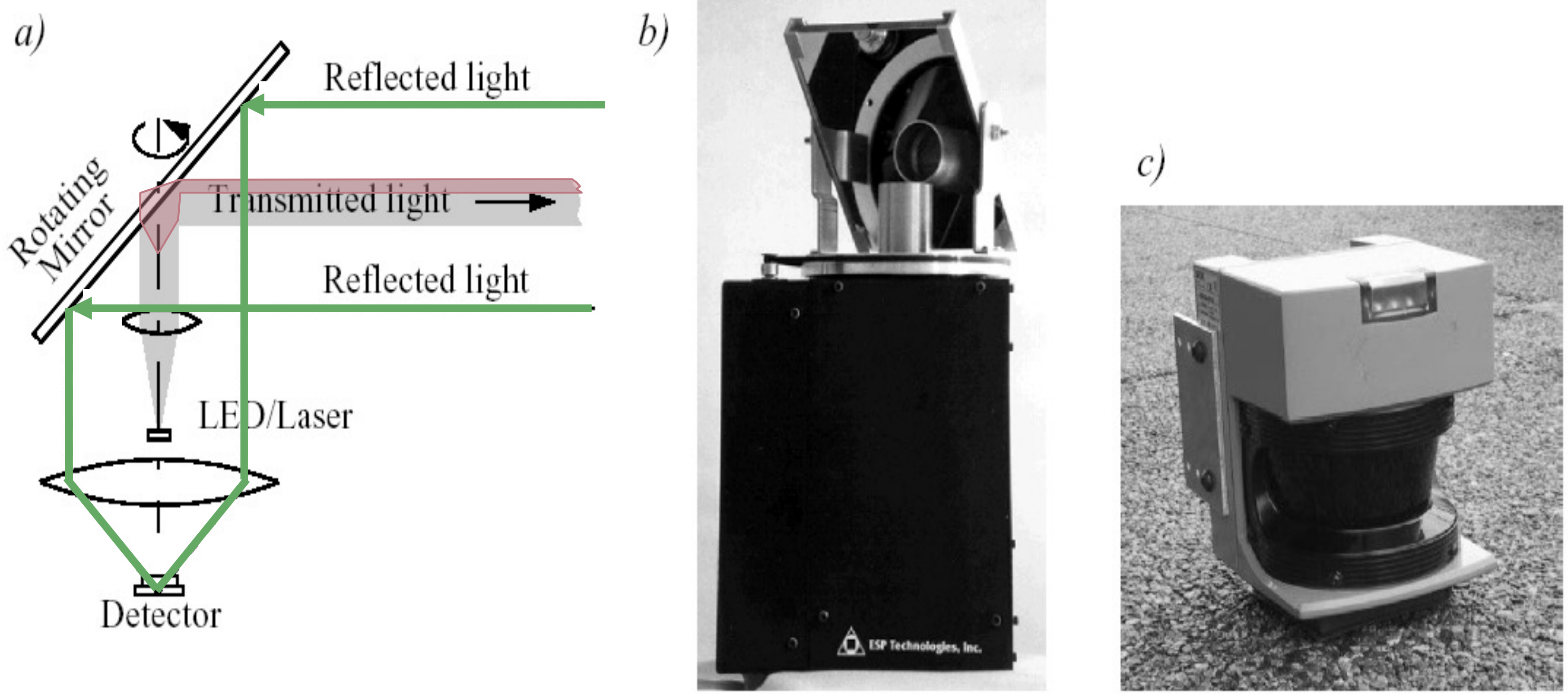
Time of flight measurement

- 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

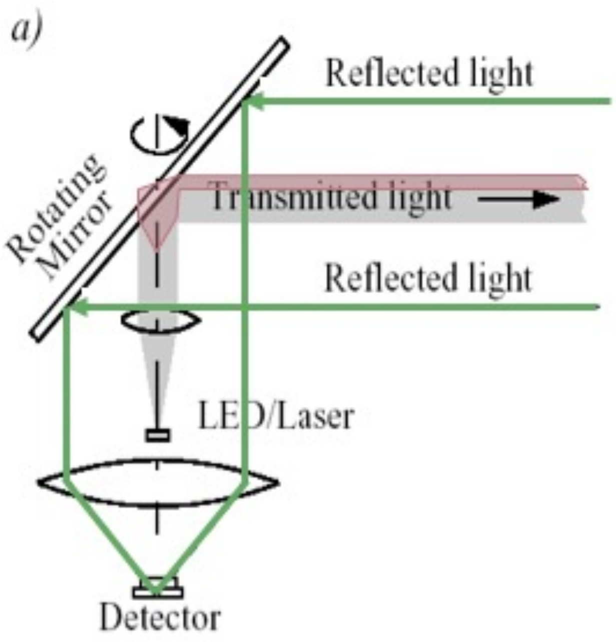
- (3D) Laser Scanner == Lidar (Light detection and ranging)

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 …



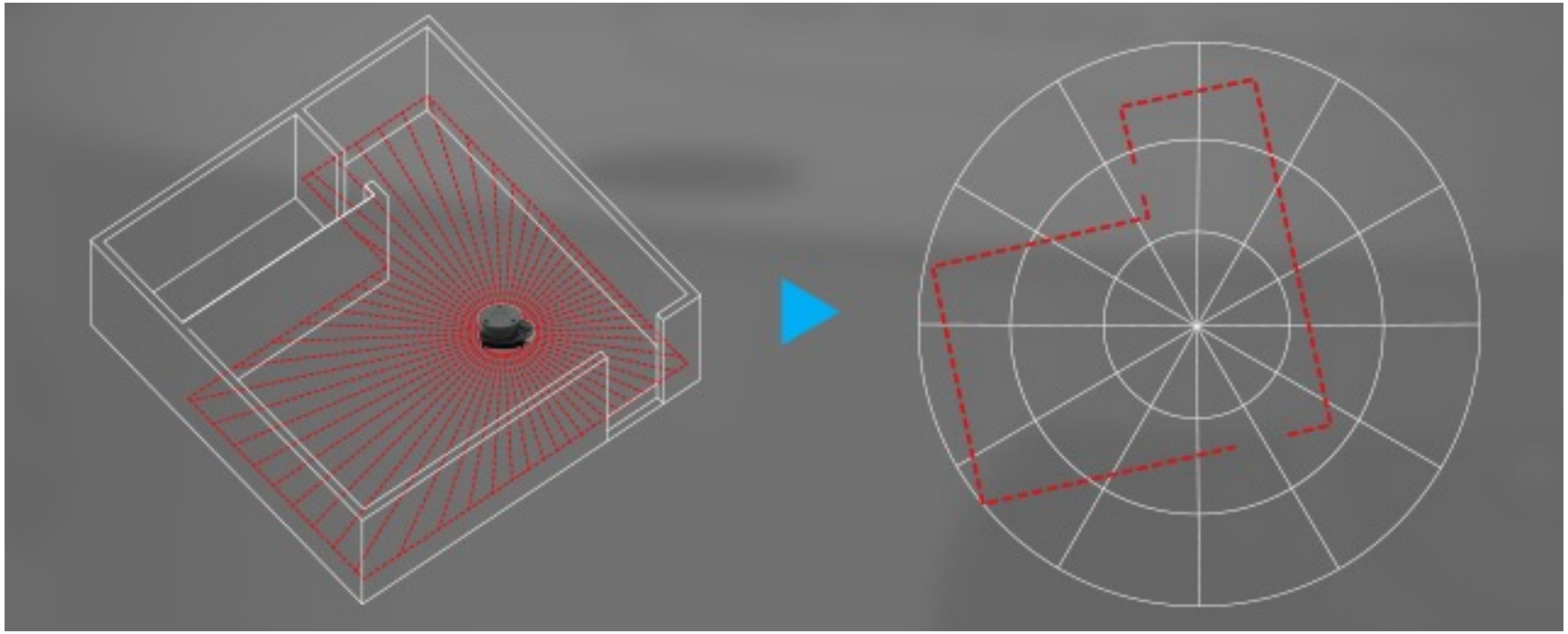

SICK


a)
Reflected light
Rotating Mirror
Transmitted light
Reflected light
LED/Laser
Detector


SICK

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: ± 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

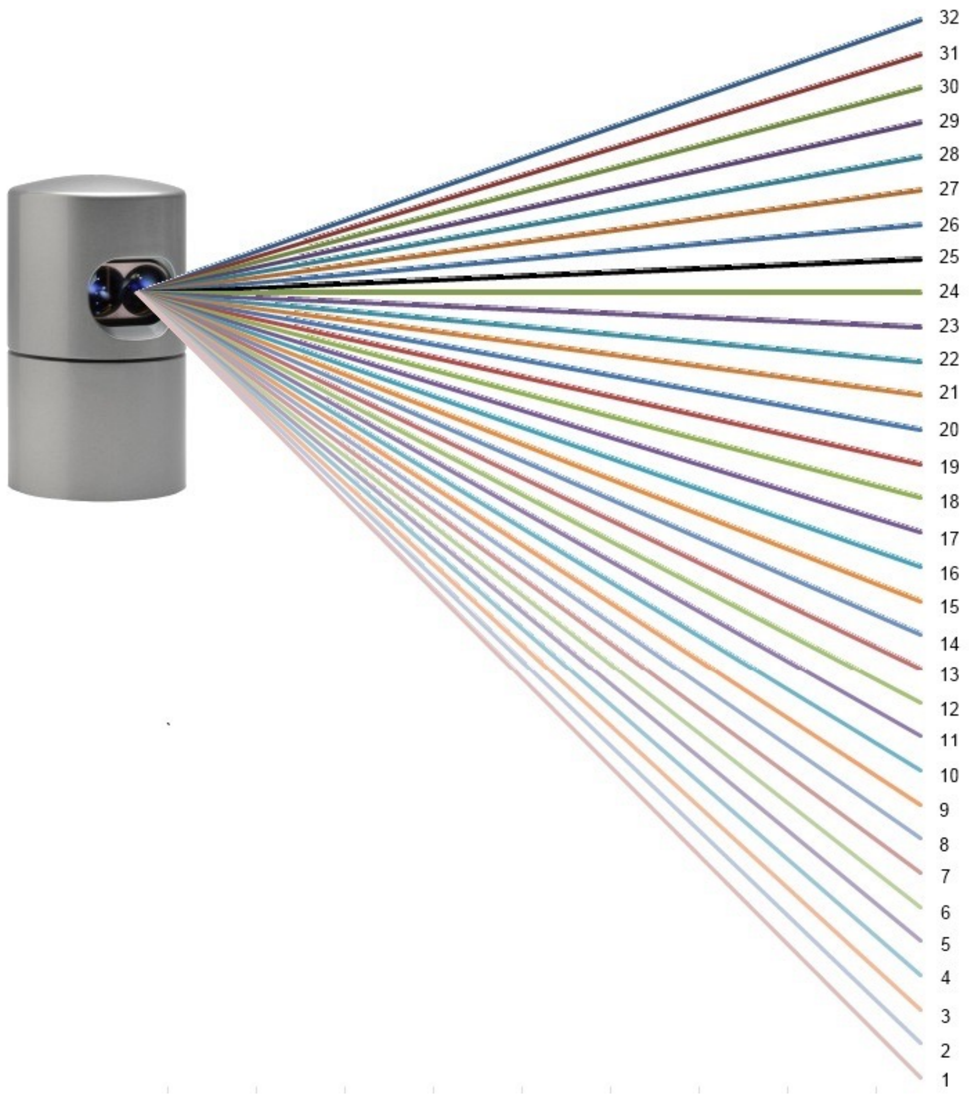
- Low-power consumption (2.5W)
- Wide-range (5600mm×240°).
- 60 to 1,000mm : ±30mm,
- 1,000 to 4,095mm : ±3% of measurement
- 10Hz
- Dimensions: 50 x 50 x 70 mm
- Weight: 160g

