16-311-Q Introduction to Robotics Fall'17

Lecture 16:
Sensors (For State Estimation) 2

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RANGE FINDER SENSORS (FOR NAVIGATION)

- **Sonars:** Time-of-flight of ultrasonics waves
- **Laser range finders:** Time-of-flight of collimated electro-magnetic beams (laser)
- **Time of flight cameras** Time-of-flight of infrared collimated (laser/LED) lighting source, matrix of sensors
- **Proximity sensors:** Visible or IR light, measure reflected intensity
- **Contact sensors:** Tactile interaction, measure applied mechanical or electrical forces
- **CCD/CMOS cameras:** Measure gathered intensity of visible light, use disparity or optical flow for space-time measures

Exteroceptive sensors

Range Sensors (time of flight) (1)

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

$$d = c \cdot t$$

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

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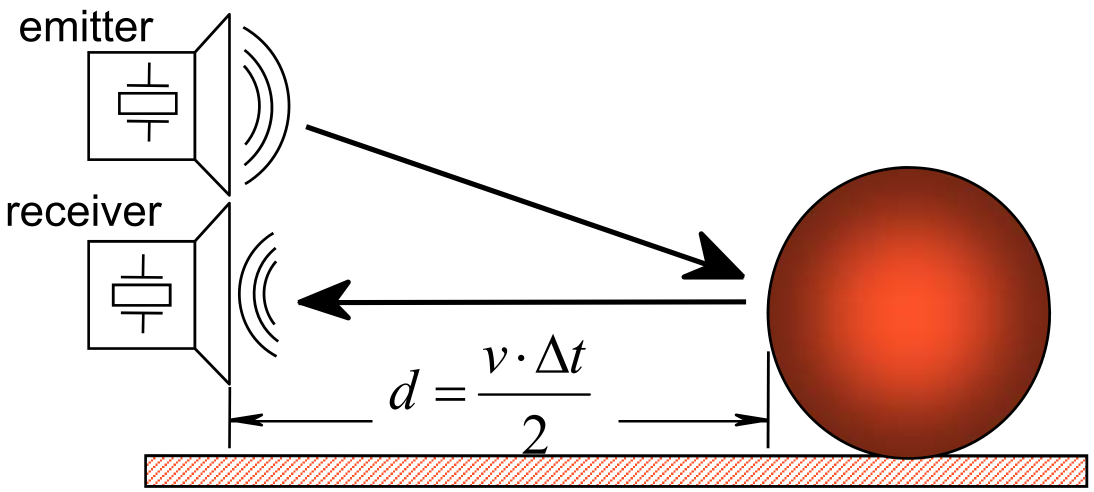
Range Sensors (time of flight) (2)

- It is important to point out
  - **Propagation speed v of sound: 0.3 m/ms**
  - **Propagation speed v of of electromagnetic signals: 0.3 m/ns,**
  - **Electromagnetic signals travel one million times faster.**
  - 3 meters
    - Equivalent to **10 ms** for an ultrasonic system
    - Equivalent to only **10 ns** for a laser range sensor
    - Measuring time of flight with electromagnetic signals is not an easy task
    - laser range sensors expensive and delicate

- The quality of time of flight range sensors mainly depends on:
  - **Inaccuracies** in the time of fight **measurement** (laser range sensors)
  - **Opening angle** of transmitted beam (especially ultrasonic range sensors)
  - Interaction with the target (surface, specular reflections)
  - **Variation of propagation speed (sound)**
  - **Speed of mobile robot and target (if not at stand still)**

Factsheet: Ultrasonic Range Sensor



<http://www.robot-electronics.co.uk/shop/Ultrasonic_Rangers1999.htm>

1. Operational Principle

An ultrasonic pulse is generated by a piezo-electric emitter, reflected by an object in its path, and sensed by a piezo-electric receiver. Based on the speed of sound in air and the elapsed time from emission to reception, the distance between the sensor and the object is easily calculated.

2. Main Characteristics

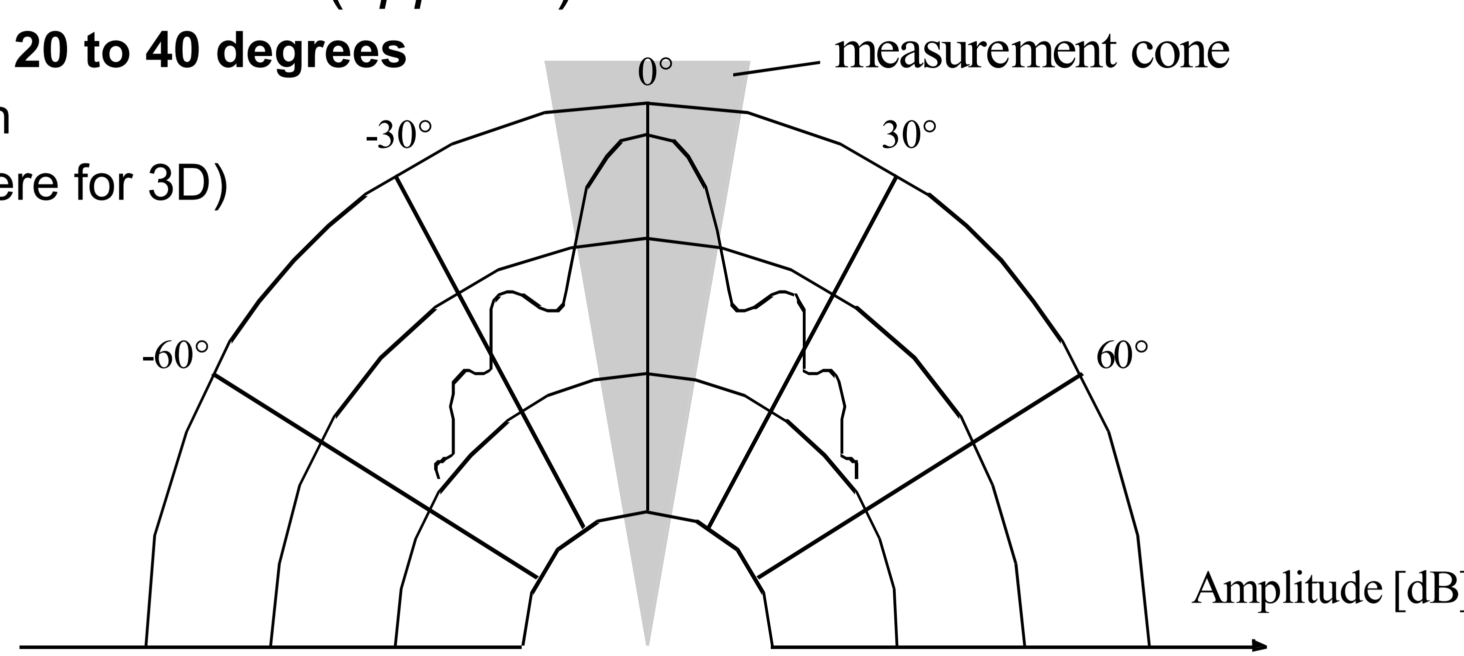
- Precision influenced by angle to object (as illustrated on the next slide)
- Useful in ranges from several cm to several meters
- **Typically relatively inexpensive**

