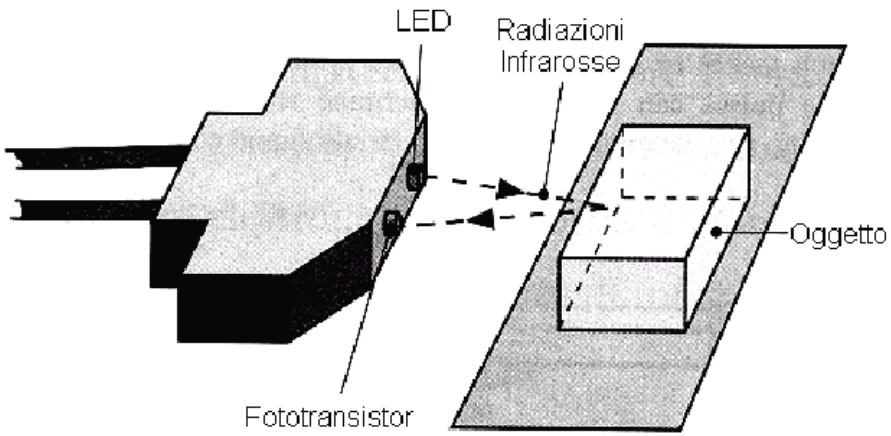
Proximity Sensors

An emitter (e.g., a LED) transmits a light radiation with a defined wavelength

Light eventually reflected back from a nearby object e.g. perceived by a photoresistor.

Proximity/distance sensors - 1

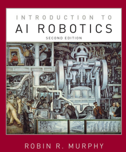
- infrared: a light source (LED) emitting a ray beam (at 850±70 nm) which is then captured by a receiver (photo-transistor), after reflection by an object
- received intensity is related to distance
  - narrow emitting/receiving angle; use only indoor; reflectance varies with object color
- typical sensitive range: 4÷30 cm or 20÷150 cm
- cost: 15 €



IR sensor SHARP GP2
(supply 5V, range 10÷80 cm)

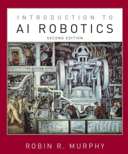
Infrared and Thermal

- Actually a spectrum of wavelengths, often emitted from heat
- "IR" is cheap, used in remotes
- True infrared, FLIR (forward looking infrared red) produces thermal imagery
  - Breakthrough in micro-bolometers
- Night-vision is not really IR, it's light amplification



Infrared Sensing

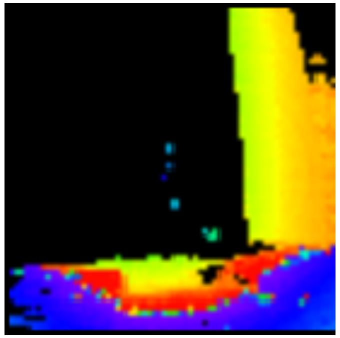
- About them:
  - Usually a *point sensor*, active
  - Emits a particular wavelength, then detects time to bounce back
  - Popular for indoor detection of collisions, “negative obstacles”
- Advantages
  - Cheap
  - Can also detect dark/light (via strength)
- Disadvantages
  - Sensitive to lighting conditions
  - Specular reflection
  - Coverage of a line
  - Short range so can’t go fast

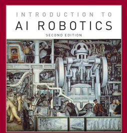


IR: In Development

- Canesta range sensor, Swiss Ranger
  - Make an array of miniature IR range sensors

- Uses near infrared light
- 64x64 pixel resolution
- 5x2x2 dimensions
- Detects phase shift of the light
- Produces three different views

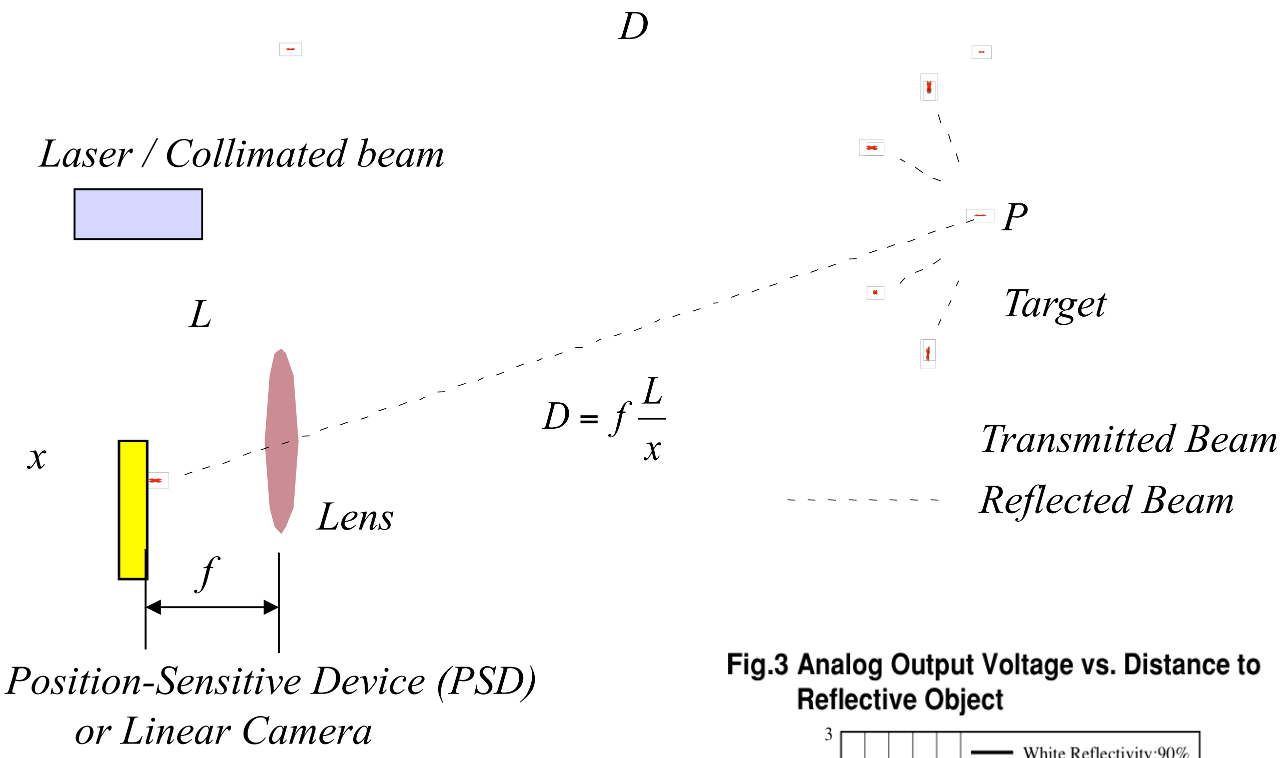




Triangulation Ranging

- 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

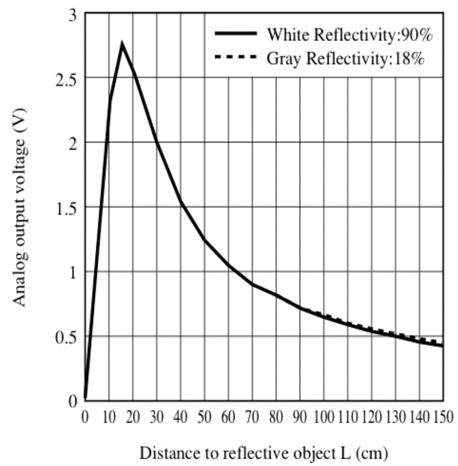
Laser Triangulation (1D)



Principle of 1D laser triangulation.

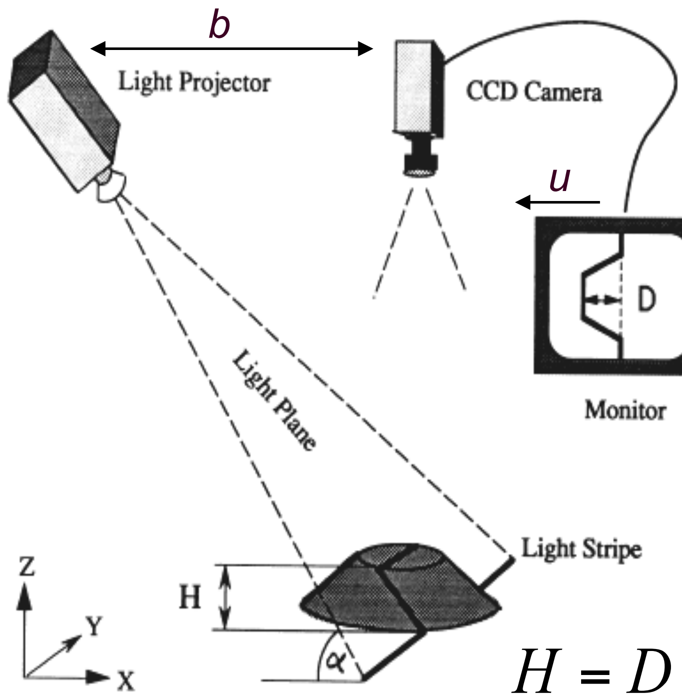
$$D = f\frac{L}{x}$$

Fig.3 Analog Output Voltage vs. Distance to Reflective Object



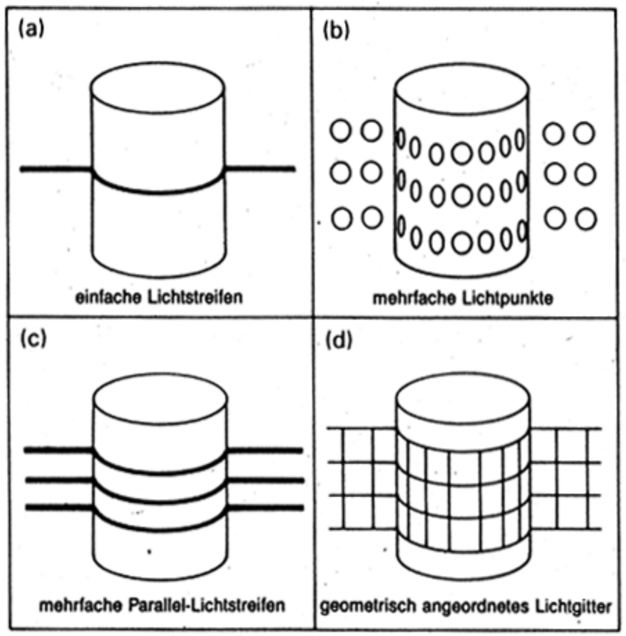
Structured Light (vision, 2 or 3D)

a



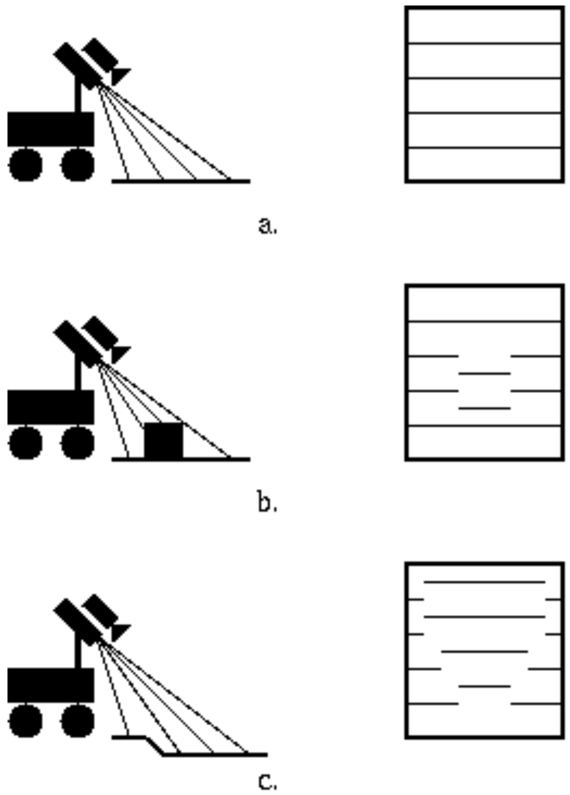
$$H = D \cdot \tan \alpha$$

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.