- Cost: about 6,500 RMB

Velodyne hdl-32e

- 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

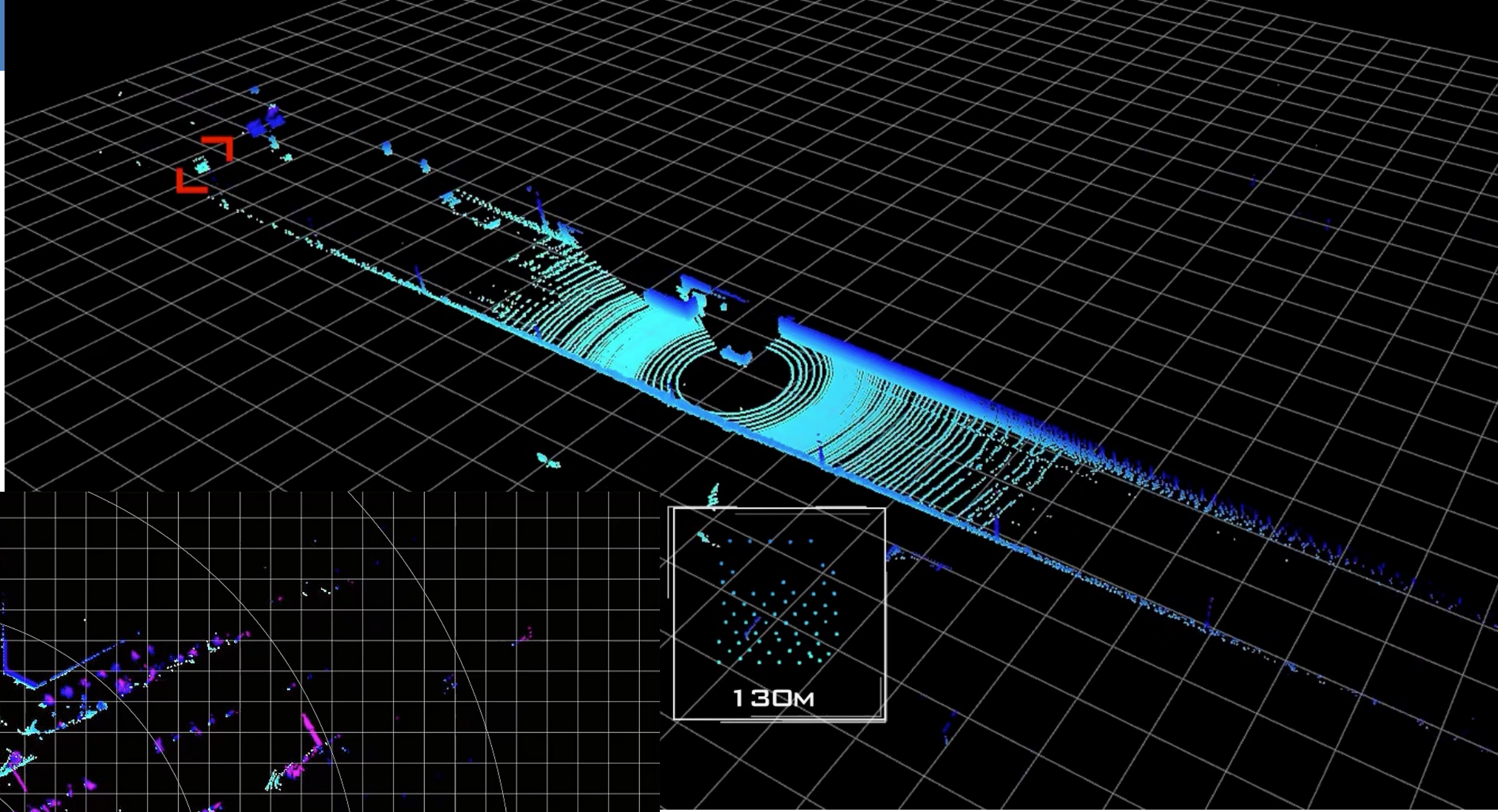


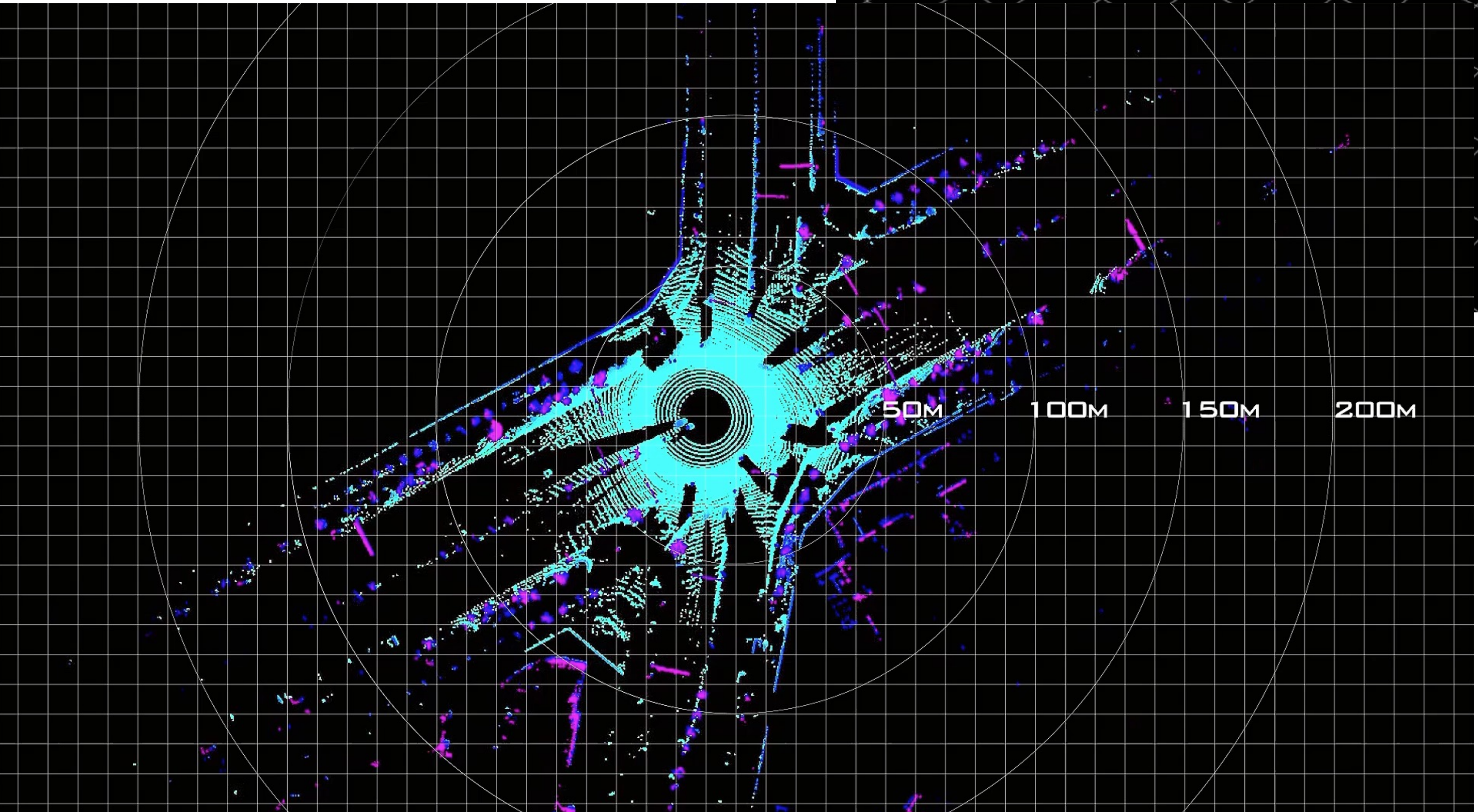
RoboSense Ruby

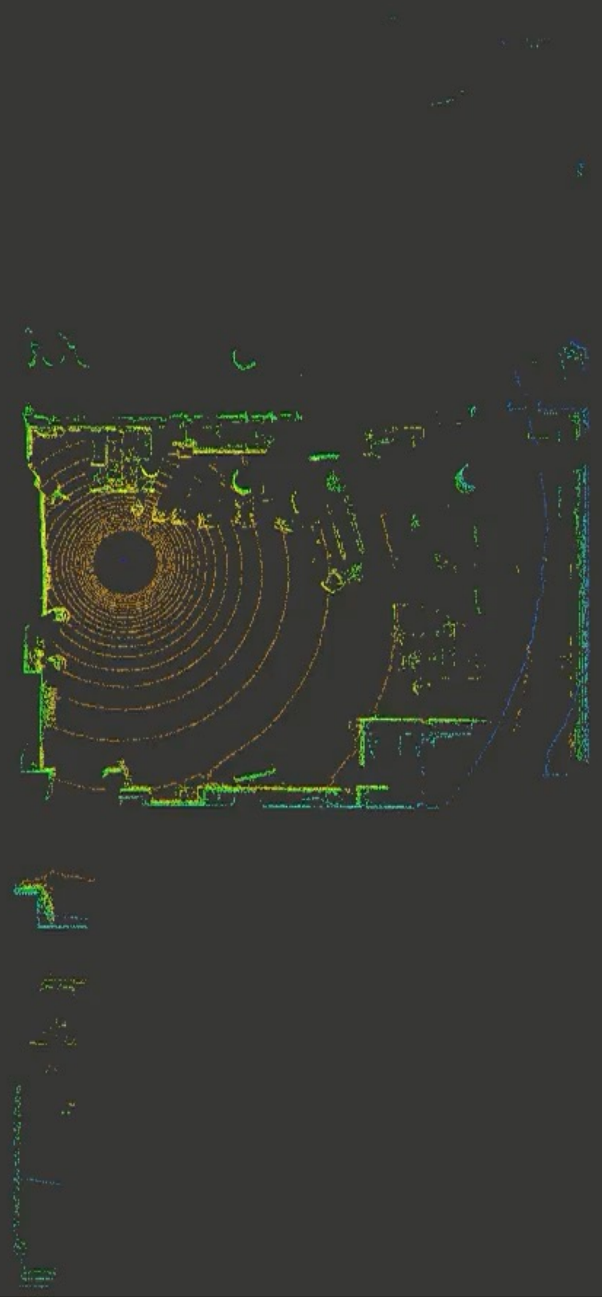
- 128 beams
- Range: 250m (200m@10% NIST)
- Range Accuracy (Typical): Up to ±3cm
- Vertical FOV: 40°
- Horizontal Resolution: 0.1°/ 0.2°/ 0.4°
- Vertical Resolution: Up to 0.1°
- Frame Rate: 5Hz/10Hz/20Hz
- Points Per Second: 2,304,000pts/s (Single return Mode)
- Points Per Second: 4,608,000pts/s (Dual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

- Cost: about RMB 500,000

RoboSense Ruby on Road



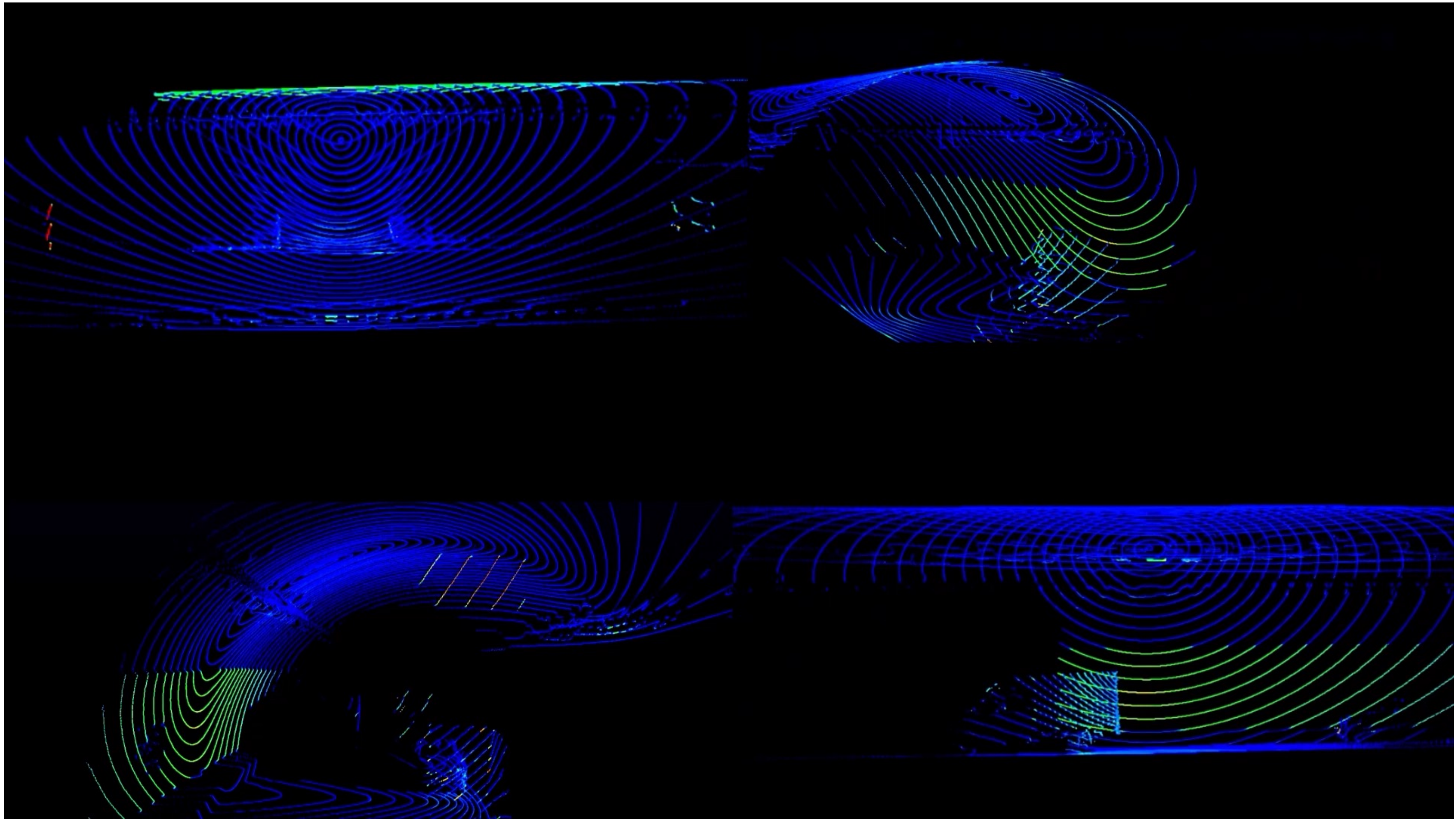




RoboSense Bpearl

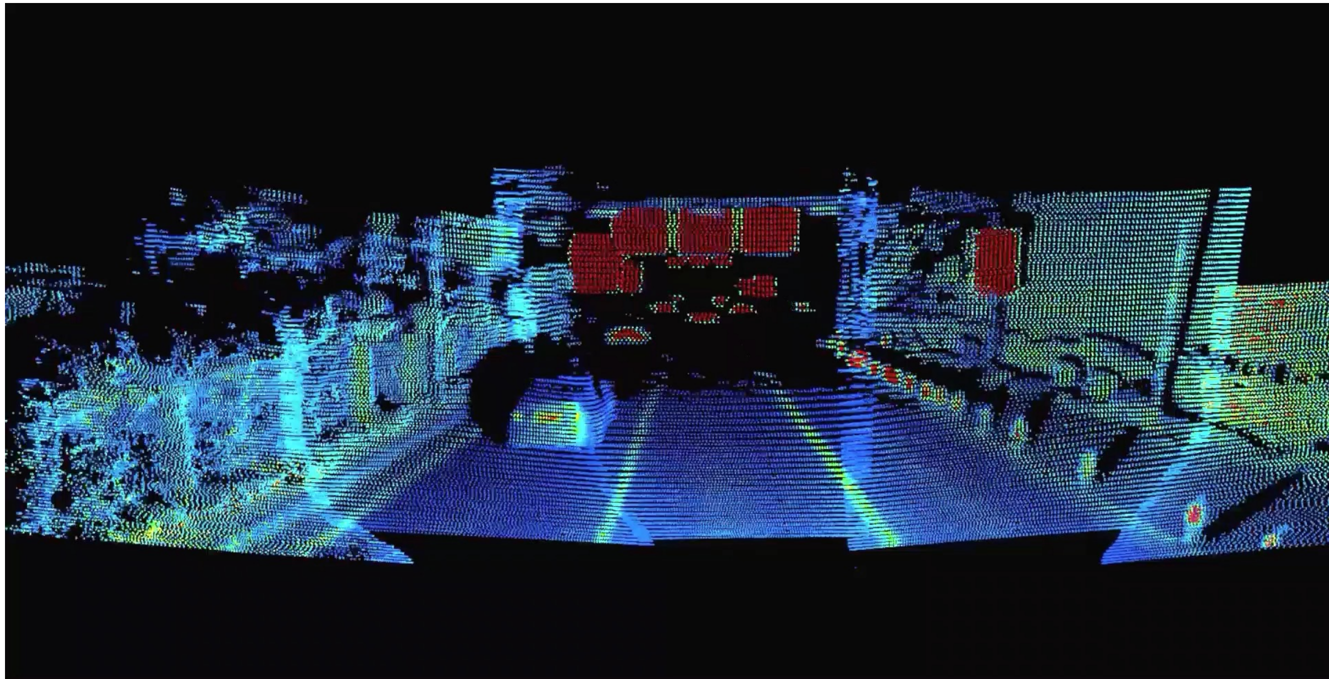
- Hemispherical Lidar
- 32 beams

- Range: 100m (30m@10% NIST)
- Range Accuracy (Typical): Up to ±3cm
- 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: ~0.92 kg



RoboSense Lidar M1

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



Intel RealSense L515

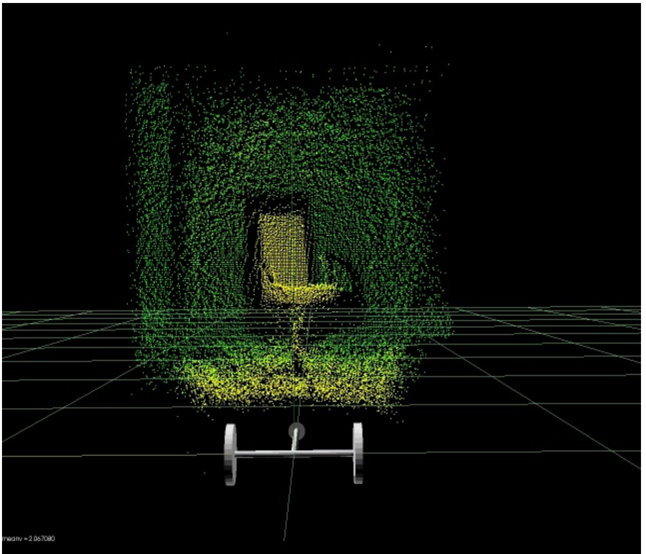
- 9m distance
- Depth: 1024 x 786 pixel @ 30Hz => 23mill pts per second
- RGB: 1920 × 1080 @ 30Hz
- Depth FOV: 70° × 55° (±2°)
- Weight: 100g
- With IMU

- Solid state laser with RGB camera

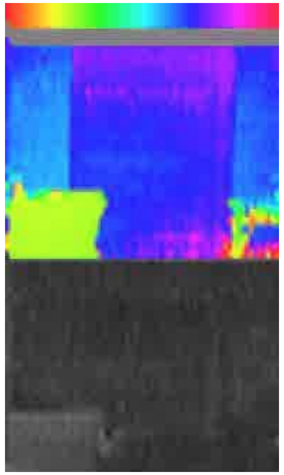
- Sensitive to ambient infrared light =>
  Does NOT work outdoors!

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!



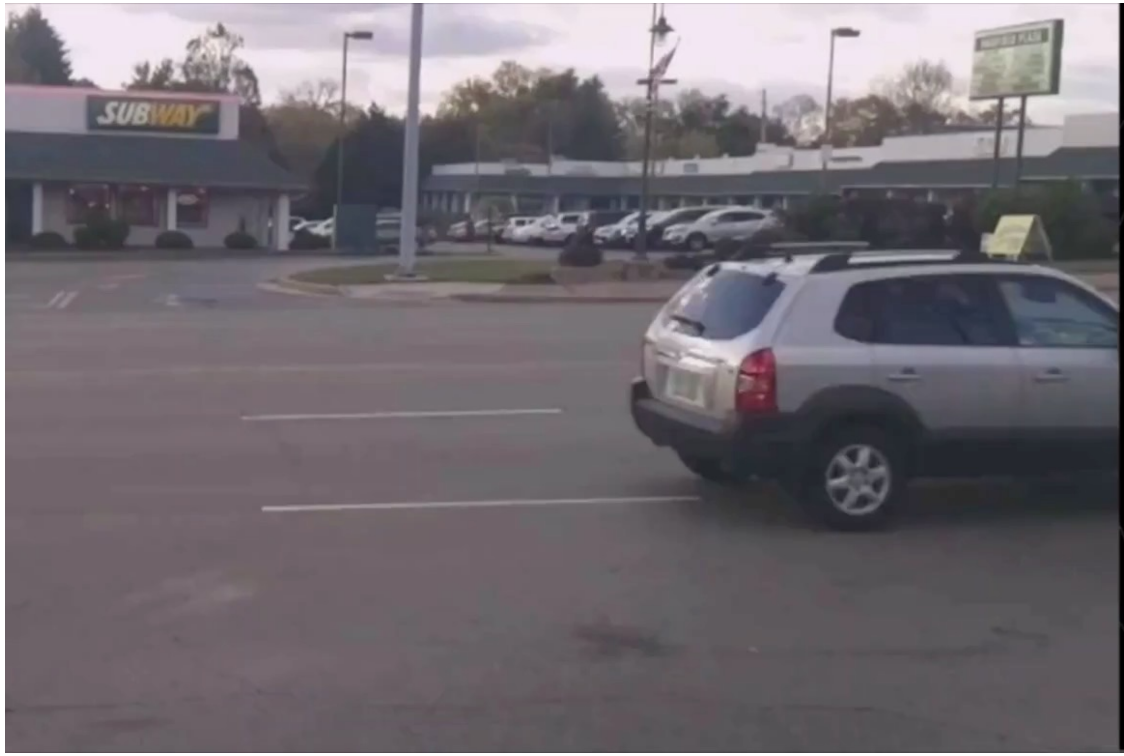
Swiss Ranger 3000 (produced by MESA)

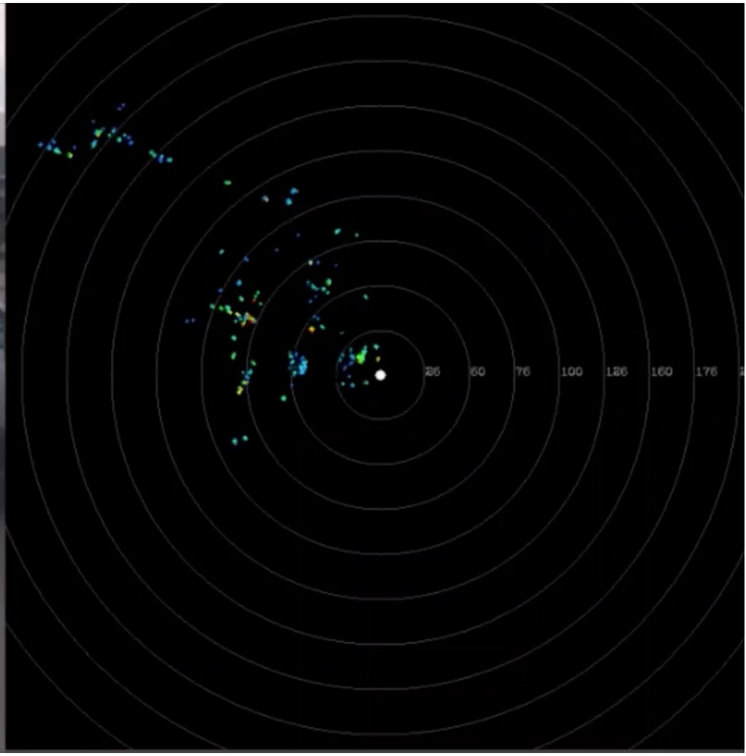


- Kinect 2
- Resolution 1920x1080 pixels
- Field of view: 70 deg (H), 60 deg (V)
- Claimed accuracy: 1 mm
- Claimed max range: 6 meters

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+
- <1º Resolution
- 120º FOV



