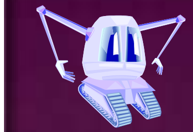
Lecture 4-1

Switch on the Light:
Simple Sensors

Sonar and Laser:
Complex Sensors

The Robotics Primer (Ch. 8, 9)



Course Announcements

- Bring your laptop and robot everyday
- Bring a calculator for Tuesday's Quiz on **Complex Sensors/Perception** (open notes)
- Lab 3 demo due Thursday, 4/02/09
- Lab 3 memo and code due by midnight on Friday, 4/03/09
- Upload memo and code to Angel
- Memo and Code grades on Angel by Friday, 4/03/09

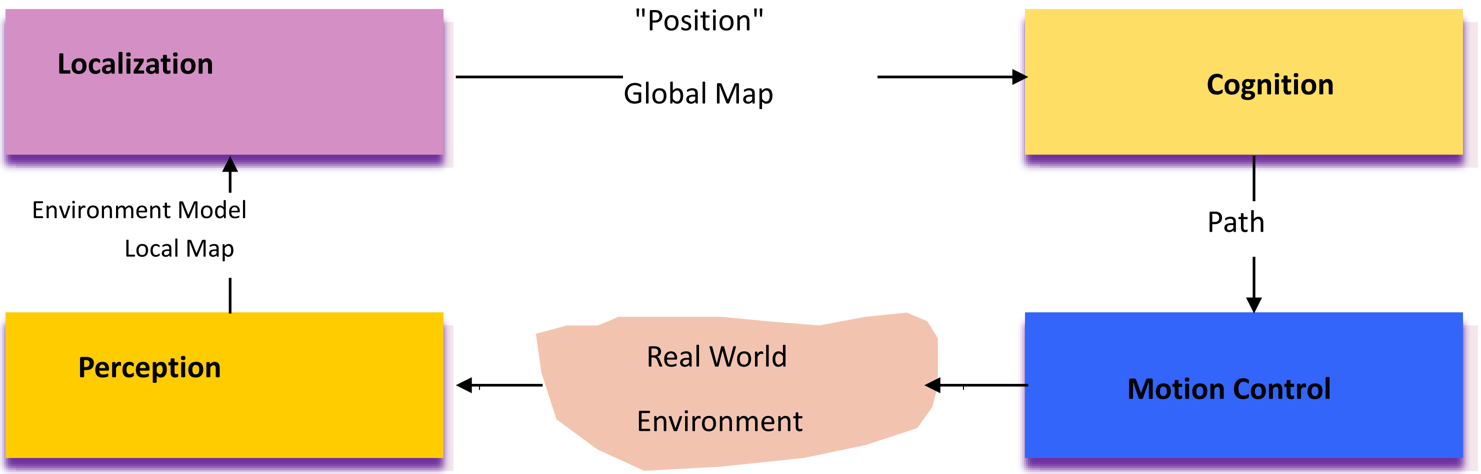
Quote of the Week

“A common mistake people make when trying to design something completely foolproof is to underestimate the ingenuity of complete fools.”

D. Adams

Perception

One of the most important tasks of an autonomous mobile robot is ***perception***. Perception is used for the robot to acquire knowledge from it's environment. Perception involves taking measurements using various sensors and extracting meaningful information.



Localization

"Position"

Global Map

Cognition

Environment Model

Local Map

Path

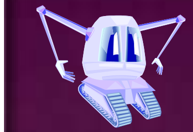
Perception

Real World

Environment

Motion Control

More Simple Sensors



Shaft Encoders

- One of the most common break beam sensors is a **shaft encoder** on a motor
- Shaft encoders measure the angular rotation of a shaft or an axle
- They provide position and/or velocity information about the shaft they are connected to (i.e. speedometer and odometer)
- An encoder can also be used in the reflectance configuration by painting a disk with contrasting colors

Feedback from Encoders

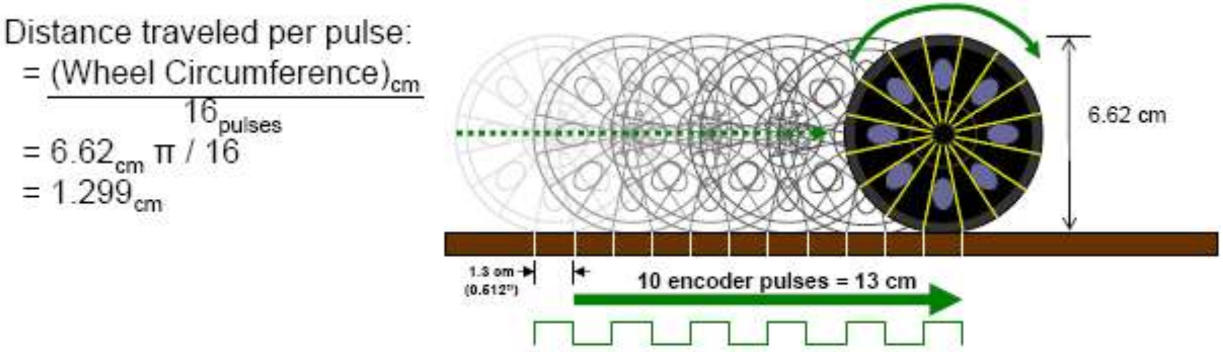
- Position and velocity information from encoders can be used to drive the robot a certain distance or turn a certain angle.
- These movements will not be precise because of slip and slide and backlash in the gearing mechanism
- The encoder can correct for odometry error but some error is still avoidable
- There is no perfect sensor and there will always be some uncertainty

Quadrature shaft encoding

- Quadrature shaft encoding measures the direction of rotation of a motor shaft. This technology is used in a ball-type computer mouse
- There are 2 encoders aligned 90 degrees out of phase so by comparing the output of the state change to the previous step it is possible to tell if the direction changed
- When the shaft moves one direction the counter increments and decrements for the opposite direction

Encoders:
Measuring wheel distance

- Relative position estimation is dependent on the measurement of the robot's velocity
- Optical encoders can be used on each wheel to measure angular position and or velocity
- If the robot moves straight ahead, you can count encoder pulses to determine its new location
- If 10 encoder pulses = 13 cm then distance can have an error up to 1.3 cm
  - This can be serious for short distances
  - Accumulated error can cause problems



Distance traveled per pulse:

$$= \frac{(\text{Wheel Circumference})_{cm}}{16_{pulses}}$$

$$= 6.62_{cm}\,\pi / 16$$

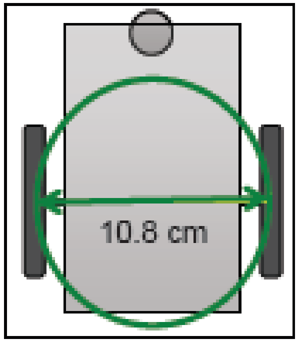
$$= 1.299_{cm}$$

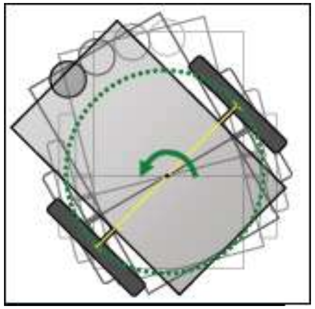
http://www.scs.carleton.ca/~lanthier/teaching/COMP4900A/Notes/5%20-%20PositionEstimation.pdf

Encoders:
Measuring spin angle

- Assuming the robot turns around it's center ($v_1 = -v_2$)
- If the robot has a diameter of 10.8 cm, the circumference is *$\pi d = \pi(10.8) = 33.93$ cm*
- If each encoder pulse indicates a travel distance of 1.3 cm

$$(1.3 \text{ cm/pulse})/(33.93 \text{ cm})(360\,°) = 13.79\,°/\text{pulse}$$





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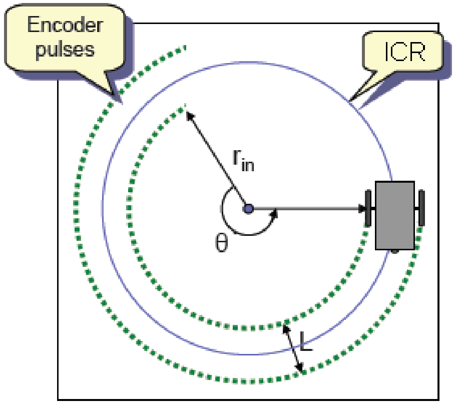
Encoders: Measuring turn angle



When the wheel velocities are not equal

- Each wheel traces out a circle with a different circumference
- The diameter of the robot L = 10.8 cm and a resolution of 1.3 cm per pulse
- Length of the inner arch → $s_2 = r_{in}\,\theta$
- Length of the outer arch → $s_1 = (r_{in} + L)\theta = s_2 + L\,\theta$
- So $\theta = (s_1 - s_2)/L$
- The length of the arcs can be described in terms of the encoder pulses for the right (p_1) and left (p_2) wheels.
- the difference in the encoder pulses, $p_\Delta = p_1 - p_2$

Encoders: Measuring turn angle, cont.

