Sensors and Range Measurement

Chapter 8

Objectives

- To understand various types of sensors
- To understand how common range sensors are used in robotics
- To understand the advantages and disadvantages of various range sensors
- To briefly look at how stereo vision works
- To examine some results of combining sensors

What's in Here ?

- Sensors
- Range Sensors
  - Tactile Sensors
  - Proximity Sensors
- Ultrasonic Range Sensors
- IR Range Sensors
- Laser Range Finders
- Stereo Camera Ranging Systems
- Sensor Selection

Sensors

Sensing

- Sensing is the sole way of obtaining environmental information.
- A robot's abilities (i.e., usefulness) depends on:
  - The quantity and quality of its sensors
  - The ability and speed to process sensory input
  - The ability to act on what it perceives
- The ability of a robot to become aware of its environment through sensing is called ***perception***.
- A robot must take in sensory input and then extract useful information from the data.

Sensors

- Robots are equipped with a variety of different kinds of sensors so as to allow:
  - *flexibility* in type of data sensed (e.g., distance, direction, light, sound, temperature, etc...)
  - ability to *combine sensor data* to obtain more accurate representation of the world (e.g., light-based sensors cannot detect glass, whereas sonar can)

- Use of multiple copies of certain sensors:
  - *speeds up rate* of environmental readings
  - provides redundancy for *fault tolerance*
  - *saves power* (e.g., robot may not have to rotate a sensor to get a 360° reading)

Sensors

- Sensors vary in terms of:
  - size, weight, price, accuracy and precision.
- *Accuracy* is the quality of "nearness" to the true value
- *Precision* is the quality of being reproducible in amount or performance.
- Store-bought sensors usually come with statistics that indicate the degree of accuracy and precision that the sensor is able to obtain.

Sensors

- There are two categories of sensors:
  - *Passive*

    Sense the environment without altering it.

    (e.g., touch, heat, sound & light sensors, cameras)

  - *Active*

    Alter the environment by sending out some kind of signal which is usually modified in some way by the environment and then detected again.

    (e.g., sonar, infrared, laser range finders)

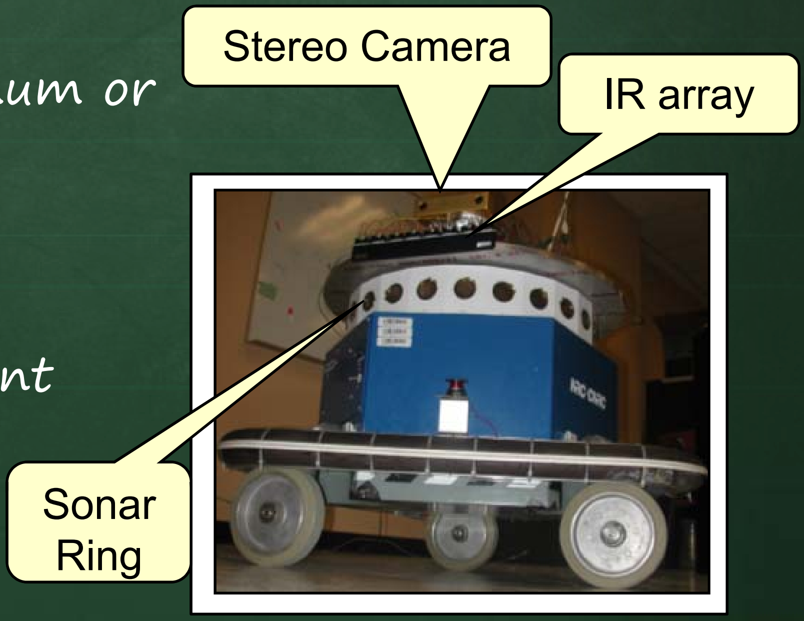
Sensors

- Passive sensors are often preferred over active sensors since they do not add extra signals or noise to the environments.
- Active sensors are sometimes preferred over passive sensors since they have less difficulty extracting relevant information.
- Passive sensors are usually preferred in multi-robot environments since signals from active sensors can interfere with other robots.

Sensor Fusion

- To account for inaccuracy, multiple sensor readings are often combined (or fused)

- *Sensor fusion* combines sensor readings from:
  - Same sensor
    - Usually taken as an average, minimum or maximum over small time interval
  - Multiple similar kinds of sensors
    - Individual sensors read from different directions (e.g. sonar ring)
  - Different kinds of sensors
    - e.g., combining sonar with IR and vision measurements



Sensors

- There is an endless number of sensors for a variety of purposes.