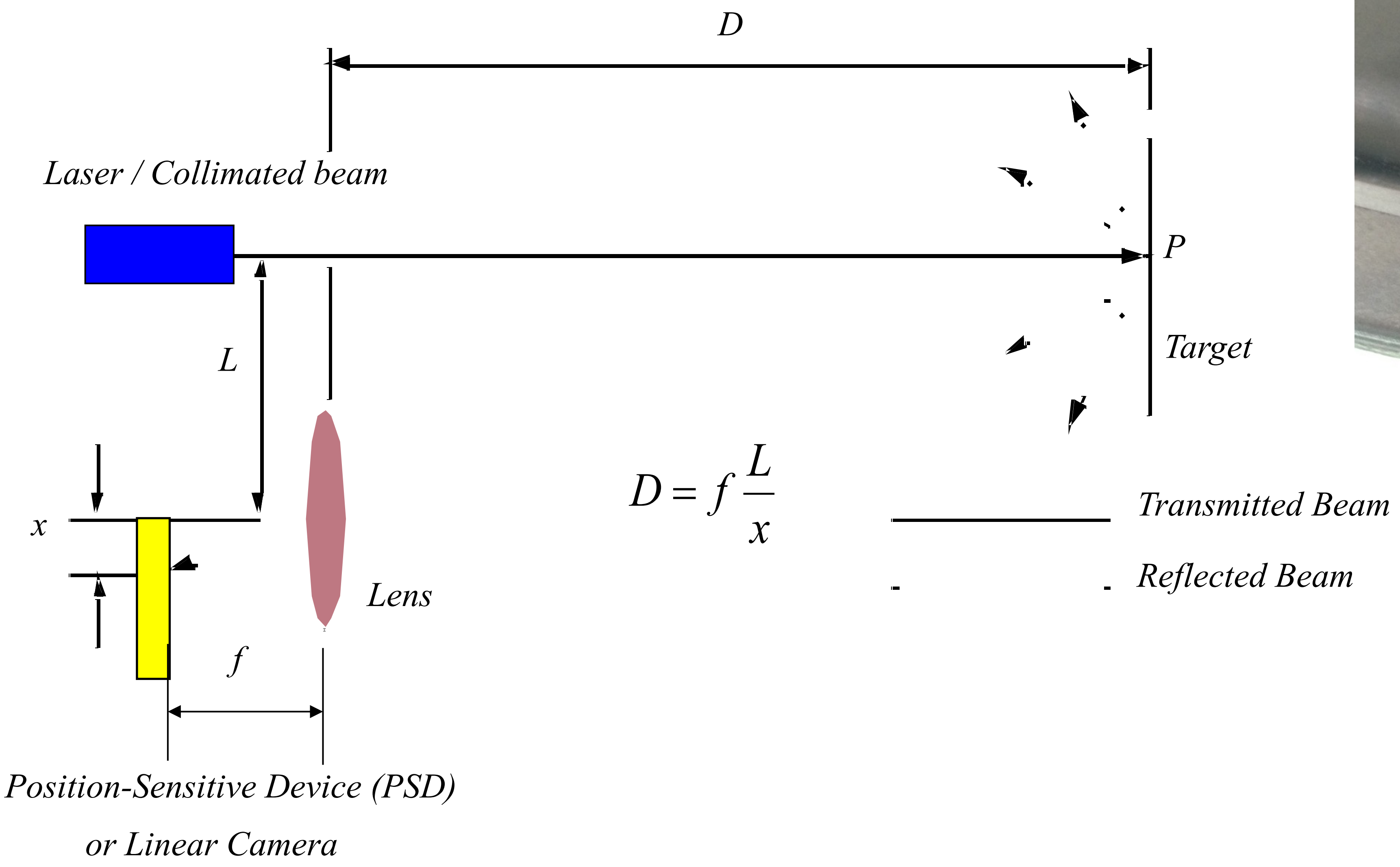


RANGE SENSING: PROJECTED PATTERN

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 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)

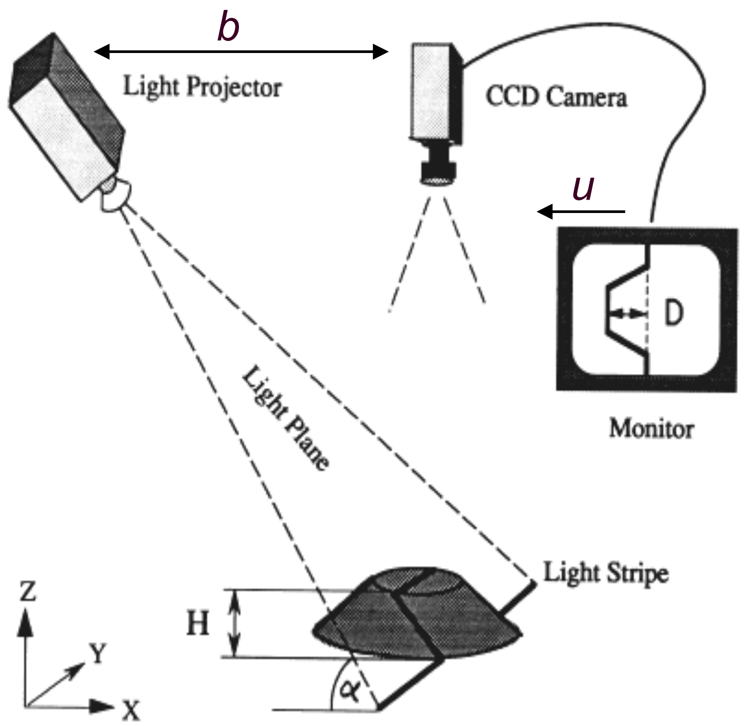


$$D = f\frac{L}{x}$$

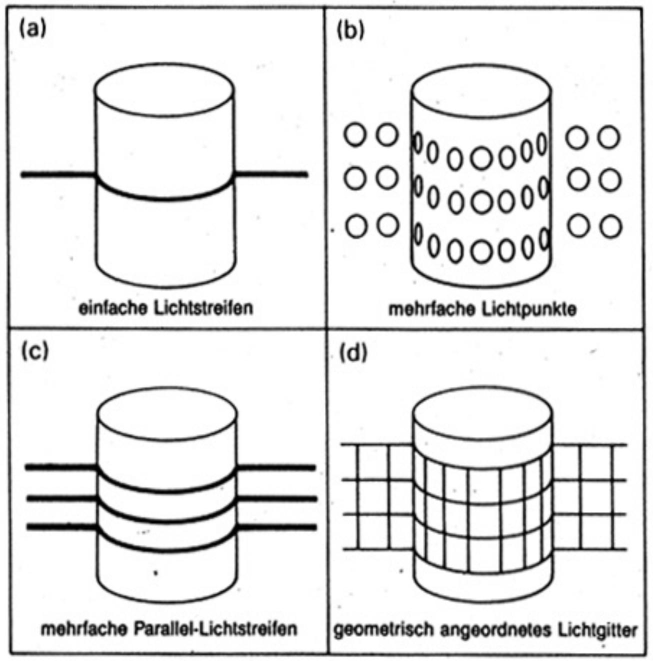
Cliff sensor on Turtle-bot

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)

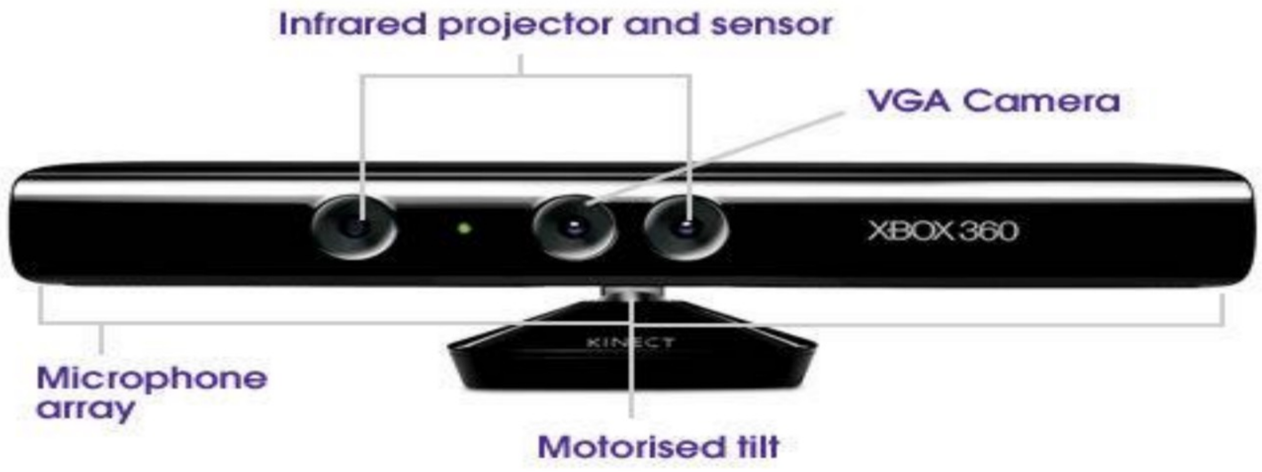
- Baseline length *b*:
  - the smaller b is the more compact the sensor can be.
  - the larger b is the better the range resolution is.

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

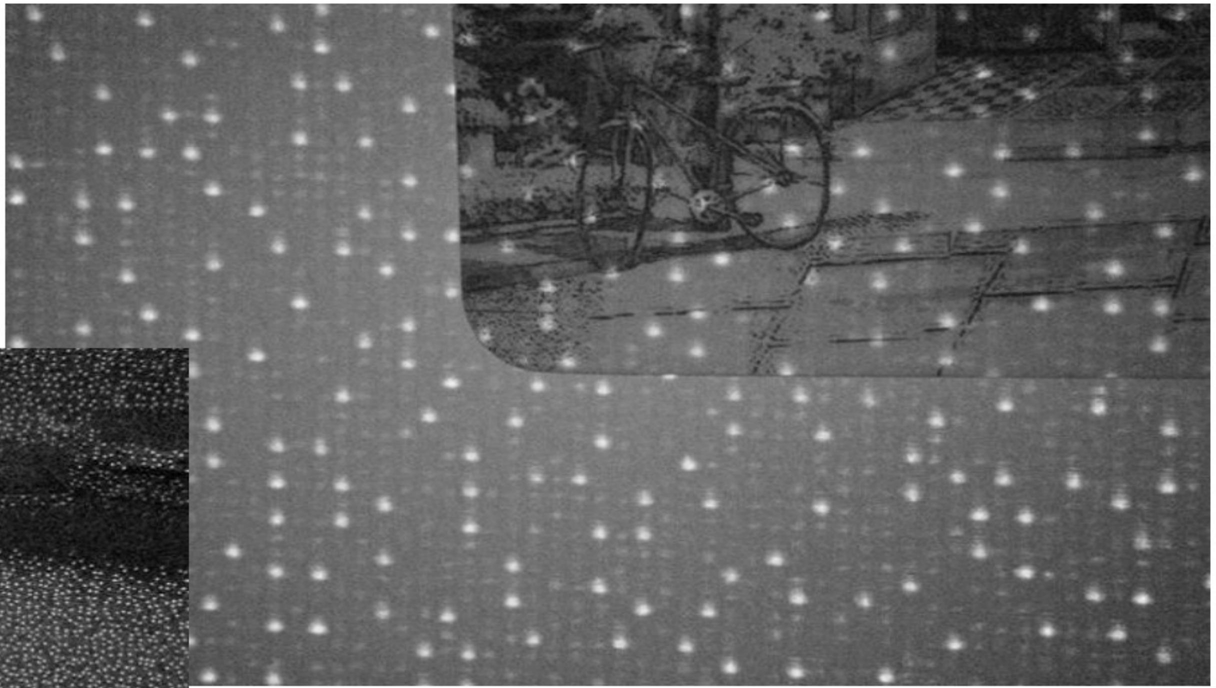
- Devices: Microsoft Kinect and Asus Xtion
- Developed by Israeli company PrimeSense in 2010



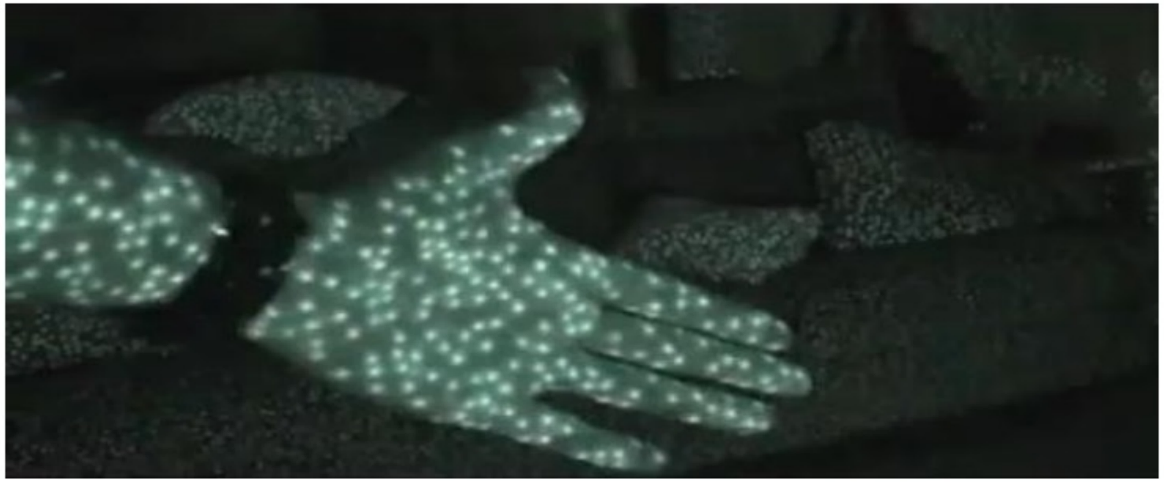
- Components:
  - IR camera (640 x 480 pixel)
  - IR Laser projector
  - RGB camera (640 x 480 or 1280 x 1024)
  - Field of View (FoV):
    - 57.5 degrees horizontally,
    - 43.5 degrees vertically

IR Pattern

Sensitive to infrared light
=>
Does NOT work outdoors!



Depth Map



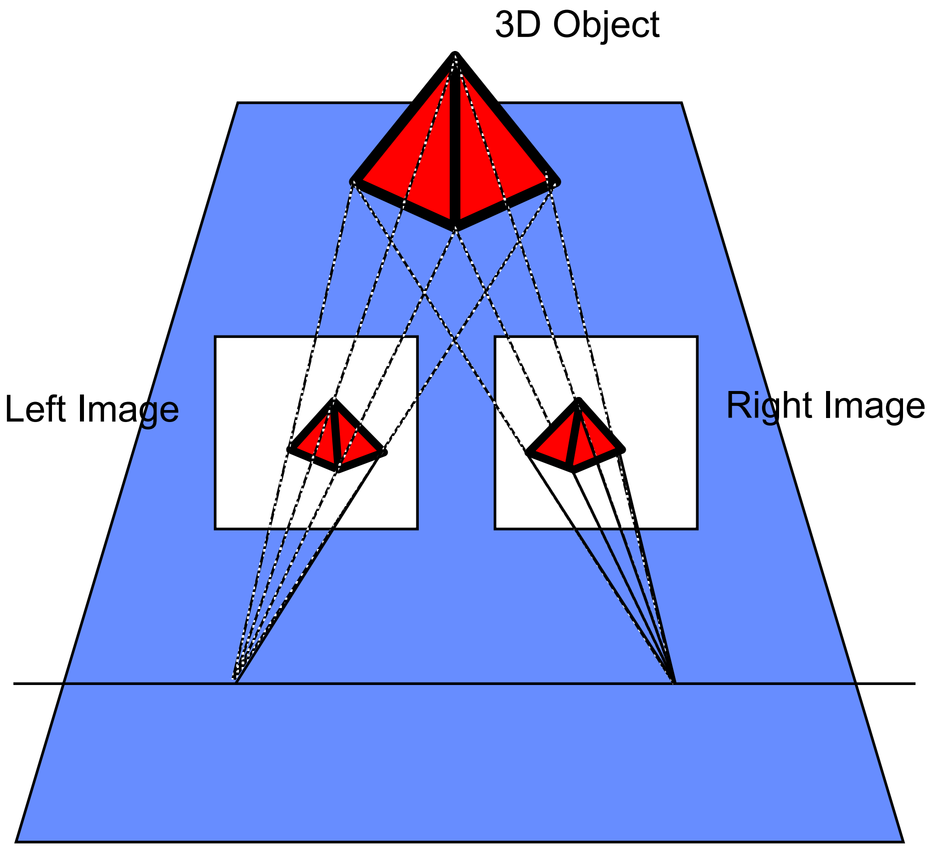
Microsoft Kinect: Depth Computation (1)

- **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

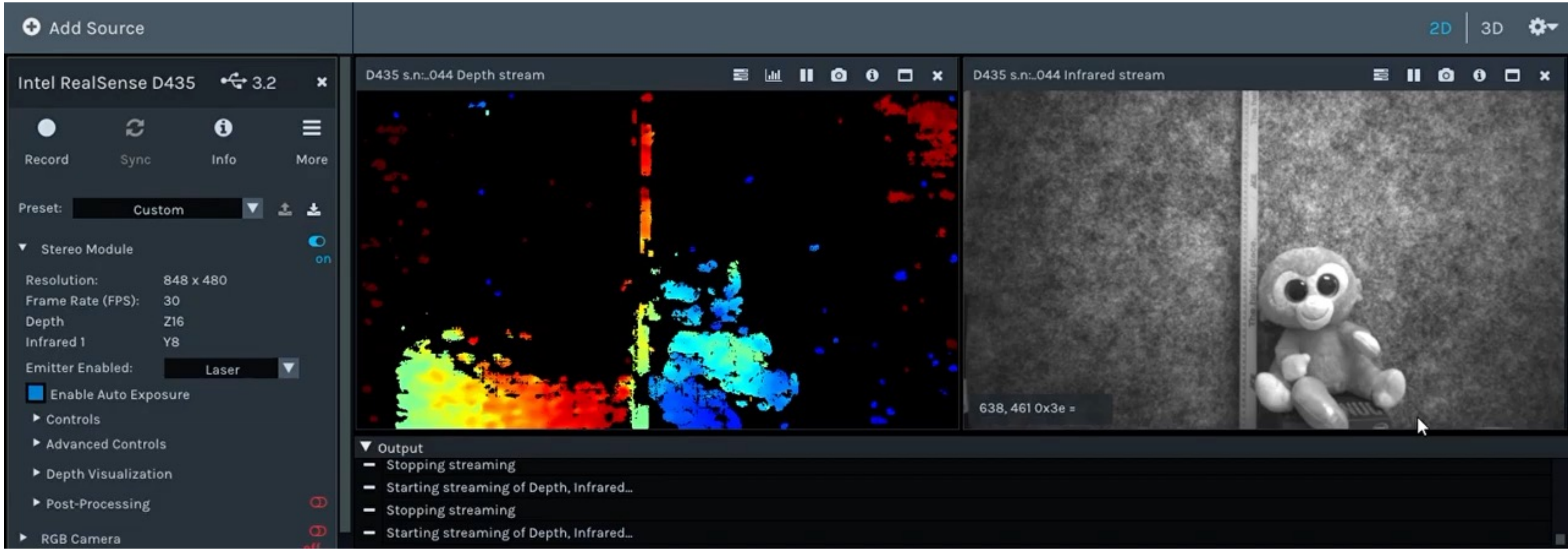


Stereo example: ZED camera

- 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° × 57° (±3°)
- RGB: 1920 × 1080
- Small and lightweight
- With IMU

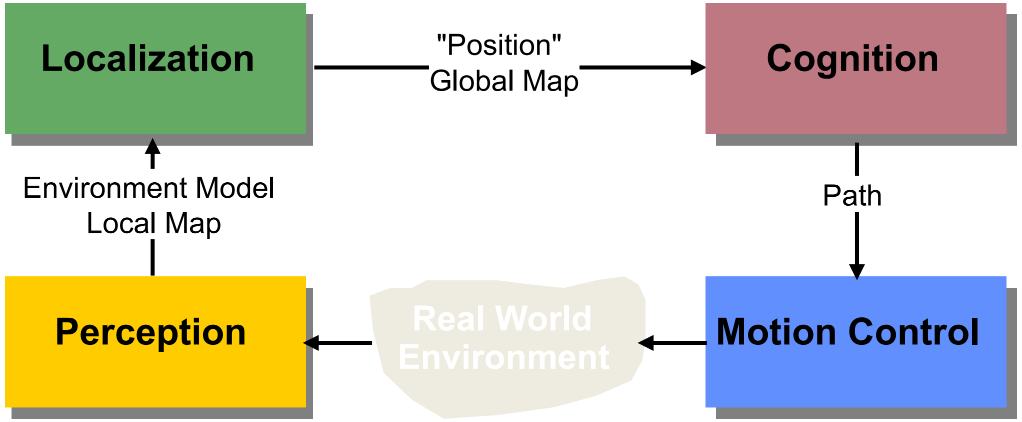


ADMIN

Admin

- HW 2 is published – due March 29.
- Project:
  - Have appointment with Prof. and graduate advisor this week!
  - Next week no lectures – work on the project proposal and paper presentations.
  - See Project Proposal Instructions on the website: Due April 5
  - See Paper Presentation Instructions on the website: Due April 11

	Topic	Student1	Student2	Student3	Graduate Advisor	1st meeting	
1	Campus Autonomy	zhangjj2023	zhangyq2023		Porf.		done
2	Car data collection	majx2023	guszh2023	linyx2023	Bowen	Wed. 5:30pm	OK
3	Robot Dog	duanxin2023	guojing2023		Xin Duan	Tuesday 5:30pm	OK
4	Mission Planning LLM	zhangjt12023	renwq2023	maxu2023	Fujing	Wed. 5:00pm	OK
5	Path Planning LLM	xiefj	liuxzh2023		Fujing		done
6	Steamdeck	wushx2023	zhangsa2023		Bowen	Tuesday 1:30pm	done
7	Grasping	wangyzh2023	taoheng2023	shiyd2023	Yaxun	Wed. 4:30pm	?
8	Fetch	luoxr2023	yushb2023	hanzht2022	Prof. & Yaxun	Wed. 6:00pm	?
9	Industrial	lipc			Prof.		done
10	Sophia	zhoutt2023	xuteng		Prof.	Tuesday 6:00pm	?

