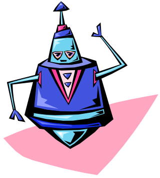
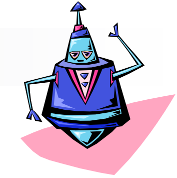


ECE497: Introduction to Mobile Robotics Lecture 3

Dr. Carlotta A. Berry

Spring 06 - 07



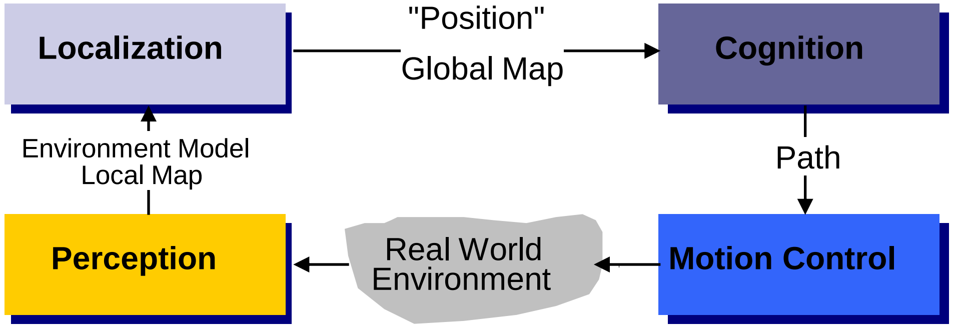
Quote of the Week

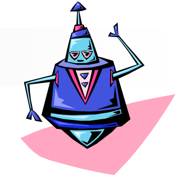
"Just as some newborn race of superintelligent robots are about to consume all humanity, our dear old species will likely be saved by a Windows crash. The poor robots will linger pathetically, begging us to reboot them, even though they'll know it would do no good."

Anonymous

Perception (4.1)

One of the most important task 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.





Sensor Classification (4.1.1)

- *Proprioceptive*
  - *Sensors that measure values internal to the robot*
    - *(motor speed, wheel load, battery voltage)*
- *Exteroceptive*
  - *Sensors that acquire information from the robots environment*
    - *Distance measurement, light intensity, sound amplitude*
  - *Used by the robot to extract meaningful environment features*
- *Passive*
  - Measure ambient environment energy entering the sensor
    - Temperature probes, microphones, cameras
- *Active*
  - Emit energy into the environment then measure the reaction
    - (wheel quadrature encoders, ultrasonic sensors, laser rangefinders)
- *Contact versus non-contact*
- *Visual versus non-visual*
  - vision-based sensing, image processing, video camera

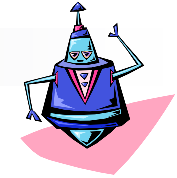
General Classifications (Table 4.1)

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Tactile sensors (detection of physical contact or closeness; security switches)	Contact switches, bumpers Optical barriers Noncontact proximity sensors	EC EC EC	P A A
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders Potentiometers Synchros, resolvers Optical encoders Magnetic encoders Inductive encoders Capacitive encoders	PC PC PC PC PC PC PC	P P A A A A A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass Gyroscopes Inclinometers	EC PC EC	P P A/P

A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

General Classifications (Table 4.1)

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Ground-based beacons (localization in a fixed reference frame)	GPS Active optical or RF beacons Active ultrasonic beacons Reflective beacons	EC EC EC EC	A A A A
Active ranging (reflectivity, time-of-flight, and geo-metric triangulation)	Reflectivity sensors Ultrasonic sensor Laser rangefinder Optical triangulation (1D) Structured light (2D)	EC EC EC EC EC	A A A A A
Motion/speed sensors (speed relative to fixed or moving objects)	Doppler radar Doppler sound	EC EC	A A
Vision-based sensors (visual ranging, whole-image analy-sis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P



Sensor Suite

The ensemble of *proprioceptive* and *exteroceptive* sensors constitute the robot's *perceptual system*

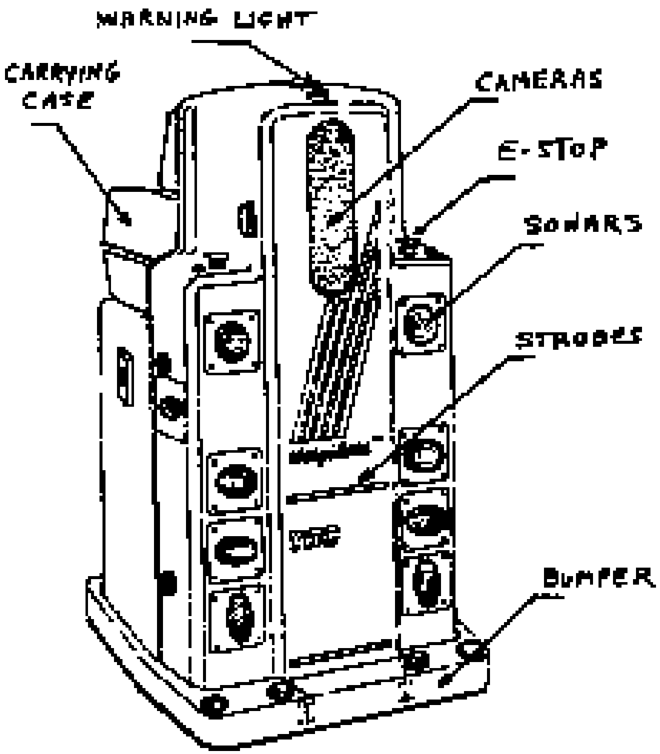
Physical Property	Sensor
contact	switch
distance	ultrasound, radar, infrared
light level	photocells, cameras
sound level	microphone
rotation	encoders and potentiometers
acceleration	accelerometers gyroscopes

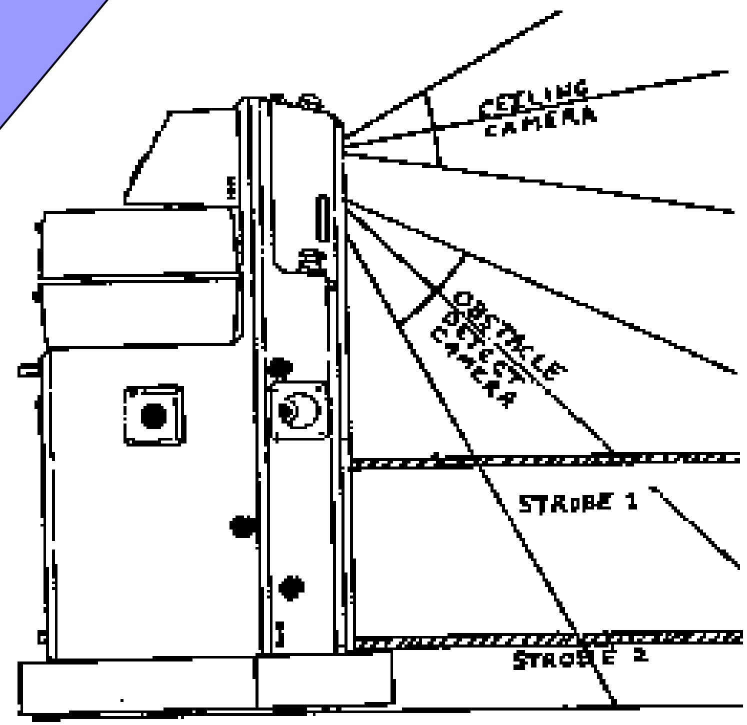
More Sensors

Physical Property	Sensor
magnetism	compass
smell	chemical
temperature	thermal, infrared
inclination	inclinometers, gyroscopes
pressure	pressure gauges
altitude	altimeters
strain	strain gauges

Examples of Multi-sensor systems

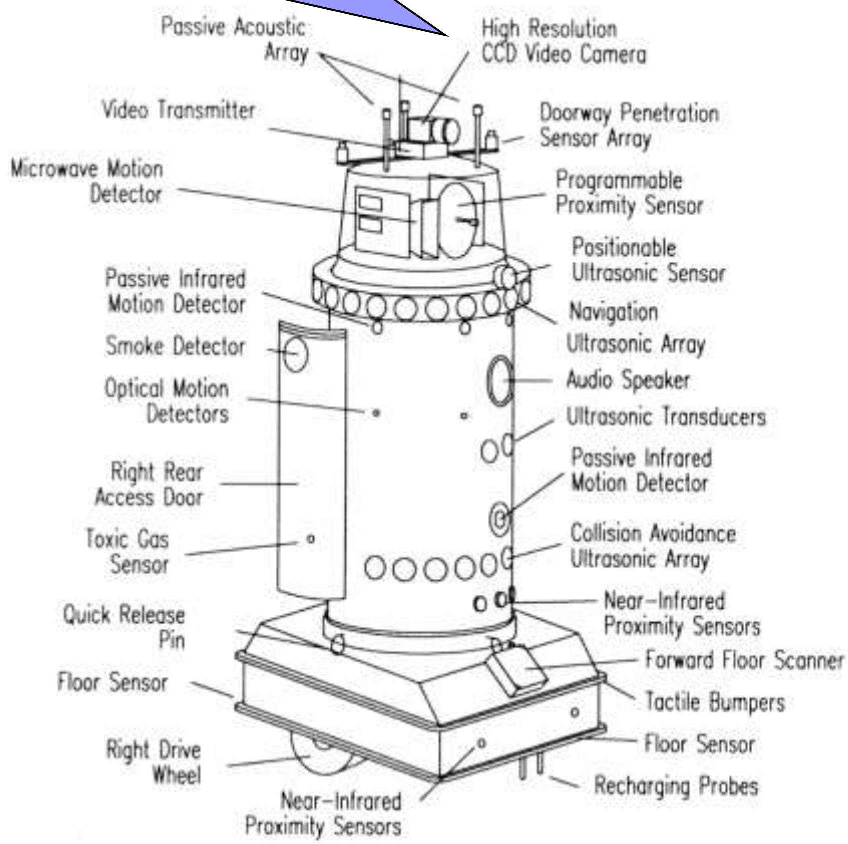
HelpMate, Transition Research Corp.



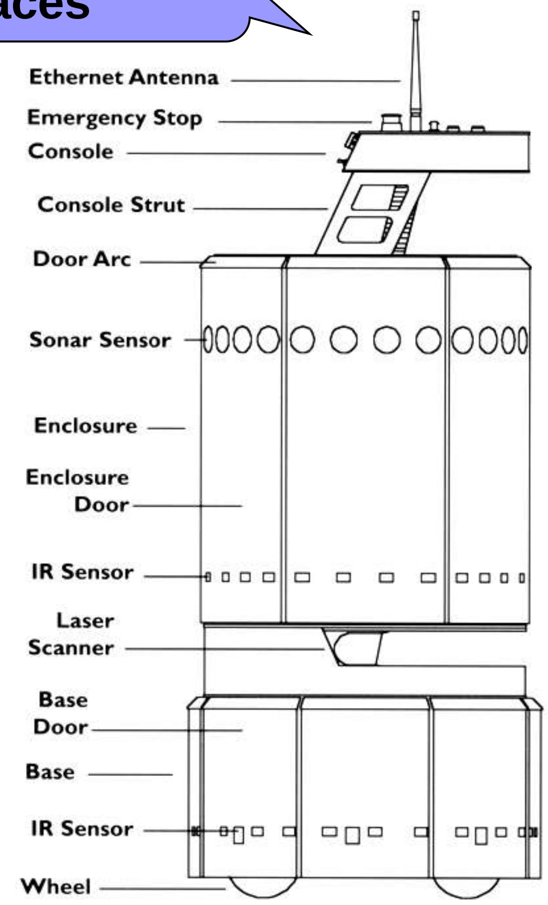


Examples of Multi-sensor systems

Robart II, H.R. Everett



B21, Real World Interfaces



Examples of Multi-sensor Mobile Robots

IMU
Inertial Measurement Unit

Emergency Stop Button

Wheel Encoders

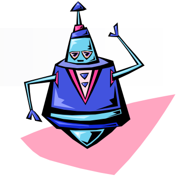
Omnidirectional Camera

Pan-Tilt Camera

Sonar Sensors

Laser Range Scanner

Bumper

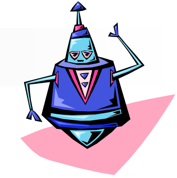


Types of Sensors

- Sensors provide raw measurements that need to be processed
- Depending on how much information they provide, sensors can be simple or complex
- *Simple* sensors:
  - A switch: provides 1 bit of information (on, off)
- *Complex* sensors:
  - A camera: 512x512 pixels
  - Human retina: more than a hundred million photosensitive elements

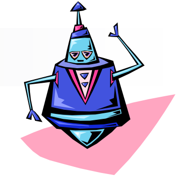
Information Extraction

- Given a sensory reading, what should I do?
  - Deals with robot ***actions*** in the environment
- Given a sensory reading, what does the environment look like?
  - Deals with ***reconstruction*** of the robot's environment
- *Simple sensors* can answer the first question
  - Their output can be used directly
- *Complex sensors* can answer both questions
  - Their information needs to be processed



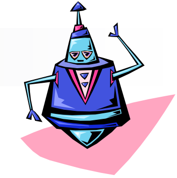
Signal to Symbol Problem

- Sensors produce only signals, not symbolic descriptions of the world
- To extract the information necessary for making intelligent decisions a lot of *sensor pre-processing* is required
  - Symbols are abstract representations of the sensory data
- *Sensor pre-processing*
  - Uses methods from electronics, signal processing and computation



Signal Processing

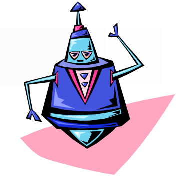
- To determine if a switch is open or closed
  - Measure voltage across the circuit ⇒ **electronics**
- Use a microphone to recognize voices
  - Separate the signal from noise, compare with stored voices for recognition ⇒ **signal processing**
- Use a surveillance camera to find people in an image and recognize intruders
  - compare data large image database ⇒ **computation**



Perception Requirements

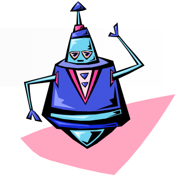
Perception requires more than just sensors:

- *Sensors*
  - Power and electronics
- *Computation*
  - Extract relevant information
- *Integration*
  - Consolidate information into knowledge about environment (i.e. fusion)



How Would You Detect People?

- *Camera:*
  - great deal of processing
- *Movement:*
  - if everything else is static: movement means people
- *Color:*
  - If you know the particular color people wear or skin color range
- *Temperature:*
  - use sensors to detect the range of human body heat
- *Distance:*
  - If any open-range becomes blocked

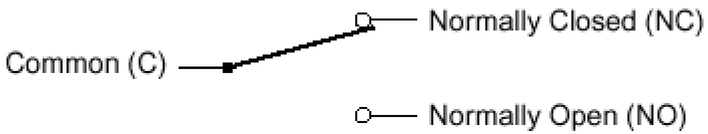


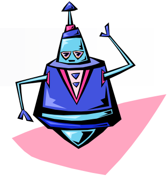
How Would You Measure Distance?

- *Ultrasound sensors (sonar)*
  - provide distance measurement directly (time of flight)
- *Infrared sensors*
  - provide return signal intensity
- *Two cameras (i.e., stereo)*
  - can be used to compute distance/depth
- *A laser and a camera*
  - triangulate distance
- *Laser-based structured light*
  - overlay grid patterns on the world, use distortions to compute distance

Switch Sensors

- Among the simplest sensors of all
- Do not require processing, work at "circuit" level
- If the switch is *open* ⇒ there is no current flowing
- If the switch is *closed* ⇒ current will flow
- Can be
  - Normally open (more commo
  - Normally closed

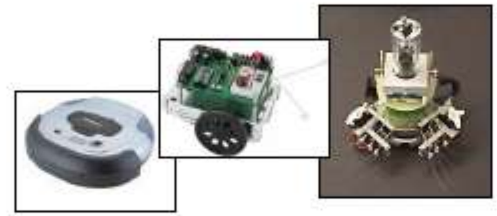




Uses of Switch Sensors

- *Contact (tactile) sensors:*
  - detect contact with another object (e.g., triggers when a robot hits a wall or grabs an object, etc.)
- *Limit sensors:*
  - detect when a mechanism has moved to the end of its range (e.g., triggers when a gripper is wide open)
- *Shaft encoder sensors:*
  - detect how many times a shaft turns (e.g., a switch clicks at every turn, clicks are counted)

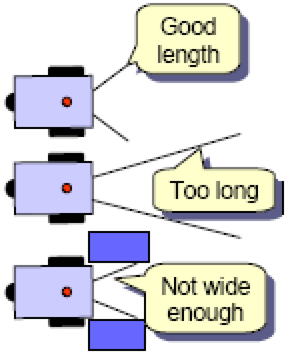
Example of Switch Uses



- *Everyday Life*
  - Light switches, computer mouse, keys on the keyboard, buttons on the phone
- *Robotics*
  - Bump switch: detect hitting an obstacle
  - Whisker:

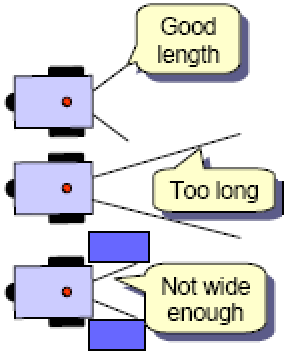
1. Attach a long metal whisker to a switch; when the whisker has bent enough the switch will close
2. Place a conductive wire (whisker) inside a metal tube; when the whisker bends it touches the tube and closes the circuit

Tactile Sensors



- Detect distance through physical contact
  - One or more bumpers
  - Two or more whiskers
- Detects obstacles within a fixed distance of the robot
- Detection range is usually 1 mm to 2 cm

Tactile Sensors



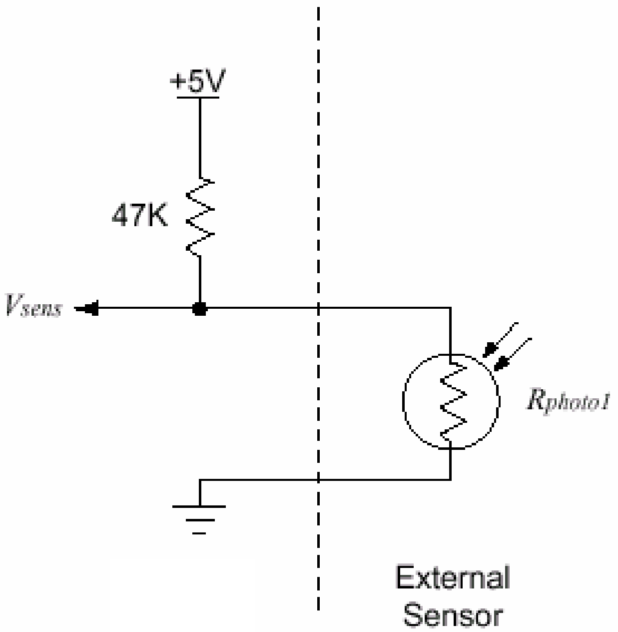
- Advantages
  - Simple
  - Reliable
- Disadvantages
  - Course resolution
  - Solid contact (dangerous for obstacles, may damage robot)
  - Whiskers can become tangled
  - Whiskers oscillate when released, spurious readings
  - Whiskers may require mechanical adjustment or repair

Proximity Sensors

- Detect objects within a specific range from the robot
- Provide a *binary* signal according to some threshold
- Tactile sensors are an example of proximity sensors
- Non-tactile sensors that detect the absence or presence of a light reflect are ***encoders***
- Non-tactile sensors are usually active
- Range sensors can be configured as proximity sensors by setting a threshold

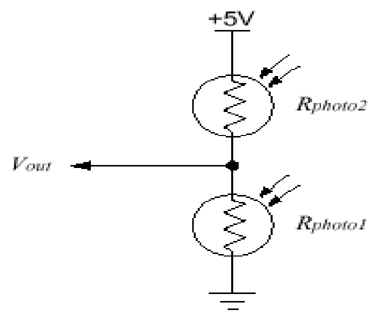
Light Sensors

- Light sensors measure the amount of light impacting a photocell
- The sensitivity of the photocell to light is reflected in changes in *resistance*
  - Low when illuminated $V_{sens} \approx 0V$
  - High when in the dark: $V_{sens} \approx 5V$
- Light sensors are *"dark"* sensors
- Could invert the output so that low means dark and high means bright



Uses of Light Sensors

- Can measure the following properties
  - Light intensity: how light/dark it is
  - Differential intensity: difference between photocells
  - Break-beams: changes in intensity
- Photocells can be shielded to improve accuracy and range



Differential Photocell Sensor

$R_{photo2} = R_{photo1}$

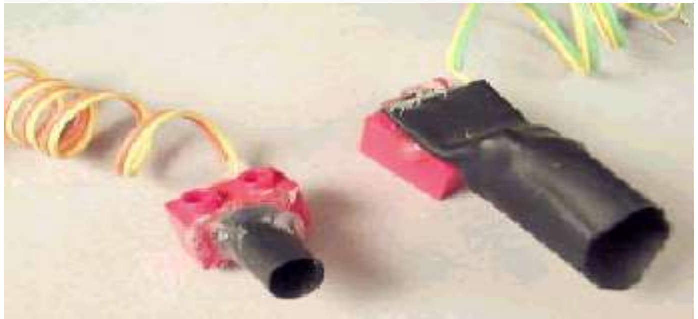
$V_{out} = 2.5$ v

$R_{photo2} << R_{photo1}$

V_{out} ~= +5 v (R2 more light)

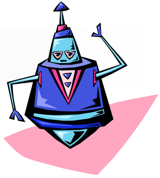
$R_{photo2} >> R_{photo1}$

V_{out} ~= gnd



Resistive Position Sensors

- 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

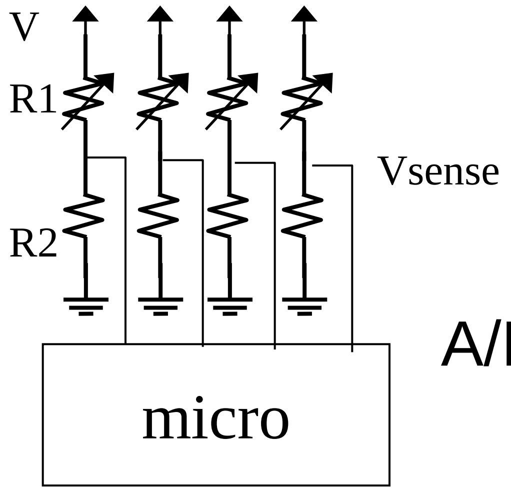


Inputs for Resistive Sensors

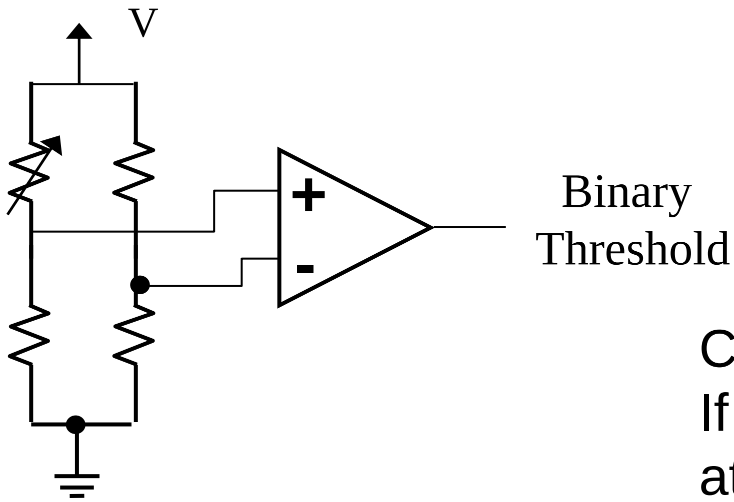
Voltage divider:

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

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

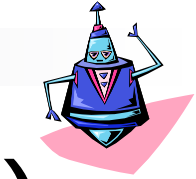


A/D converter



Digital I/O

Comparator:
If voltage at + is greater than at -, digital high out



Sensor Characteristics (4.1.2.1)

- *Dynamic range*
  - Measure of the spread between lower and upper limits of input values to sensor while maintaining normal operation
  - Defined as the ratio of max input value to minimum measurable input value in dB

$$20 \cdot \log\left[\frac{20}{0.001}\right] = 86dB$$ Voltage

$$10 \cdot \log\left[\frac{20}{0.001}\right] = 43dB$$ Power

- *Resolution*
  - Minimum difference between 2 values that can be detected by a sensor
- *Linearity*
  - Measures the behavior of the output signal as the input signal varies
- *Bandwidth or frequency*
  - Measures the speed with which a sensor can provide a stream of readings. *Frequency* is the number of measurements per second (Hz).

In Situ Sensor Performance (4.1.2.2)

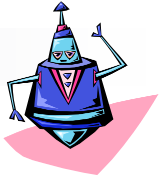
The previous sensor characteristics can be reasonably measured in a laboratory environment and the performance extrapolated to real-world deployment.

In Situ sensors must be measured in the natural environment.