3. Applications

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

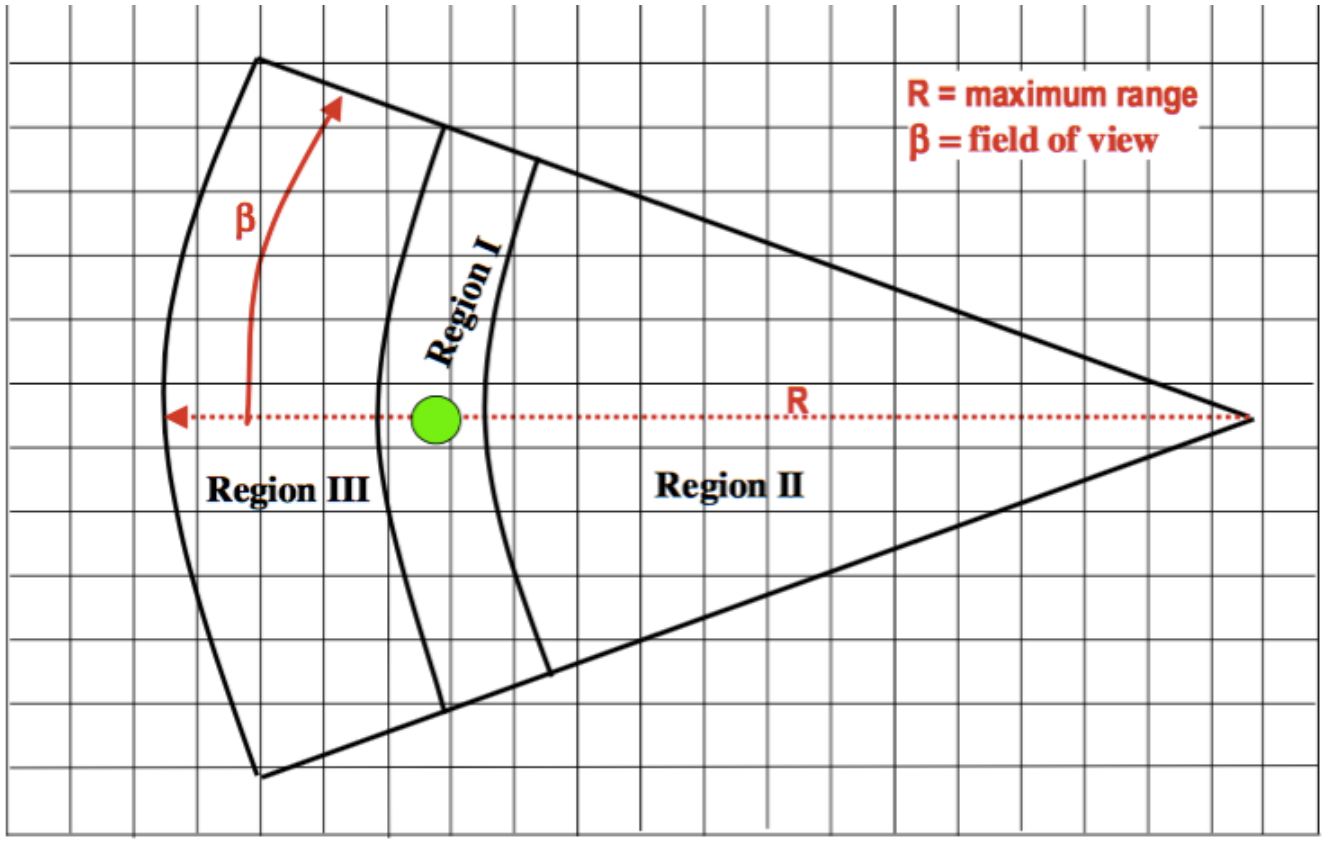
Ultrasonic Sensor (time of flight, sound) (2)

- typical frequency: 40kHz - 180 kHz
  - Lower frequencies correspond to longer maximal sensor range
- generation of sound wave via piezo transducer
  - transmitter and receiver can be 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

SENSING REGIONS



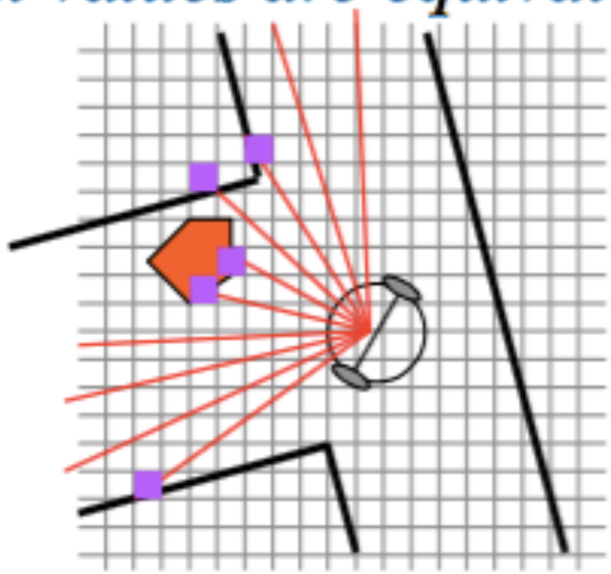
- It's not a collimated beam from the sensor, but a cone.
- Sonar range readings have inherent resolution error
- Thus, specific reading might actually indicate range of possible values in the *cone*
- E.g., reading of 0.87 meters actually means within (0.82, 0.92) meters, anywhere in Region I
- *Tolerance* in this case is 0.05 meters.
- Tolerance gives width of Region I → Need for probabilistic adjustments

POLAR HISTOGRAMS WITH OCCUPANCY ESTIMATES

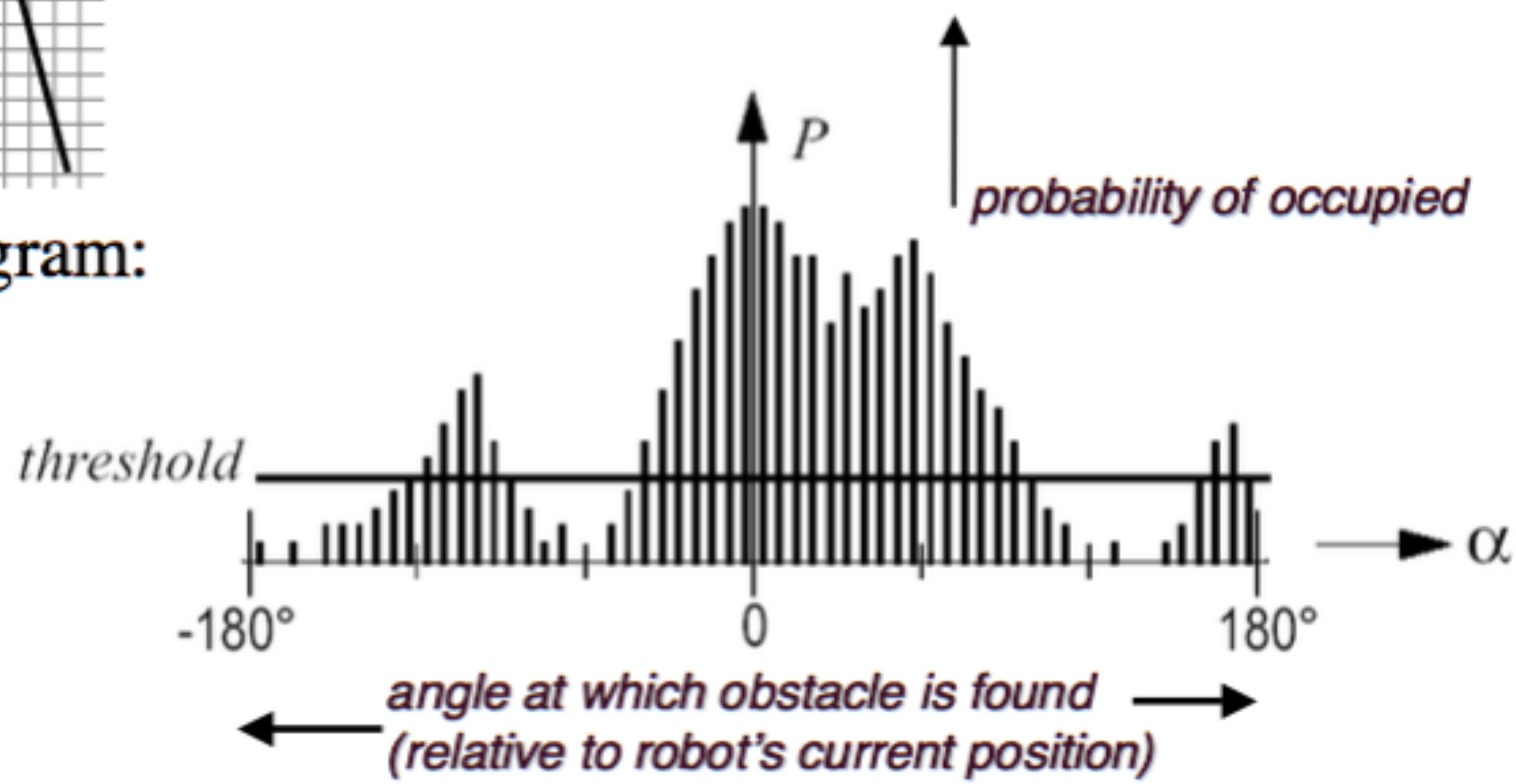
- Environment represented in a grid (2 DOF)