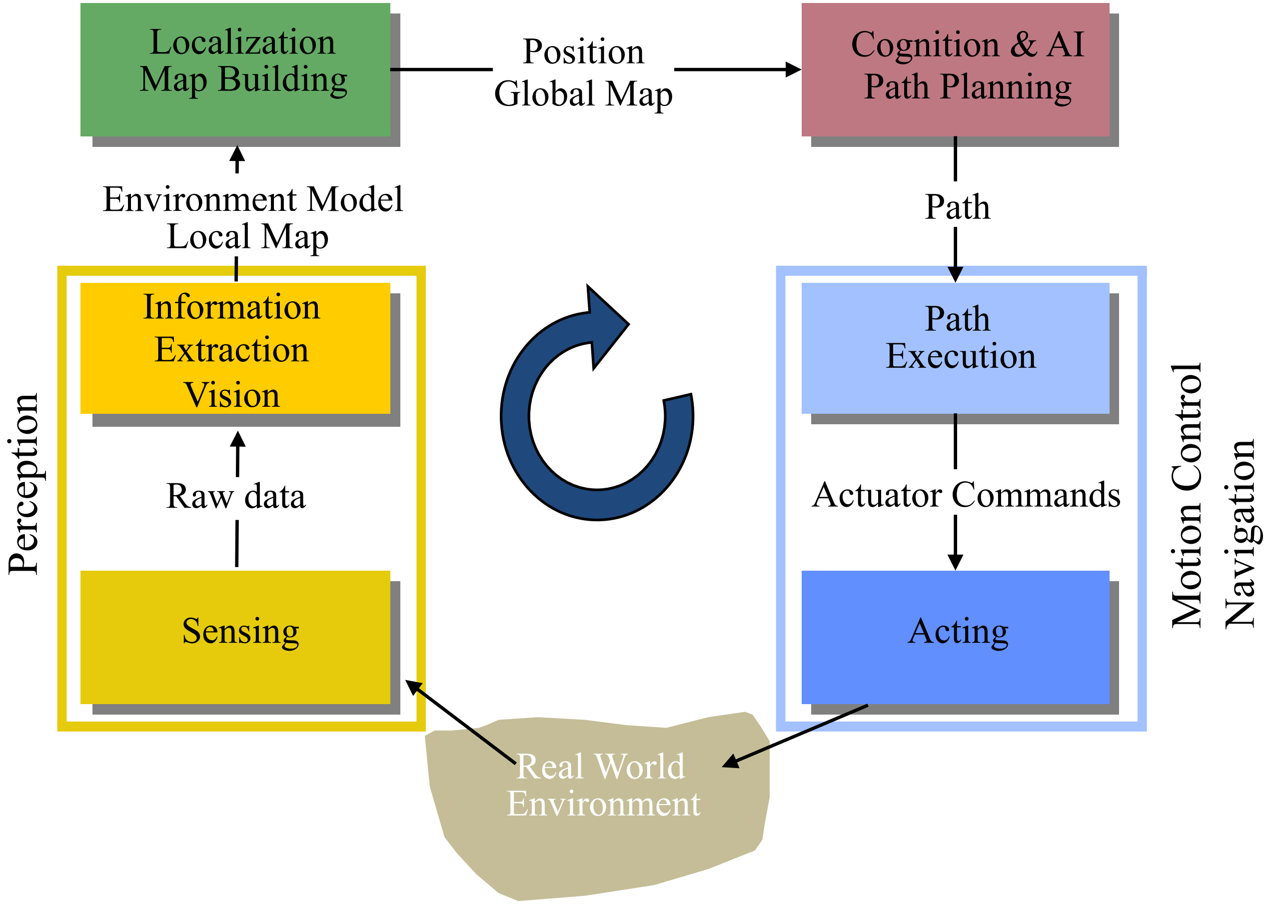


PERCEPTION

Line extraction from laser scans
Vision

Sildes from Roland Siegwart and Davide Scaramuzza, ETH Zurich

General Control Scheme for Mobile Robot Systems



With material from Roland Siegwart and Davide Scaramuzza, ETH Zurich

LINE EXTRACTION

Split and merge
Linear regression
RANSAC
Hough-Transform

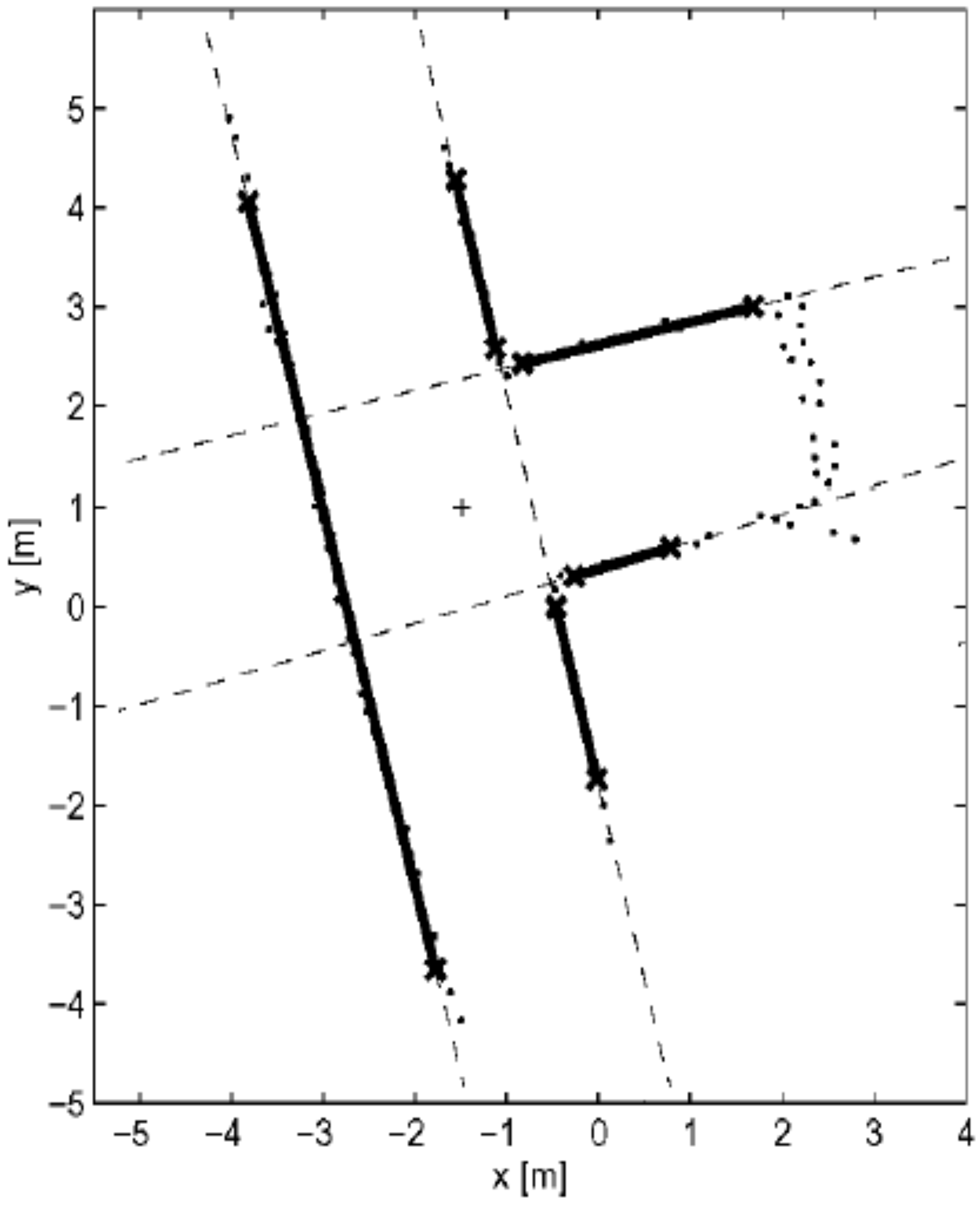
Line Extraction: Motivation

- 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)

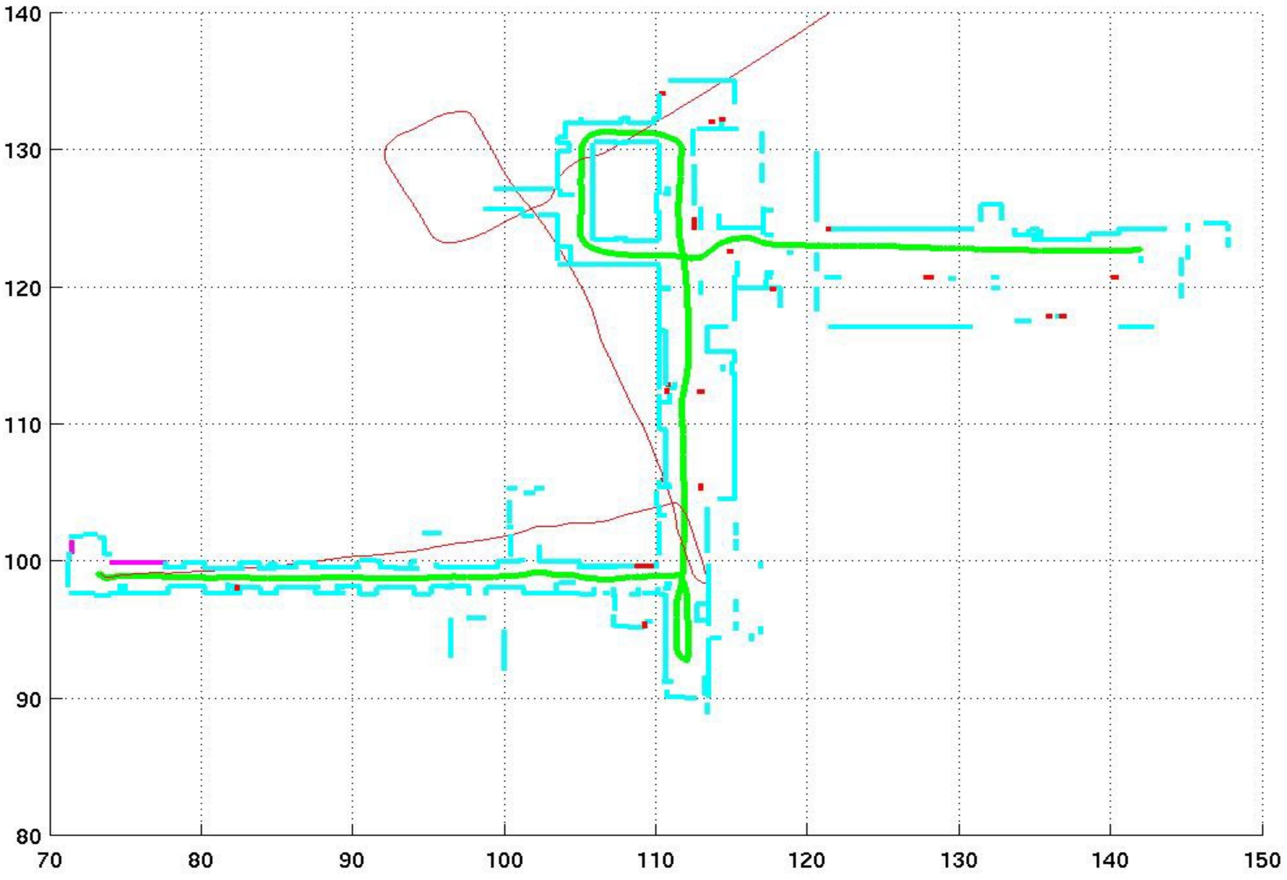
  OR

  - Mapping using line representation



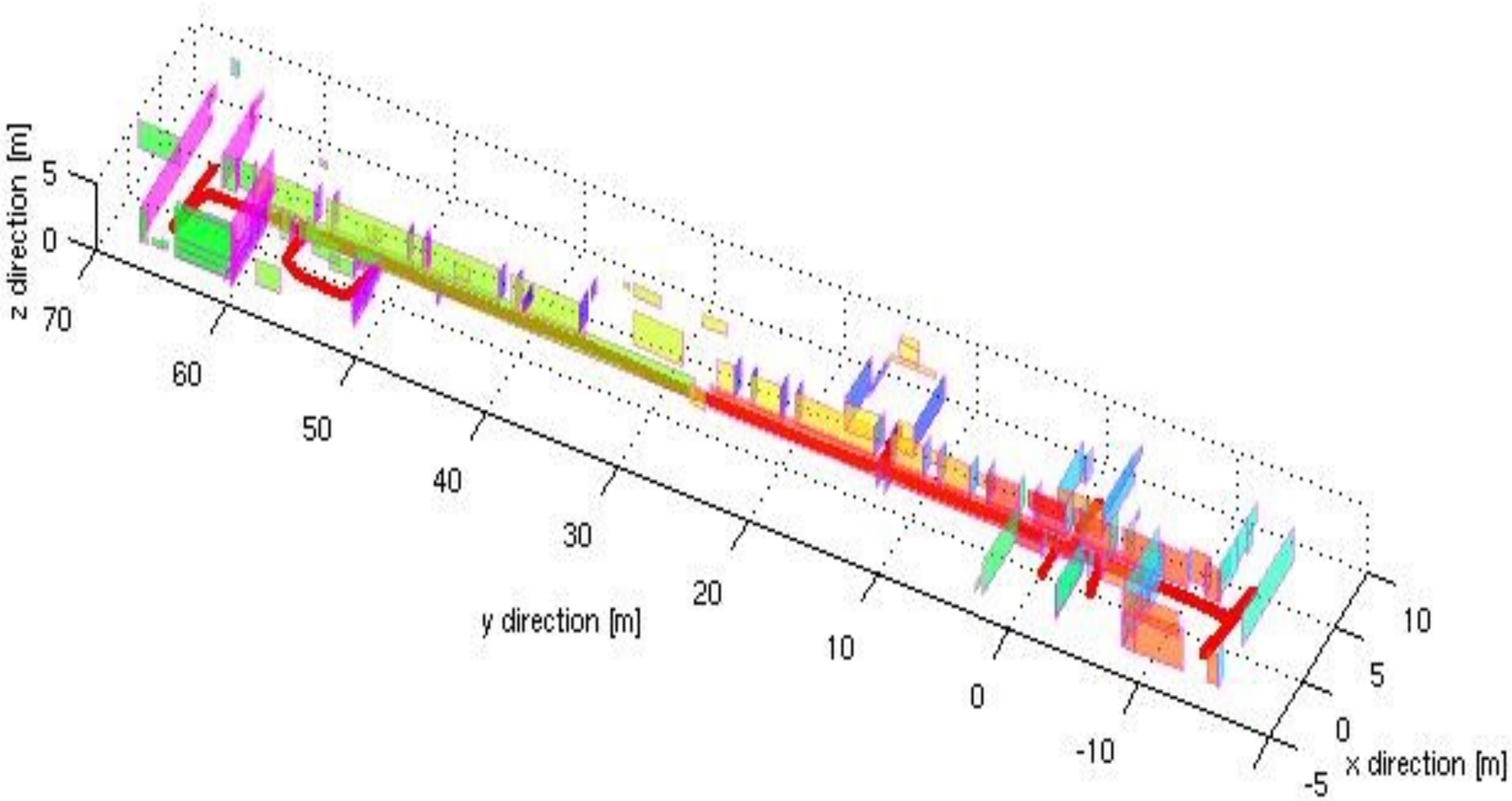
Line Extraction: Motivation

- Map of hallway built using line segments



Line Extraction: Motivation

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

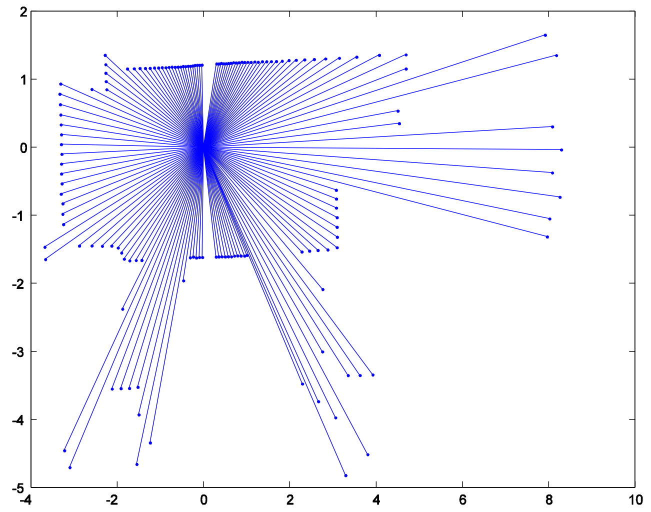


Line Extraction: Motivation

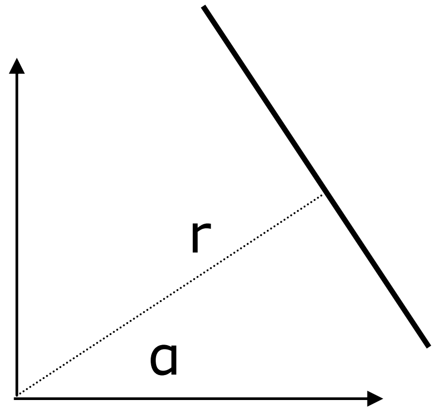
- Why laser scanner:
  - Dense and accurate range measurements
  - High sampling rate, high angular resolution
  - Good range distance and resolution.