Light Striper



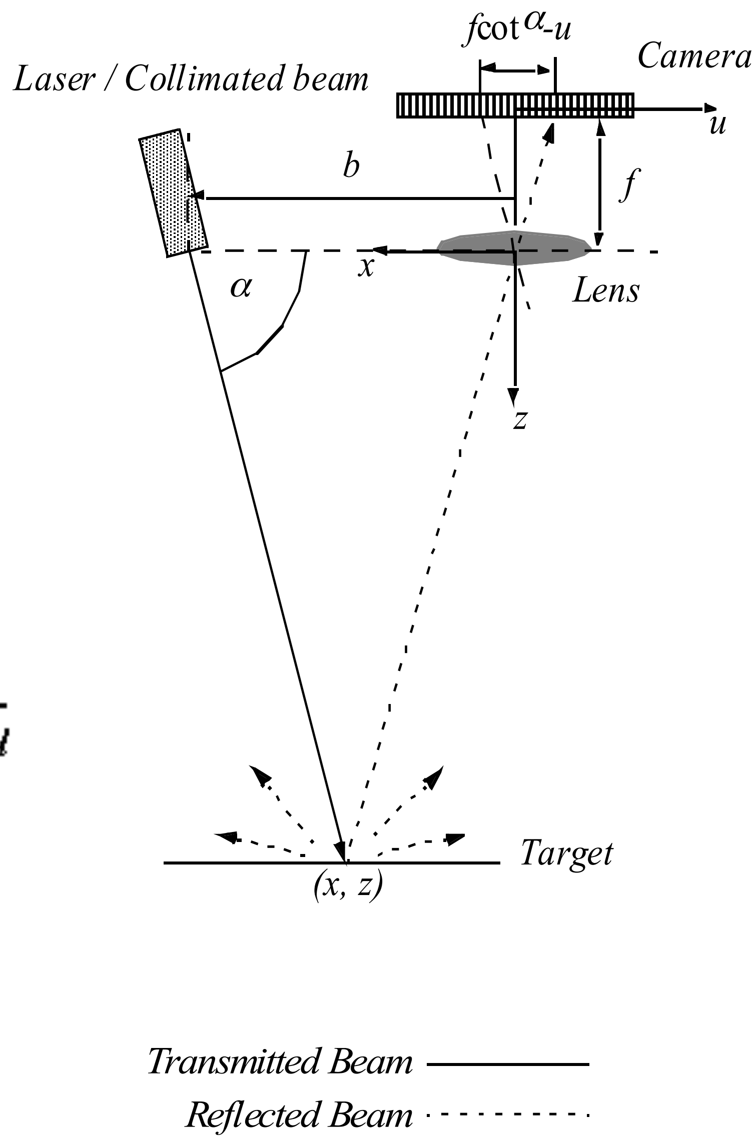
Works the same as a Light striper, only no camera, Just laser and only 1 line

Structured Light (vision, 2 or 3D)

- One dimensional schematic of the principle

- From the figure, simple geometry shows that:

$$x = \frac{b \cdot u}{f\cot\alpha - u}\ ; \quad z = \frac{b \cdot f}{f\cot\alpha - u}$$



4a
64

Structured Light (vision, 2 or 3D)

- Range resolution is defined as the triangulation gain G_p :

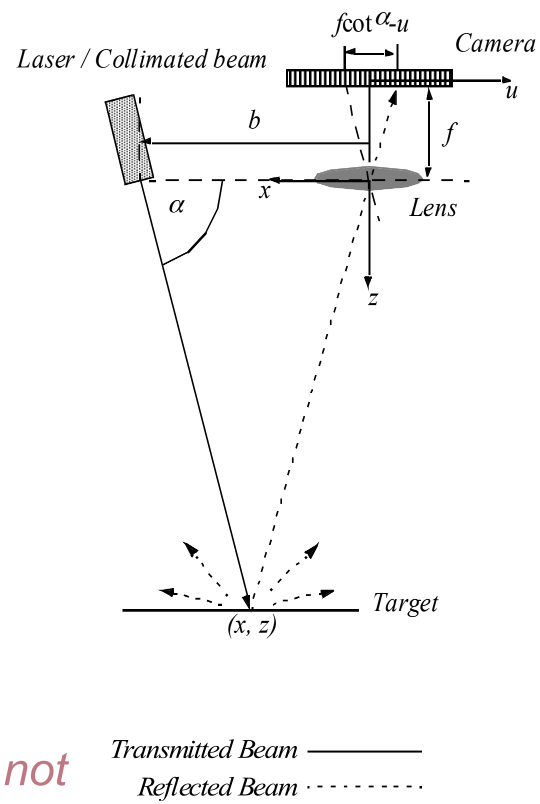
$$\frac{\partial u}{\partial z} = G_p = \frac{b \cdot f}{z^2}$$

- Influence of α:

$$\frac{\partial \alpha}{\partial z} = G_\alpha = \frac{b \sin \alpha^2}{z^2}$$

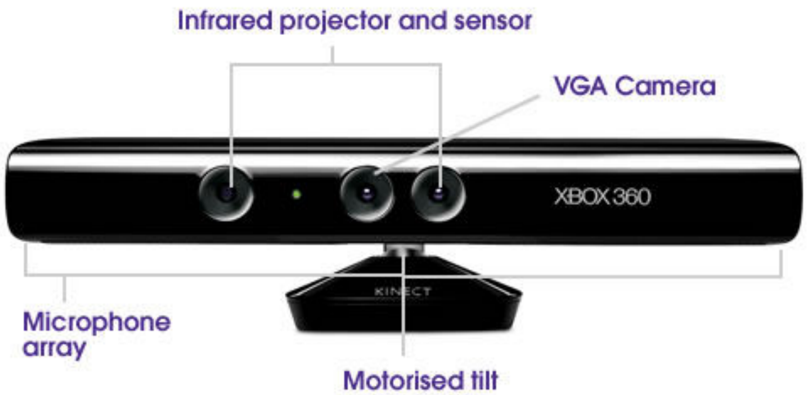
- Baseline length *b*:
  - the smaller b is the more compact the sensor can be.
  - the larger b is the better the range resolution is.

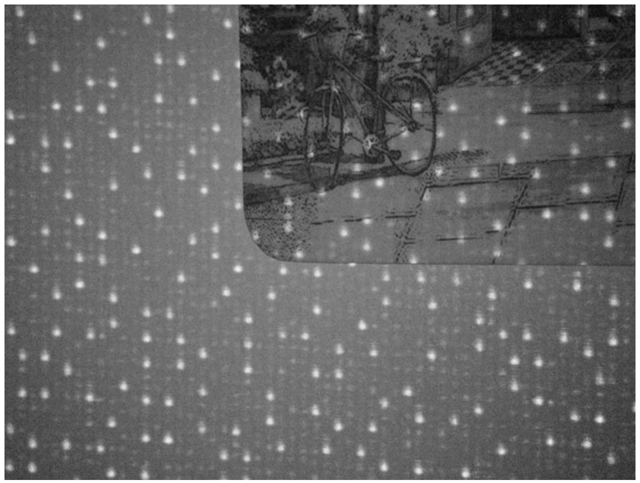
  Note: for large b, the chance that an illuminated point is not visible to the receiver increases.
- Focal length f:
  - larger focal length f can provide
    - either a larger field of view
    - or an improved range resolution
  - however, large focal length means a larger sensor head



Structured light | Kinect sensor

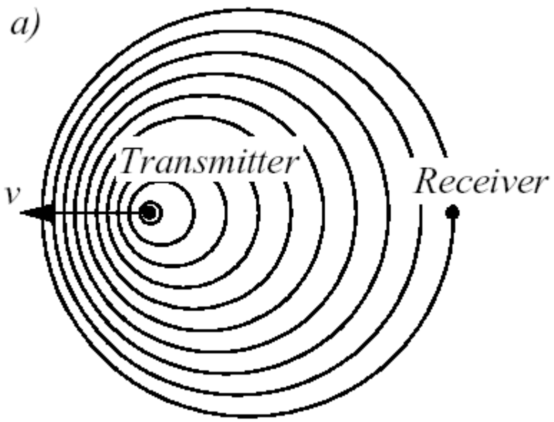
- Major components
  - IR Projector
  - IR Camera
  - VGA Camera
  - Microphone Array
  - Motorized Tilt

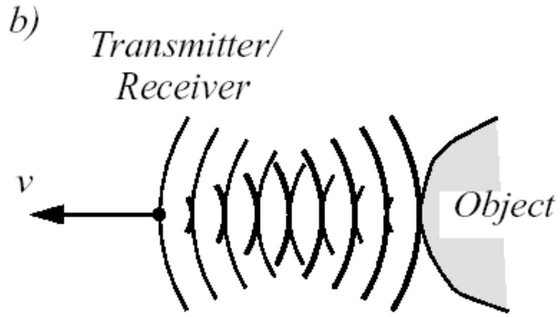




Doppler Effect Based (Radar or Sound)

10.3.2008 – 25 minutes of 2st hour





- a) between two moving objects   b) between a moving and a stationary object
- $f_r = f_t(1 + v/c)$ if transmitter is moving $f_r = f_t \dfrac{1}{1 + v/c}$ if receiver is moving
- $\Delta f = f_t - f_r = \dfrac{2 f_t v \cos\theta}{c}$ Doppler frequency shift $v = \dfrac{\Delta f \cdot c}{2 f_t \cos\theta}$ relative speed
- Sound waves: e.g. industrial process control, security, fish finding, measure of ground speed
- Electromagnetic waves: e.g. vibration measurement, radar systems, object tracking
- q = relative angle between direction of motion and beam axis.

