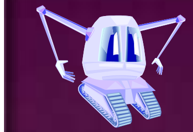
Lecture 4-1

Switch on the Light:
Simple Sensors

Sonars, Lasers, and Cameras:
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**
- 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

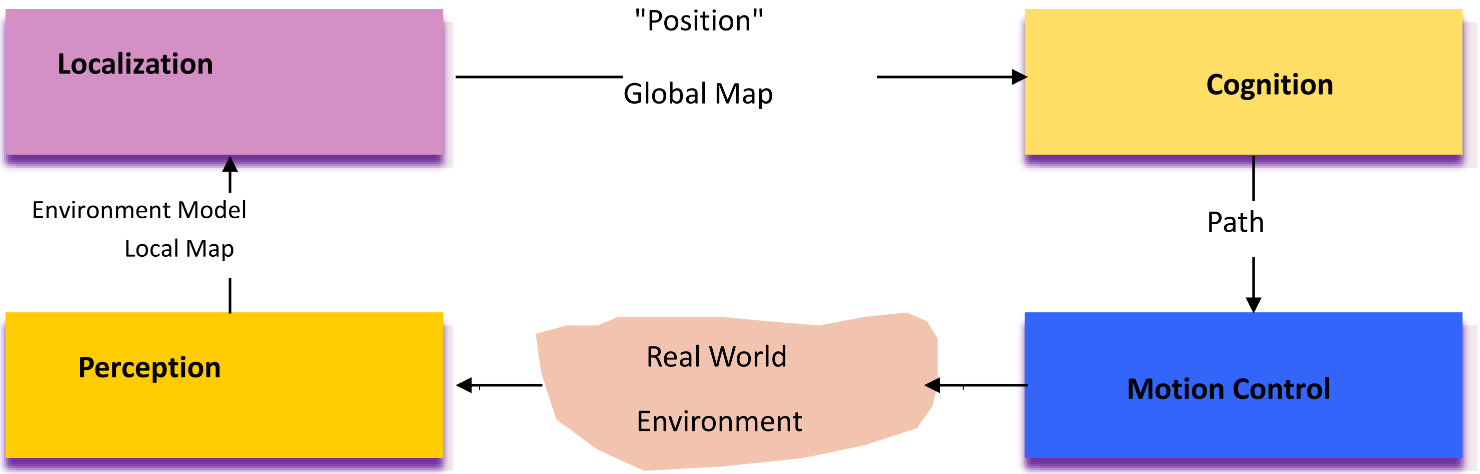
Quote of the Week

"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.



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 me 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

Resistive Position Sensors

- Just as some devices change resistance based upon incidence light, other devices have a change in resistance changes when they are bent
- Potentiometers (variable resistors) are used for manual tuning of analog devices. Turning a knob or a slider changes the resistance of the sensor.
- Useful for contact sensing and wall-tracking
- Electrically, the bend sensor is a

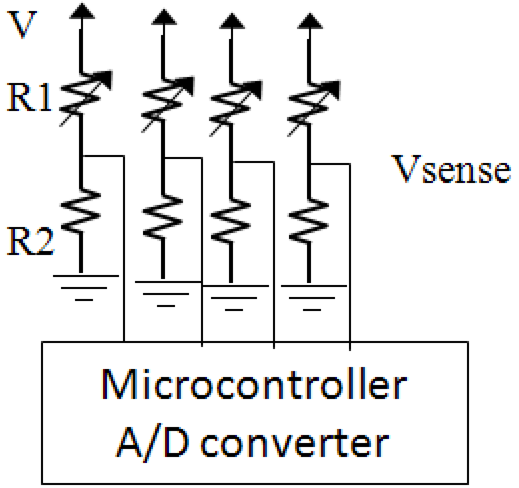
  simple resistance
- The **resistance** of a material increases as it is bent
- The bend sensor is less robust than a light sensor, and requires strong protection at its base, near the electrical contacts
- Unless the sensor is well-protected from direct forces, it will fail over time

Resistive Sensor Circuits

Voltage divider:

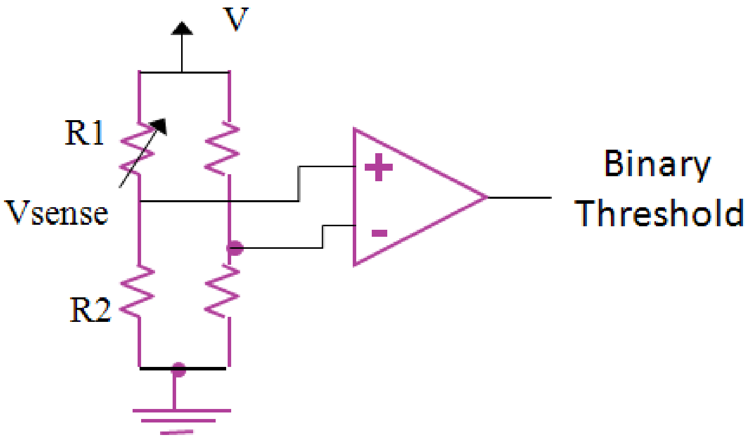
You have two resistors, one is fixed and the other varies, as well as a constant voltage

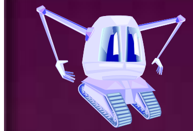
$$V_{sense} = \frac{R_2}{R_1 + R_2} V$$



A/D Converter:
Converts analog voltage from voltage divider circuit to a digital representation

Digital I/O
Comparator:
If Vsense is greater than V-, digital high out





Heading Sensors

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

Compass

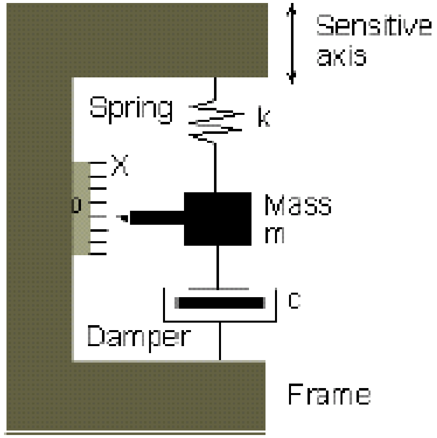
- A ***compass*** uses the earth's magnetic field to determine absolute measure for robot orientation.
- Large variety of solutions to measure the earth magnetic field
  - mechanical magnetic compass
  - direct measure of the magnetic field
- Major drawbacks:
  - weakness of the earth field
  - easily 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

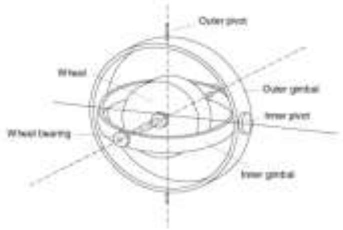
Accelerometers

- 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



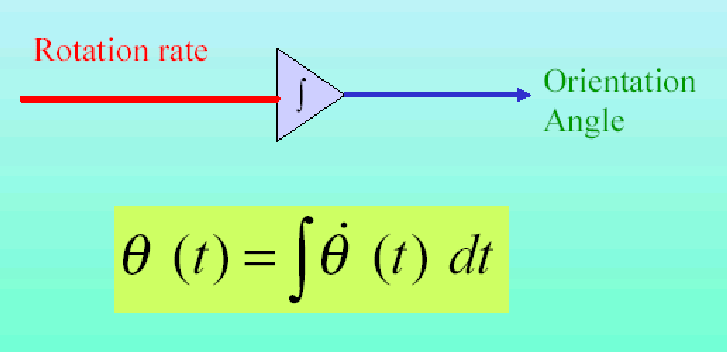
$$F = m\frac{d^2x}{d^2t} + c\frac{dx}{dt} + kx$$

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

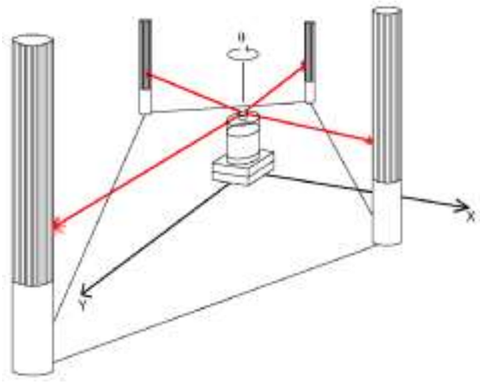


$$\theta(t) = \int \dot{\theta}(t)\, dt$$

- **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

Ground-Based Beacons

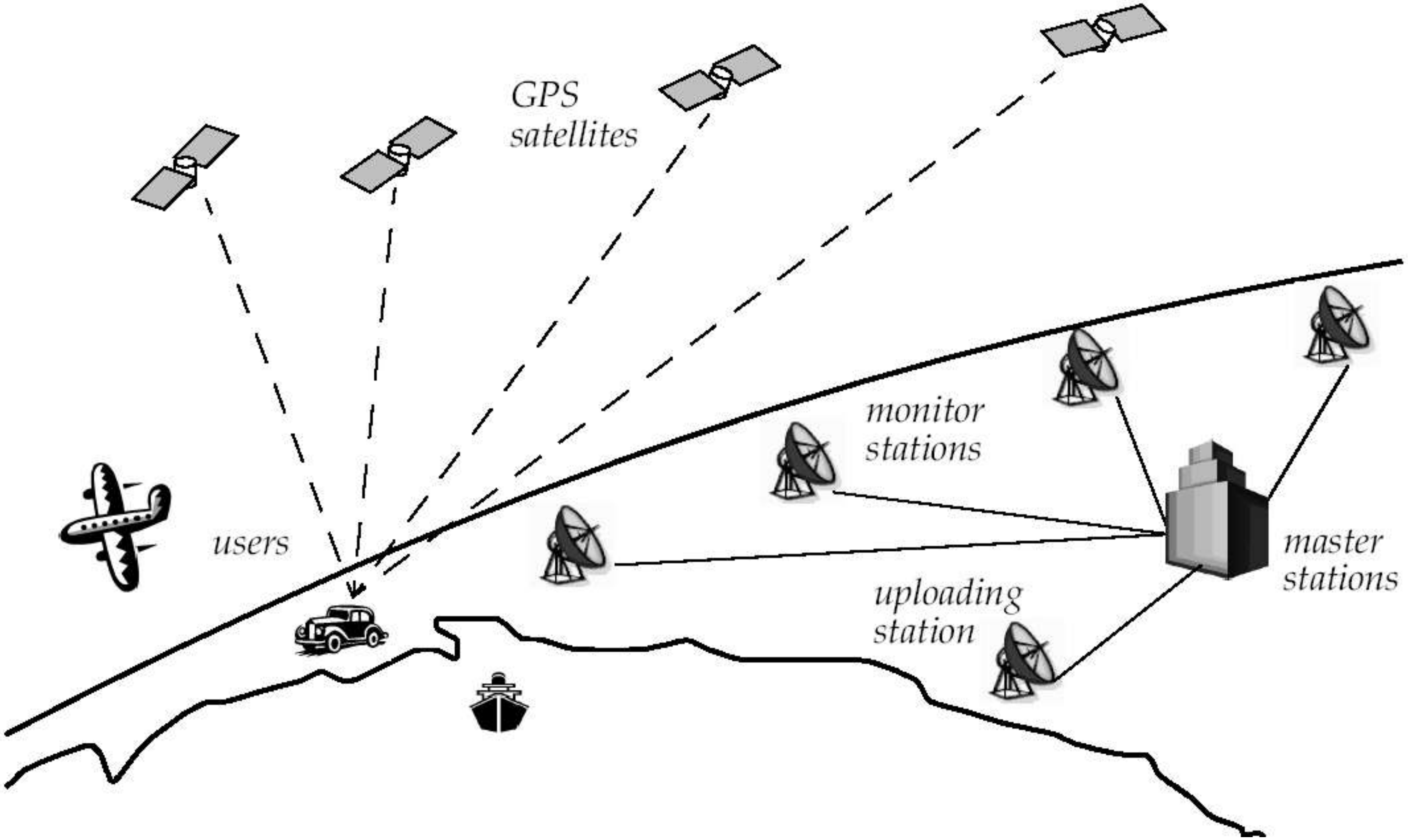
- An elegant way to solve the localization problem in mobile robotics is to use *active* or *passive* beacons
- ***Beacons*** are signaling guiding devices with a precisely known position
- The *Global Positioning System* (GPS) revolutionized modern navigation technology
    - Extremely effective and 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.



Global Positioning System

- Technical challenges:
  - Satellite transmissions are extremely low-power and successful reading requires a direct line-of-sight communication
  - 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)

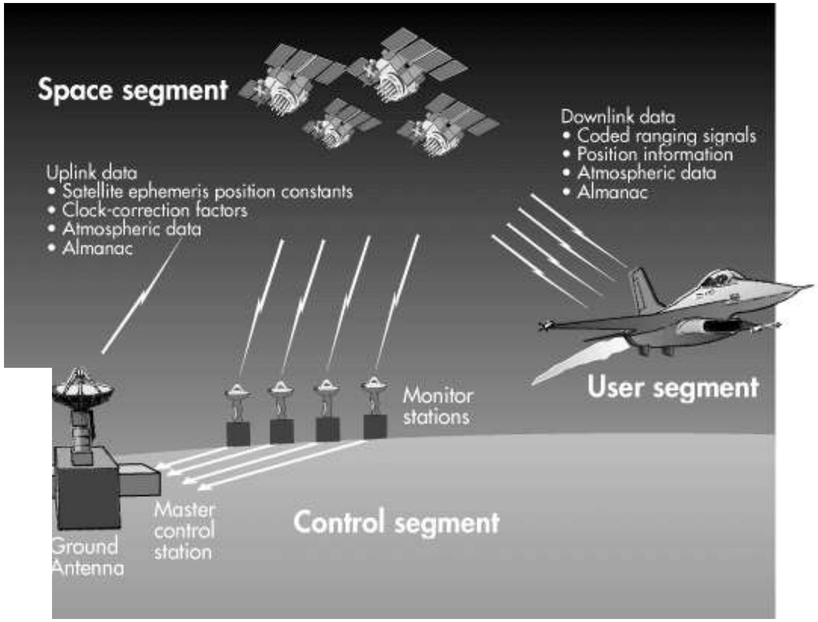
GPS Calculations



Global Positioning System (GPS)

24 satellites (+several spares)

broadcast time, identity, orbital parameters (latitude, longitude, altitude)



http://www.cnde.iastate.edu/staff/swormley/gps/gps.html

Space Segment

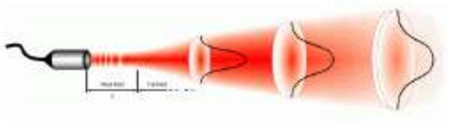
Noise Issues

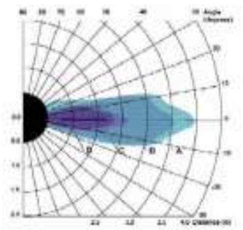
- Real sensors are noisy
- Origins: natural phenomena + less-than-ideal engineering
- Consequences: limited accuracy and precision of measurements
- Filtering:
  - software: averaging, signal processing algorithm
  - hardware tricky: capacitor

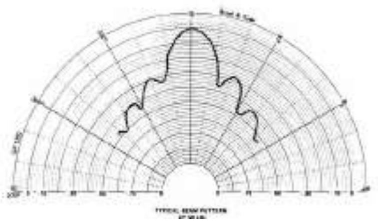
The Robotics Primer, Matarić, Chapter 9

Complex Sensors

SONAR



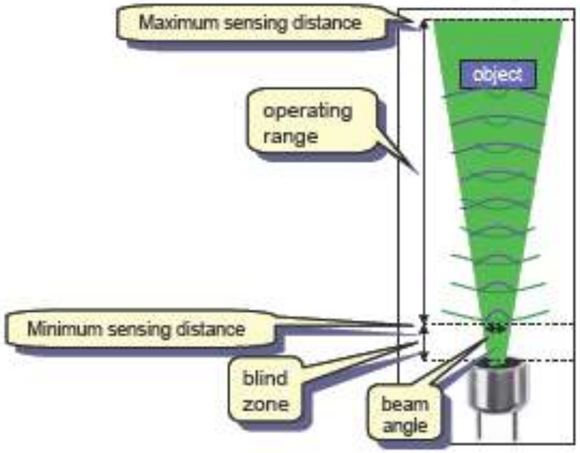




- *Sound Navigation and Ranging (SONAR)*
  - bounce sound off of objects
  - measure time for reflection to be heard - gives a range measurement
  - It measures change in frequency and gives the relative speed of the object (Doppler effect)
  - bats and dolphins use it with amazing results
  - robots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

Ultrasonic Range Sensors time of flight (sound)

- *Ultrasonic Sensors* emit a sound wave signal and measure the time it takes for that signal to be returned
- *Transducer* emits and receives the sound signal
- Time taken for the sound to travel the distance is determined
- *Blind zone* is when an echo arrives before the transducer is ready to receive and objects are not detected reliably
- *Detection Distance is 1" – 10' for the Parallax Sonar on the Traxster*