- 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:
  - $x \cos \alpha + y \sin \alpha = r$
  - $-\pi < \alpha <= \pi$
  - $r >= 0$

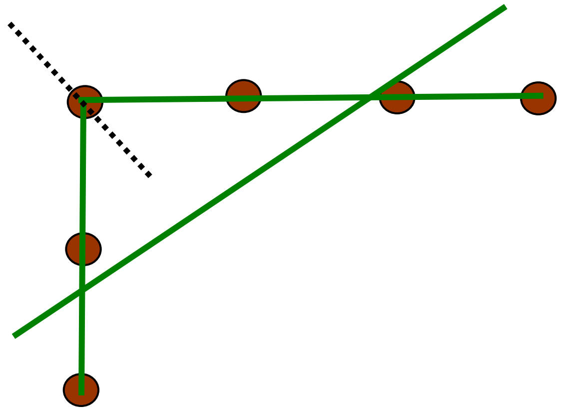


Line Extraction: The Problem (2)

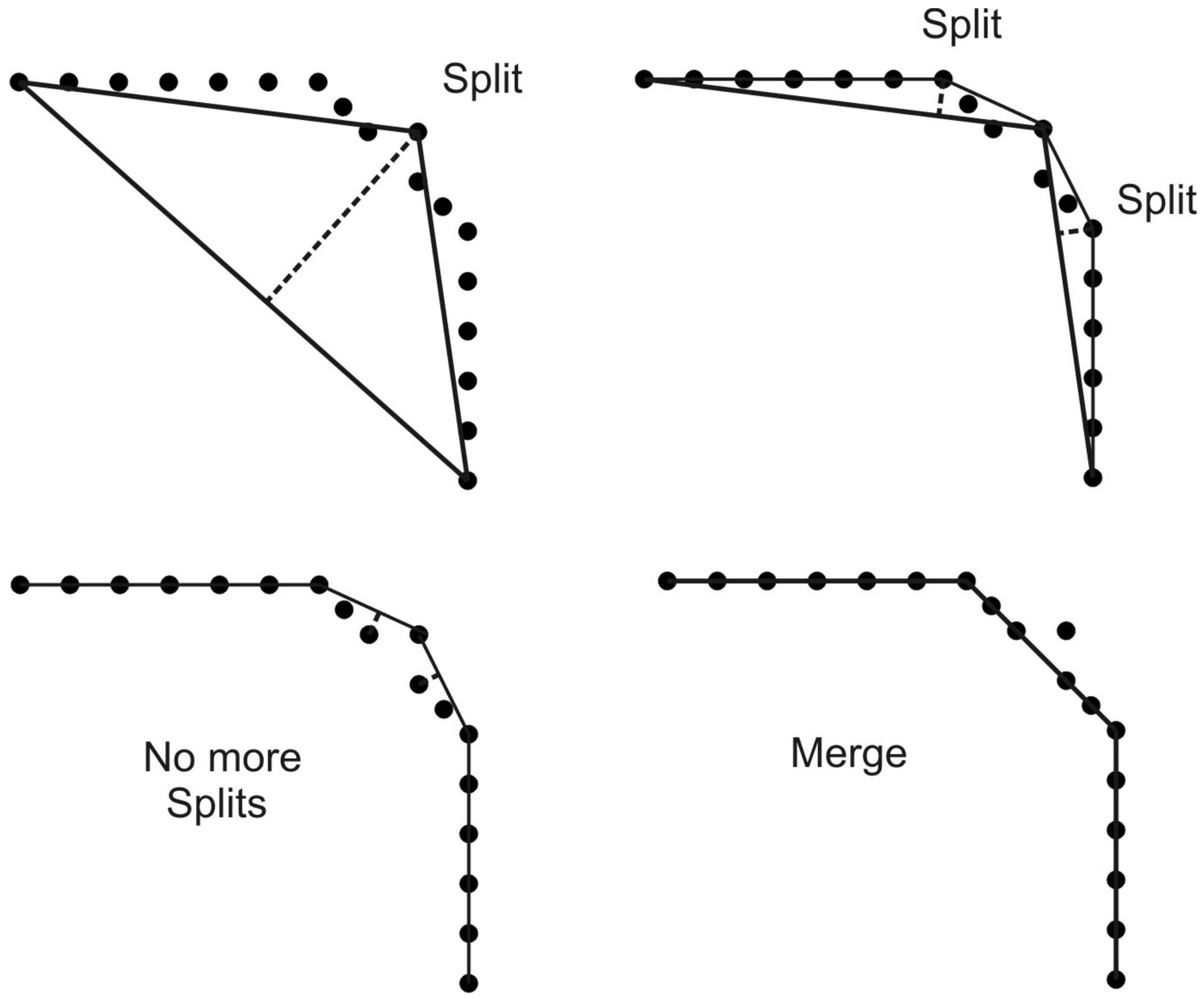
- Three main problems:
  - How many lines ?
  - Which points belong to which line ?
    - This problem is called SEGMENTATION
  - Given points that belong to a line, how to estimate the line parameters ?
    - This problem is called LINE FITTING
- The Algorithms we will see:
  1. Split and merge
  2. Linear regression
  3. RANSAC
  4. Hough-Transform

Algorithm 1: Split-and-Merge (standard)

- The most popular algorithm which is originated from computer vision.
- A recursive procedure of fitting and splitting.
- A slightly different version, called Iterative-End-Point-Fit, simply connects the end points for line fitting.



Algorithm 1: Split-and-Merge (Iterative-End-Point-Fit)

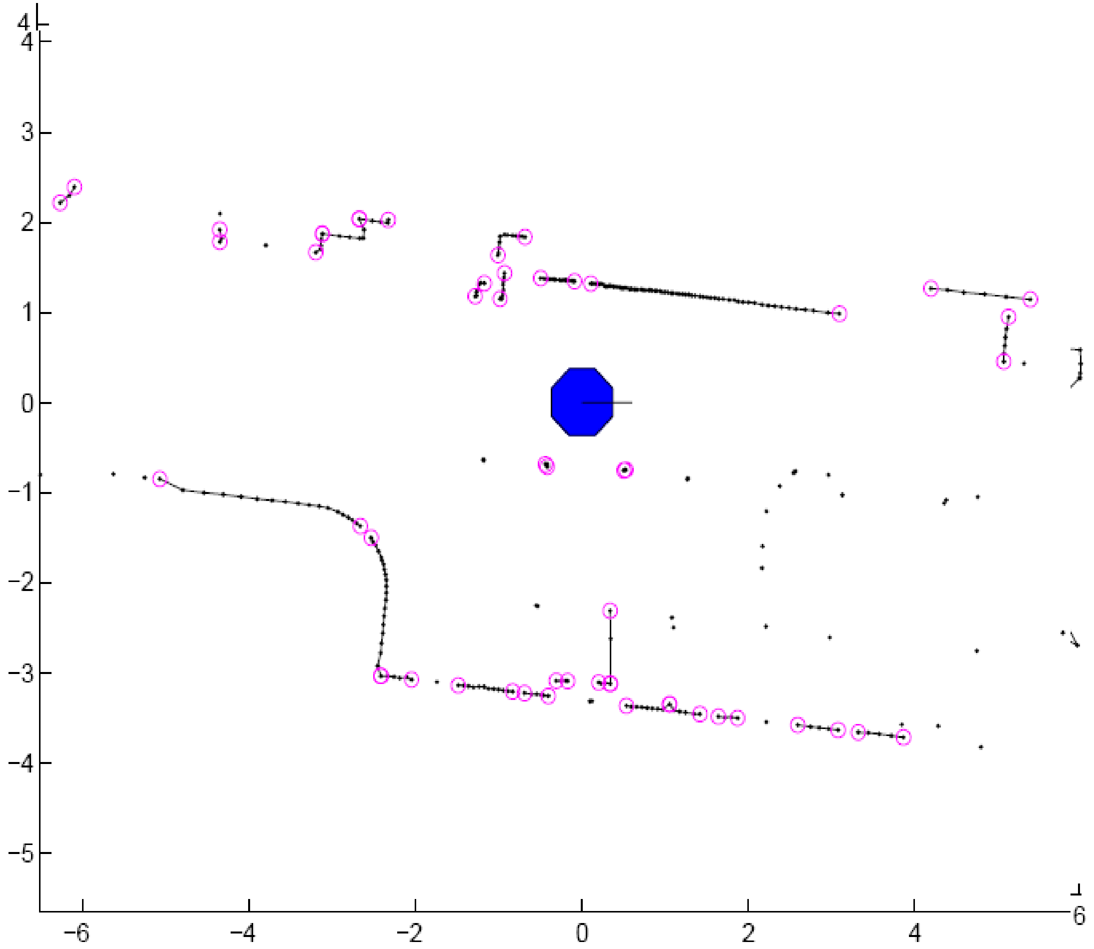


Algorithm 1: Split-and-Merge

Algorithm 1: *Split-and-Merge*

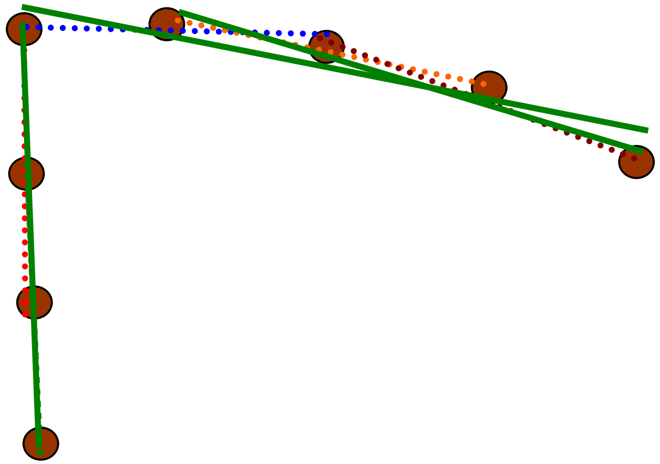
1. Initial: set s_1 consists of N points. Put s_1 in a list L
2. Fit a line to the next set s_i in L
3. Detect point P with maximum distance d_P to the line
4. If d_P is less than a threshold, continue (go to step 2)
5. Otherwise, split s_i at P into s_{i1} and s_{i2}, replace s_i in L by s_{i1} and s_{i2}, continue (go to 2)
6. When all sets (segments) in L have been checked, merge collinear segments.

Algorithm 1: Split-and-Merge: Example application



Algorithm 2: Line-Regression

- Uses a “sliding window” of size *Nf*
- The points within each “sliding window” are fitted by a segment
- Then adjacent segments are merged if their line parameters are close



$Nf = 3$

Algorithm 2: Line-Regression

Algorithm 2: *Line-Regression*

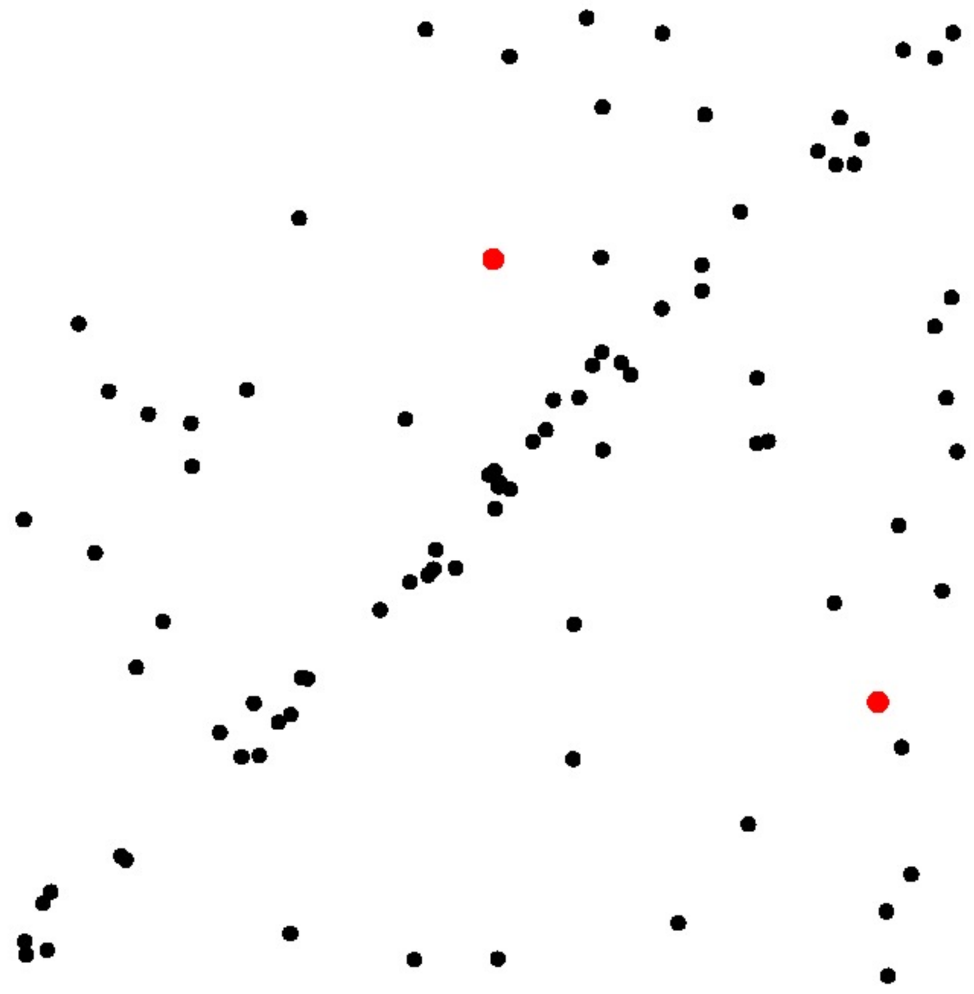
1. Initialize sliding window size N_f
2. Fit a line to every N_f consecutive points (a window)
3. Compute a line fidelity array, each is the sum of Mahalanobis distances between every three adjacent windows
4. Construct line segments by scanning the fidelity array for consecutive elements having values less than a threshold, using an AHC algorithm
5. Merge overlapped line segments and recompute line parameters for each segment

Algorithm 3: RANSAC

- Acronym: **Ran**dom **Sa**mple **C**onsensus.
- Generic & robust fitting algorithm of models with outliers
  - Outliers: points which do not satisfy a model
- RANSAC: apply to any problem where:
  - 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 method & non-deterministic
- Drawback: A nondeterministic method, results are different between runs.