- $\theta = (s_1 - s_2)/L$
- Using p_Δ to find the change in the angle

$$\theta = (p_\Delta)(1.3 \text{ cm/pulse})/10.8 \text{ cm}$$

$$= 0.12037\, p_\Delta \text{ radians} =(6.897)\, p_\Delta{}^\circ$$

- Note that when the pulses of both wheels are equal (i.e. same velocity), $\theta = 6.897\, p_\Delta{}^\circ = (6.897)(2p_1) = 13.79\, p_1{}^\circ$
- To find the (x, y) position of the robot substitute encoder pulses for velocities in the forward kinematic equations

Heading Sensors

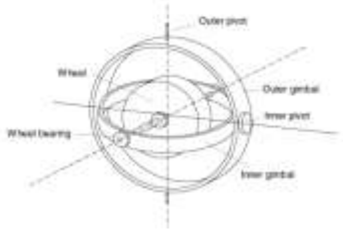
- Heading sensors can be *proprioceptive* (gyroscope, inclinometer, accelerometers) or *exteroceptive* (compass)
- They are used to determine the robots orientation and inclination
- They may be used with appropriate velocity information to integrate the movement to a position estimation (i.e. *dead reckoning* (ship navigation))

Compass

- A ***compass*** uses the earth's magnetic field to determine absolute measure for robot orientation.
- Large variety of solutions to measure the earth magnetic field
  - mechanical magnetic compass
  - direct measure of the magnetic field
- Major drawbacks:
  - weakness of the earth field
  - easily disturbed by magnetic objects or other sources
  - Bandwidth limitation of electronic compasses and susceptibility to vibration
  - not feasible for indoor environments (conceivably could provide useful local orientation)

Inertial Sensors

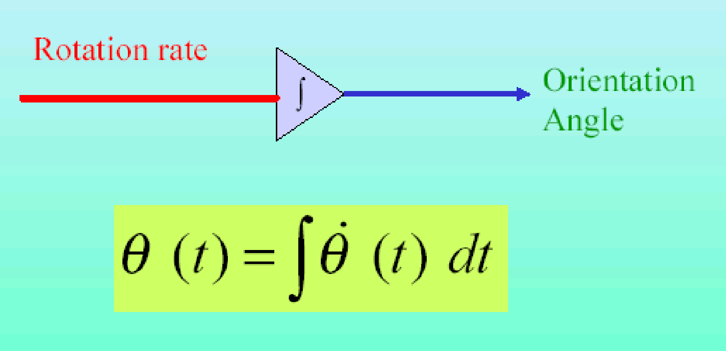
- **Gyroscopes**
  - Measure the rate of rotation independent of the coordinate frame
  - Uses the principle of conservation of angular momentum
  - Common applications:
    - Heading sensors, Full Inertial Navigation systems (INS)
- **Accelerometers**
  - Measure accelerations with respect to an inertial frame
  - Common applications:
    - Tilt sensor in static applications, Vibration Analysis, Full INS Systems



Gyroscopes

- These devices return a signal proportional to the rotational velocity.
- There is a large variety of gyroscopes that are based on different principles

- ***Gyroscopes*** are heading sensors, that keep their orientation in relation to a fixed frame
  - Provide an absolute measure for the heading of a mobile robot
  - There are *mechanical* and *optical* gyroscopes

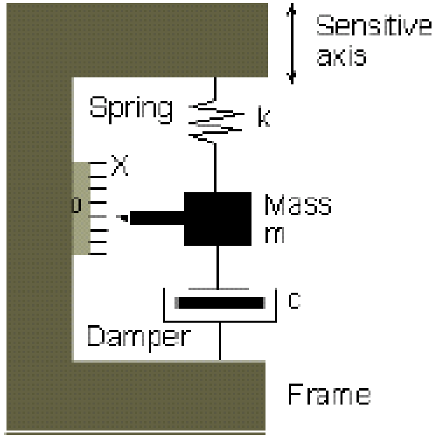


$$\theta\ (t) = \int \dot{\theta}\ (t)\ dt$$

- **Mechanical Gyroscopes**
  - Standard gyro - relies on standard properties of a fast-spinning rotor
  - Rated gyro – measures angular speeds instead of absolute orientation
  - If the spinning axis is aligned with the north-south meridian, the earth's rotation has no effect on the gyro's horizontal axis
  - If the spinning axis points east-west, the horizontal axis reads the earth rotation
- **Optical Gyroscopes**
  - Use light beams or lasers instead of mechanical parts
  - Measures angular speed

Accelerometers

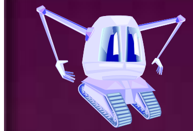
- They measure the inertia force generated when a mass is affected by a change in velocity.
- This force may change
  - The tension of a string
  - The deflection of a beam
  - The vibrating frequency of a mass
- Main elements are a mass, suspension mechanism and sensing element
- High quality accelerometers include a servo loop to improve linearity of the sensor



$$F = m\frac{d^2x}{d^2t} + c\frac{dx}{dt} + kx$$

The Robotics Primer, Matarić, Chapter 9

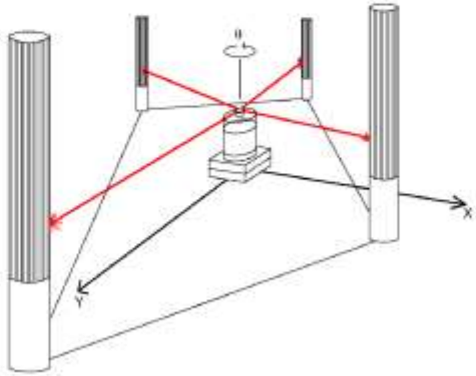
Complex Sensors



Complex Sensors

- These sensors require a great deal or processing compared to simple sensors
- Additionally after processing, the information they provide is much more varied and useful than simple sensors

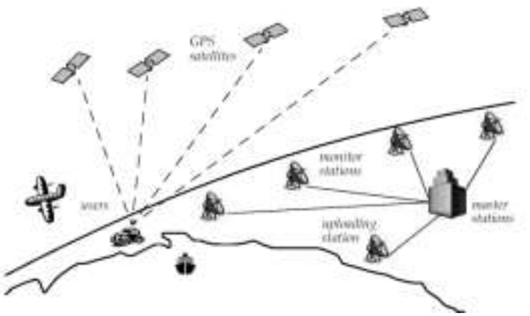
Ground-Based Beacons



- An elegant way to solve the localization problem in mobile robotics is to use *active* or *passive* beacons
- ***Beacons*** are signaling guiding devices with a precisely known position
- The *Global Positioning System* (GPS) revolutionized modern navigation technology
  - Extremely effective and one of the key sensors for outdoor mobile robotics
  - 24 GPS satellites available at all times for civilian navigation
  - Passive, extereoceptive sensors
  - Triangulation of 3 data points helps the receiver infer its own position
  - For indoor robots GPS is not applicable
- Major drawback with the use of beacons indoor:
  - Beacons require changes in the environment
  - Limit flexibility and adaptability to changing environments.

Space Segment

Global Positioning System



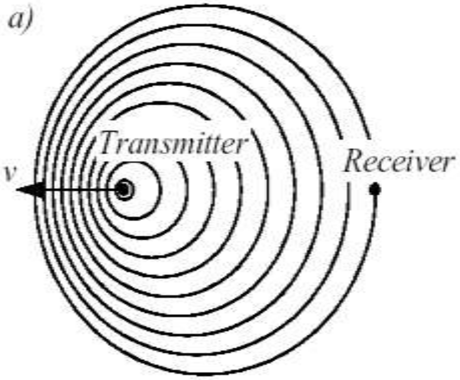
Technical challenges:

- Satellite transmissions are extremely low-power and successful reading requires a direct line-of-sight communication
- It requires 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
- Interference with other signals
- GPS uses psuedorange and performs at a resolution of 15 meters
- *Differential GPS* (DGPS) uses a second receiver that is static at a known position (corrects error with the reference)
- The bandwidth has a 200 – 300 ms latency or no better than 5 Hz GPS updates (a problem on fast-moving mobile robots)