Ultrasonic Range Sensors

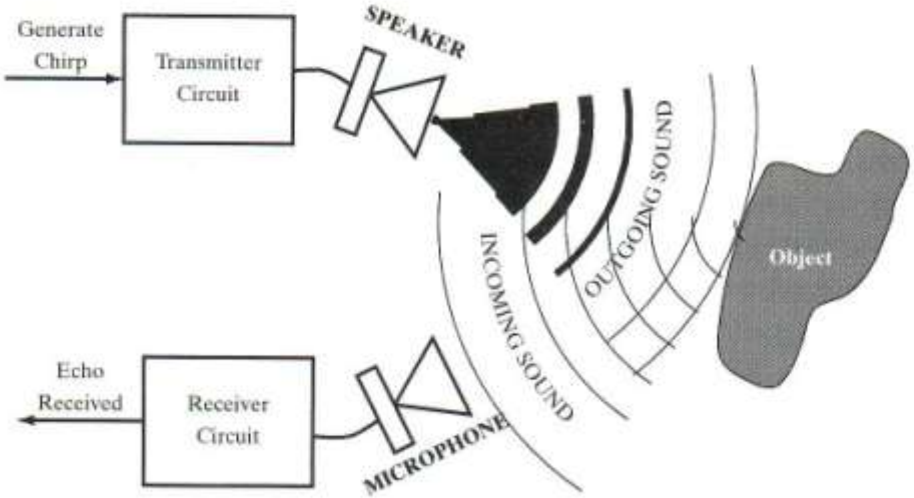
- Basic principle of operation:
  - Emit a quick burst of ultrasound
  - Measure the elapsed time until the receiver indicates that an echo is detected.
  - Determine how far away the nearest object is from the sensor

d = ct

d = round trip distance

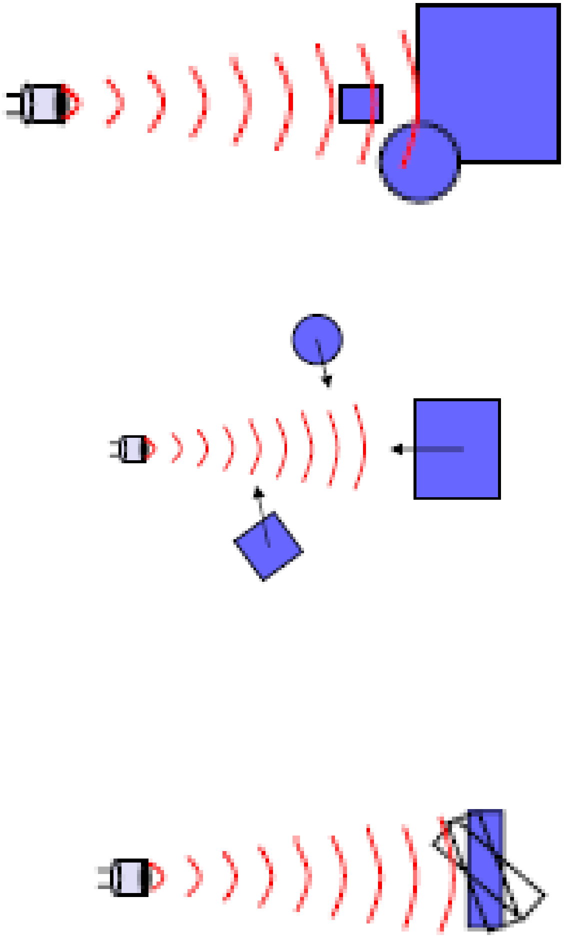
c = speed of sound (340 ms)

T = time of flight

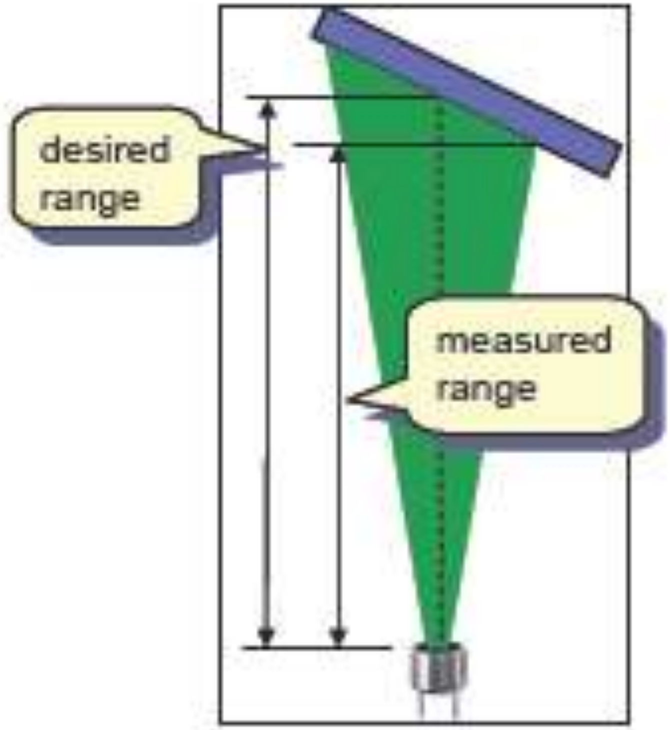


Ultrasonic Range Sensors

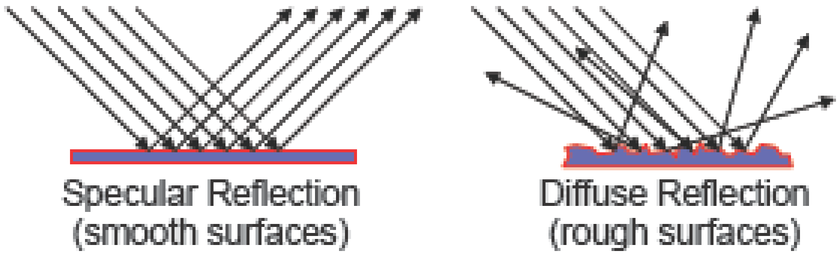
- **Sensor readings vary based upon:**
  - Distance to object(s)
  - Angle that object makes with respect to sensor axis
  - Direction that objects enter sensing range



Ultrasonic Range Sensors: Sensitivity

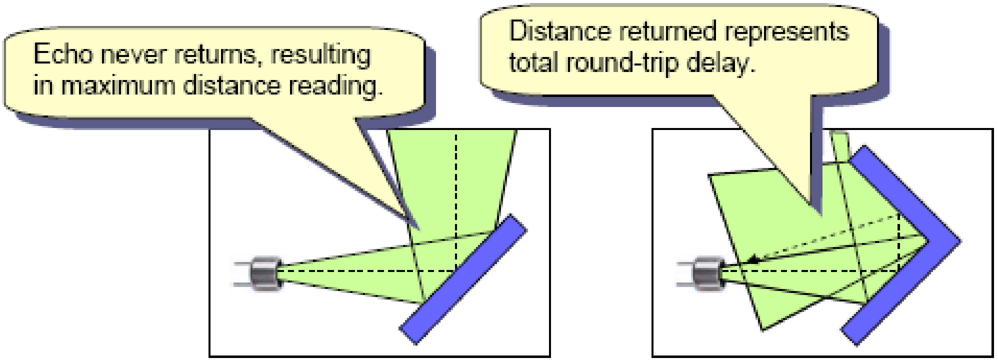


- *Sensitivity* to obstacle angle can result in improper range readings
- When the beam angle of incidence falls below a certain critical angle *specular reflection* errors occur



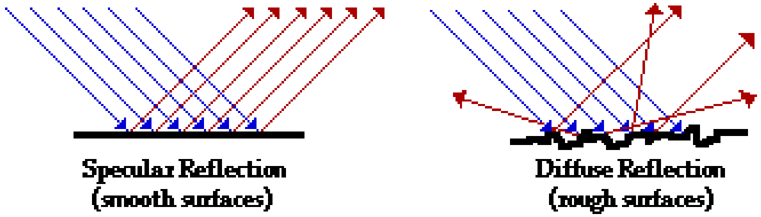
Ultrasonic Range Sensors: Specular Reflection

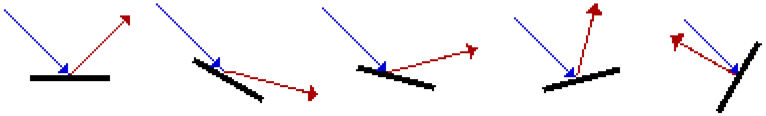
- Specular reflection can cause reflected sound to
  - Never return to the transducer
  - Return to the transducer too late
- The results is that the distance measurement is too large and inaccurate

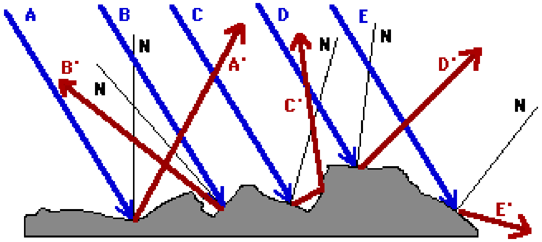


Reflectance

- 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

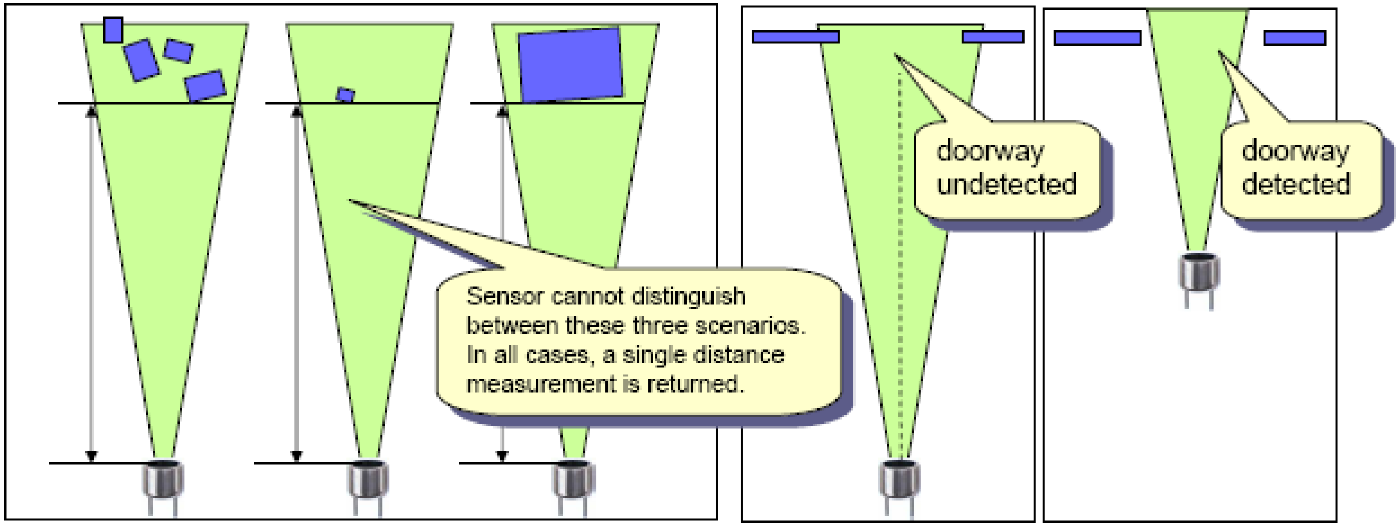




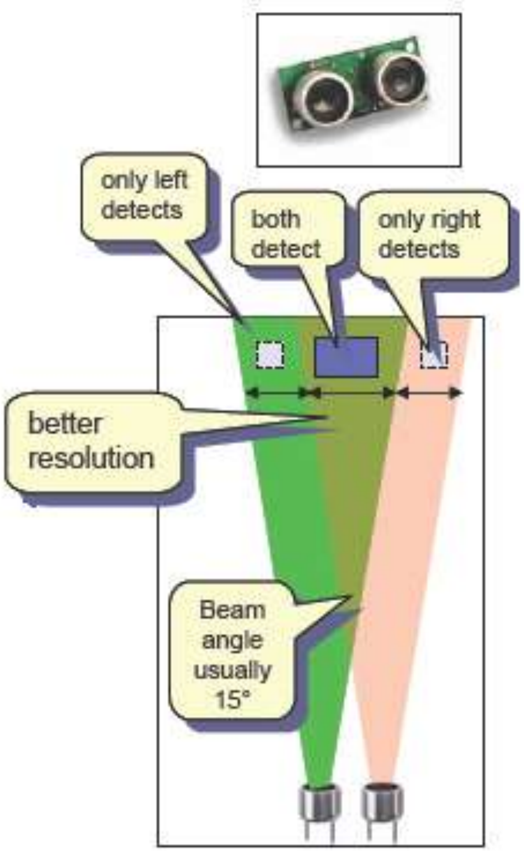


Ultrasonic range sensors: Resolution

- 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



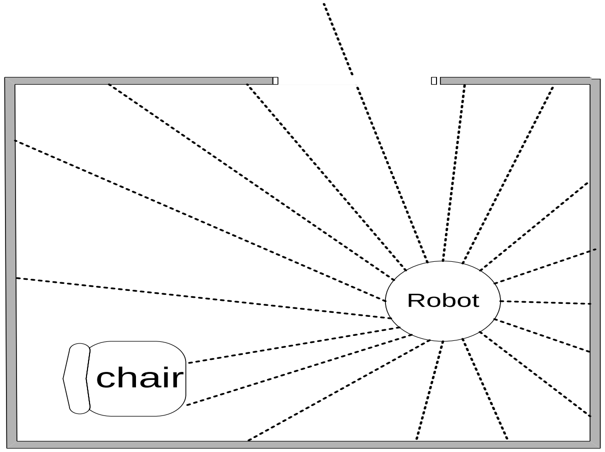
Ultrasonic Range Sensors: Redundancy

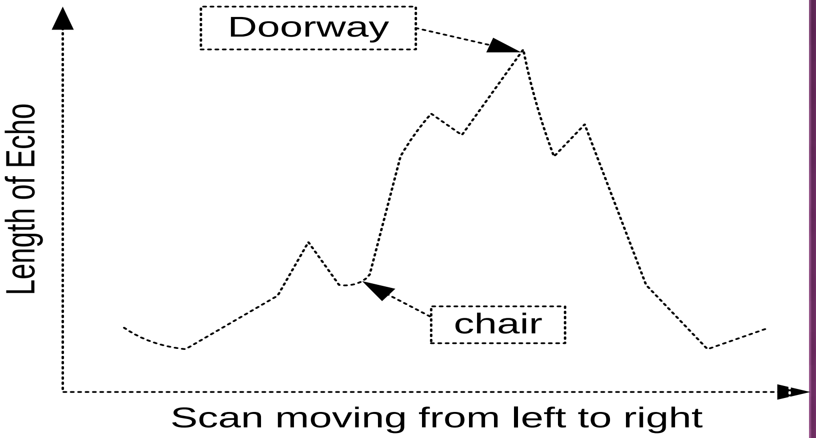


- To increase beam width (*resolution*), two sensors are used together
- Detection in either or both sensors allows for increased resolution