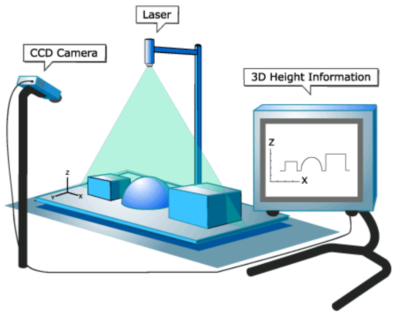
Range sensors

- Sonar

- Laser range finder

- Time of Flight Camera

- Structured light (triangulation)



Range Sensors (time of flight)

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

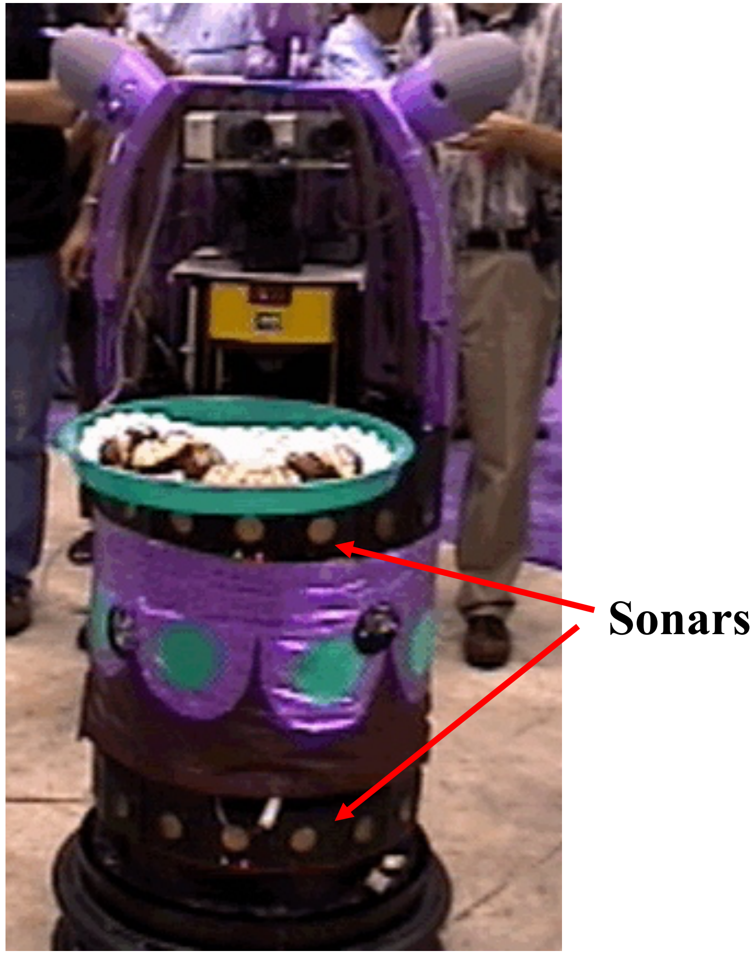
$$d = c \cdot t$$

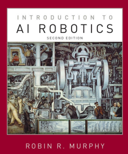
Range Sensors (time of flight)

- It is important to point out
  - Propagation speed of sound: **0.3 m/ms**
  - Propagation speed 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)

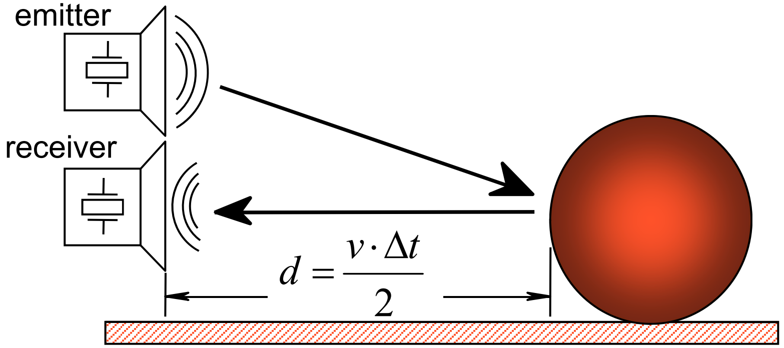
Ultrasonics

- About them
  - Emit a sound (click) and measure time of flights
- Advantages
  - Cheap
  - Good coverage: 30 deg cone, 25 feet
- Disadvantages
  - Highly unreliable
  - Poor resolution
  - High power consumption





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) (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

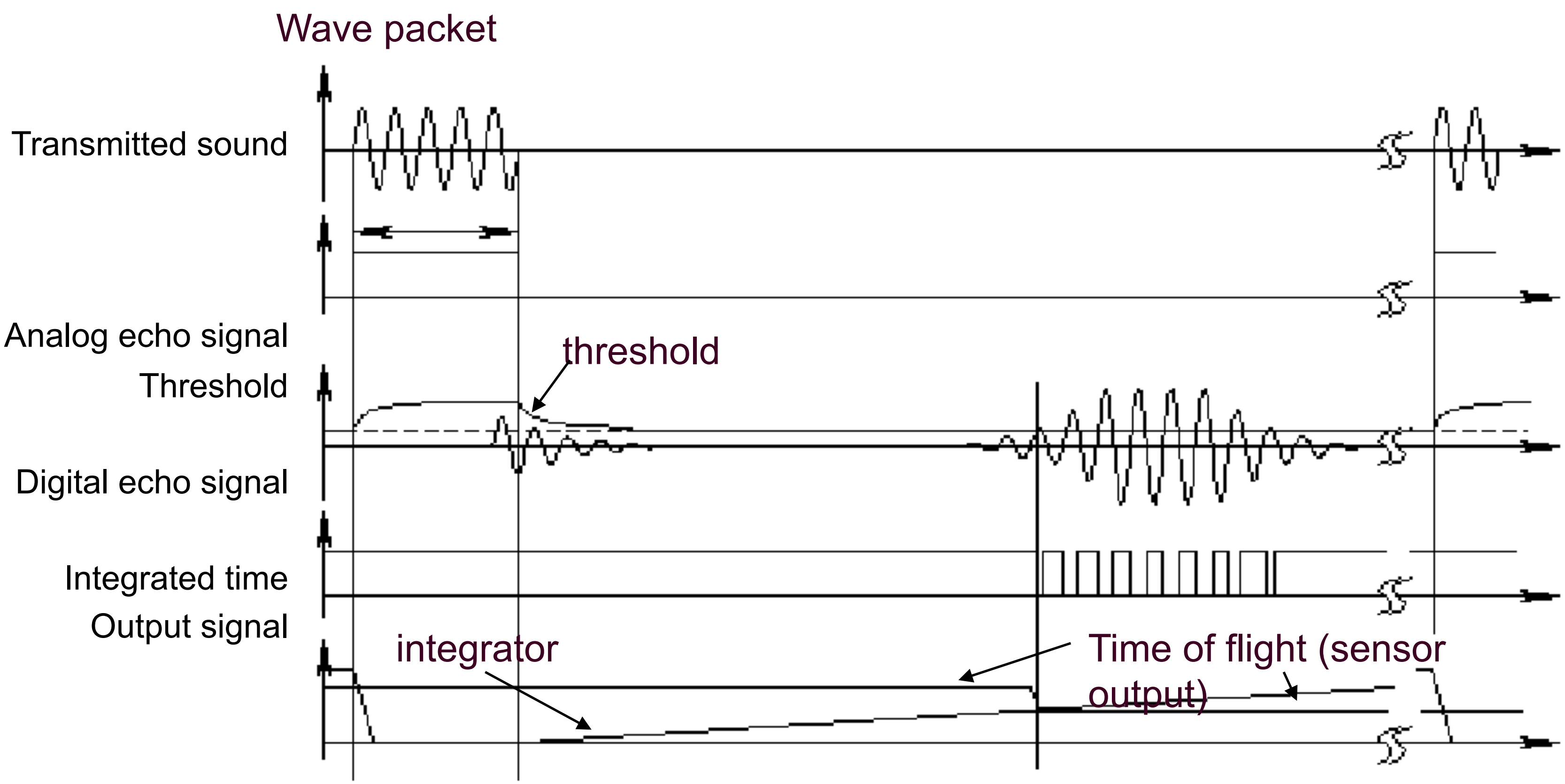
Where $c = \sqrt{\gamma \cdot R \cdot T}$

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

R: gas constant

T: temperature in degree Kelvin

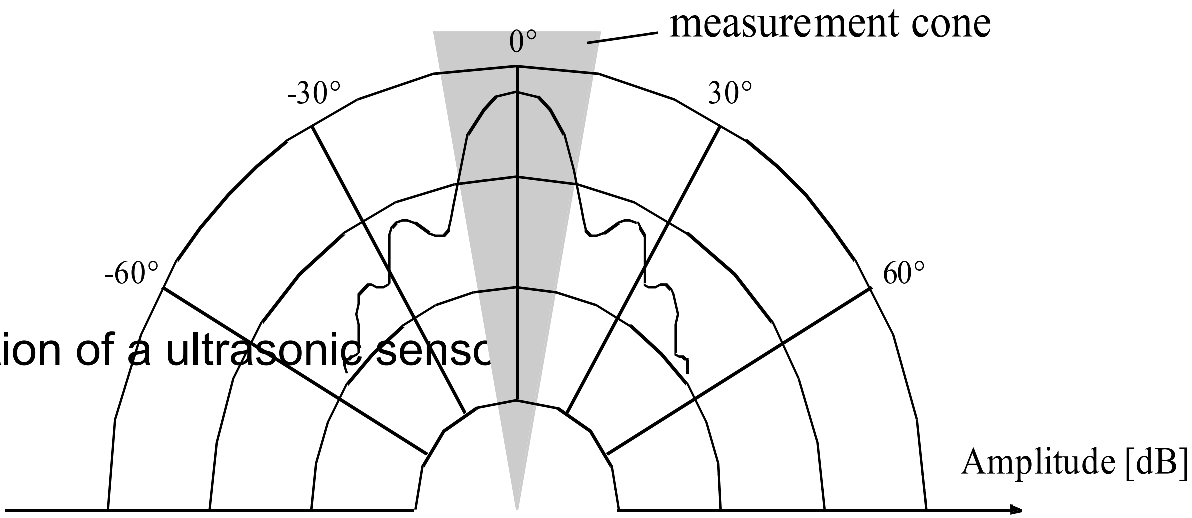
Ultrasonic Sensor (time of flight, sound) (2)



Signals of an ultrasonic sensor

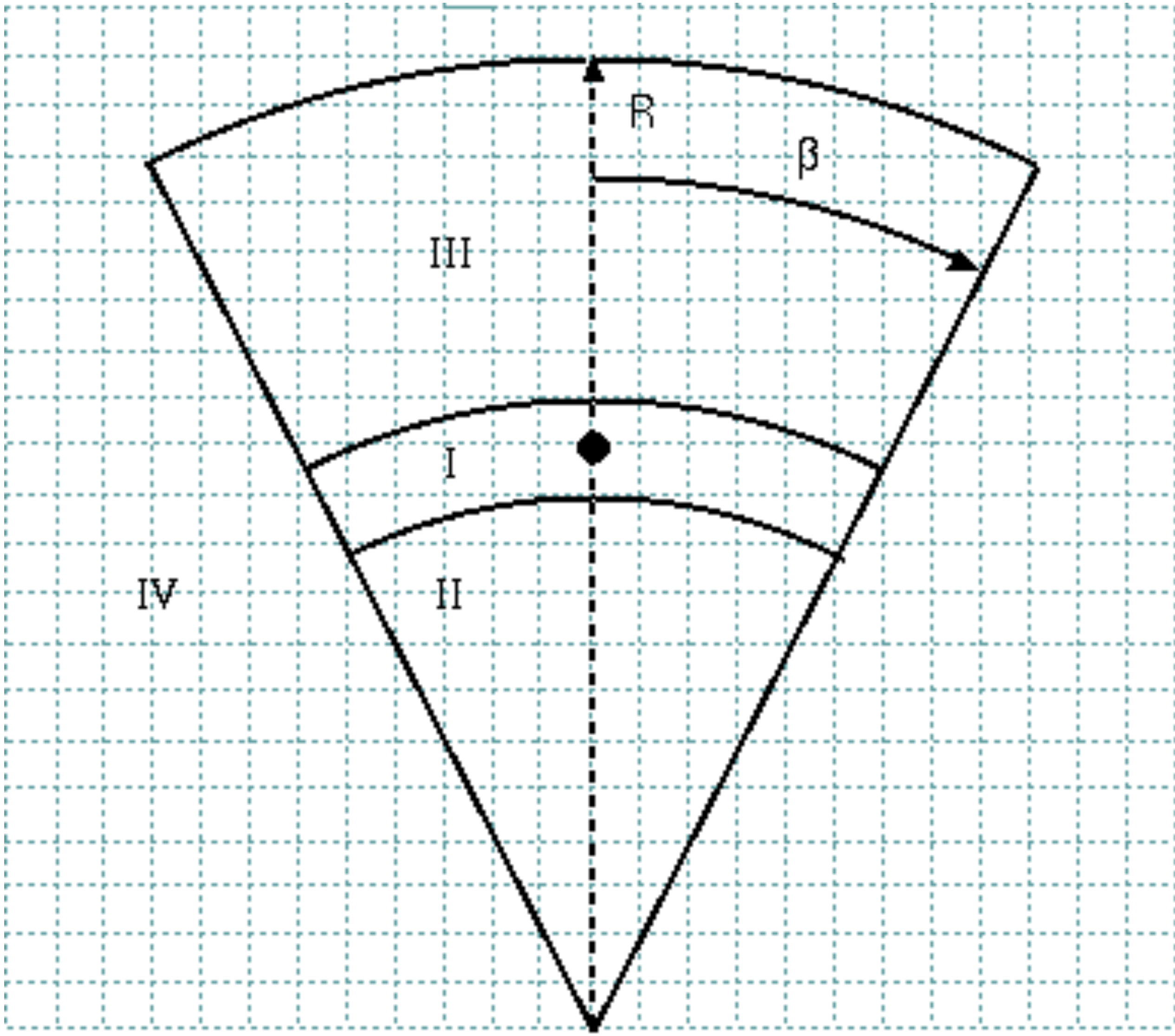
Ultrasonic Sensor (time of flight, sound) (3)