- We are interested in looking at just a few of the common types of sensors used on mobile robots.

- We will focus mainly on *range sensors* which reports the distance from the sensor to an object.

Range Sensors

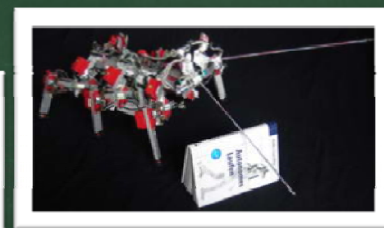
Range Sensors

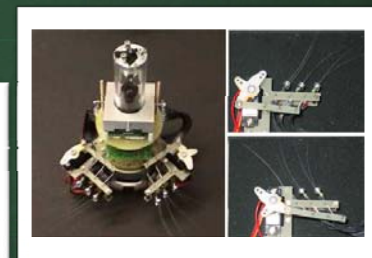
- Commonly used range sensors in robotics:
  - Tactile and Proximity sensors
  - Ultrasonic Sensors
  - IR Range Sensors
  - Laser Range Finders
  - Vision Systems

- Each varies in complexity, size, weight, expense, accuracy, etc..
- The ***detection range*** is defined as the maximum distance that the sensor can read reliably from.

Tactile Sensors

- *Tactile sensors* detect distance through physical contact and are usually in the form of:
  - One or more bumpers
  - Two or more whiskers



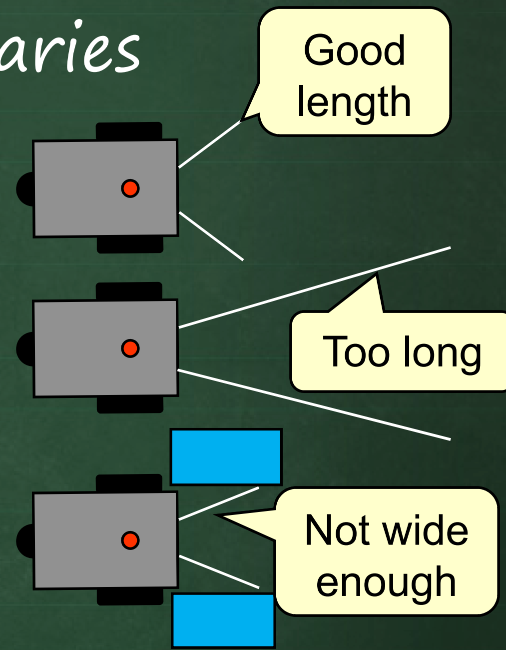


- They are usually set to detect obstacles at (or within) a fixed distance from the robot.

- The detection range of bumpers is usually anywhere from 1_{mm} to 2_{cm}.

Tactile Sensors

- Whiskers have a detection range that varies according to their length.
  - Usually placed at front and extend long enough to ensure safe stopping distance
  - Should extend entire body width so as to detect successfully any obstacles.



- Tactile sensors have the tremendous advantage over all other sensors in that they are:
  + simple – provide a binary signal ("yes" or "no" obstacle)
  + trustworthy – simple things rarely break down.

Tactile Sensors

- Tactile sensors of course, do have their disadvantages:
  - They provide only poor or coarse resolution
  - Bumpers require robot to make solid contact with obstacles (dangerous for obstacles + unhealthy for robot)
  - Whiskers can become tangled or caught in cracks
  - Whiskers oscillate when released after bending, resulting in spurious readings until they settle again
  - Whiskers may require mechanical adjustments or repair

Proximity Sensors

- *Proximity sensors* are sensors that detect obstacles within a specific range from the robot.
- Provide binary signal according to some threshold distance: obstacle "within range" or "out of range"

- Tactile sensors are examples of proximity sensors.
- There are non-tactile proximity sensors.
  - e.g., encoders are examples of proximity sensors that detect the absence or presence of a light reflection

- Non-tactile proximity sensors are usually active.