Koren & Borenstein, ICRA 1990

  - *cell values are equivalent to the probability that there is an obstacle*

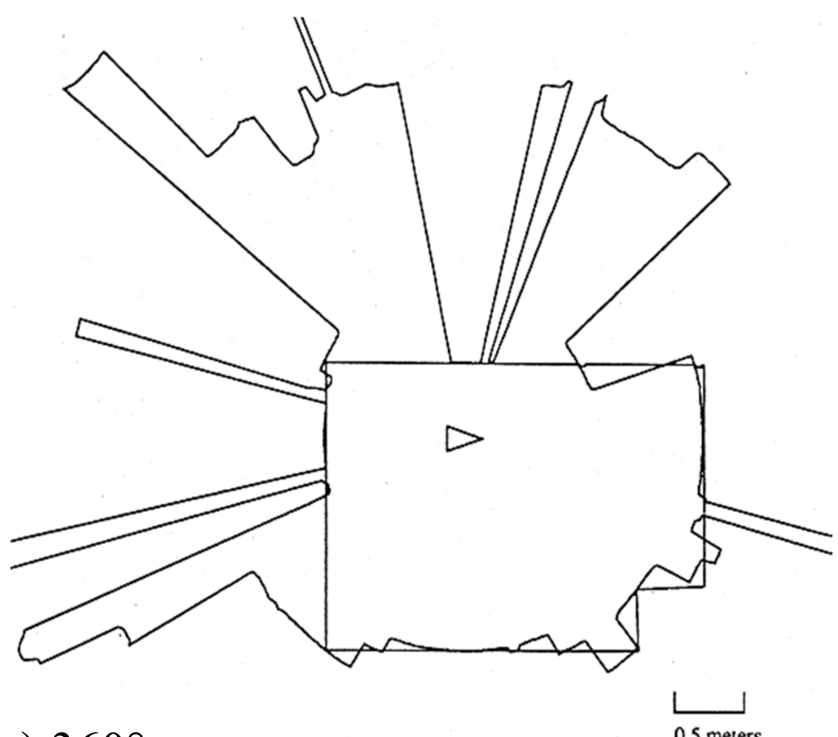


- Generate polar histogram:

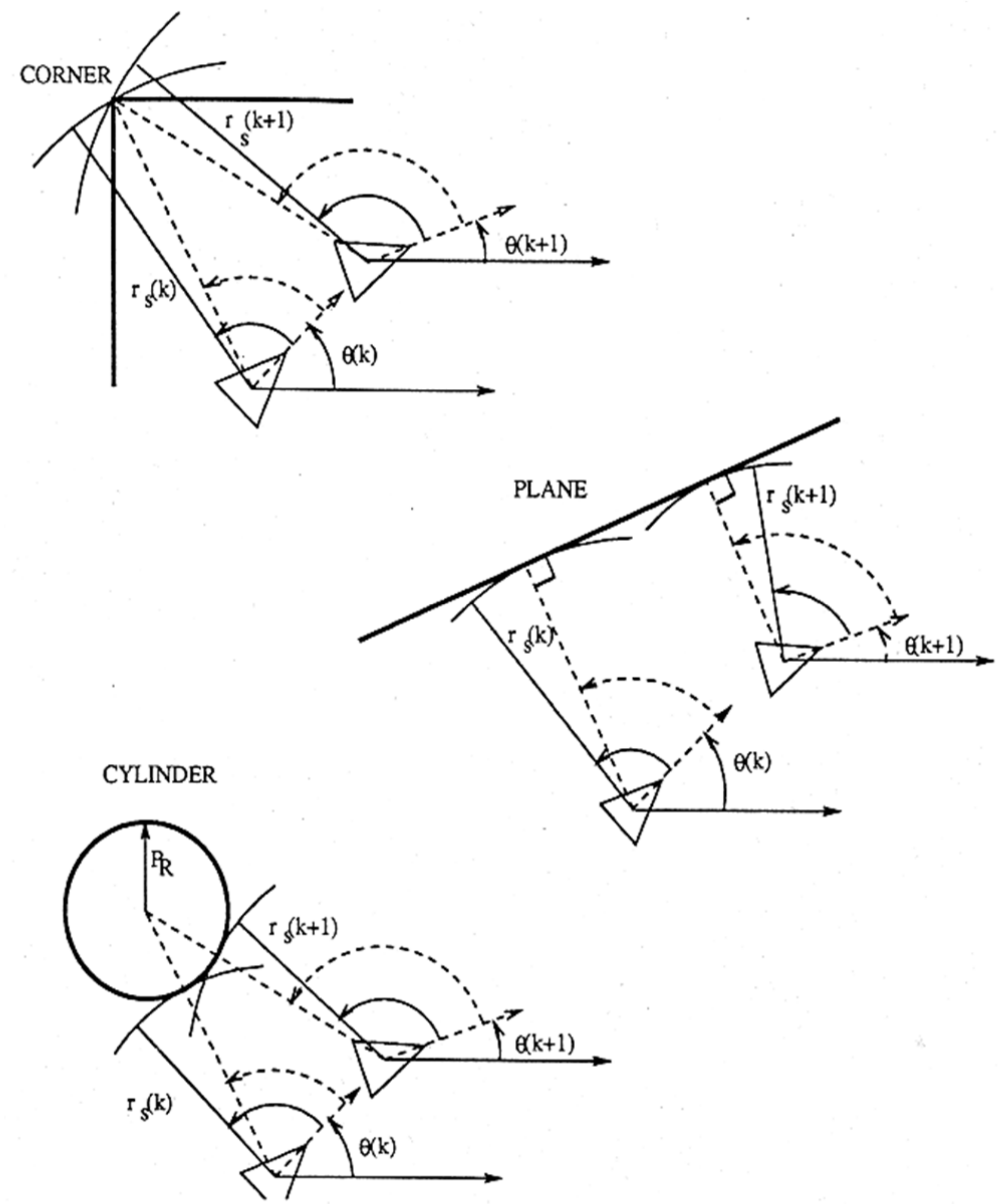


Ultrasonic Sensor (time of flight, sound) (3)

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



a) 360° scan



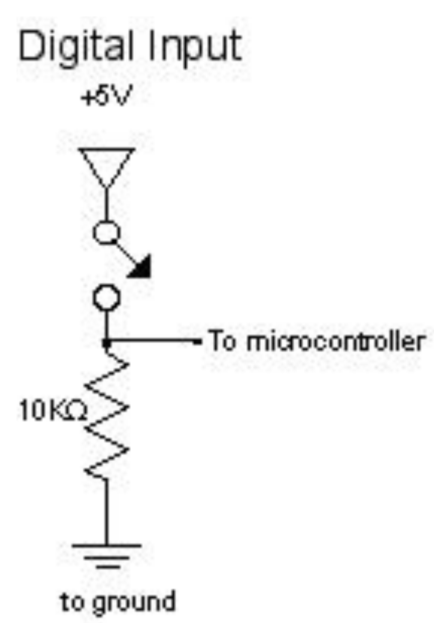
b) results from different geometric primitives

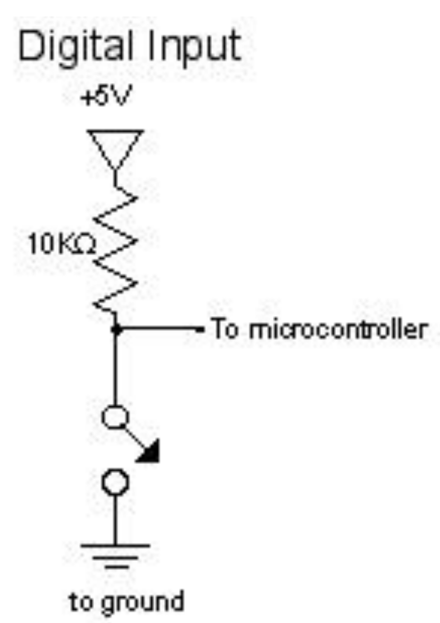
Ultrasonic Sensor (time of flight, sound) (4)

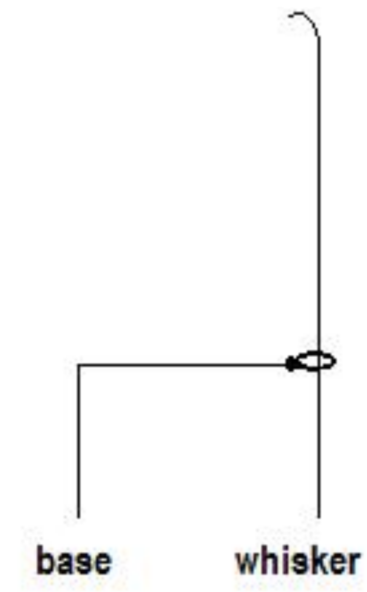
- Bandwidth
  - **measuring the distance to an object that is 3 m away will take such a sensor 20 ms, limiting its operating speed to 50 Hz**. But if the robot has a **ring of 20 ultrasonic sensors**, each firing sequentially and measuring to minimize interference between the sensors, then the ring's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

CONTACT SENSORS

- **Bumper switches:** use some form of mechanical bumper to press a button when the robot comes in contact with an object.
- Need to be unpressed to release the switch