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



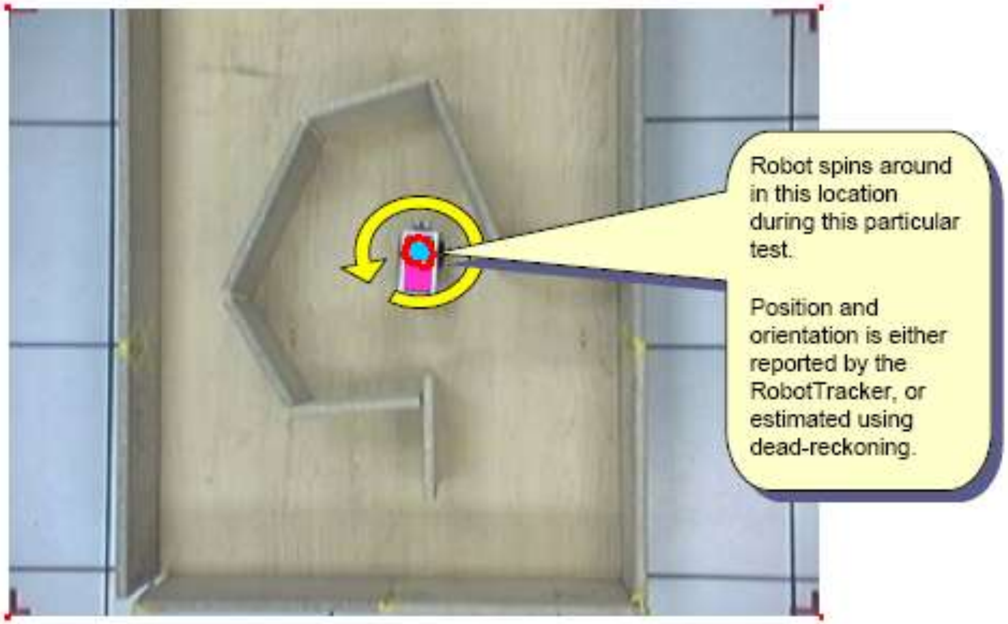


Ultrasonic Range Sensors: Mapping

- 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

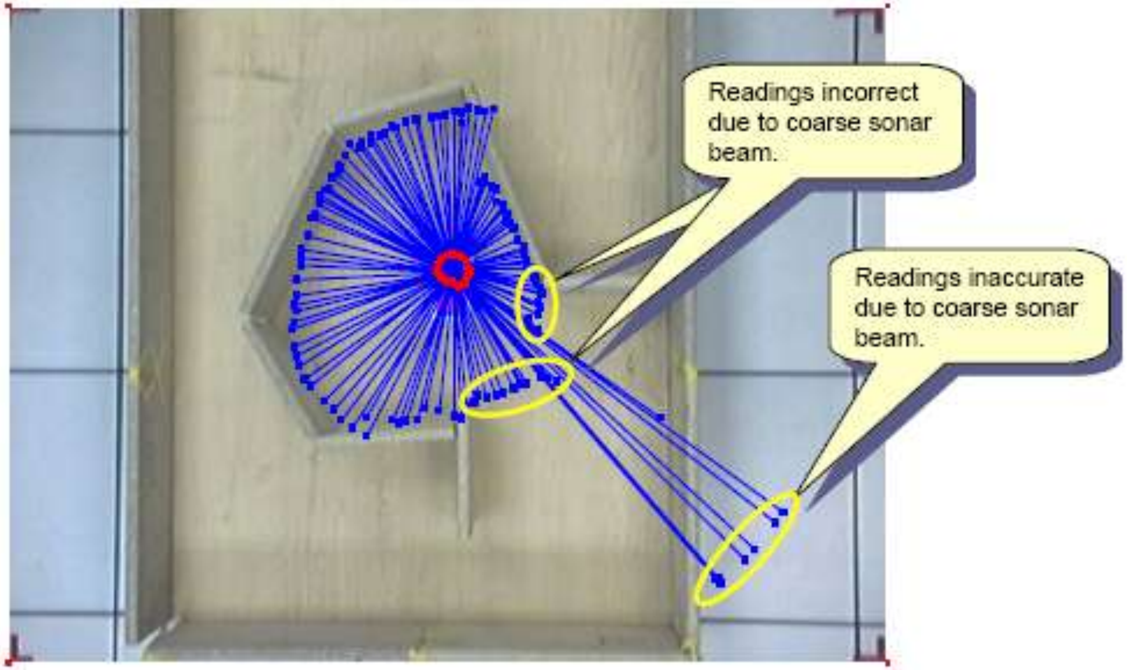


Robot spins around in this location during this particular test.

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

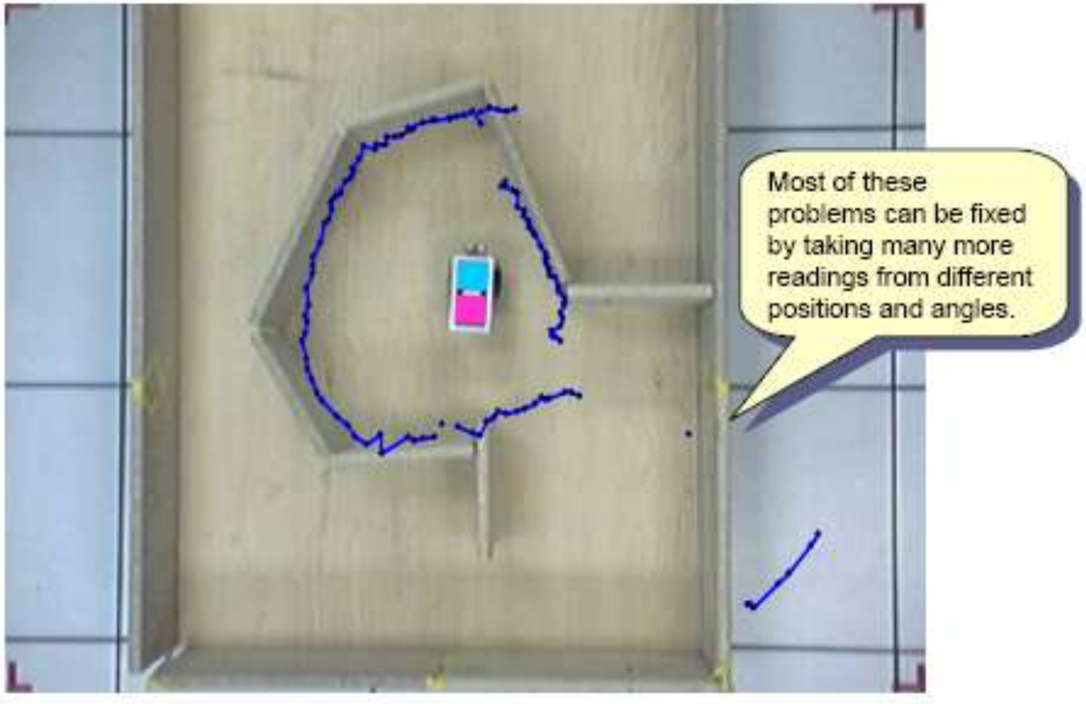
Ultrasonic Range Sensors: Mapping Example

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



Ultrasonic Range Sensors: Mapping Example

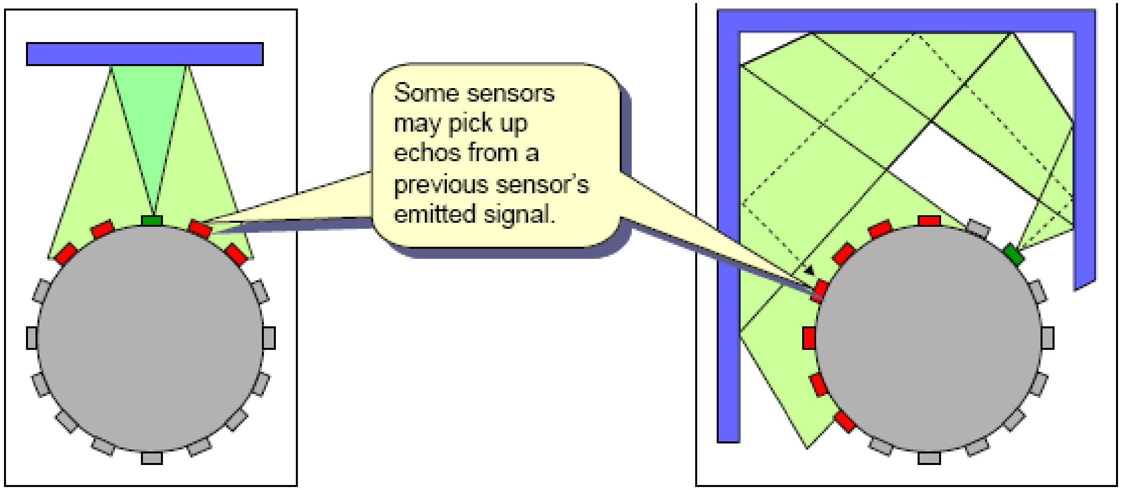
The sonar data produces a ‘rough’ outline of the environment with some inaccurate readings



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

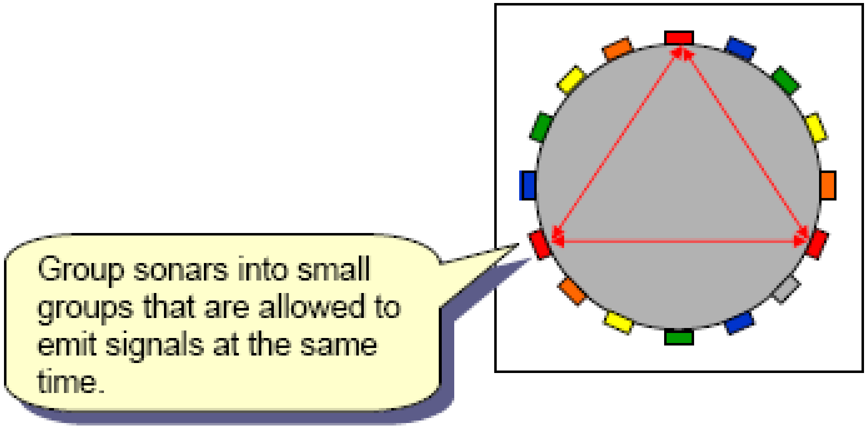


Some sensors may pick up echos from a previous sensor's emitted signal.

Ultrasonic Range Sensors: Crosstalk

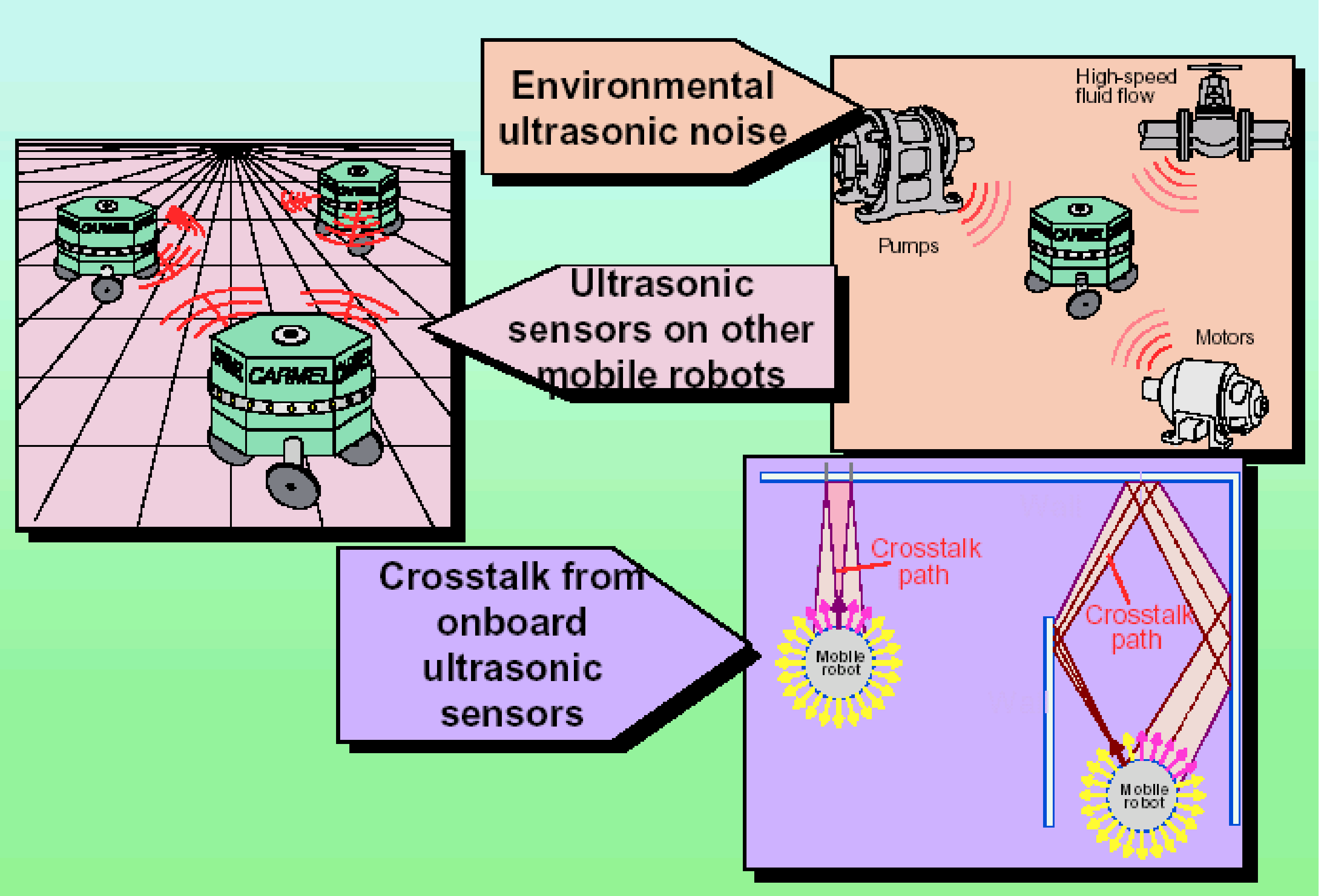
- Crosstalk signals are impossible to detect unless signals are unique (coded)
- Crosstalk can be reduced by carefully timing the emitting of signals

- Emit from one and wait for a time interval
- Emit from a selected few that may not have interference



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

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

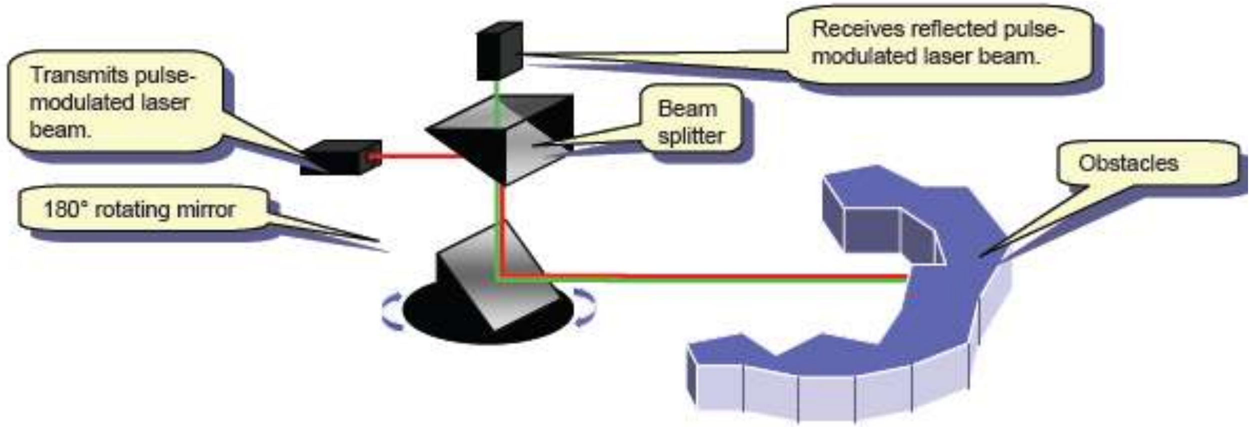
Laser Range Finders

Laser Range Finders

- Laser are the most accurate sensors for measuring distance
- Similar to IR, light is emitted and detected
- 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: Pulsed Modulation

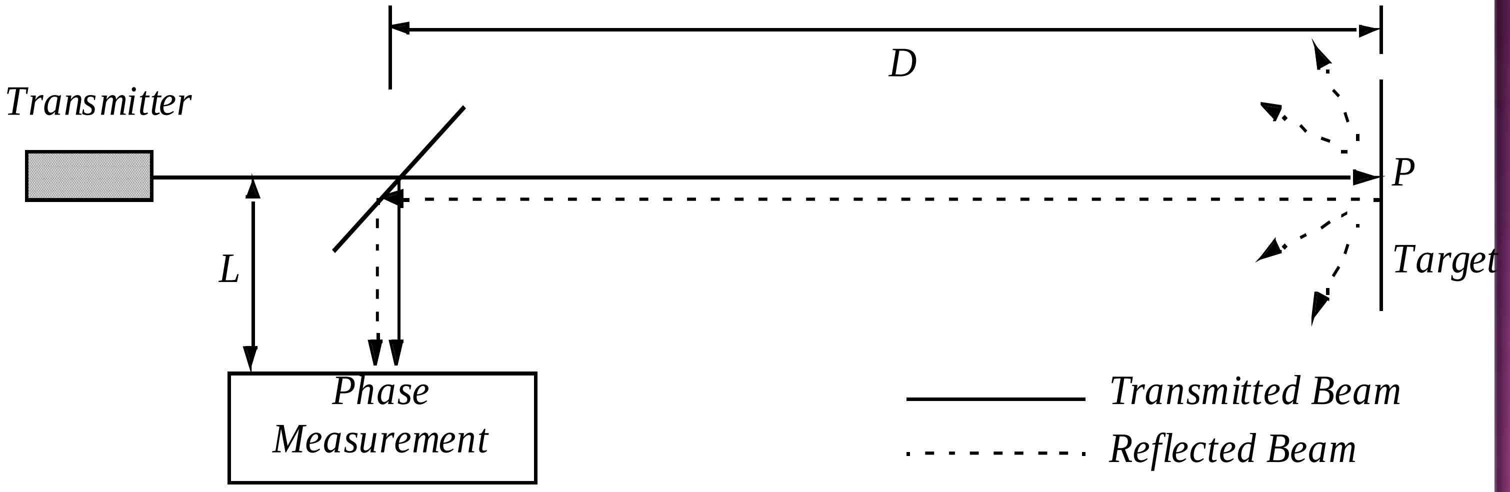
- A Pulsed Modulation LIDAR system (i.e. Sick sensor)
  - Emits a pulsed laser light beam
  - Reflected light returned to the detector
  - Rotating mirrors are used to direct
  - Outgoing and incoming light perform 180° scan