Motion/Speed Sensors

Motion/speed sensors

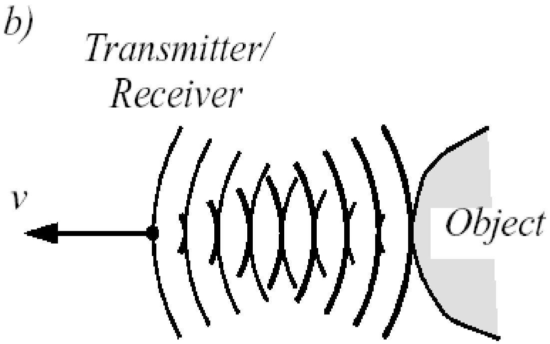
- *Motion or Speed sensors* measure directly the relative motion between the robot and its environment
- For fast moving robots, Doppler-based motion sensors detect the obstacle by measuring frequency shift
- A transmitter emits an electromagnetic sound wave with a frequency f_t
- It is reflected from an object and measured by a receiver
- The measured frequency f_r at the receiver is a function of the relative speed v between the transmitter and receiver *(Doppler frequency)*



$$f_r = f_t(1 + v/c)$$

Motion Sensor : Doppler Effect Based (Radar or Sound)

- The reflected wave is typically measured by the *Doppler shift*, Δf
- The *Doppler shift* can be used to find the relative speed



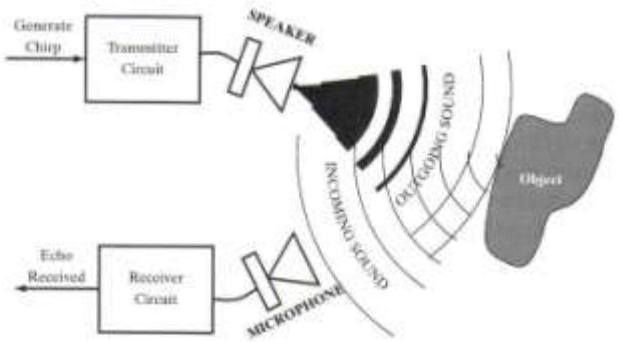
$$f_r = f_t \frac{1}{1 + v/c}$$

$$\Delta f = f_t - f_r = \frac{2 f_t v \cos\theta}{c}$$

$$v = \frac{\Delta f \cdot c}{2 f_t \cos\theta}$$

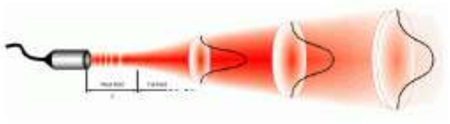
SONAR

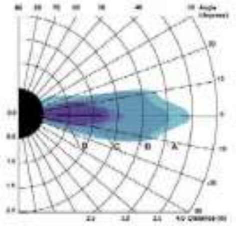
SONAR

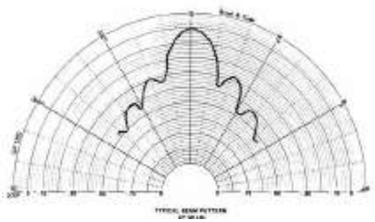


- Ultrasound (sonar) refers to the range of frequencies of sound that are beyond human hearing
- The process of finding your location based upon sonar is echolocation
- Sonar are active sensor that emit a chirp or ping and use time of flight to determine distance
- A transducer is a device that transforms one form of energy into another
- The transducer on a sonar emits the chirp/ping and receives the sound (echo) that comes back.
- Mechanical energy is concerted into sound as the membrane on the transducer flexes to produce a ping

SONAR



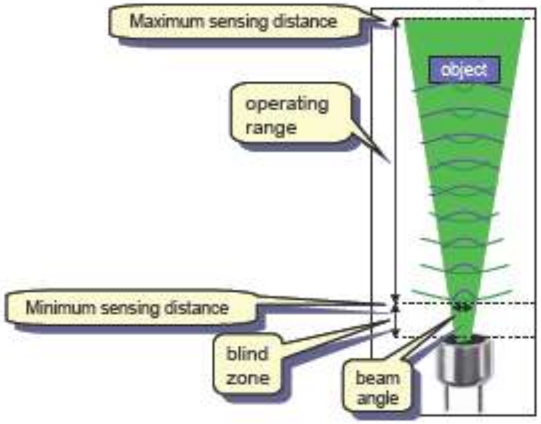


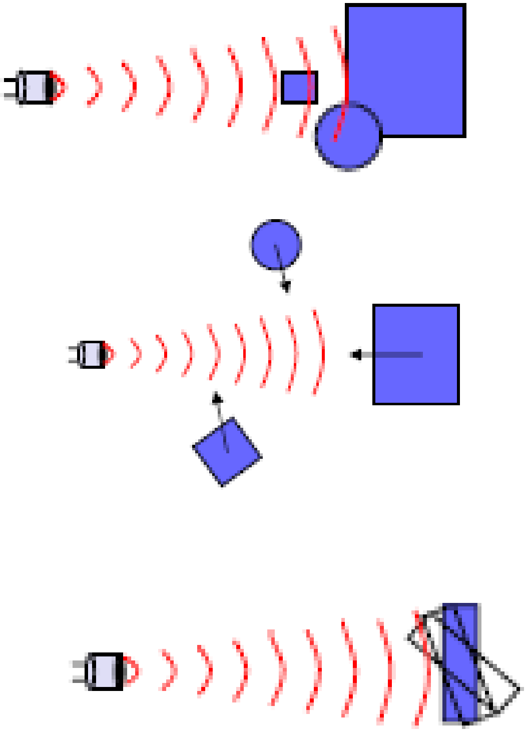


- *Sound Navigation and Ranging (SONAR)*
  - bounce sound off of objects
  - measure time for reflection to be heard - gives a range measurement
  - It measures change in frequency and gives the relative speed of the object (Doppler effect)
  - bats and dolphins use it with amazing results
  - robots use it with less than amazing results
- Wider objects near the center of the beam result in better accuracy

Sonar: Reliability

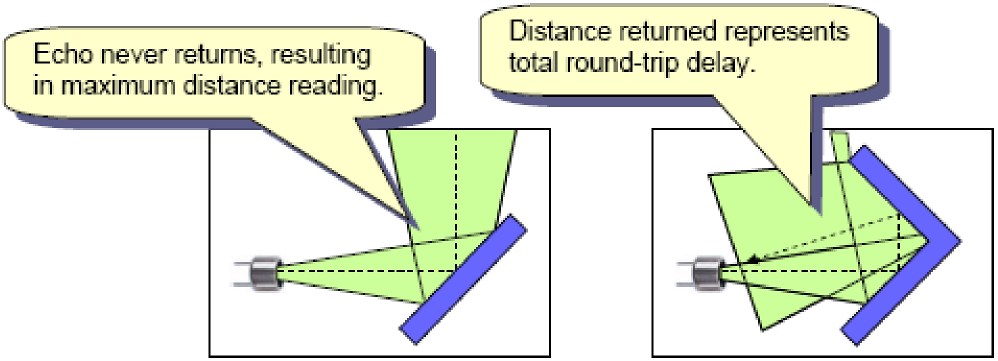
- **Blind zone** is when an echo arrives before the transducer is ready to receive and objects are not detected reliably
- Sensor readings vary based upon:
  - Distance to object(s)
  - Angle that object makes with respect to sensor axis
  - Direction that objects enter sensing range





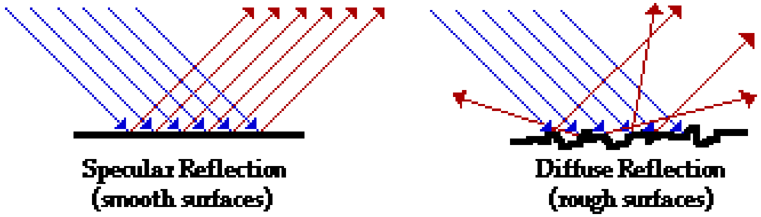
Sonar:
Specular Reflection

- Specular reflection can cause reflected sound to
  - Never return to the transducer
  - Return to the transducer too late
- The results is that the distance measurement is too large and inaccurate



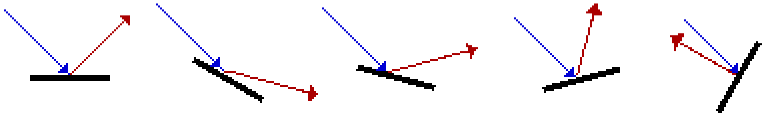
SONAR:
Specular Reflectance

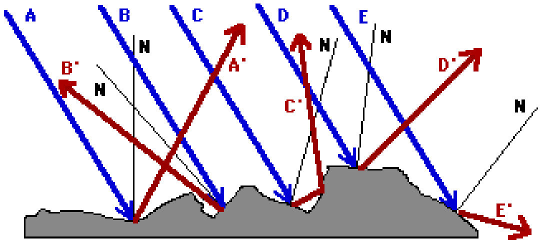
- Brightness depends on
  - reflectance of the surface patch
  - position and distribution of the light sources in the environment
  - amount of light reflected from other objects in the scene onto the surface patch
- Two types of reflection
  - Specular (smooth surfaces)
  - Diffuse (rough surfaces)
- Necessary to account for these properties for correct object reconstruction ⇒ complex computation