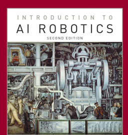
- typical frequency: 40 - 180 kHz
- generation of sound wave: piezo transducer
  - transmitter and receiver separated or not separated
- sound beam propagates in a cone (*approx*.)
  - opening angles around 20 to 40 degrees
  - regions of constant depth
  - segments of an arc (sphere for 3D)



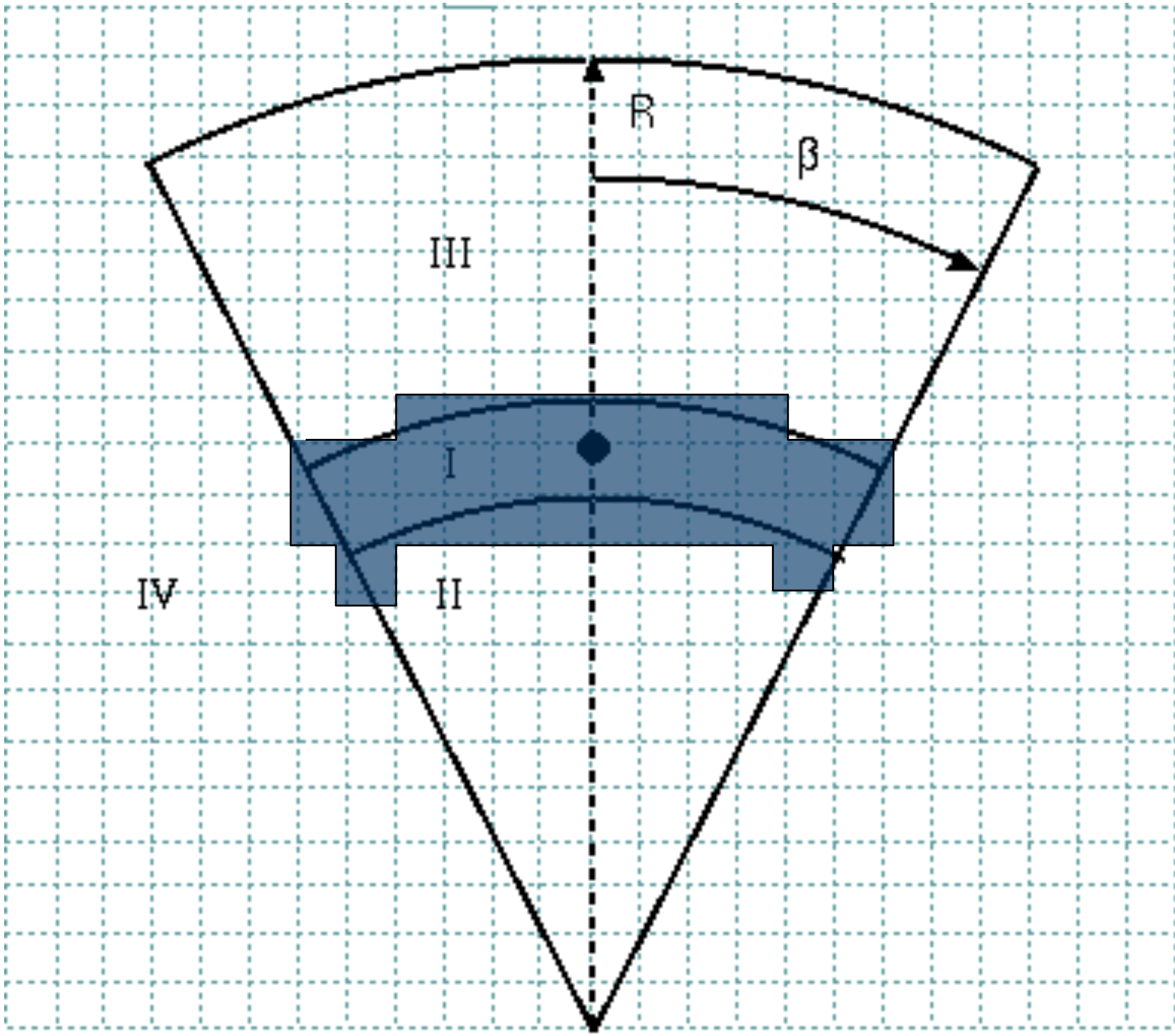
Typical intensity distribution of a ultrasonic senso

Occupancy Grid



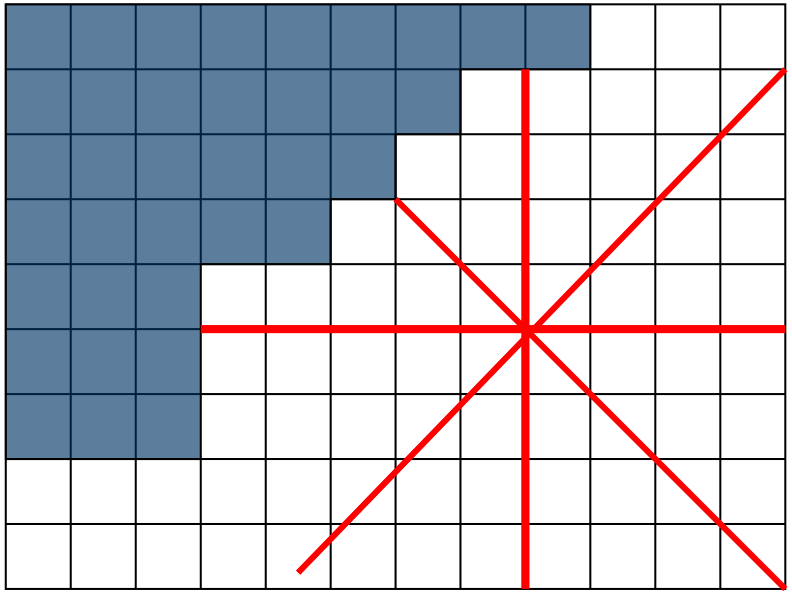


Occupancy Grid



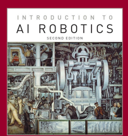
10 Polar Plot of Virtual Sensor

- Create a grid of surrounding area
- Populate as occupied, empty
- Sample grid with ***virtual sensors***



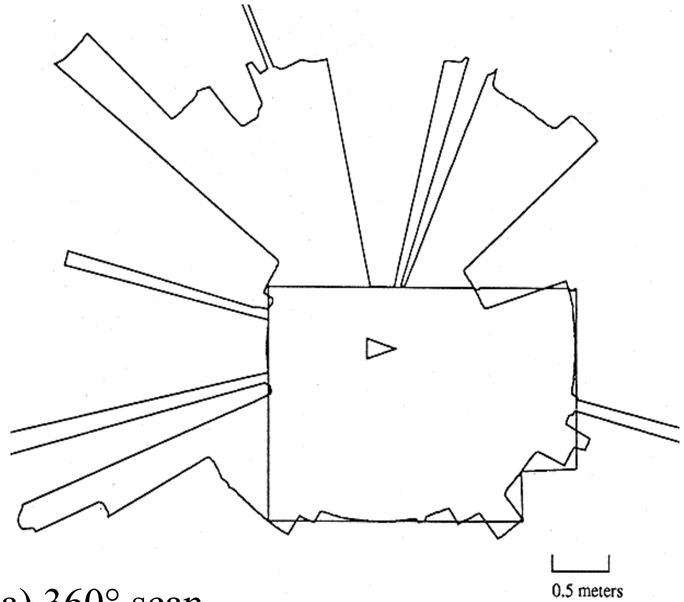
The polar plot is a list* of (distance, angle)

*Often a 1D array or just a row, which is also referred to by programmers as a vector

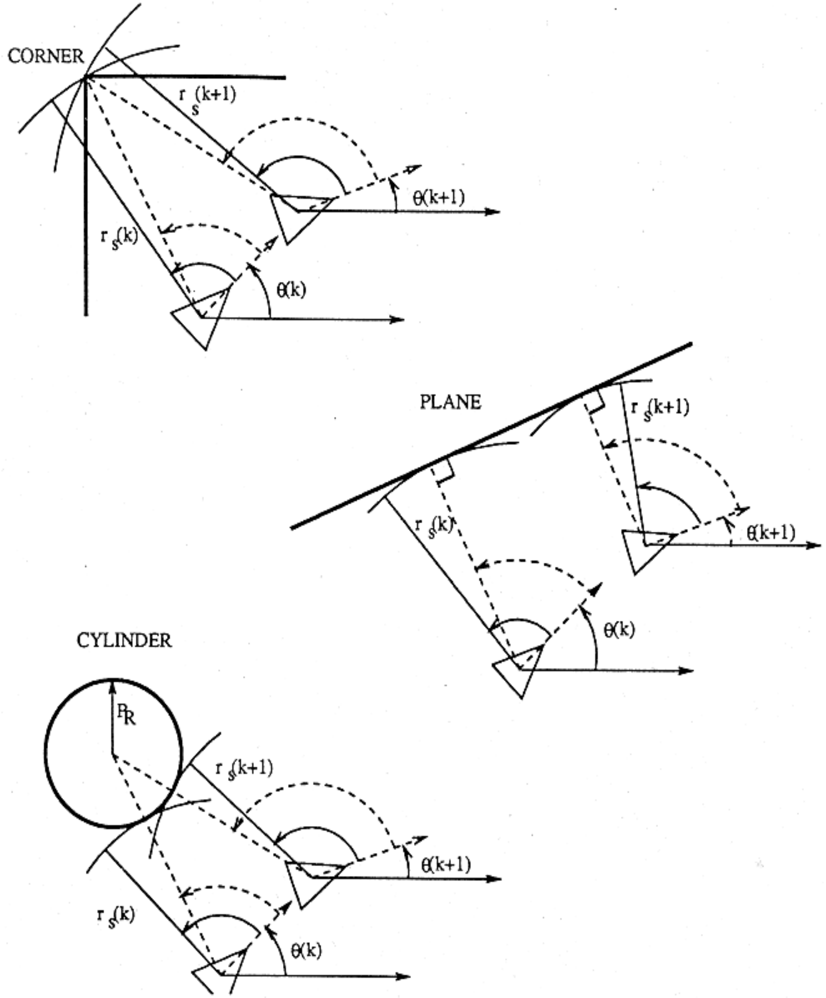


Ultrasonic Sensor (time of flight, sound) (4)