- ***Sensitivity***
  - ratio of output change to input change
  - however, in real world environment, the sensor has very often high sensitivity to other environmental changes, e.g. illumination
- ***Cross-sensitivity***
  - sensitivity to environmental parameters that are orthogonal to the target parameters
- ***Error***
  - difference between the sensor's output measurements and the true values being measured
- ***Accuracy***
  - The degree of conformity between the sensor's measurement and the true value

error

$$\left(accuracy = 1 - \frac{|m - v|}{v} \right)$$

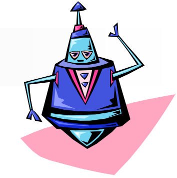


In Situ Sensor Performance (2)

Characteristics that are especially relevant for real world environments

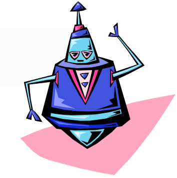
- *Systematic error -> deterministic errors*
  - caused by factors that can (in theory) be modeled -> prediction
  - e.g. calibration of a laser sensor
- *Random error -> non-deterministic*
  - no prediction possible
  - however, they can be described probabilistically
  - e.g. Hue instability of camera, black level noise of camera ..
- *Precision*
  - *reproducibility* of sensor results

$$precision = \frac{output\_range}{\sigma}$$



Characterizing Error:
The Challenges in Mobile Robotics (4.1.2.3)
Blurring of systematic and random errors

- Mobile robots have to perceive, analyze and interpret the state of their surroundings
- However, measurements in real world environments are dynamically changing and error prone
- Examples:
  - changing illuminations
  - specular reflections
  - light or sound absorbing surfaces
  - There is cross-sensitivity between a robot's sensor and the robot's pose or environment dynamics (i.e. sonar, CCD camera)
    - rarely possible to model because they appear as random errors
    - systematic errors and random errors might be well defined in controlled environment.
    - ***But this is not the case for mobile robots !!***



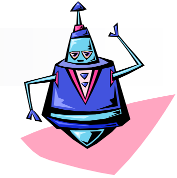
Characterizing Error: Multi-Modal Error Distributions (4.1.2.3)

The behavior of sensors is modeled by probability distribution (random errors)

- There is usually very little knowledge about the causes of random errors
- Often the probability distribution is assumed to be *symmetric, Gaussian* and/or *unimodal*
- However some examples that do not abide by these assumptions are:
  - Sonar (ultrasonic) sensors
    - may overestimate the distance in real environments (not symmetric)
    - the sonar sensor error might be best modeled by two modes (not unimodal):
      - mode for the case that the signal returns directly
      - mode for the case that the signals returns after multi-path reflections.
  - Stereo vision camera system
    - might correlate 2 images incorrectly, thus causing results that make no sense at all (not symmetric or Gaussian)

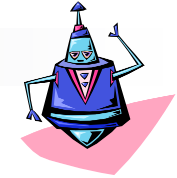
Heading Sensors (4.1.4)

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



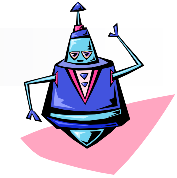
Compasses (4.1.4.1)

- 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 moementum
  - 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



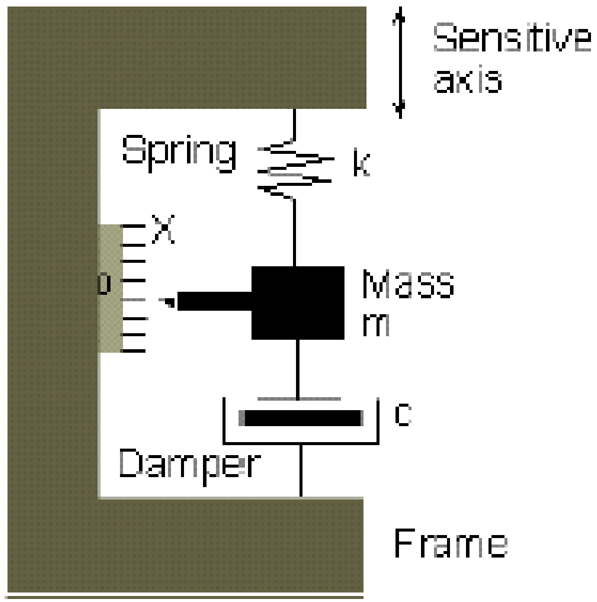
Accelerometers

- 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

Accelerometer

- Main elements of an accelerometer:

1. Mass 2. Suspension mechanism 3. Sensing element

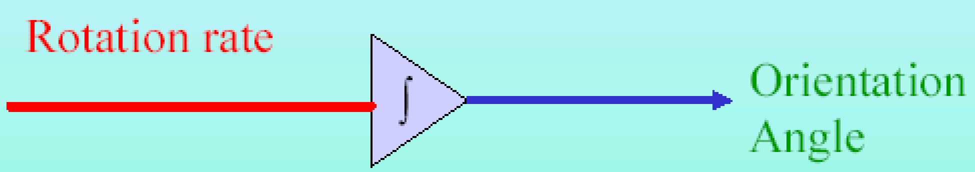


$$F = m\frac{d^2x}{d^2t} + c\frac{dx}{dt} + kx$$

High quality accelerometers include a servo loop to improve the linearity of the sensor.

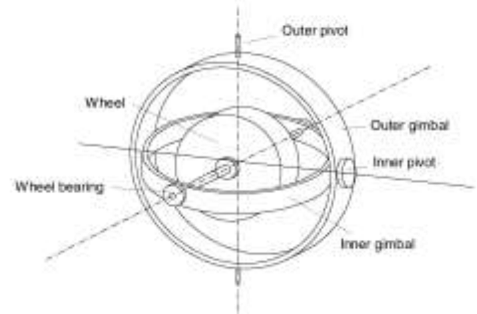
Gyroscopes

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



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

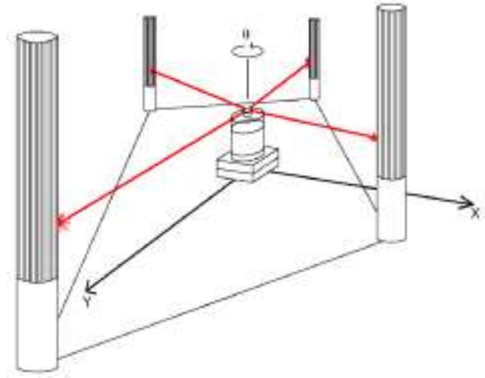
Gyroscopes(4.1.4.2)



- ***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
- **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

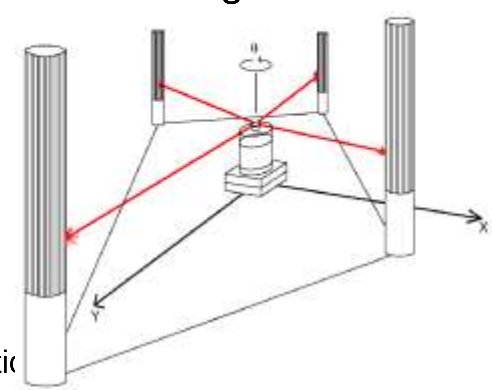
Ground-Based Beacons (4.1.5)

- 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.



Ground-Based Beacons (4.1.5)

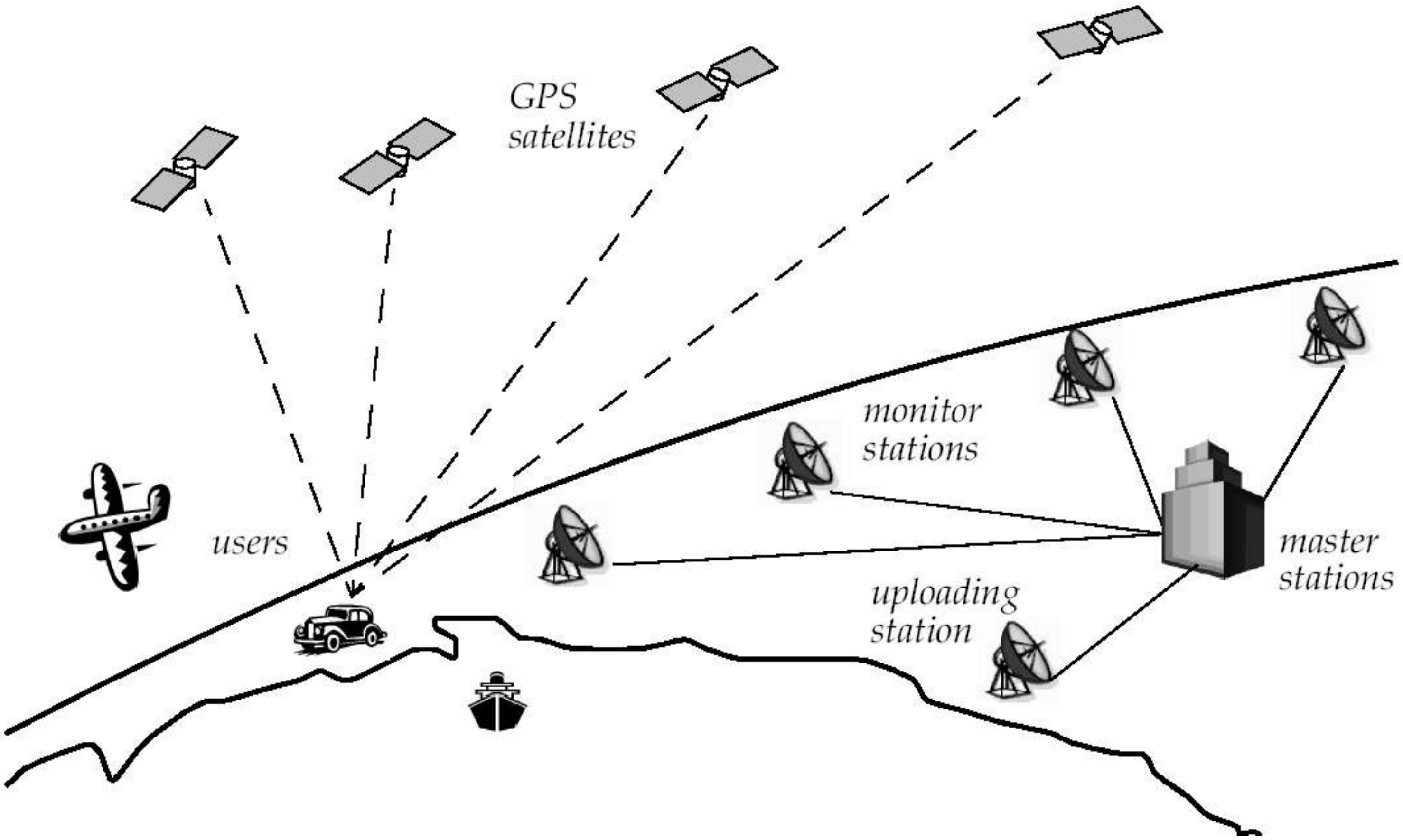
- Elegant way to solve the localization problem in mobile robotics is to use *active* or *passive* beacons
- ***Beacons*** are signaling guiding devices with a precisely known position
- The *Global Positioning System* (GPS) revolutionized modern navigation technology
  - Extremely effective and one 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
  - allows to identify the three values (x, y, z) for the position and the clock correction ΔT
  - Location of any GPS receiver is determined through a time of flight measurement
  - 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 (4.1.5)

- 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)

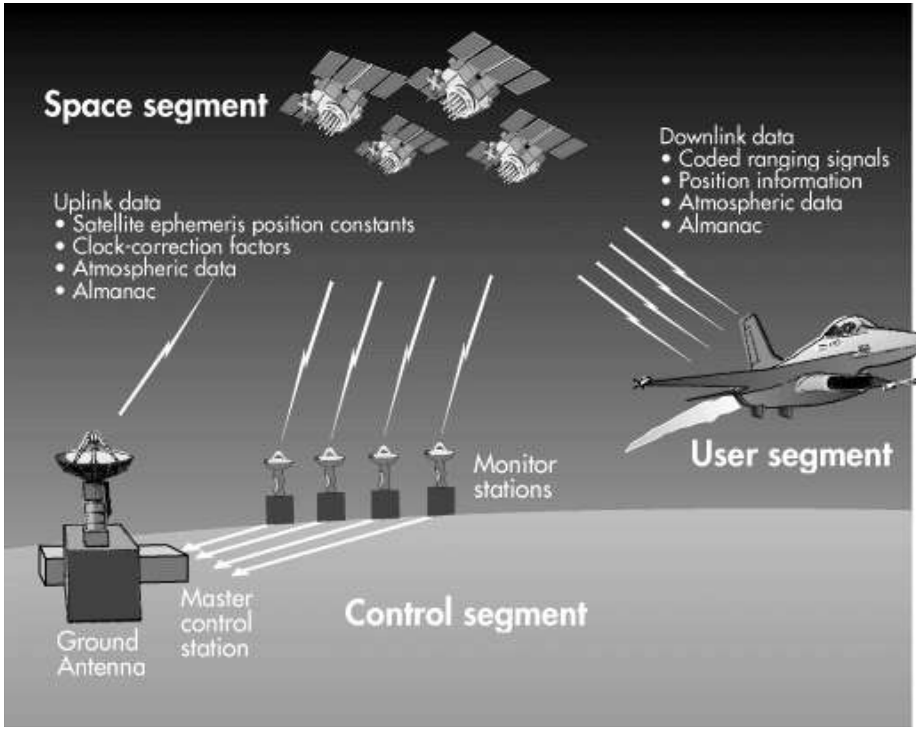
GPS Calculations (4.1.5)



Global Positioning System (GPS)

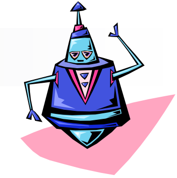
24 satellites (+several spares)

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



Space Segment

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



Noise Issues

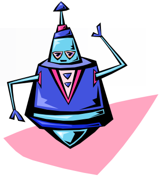
- Real sensors are noisy
- Origins: natural phenomena + less-than-ideal engineering
- Consequences: limited accuracy and precision of measurements
- Filtering:
  - software: averaging, signal processing algorithm
  - hardware tricky: capacitor

Sensing

- Sensing is the only way of obtaining environmental information
- A robot's intelligence depends on
  - The *quality* and *quantity* of its sensors
  - The ability to and speed of *processing* sensory input
- The ability of a robot to gain meaningful information about its environment through sensing is *perception*

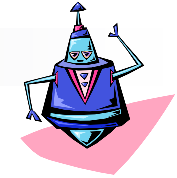
Sensor Diversity

- Robots have different types of sensors to allow:
  - Flexibility in type of data (direction, distance, light, sound, temperature)
  - Sensor fusion to obtain a more accurate representation of the world
- Multiple Sensors
  - Speed up the rate of environment readings
  - Provide redundancy and fault tolerance
  - Save power



Passive versus Active Sensors

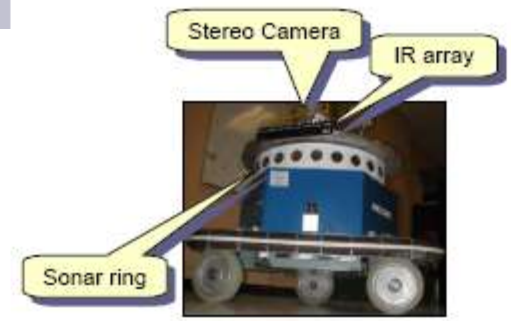
- *Passive Sensors*
  - Sense the environment without altering it
  - touch, heat, sound, light, camera
- *Active sensors* are sometimes preferred
  - Alter the environment by sending out some kind of signal which usually modified in some way be the environment and then detected again
  - Sonar, infrared, laser



Passive versus Active Sensors

- *Passive Sensors* are sometimes preferred:
  - because they do not add extra signals or noise to the environment
  - Active sensors can interfere with other robots in multi-robot environments
- *Active sensors* are sometimes preferred
  - Because there is less difficulty extracting relevant information

Sensor Fusion



- To account for inaccuracies, multiple sensors are often combined (or fused)
- *Sensor Fusion* combines sensor readings from
  - The same sensor
    - Taken as an average, minimum or maximum over some small time interval (infrared sensor)
  - Multiple similar sensors
    - Individual sensors read from different directions (sonar ring)
  - Different kinds of sensors
    - Combine sonar, infrared, and vision measurements

Range Sensors

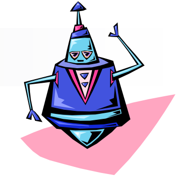
Active ranging (4.1.6)

- *Active ranging sensors* are the most popular sensors in mobile robotics
- *Active ranging sensors* are used for
  - Obstacle detection
  - Obstacle avoidance
  - Localization
  - Environment modeling
- Ultrasonic sensors and laser range sensors use the propagation speed of sound or electromagnetic waves.

Range Sensors

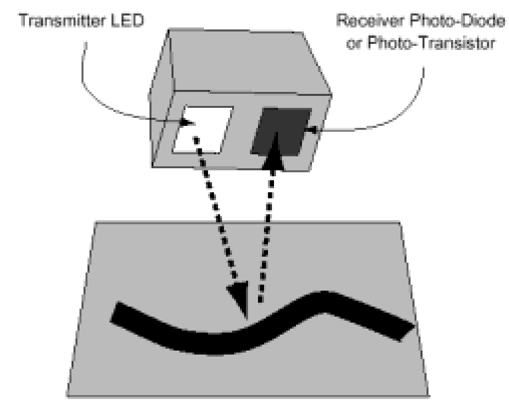
- ***time of flight*** is used to determine distance to objects
- The measured pulses typically come form ultrasonic, RF and optical energy sources.
  - **d = c * t**
  - d = round-trip distance
  - c = speed of wave propagation
  - t = time of flight

Range Sensors

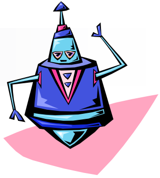


- Commonly used range sensors in robotics include:
  - Tactile and proximity sensors
  - Ultrasonic sensors
  - Infrared range sensors
  - Laser range finders
  - Vision systems
- Each varies in complexity, size, weight, expense, accuracy, etc..
- The ***detection range*** is defined as the maximum distance that the sensor can read reliably

Range Sensors: Reflective Optosensors



- Reflective Optosensors Include:
  - a source of light, the ***emitter*** (light emitting diode (LED))
  - a light ***detector*** (photodiode or phototransistor)
- Two arrangements:
  - Reflectance sensors:
    - Emitter and detector are side by side
    - Light reflects from the object back into the detector
  - Break-beam sensors:
    - The emitter and detector face each other
    - Object is detected if light between them is interrupted

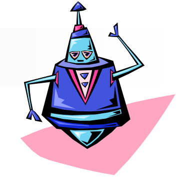


Active Ranging (4.1.6.1)

- The quality of time of flight range sensors mainly depend on:
  - Uncertainties about the exact time of arrival of the reflected signal
  - Inaccuracies in the time of fight measure (laser range sensors)
  - Opening angle of transmitted beam (ultrasonic range sensors)
  - Interaction with the target (surface, specular reflections)
  - Variation of propagation speed
  - Speed of mobile robot and target (if not at stand still)

Reflectance Sensing: Applications

- Detect the presence of an object
- Detect the distance to an object
- Detect some surface feature
  - Wall following
  - Line following
- Bar code reading
- Rotational shaft encoding



Reflectance Sensing:
Properties of Reflectivity

- *Reflectivity* is dependent on the color and texture of the surface
  - Light colored surfaces reflect better
  - A matte black surface may not reflect light at all
- Lighter objects farther away seem closer than darker objects close by
- Another factor that influences reflective light sensors is
  - Ambient light
  - How can a robot tell the difference between a stronger reflection and simply an increase in light in the robot's environment?

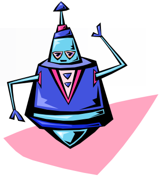
Reflectance Sensing: Ambient light

- Ambient / background light can interfere with sensor measurement
- To correct it subtract the ambient light level from the sensor measurement
- This is how:
  - take two (or more, for increased accuracy) readings of the detector, one with the emitter on, one with it off,
  - Subtract the values
- The result is the ambient light level

Reflectance Sensing: Calibration

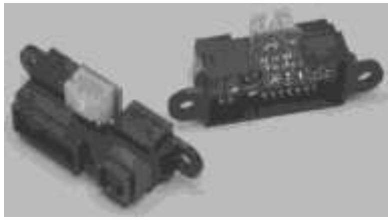
- *Calibration is* the process of adjusting a mechanism to maximize its performance
- Ambient light can change $\Rightarrow$ sensors need to be calibrated repeatedly
- Detecting ambient light is difficult if the emitter has the same wavelength
  - Adjust the wavelength of the emitter

Infrared Sensors

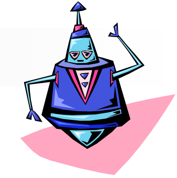


Infrared Range Sensors

- Emit a beam of infrared light and measure the amount of light being reflected from the object
- Infrared light beam is not visible

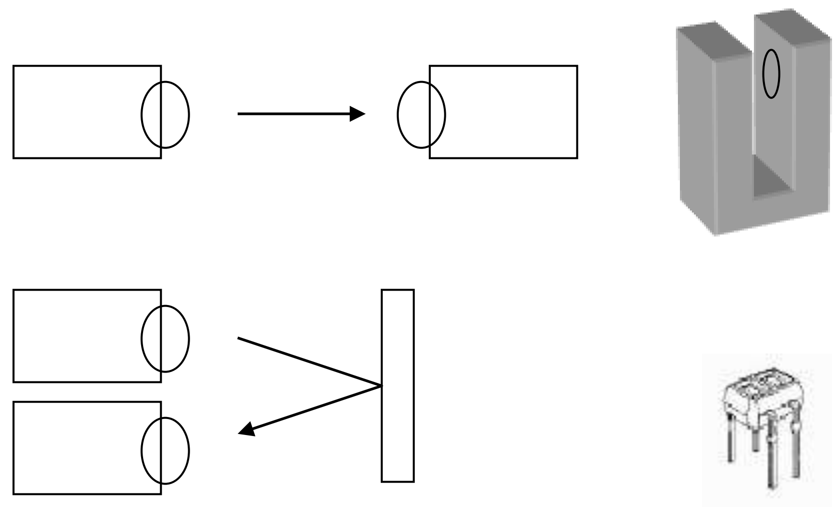


- Modes of operation
  - Reflective
    - Measures strength of light reflected from object
  - Transmissive
    - Detects presence of object between emitter and detector
  - Modulated
    - Modulates beam to reduce noise
  - Triangulation
    - Measures angle at which the light is reflected back



Infrared Sensors:

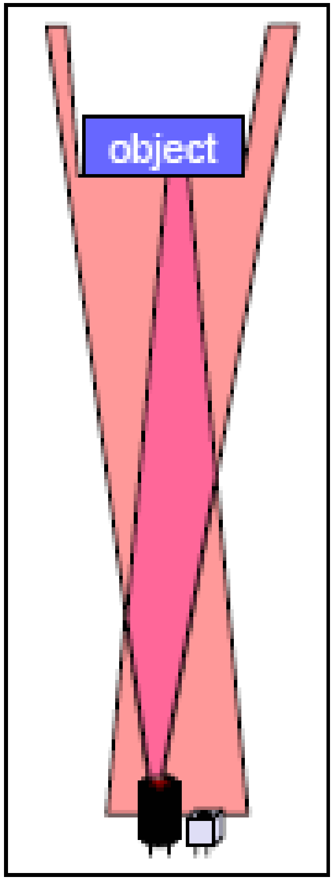
Types

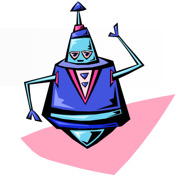


- Intensity based infrared
  - Reflective sensors
  - Easy to implement
  - susceptible to ambient light
- Modulated Infrared
  - Proximity sensors
  - Requires modulated IR signal
  - Insensitive to ambient light
- Infrared Ranging
  - Distance sensors
  - Short range distance measurement
  - Impervious to ambient light, color and reflectivity of object

Infrared Sensors
Proximity detection

- Emit light from Infrared LED
- Light is reflected from object
- Receiver measures strength of light returned
- Range depends on object properties
  - Shiny objects (metal) are difficult to detect
  - Cannot detect glass
  - White/black surfaces report different ranges



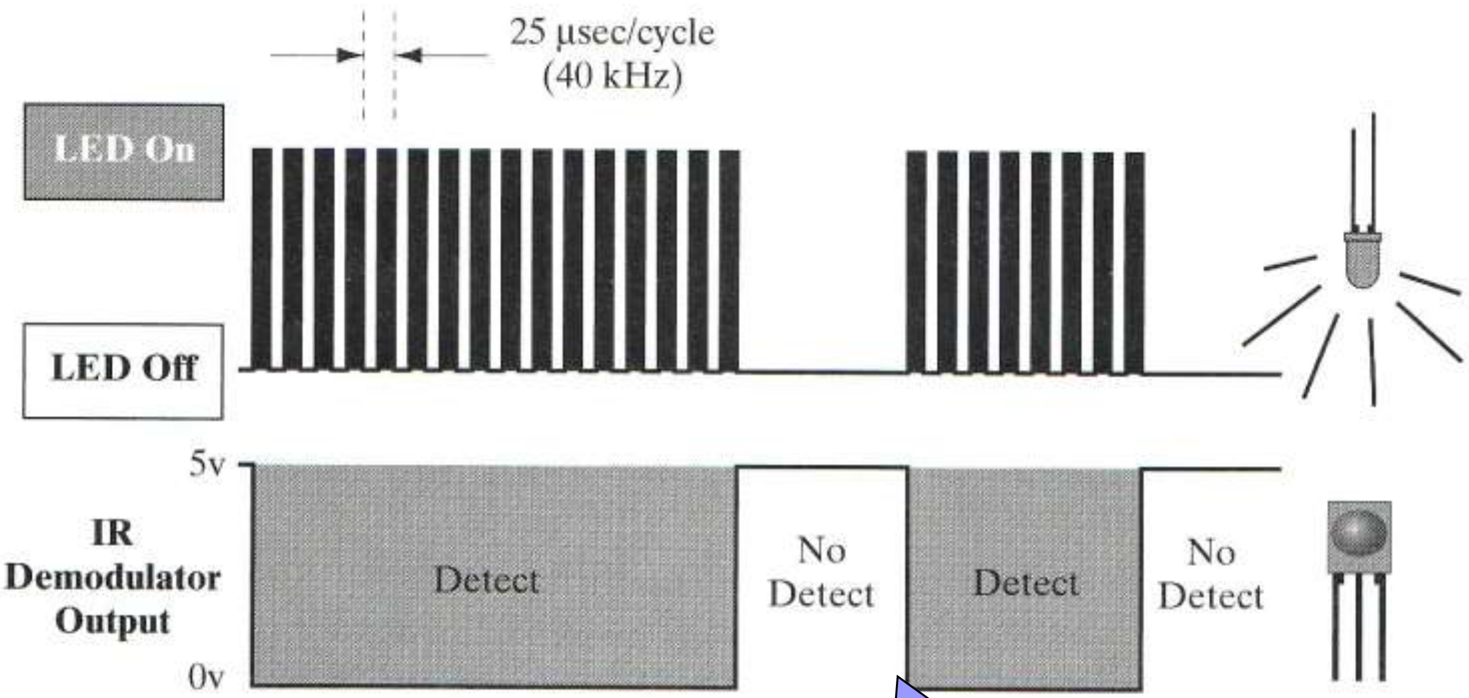


Infrared Sensors
Modulated Infrared

- Signal is IR LED flashing at 40 kHz
- Receiver has additional circuitry so that it only respond to a matching modulated IR signal
- Reduces outside IR noise and interference with other IR devices operating at different frequencies
- Multiple robots can be equipped with IR sensors operating at different frequencies to avoid interference