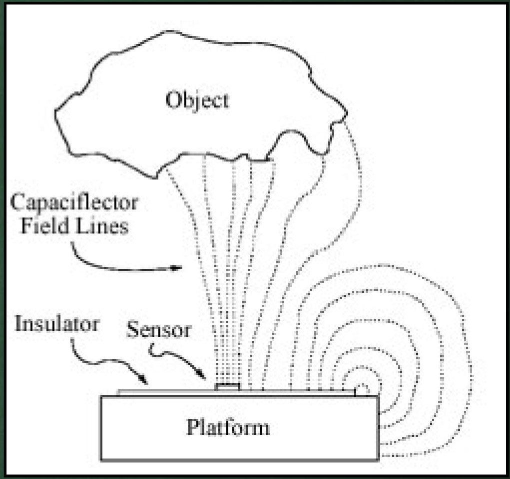
Proximity Sensors

- Any range sensor can be configured as a proximity sensor simply by setting a threshold
- Proximity sensors operate using various mediums:
  - Light (infrared (IR))
  - Sound (ultrasonic)
  - Capacitance (electrostatic fields)
  - Inductance (magnetic fields)

- We will discuss capacitance and inductance first, then in more detail regarding light-based and sound-based sensors.

Capaciflectors

- *Capacitance sensors* (a.k.a. capaciflectors) detect change in capacitance around it.
  - When power is applied to the sensor, an electrostatic field is generated and reacts to changes in capacitance caused by the presence of an obstacle.
- Can detect obstacles from up to 46_{cm} away from the platform.



8 capaciflectors on the bottom on this robot.

Capaciflectors

- Advantages:
  - + lightweight, cheap, robust, fast obstacle detection
  - + can detect proximity of various types of obstacles within some threshold range

- Disadvantages:
  - – Range estimate depends on dielectric constant of obstacle it is sensing; the higher the dielectric constant, the more sensitive a capacitive sensor is to that obstacle.
  - – Different materials have different characteristics resulting in variety of range readings

  - – Cannot detect accurate distance unless obstacle material is known

Inductive Proximity Sensors

- *Inductive Sensors* detect changes in magnetic fields caused by other objects within close range.
  - Sensor generates magnetic field which induces Eddy currents in the object.
  - The Eddy currents in the object magnetically pushes back and dampens inductive sensors' oscillation field.
  - sensor's detection circuit monitors the dampening effect and when magnetic effect becomes sufficiently damped, it triggers the output circuitry.

Inductive Proximity Sensors

- Advantages:
  - + Very robust under hard/noisy conditions (industrial)
  - + Highly accurate
  - + Great for assembly lines and industrial applications

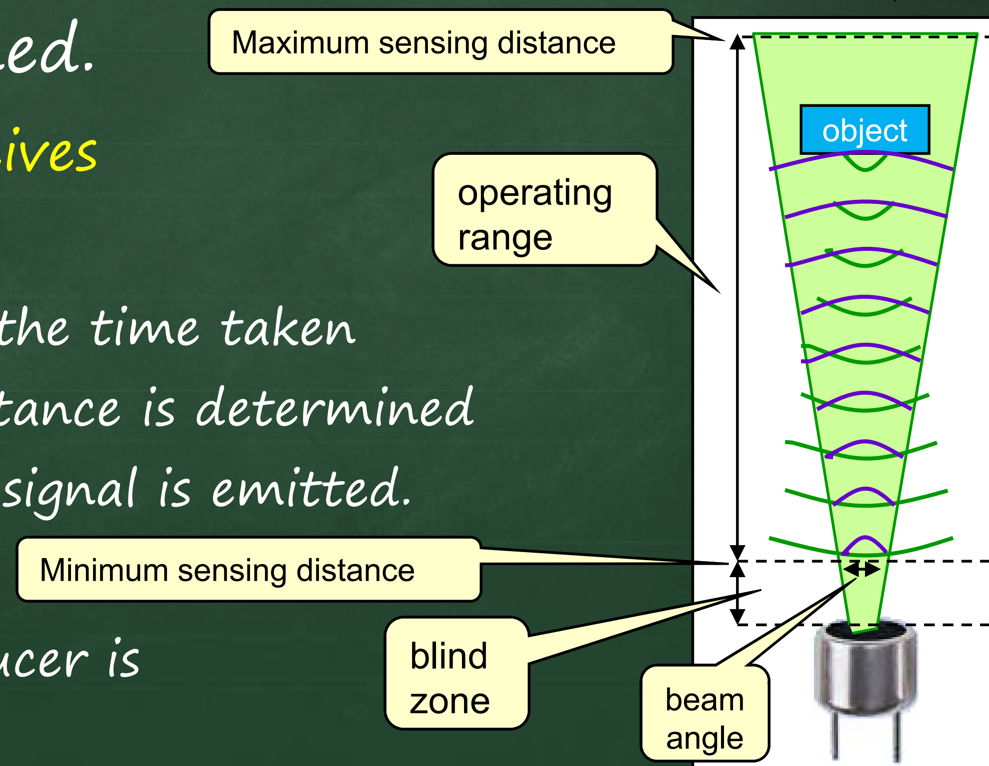
- Disadvantages:
  - – Very small detection range (0.0001_{in} to 1_{in})
  - – Only works for sensing certain types of metal objects.
  - – Range measurement varies according to metal type.