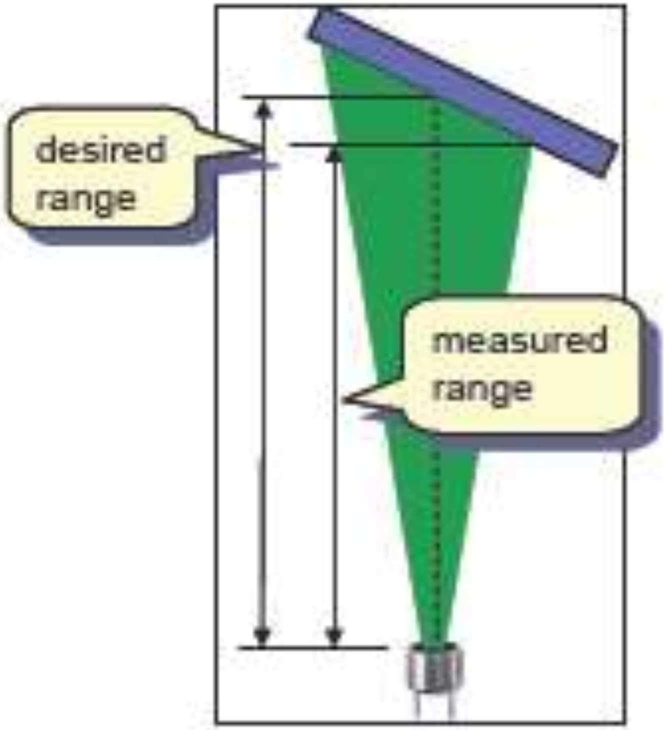
Specular Reflection
(smooth surfaces)

Diffuse Reflection
(rough surfaces)

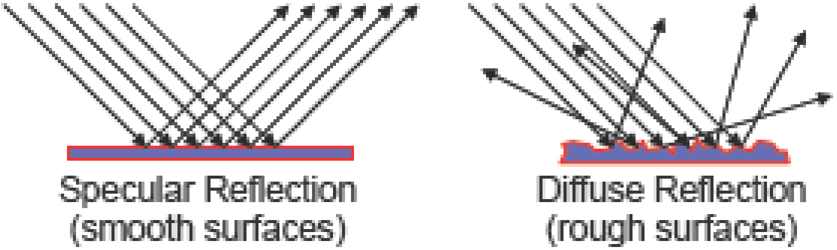




Sonar: Sensitivity

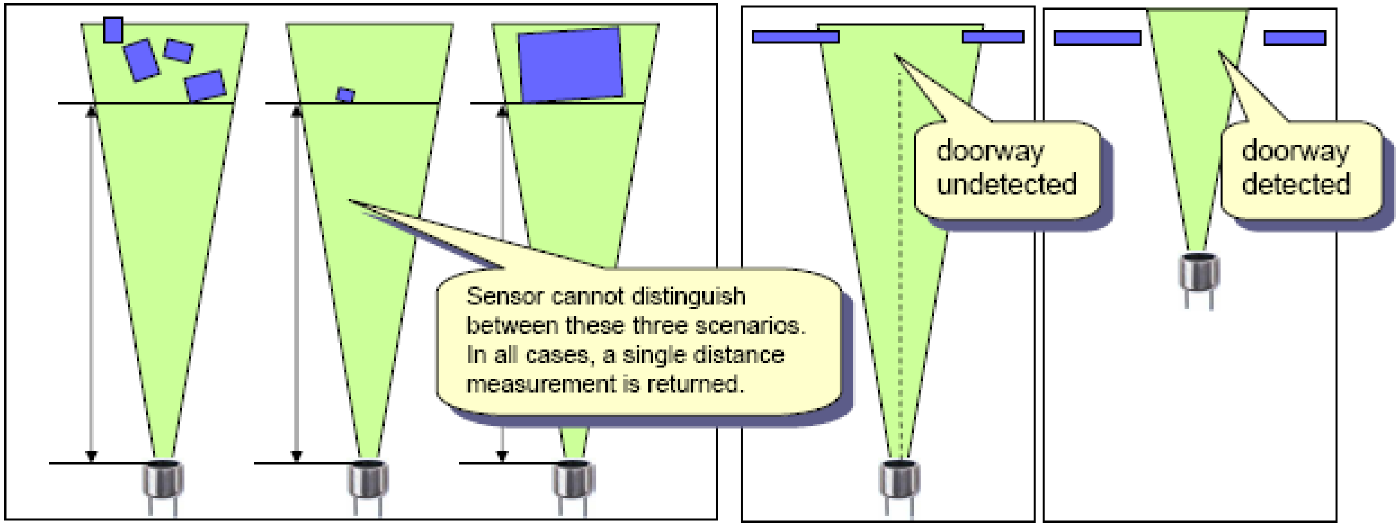


- *Sensitivity* to obstacle angle can result in improper range readings
- When the beam angle of incidence falls below a certain critical angle *specular reflection* errors occur



SONAR: Resolution

- Distance and angular resolution decreases as objects become further from the sensor
  - Multiple close objects cannot be distinguished
  - Gaps such as doorways cannot be detected

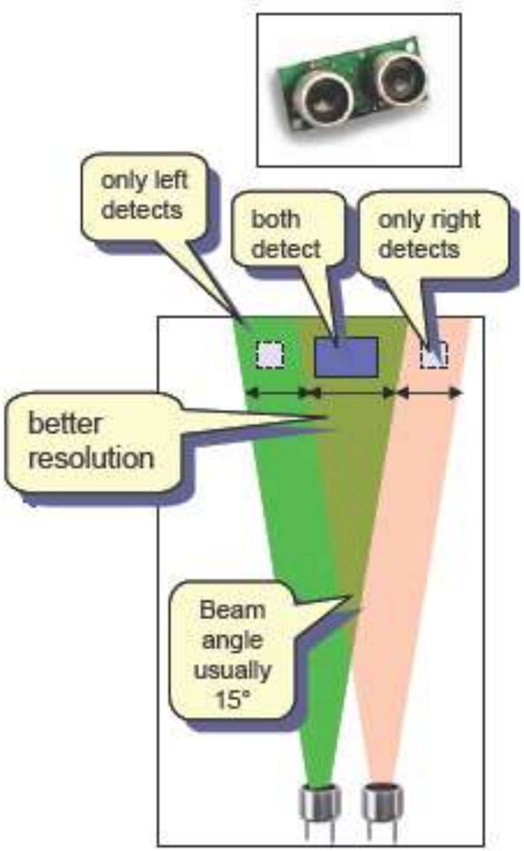


Sensor cannot distinguish between these three scenarios. In all cases, a single distance measurement is returned.

doorway undetected

doorway detected

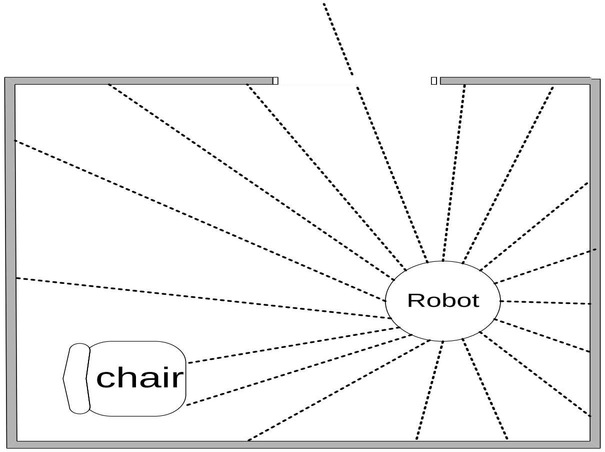
Ultrasonic Range Sensors: Redundancy

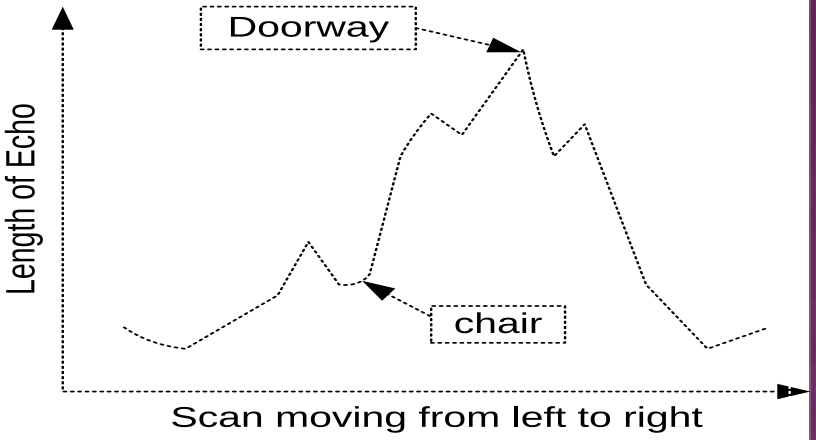


- To increase beam width (*resolution*), two sensors are used together
- Detection in either or both sensors allows for increased resolution