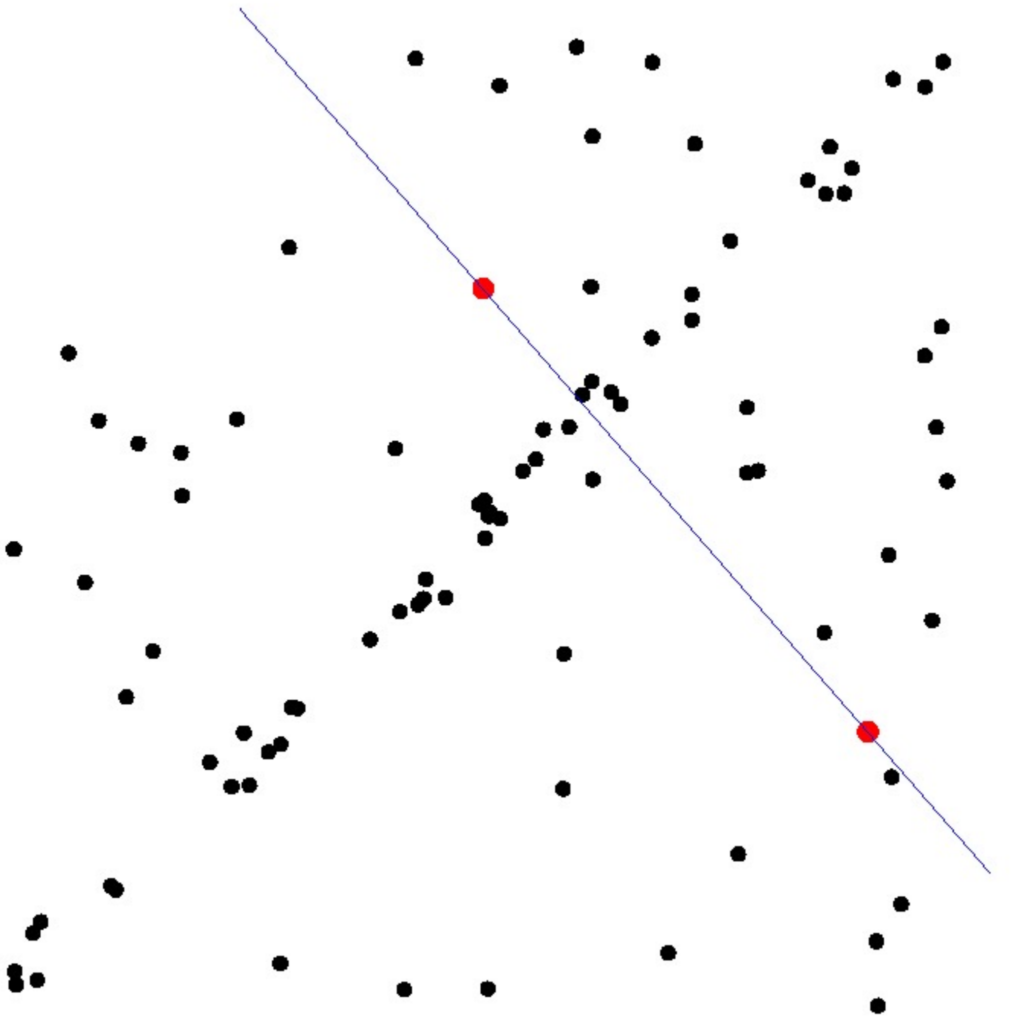
Algorithm 3: RANSAC

Algorithm 3: RANSAC



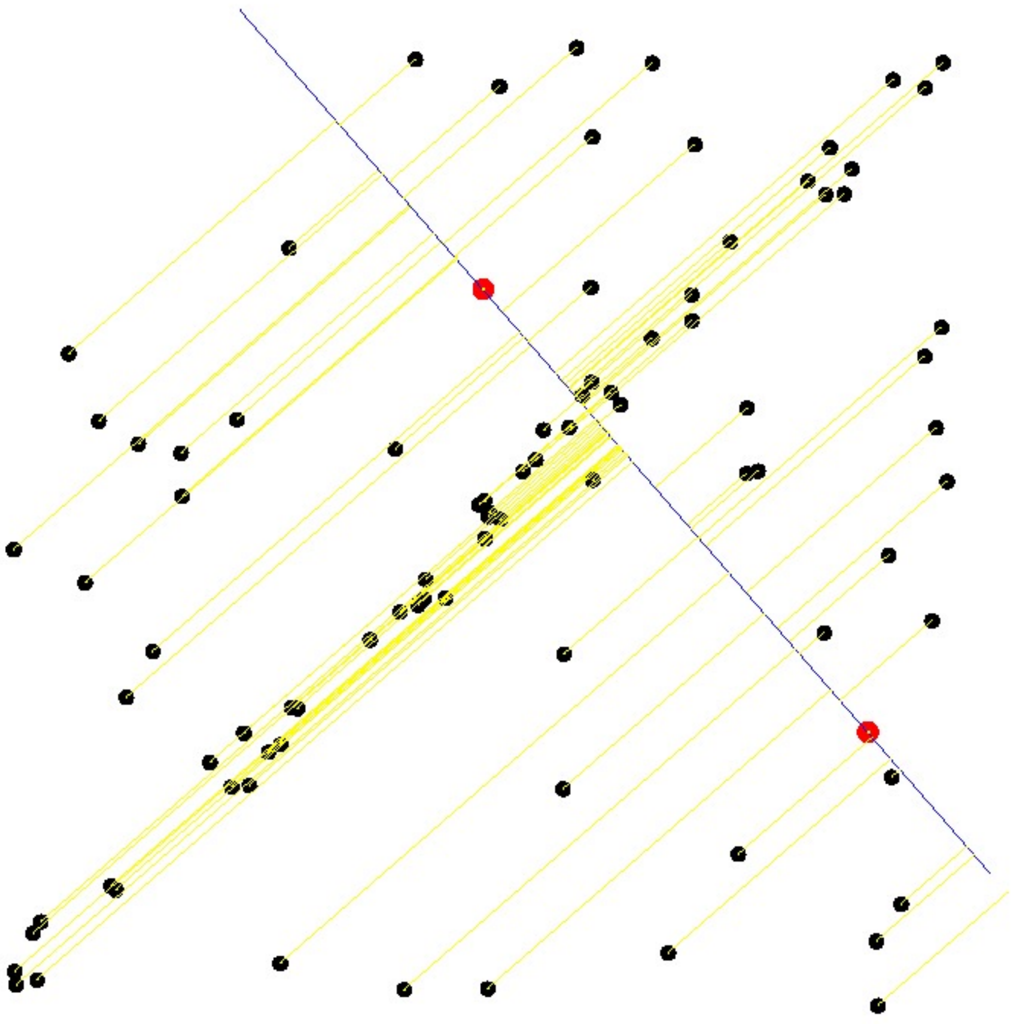
- **Select sample of 2 points at random**

Algorithm 3: RANSAC



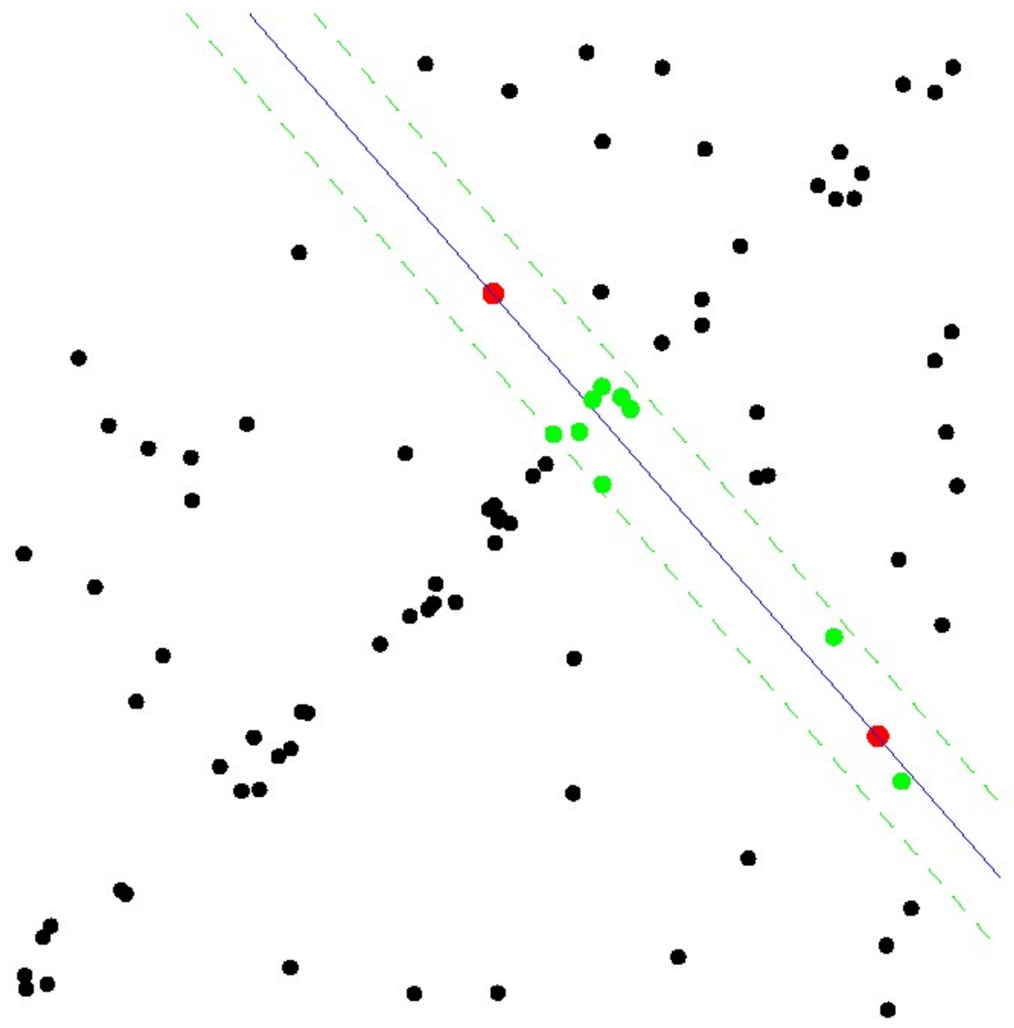
- Select sample of 2 points at random
- **Calculate model parameters that fit the data in the sample**

RANSAC



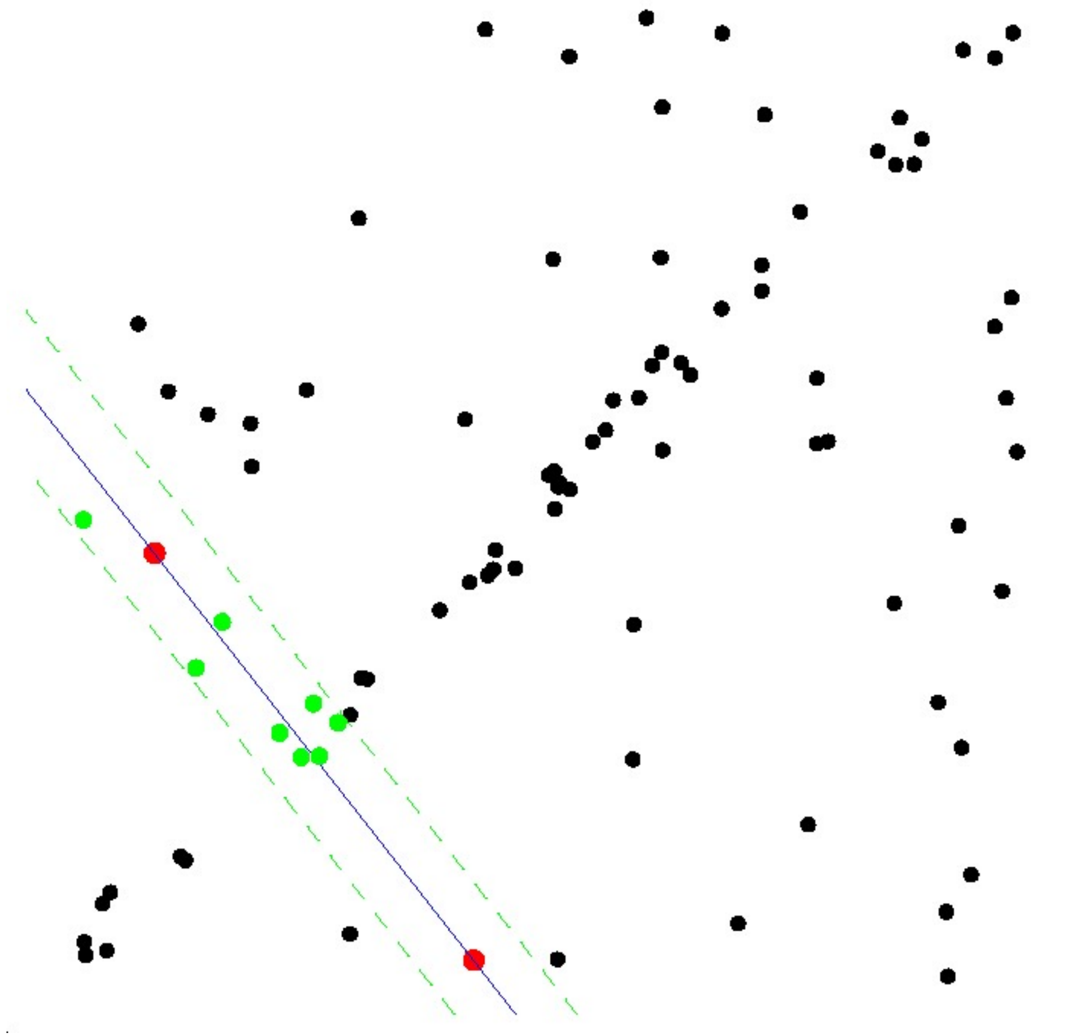
- Select sample of 2 points at random
- Calculate model parameters that fit the data in the sample
- **Calculate error function for each data point**

Algorithm 3: RANSAC



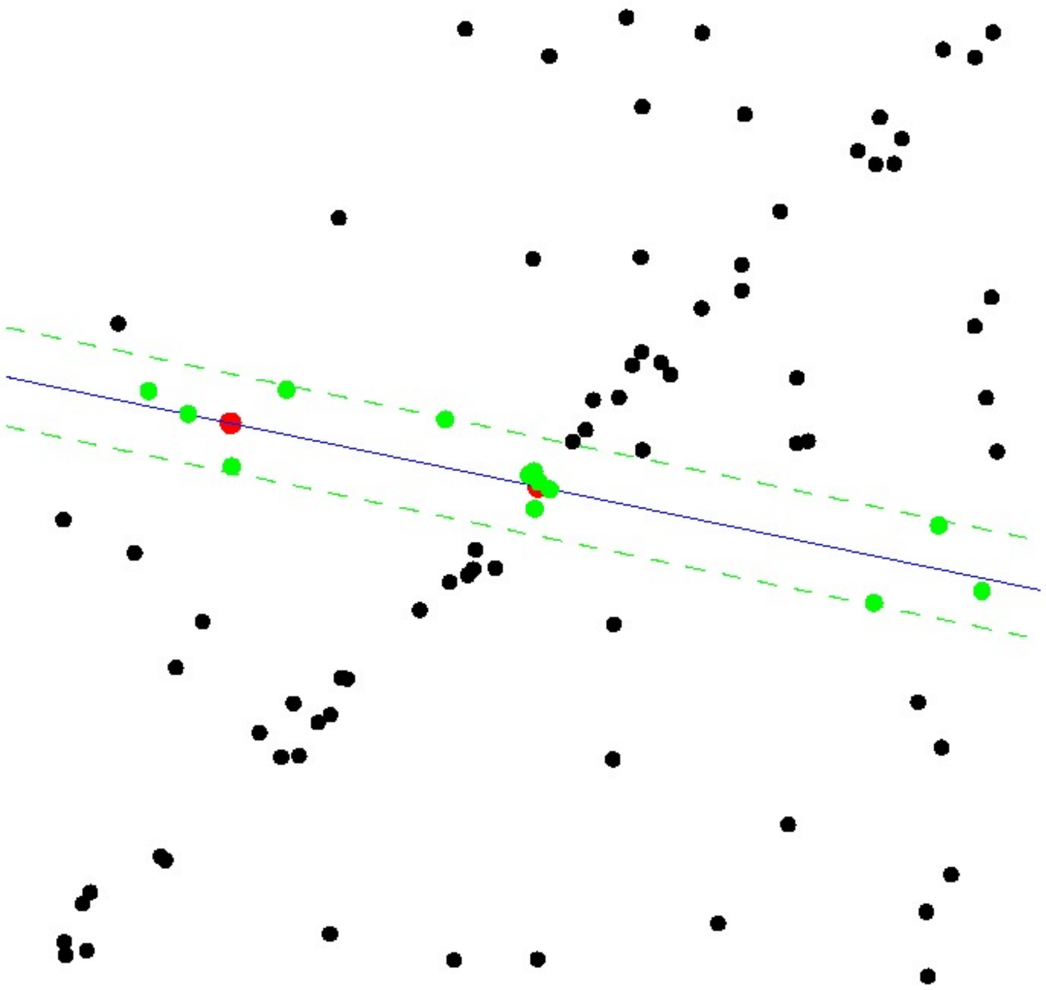
- Select sample of 2 points at random
- Calculate model parameters that fit the data in the sample
- Calculate error function for each data point
- **Select data that support current hypothesis**

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**

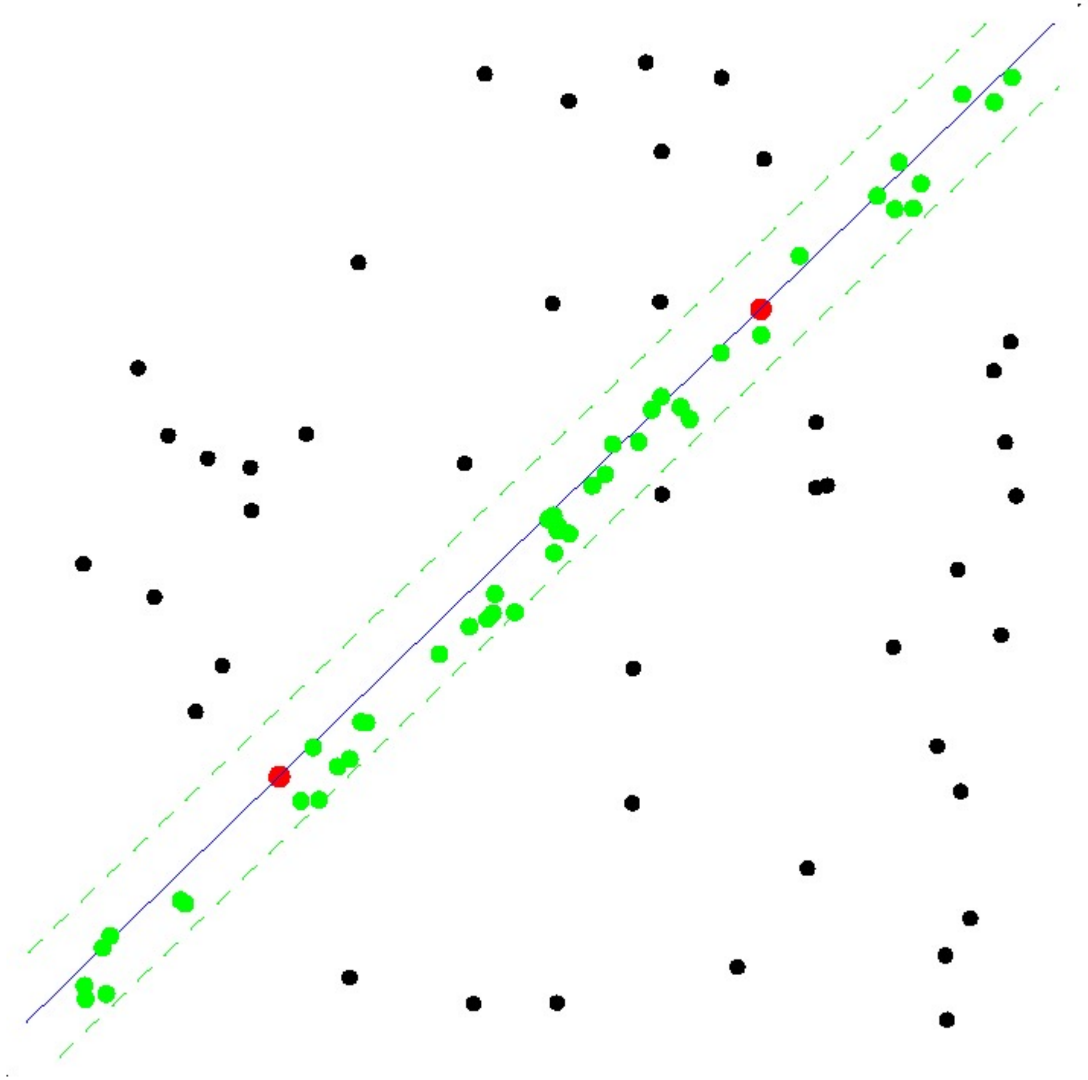
Algorithm 3: RANSAC



- 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*

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

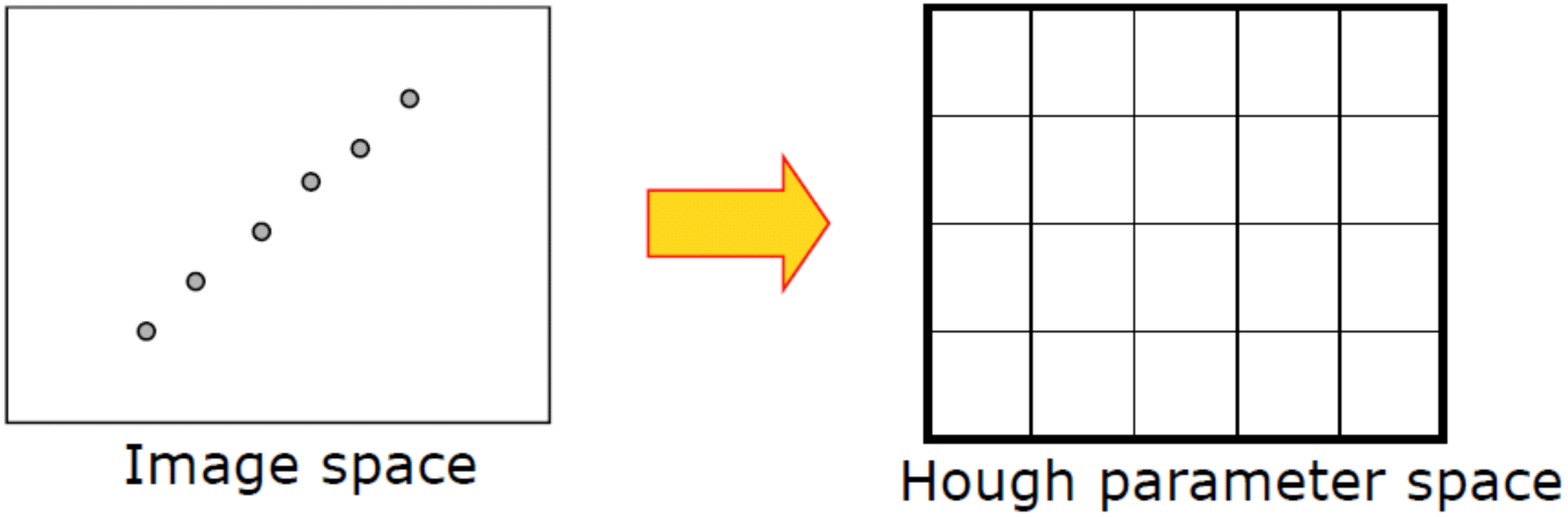
Algorithm 3: RANSAC

How many iterations does RANSAC need?