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



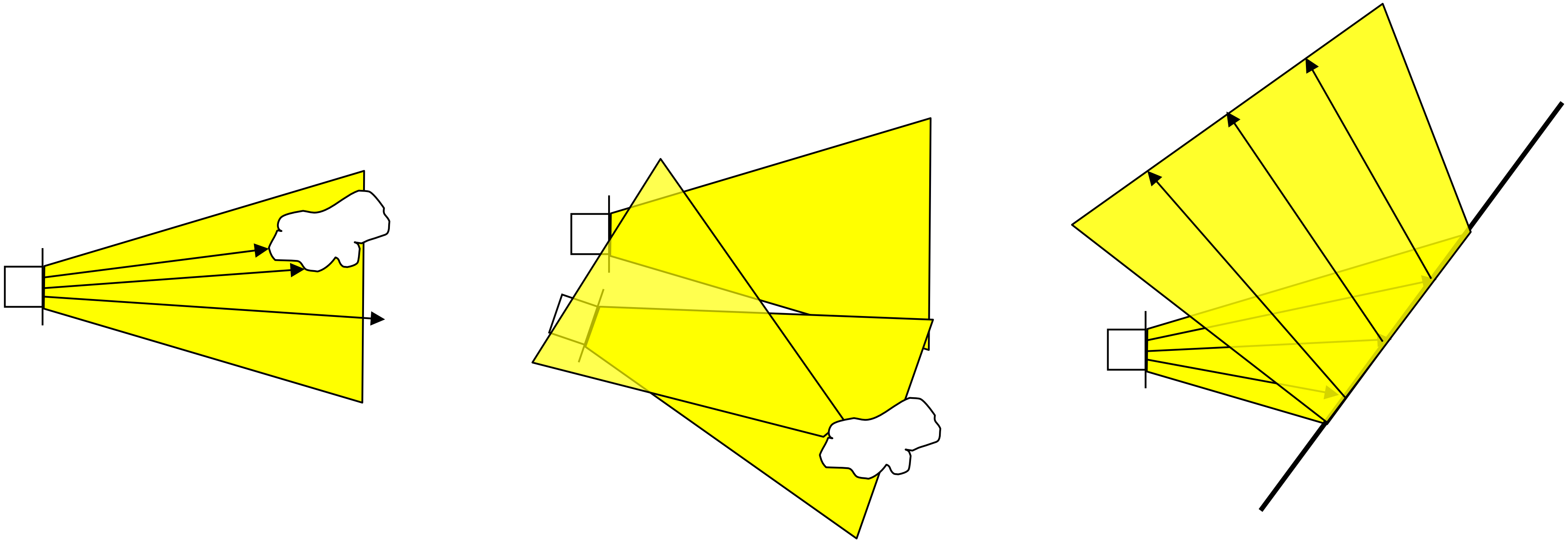
a) 360° scan



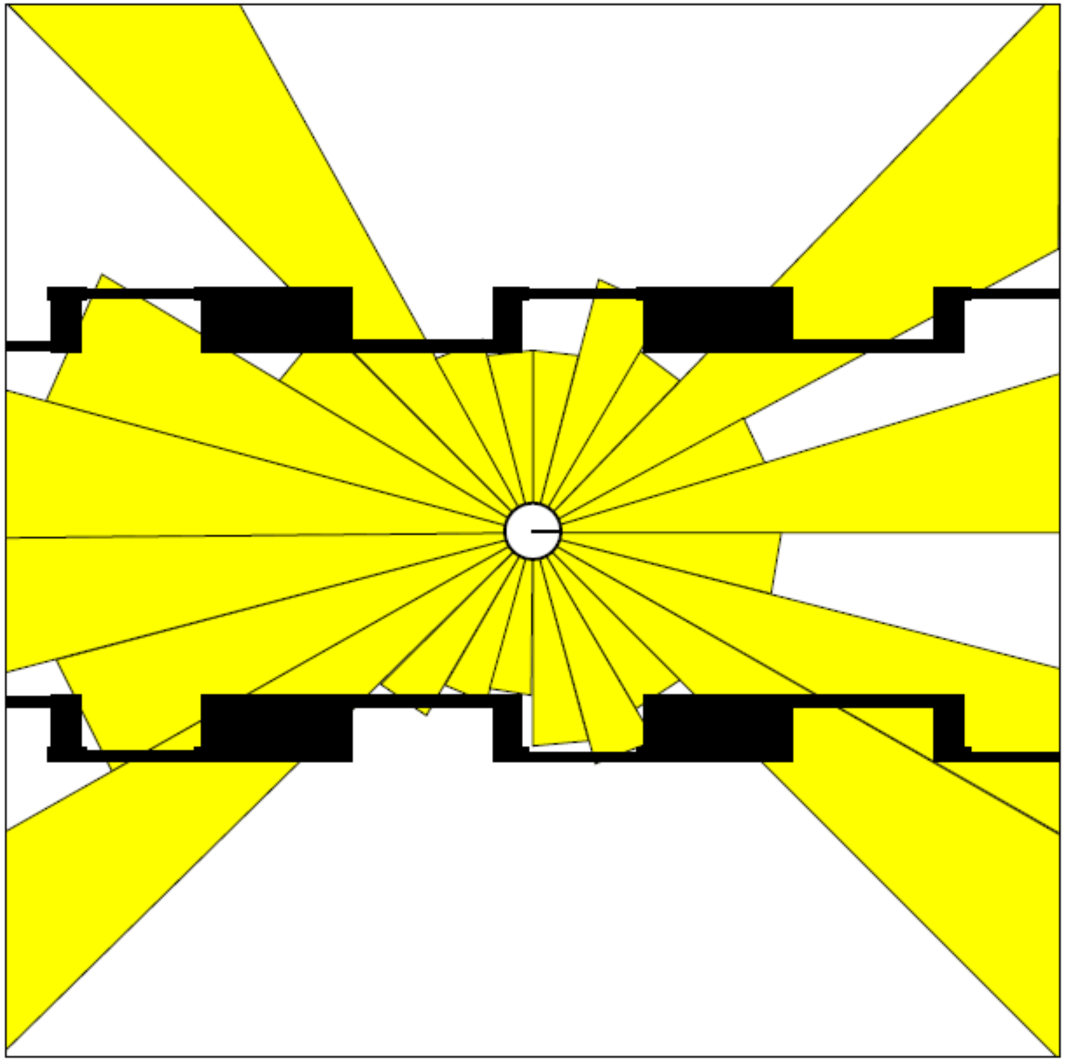
b) results from different geometric primitives

Sources of Error

- Opening angle
- Crosstalk
- Specular reflection

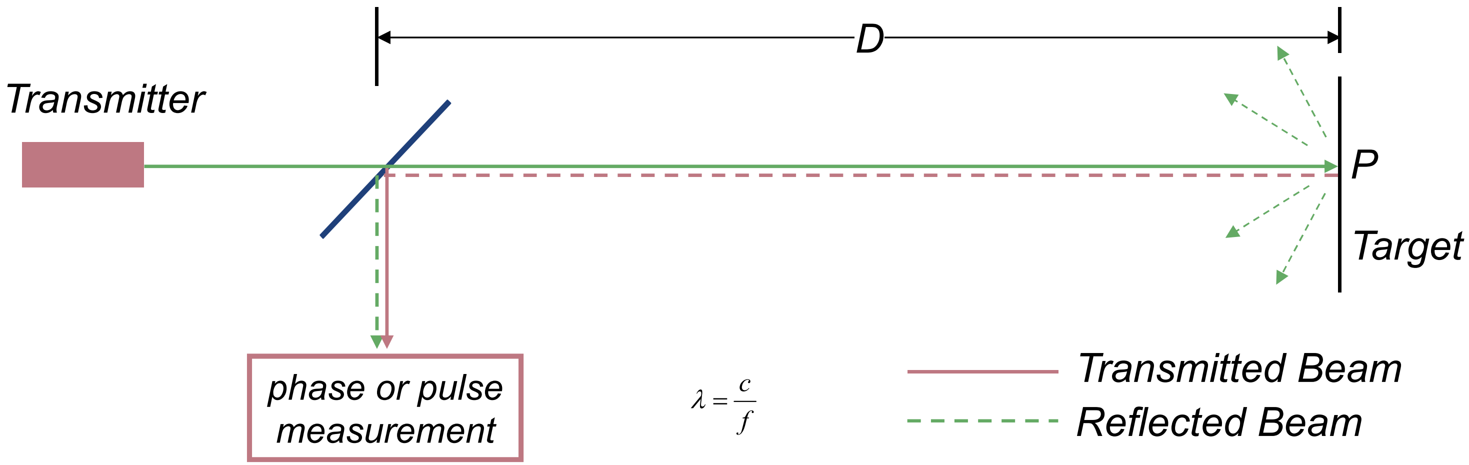


Typical Ultrasound Scan



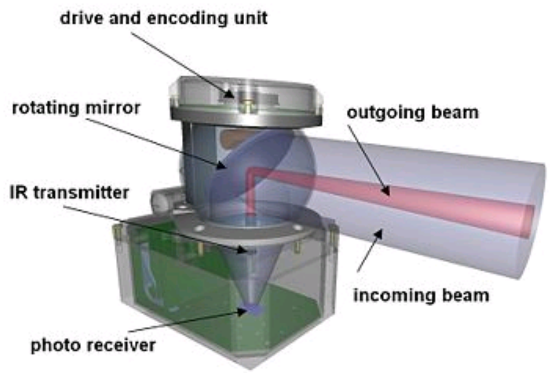
Laser Range Sensor (time of flight, electromagnetic)

- *Phase-Shift Measurement (today rather pulse measurements)*



$$\lambda = \frac{c}{f}$$

$$D' = 2D = \frac{\theta}{2\pi}\lambda$$



Where:

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

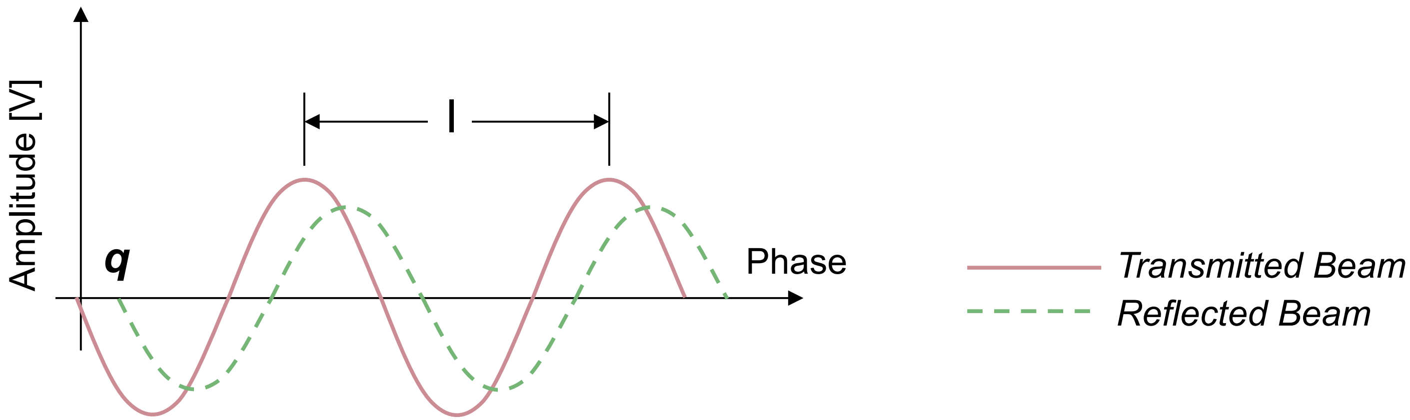
- for f = 5 MHz (as in the A.T&T. sensor), λ = 60 meters

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

- Distance D, between the beam splitter and the target

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

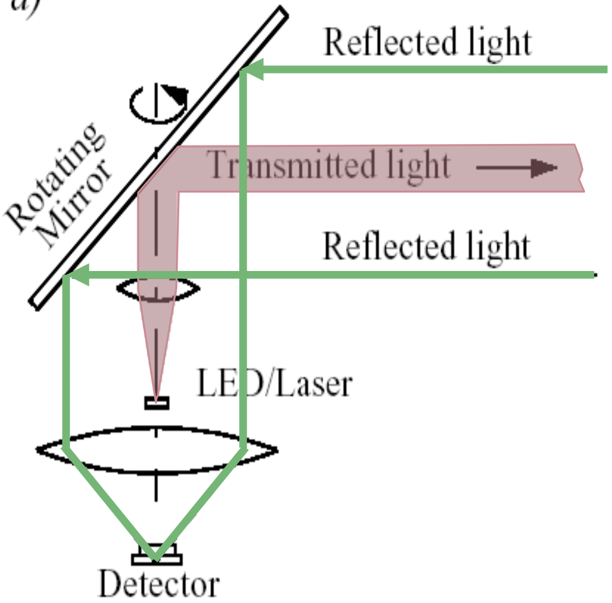
- where
  - θ: phase difference between transmitted and reflected beam
- Theoretically ambiguous range estimates
  - since for example if λ = 60 meters, a target at a range of 5 meters = target at 35 meters



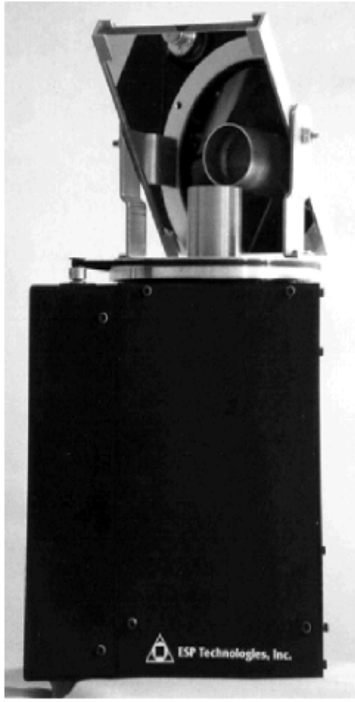
Laser Range Sensor (time of flight, electromagnetic) (5)

- Confidence in 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 …

a)



b)



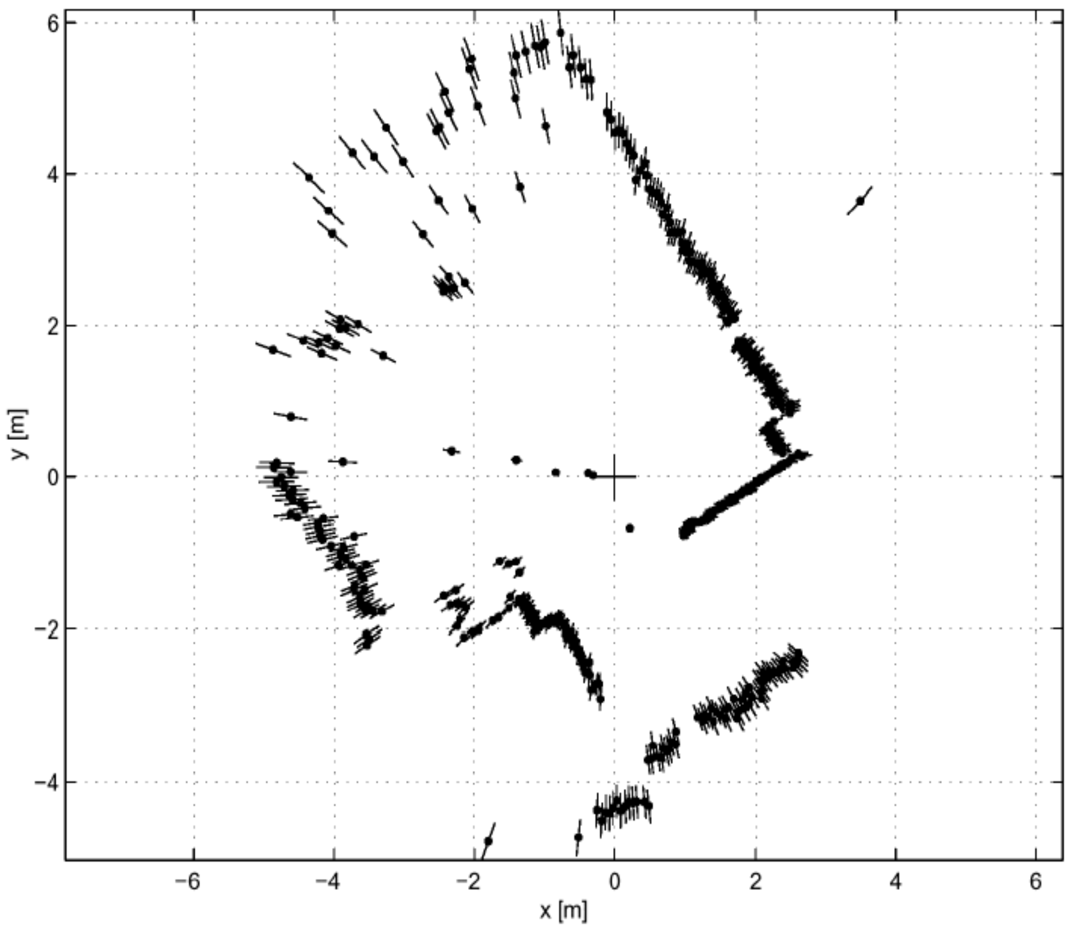
Why does Sick only measure 180°?

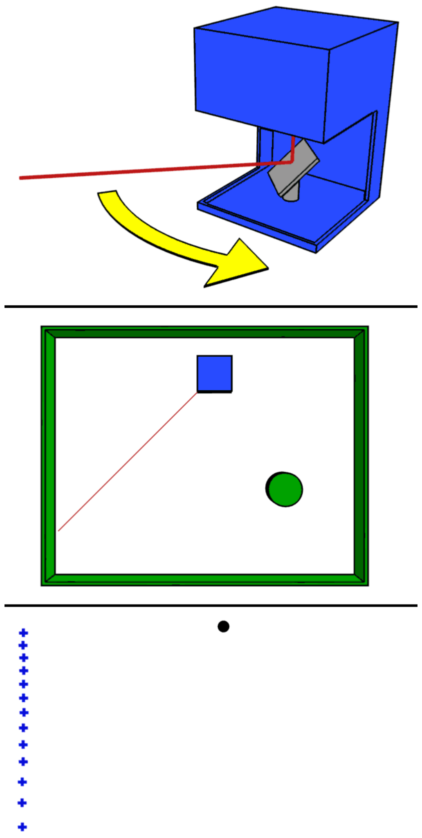
c)

Laser Range Sensor (time of flight, electromagnetic)

10.3.2008 – after 1st hour

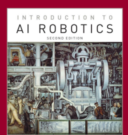
- Typical range image of a 2D laser range sensor with a rotating mirror. The length of the lines through the measurement points indicate the uncertainties.



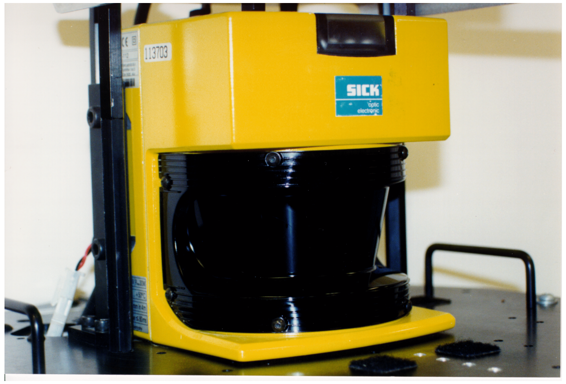


10

Sick



- Accuracy & repeatability
  - Excellent results
- Responsiveness in target domain
- Power consumption
  - High; reduce battery run time by half
- Reliability
  - good
- Size
  - A bit large
- Computational Complexity
  - Not bad until try to “stack up”
- Interpretation Reliability
  - Much better than any other ranger



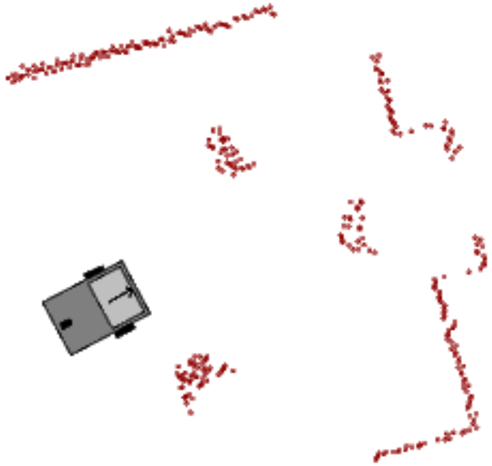
Laser Range Finders (LRFs)

- Found on many robots
- Highly accurate, high data rate
- Measures distances and angles to surrounding objects
- Returns distances d_i and angles α_i, with $i \in [0 \ldots FOV/resolution]$

SICK LMS200

Hokuyo URG

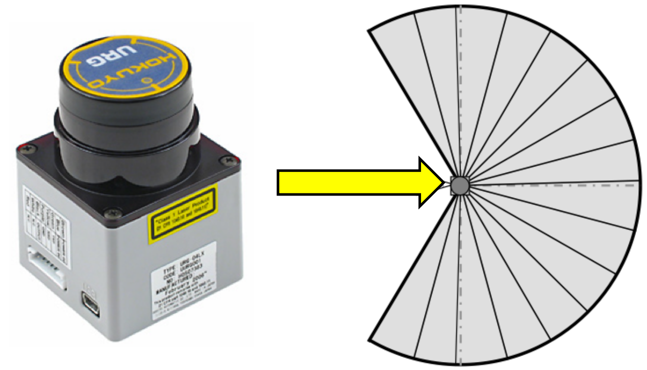
	Sick LMS200	Sick S300	Hokuyo URG-04LX
Weight	4500 g	1200 g	160 g
Volume	$\approx 20\, cm^3$	$\approx 15\, cm^3$	$\approx 5\, cm^3$
FOV	180°	270°	240°
Max. Range	80 m	30 m	4 m
Max. Ang. Res.	0.25°	0.5°	0.36°
Accuracy	± 15 mm	± 30 mm	± 10 mm
Scans per second	30	20	10
Interface	RS-232/RS-422	RS-232/RS-422	RS-232/USB