Ultrasonic Range Sensors: Applications

- Distance Measurement
- *Mapping:* Rotating proximity scans (maps the proximity of objects surrounding the robot)
  - Scanning at an angle of 15º apart can achieve best results



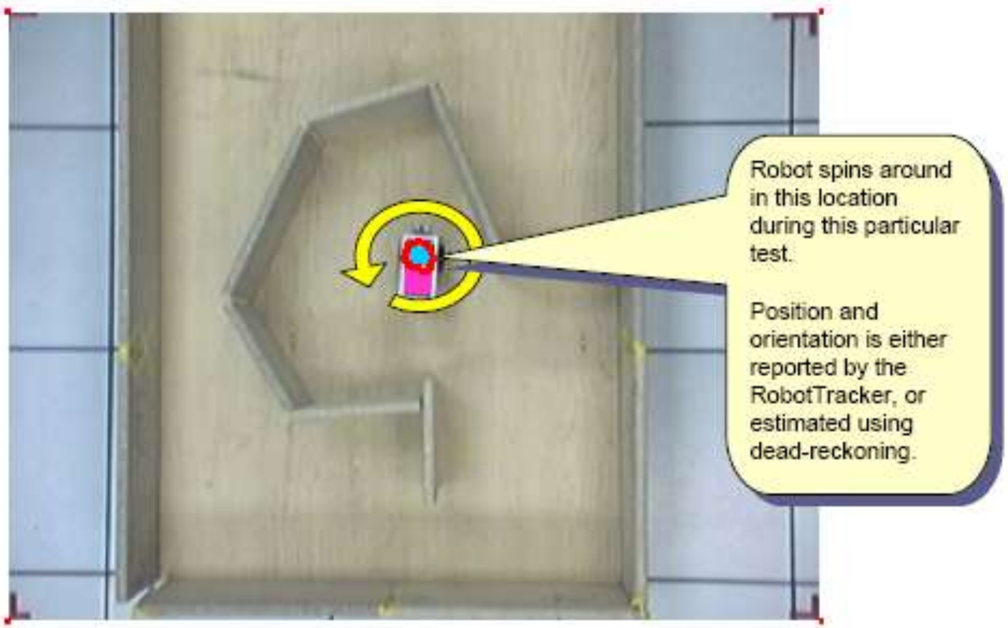


Ultrasonic Range Sensors: Mapping

- To perform mapping take multiple readings:
  - Rotate the sensors
  - Rotate the robot chassis
  - Use multiple sensors at fixed positions on chassis

Ultrasonic Range Sensors: Mapping Example

Use sonar mounted to the front of a robot to compute the ranges to obstacles from a location in the environment

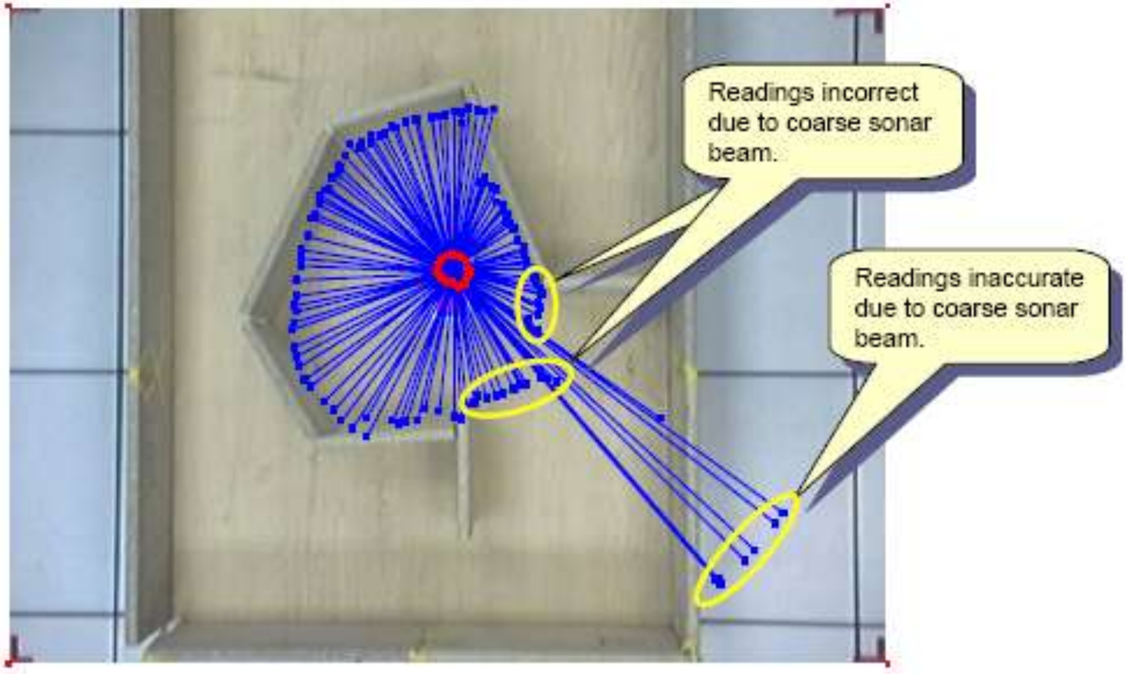


Robot spins around in this location during this particular test.

Position and orientation is either reported by the RobotTracker, or estimated using dead-reckoning.

Ultrasonic Range Sensors: Mapping Example

Blue lines show sonar readings detected from the robot's position (x, y) to the obstacle position (x_o, y_o)

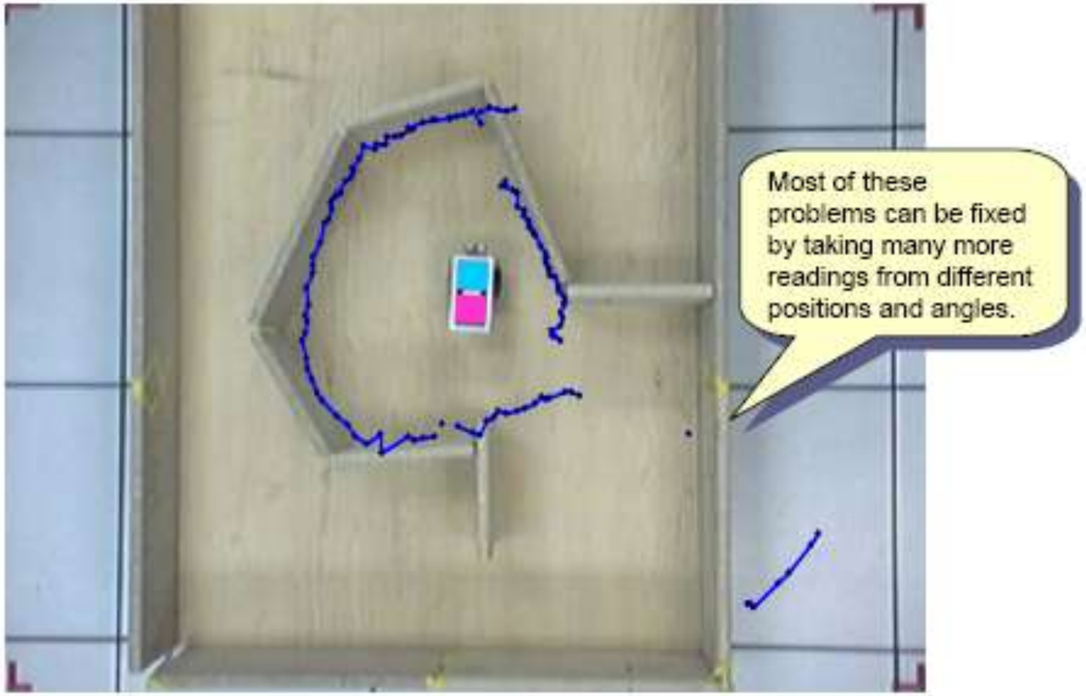


Readings incorrect due to coarse sonar beam.

Readings inaccurate due to coarse sonar beam.