Laser Range Finders:
Range Calculation

- Range calculated as d = ct/2, where
  - t = time taken for light to return
  - c = speed of light ≈ $3x10^8$ 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)*

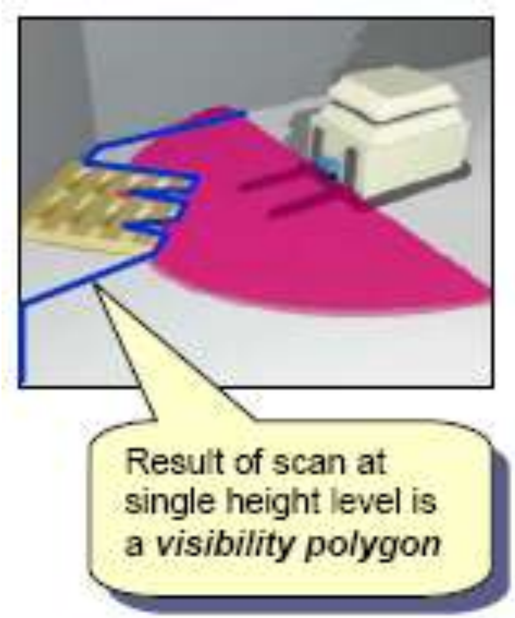
Laser Range Sensor



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

Laser Range Finders: Accuracy

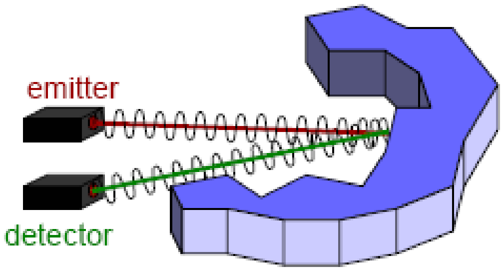
- Accuracy
  - ±1.5 cm in short range (1m – 8m)
  - ±4.0 cm in long range (8m – 20m)
- Typically measures ranges up to 50m
- Scanning at multiple heights, produces contour lines that can be stacked to form a model

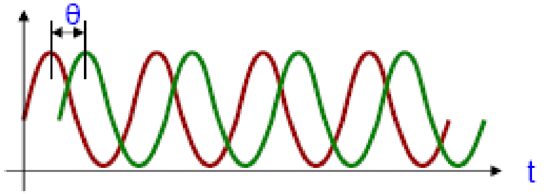


Result of scan at single height level is a *visibility polygon*

Laser Range Finders:
AMCW sensors

- 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



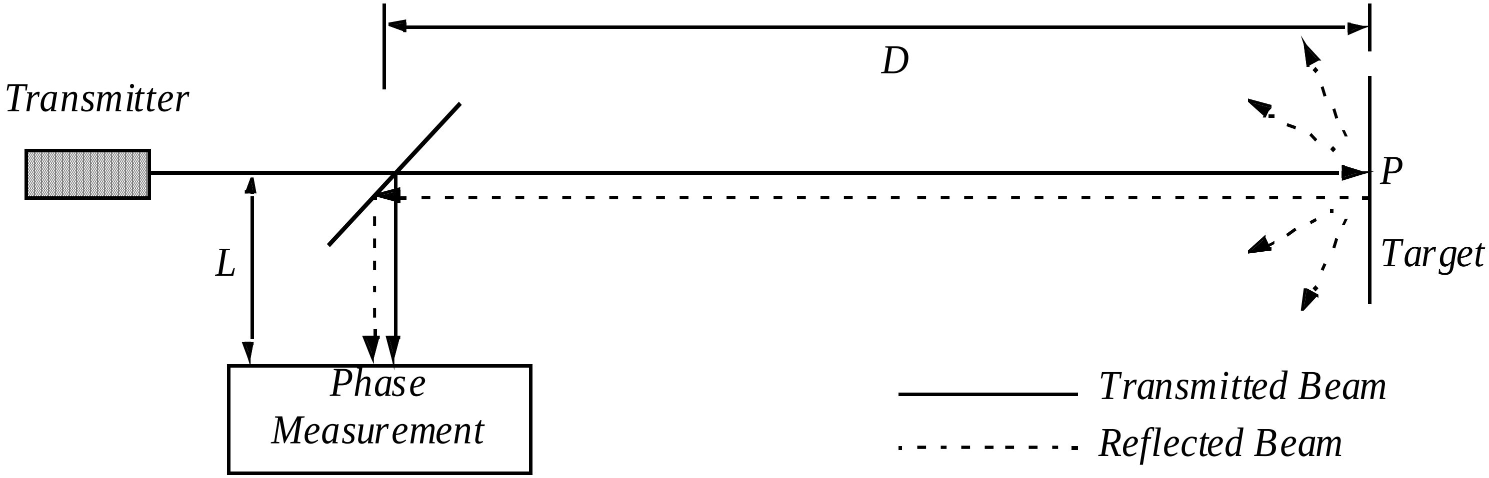


Range calculated as $r = \theta c / 4\pi f$ where

θ = phase shift

f = frequency of modulated signal

Laser Range 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

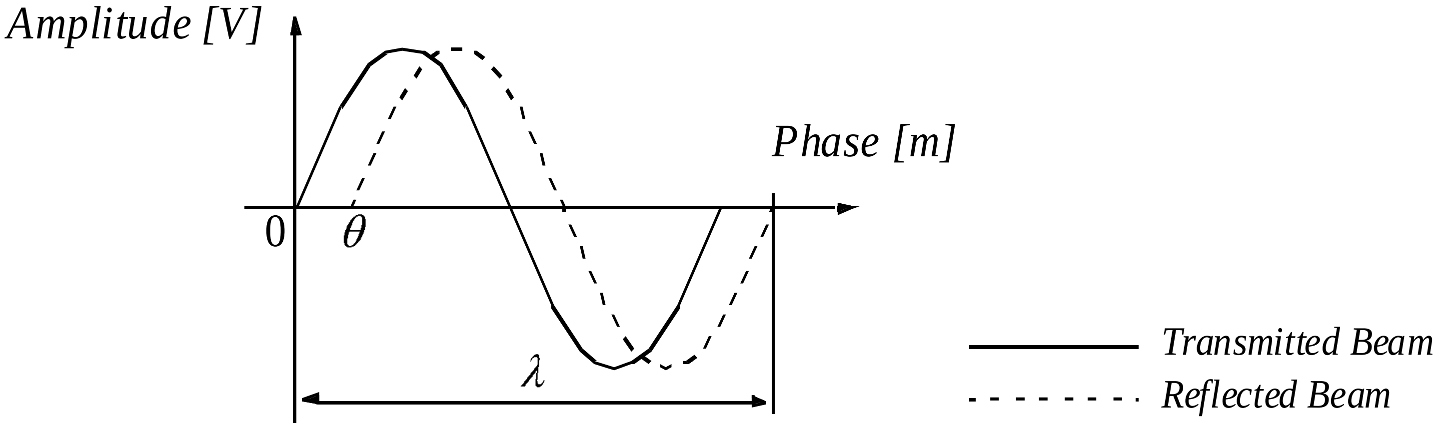
for f = 5 Mhz (as in the A.T&T. sensor), $\lambda = 60$ meters

Laser Range Sensor

D is the distance between the beam splitter and the target

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

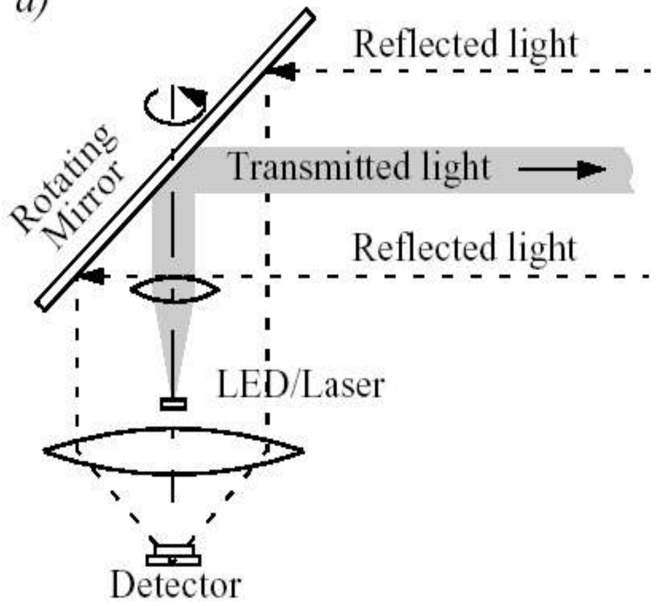
where θ is the phase difference between the transmitted signal



Laser Range Sensor:
3 types

Scanning range sensor

a)



Laser with rotating mirror

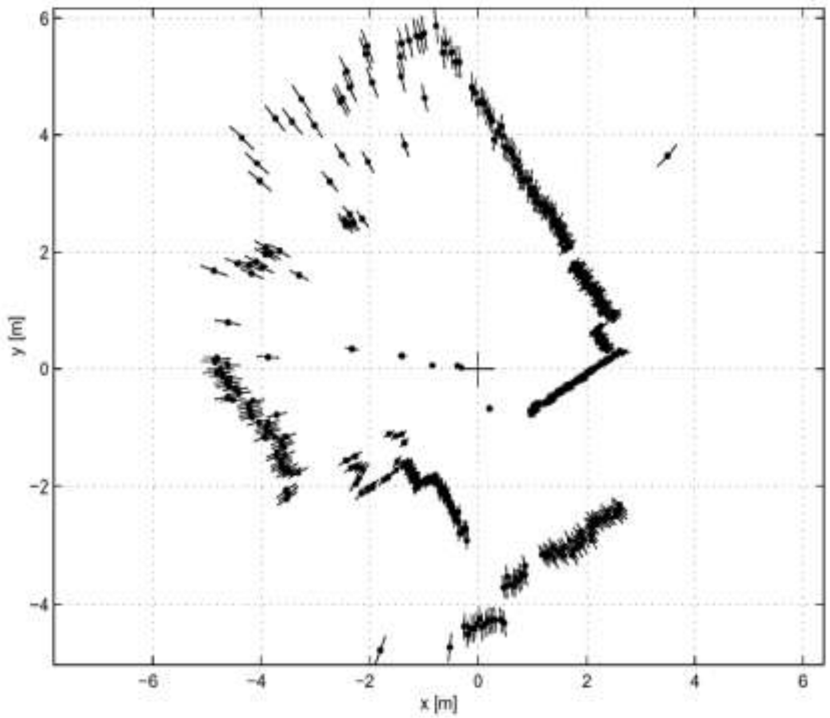
b)

c)

180° laser range sensor

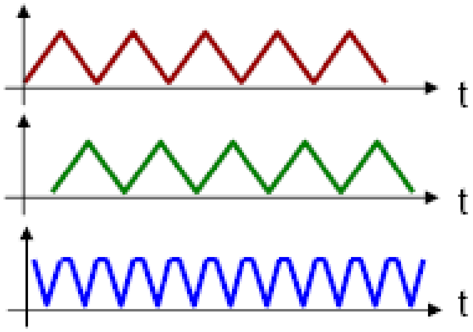
Laser Range Sensor

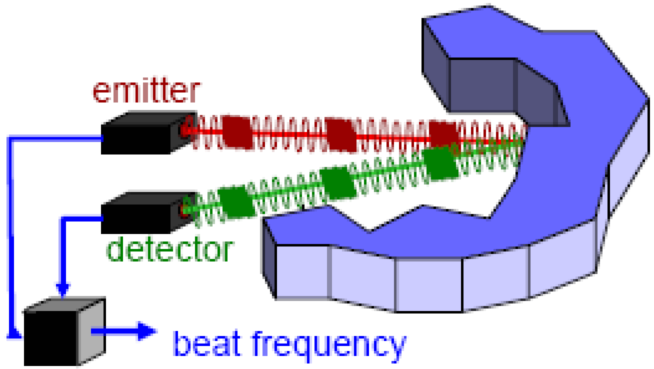
Typical range image of a 2D laser range sensor with a rotating mirror. The length of the lines through the measurement points indicate the uncertainties.



Laser Range Finders:
FMCW sensors

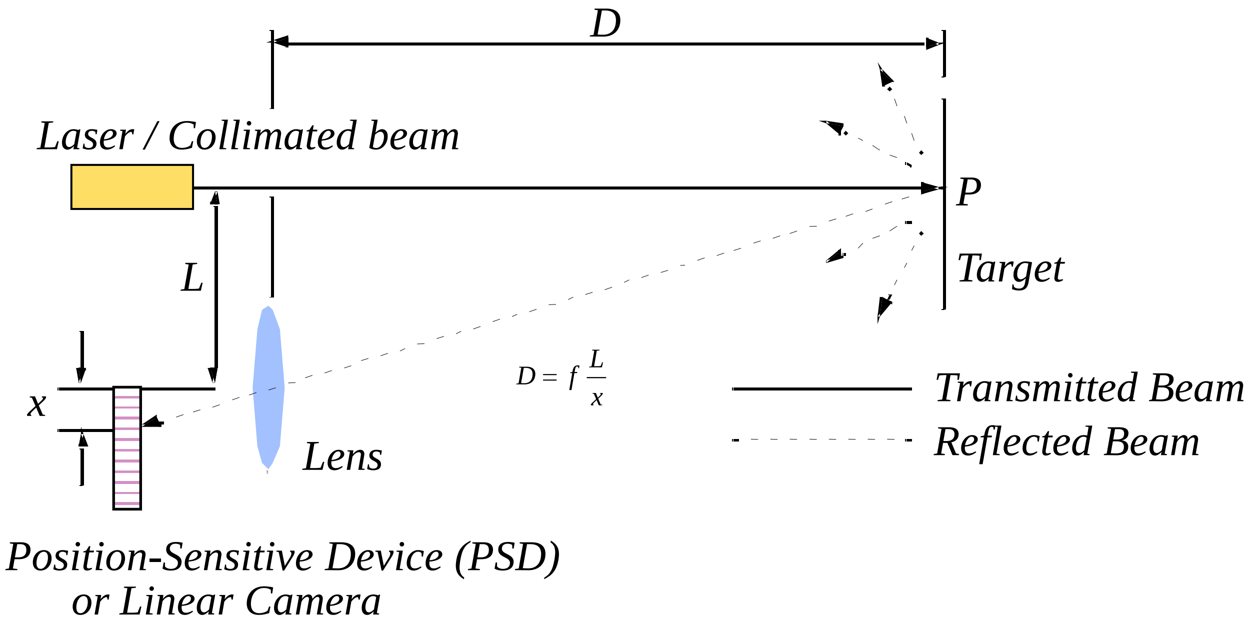
- AMCW is simpler and hence lower cost laser
- Resolution is limited by modulating frequency
- FMCW sensors emit a continuous laser beam, but is modulated by *frequency*
  - Emitted signal is mixed with the reflected signal
  - The result is a difference in frequency





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

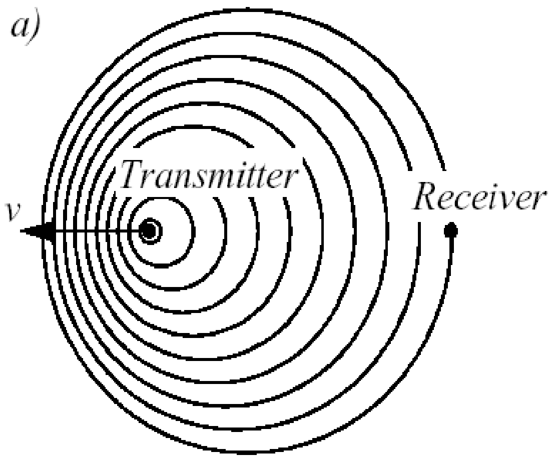
Motion/Speed Sensors

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 detects are the obstacle detection sensor of choice

Motion Sensor: Doppler Effect Based (Radar or Sound)