Infrared Sensors

Modulated Infrared



Negative "True" Logic
Detect = 0V
No Detect = 5V

Infrared Sensors

Distance Sensors

- Basic principle of operation:
  - IR emitter + focusing lens + position-sensitive detector
  - Modulated Infrared
  - Location of the spot on the detector corresponds to the distance to the target surface. Optics used to convert horizontal distance to vertical distance

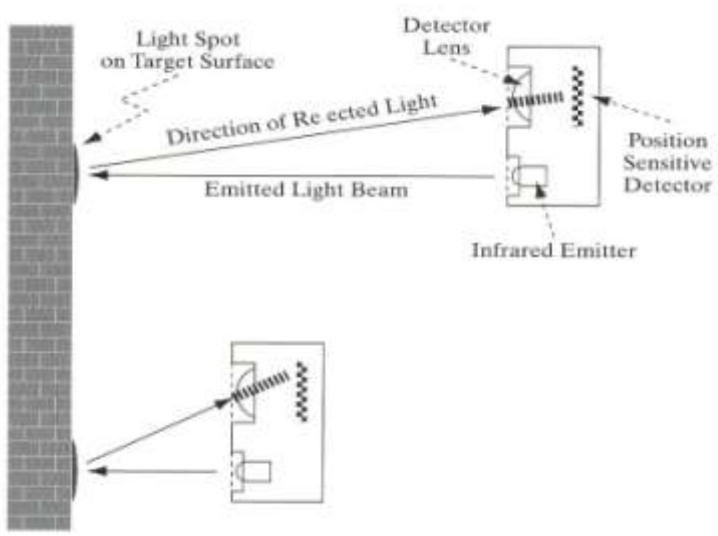
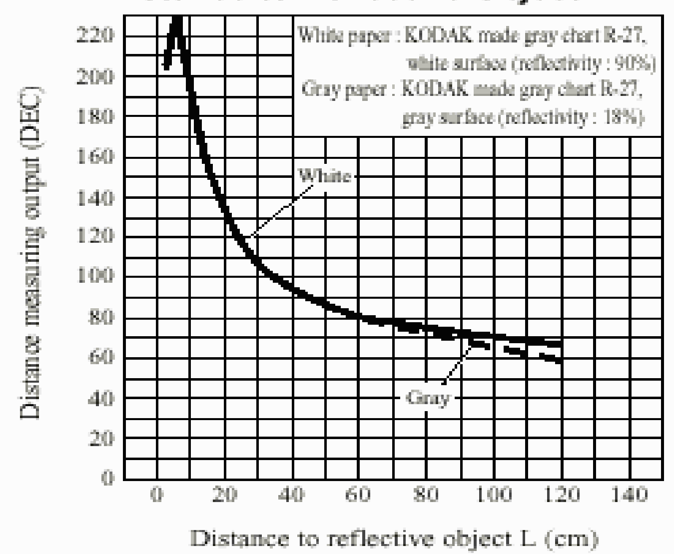
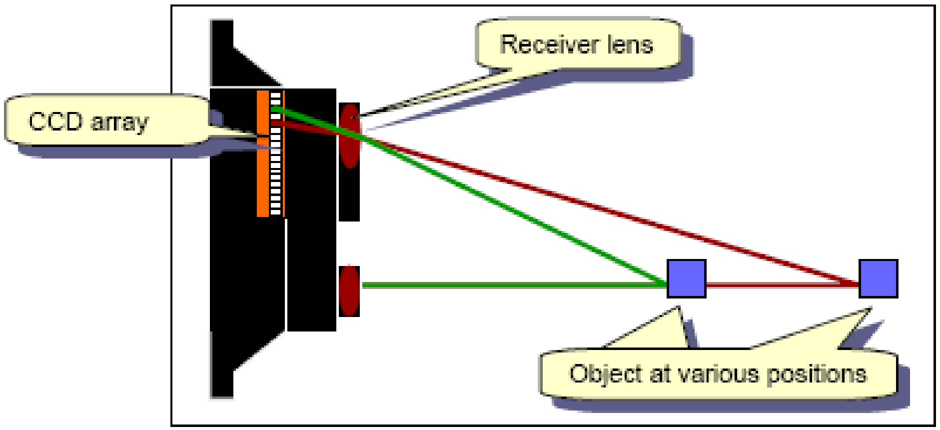


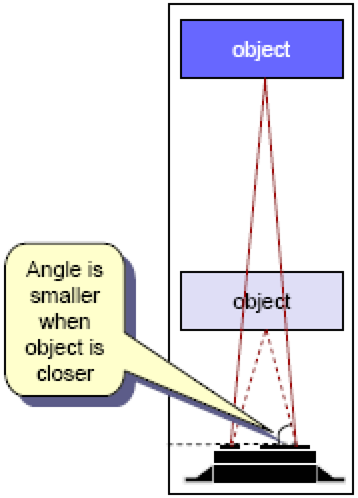
Fig. 1 Distance Measuring Output vs. Distance to Reflective Object



Infrared Range Sensors: Triangulation

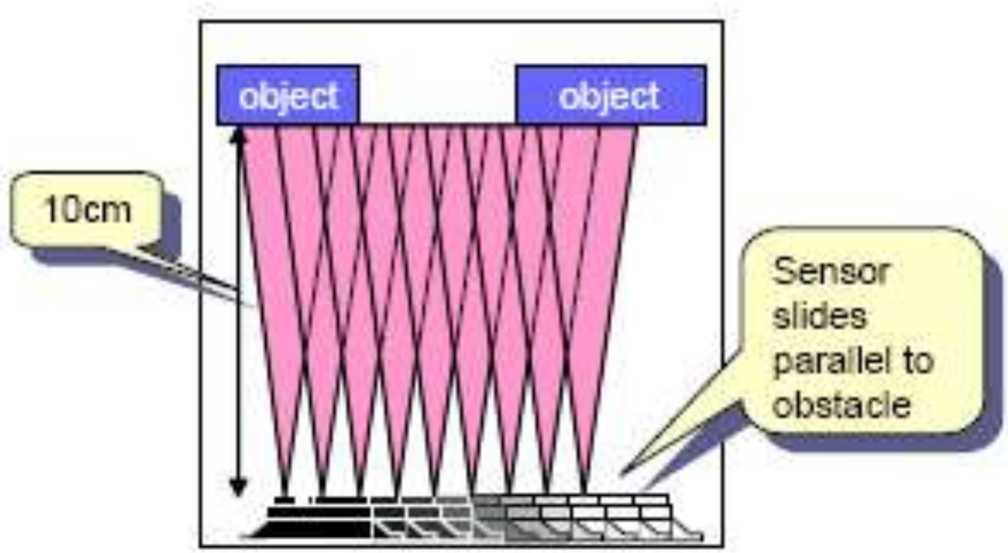
- Senses the angle at which the reflected light is returned to the sensor
- Receiver has a lens that projects the returned light onto a CCD array

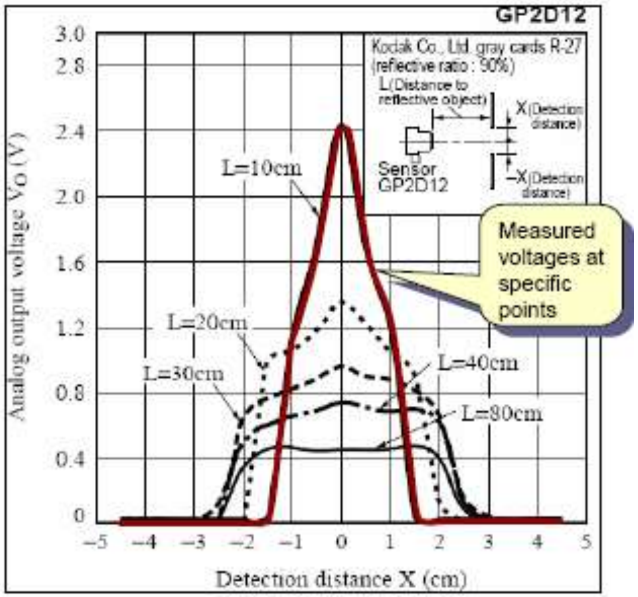




Infrared Range Sensors: Sharp GP2D12

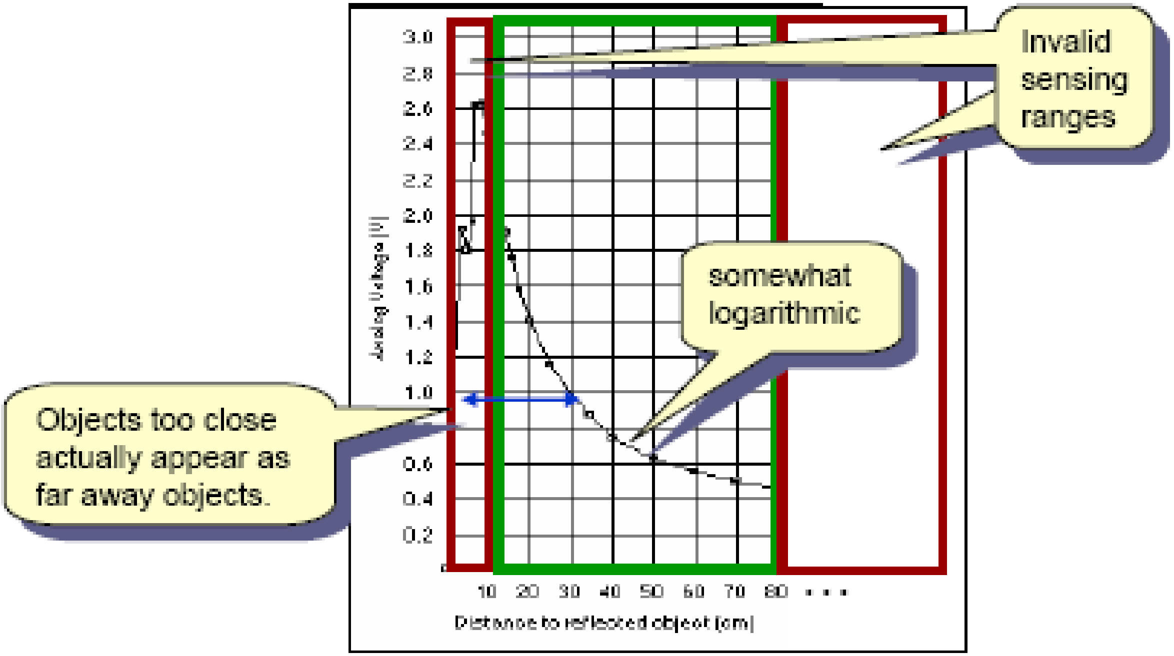
The sensor cannot always distinguish features at far distances





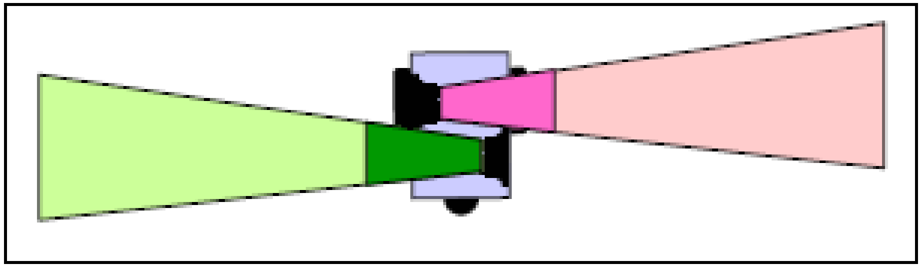
Infrared Range Sensor:
Sharp GP2D12

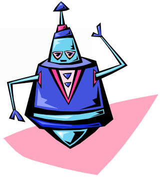
The distance versus voltage graph is nonlinear



Infrared Range Sensors: Collision avoidance range

- Close objects (within 8 cm) are within a dangerous *collision avoidance range*
  - Object may be detected at 12 cm, by the time the robot stops, the object is in 6 cm range
  - The robot will then detect it at 12 cm and think it is still far away form it
- This can be rectified by pushing sensors further back on the robot (*cross firing*)



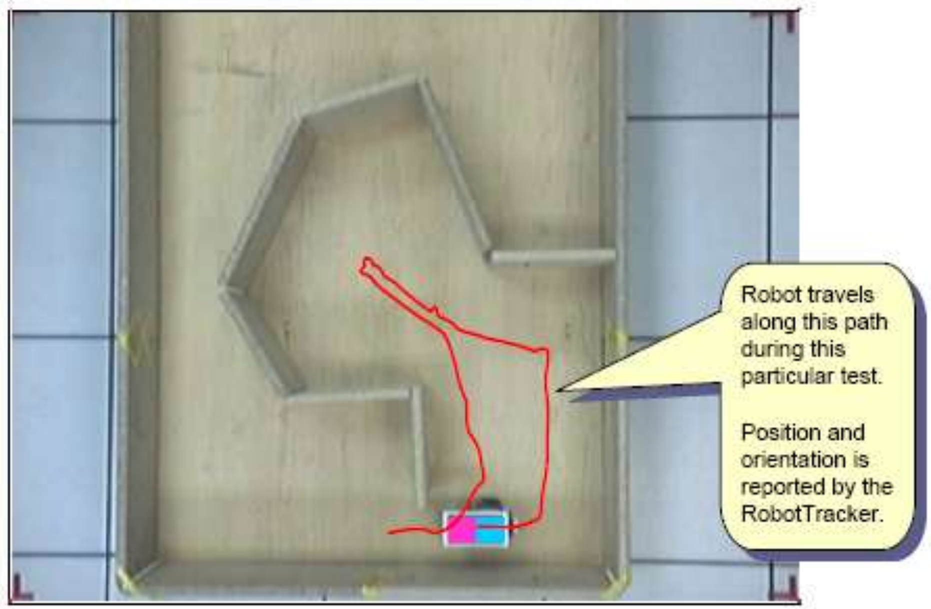


Infrared Range Sensors:
Advantages and Disadvantages

- Advantages
  - Reliable with good precision
  - Small beam angle
  - inexpensive
- Disadvantages
  - Sensitive to smoothness
  - Sensitive to angle to obstacles
  - Short range
  - Prone to interference from ambient light
  - Cannot detect glass, mirror, shiny surfaces

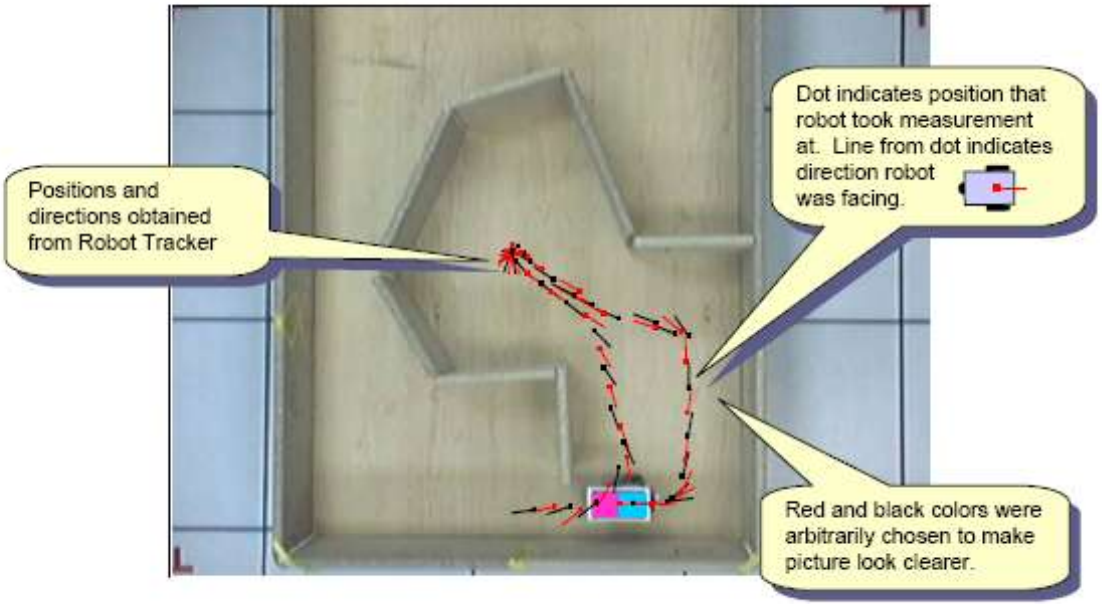
Infrared Sensors: Mapping Example

- Use the IR sensor to compute the range to obstacles along a long a path in the following environment



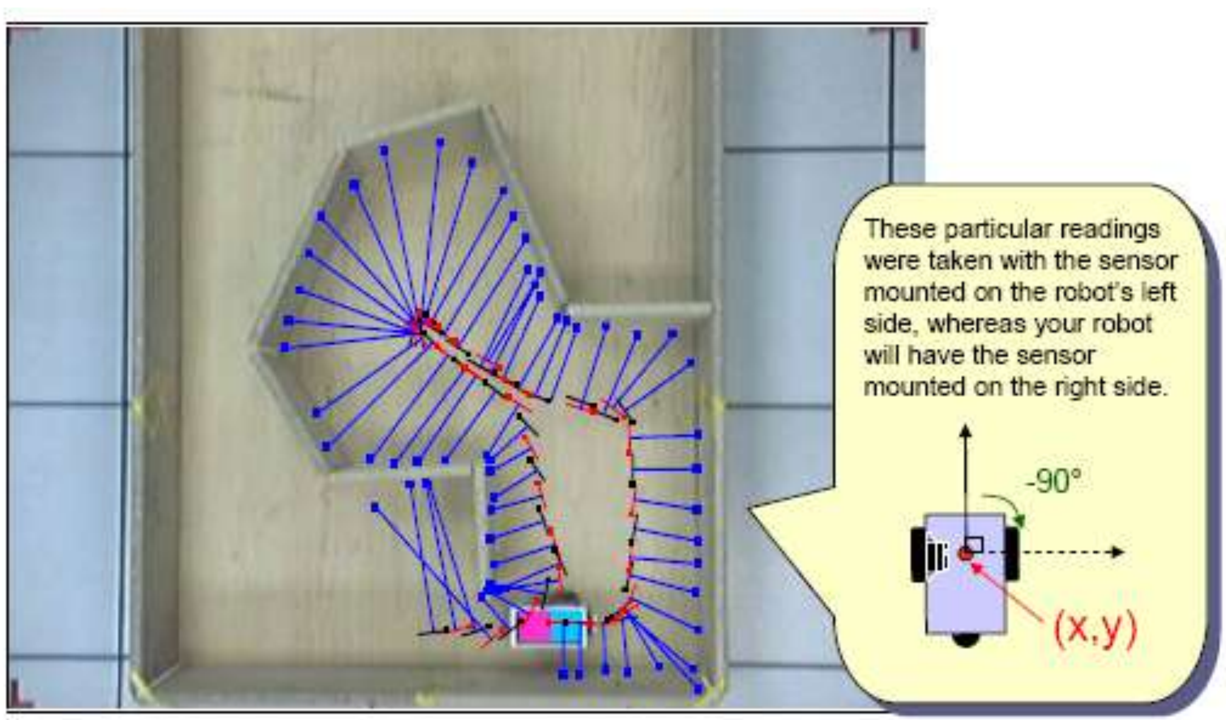
Infrared Sensors: Mapping Example

Take measurements along the path at particular locations



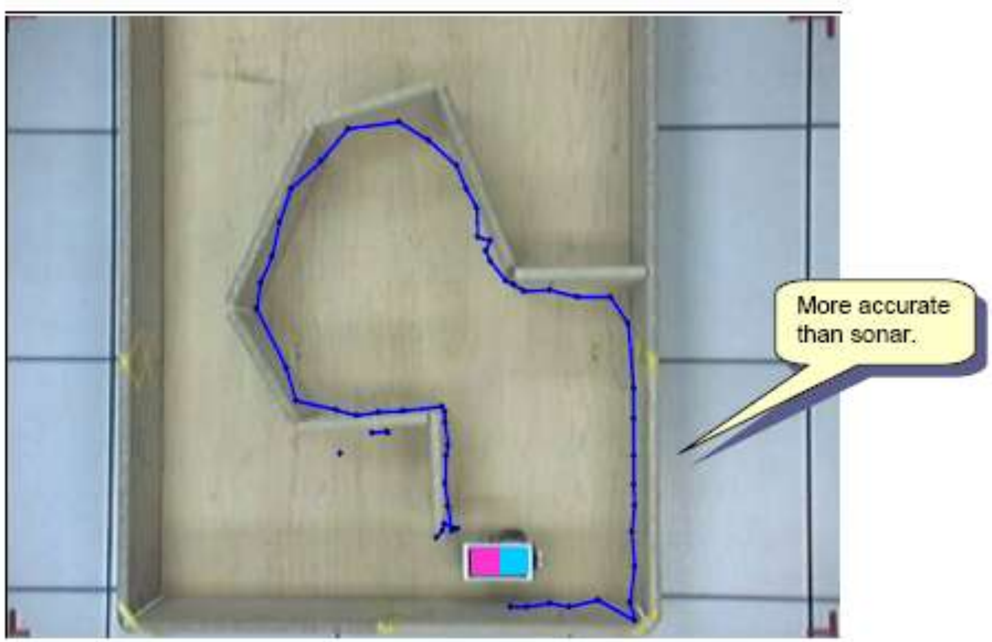
Infrared Sensors:
Mapping Example

Blue lines show readings to obstacles form the robot's center position (x, y)



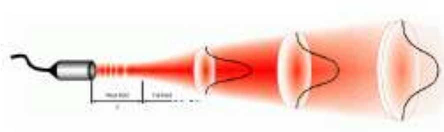
Infrared Sensors: Mapping Example

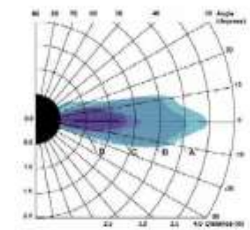
- The resulting map has reasonable accuracy
- The map can be refined by taking additional readings

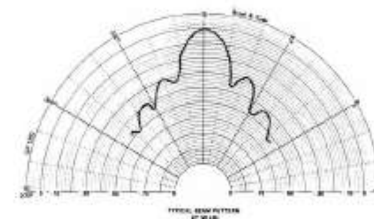


Ultrasonic Sensors

SONAR



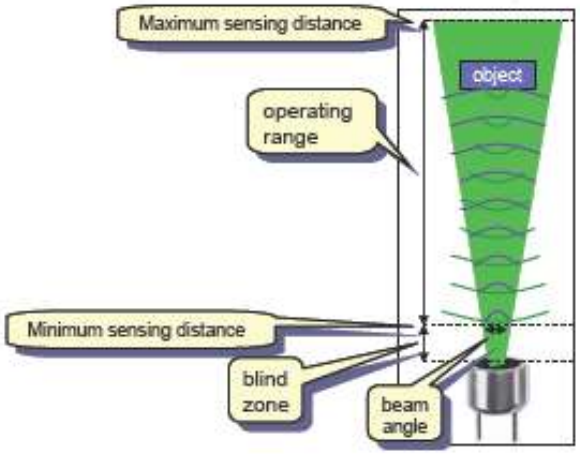




- *Sound Navigation and Ranging*
  - bounce sound off of objects
  - measure time for reflection to be heard - gives a range measurement
  - It measures change in frequency and gives the relative speed of the object (Doppler effect)
  - bats and dolphins use it with amazing results
  - robots use it 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(4.1.6)