Ultrasonic Range Sensors: Mapping Example

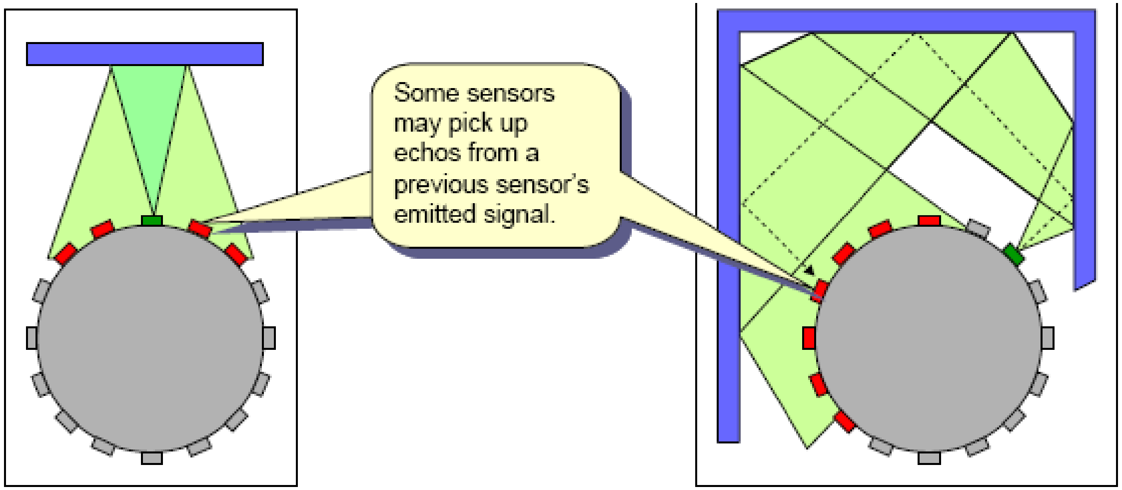
The sonar data produces a ‘rough’ outline of the environment with some inaccurate readings



Most of these problems can be fixed by taking many more readings from different positions and angles.

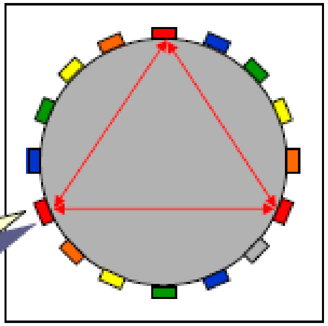
Ultrasonic Range Sensors: Crosstalk

- Using multiple fixed sensors can lead to *crosstalk*
- *Crosstalk* is interference in which echoes emitted from one sensor are detected by others



Some sensors may pick up echos from a previous sensor's emitted signal.

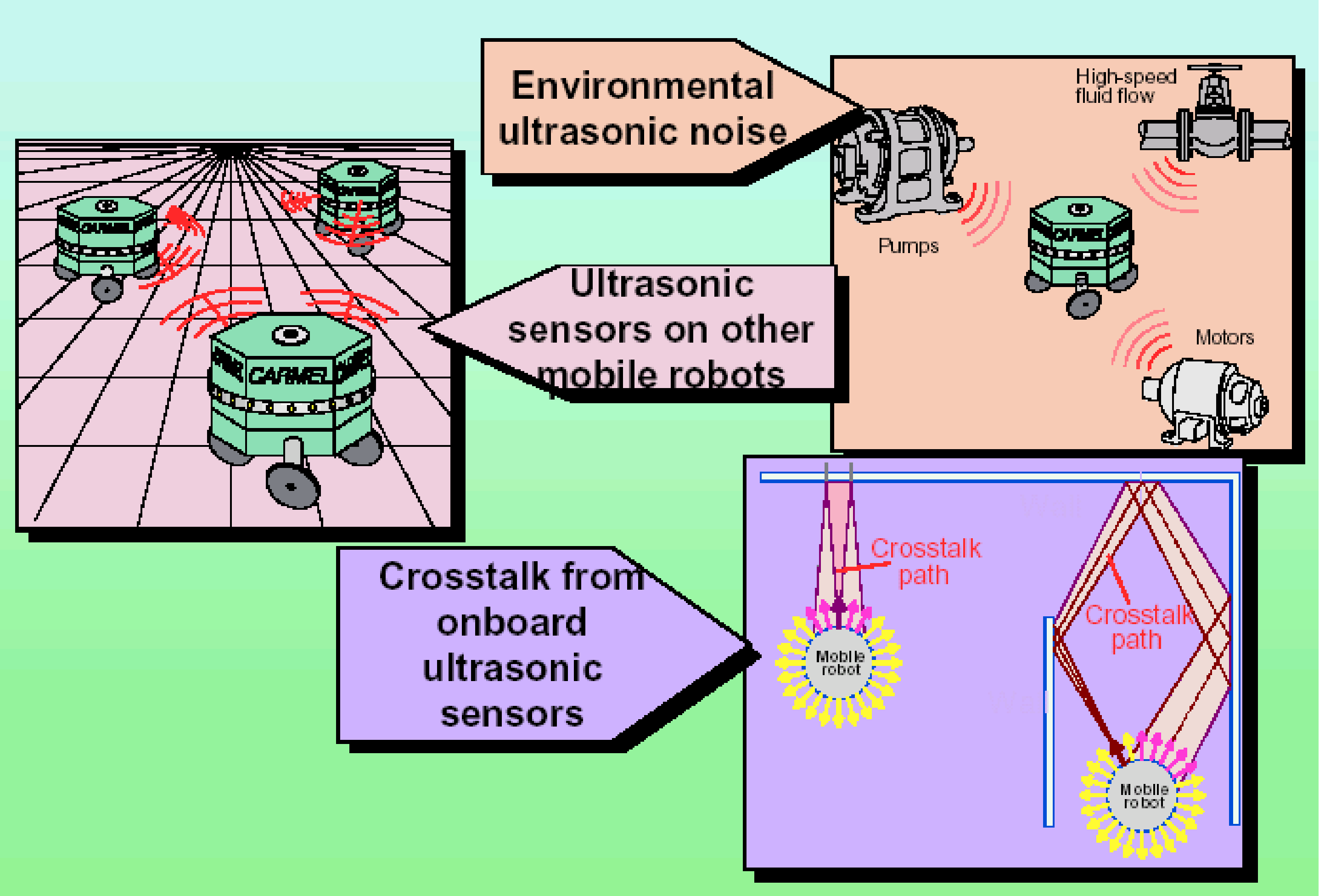
Ultrasonic Range Sensors: Crosstalk Solution



Group sonars into small groups that are allowed to emit signals at the same time.

- Crosstalk signals are impossible to detect unless signals are unique (coded)
- Crosstalk can be reduced by carefully timing the emitting of signals
  - Emit from one and wait for a time interval
  - Emit from a select few that may not have interference
- Emit adjacent sensors at different frequencies

Ultrasonic Range Sensors: Noise Issues



Ultrasonic Range Sensors: Advantages and Disadvantages

- Advantages
  - Reliable with good precision
  - Not as prone to outside interference
  - Good maximum range
  - Inexpensive

- Disadvantages
  - Sensitive to smoothness
  - Sensitive to angle to obstacles *(specular reflection)*
  - Poor resolution
  - Prone to self-interference from echoes
  - Cannot detect obstacles too close
  - Soft surfaces absorb sound energy
  - Bandwidth

Laser Range Finders

Laser Sensors

- Unlike sonar sensors, lasers are not very susceptible to specular reflection
- However, there are some trade-offs as well as a significant cost to using lasers
- Lasers emit highly amplified and coherent radiation at one or more frequencies
- It may or may not be in the visible spectrum
- Lasers also use the time of flight principle
- They are much faster than sonar because the speed of light is much faster than the speed of sound

Laser Range Finders

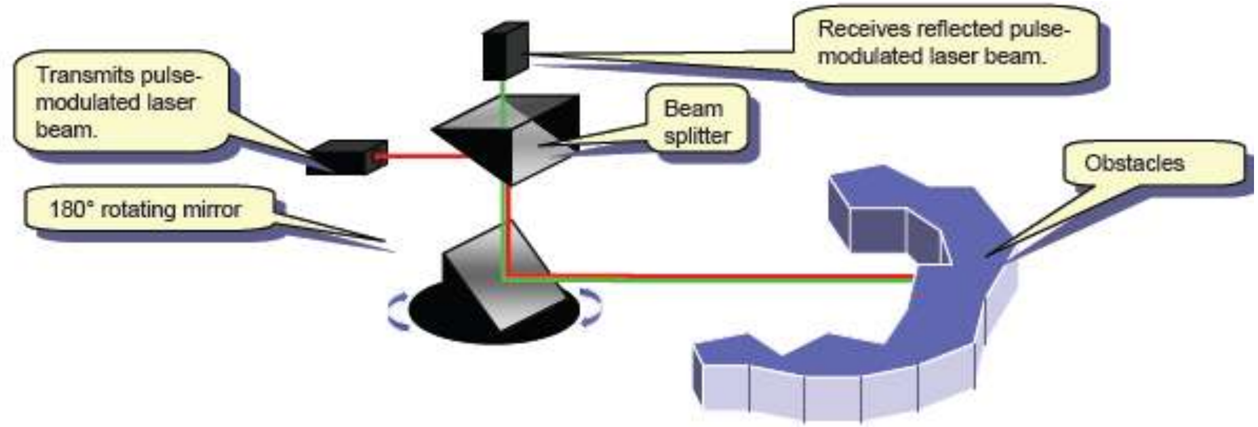
- Some laser use phase-shift rather than time of flight distance measurement
- Laser are the most accurate sensors for measuring distance
- Similar to IR, light is emitted and detected
- Unlike sonar, light is projected in a beam rather than a cone
- Sensors are LIDAR (Light Detection and Ranging) Systems
- LIDAR systems use one of 3 techniques
  - Pulsed modulation
  - Amplitude modulation continuous wave (AMCW)
  - Frequency modulation Continuous Wave (FMCW)