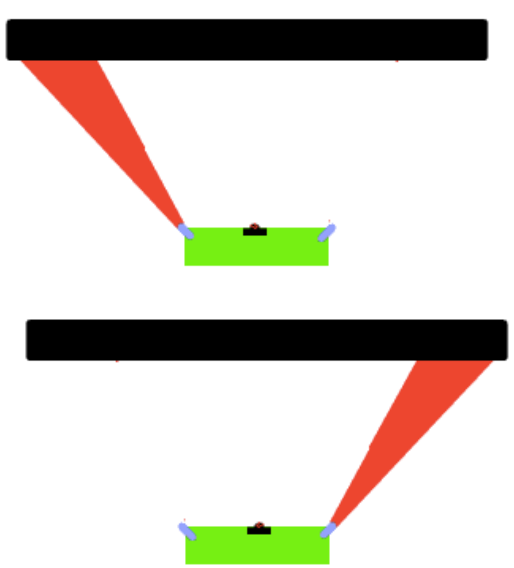


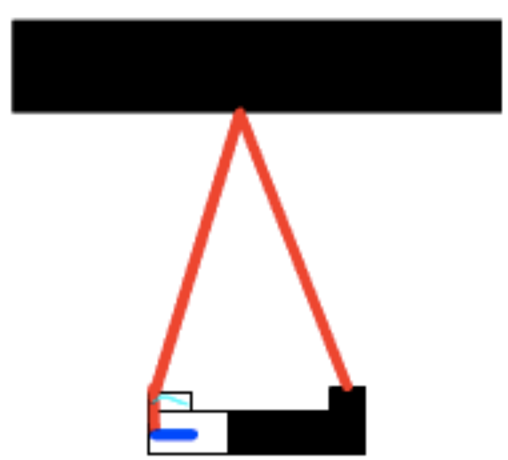


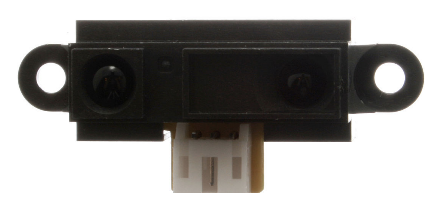
- **Whiskers:** simpler and cheaper method with 2 pieces of wire. The base, is L-shaped with a small loop at one end. The whisker is passed through the loop on the end of the base wire. Under normal or inactive conditions, the whisker wire does not make contact with the loop, thus creating an *open circuit*. Only when the whisker wire bumps into an object, is the *circuit closed*

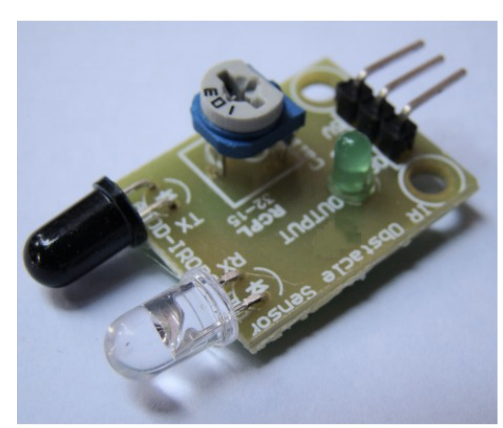
PROXIMITY SENSORS

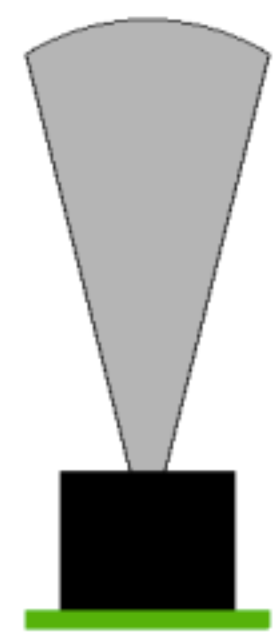
- **Visible or IR light:** projects a pulse of light and look for the reflection. If the reflection is strong enough, it can be inferred that an obstacle lies within a certain range of the sensor depending on the measured received strength
- Intensity of the reflected visible/IR light from an obstacle to estimate distance can be significantly affected by the color/reflectivity of the obstacle, presence, of external light sources, environment temperature
- Multiple light sources can be pulsed on in sequence to give more resolution
- A beam of light projected at an angle and a strip of detectors spaced away from the emitter as in the animation to the right.











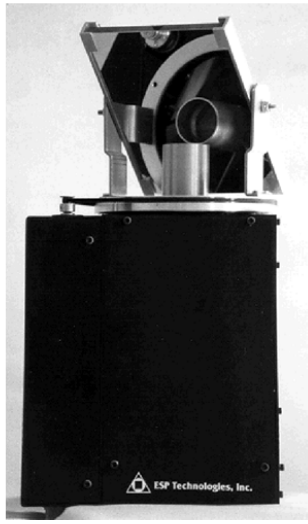
SONAR
WIDE CONE
LONG RANGE

IR
NARROW BEAM
SHORT RANGE

4a 65 Laser Range Sensor (time of flight, electromagnetic) (1)