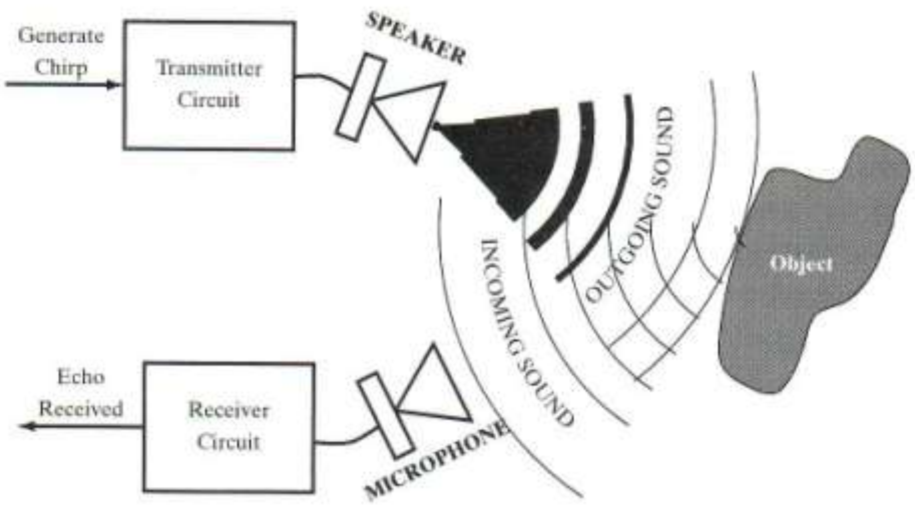
- Basic principle of operation:
  - Emit a quick burst of ultrasound
  - Measure the elapsed time until the receiver indicates that an echo is detected.
  - Determine how far away the nearest object is from the sensor

d = ct

d = round trip distance

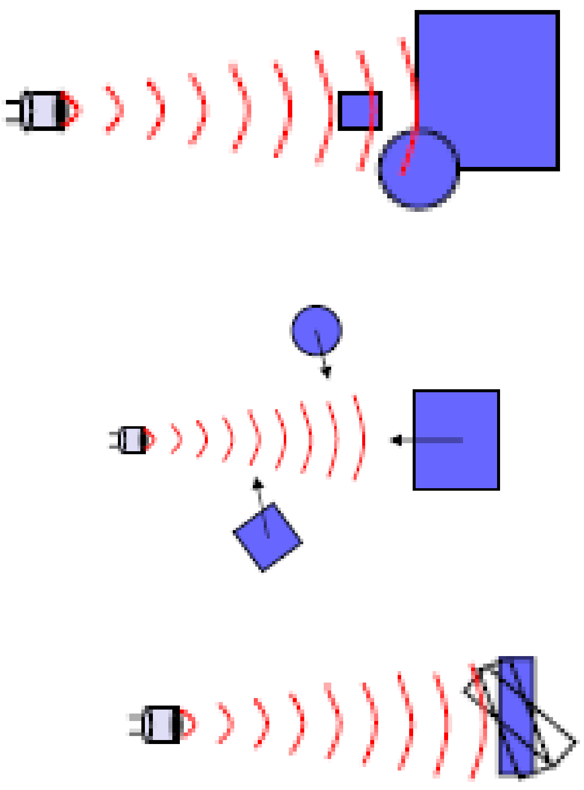
c = speed of sound (340 ms)

T = time of flight

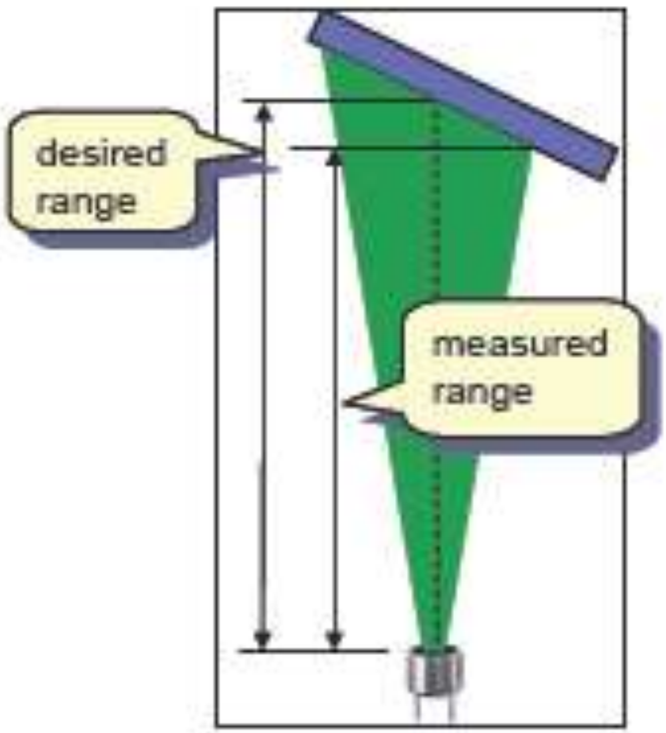


Ultrasonic Range Sensors

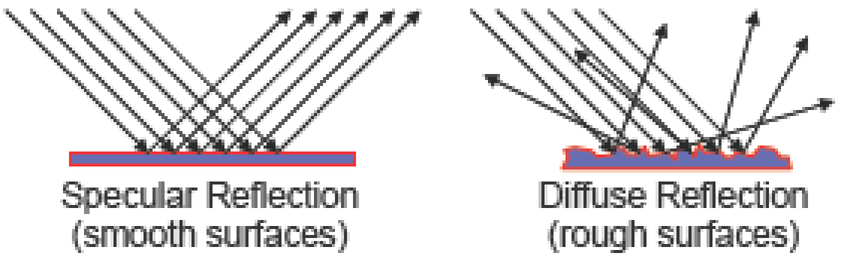
- **Sensor readings vary based upon:**
  - Distance to object(s)
  - Angle that object makes with respect to sensor axis
  - Direction that objects enter sensing range



Ultrasonic Range Sensors: Sensitivity

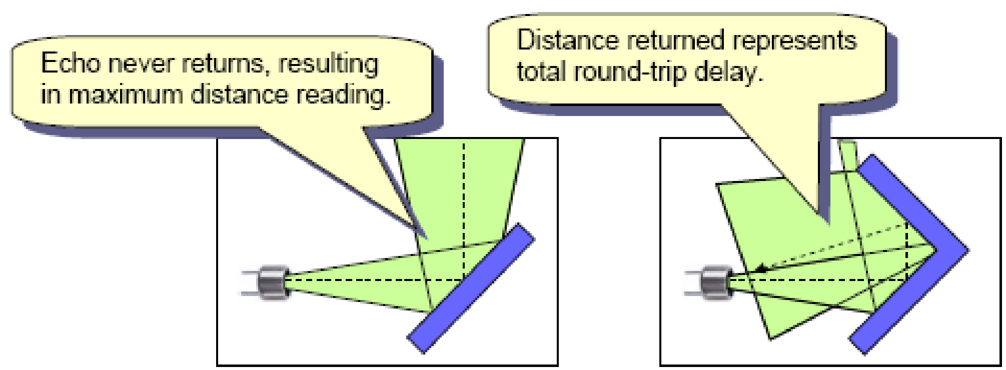


- *Sensitivity* to obstacle angle can result in improper range readings
- When the beam angle of incidence falls below a certain critical angle *specular reflection* errors occur



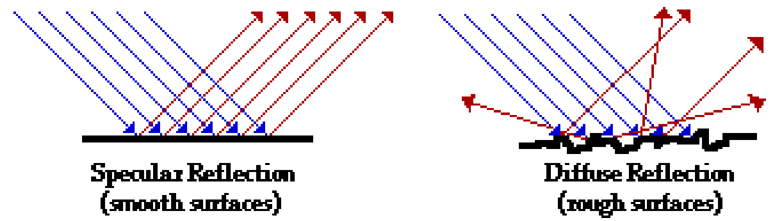
Ultrasonic Range Sensors: Specular Reflection

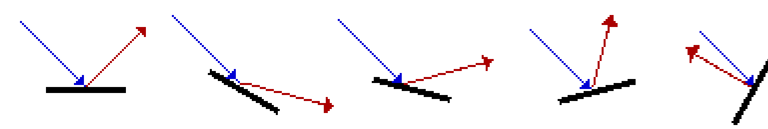
- Specular reflection can cause reflected sound to
  - Never return to the transducer
  - Return to the transducer too late
- The results is that the distance measurement is too large and inaccurate

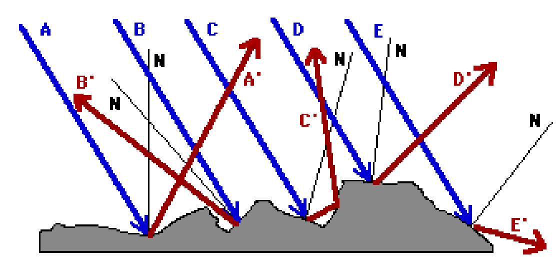


Reflectance

- 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

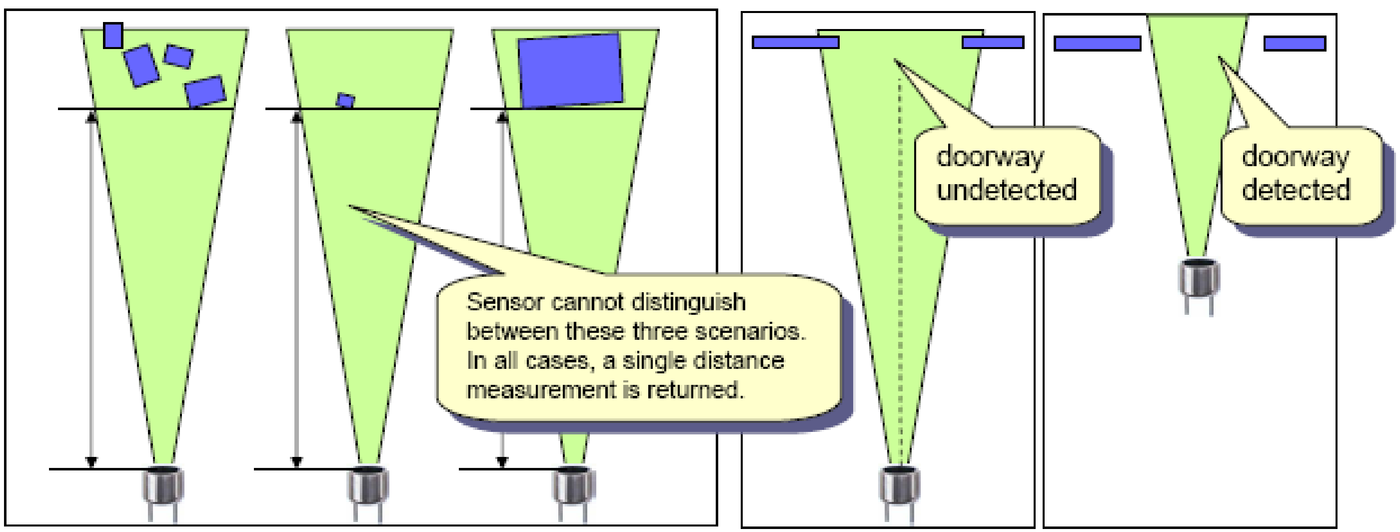




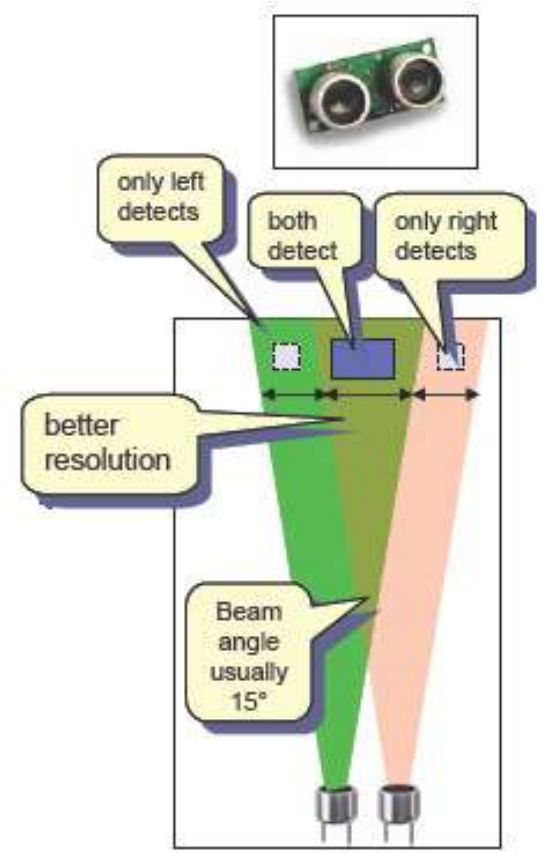


Ultrasonic range sensors: Resolution

- 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



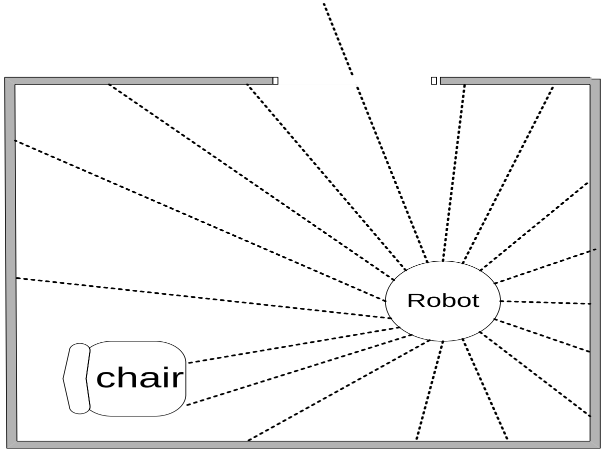
Ultrasonic Range Sensors: Redundancy

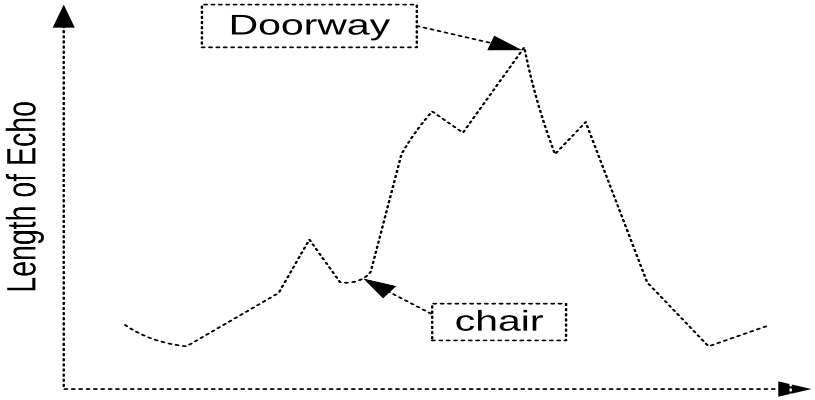


- To increase beam width (*resolution*), two sensors are used together
- Detection in either or both sensors allows for increased resolution

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





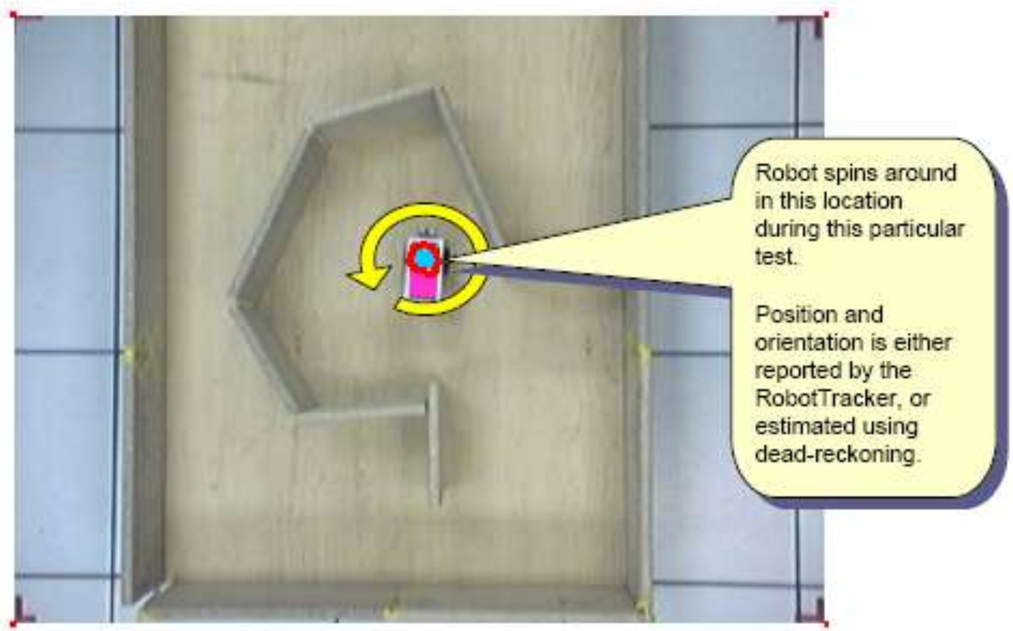
Ultrasonic Range Sensors: Mapping

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



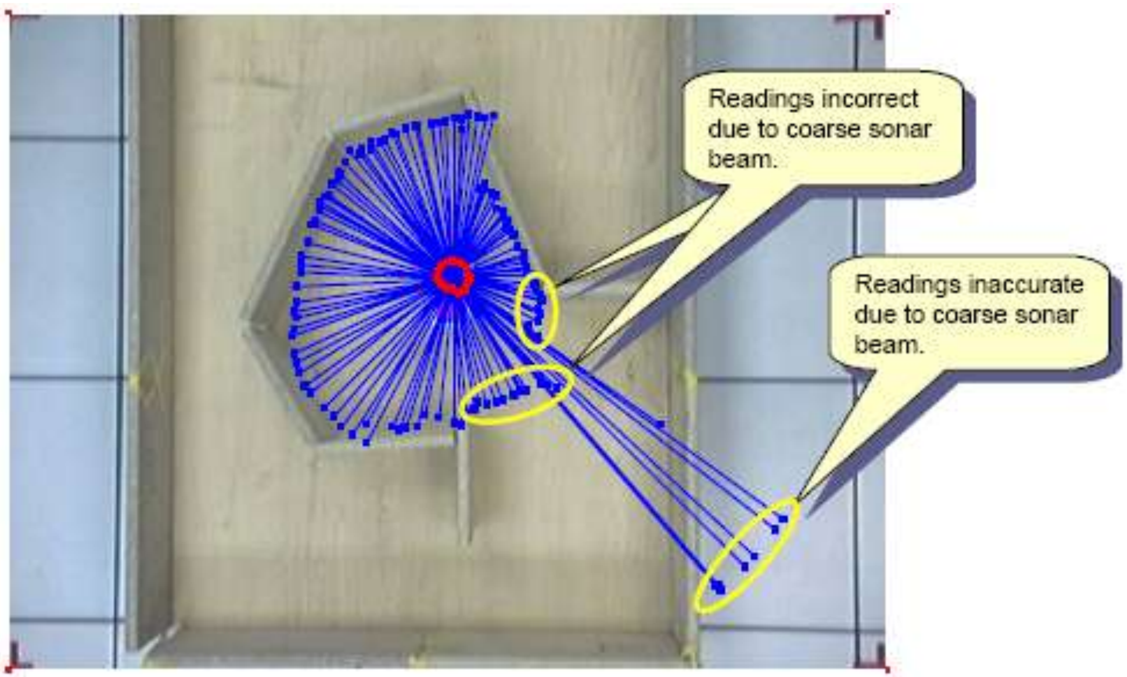
Ultrasonic Range Sensors: Mapping Example

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



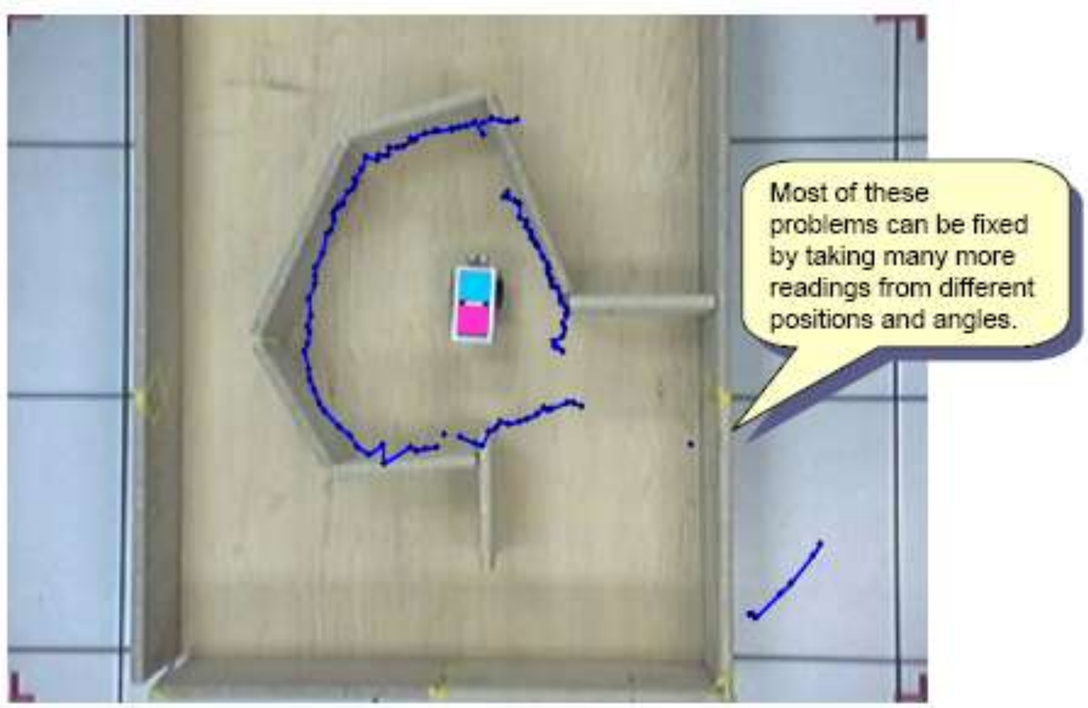
Ultrasonic Range Sensors: Mapping Example

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



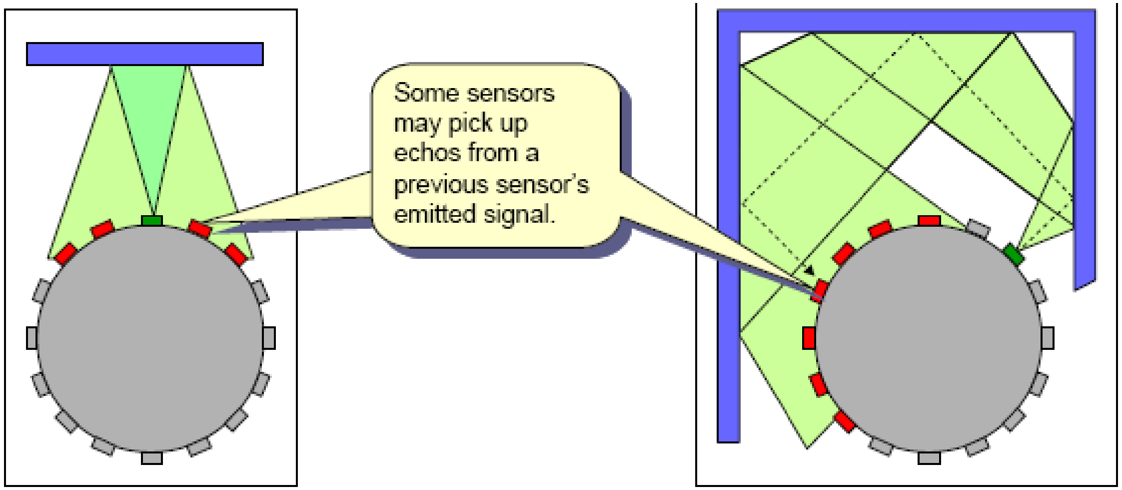
Ultrasonic Range Sensors: Mapping Example

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



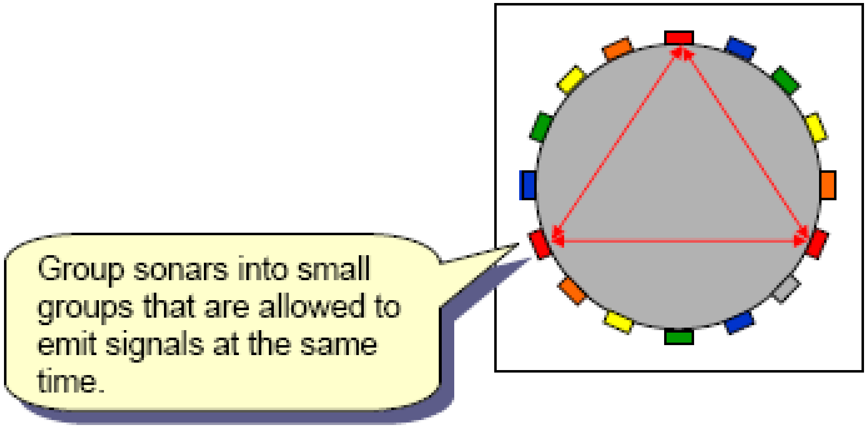
Ultrasonic Range Sensors: Crosstalk

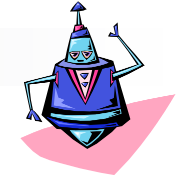
- Using multiple fixed sensors can lead to *crosstalk*
- *Crosstalk* is interference in which echoes emitted from one sensor are detected by others