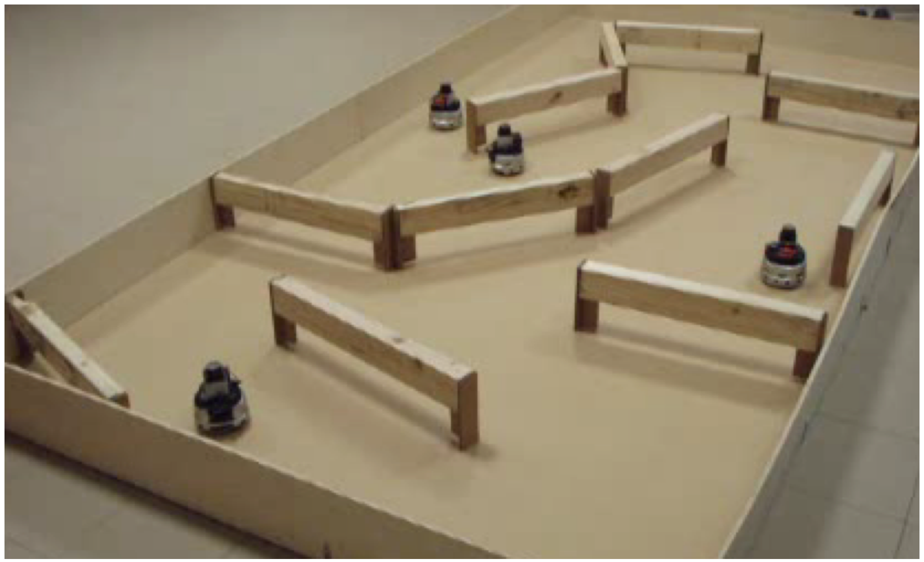


Scan taken on a soccer field

A smaller laser scanner

- Hokuyo URG-04X
  - size: $50 \times 50 \times 70$ mm
  - weight: 160 g
  - angular range: max 240°
  - angular resolution: 0.36°
  - response: 100 msec/scan
  - range: $0.02 \div 4$ m
  - depth resolution:
    ± 1 cm (up to 1 m)
    $\pm 1\%$ (beyond 1 m)
  - interface: RS-232, USB 2.0
  - supply: 5V DC
  - cost: 945 € (1080 US$)
    - 2 years ago was 1750 € ...

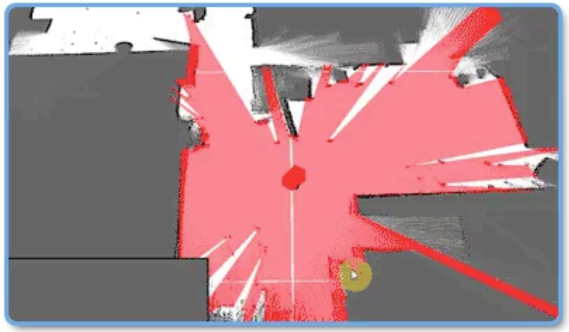




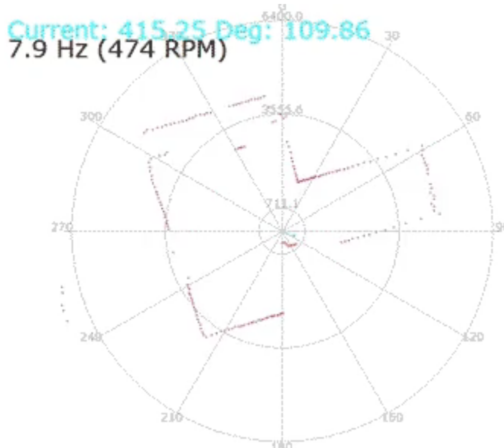
4 small Khepera with Hokuyo sensors
@ DIAG Robotics Lab

Rotating laser scanner

- RoboPeak RPLidar A1M1
  - 360° 2D-scan, 6 m measurement range
  - size: $70 \times 98.5 \times 60$ mm
  - weight: 200 g
  - variable scanning rate: $2 \div 10$ Hz
    - by varying the motor PWM signal
  - angular resolution: $\approx 1^\circ$ @5.5 Hz rate
    - 2000 samples/s @5.5 Hz rate
  - depth resolution: ± 20 mm (0.2% of current depth)
  - cost: 335 € (383 US$) in development kit
  - ROS & SLAM ready



Realtime ICP-SLAM based on RPLIDAR



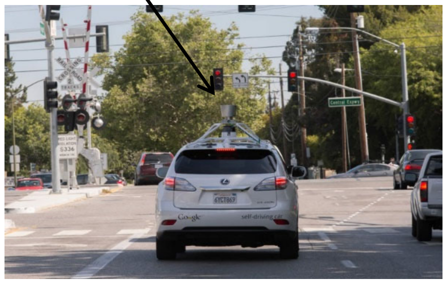
LIDAR VS. LRF (LASER RANGE FINDER)

- The term *lidar* was originally a portmanteau of *light* and *radar*.[1][2] It is now also used as an acronym of *"light detection and ranging"*[3] and *"laser imaging, detection, and ranging"*.[4][5]

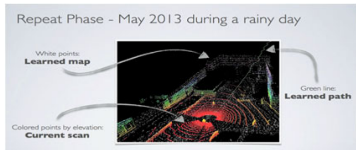
- Lidar sometimes refers to **3-D laser scanning**, a special combination of a 3-D scanning and laser scanning.

Today | 3D laser sensors → map based navigation

Expensive, complex and cumbersome



- Google Self-Driving Car Project (status summer 2015)
  - > 20 vehicles in use
  - > 2,7 mio km, 1.5 mio km in autonomous mode
  - > 11 accidents
    - No people insured
    - Non of them caused by car control algorithm

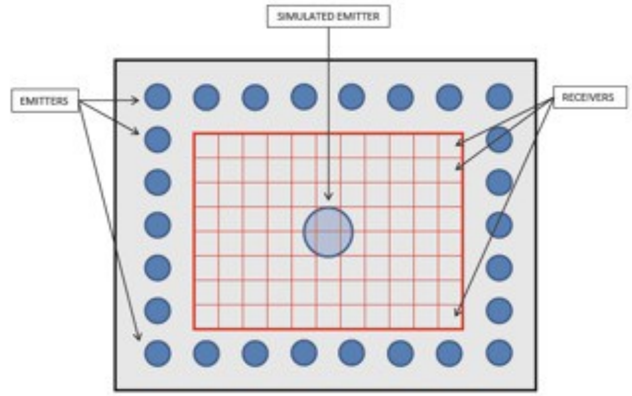


https://www.youtube.com/watch?v=eJCR2TaeSFc

Time of Flight Cameras

Meeting point between LiDARs and digital cameras.

IR light emitters illuminalte the scene. a 2D imaging sensor (e.g., a CMOS) sensible to the projected light



LIDAR in Phones and Tablets

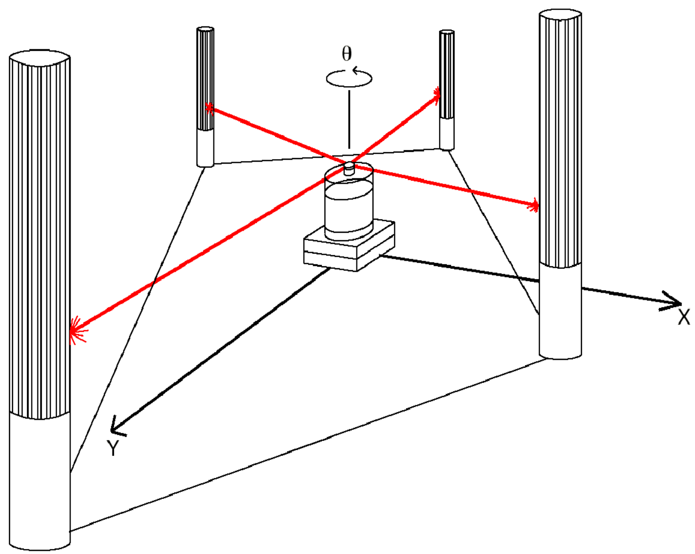
3D lidar scanner integrated in phones and tablets

3D scans of objects and environments

Augmented reality applications

Ground-Based Active and Passive Beacons

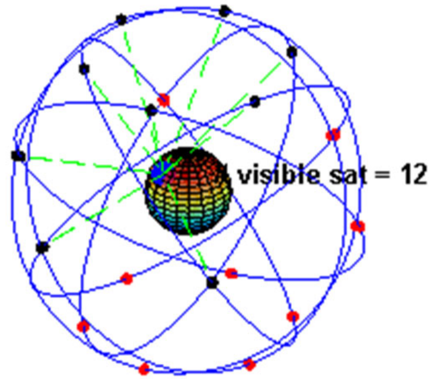
- “Elegant” way to solve the localization problem in mobile robotics
- Beacons are signaling guiding devices with a precisely known position
- Beacon base navigation is used since the humans started to travel
  - Natural beacons (landmarks) like stars, mountains or the sun
  - Artificial beacons like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



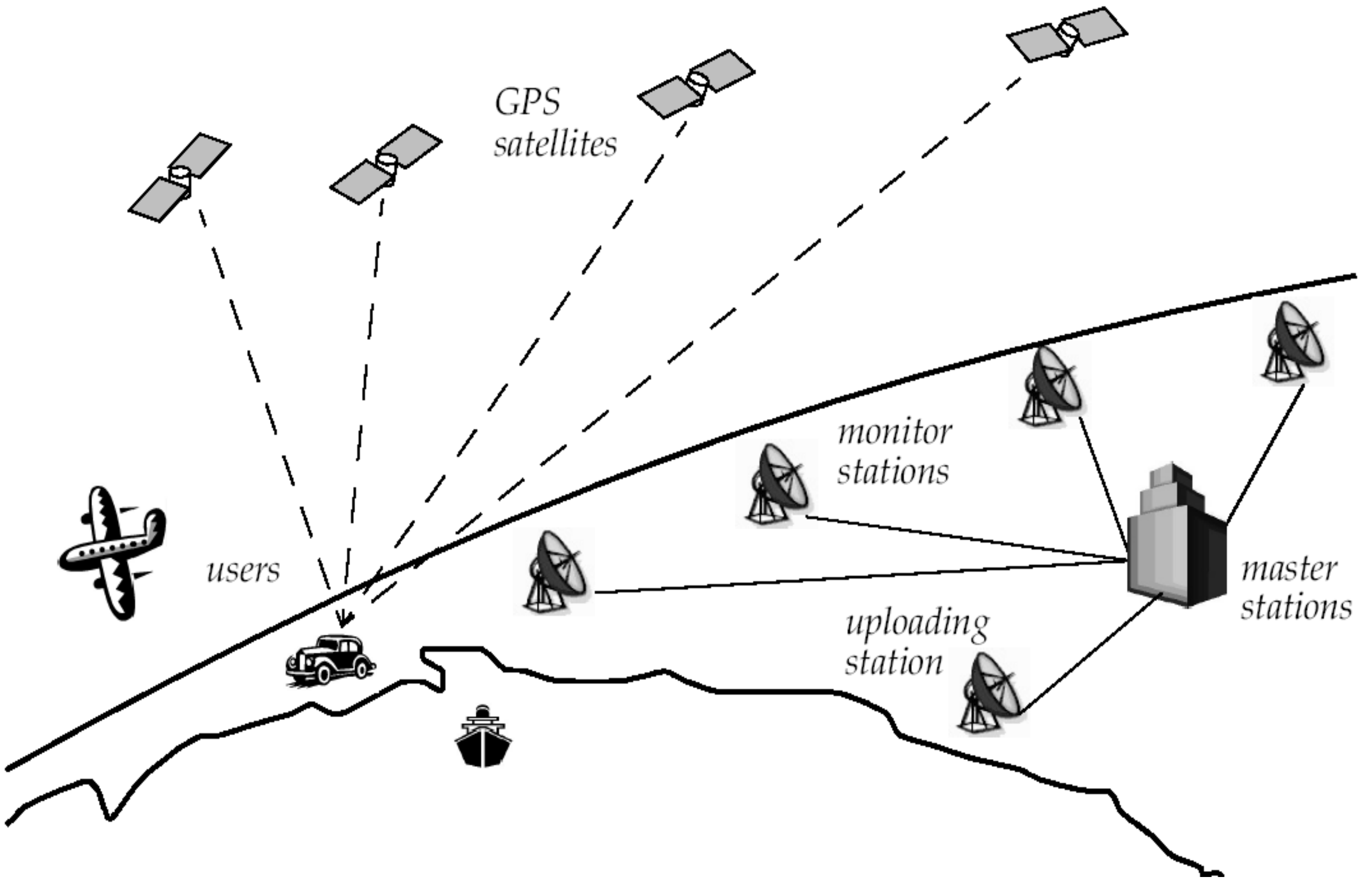
Global Positioning System (GPS)