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

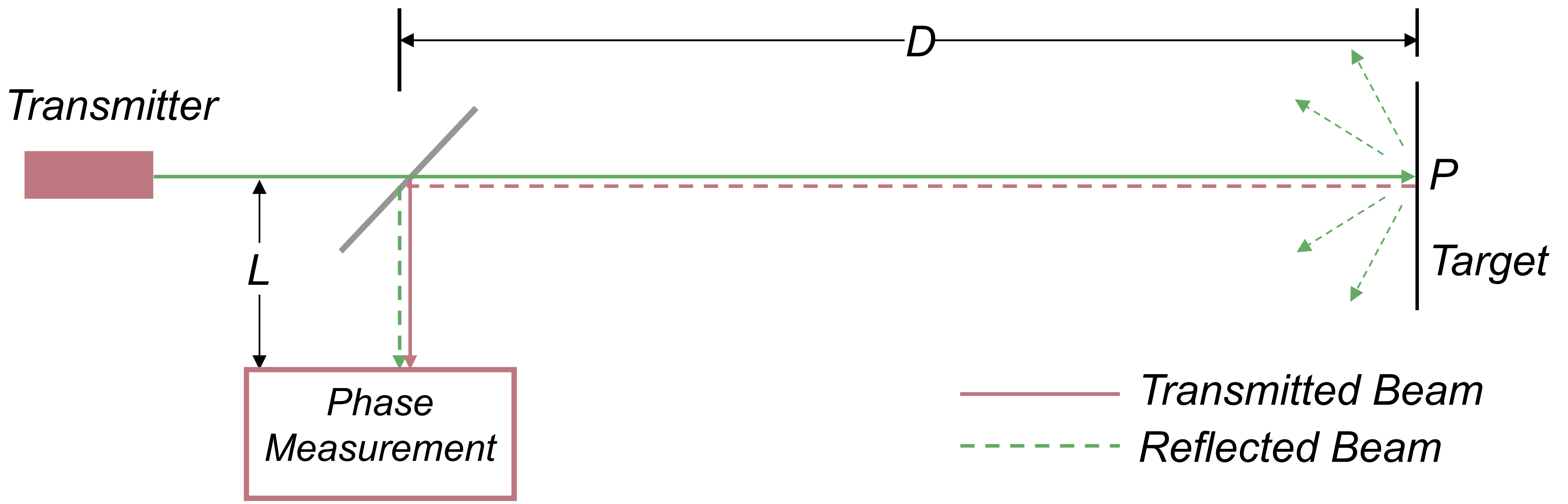
SICK



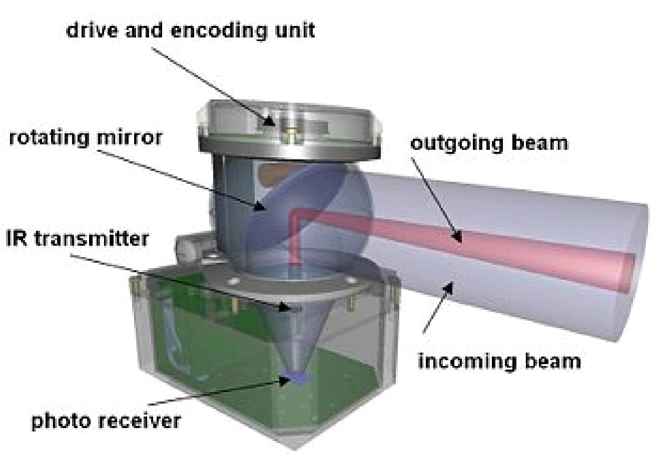
Alaska-IBEO

Hokuyo

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



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

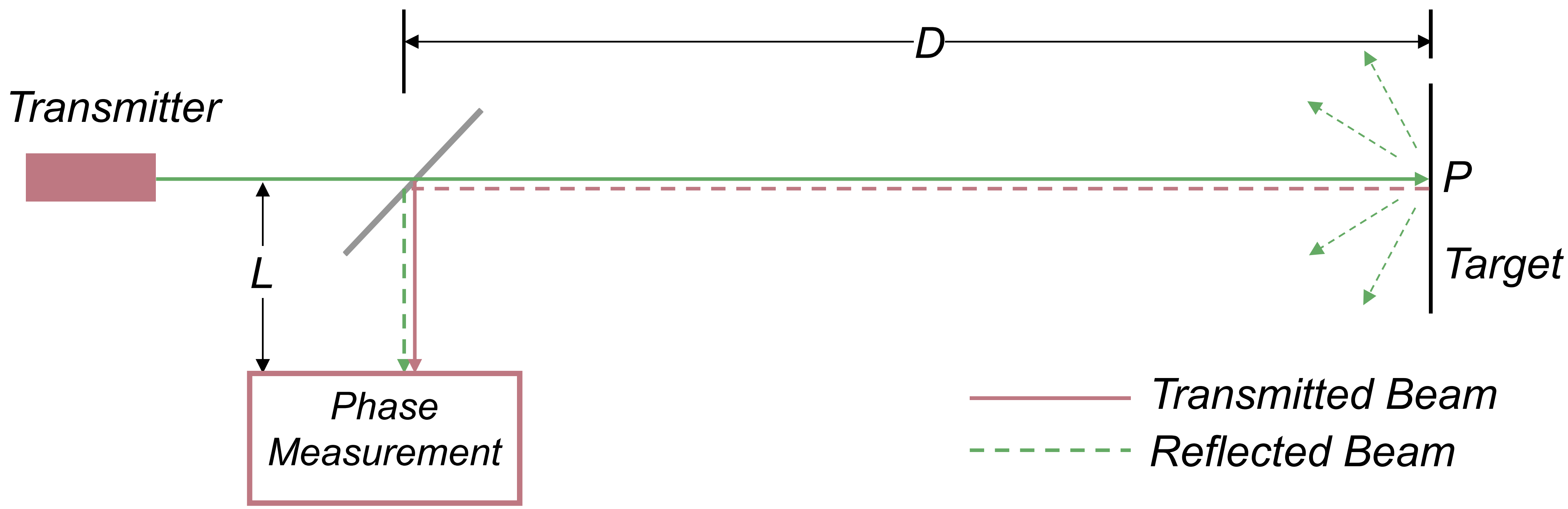


Laser Range Sensor (time of flight, electromagnetic) (2)

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

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

- *Phase-Shift Measurement*



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

Where:

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

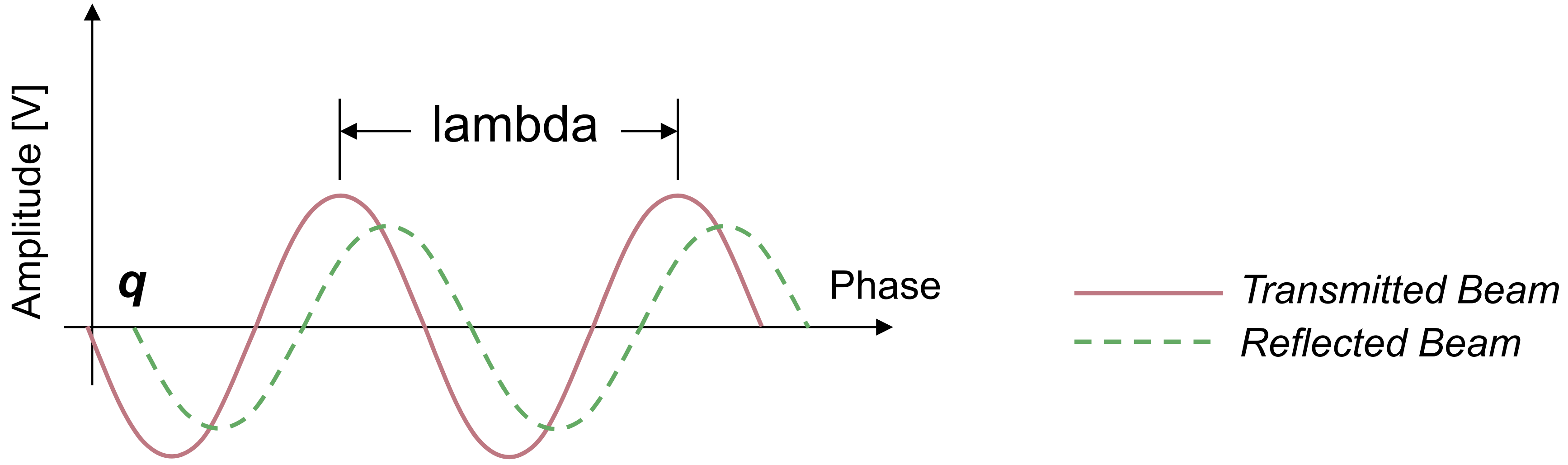
- for f = 5 MHz (as in the A.T&T. sensor), λ = 60 meters