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

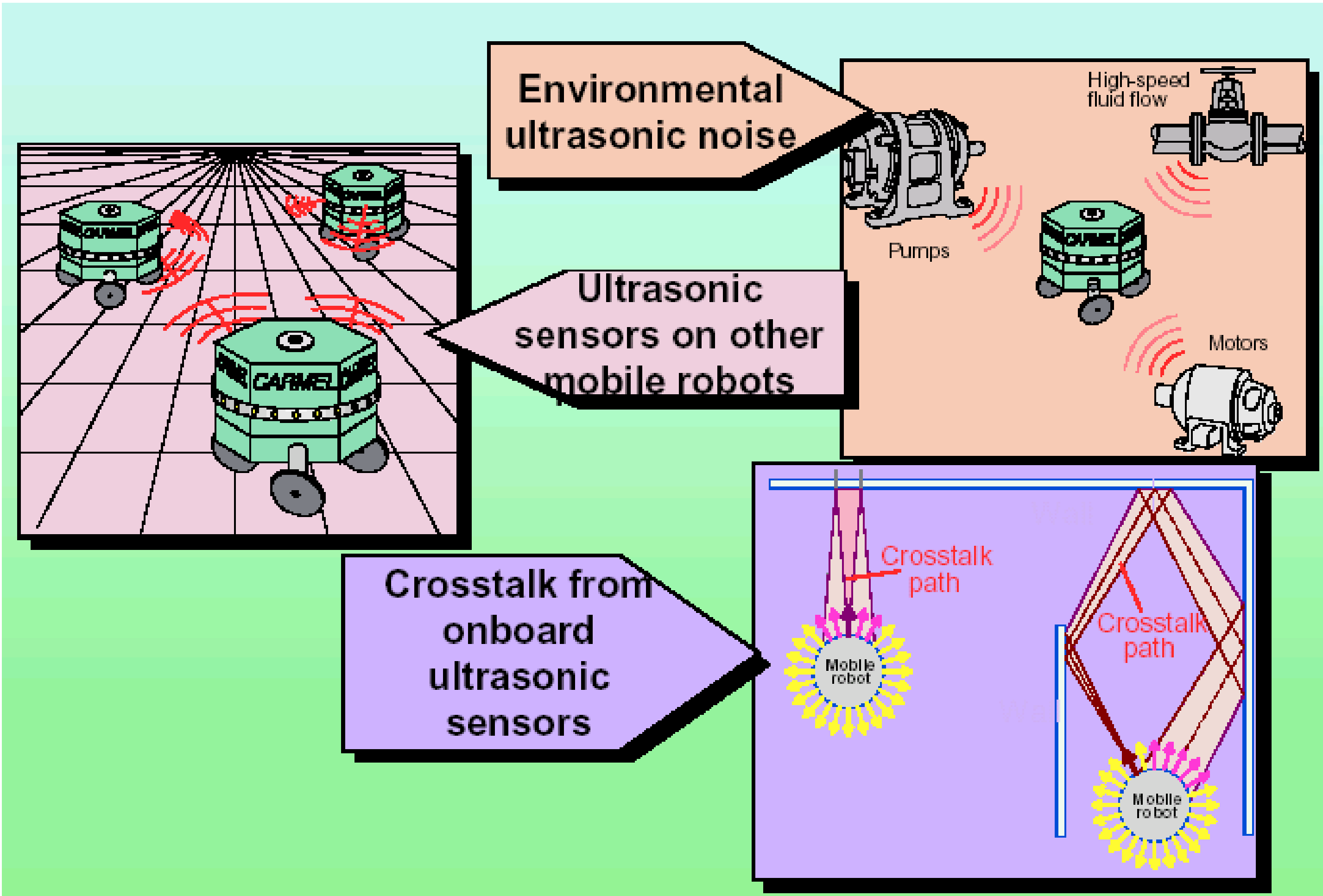




Ultrasonic Range Sensors: Advantages and Disadvantages

- 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

Ultrasonic Sensors: Noise Issues



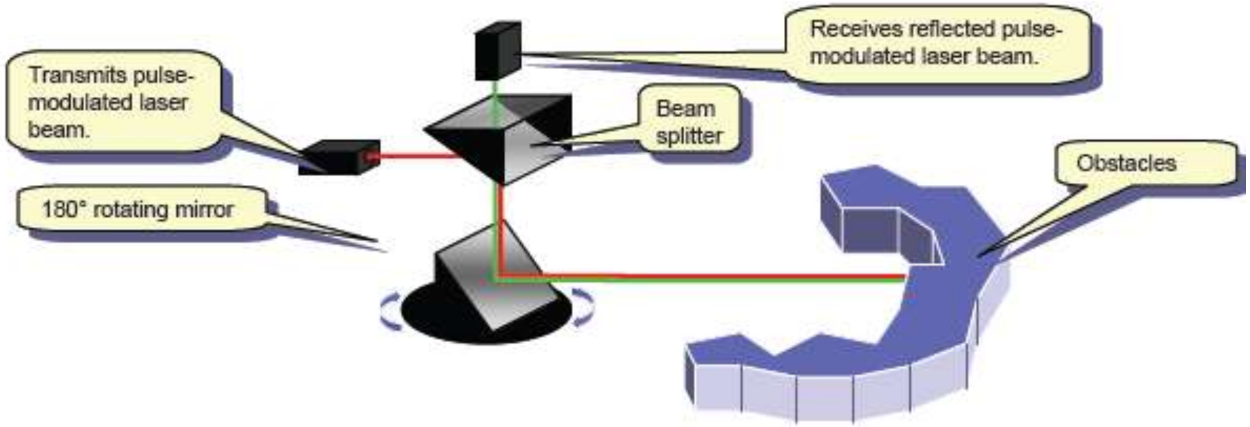
Laser Range Finders

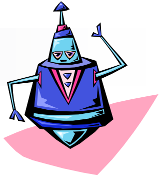
Laser Range Finders

- 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

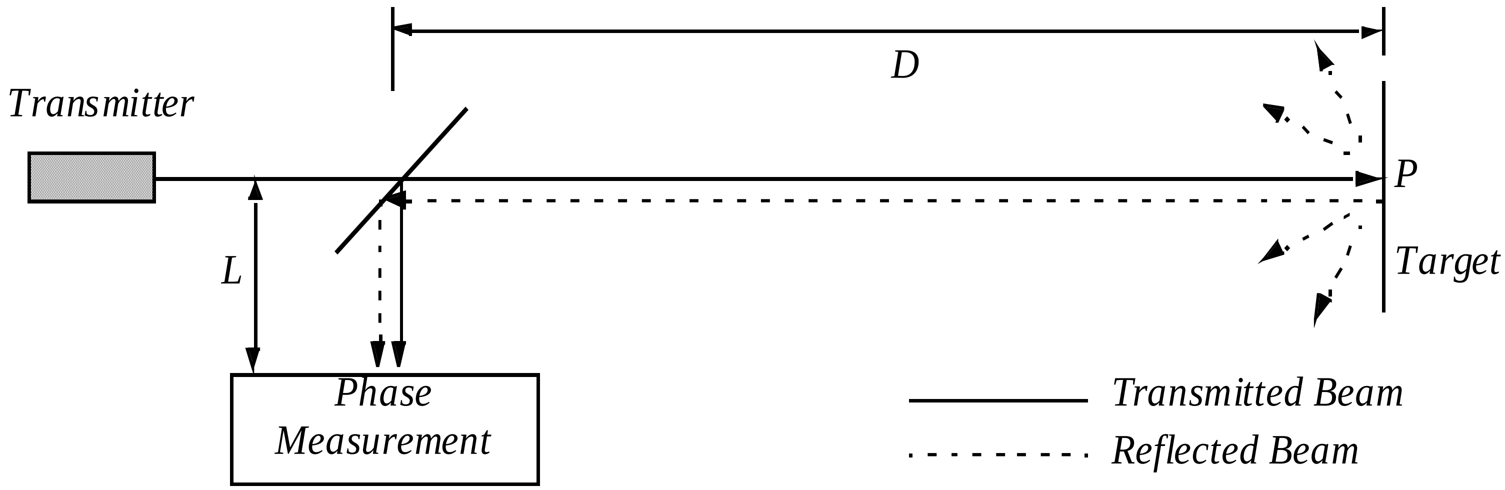




Laser Range Finders:
Range Calculation

- Range calculated as $r = ct/2$, where
  - t = time taken for light to return
  - c = speed of light $\approx 3\times10^8$ 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)*

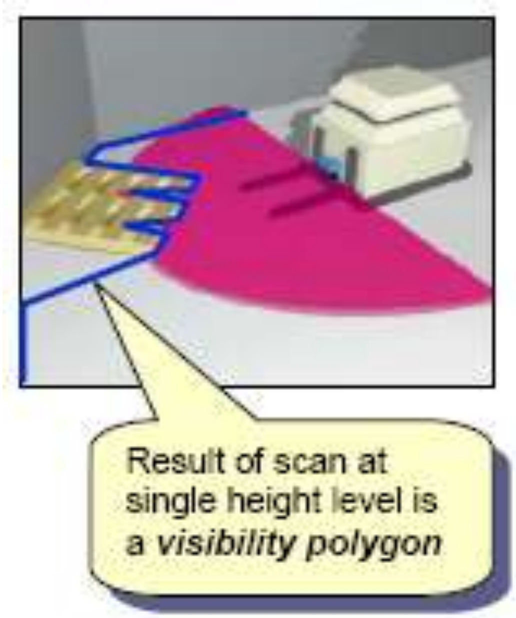
Laser Range Sensor (4.1.6)



- 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

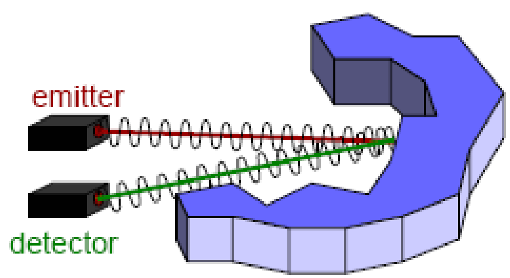
Laser Range Finders: Accuracy

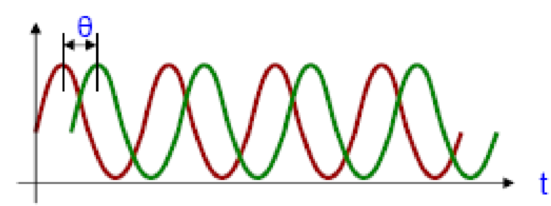
- Accuracy
  - ±1.5 cm in short range (1m – 8m)
  - ±4.0 cm in long range (8m – 20m)
- Typically measures ranges up to 50m
- Scanning at multiple heights, produces contour lines that can be stacked to form a model



Laser Range Finders:
AMCW sensors

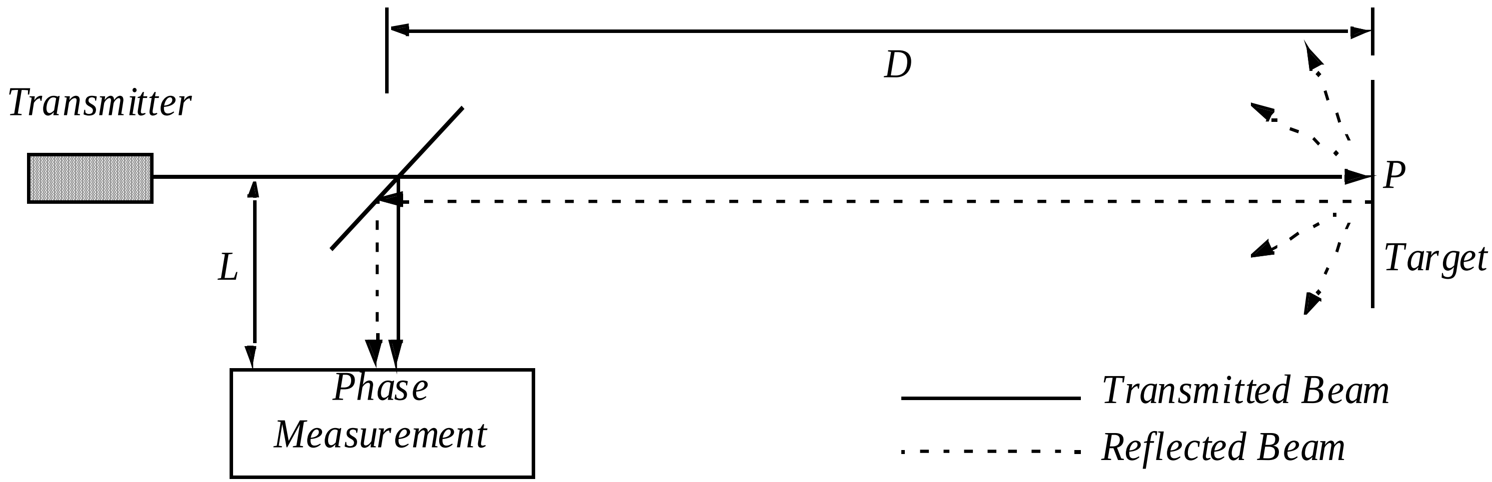
- Emitter sends out a continuous modulated laser signal
  - Intensity of beam is modulated using a wave pattern (i.e. sinusoid)
  - Detected light has the same amplitude but is phase shifted
  - Difference in phase shift indicates the range
  - Range calculated is $r = \theta c/(4\pi f)$, where
    - 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 (4.1.6)



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

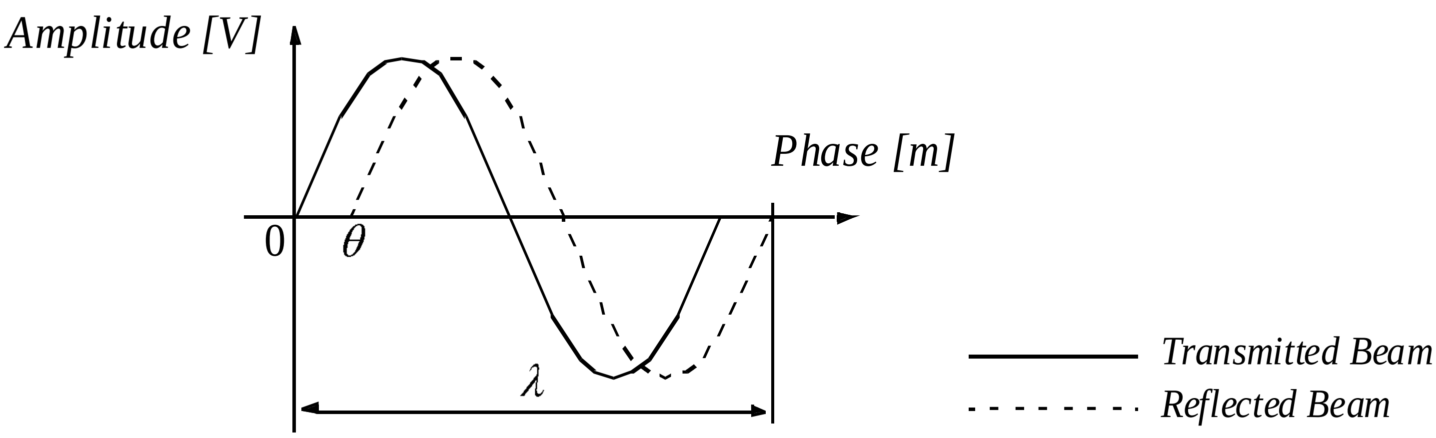
for f = 5 Mhz (as in the A.T&T. sensor), λ = 60 meters

Laser Range Sensor (4.1.6)

D is the distance between the beam splitter and the target

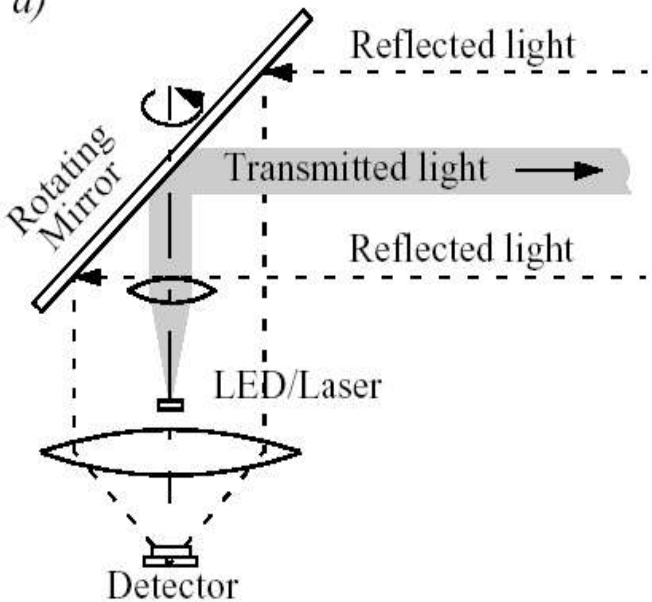
$$D = \lambda\theta/(4\pi) \quad (2.33)$$

where θ is the phase difference between the transmitted signal



Laser Range Sensor: 3 types

a)



Laser with rotating mirror

b)

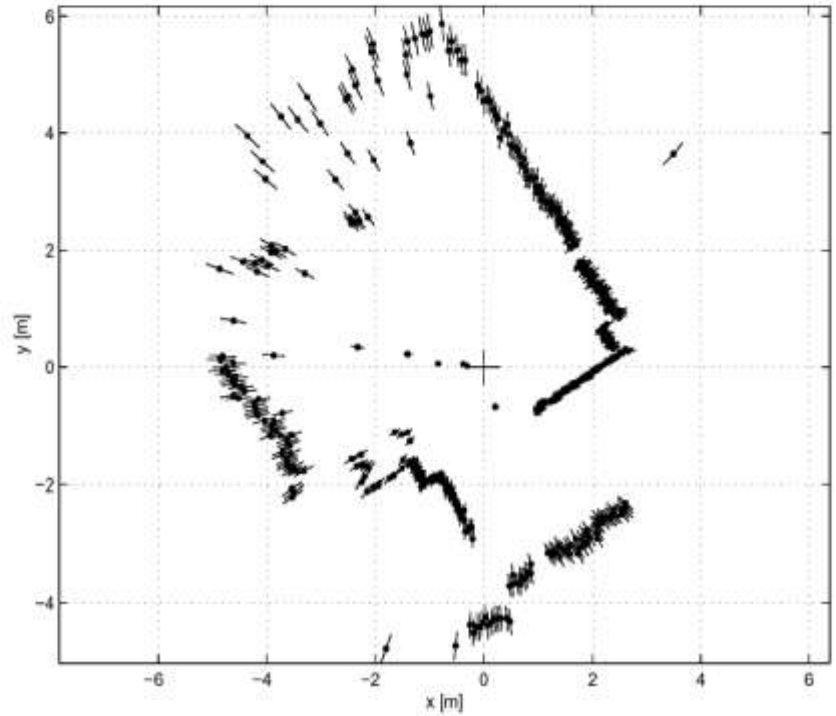
Scanning range sensor

c)

180° laser range sensor

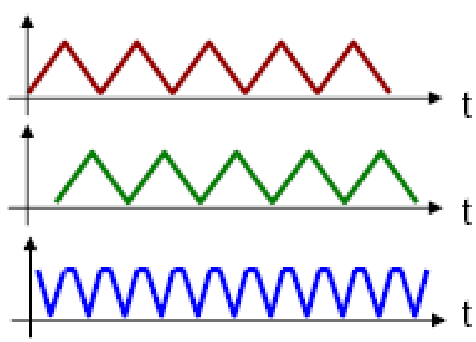
Laser Range Sensor (4.1.6)

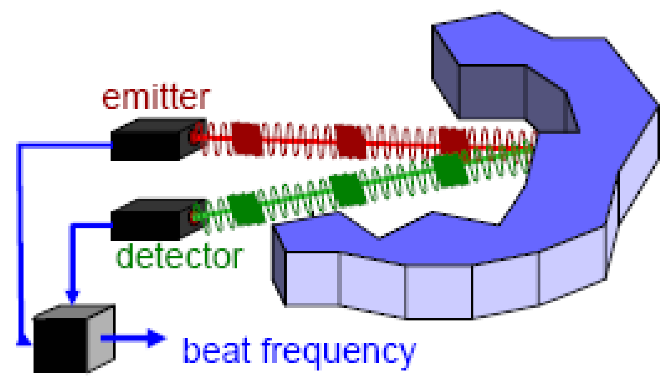
Typical range image of a 2D laser range sensor with a rotating mirror. The length of the lines through the measurement points indicate the uncertainties.



Laser Range Finders:
FMCW sensors

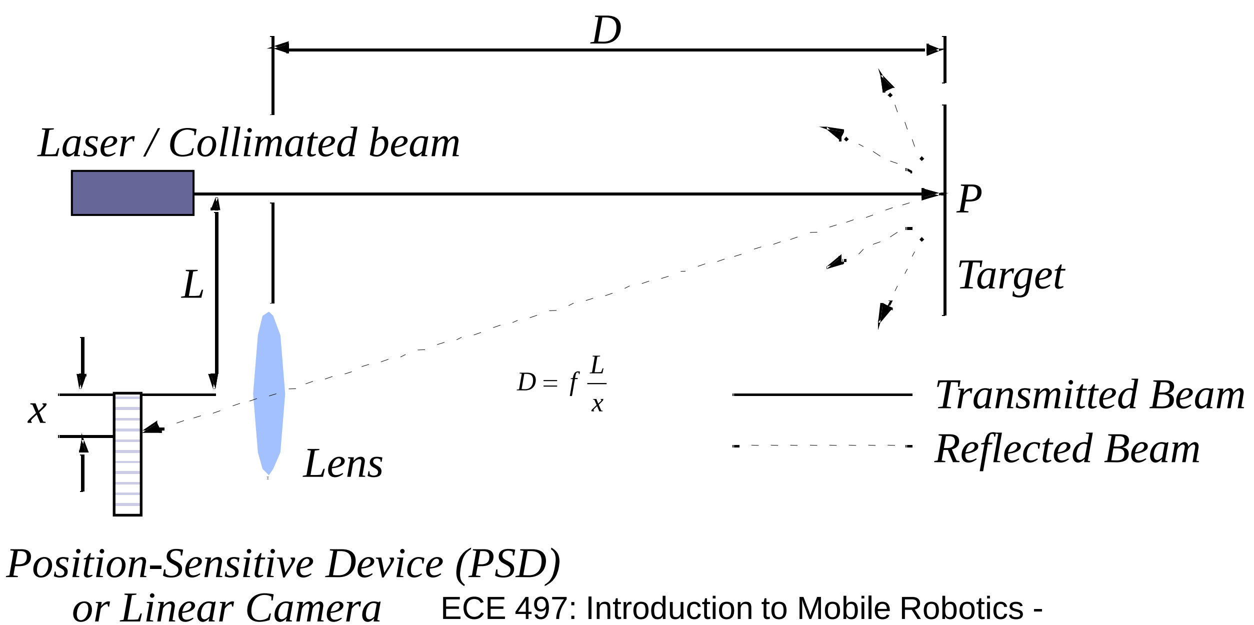
- AMCW is simpler and hence lower cost laser
- Resolution is limited by modulating frequency
- FMCW sensors emit a continuous laser beam, but is modulated by *frequency*
  - Emitted signal is mixed with the reflected signal
  - The result is a difference in frequency





Optical Triangulation (1D Sensor)

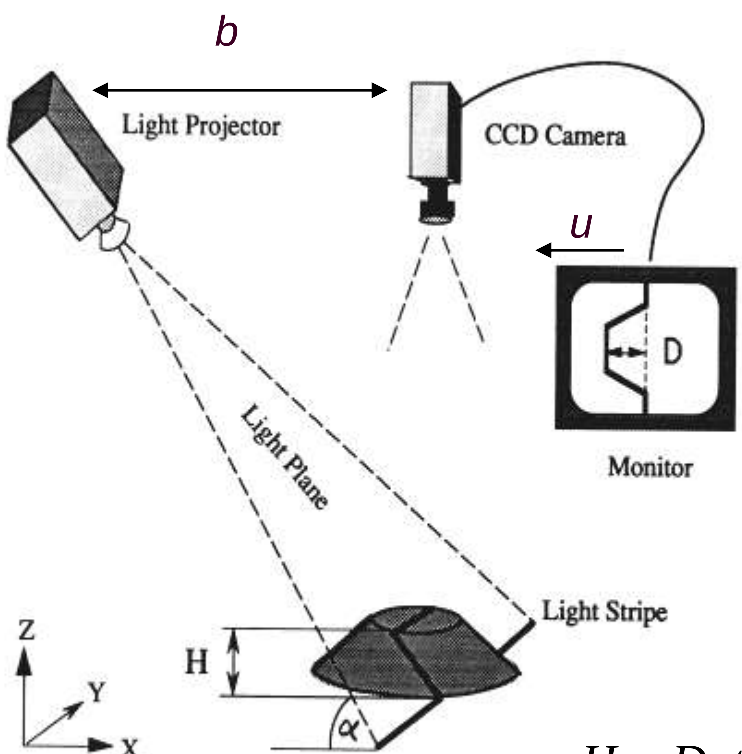
- *Triangulation-based* ranging sensors use geometric properties to measure the distance to objects
- $D = f \cdot L/x$
- Sensor resolution is best for close objects



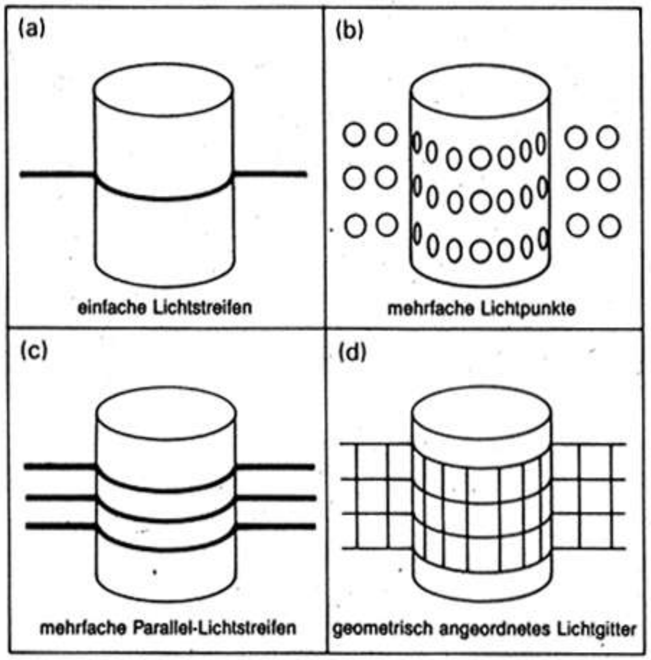
Structured Light (vision, 2 or 3D)