- Because we cannot know in advance if the observed set contains the maximum number of inliers, the ideal would be to check all possible combinations of 2 points in a dataset of N points.
- The number of combinations is given by N(N-1)/2, which makes it computationally unfeasible if N is too large. For example, in a laser scan of 360 points we would need to check all 360*359/2= 64,620 possibilities!
- Do we really need to check all possibilities or can we stop RANSAC after iterations? The answer is that indeed we do not need to check all combinations but just a subset of them if we have a rough estimate of the percentage of inliers in our dataset
- This can be done in a probabilistic way

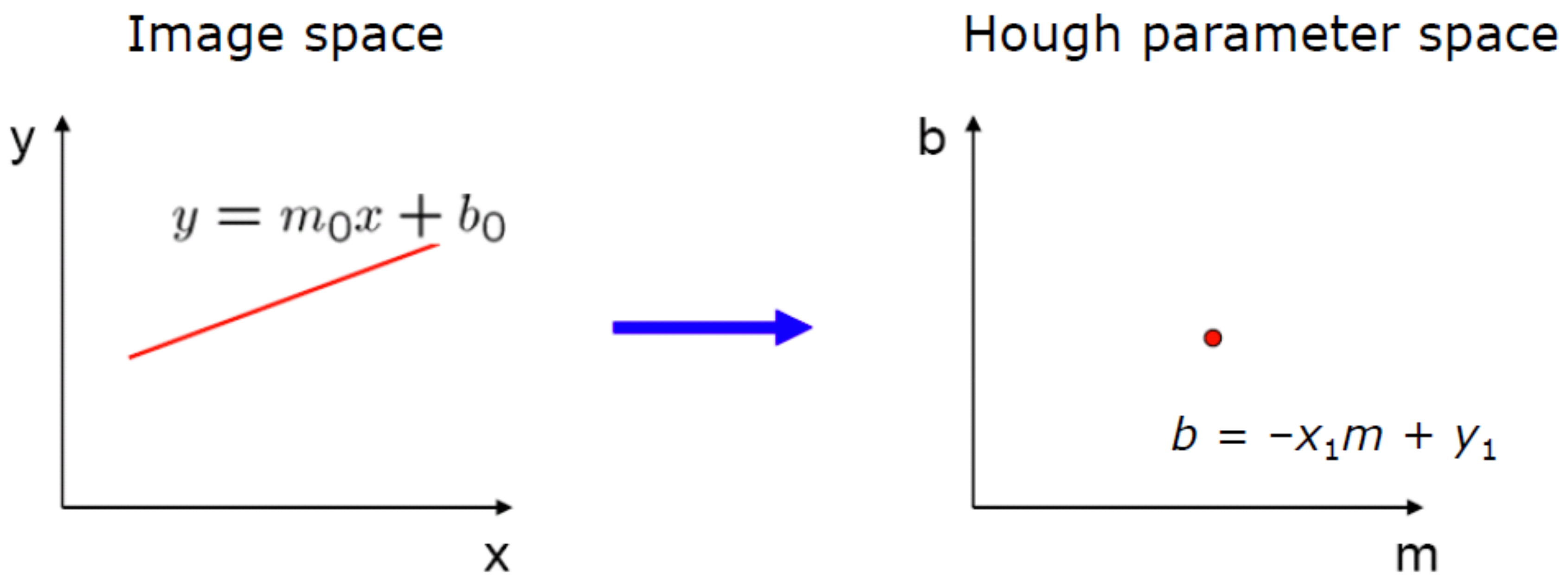
Algorithm 4: Hough-Transform

- Hough Transform uses a voting scheme



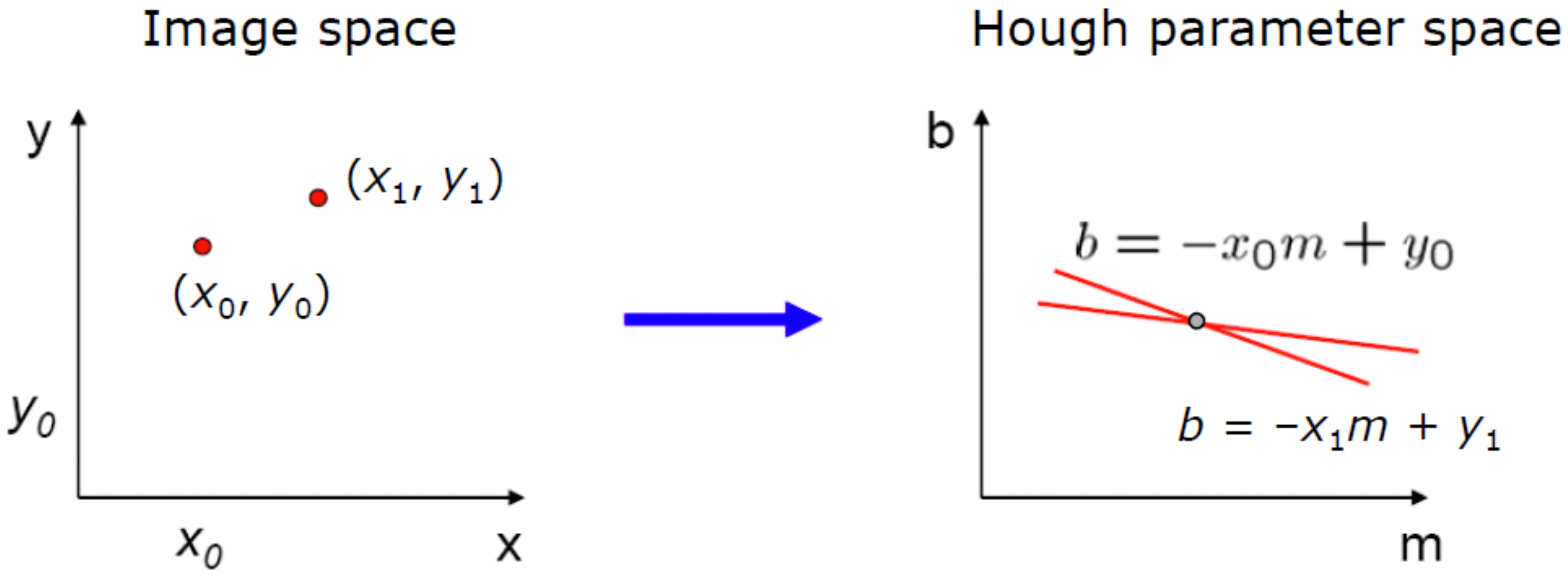
Algorithm 4: Hough-Transform

- A line in the image corresponds to a point in Hough space



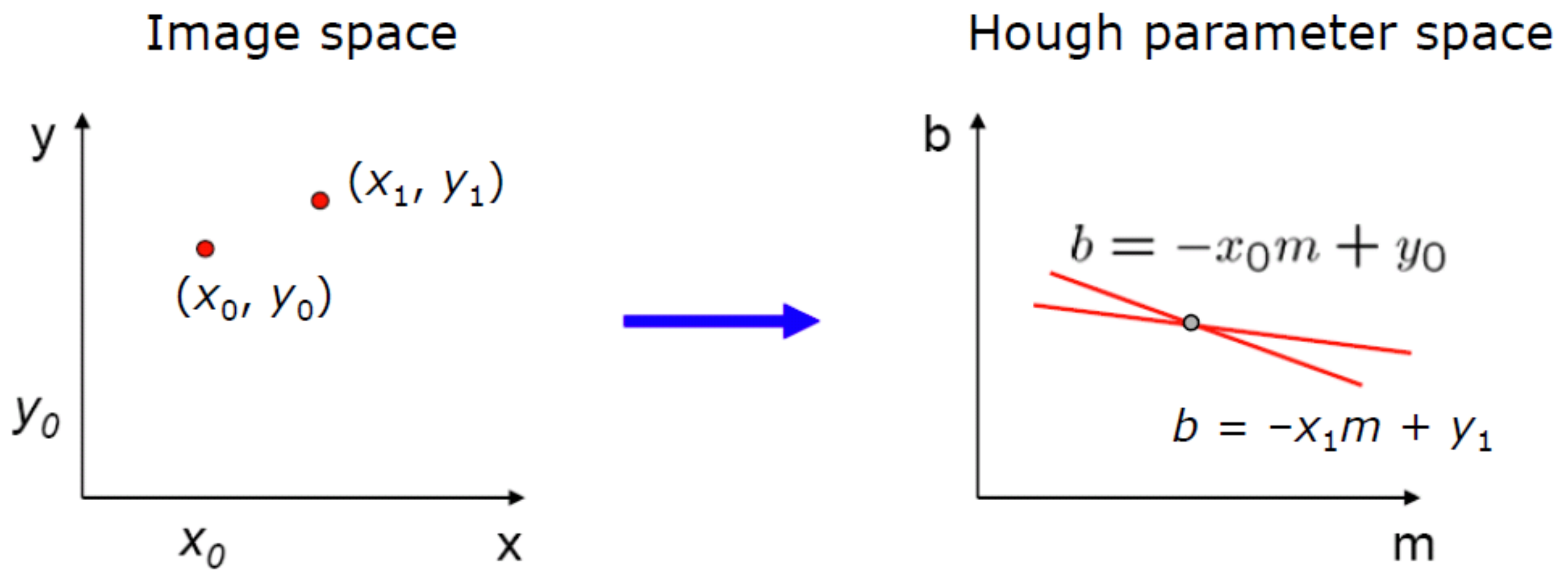
Algorithm 4: Hough-Transform

- What does a point (x_0, y_0) in the image space map to in the Hough space?



Algorithm 4: Hough-Transform

- Where is the line that contains both (x_0, y_0) and (x_1, y_1)?
  - It is the intersection of the lines $b = -x_0m + y_0$ and $b = -x_1m + y_1$



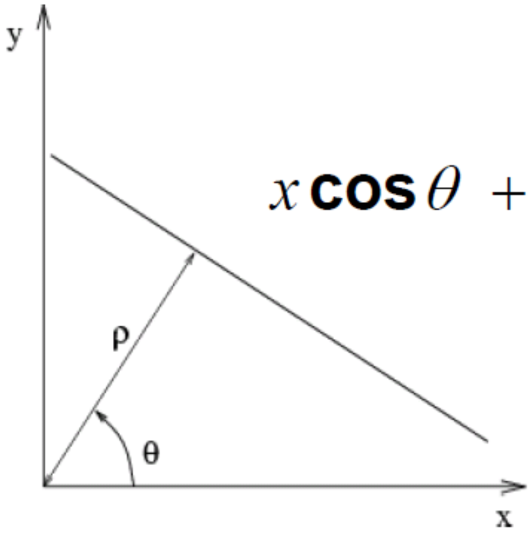
Algorithm 4: Hough-Transform

- Problems with the (m,b) space:
  - Unbounded parameter domain
  - Vertical lines require infinite m

Algorithm 4: Hough-Transform

- Problems with the (m,b) space:
  - Unbounded parameter domain
  - Vertical lines require infinite m

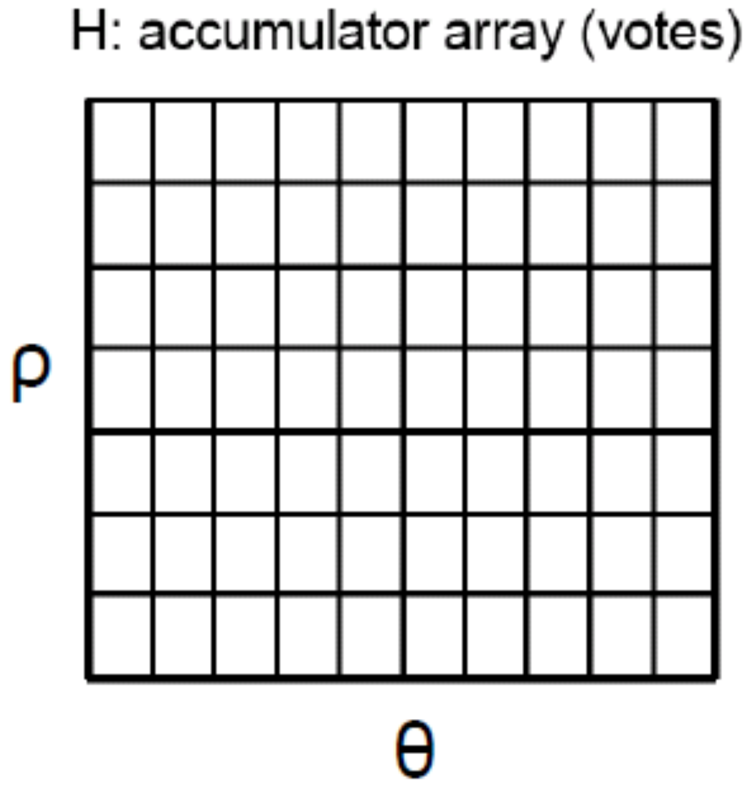
- Alternative: polar representation



$$x\cos\theta + y\sin\theta = \rho$$

Each point will add a sinusoid in the (θ,ρ) parameter space

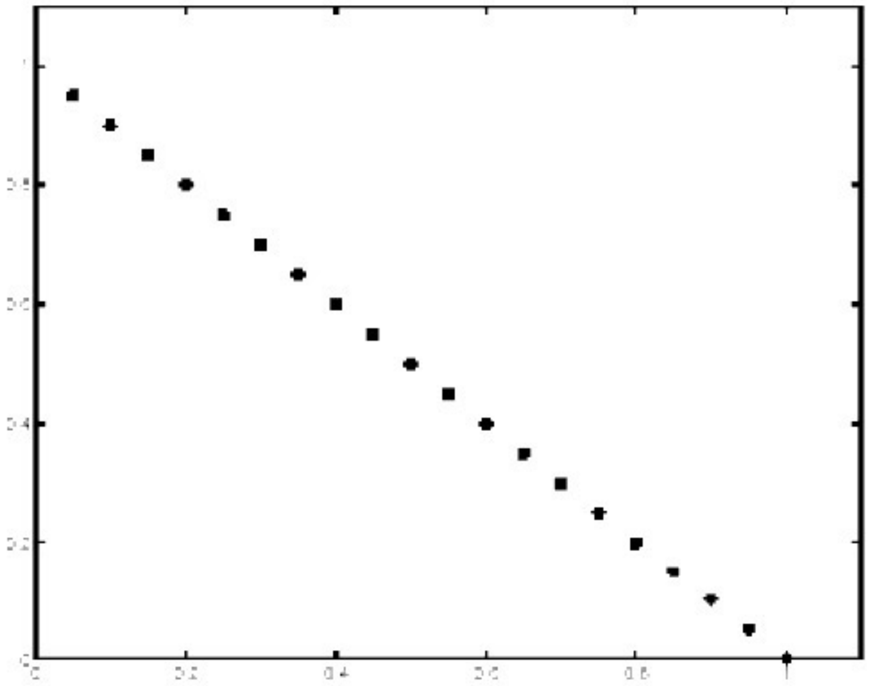
Algorithm 4: Hough-Transform



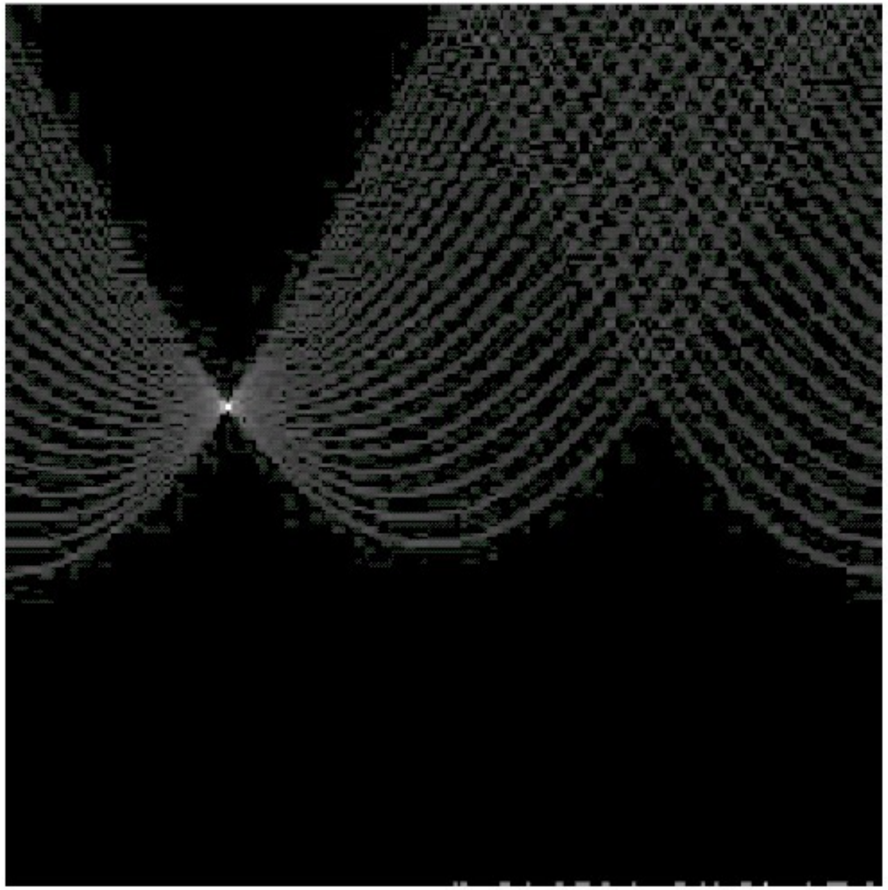
1. Initialize accumulator H to all zeros
2. For each edge point (x,y) in the image
   - For $\theta = 0$ to 180 (with a step size of e.g. 18)
     - $\rho = x \cos \theta + y \sin \theta$
     - $H(\theta, \rho) = H(\theta, \rho) + 1$
   - end

   end
3. Find the values of (θ, ρ) where $H(\theta, \rho)$ is a local maximum
4. The detected line in the image is given by $\rho = x \cos \theta + y \sin \theta$