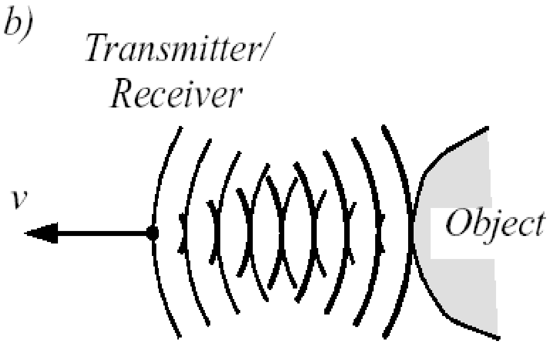
- A transmitter emits and electromagnetic or sound wave with a frequency f_t
- It is either received by a receiver or reflected from an object
- The measured frequency f_r at the receiver is a function of the relative speed v between the transmitter and receiver *(Doppler frequency)*



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

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



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

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

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

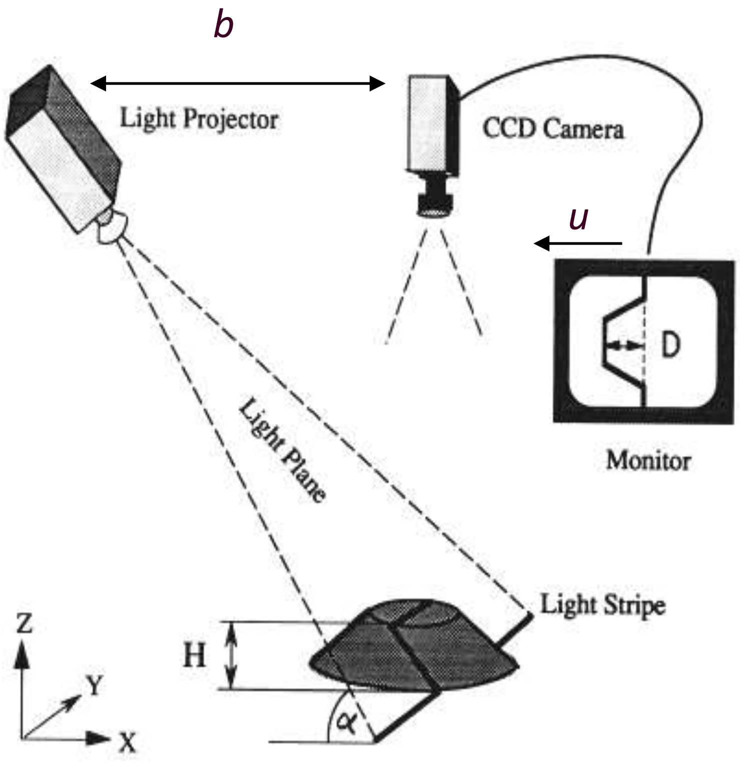
Stereo Camera Ranging System

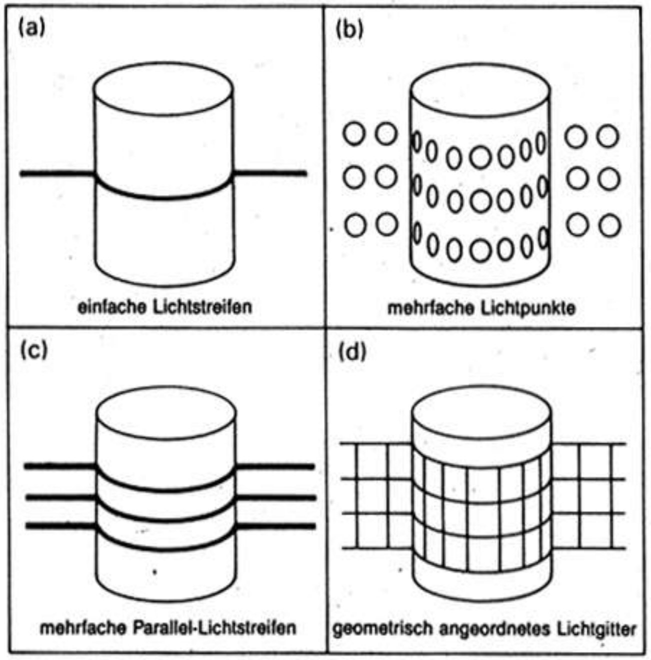
Structured Light (vision, 2 or 3D)

- *Triangulation* can be used to find the distance to a large set of points by replacing a 2D receiver by a CCD or CMOS camera

- The emitter must project a known patter, or *structured light*, onto the environment
  - Light textures
  - Collimated light with a rotating mirror
  - Laser stripe using a prism

Structured Light (vision, 2 or 3D)

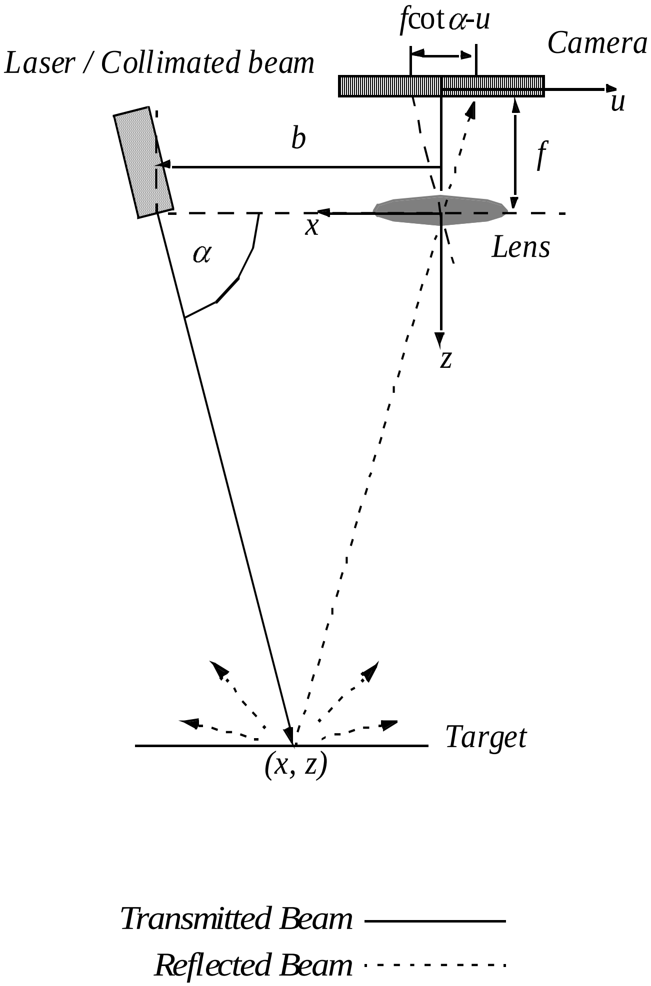




$$H = D \cdot \tan\alpha$$

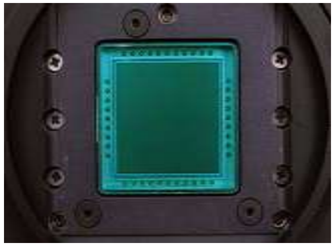
Structured Light (vision, 2 or 3D)

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



Vision-based Sensors: Hardware

- CCD (*light-sensitive, discharging capacitors of 5 to 25 micron*)


2048 x 2048 CCD array


Orangemicro iBOT Firewire


Sony DFW-X700


Cannon IXUS 300

- CMOS (*Complementary Metal Oxide Semiconductor technology*)

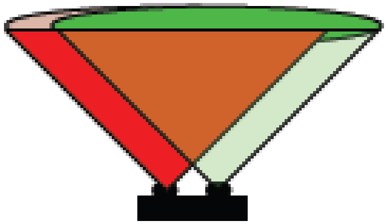
Vision ranging sensors

- In mobile robotics, it is natural to attempt to implement ranging using vision
- Vision collapses the 3D world into a 2D image
- To recover depth information look at several images of a scene
  - The images must be different
  - They should provide differ viewpoints yielding *stereo or motion algorithms*
  - Alternately, do not change the viewpoint but change the camera geometry (i.e. focus or lens iris) yielding *depth from focus algorithms*

Stereo Ranging Systems

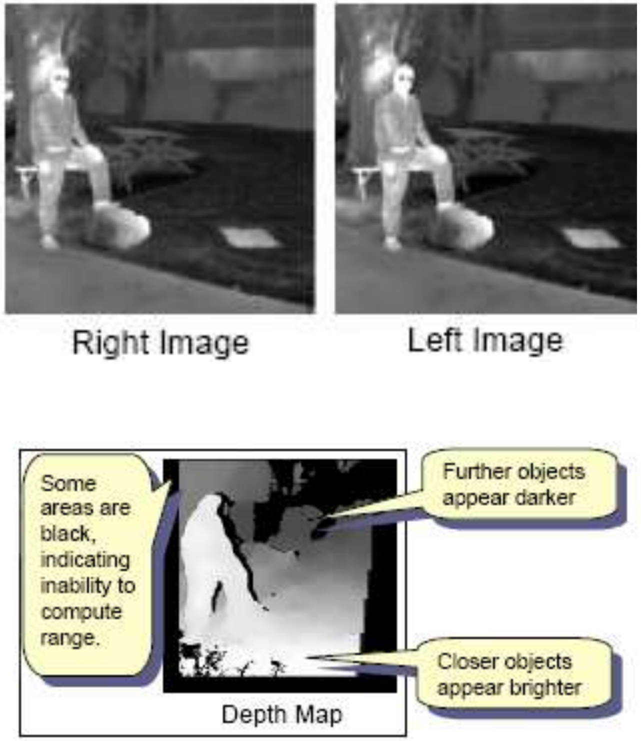
- Similar to laser, robots with stereo cameras can obtain 3D range maps of the environment
- Usually implemented with 2 cameras or one used from multiple locations
- Resolution
  - 640 x 480 frames/s
  - 1024x768 frames/s
- Camera covers roughly a 45° cone

A ~$2k stereo camera from ptgrey.com



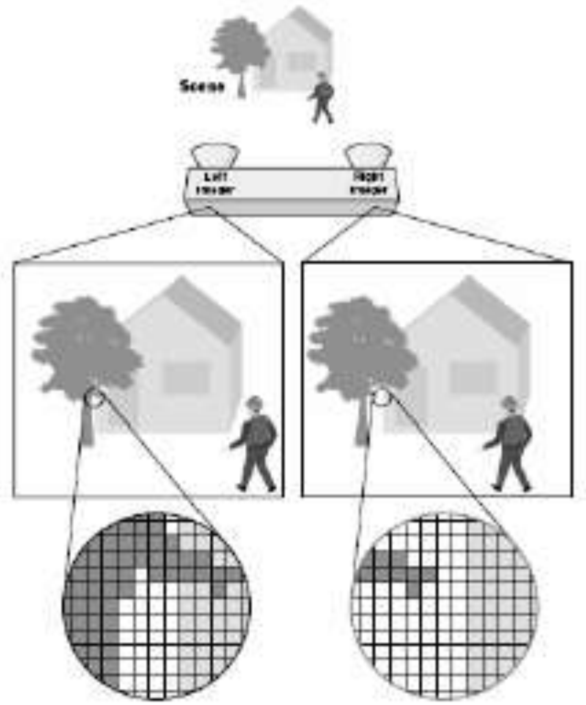
Stereo Ranging Systems: Goal

- Calculate the depth or distance of features in an image relative to the sensors (construct a *depth map*)
  - Use images from dual cameras aimed at the same object
  - Locate the same 'feature' in both images
  - Use geometric relationships between the 2 cameras and the location of the feature in each image
  - The depth of each feature can be triangulated and a depth map constructed



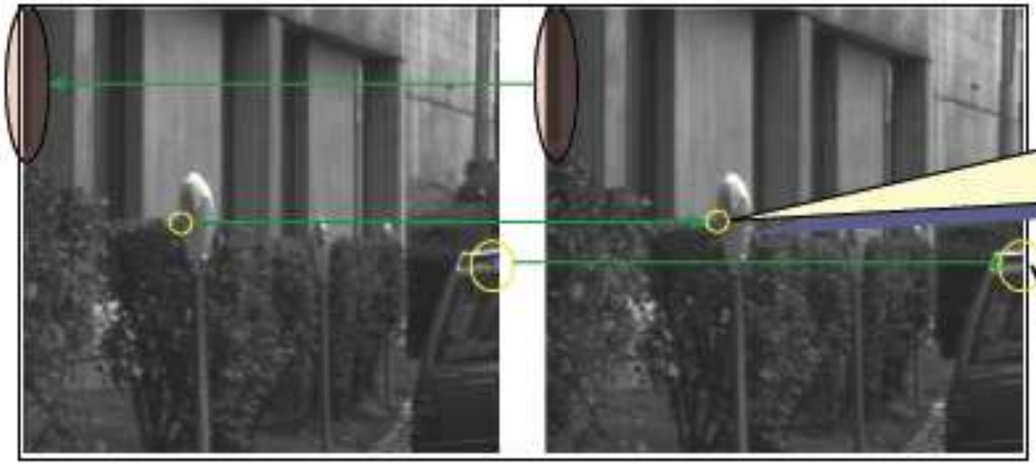
Stereo Ranging Systems:
Stereo Vision

- Objects in left camera appear horizontally shifted from objects seen in right camera
- The size of the shift is the *disparity*
- The ideas is to find a *correspondence* (or match) between points in one image with points in other image



Stereo Ranging Systems:
Stereo Vision

- It is difficult to find corresponding pixels in 2 images
- It is better to find the most likely match
- In some cases, the pixel in one image may not be visible in the other (*occlusion*)



Can be due to closer obstacles hiding objects behind them at certain angles.

Can be due to unavailable data due to viewing region.

Stereo Ranging Systems: Stereo Vision

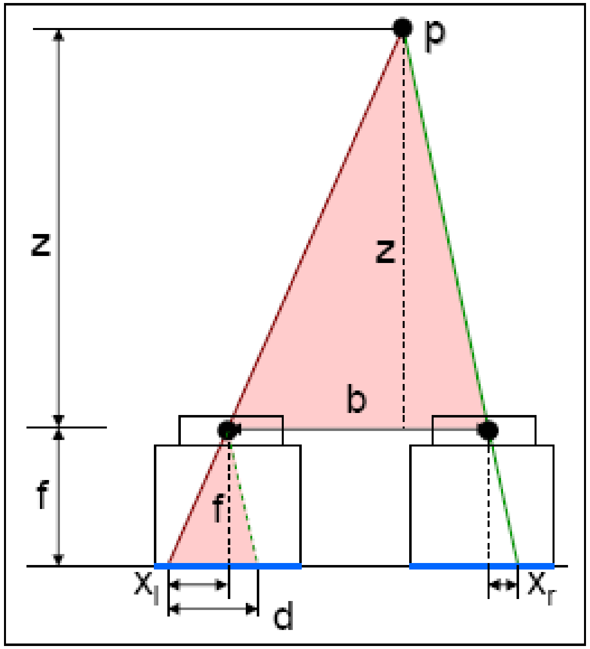
- If cameras are point in the same direction and are aligned use geometry
  - b = baseline of camera
  - z = depth of point p
  - d = disparity = $x_l - x_r$
  - f = focal point of cameras
- The 2 shaded triangles are *similar*, so

$$z = (f*b)/d$$

$$y_l = y_r = yf/z$$

$$x_l = fx/z$$

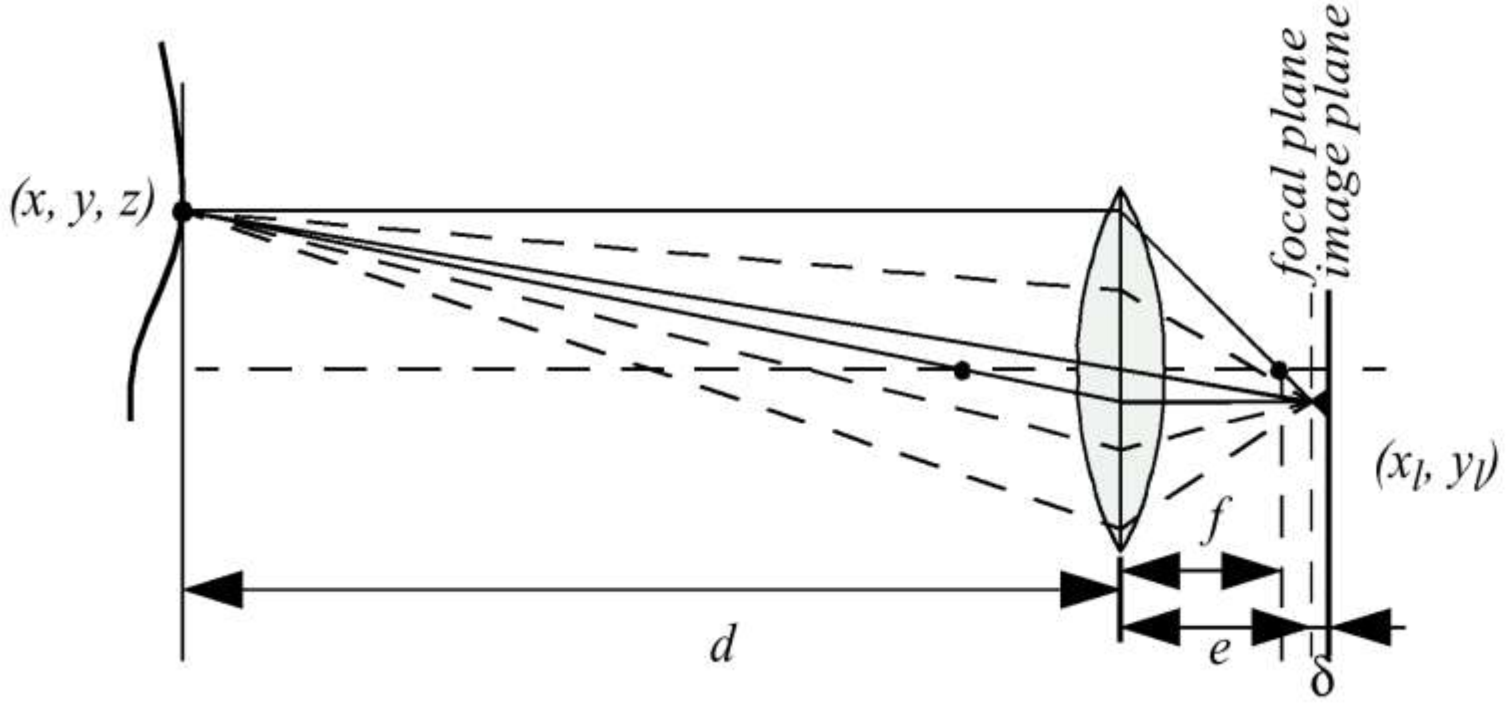
$$x_r = f(x - b)/z$$



Stereo Ranging Systems:
Stereo Vision

- Image depth is inversely proportional to disparity
    - Stereo is most accurate for close objects
- *Disparity* is an integer since it is a difference in x values of pixels
- Accuracy of depth can be increased by increasing baseline distance between cameras
    - However this reduces the overlap of the camera and scene width
    - It is more difficult to match pairs of points since the left and right images have less in common due to larger difference in viewing angle