- *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)

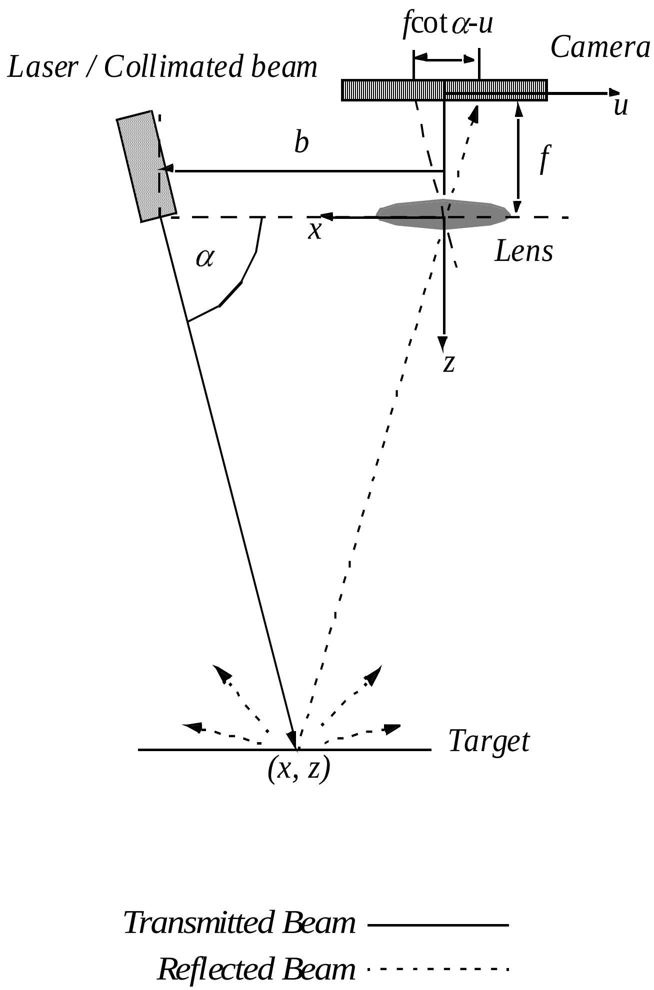


$$H = D \cdot \tan\alpha$$

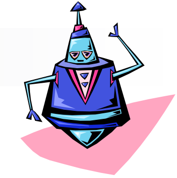


Structured Light (vision, 2 or 3D)

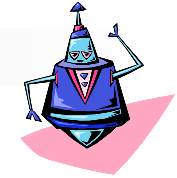
$$x = \frac{b \cdot u}{f\cot\alpha - u} \; ; \quad z = \frac{b \cdot f}{f\cot\alpha - u}$$



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



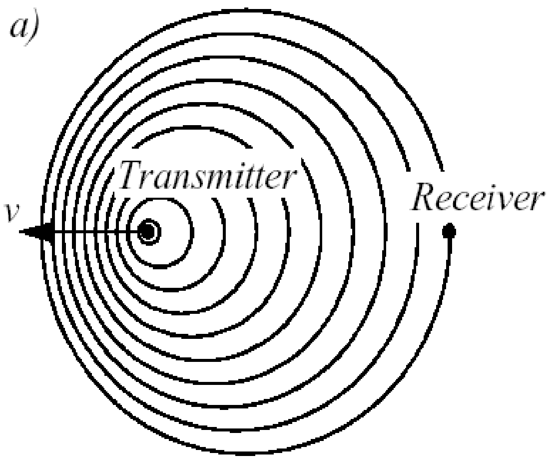
Motion/Speed Sensors

Motion/speed sensors (4.1.7)

- *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 (4.1.7): Doppler Effect Based (Radar or Sound)

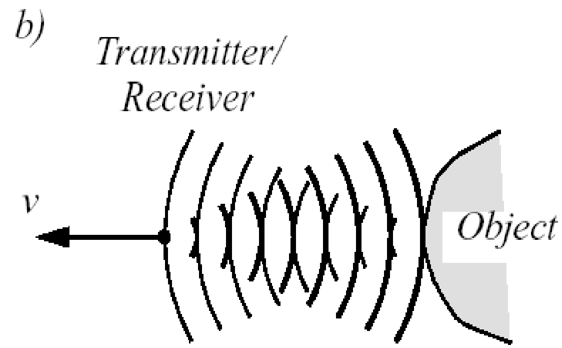
- A transmitter emits and electromagnetic or sound wave with a frequency f_t
- It is either received by a receiver or reflected from an object
- The measured frequency f_r at the receiver is a function of the relative speed v between the transmitter and receiver *(Doppler frequency)*



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

Motion Sensor (4.1.7): 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



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

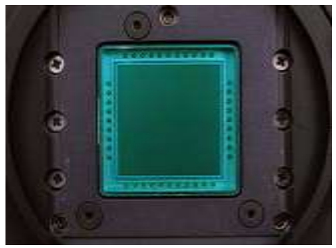
$$\Delta f = f_t - f_r = \frac{2 f_t v \cos\theta}{c}$$

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

Stereo Camera Ranging System

Vision-based Sensors: Hardware (4.1.8)

- 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*)

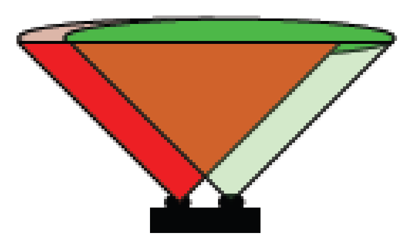
Vision ranging sensors (4.1.8)

- 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

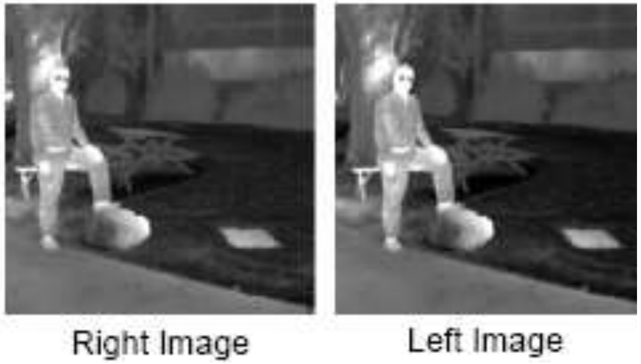
- Similar to laser, robots with stereo cameras can obtain 3D range maps of the environment
- Usually implemented with 2 cameras or one used from multiple locations

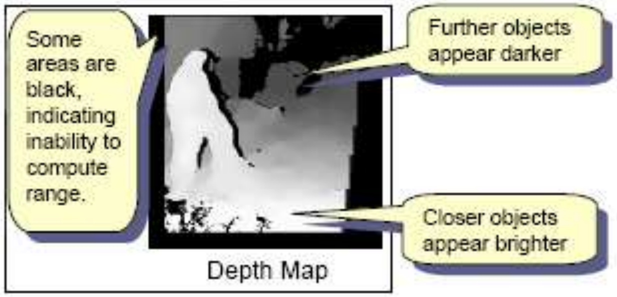
- Resolution
  - 640 x 480 frames/s
  - 1024x768 frames/s
- Camera covers roughly a 45° cone



Stereo Ranging Systems: Goal

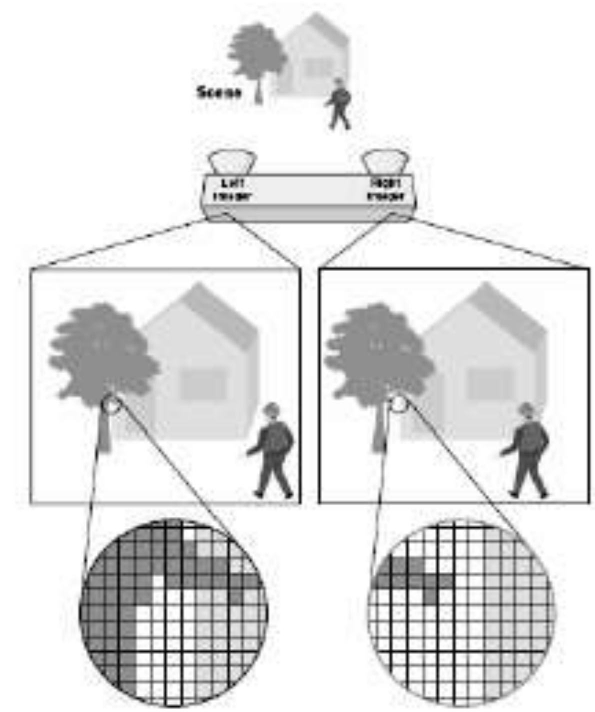
- Calculate the depth or distance of features in an image relative to the sensors (construct a *depth map*)
  - Use images from dual cameras aimed at the same object
  - Locate the same 'feature' in both images
  - Use geometric relationships between the 2 cameras and the location of the feature in each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





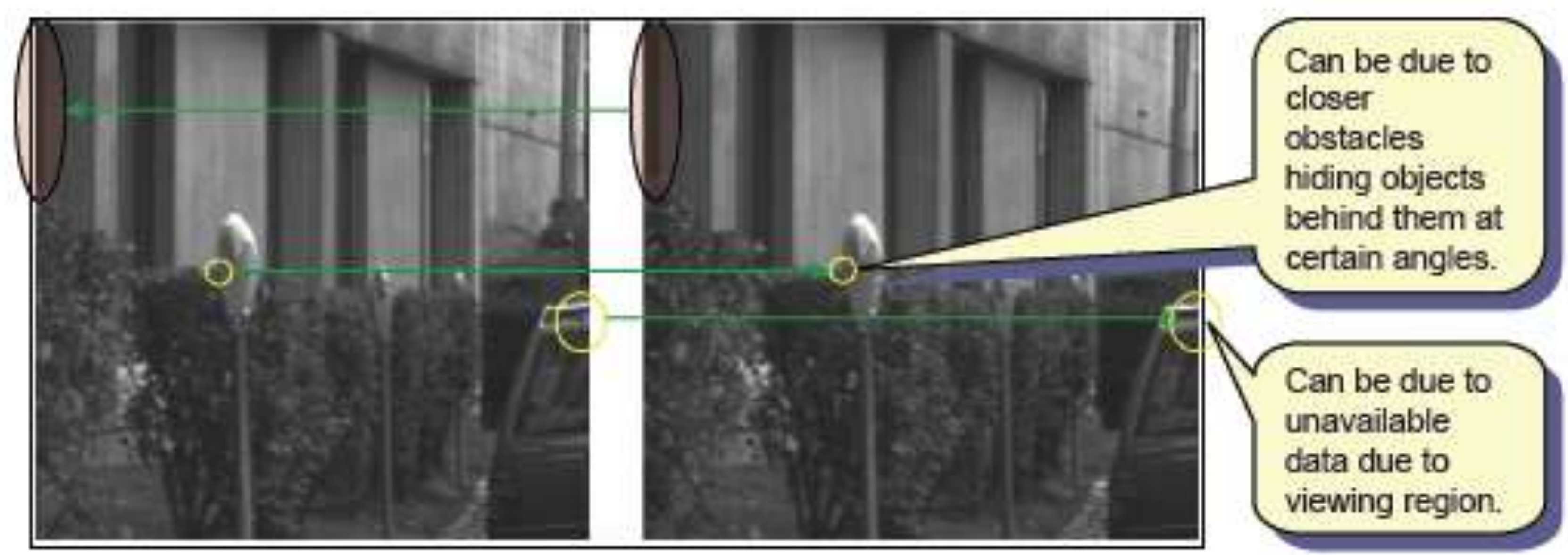
Stereo Ranging Systems:
Stereo Vision

- 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*)



Stereo Ranging Systems: Stereo Vision

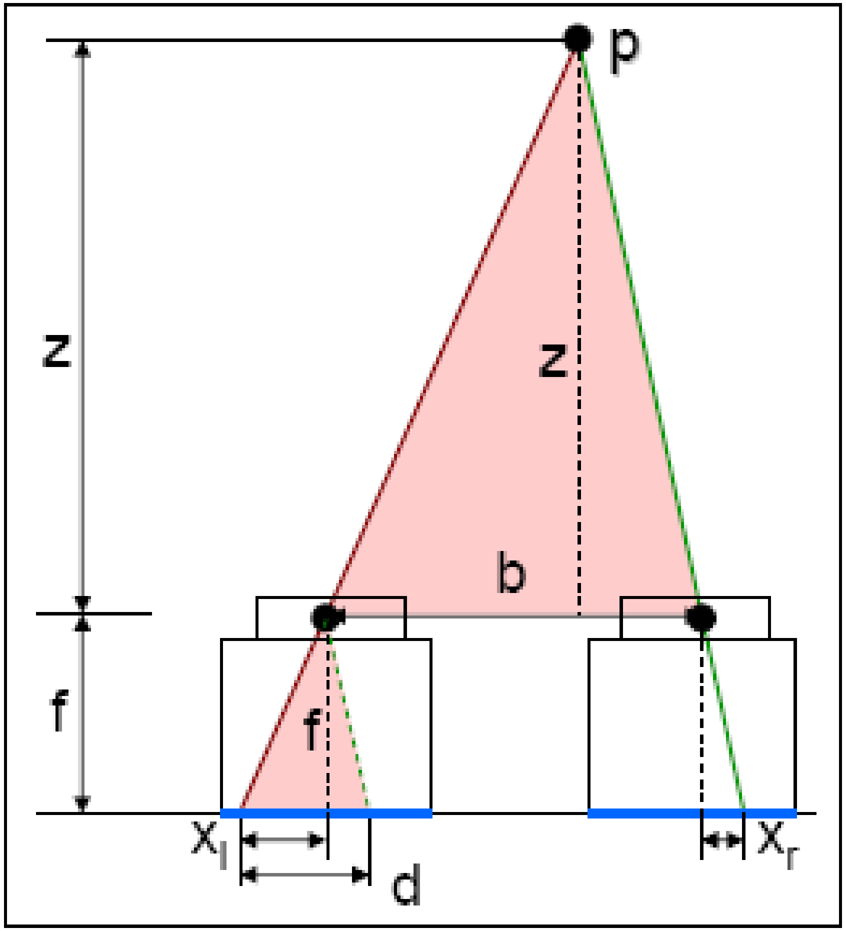
- If cameras are point in the same direction and are aligned use geometry
  - b = baseline of camera
  - z = depth of point p
  - d = disparity = $x_l - x_r$
  - f = focal point of cameras
- The 2 shaded triangles are *similar*, so

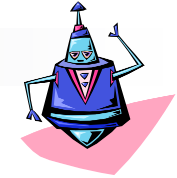
$$z = (f*b)/d$$

$$y_l = y_r = yf/z$$

$$x_l = fx/z$$

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

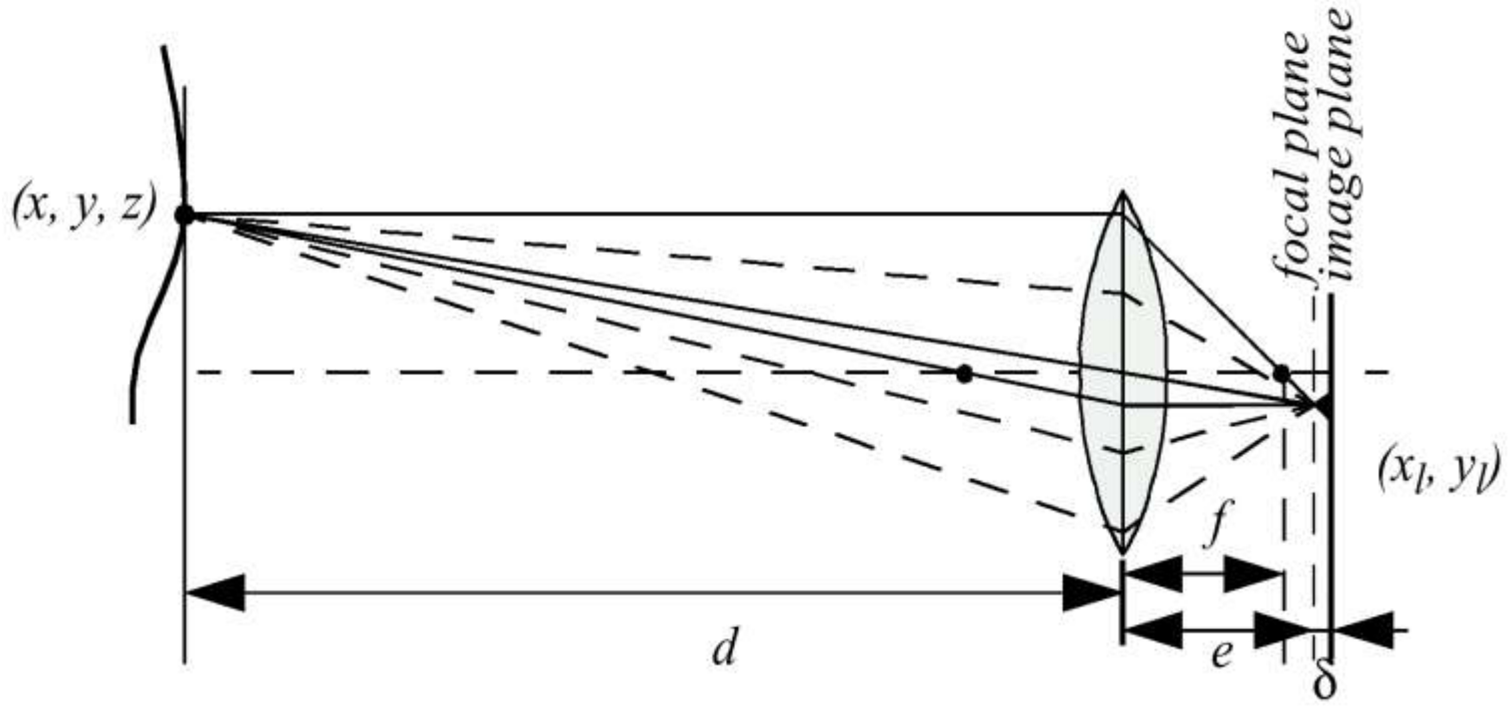




Stereo Ranging Systems:
Stereo Vision

- 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

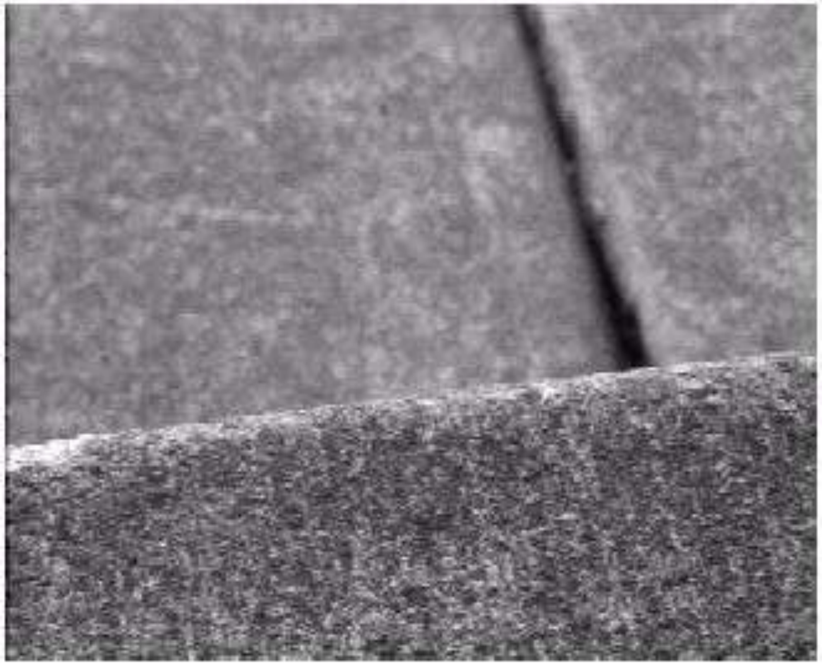
Depth from Focus

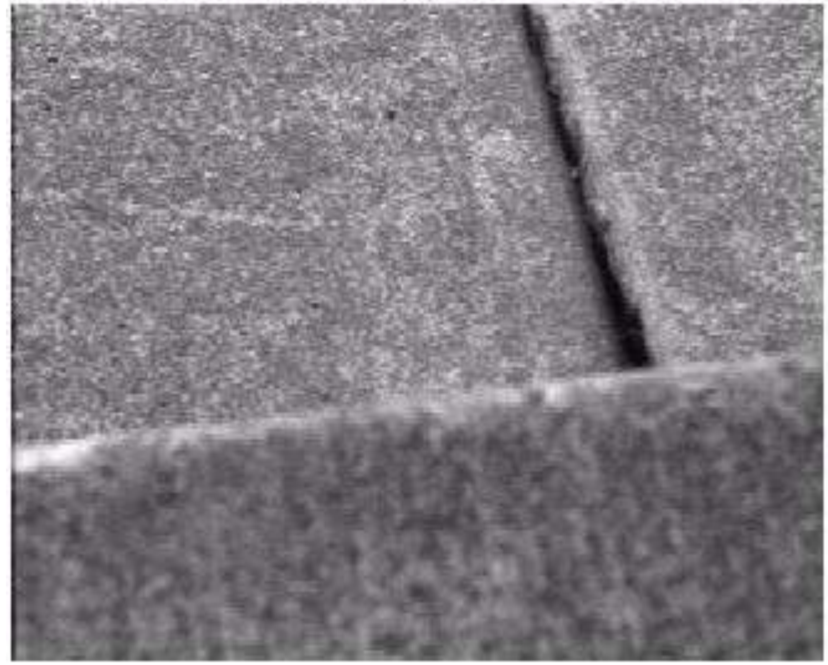


$$\frac{1}{f} = \frac{1}{d} + \frac{1}{e}$$

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

Depth from Focus (4.1.8)





Measure of sub-image gradient:

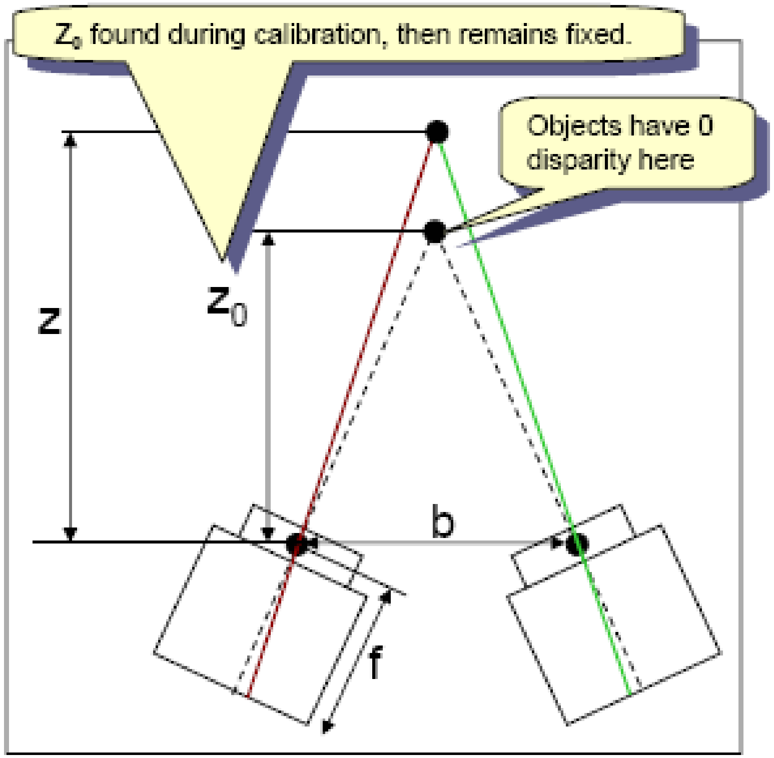
$$sharpness_1 = \sum_{x,y} |I(x,y) - I(x-1,y)|$$

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

Stereo Ranging Systems: Stereo Vision

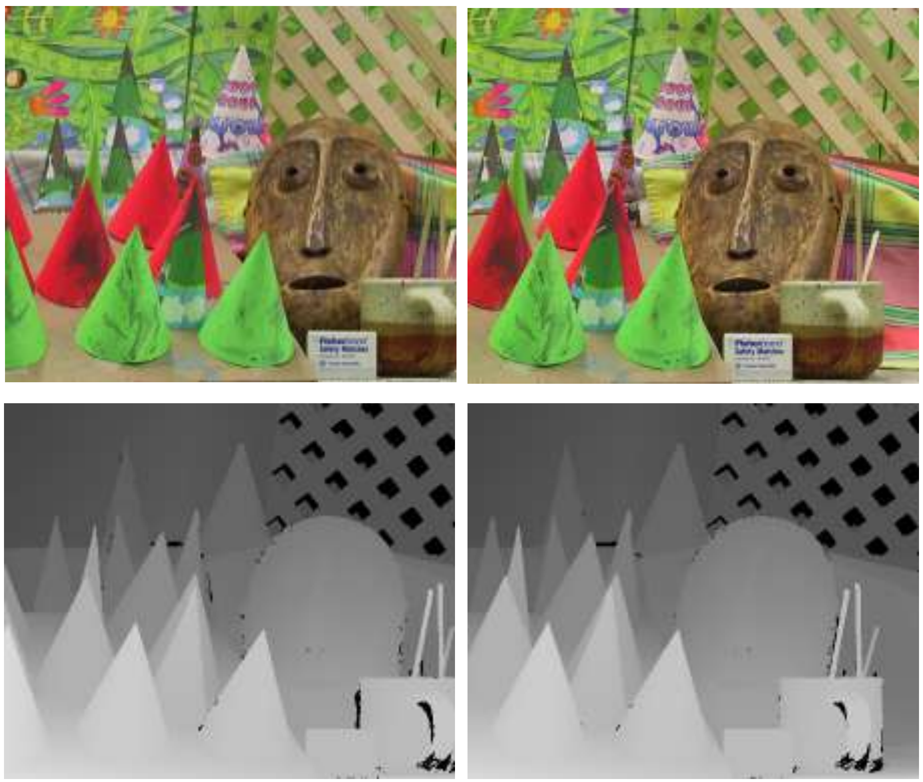
- A more realistic scenario is when the cameras do not lie on the same plane