Algorithm 4: Hough-Transform



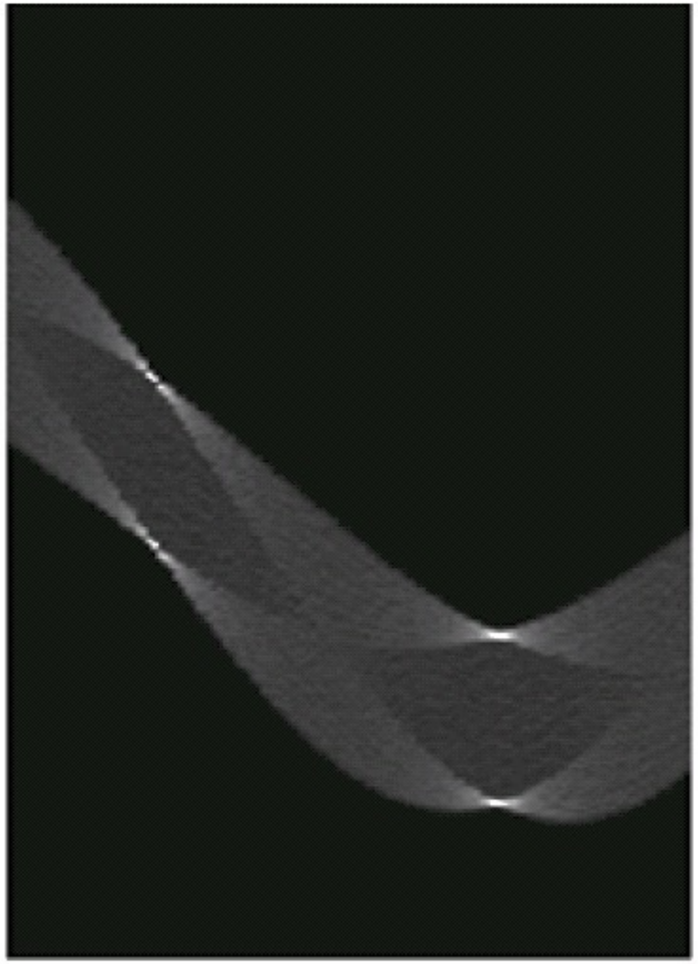
features



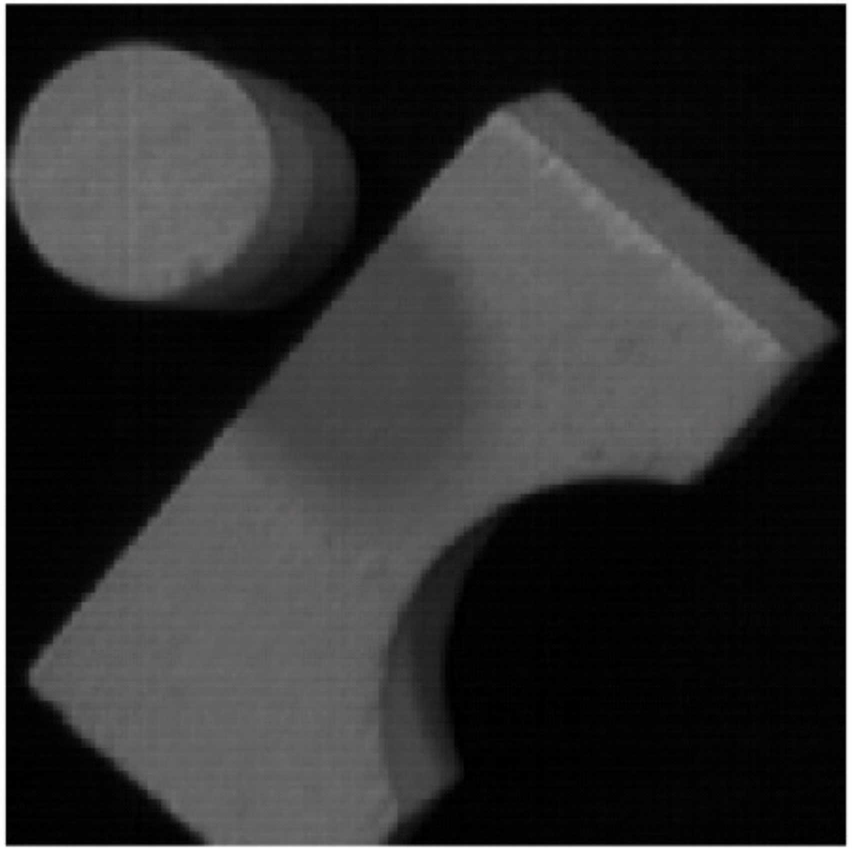
votes

Algorithm 4: Hough-Transform

Square

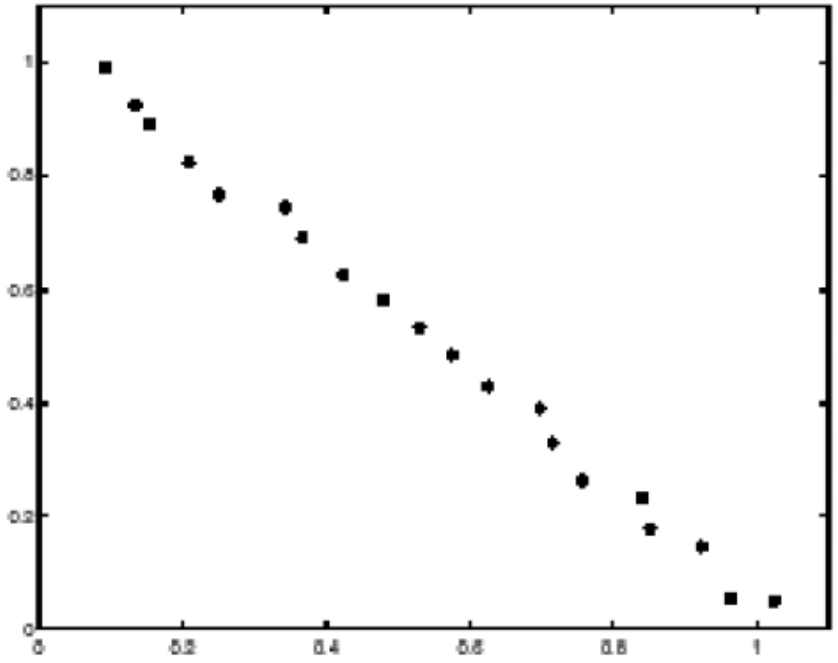


Algorithm 4: Hough-Transform

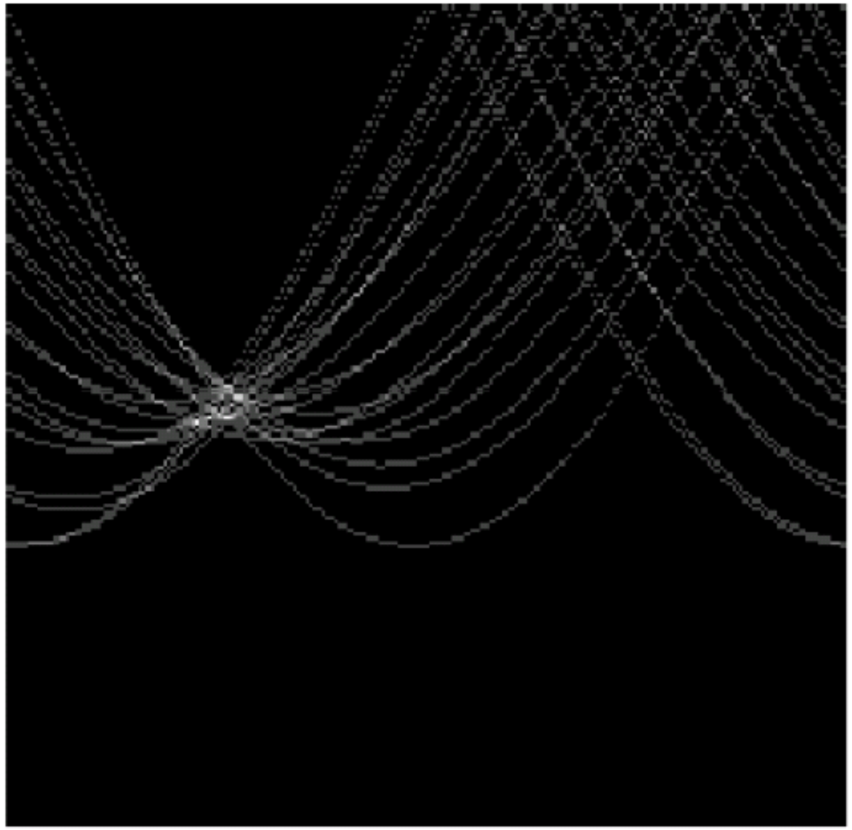


Algorithm 4: Hough-Transform

Effect of Noise



features

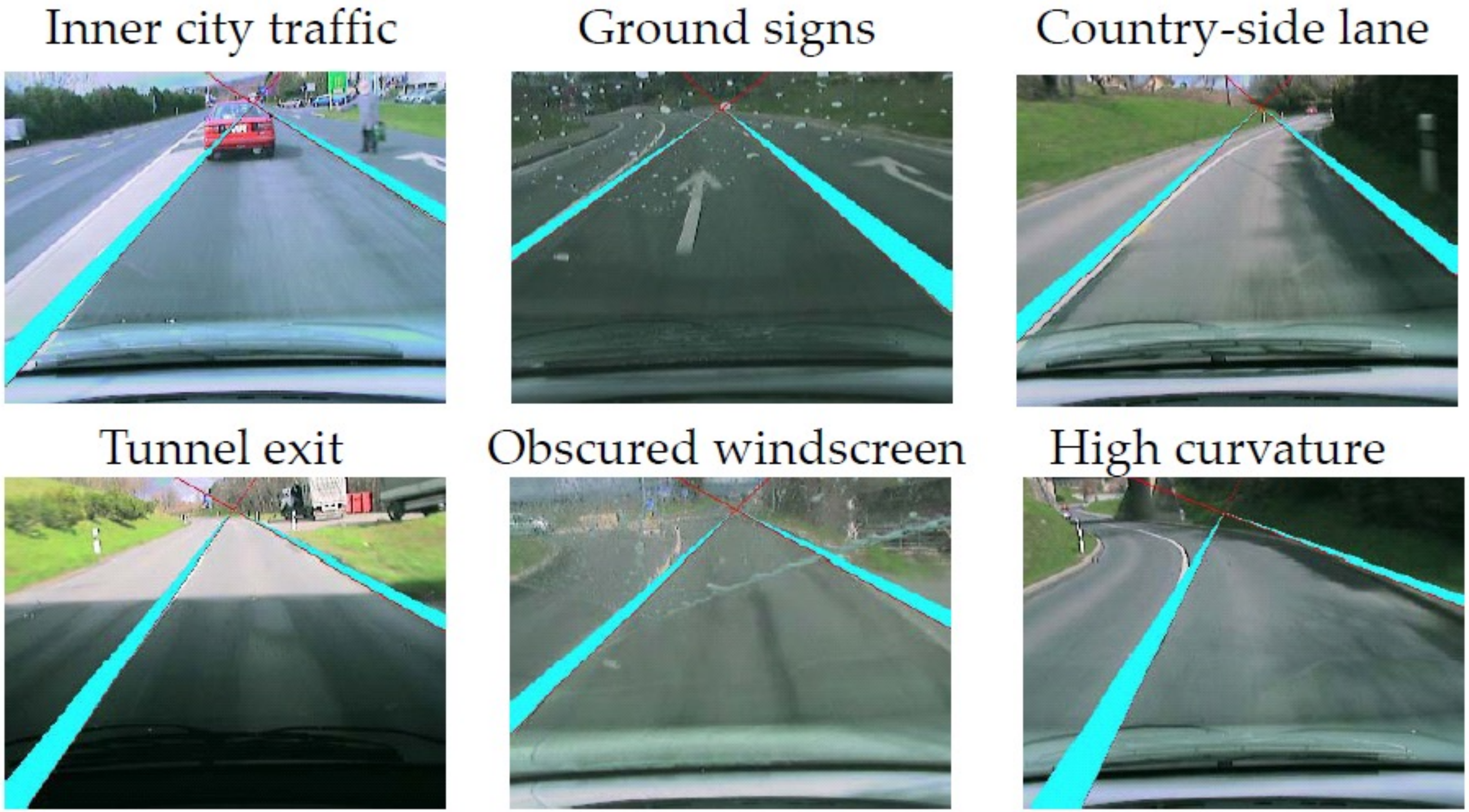


votes

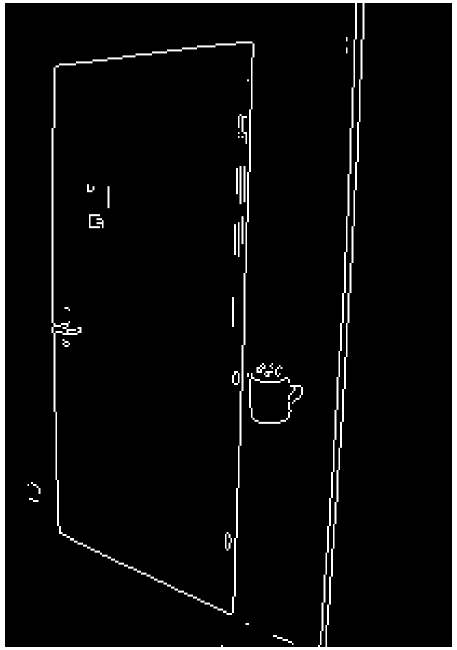
- Peak gets fuzzy and hard to locate

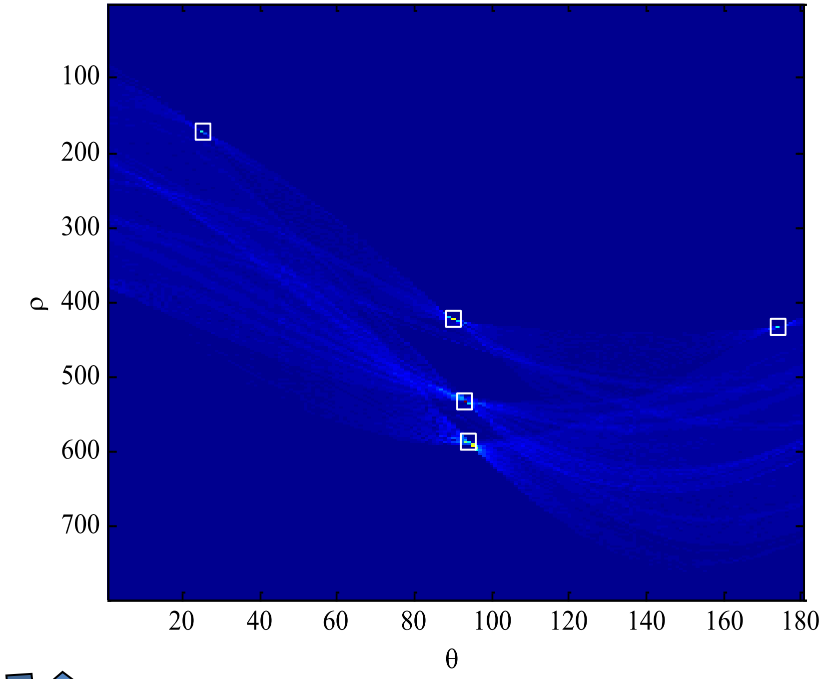
Algorithm 4: Hough-Transform

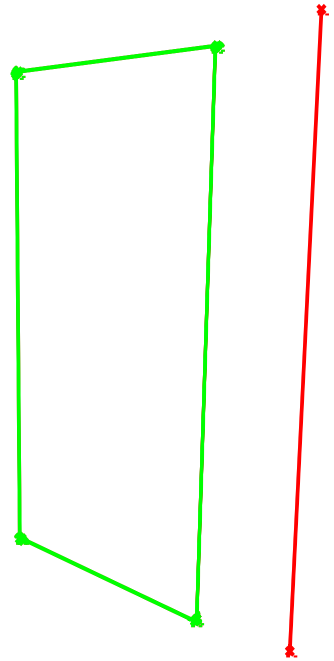
Application: Lane detection



Example – Door detection using Hough Transform







Hough Transform

Hough Transform: other features

Lines:

$$p = (d, \upsilon)$$

$$g(x,y,p) := x \cdot \cos(\upsilon) + y \cdot \sin(\upsilon) - d$$

Circles:

$$p = (x_0, y_0, r)$$

$$g(x,y,p) := (x - x_0)^2 + (y - y_0)^2 - r^2$$

Ellipses:

$$p = (x_0, y_0, a, b, \psi)$$

$$g(x,y,p) := \frac{\left[(x - x_0)\cdot\cos(\psi) + (y - y_0)\cdot\sin(\psi)\right]^2}{a^2} + \frac{\left[(y - y_0)\cdot\cos(\psi) - (x - x_0)\cdot\sin(\psi)\right]^2}{b^2} - 1$$

Hough Transform

- Advantages
  - Noise and background clutter do not impair detection of local maxima
  - Partial occlusion and varying contrast are minimized
- Negatives
  - Requires time and space storage that increases exponentially with the dimensions of the parameter space

Comparison **Line Detection**

- Deterministic methods perform better with laser scans
  - Split-and-merge, Line-Regression, Hough transform
  - Make use of the sequencing property of scan points.
- Nondeterministic methods can produce high False Positives
  - RANSAC
  - Do not use the sequencing property
  - But it can cope with outliers
- Overall:
  - Split-and-merge is the fastest, best real-time application