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

- Distance D, between the beam splitter and the target

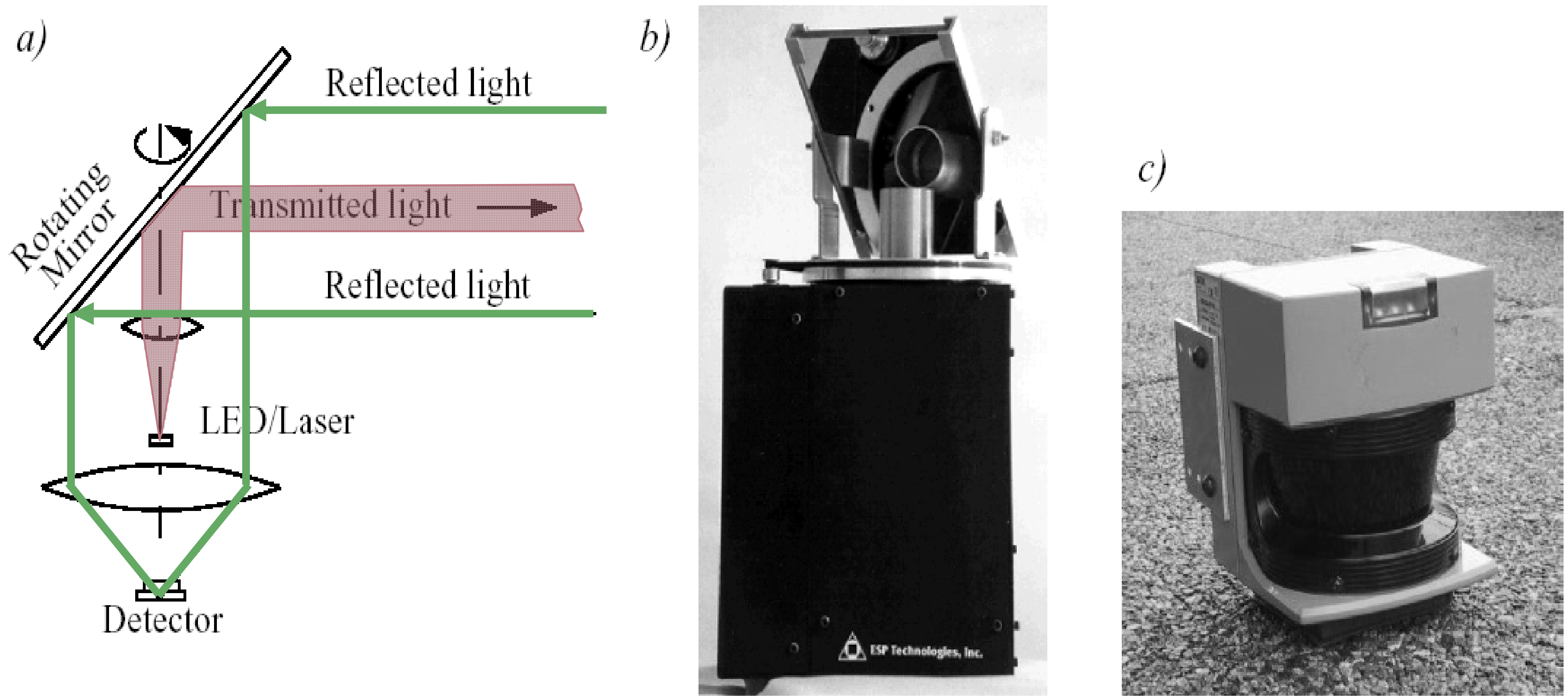
$$D = \frac{\lambda}{4\pi}\theta$$

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



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

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



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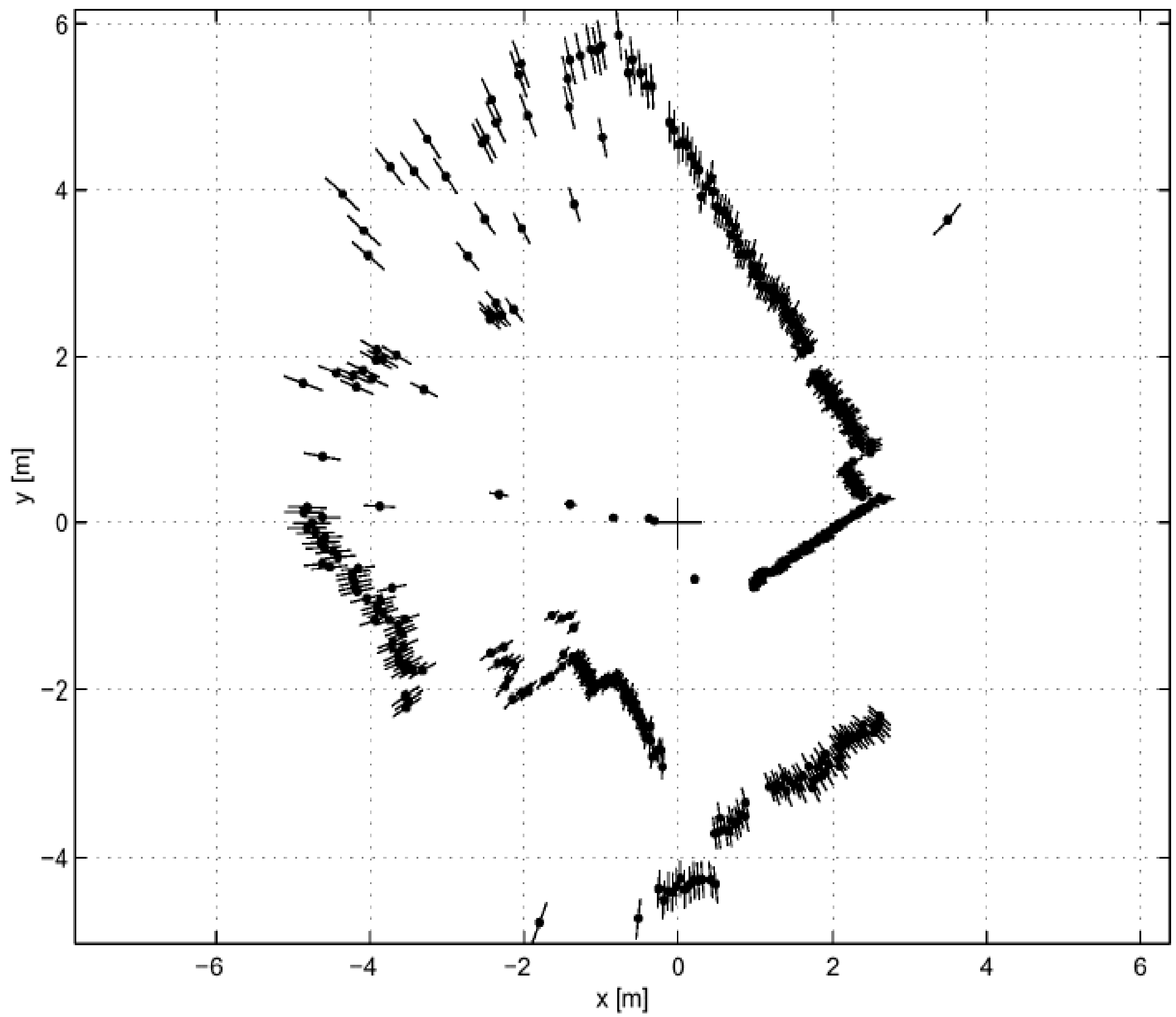
Laser Range Sensor (time of flight, electromagnetic)

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

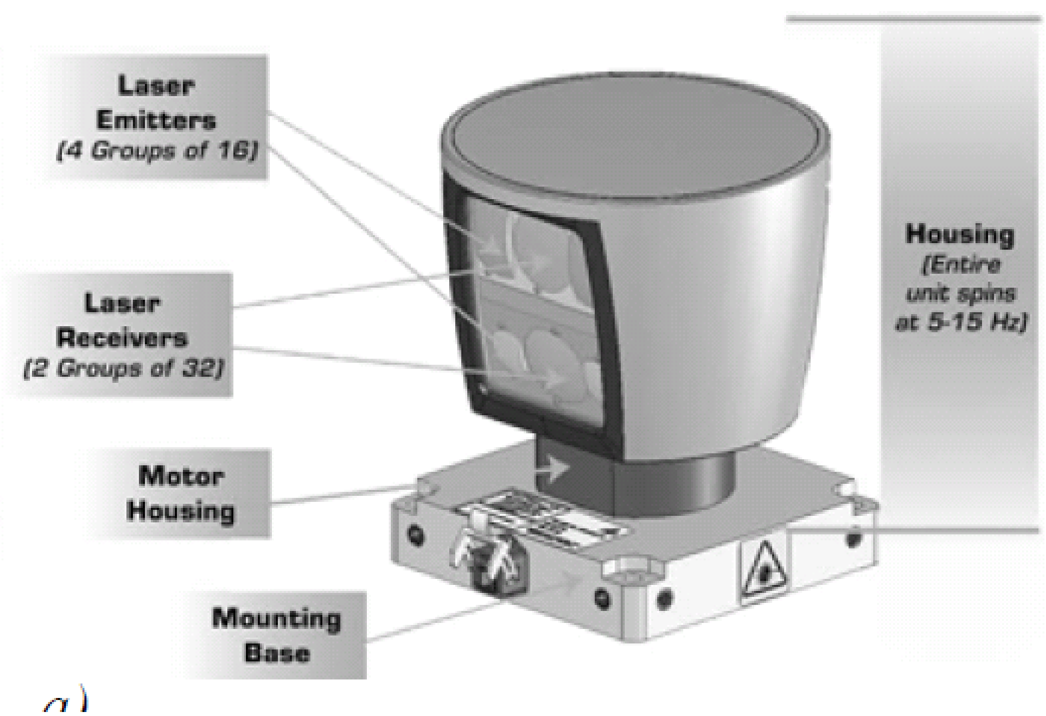


The SICK LMS 200 Laser Scanner

- Angular resolution 0.25 deg
- Depth resolution ranges between 10 and 15 mm and the typical accuracy is 35 mm, over a range from 5 cm up to 20 m or more (up to 80 m), depending on the reflectivity of the object being ranged.
- This device performs seventy five 180-degrees scans per second

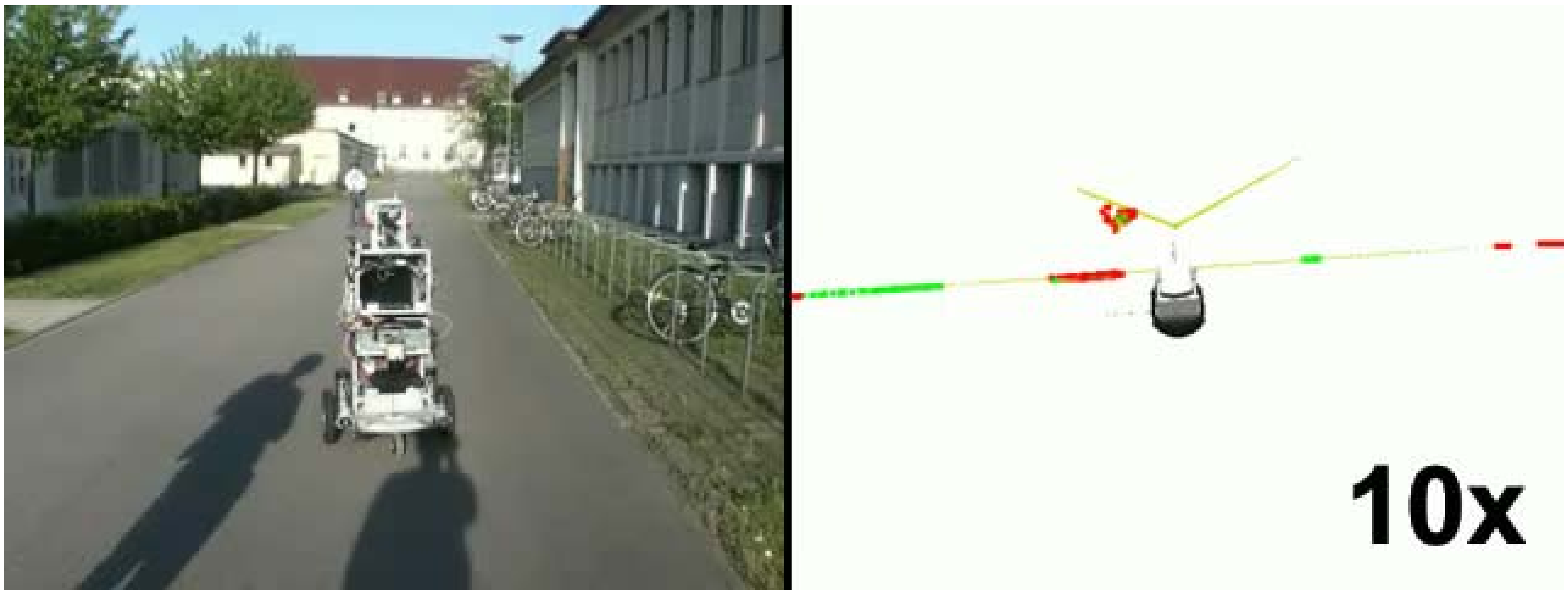
3D Laser Range Finder (2)

- The Velodyne HDL-64E uses 64 laser emitters.
  - Turn-rate up to 15 Hz
  - The field of view is 360° in azimuth and 26.8° in elevation
  - Angular resolution is 0.09° and 0.4° respectively
  - **Delivers over 1.3 million data points per second**
  - The distance accuracy is better than 2 cm and can measure depth up to 50 m
  - This sensor was the primary means of terrain map construction and obstacle detection for all the top DARPA 2007 Urban Challenge teams. However, the Velodyne iscurrently still much more expensive than Sick laser range finders (SICK ~ 5000 Euros, Velodyne ~50,000 Euros!)