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



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 (4.1.8)

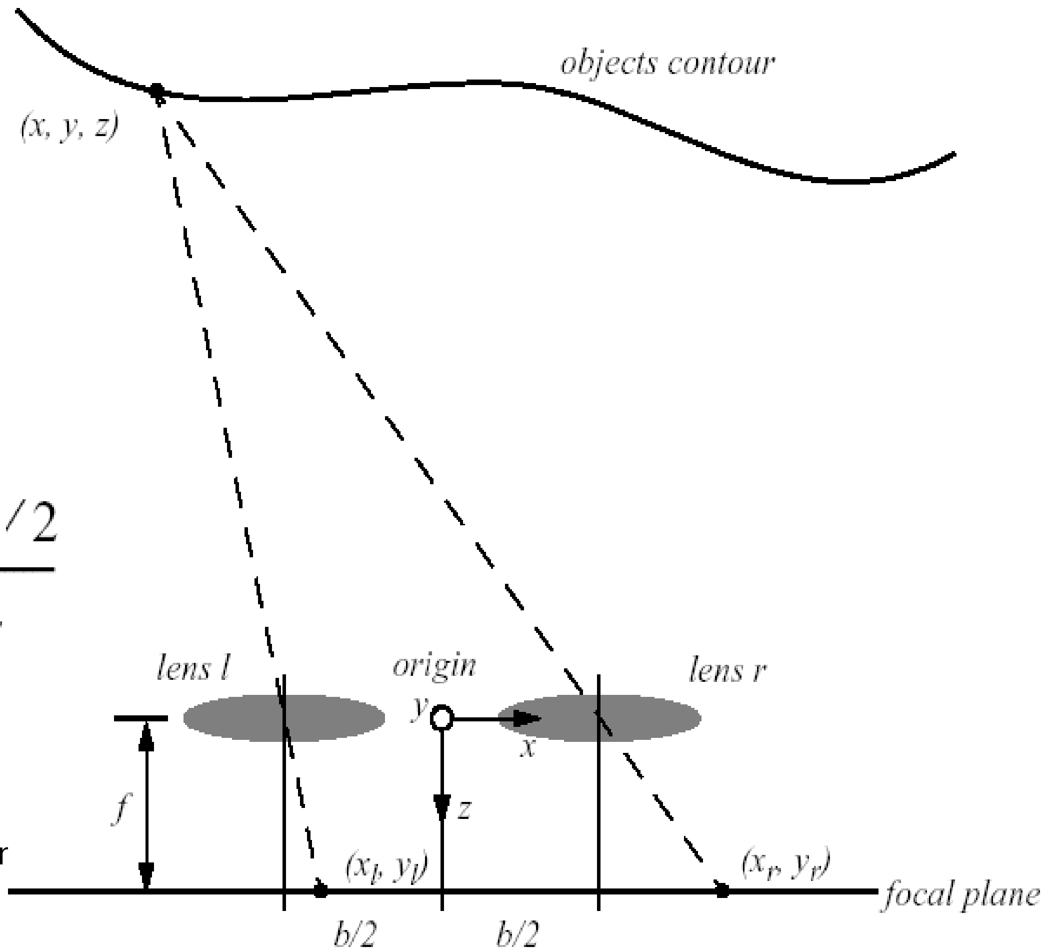
- The camera geometry is used for stereo vision
- The disparity between two images is used to compute depth

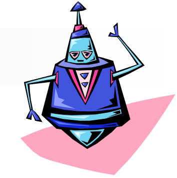
$$\frac{x_l}{f} = \frac{x + b/2}{z} \text{ and } \frac{x_r}{f} = \frac{x - b/2}{z}$$

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

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

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





Stereo Vision (4.1.8)

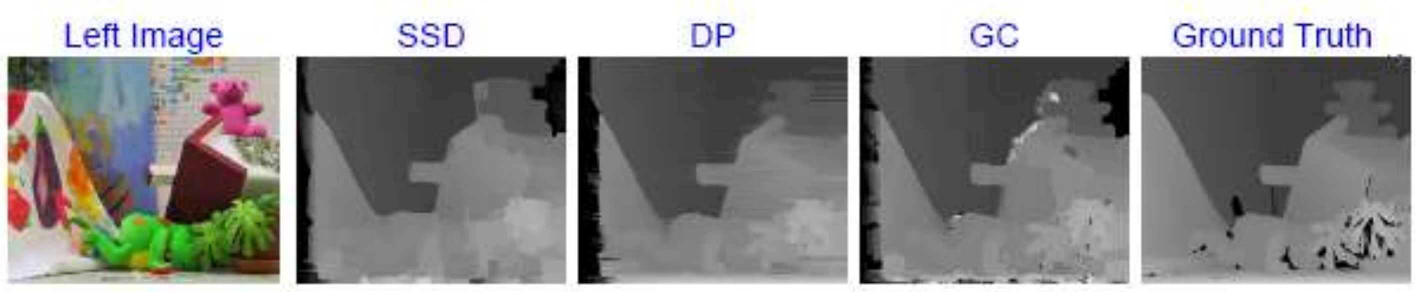
1. Distance is inversely proportional to *disparity*
   - closer objects can be measured more accurately
2. Disparity is proportional to b.
   - For a given disparity error, the accuracy of the depth estimate increases with increasing baseline b.
   - However, as b is increased, some objects may appear 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

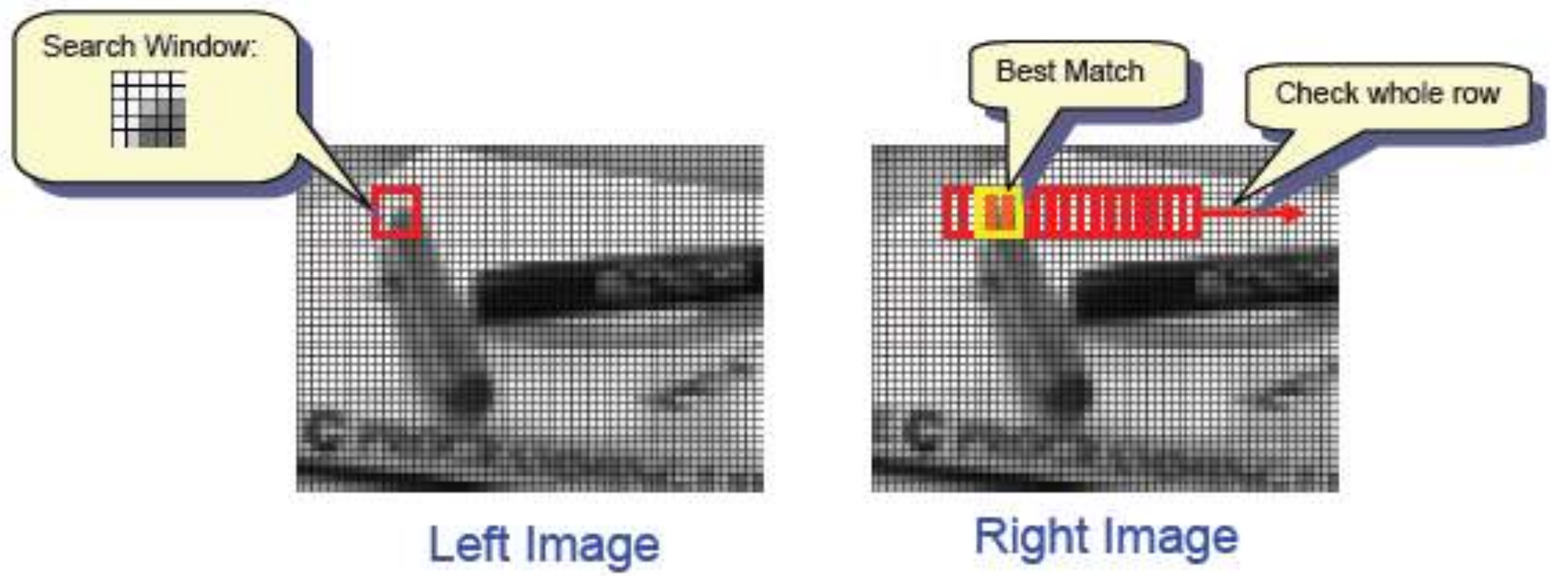
Stereo Ranging Systems: Correlation

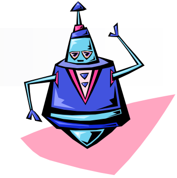
- There are several methods
  - Sum of Squared Difference (SSD)
  - Dynamic Programming (DP)
  - Graph Cut (GC)
  - Belief Propagation (BP)
  - Markov Random Fields (MRF)



Stereo Vision:
SSD Correlation

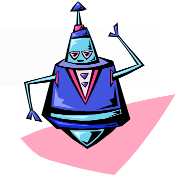
- Take a small area of data in left image and compare it with similar-size area in the right image along the same *epipolar line* (i.e. same height in the image if the cameras are horizontally level)





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

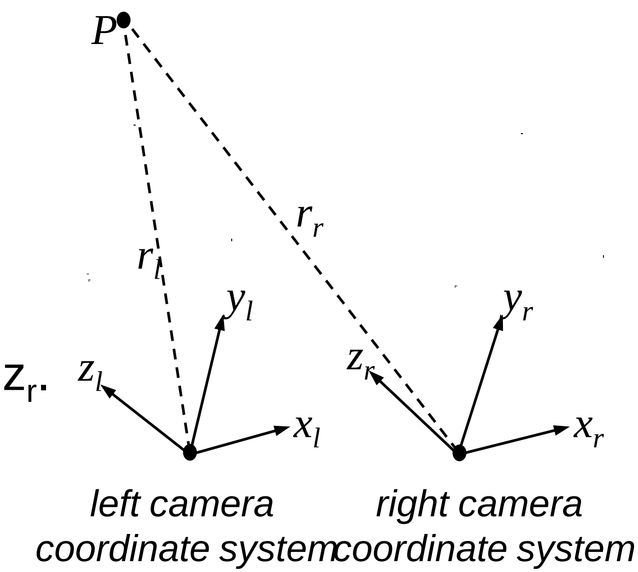


Stereo Vision: General case (4.1.8)

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

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

- 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.



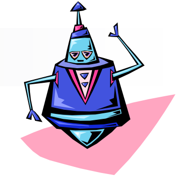
Stereo Vision Example (4.1.8)

- 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

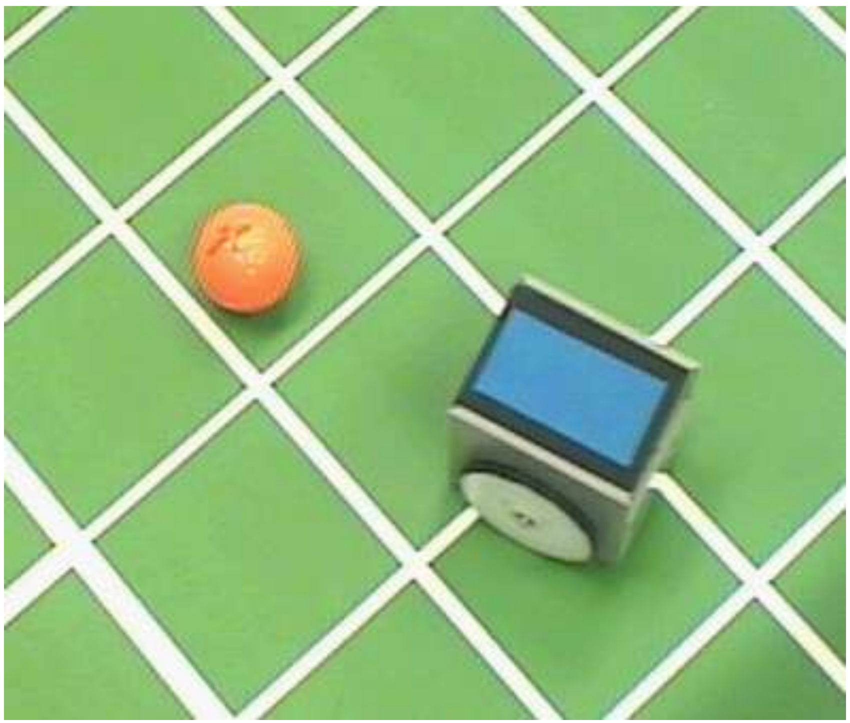


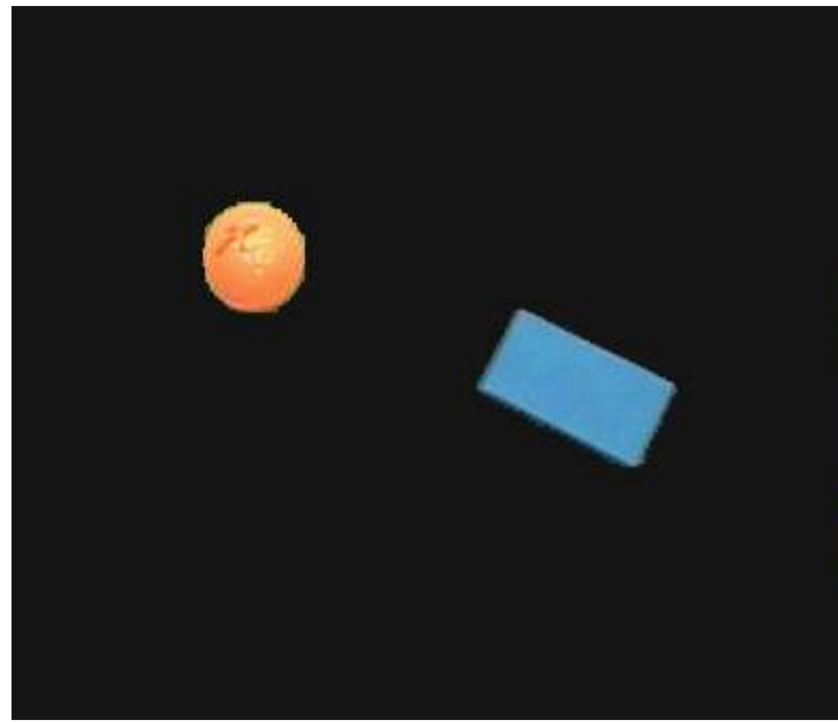
Vision from Motion

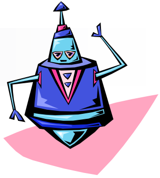
- Take advantage of motion to facilitate vision
- Static system can detect moving objects
  - Subtract two consecutive images from each other $\Rightarrow$ the movement between frames
- Moving system can detect static objects
  - At consecutive time steps continuous objects move as one
  - Exact movement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

Color Tracking Sensors (4.1.8)

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







Color-tracking sensors (4.1.8)

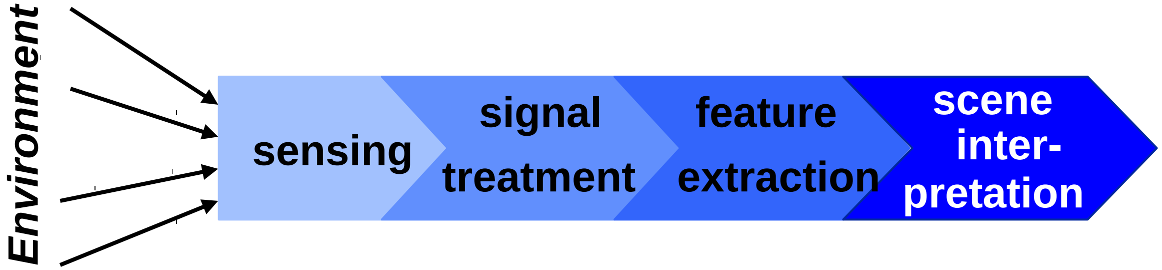
- There is no correspondence problem to be solved in such algorithms (it only requires one image)
- By using sensor fusion, color tracking can produce significant information gains

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

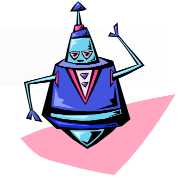
Feature Extraction:
Scene Interpretation (4.3)

- 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***



Feature Extraction:

Features (4.3)



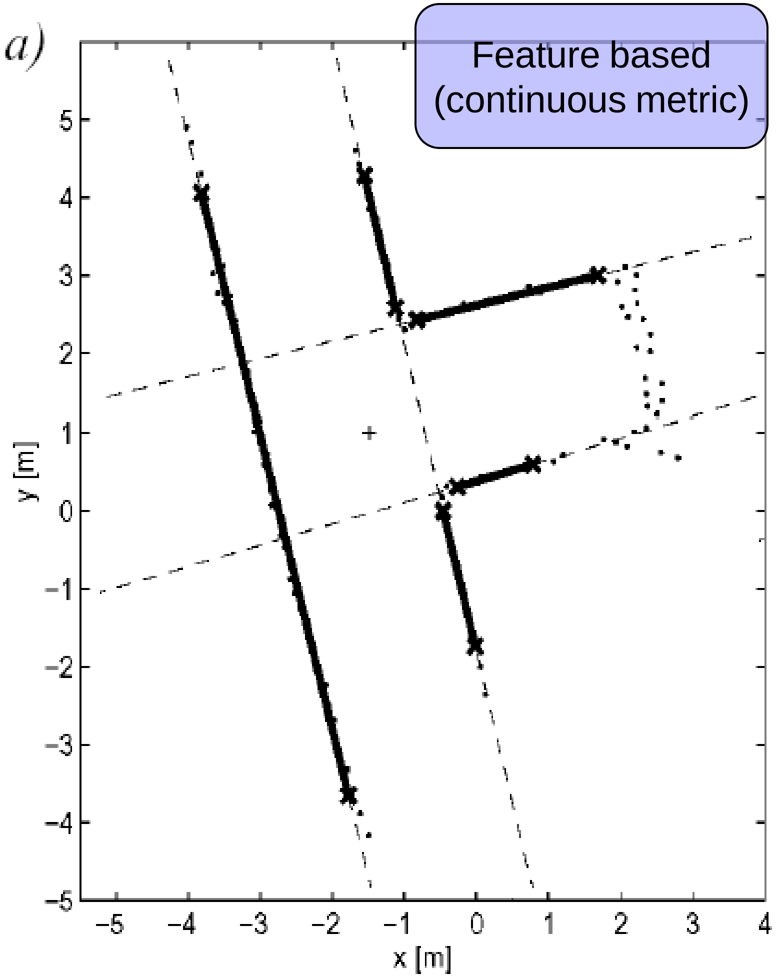
- Features are distinctive elements or geometric primitives of the environment.
- Good features are always perceivable and easily detectable form the environment
- They usually can be extracted from measurements and mathematically described.
  - *low-level features* include *geometric primitives* like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

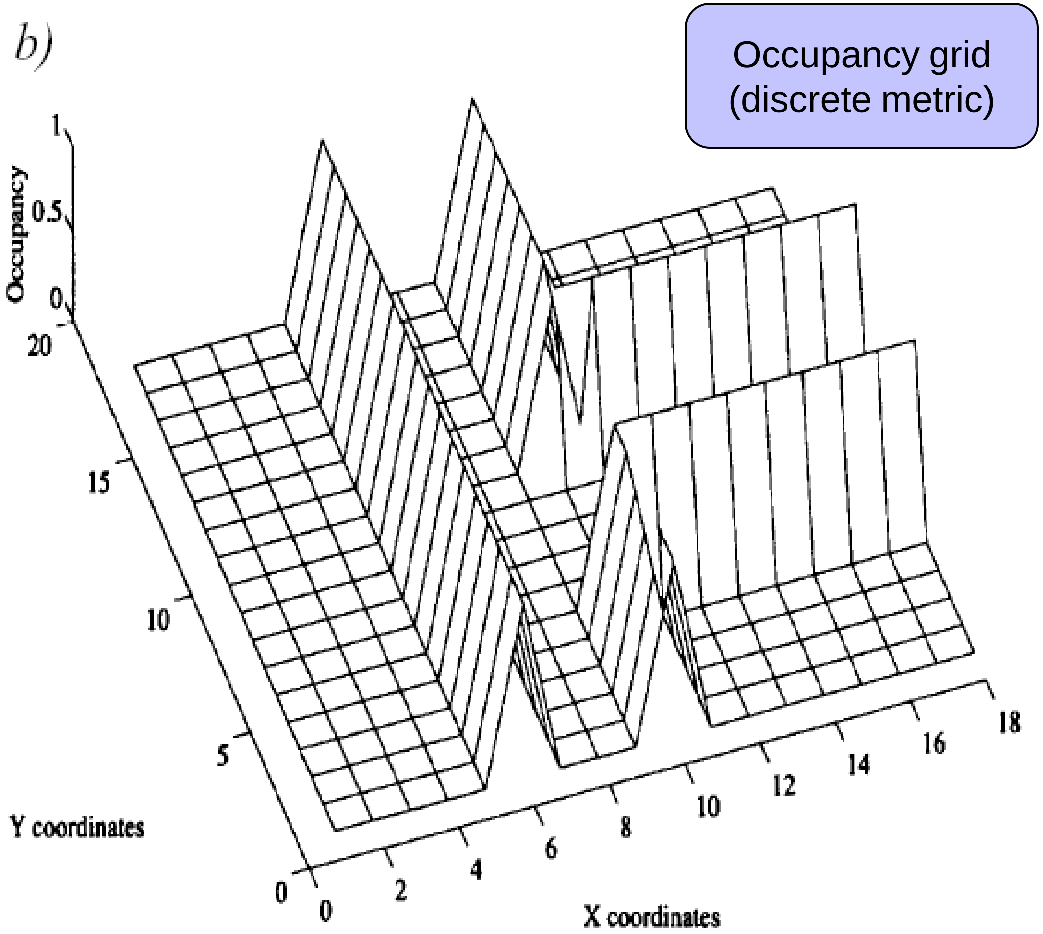
In mobile robotics, features help for localization and map building.