Laser Range Finders: Range Calculation

- Range calculated as $d = ct/2$, where
  - t = time taken for light to return
  - c = speed of light ≈ 3×10^8 m/s
- Must have fast processing because the return times are small
- Makes the sensor expensive *(≈$10k)*
- Tradeoff for the price is high resolution *(180° at 0.5° resolution)*

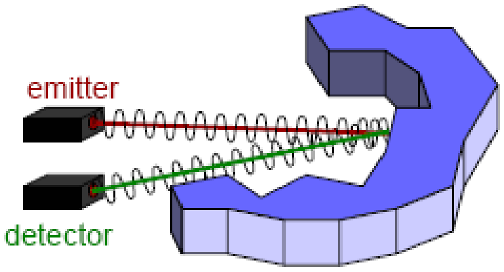
Laser Range Finders: Pulsed Modulation

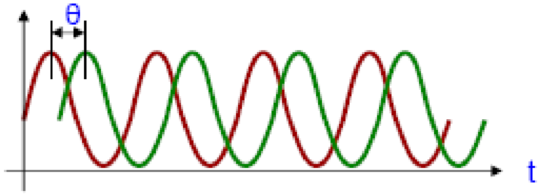
- A Pulsed Modulation LIDAR system (i.e. Sick sensor)
  - Emits a pulsed laser light beam
  - Reflected light returned to the detector
  - Rotating mirrors are used to direct
  - Outgoing and incoming light perform 180° scan



Laser Range Finders: Amplitude Modulation

- Emitter sends out a continuous modulated laser signal
  - Intensity of beam is modulated using a wave pattern (i.e. sinusoid)
  - Detected light has the same amplitude but is phase shifted
  - Difference in phase shift indicates the range
  - Range calculated is $r = \theta c/(4\pi f)$, where
    - f = frequency of the modulated signal
    - θ = phase shift

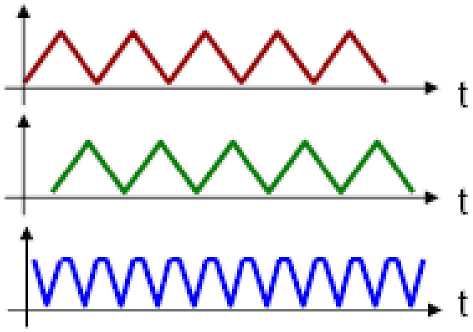


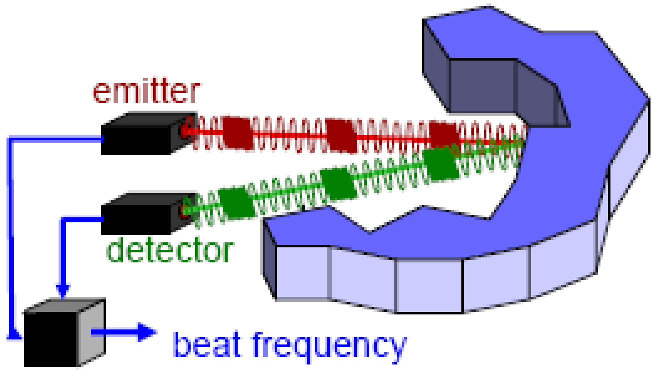


Range calculated as **$r = \theta c / 4\pi f$** where
θ = phase shift
f = frequency of modulated signal

Laser Range Finders: Frequency Modulation

- Amplitude modulation is simpler and hence lower cost laser
- Resolution is limited by modulating frequency
- Frequency modulation sensors emit a continuous laser beam, but is modulated by *frequency*
  - Emitted signal is mixed with the reflected signal
  - The result is a difference in frequency



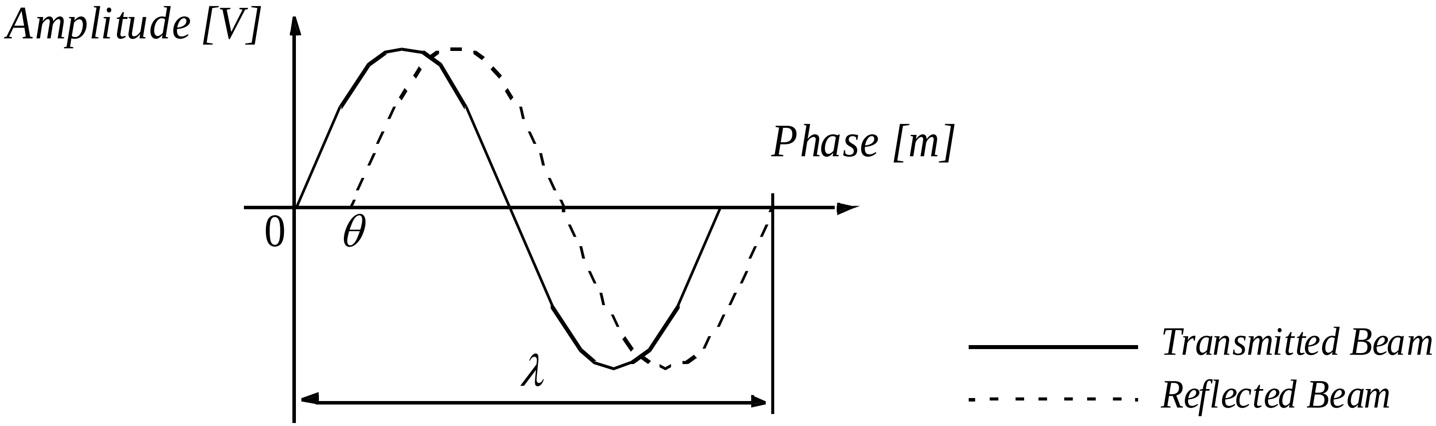


Laser Range Sensor

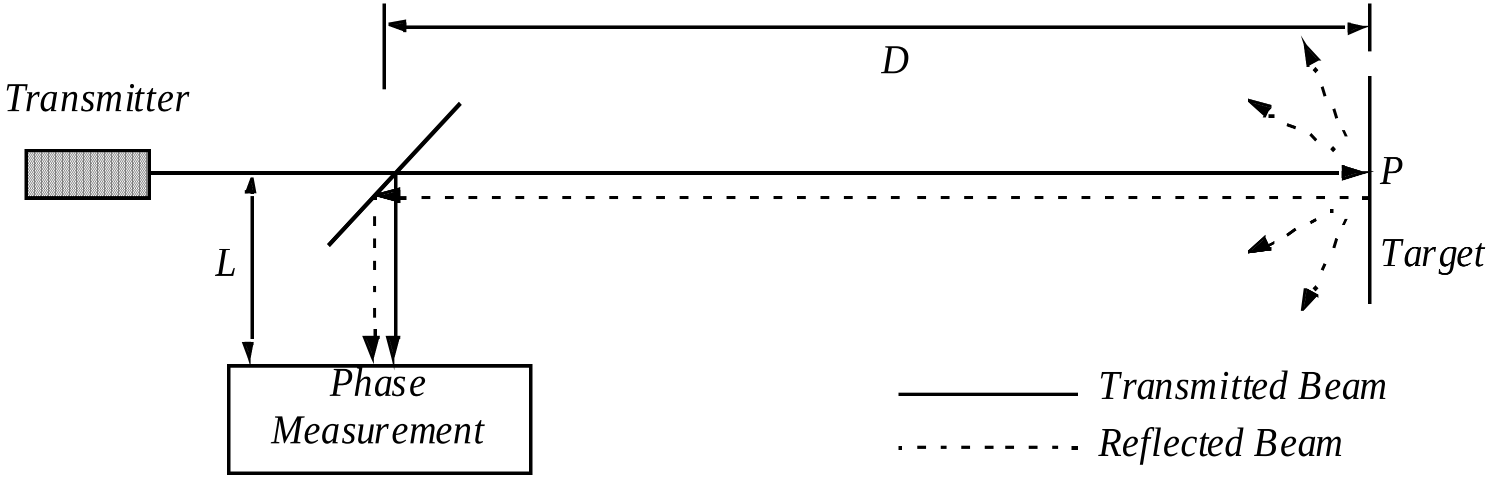
D is the distance between the beam splitter and the target