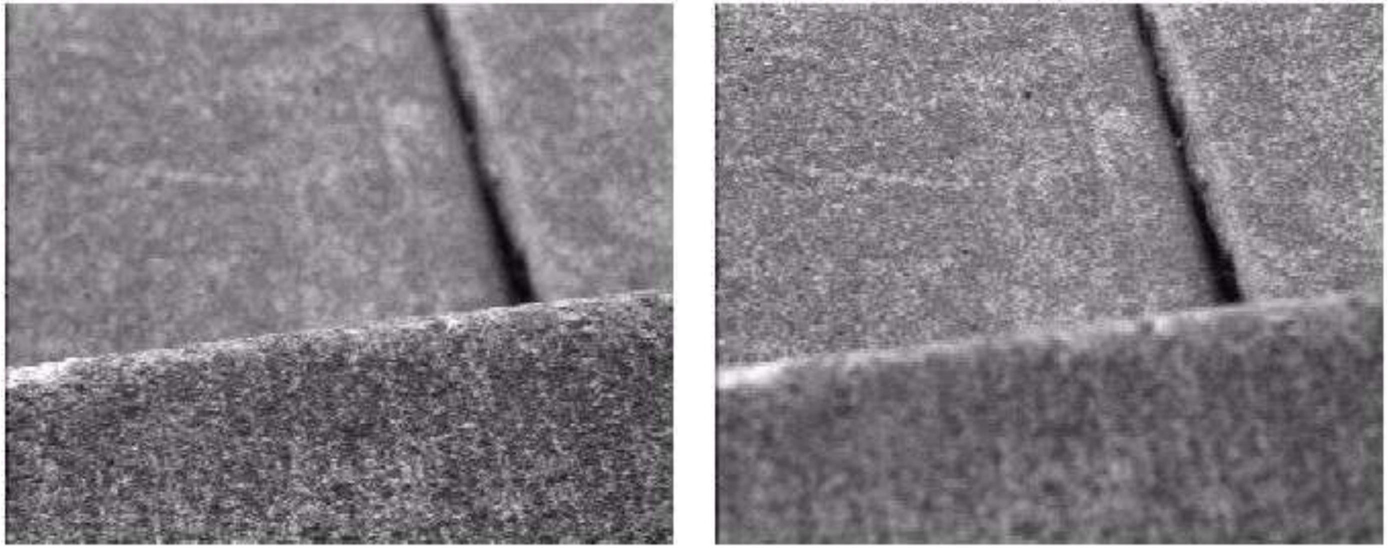
Depth from Focus



$$\frac{1}{f} = \frac{1}{d} + \frac{1}{e}$$

$$R = \frac{L\delta}{2e}$$

Depth from Focus



Measure of sub-image gradient:

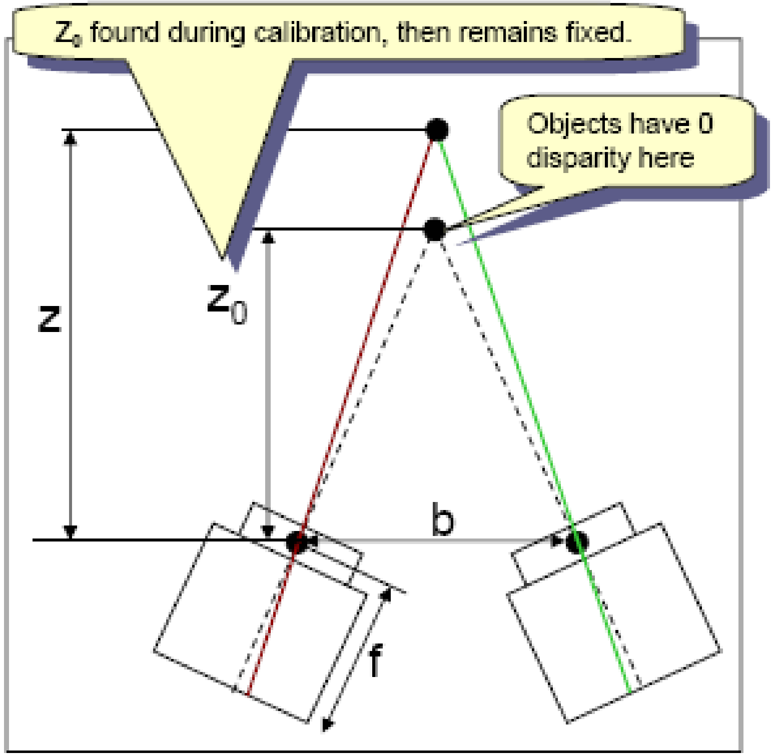
$$sharpness_1 = \sum_{x,y} \left| I(x,y) - I(x-1,y) \right|$$

$$sharpness_2 = \sum_{x,y} \left(I(x,y) - I(x-2,y-2) \right)^2$$

Stereo Ranging Systems: Stereo Vision

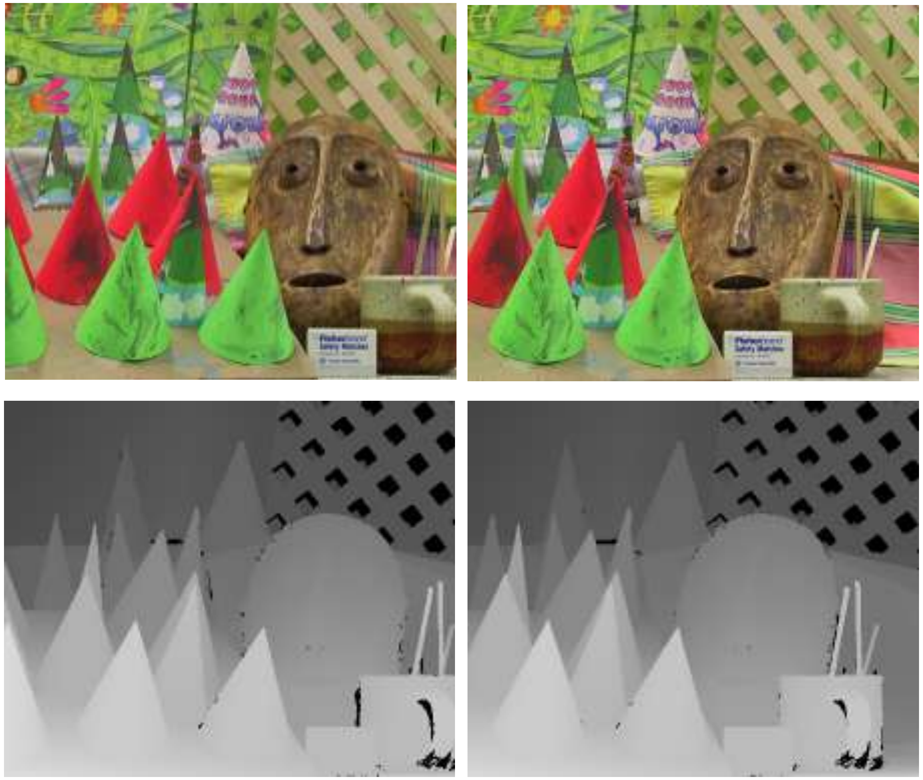
A more realistic scenario is when the cameras do not lie on the same plane

$z = (f \cdot b)/(d + (f \cdot b)/z_o)$



Stereo Vision

- 3D information can be computed from two images



- Compute *disparity*
  - displacement of a point in 2D between the two images
- Disparity is inverse proportional with actual distance in 3D
- Compute relative positions of cameras

Stereo Vision

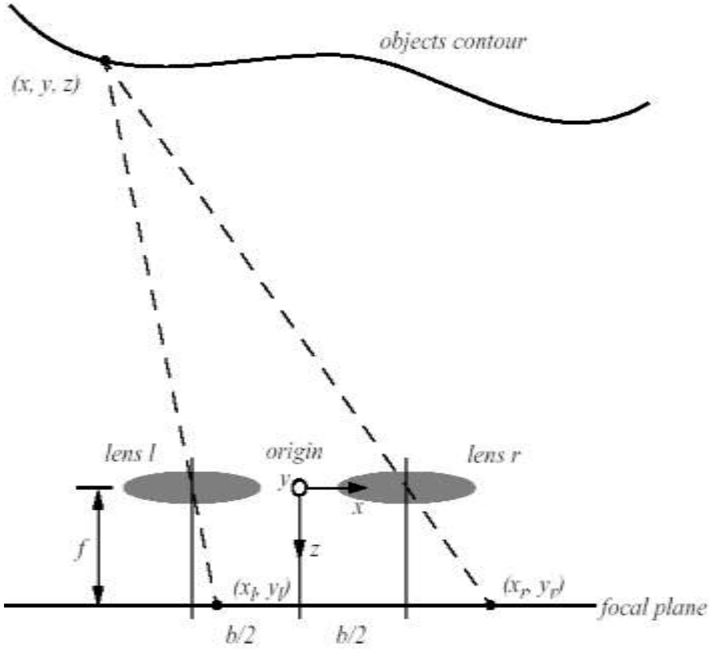
- The camera geometry is used for stereo vision
- The disparity between two images is used to compute depth

$$\frac{x_l}{f} = \frac{x + b/2}{z} \text{ and } \frac{x_r}{f} = \frac{x - b/2}{z}$$

$$\frac{x_l - x_r}{f} = \frac{b}{z}$$

$$x = b\frac{(x_l + x_r)/2}{x_l - x_r} \; ; \quad y = b\frac{(y_l + y_r)/2}{x_l - x_r}$$

$$z = b\frac{f}{x_l - x_r}$$



Stereo Vision

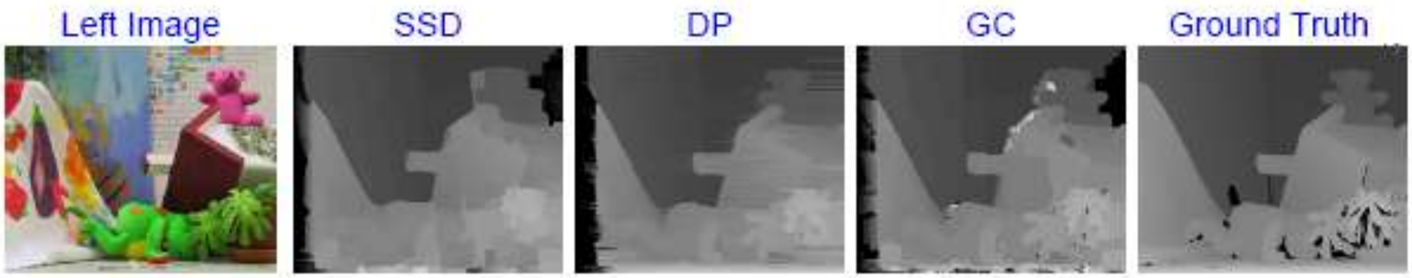
1. Distance is inversely proportional to *disparity*
    - closer objects can be measured more accurately
2. Disparity is proportional to b.
    - For a given disparity error, the accuracy of the depth estimate increases with increasing baseline b.
    - However, as b is increased, some objects may appear in one camera, but not in the other.
3. A point visible from both cameras produces *a conjugate pair*
    - Conjugate pairs lie on *epipolar line*

Stereo Ranging Systems: Correspondence

- Desired characteristics
  - Corresponding image regions are similar
  - Each point matches a single point in the other image (unlikely)
- Two main matching methods
  - *Feature-based*
    - Start from image structure (e.g. edges)
  - *Correlation-based*
    - Start from grey levels

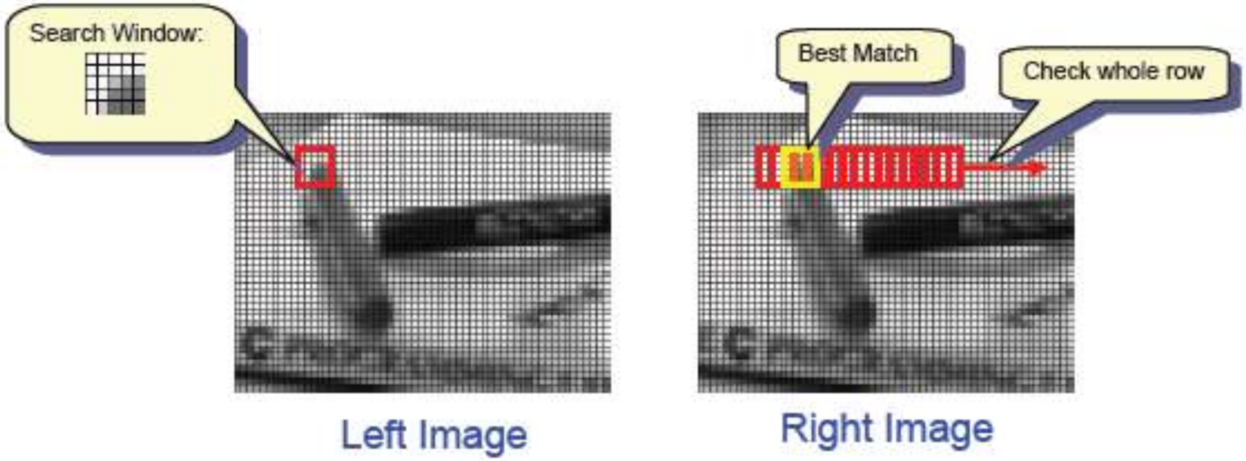
Stereo Ranging Systems: Correlation

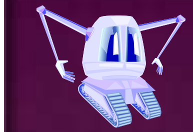
- There are several methods
  - Sum of Squared Difference (SSD)
  - Dynamic Programming (DP)
  - Graph Cut (GC)
  - Belief Propagation (BP)
  - Markov Random Fields (MRF)



Stereo Vision:
SSD Correlation

- Take a small area of data in left image and compare it with similar-size area in the right image along the same *epipolar line* (i.e. same height in the image if the cameras are horizontally level)





Stereo Vision: Correlation

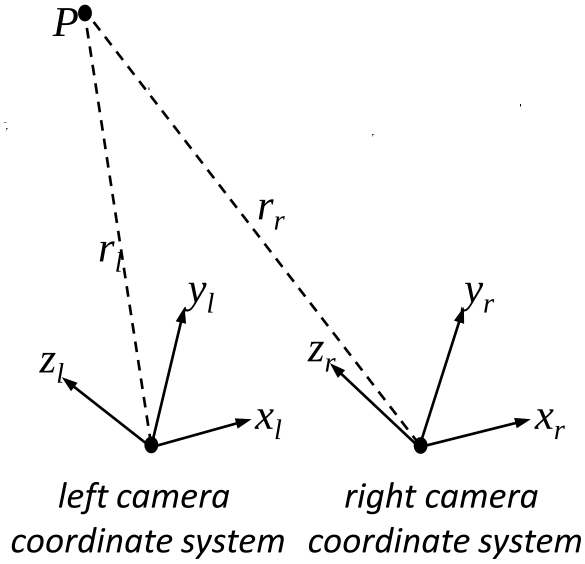
- To improve matching
  - Apply image filters before and after processing
  - Identify corners and edges to help fill in areas with no data available
  - Use sensor fusion (i.e. data from other sensors) to fill in missing gaps
  - Project structure light onto objects to improve matches