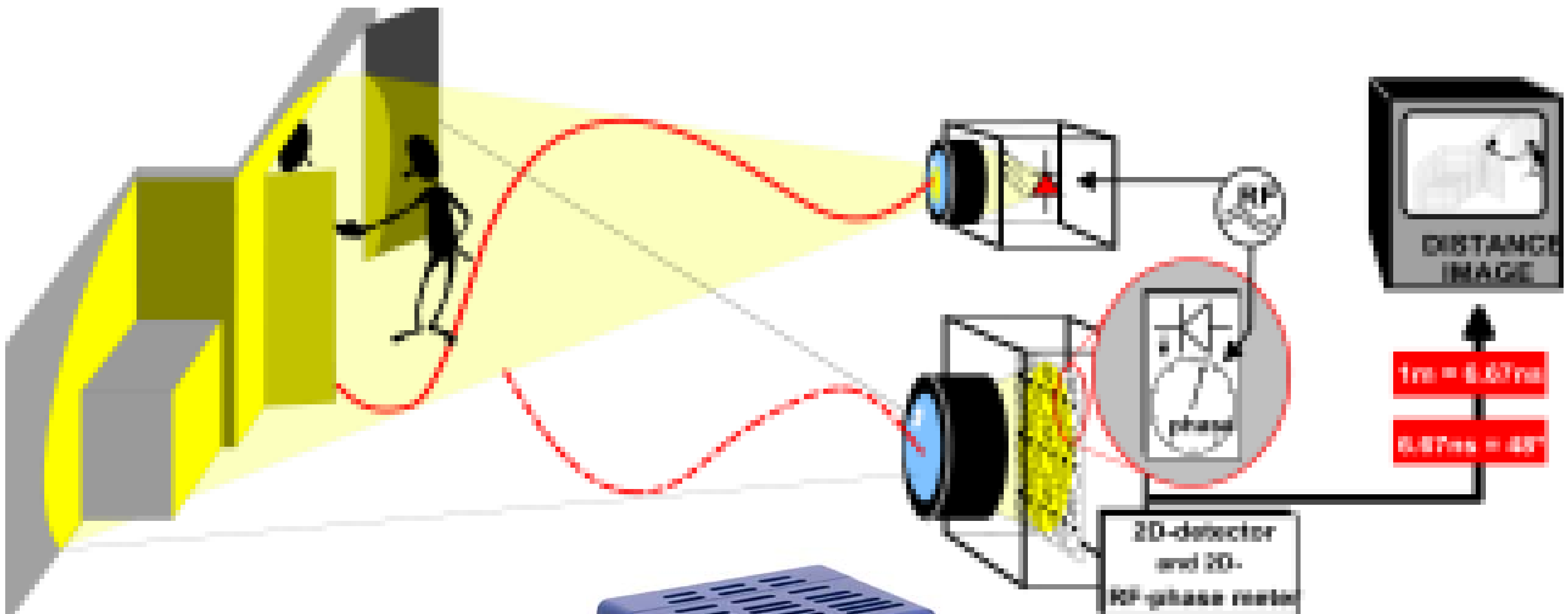
C Carnegie Mellon University

Europa Robot: Obstacle and Terrain Detection



4a 77 3D Range Sensor (4): Time Of Flight (TOF) camera

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



Swiss Ranger 3000
(produced by MESA)

4a 78 Incremental Object Part Detection

- Range Camera
  - 3D information with high data rate (100 Hz)
  - Compact and easy to manage
  - High, non-uniform measurement noise
  - High outlier rate at jump edges
  - However very low resolution (174x144 pixels)

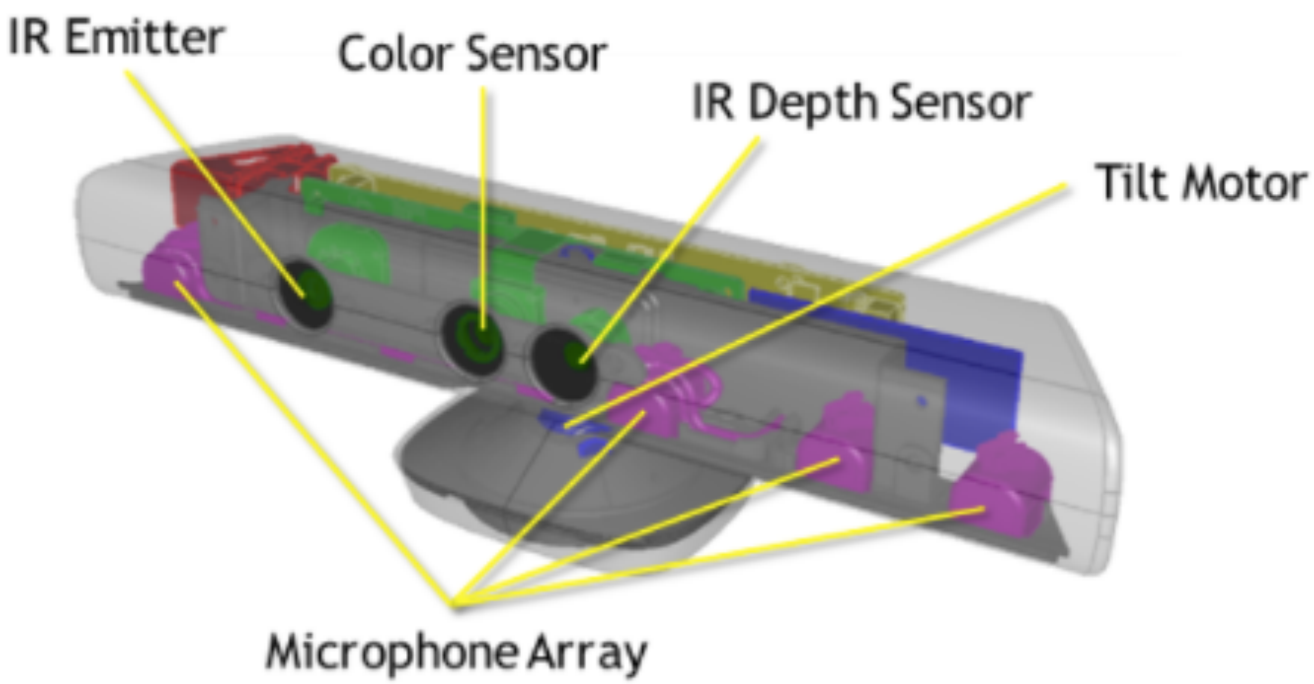
Range Camera SR-3000

C MESA Imaging AG

ORBBEC ASTRA

The Specifics	
Size/Dimensions	165 x 30 x 40 mm
Weight	0.3 kg
Range	0.4 – 2m
Depth Image Size	1280 *1024 (SXGA) @ 5FPS Windows Only 640*480 (VGA) 16bit @ 30FPS 320*240 (QVGA) 16bit @ 30FPS 160*120 (QQVGA) 16bit @ 30FPS
RGB Image Size	1280*960 @ 7FPS 640*480 @ 30FPS 320*240 @ 30FPS
Field of View	60° horiz x 49.5° vert. (73° diagonal)
Data Interface	USB 2.0
Microphones	2
Operating Systems	Windows 7/8/10, Linux, Android

KINECT



Specifications for the Kinect

Kinect	Array Specifications
Viewing angle	43° vertical by 57° horizontal field of view
Vertical tilt range	±27°
Frame rate (depth and color stream)	30 frames per second (FPS)
Audio format	16-kHz, 24-bit mono pulse code modulation (PCM)
Audio input characteristics	A four-microphone array with 24-bit analog-to-digital converter (ADC) and Kinect-resident signal processing including acoustic echo cancellation and noise suppression
Accelerometer characteristics	A 2G/4G/8G accelerometer configured for the 2G range, with a 1° accuracy upper limit.