Environment Representation and Modeling: Features (4.3)

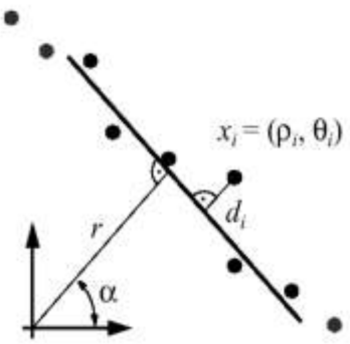
- Environment Representation
  - Continuos Metric → x,y,θ
  - Discrete Metric → metric grid
  - Discrete Topological → topological grid
- Environment Modeling
  - Raw sensor data, e.g. laser range data, grayscale images
    - large volume of data, low distinctiveness
    - makes use of all acquired information
  - 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

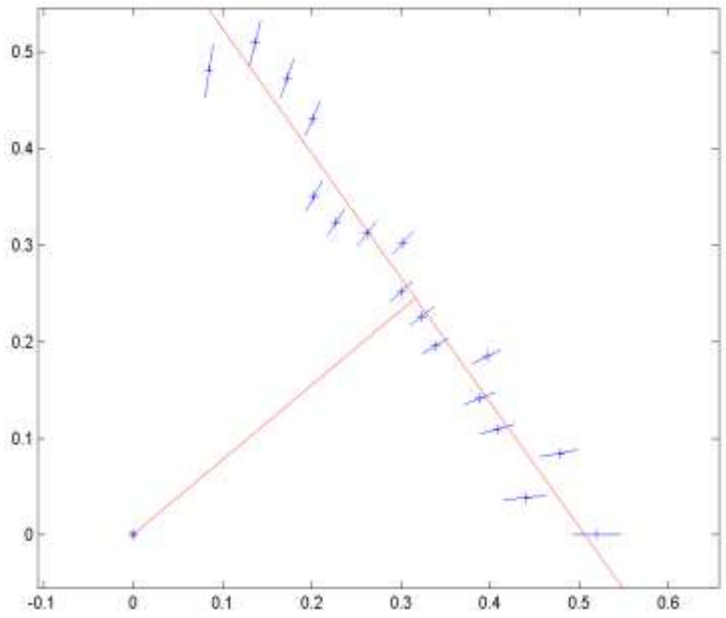




Feature extraction: Range Data (4.3.1)

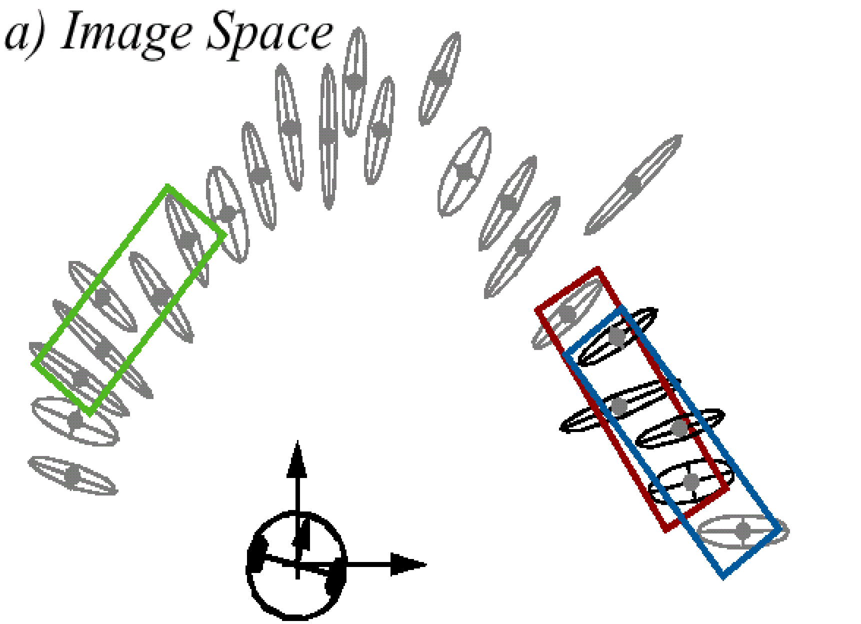


- Laser, Ultrasonic and vision-based ranging extract features that are geometric primitives such as line segments, circles, corners, edges
- Most other geometric primitives are too complex and no closed form solutions exist.
- However, lines segments are very often sufficient to model the environment,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



Segmentation for Line Extraction (4.3.1)

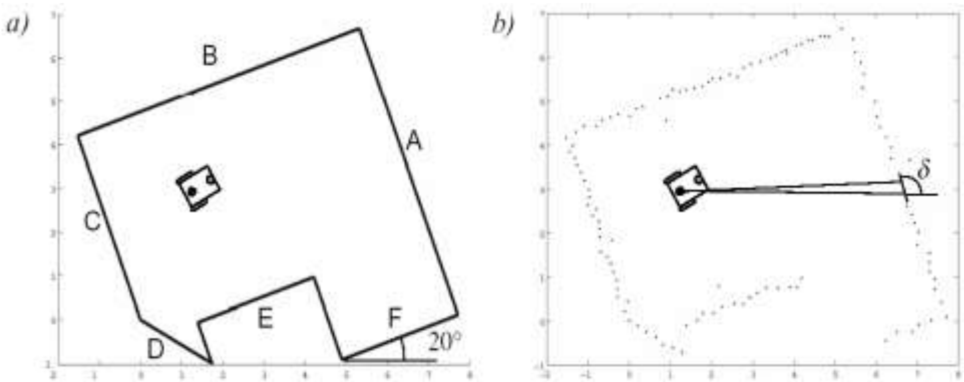
- The process of dividing up a set of measurements into subsets that can be interpreted one by one is termed *segmentation*
- *Segmentation* is important for range-based and vision-based perception

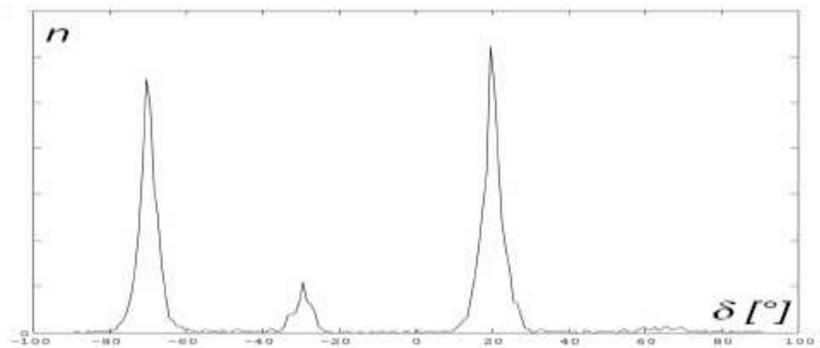


A set of n_f neighboring points of the image space

Range histogram features
Angular Histogram (4.3.1)

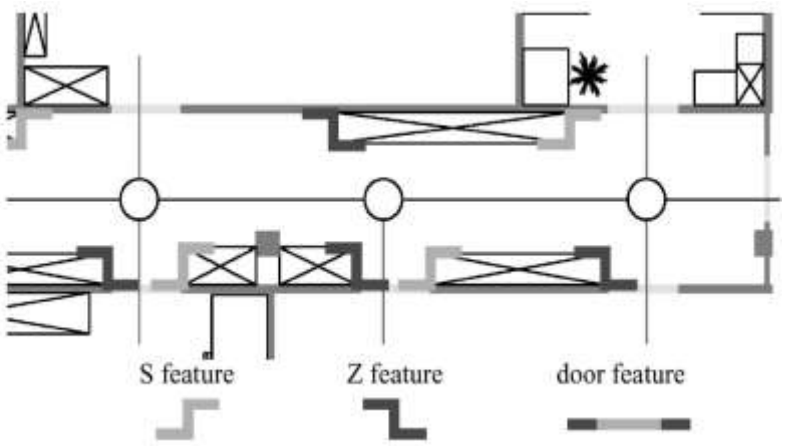
- An *angular histogram* is a simple way of combining characteristic elements of an image
  - A 360 degree range can is performed
  - The hits are recorded on a map
  - An algorithm measures the relative angle between adjacent hits

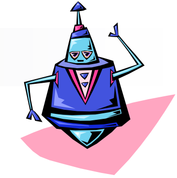




Extracting Other Geometric Features (4.3.1.4)

- 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





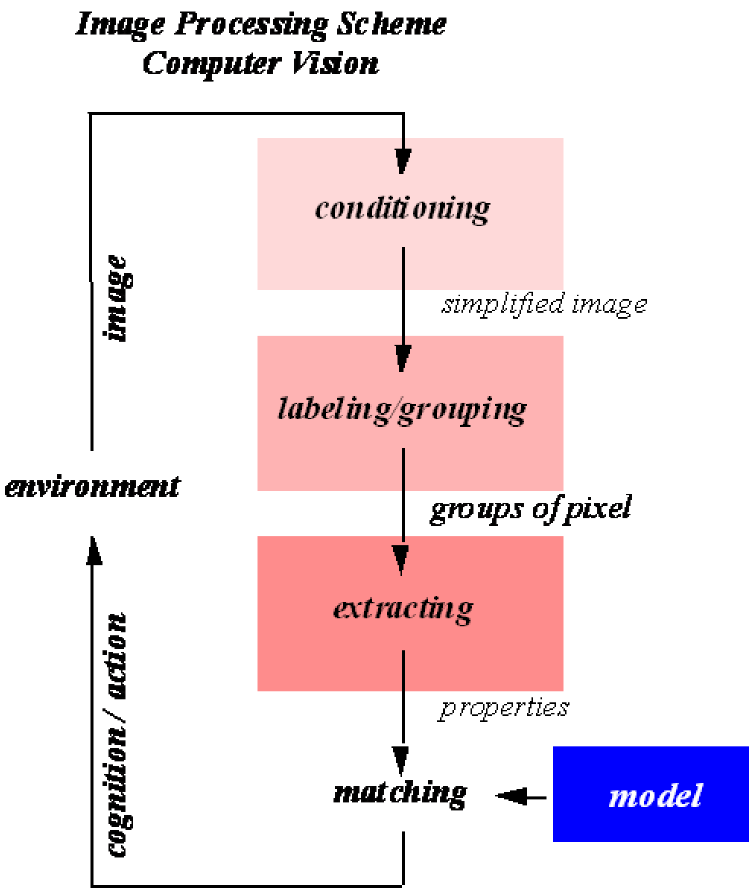
Feature extraction:
Visual appearance

- 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 (4.3.2)

- 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

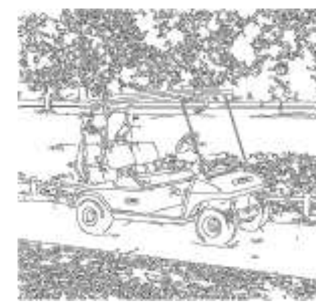


Feature Extraction:
Filtering and Edge Detection (4.3.2)

- 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

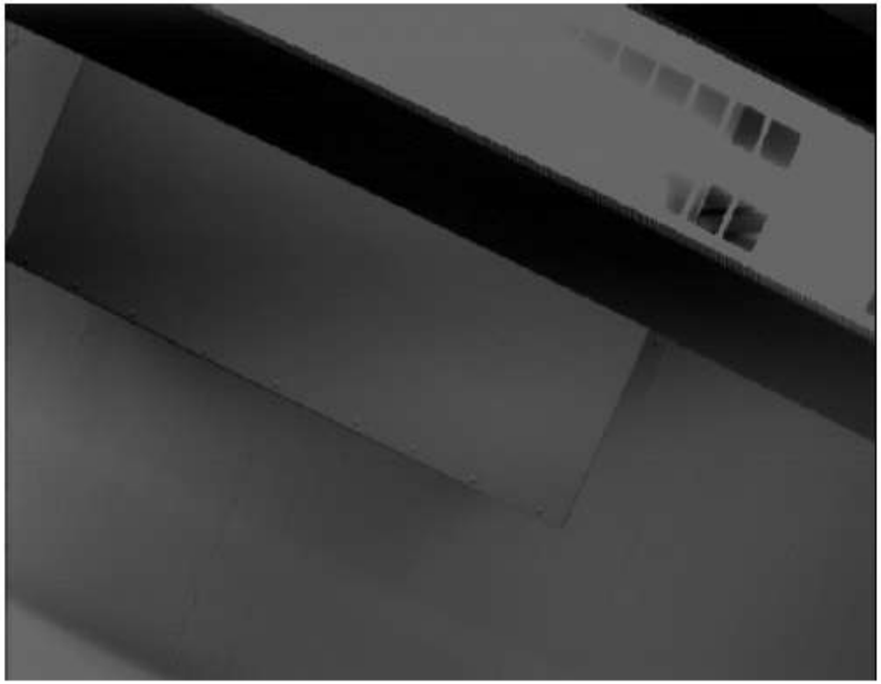
Edge Detection

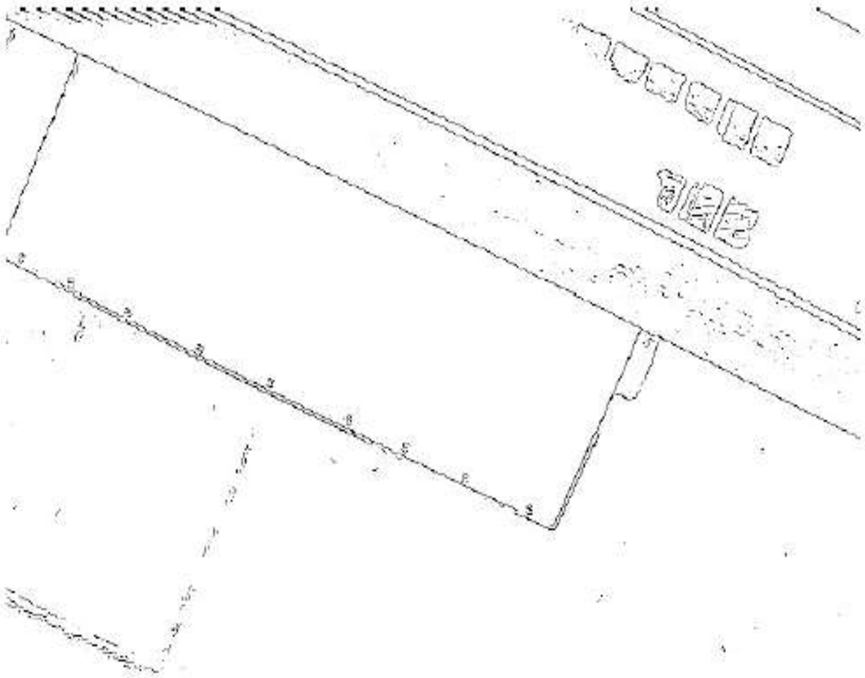
- Edge = a curve in the image across which there is a change in brightness
- Finding edges
  - Differentiate the image and look for areas where the magnitude of the derivative is large
- Difficulties
  - Not only edges produce changes in brightness: shadows, noise
- Smoothing
  - Filter the image using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



Feature Extraction: Edge Detection (4.3.2)

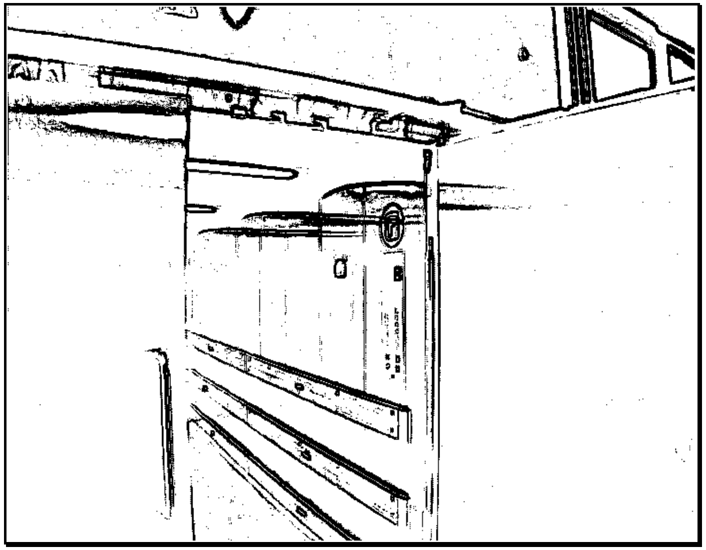
- Ultimate goal of edge detection
  - an idealized line drawing.
- Edge contours in the image correspond to important scene contours.

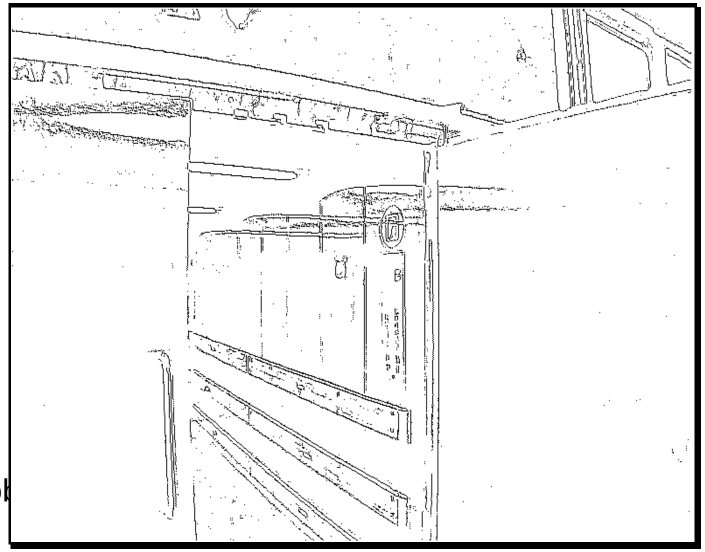




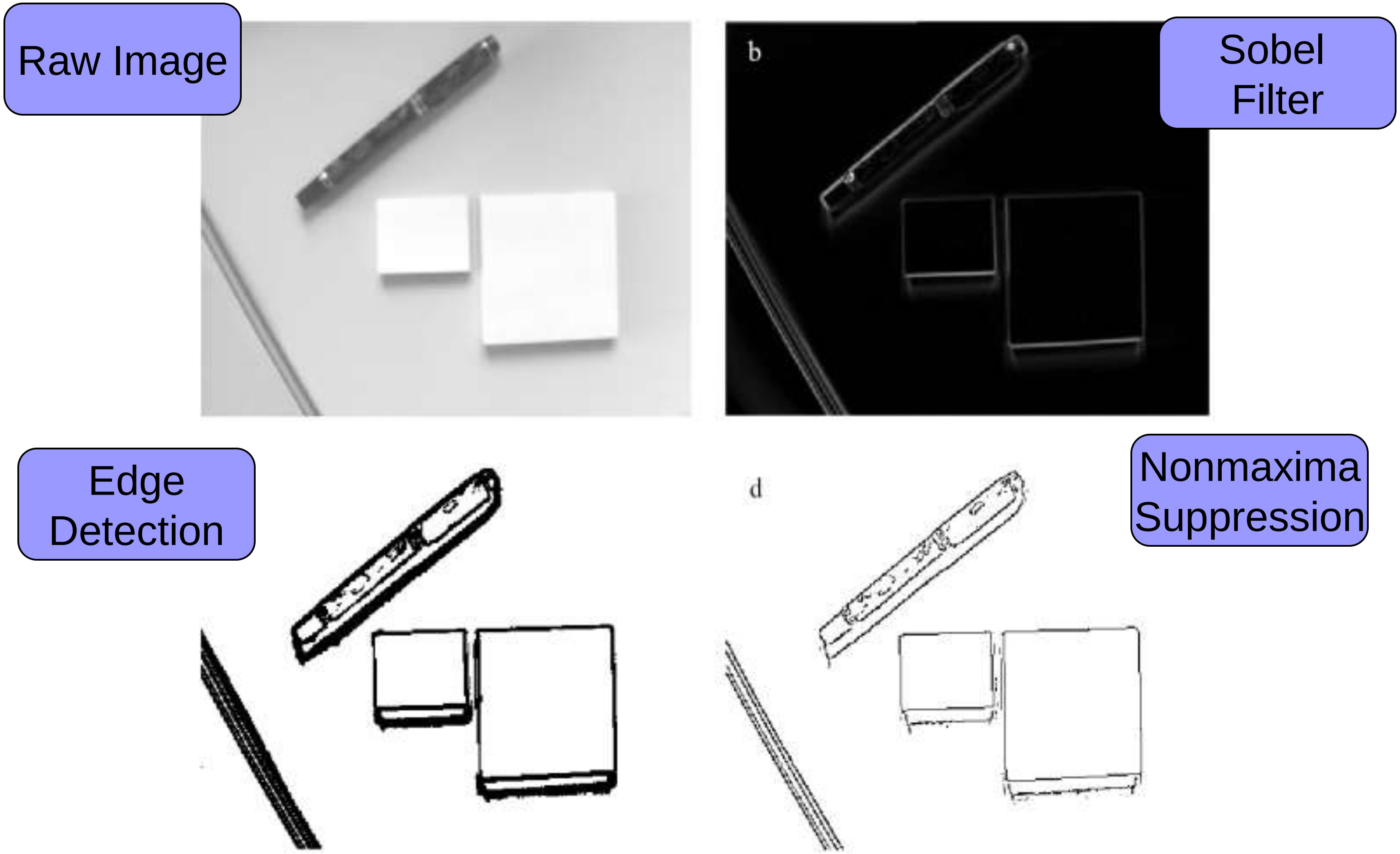
Feature Extraction: Nonmaxima Suppression

- 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

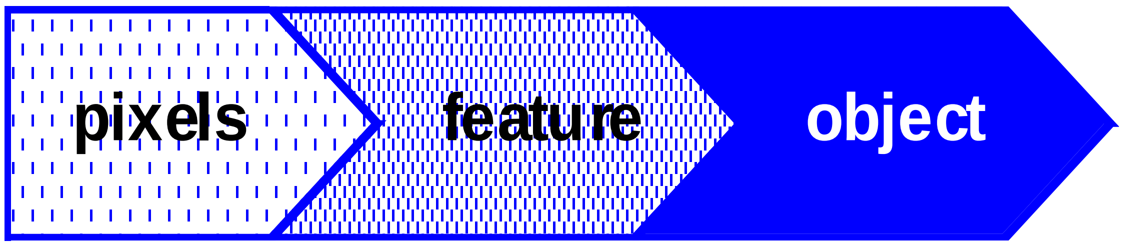




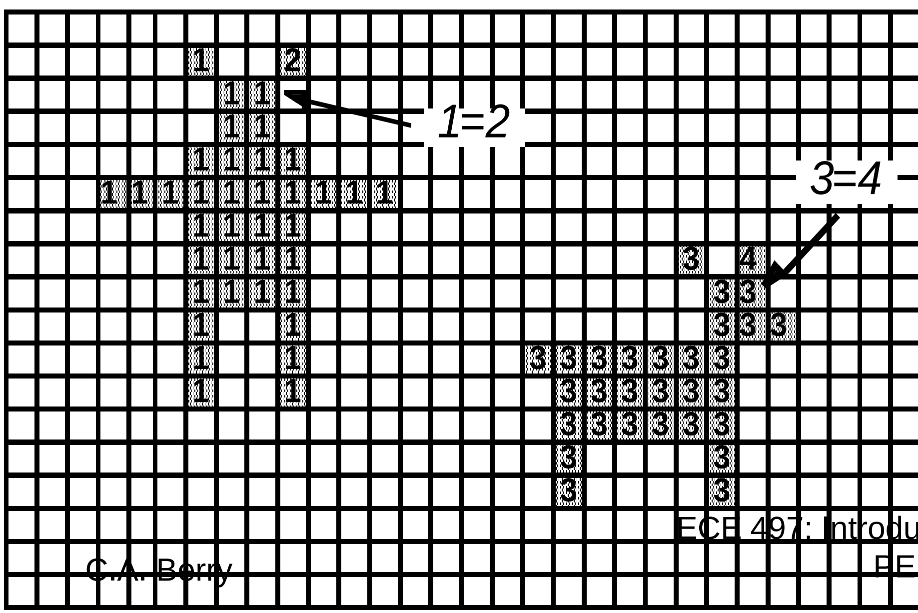
Feature Extraction Example (4.3.2)

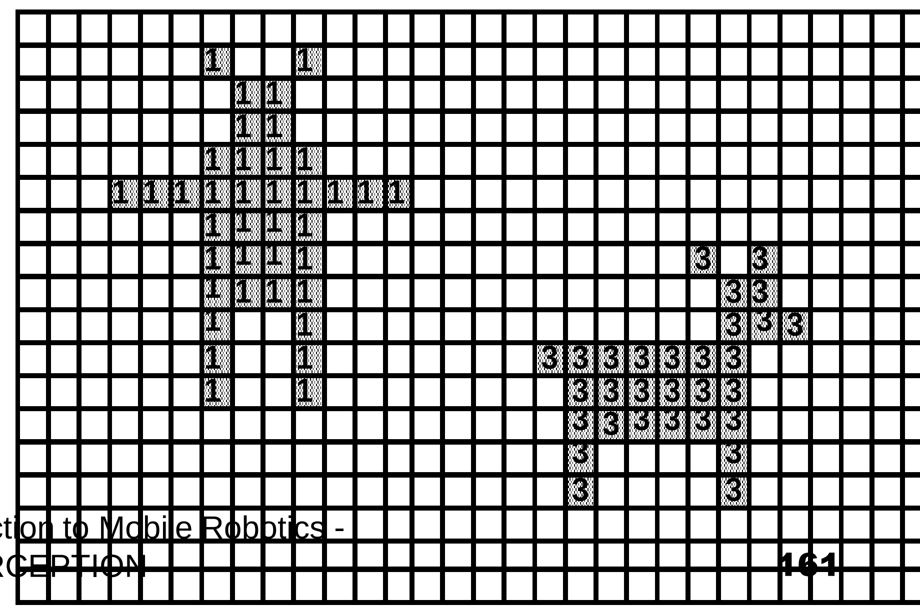


Grouping, Clustering: Assigning Features to Features



- Connected Component Labeling



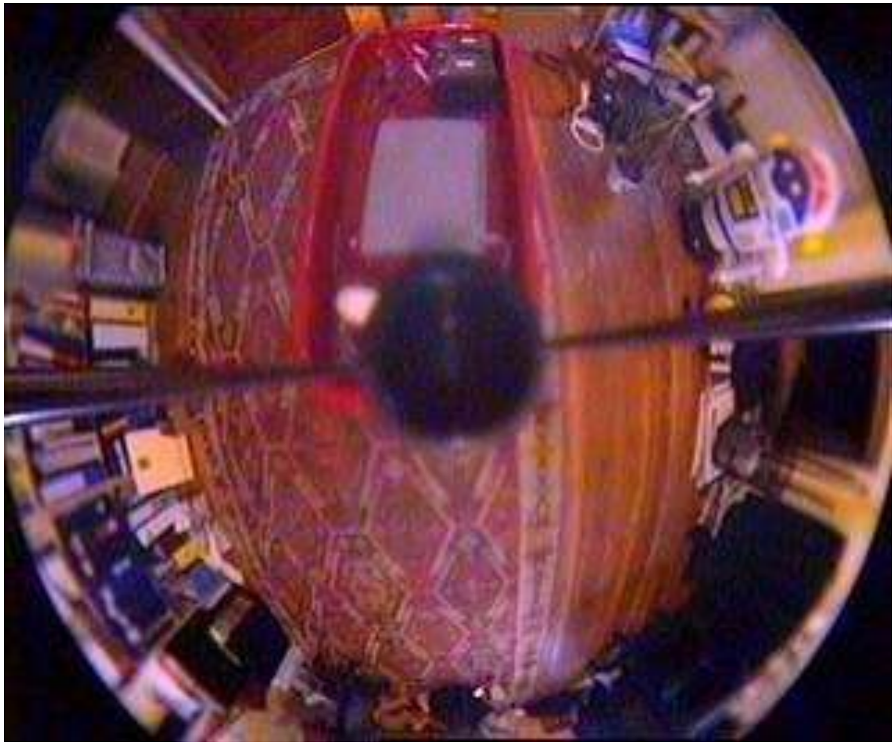


Feature Extraction:
Floor Plane Extraction (4.3.2)

- 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 (4.3.2)

- 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



Sensor Videos