Stereo Vision: General case

$$r'_r = R \cdot r'_l + r_0$$

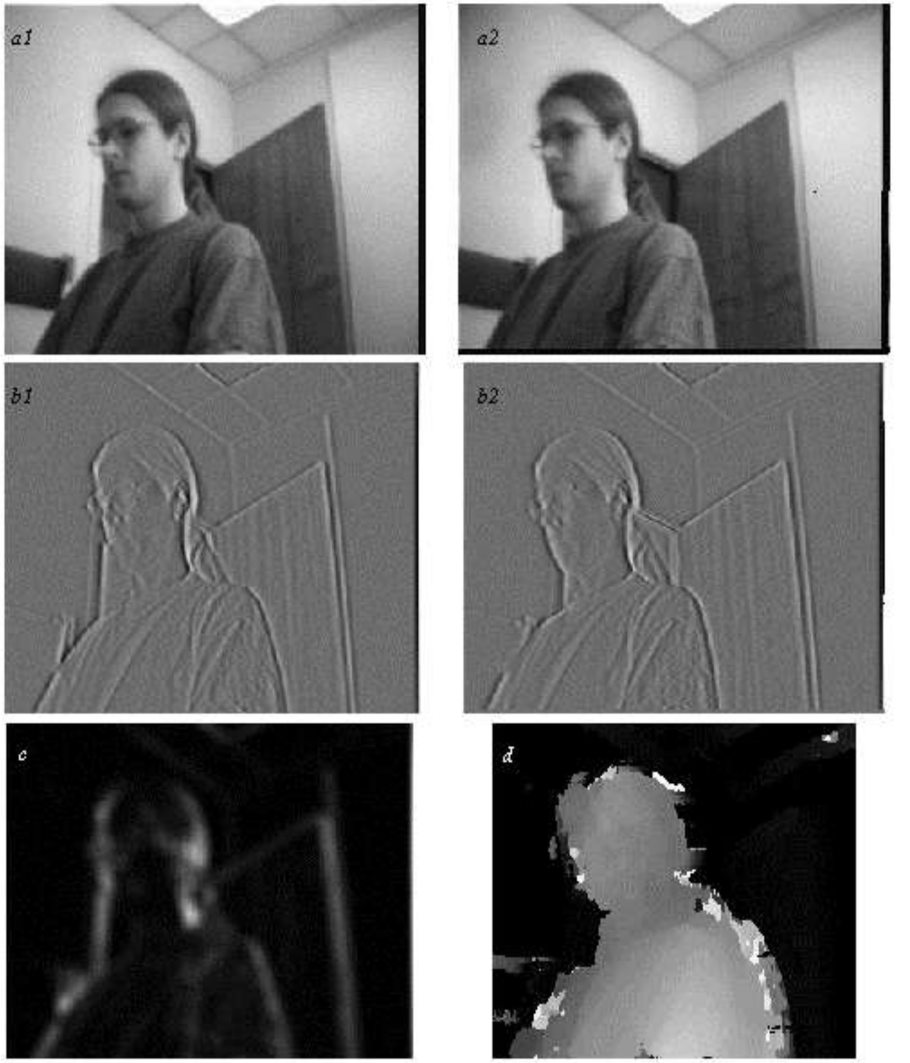
$$\begin{bmatrix} x'_r \\ y'_r \\ z'_r \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{21} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \begin{bmatrix} x'_l \\ y'_l \\ z'_l \end{bmatrix} + \begin{bmatrix} r_{01} \\ r_{02} \\ r_{03} \end{bmatrix}$$

- To optimize range of distances, cameras are turned inward toward one another
- The same point P is measured differently in the left camera image
- *R* is a 3 x 3 rotation matrix
- r_0 = offset translation matrix
- The equations can be used
    - to find r_r if R and r_l and r_0 are given (Note: For perfectly aligned cameras R=I (unity matrix))
    - to calibrate the system and find r_{11}, r_{12} … given corresponding values of x_l, y_l, z_l, x_r, y_r and z_r.
- There are 12 unknowns and it requires 12 equations:
    - we require 4 conjugate points for a complete calibration.



Stereo Vision Example

- Extracting depth information from a stereo image
  - a1 and a2: left and right image
  - b1 and b2: vertical edge filtered left and right image;
    filter = [1 2 4 -2 -10 -2 4 2 1]
  - c: confidence image:
    bright = high confidence (good texture)
  - d: depth image:
    bright = close; dark = far



Scene Reconstruction

From depth maps, 3D models can be constructed by a triangular mesh

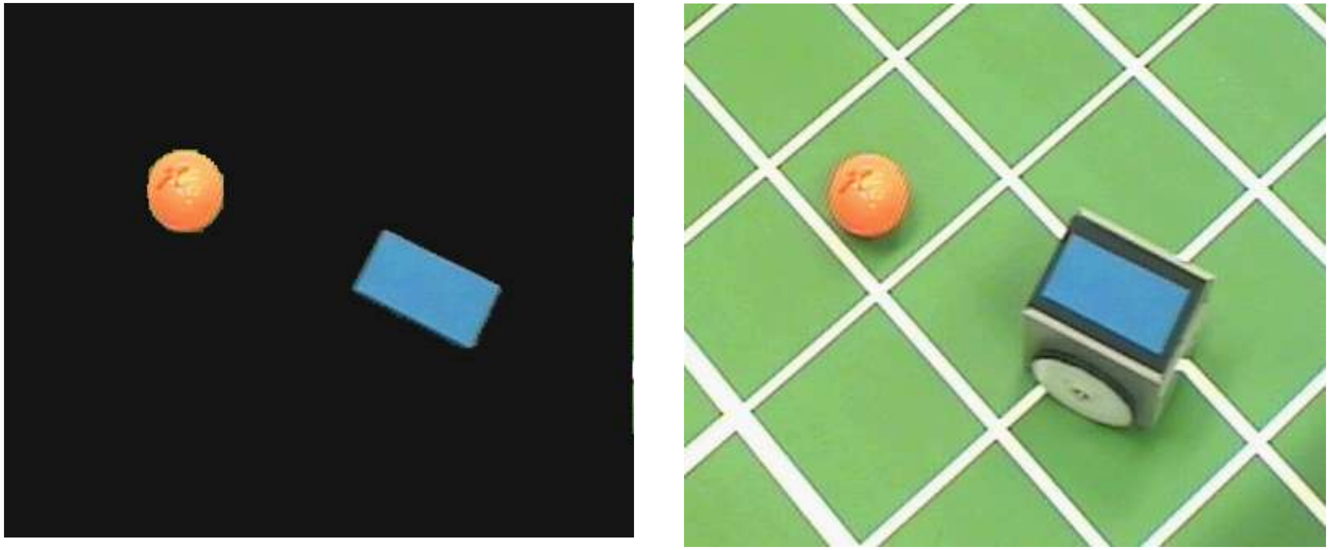
3D model from one angle 3D model from different angle Completed model

Vision from Motion

- Take advantage of motion to facilitate vision
- Static system can detect moving objects
    - Subtract two consecutive images from each other ⇒ the movement between frames
- Moving system can detect static objects
    - At consecutive time steps continuous objects move as one
    - Exact movement of the camera should be known
- Robots are typically moving themselves
    - Need to consider the movement of the robot

Color Tracking Sensors

- Unlike ultrasonic and infrared range finders, vision systems can also detect and track color in the environment



Color-tracking sensors

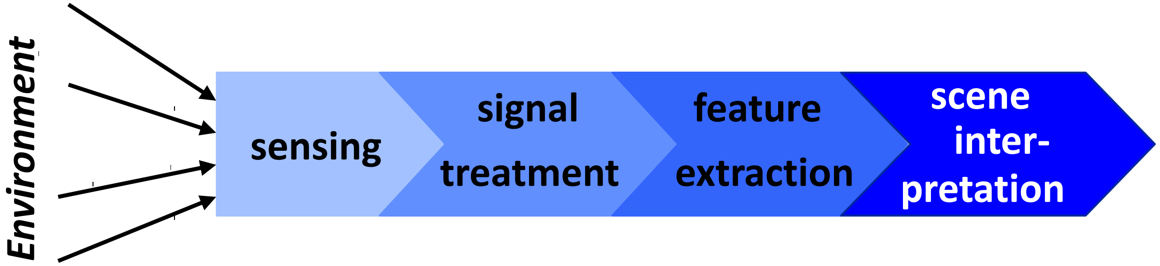
- There is no correspondence problem to be solved in such algorithms (it only requires one image)
- By using sensor fusion, color tracking can produce significant information gains

Stereo Ranging Systems

- Advantages
  - Better resolution than ultrasonic and infrared
  - Very reliable when environment is sufficiently cluttered
  - Often packaged with software to calculate depth
- Disadvantages
  - Cannot identify mirrors and/or glass
  - Sensitive to lighting conditions
  - Poor performance when environment lacks features
  - More expensive than ultrasonic and infrared
  - Larger than ultrasonic and infrared
  - Difficult to calibrate

Feature Extraction: Scene Interpretation

- A mobile robot must be able to determine its relationship to the environment by sensing and interpreting the measured signals.
  - A wide variety of sensing technologies are available
  - However, the main difficulty lies in interpreting these data, that is, in deciding what the sensor signals tell us about the environment.
  - To extract information from one or more sensor readings to generate a higher level ***percept*** to inform the robot’s environment model and action is ***feature extraction***



Environment

sensing

signal treatment

feature extraction

scene inter-pretation

Feature Extraction: Features

- Features are distinctive elements or geometric primitives of the environment.
- Good features are always perceivable and easily detectable form the environment
- They usually can be extracted from measurements and mathematically described.
  - *low-level features* include *geometric primitives* like lines, circles
  - *high-level features* include edges, doors, tables or trash cans.

In mobile robotics, features help for localization and map building.

Environment Representation and Modeling: Features

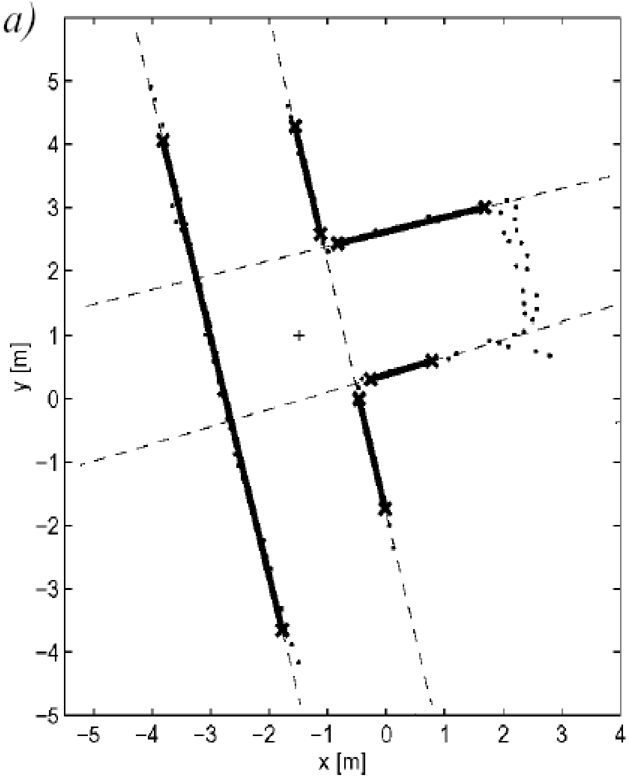
- Environment Representation
  - Continuous Metric → x,y,θ
  - Discrete Metric → metric grid
  - Discrete Topological → topological gridEnvironment Modeling
  - Raw sensor data, e.g. laser range data, grayscale images
    - large volume of data, low distinctiveness
    - makes use of all acquired information
  - Low level features, e.g. line other geometric features
    - medium volume of data, average distinctiveness
    - filters out the useful information, still ambiguities
  - High level features, e.g. doors, a car, the Eiffel tower
    - low volume of data, high distinctiveness
    - filters out the useful information, few/no ambiguities, not enough information

Environment Models: Examples

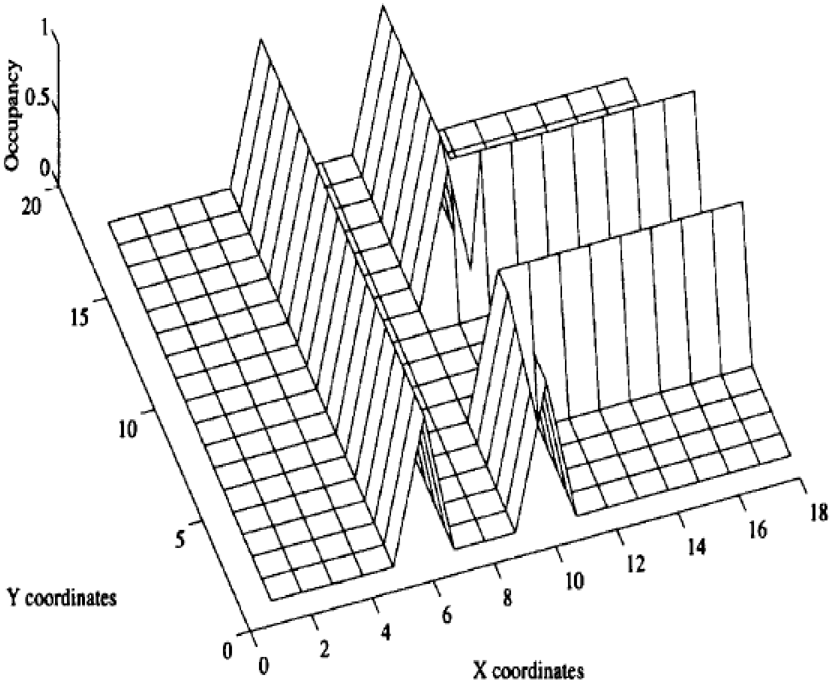
Feature based
(continuous metric)

Occupancy grid
(discrete metric)

a)

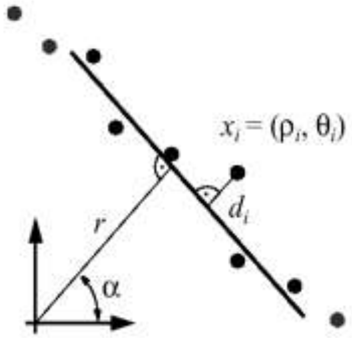


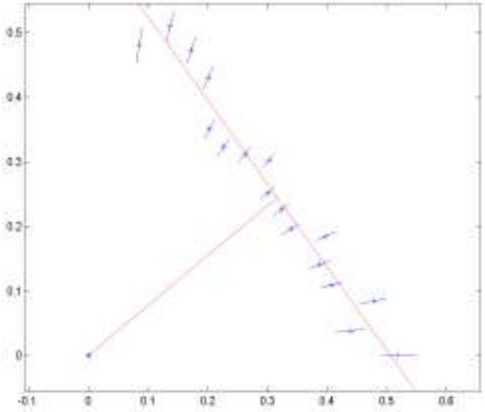
b)



Feature extraction: Range Data

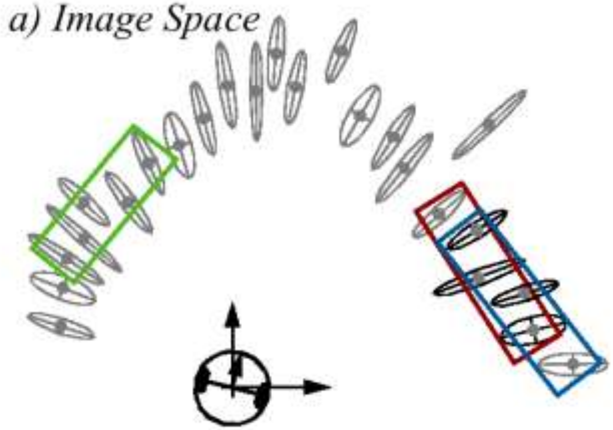
- Laser, Ultrasonic and vision-based ranging extract features that are geometric primitives such as line segments, circles, corners, edges
- Most other geometric primitives are too complex and no closed form solutions exist.
- However, lines segments are very often sufficient to model the environment, especially for indoor applications.