$$D = \lambda\theta/(4\pi)$$

where θ is the phase difference between the transmitted signal



Laser Range Sensor:
Phase-Shift Measurement



where $\lambda = c/f$, $D \ = L + 2D = L + \theta\pi/(2\pi)$

c = is the speed of light

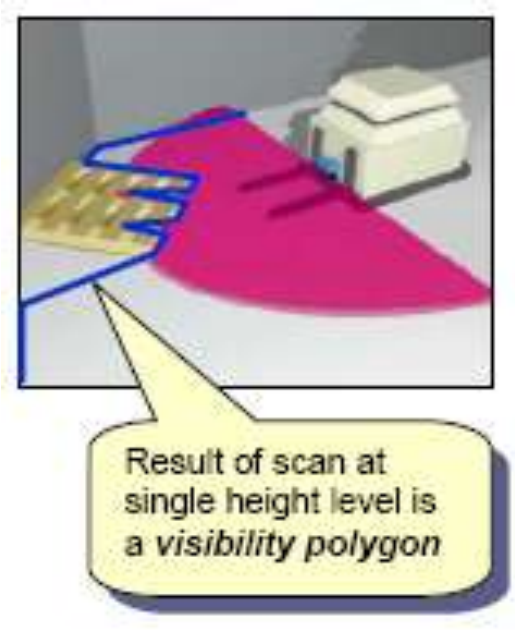
f = the modulating frequency

D' = covered by the emitted light is

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

Laser Range Finders: Accuracy

- Accuracy
  - ±1.5 cm in short range (1m – 8m)
  - ±4.0 cm in long range (8m – 20m)
- Typically measures ranges up to 50m
- Scanning at multiple heights, produces contour lines that can be stacked to form a model

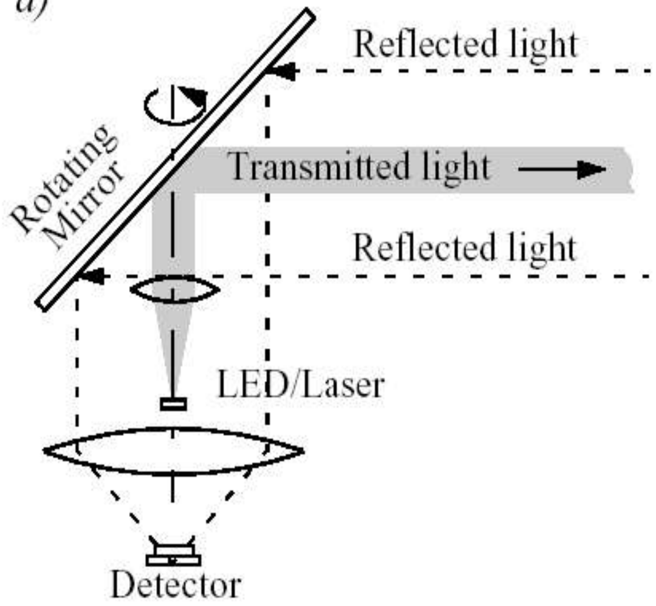


Result of scan at single height level is a *visibility polygon*

Laser Range Sensor: 3 types

Scanning range sensor

a)



Laser with rotating mirror

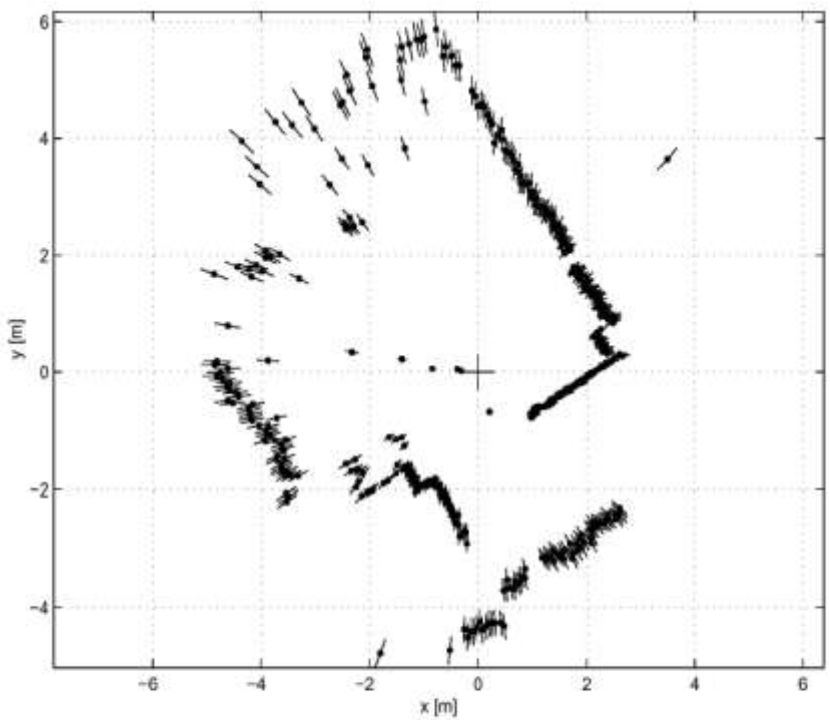
b)

c)

180° laser range sensor

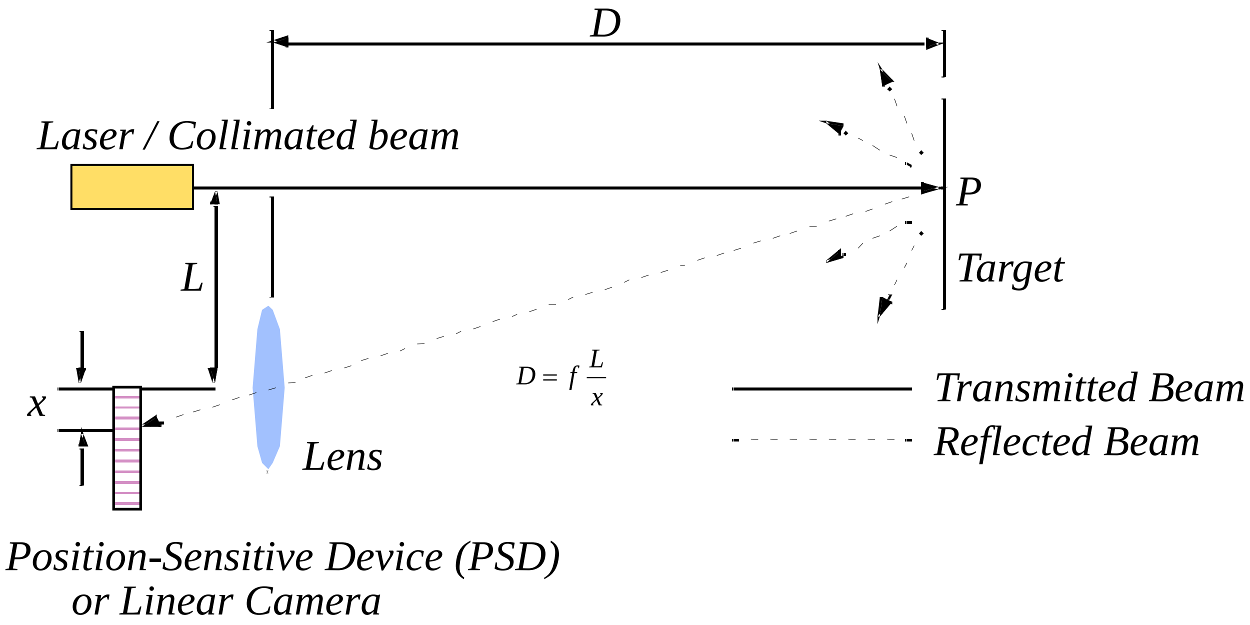
Laser Range Sensor

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.



Optical Triangulation (1D Sensor)

- *Triangulation-based* ranging sensors use geometric properties to measure the distance to objects
- $D = f \cdot L/x$
- Sensor resolution is best for close objects



Laser Range Finders: Advantages and Disadvantages

- Advantages
  - Better resolution than ultrasonic, infrared, and cameras
  - Very reliable
  - Not as sensitive to lighting conditions as cameras and infrared
  - For mapping, lasers are high quality 3D versions of IR sensors

- Disadvantages
  - Cannot identify mirrors and/or glass
  - More expensive than all other sensors
  - Larger and heavier than all other sensors