- These sensors are impractical for most mobile robot applications

Ultrasonic Range Sensors

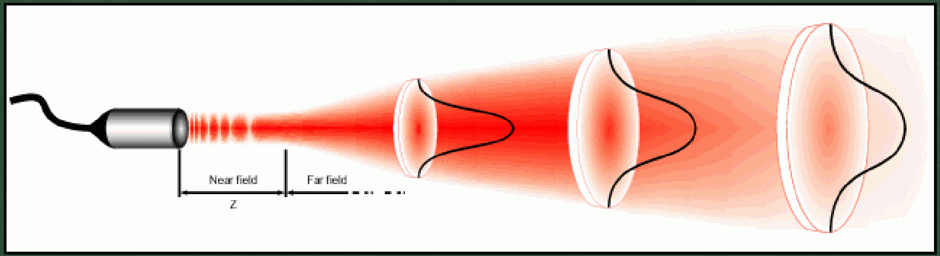
Ultrasonic Range Sensors

- ***Ultrasonic Sensors*** emit a sound wave signal and measure the time it takes for that signal to be returned.
  - *transducer* emits and receives ultrasonic signal.
    - incoming echo is checked, the time taken for sound to travel the distance is determined and corresponding output signal is emitted.
  - Blind zone exists
    - echo arrives before transducer is ready to receive.
    - objects in this dead band cannot be detected reliably.

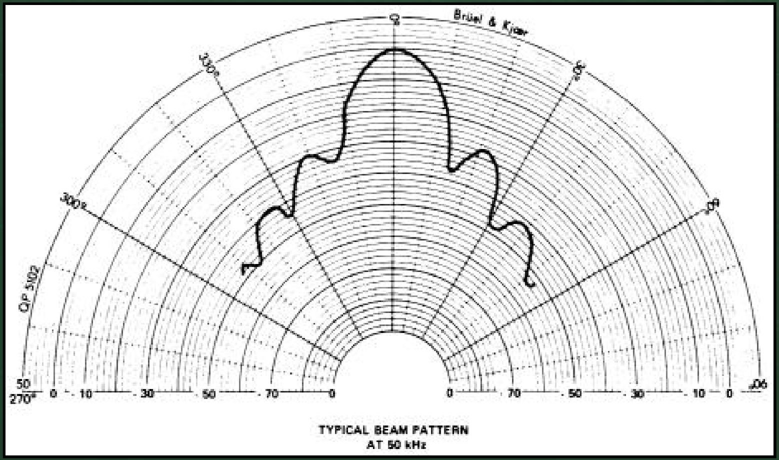


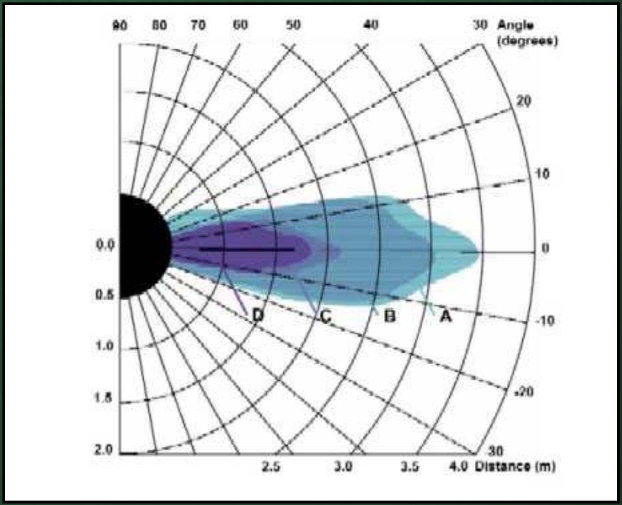
Ultrasonic Range Sensors

- Shape of beam is not a simple wedge:



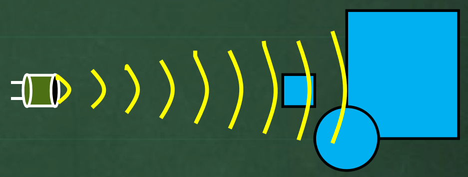
  - wider objects near center of beam result in better accuracy



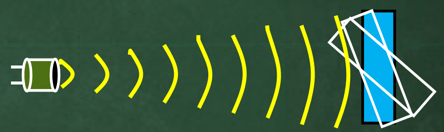


Ultrasonic Range Sensors

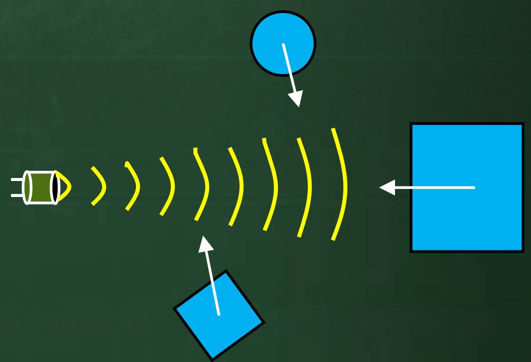
- Readings from sensor vary depending on:
  - distance to object(s)
    - Multiple objects result in only one distance reading



  - angle that object makes with respect to sensor axis
    - smoother materials require perpendicular orientation

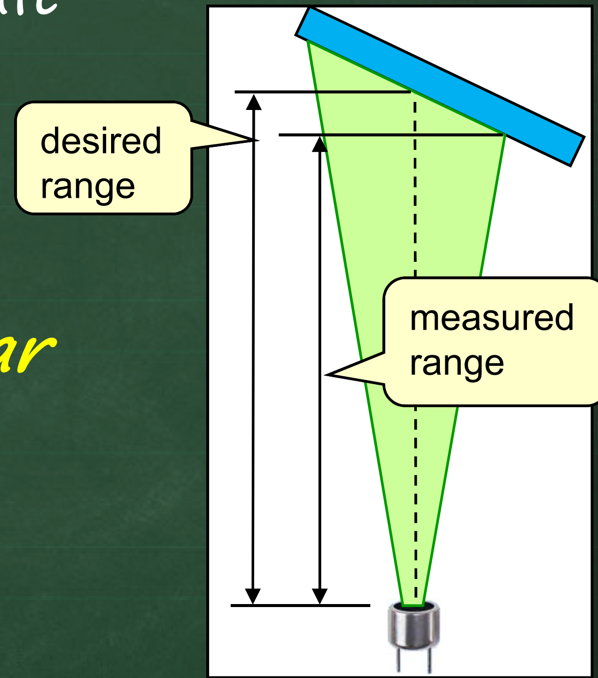


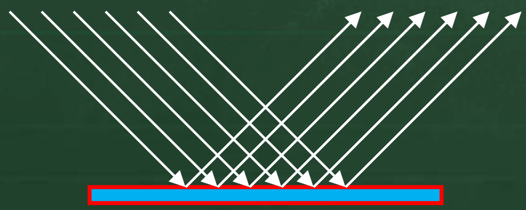
  - direction that object enters sensing range
    - smooth objects must enter from the front with their surface perpendicular to produce proper reading.



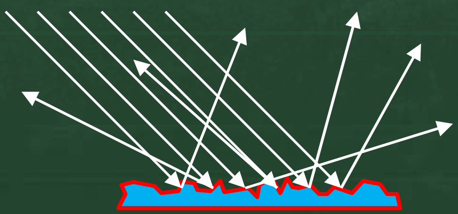
Ultrasonic Range Sensors

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





Specular Reflection
(smooth surfaces)

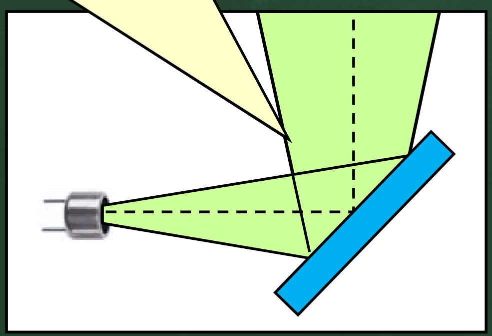


Diffuse Reflection
(rough surfaces)