- Working Principle
  - 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)



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
- **Light travels 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**
  - **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
- Commercial GPS receivers have nominal position accuracy of 3 meters

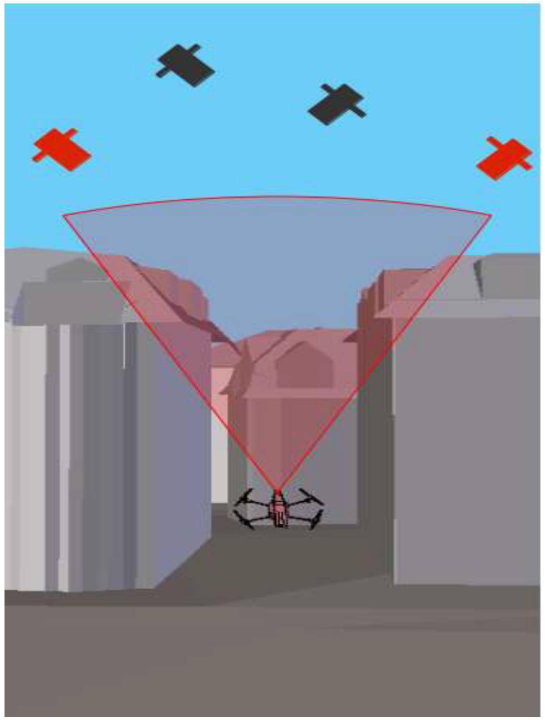
Global Positioning System (GPS) (1)

- Developed for military use
- Recently it became accessible for commercial applications
- 24 satellites (including three spares) orbiting the earth every 12 hours at a height of 20.190 km.
- Four satellites are located in each of six planes inclined 55 degrees with respect to the plane of the earth's equators
- Location of any GPS receiver is determined through a time of flight measurement

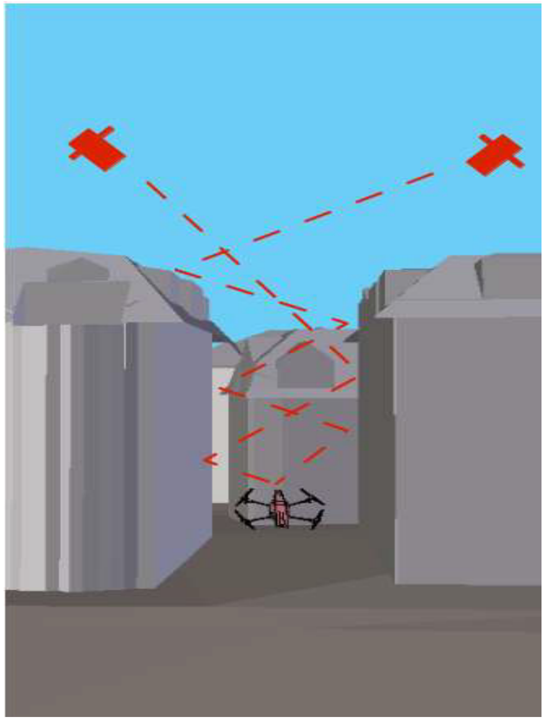
- Technical challenges:
  - Time synchronization between the individual satellites and the GPS receiver
  - Real time update of the exact location of the satellites
  - Precise measurement of the time of flight
  - Interferences with other signals

Global Positioning System (GPS)

Satellite coverage



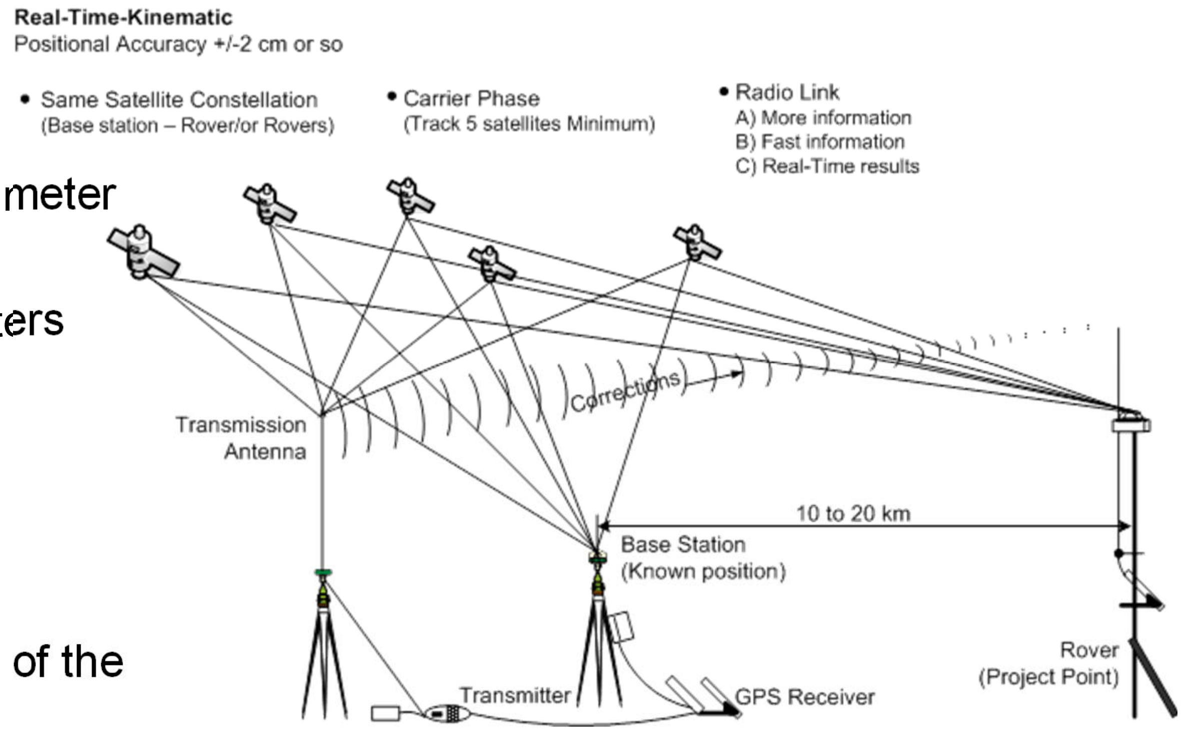
Multipath problem



GPS error sources

- Standard GPS
  - Ephemeris (satellite position) errors: 1 meter
  - Tropospheric delays: 1 meter
  - Unmodeled ionosphere delays: 10 meters
  - Multipath: 0.5 - 100 meters
  - Number of satellites under line of sight
- Real-Time Kinematic (RTK) GPS
  - Additional measurements of the phase of the signal's carrier wave
  - reference station or interpolated virtual station to provide real-time corrections

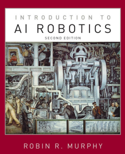
→ providing up to ***centimeter-level*** accuracy



10

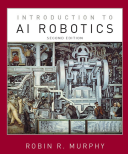
Stereo Range Maps

- About them
  - Use two cameras
- Advantages
  - Passive
  - Good coverage
- Disadvantages
  - Environment may not support interest operators
  - Computationally expensive
  - Sensitive to calibration
  - Sensitive to lighting

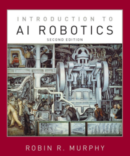


Depth from X

- About them
  - Usually single camera, single image or short image sequence
  - Useful variants include
    - Depth from motion
    - Depth from focus
    - Depth from texture
- Advantages
  - Nice theory, often computationally optimized
  - Usually have a camera anyway
- Disadvantages
  - Tend to be brittle outside of highly controlled conditions



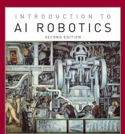
Outdoor Reactive Navigation Challenges



- Most everything has been developed for indoors
- Pressing outdoor needs
  - Foilage: tall grass == granite rock
  - Terrain anticipation
- Outdoor challenges
  - Lighting and shadows
  - Weather conditions
  - Sparse objects
  - Texture or lack of texture

Sensing for Behavioral Navigation Summary

- Have to decide between nearest protrusion and range maps
- Planar lasers work best but expensive, big, need several or need spinning head
- Ultrasonics were popular because cheap and distance, but now are hardly ever used due to their problems with specular reflection
- IR are almost never used for reliable navigation, usually just “panic” stops
- Computer vision is challenging due to lighting conditions
  - Optic flow chips can provide time-to-contact
  - Stereo can provide partial range maps
- Outdoor conditions are significantly harder than indoor



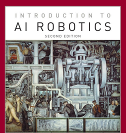
- Three combination of sensors:
  - Redundant
  - Complementary
  - Coordinated

Motivation for using multiple sensors = one sensor might be too noise or imprecise to correctly perceive the environment

- False Positive =
  the sensor detects a percept, but the percept is not there
- False Negative =
  the sensor miss to detect a percept

10 Returning to Questions

- **What sensors are essential for a robot?**
  - Movement and Navigation
    - Proprioception- joint, wheel encoders; accelerometers
    - Exteroception- at least a camera, range is helpful
    - Exproprioception- put the camera or haptics in the right place!
    - GPS
  - Health
    - Power
    - Communications status (heart beat)
    - General diagnostics!
  - Two-way audio
  - MISSION SENSORS



Summary

- Navigation needs depth perception
  - Lasers are preferred but have many drawbacks
  - Don't use sonars
- Sometimes create *occupancy grids* to improve certainty, then treat occupancy grid as the sensor output (virtual sensor)
- Reactive "object recognition" exploits (or engineers) cues such as color, heat; sometimes can use a simple Hough transform
- You don't want to "grow your own" vision algorithms, especially computer vision- there's a wealth of algorithms out there