Segmentation for Line Extraction

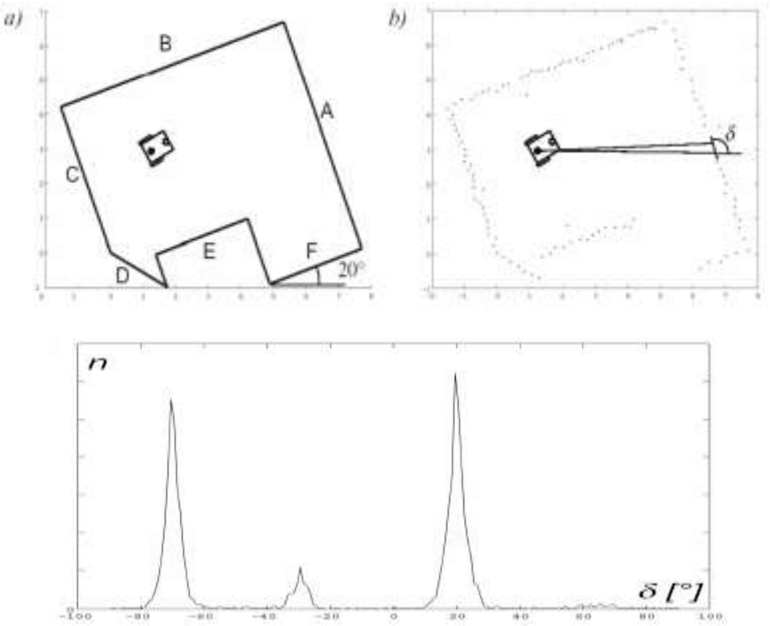
- The process of dividing up a set of measurements into subsets that can be interpreted one by one is termed *segmentation*
- *Segmentation* is important for range-based and vision-based perception



A set of n_f neighboring points of the image space

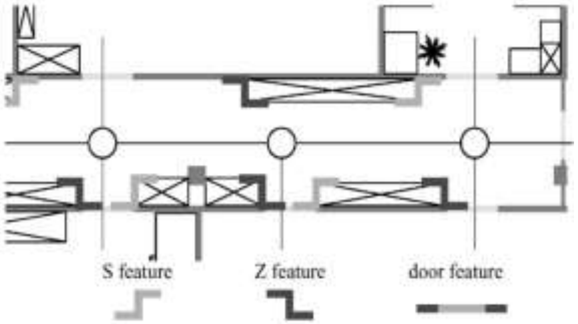
Range histogram features
Angular Histogram

- An *angular histogram* is a simple way of combining characteristic elements of an image
  - A 360 degree range can is performed
  - The hits are recorded on a map
  - An algorithm measures the relative angle between adjacent hits



Extracting Other Geometric Features

- A robot must make use of multiple features simultaneously, comprising a *feature set* appropriate for its operating environment
- *Corner features* are defined as a point feature with an orientation
- *Step discontinuities* are a step change perpendicular to the direction of travel (concave or convex)
- *Doorways* are opening of the appropriate dimension in the wall, characterized by their width



Feature extraction: Visual appearance

- Recognition of features is, in general, a complex procedure requiring a variety of steps that successively transform the iconic data to recognition information.
- The feature extraction method must operate in real time
- Handling unconstrained environments is still very challenging problem
- The method must be robust to the real-world assumptions
- *Spatially localized features* are found in sub regions of one or more images corresponding to specific locations in the physical world
- *Whole-image features* are a function of the entire image or set of images and correspond to a large visually connected are in the physical world

Visual Appearance: Image preprocessing

- Conditioning
  - Suppresses noise
  - Implemented with
    - gray-scale modification (e.g. thresholding)
    - (low pass) filtering
- Labeling
  - Determination of the spatial arrangement of the events, i.e. searching for a structure
- Grouping
  - Identification of the events by collecting together pixel participating in the same kind of event
- Extracting
  - Compute a list of properties for each group
- Matching

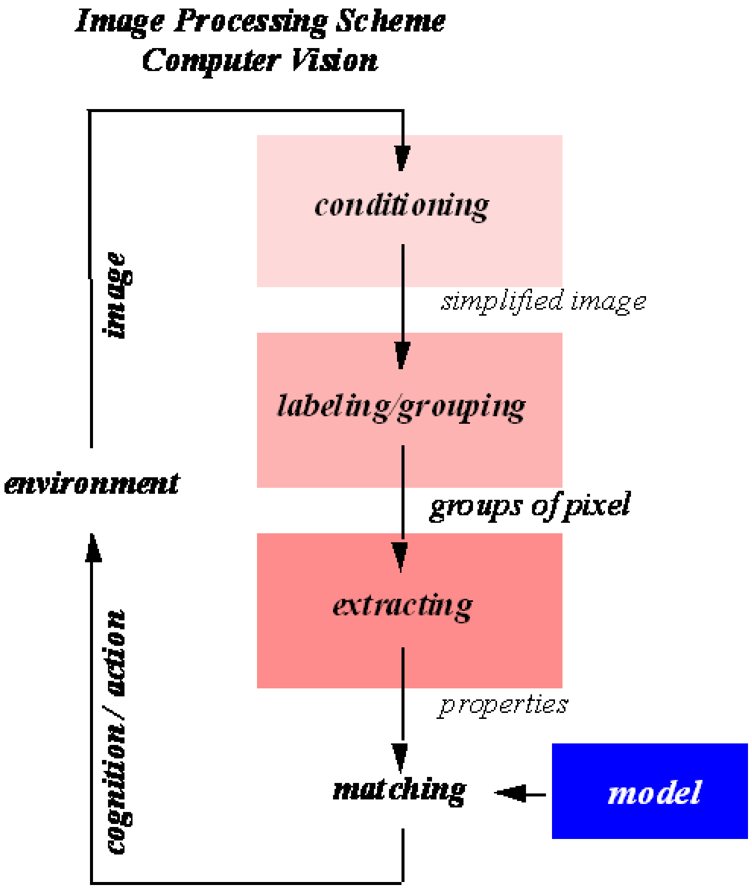


Image Processing Scheme
Computer Vision

conditioning

simplified image

labeling/grouping

groups of pixel

extracting

properties

matching

model

environment

image

cognition / action

Feature Extraction:
Filtering and Edge Detection

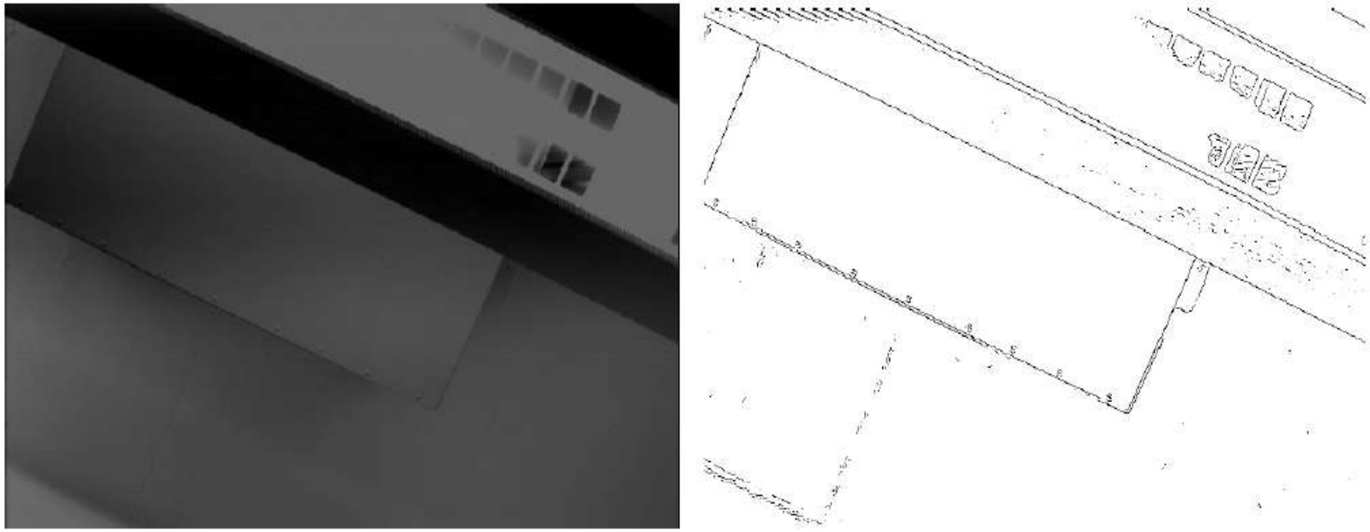
- The single most popular spatially localized feature is *edge detection*
- Edges
  - Locations where the brightness undergoes a sharp change,
  - Differentiate one or two times the image
  - Look for places where the magnitude of the derivative is large.
  - Noise, thus first filtering/smoothing required before edge detection
- Gaussian Smoothing
  - Removes high-frequency noise
  - Convolution of intensity image I with G

Edge Detection

- Edge = a curve in the image across which there is a change in brightness
- Finding edges
  - Differentiate the image and look for areas where the magnitude of the derivative is large
- Difficulties
  - Not only edges produce changes in brightness: shadows, noise
- Smoothing
  - Filter the image using convolution
  - Use filters of various orientations
- Segmentation: get objects out of the lines

Feature Extraction: Edge Detection

- Ultimate goal of edge detection
  - an idealized line drawing.
- Edge contours in the image correspond to important scene contours.

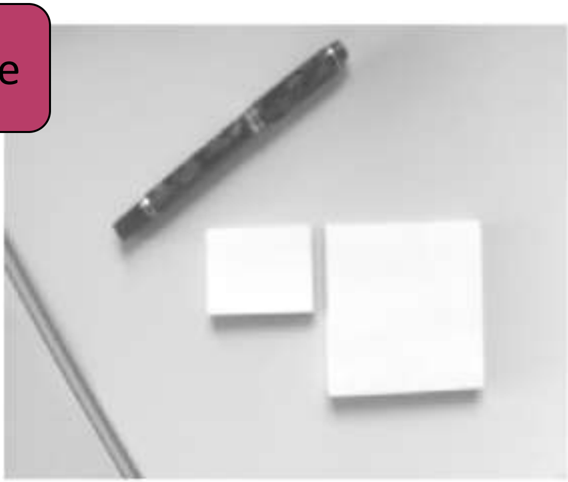


Feature Extraction: Nonmaxima Suppression

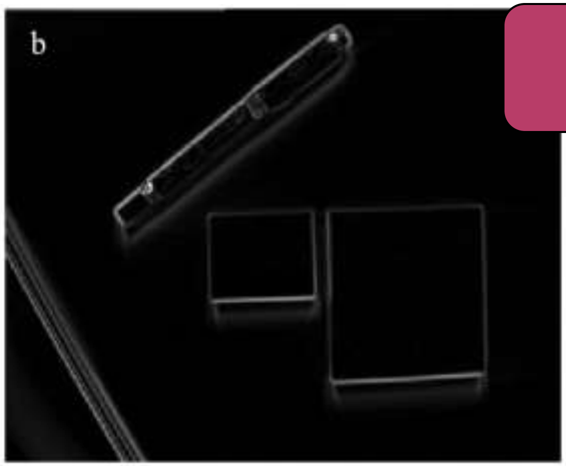
- Output of a Canny edge detector is usually a black and white image where the pixels with gradient magnitude above a predefined threshold are black and all the others are white
- *Nonmaxima suppression* sets all pixels to zero that do not represent the local maxima
- *Nonmaxima suppression* generates contours described with only one pixel thinness

Feature Extraction Example

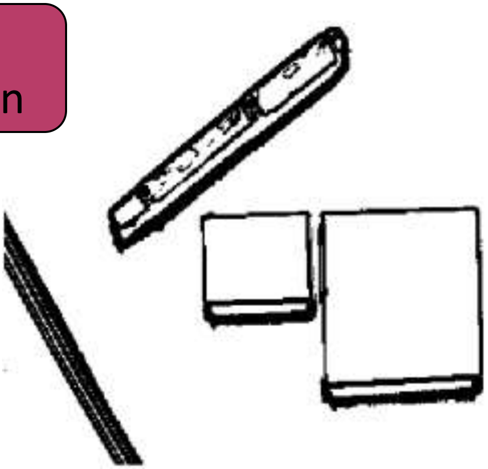
Raw Image



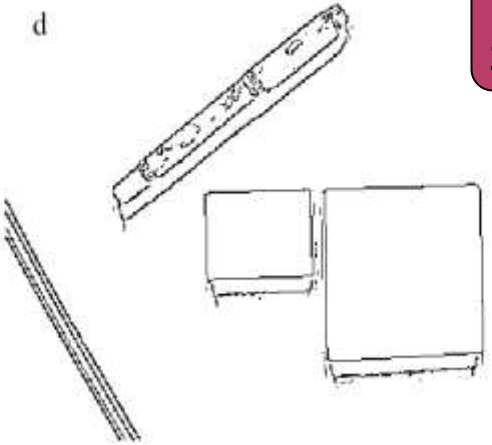
Sobel Filter



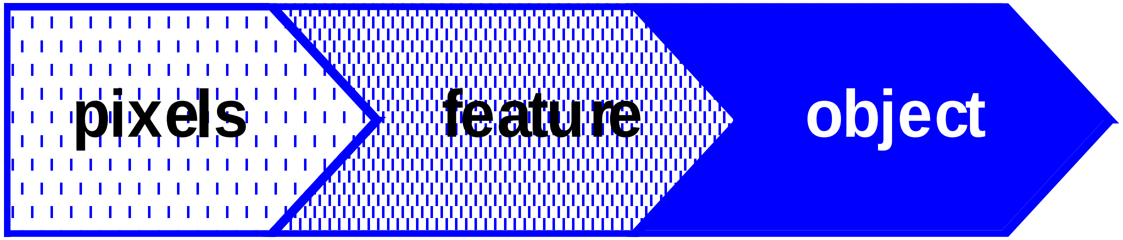
Edge Detection



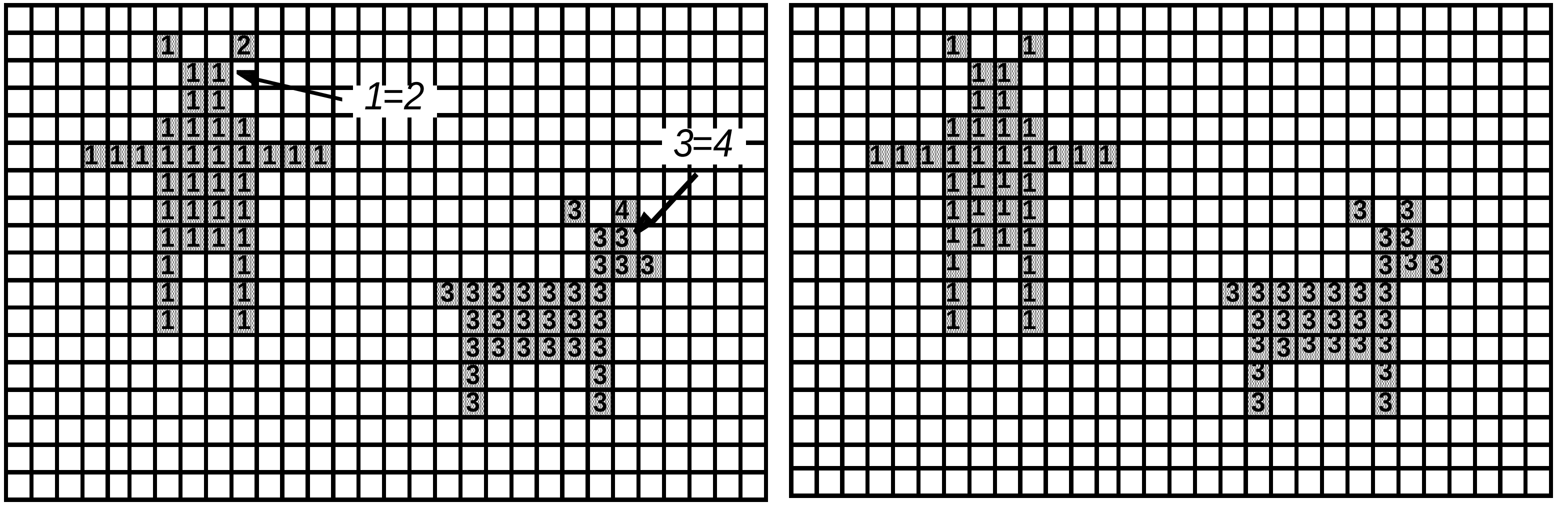
Nonmaxima Suppression



Grouping, Clustering: Assigning Features to Features


pixels
feature
object

Connected Component Labeling



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Feature Extraction: Floor Plane Extraction

- Vision based identification of a traversable path
- The processing steps
  - As pre-processing, smooth I_f using a Gaussian smoothing operator
  - Initialize a histogram array H with *n* intensity values
  - For every pixel (x,y) in I_f increment the histogram:

Feature Extraction: Whole-Image Features

- Whole-Image features are not designed to identify specific spatial structures
- They sever as a compact representation of the entire local region
- Extract one or more features that are correlated with the robot's position for localization