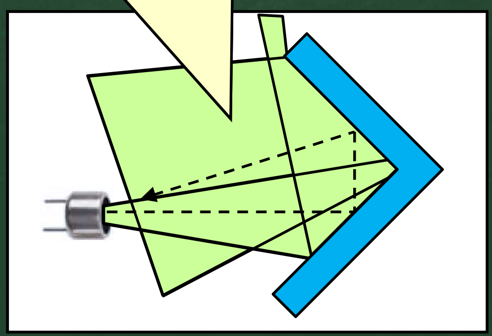
Ultrasonic Range Sensors

- Specular reflection can cause reflected sound to:
  - never return to the transducer
  - return to the transducer too late
- In either case, the result is that the distance measurement is too large and inaccurate

Echo never returns, resulting in maximum distance reading.

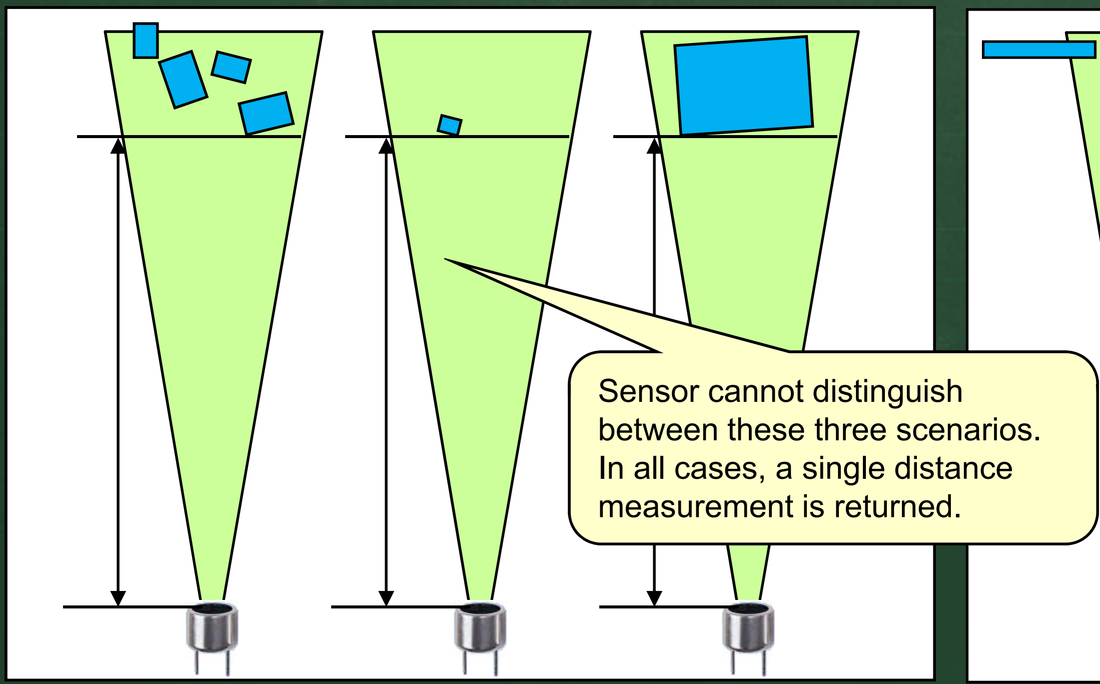


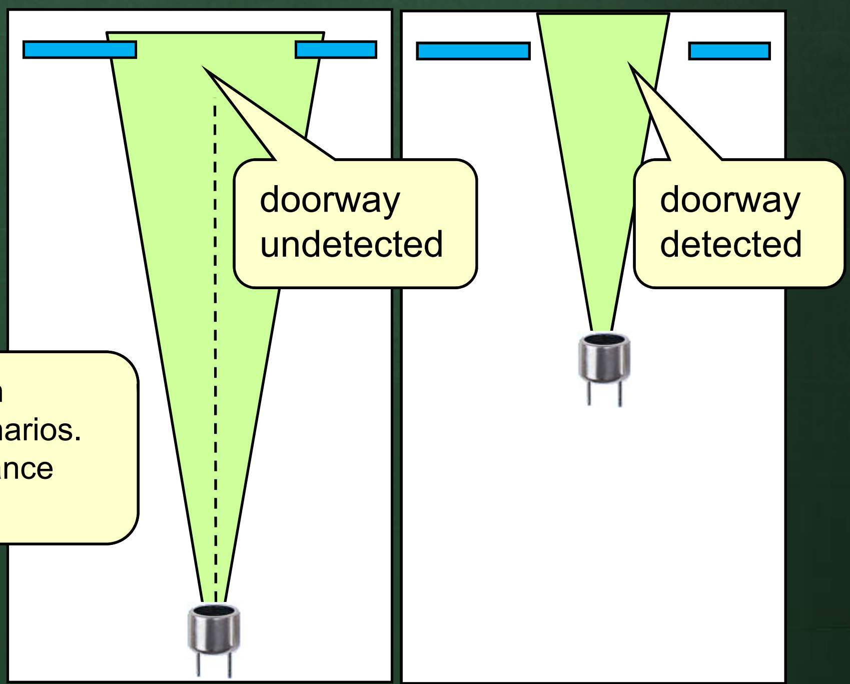
Distance returned represents total round-trip delay.