Triangulation Ranging

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

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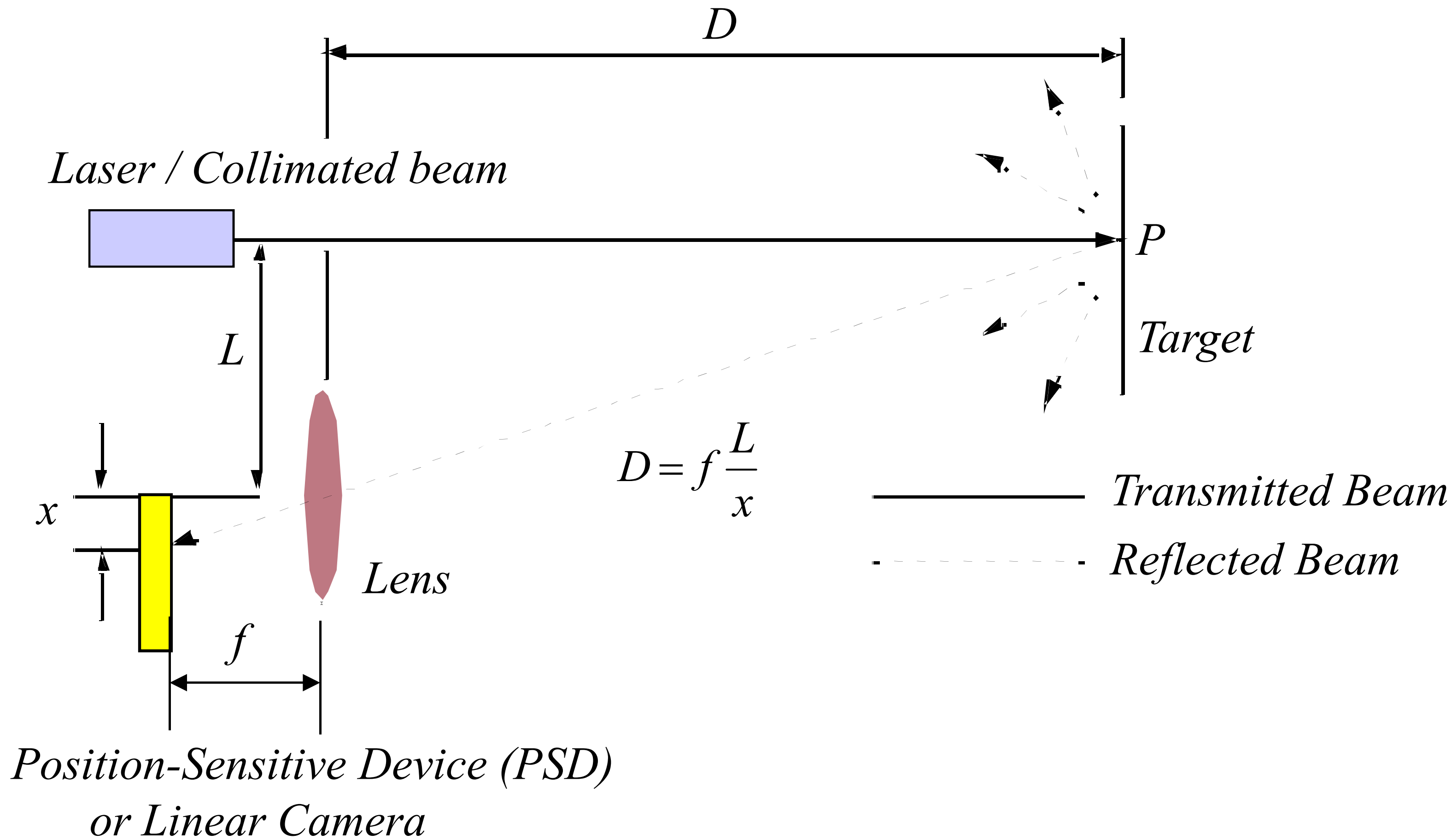
Laser Triangulation (1D)



- Principle of 1D laser triangulation: $D = f\frac{L}{x}$

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

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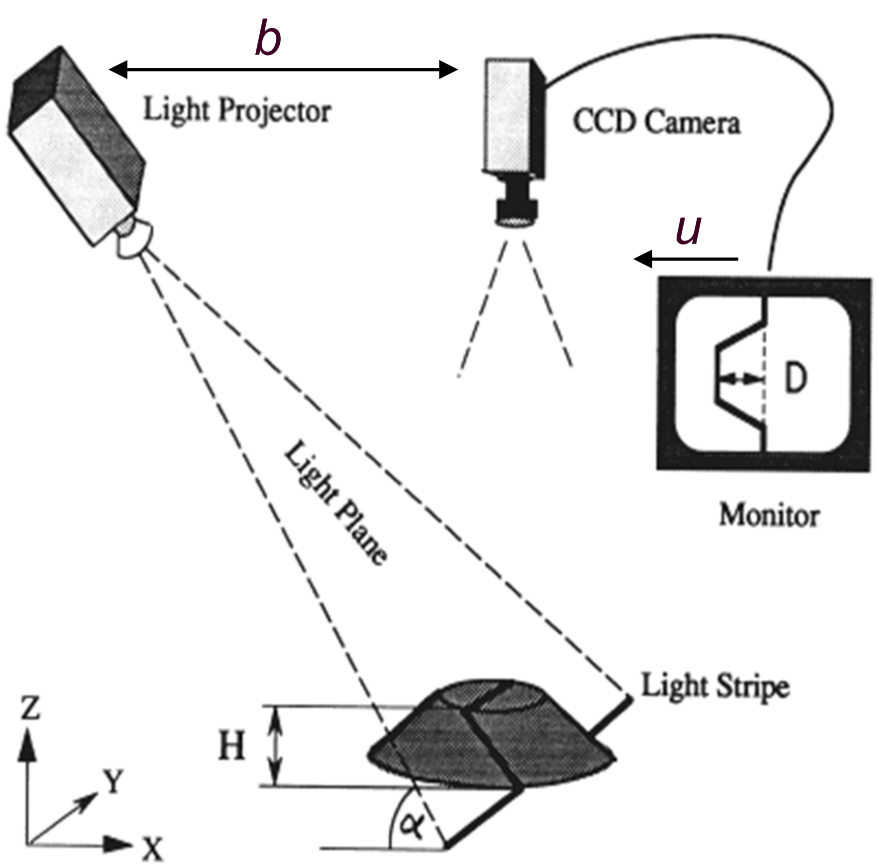

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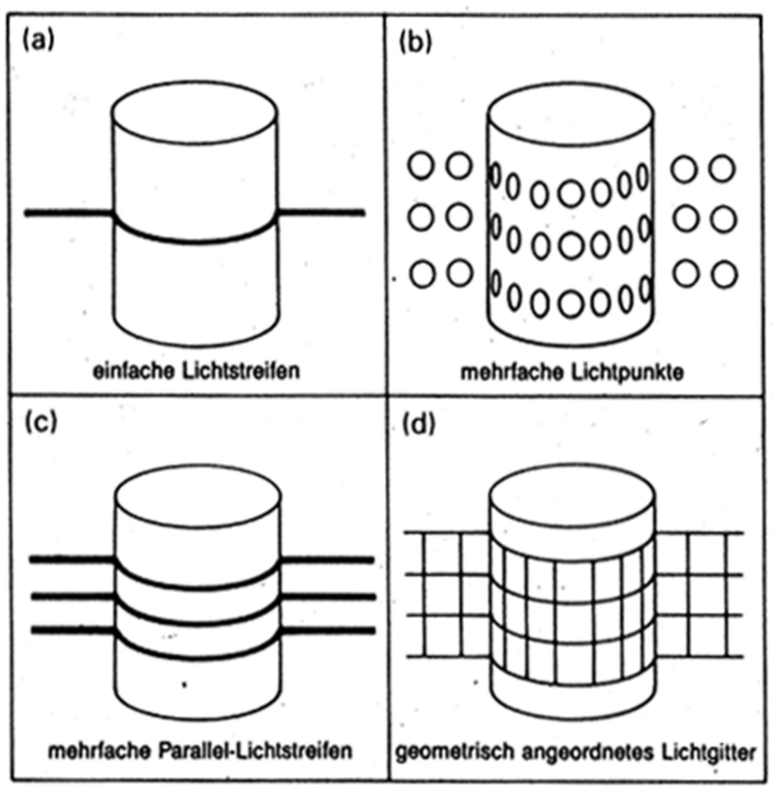

- Eliminate the correspondence problem by projecting structured light on the scene.
- Slits of light or emit collimated light (possibly laser) by means of a rotating mirror.
- Light perceived by camera
- Range to an illuminated point can then be determined from simple geometry.

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Structured Light (vision, 2 or 3D)

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

  Note: for large L, 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