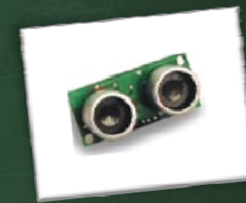
Ultrasonic Range Sensors

- Distance and angular resolution decreases as objects become further from sensor
  - multiple close obstacles cannot be distinguished
  - gaps cannot be detected (e.g., doorways)

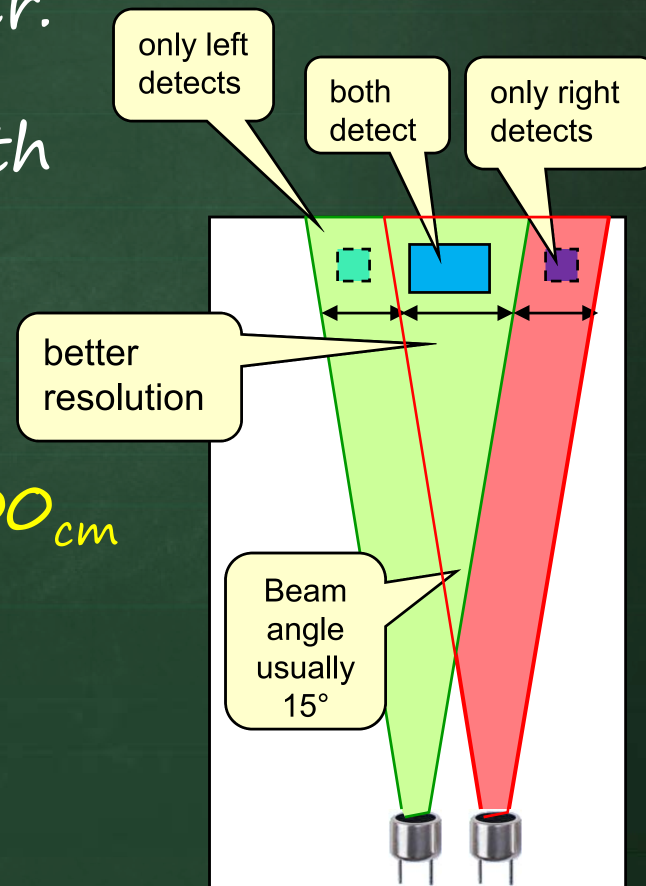




Ultrasonic Range Sensors

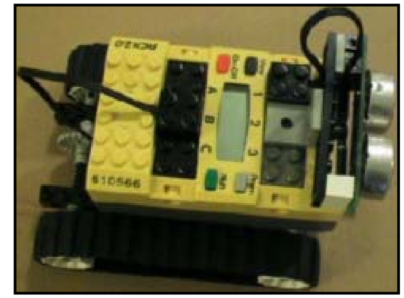


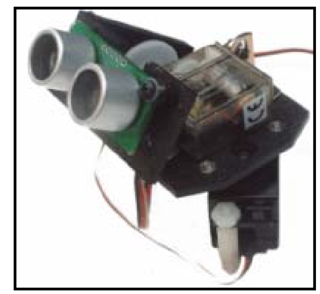
- To increase beam width (i.e., resolution) two sensors are often used together.
- Detection of object in either or both sensors allows for three detection wedges, increasing resolution.
- Typical sensor range is 15_{cm} to 300_{cm} adjustable with ±0.1% accuracy over entire range at stable temperatures.



Ultrasonic Range Sensors

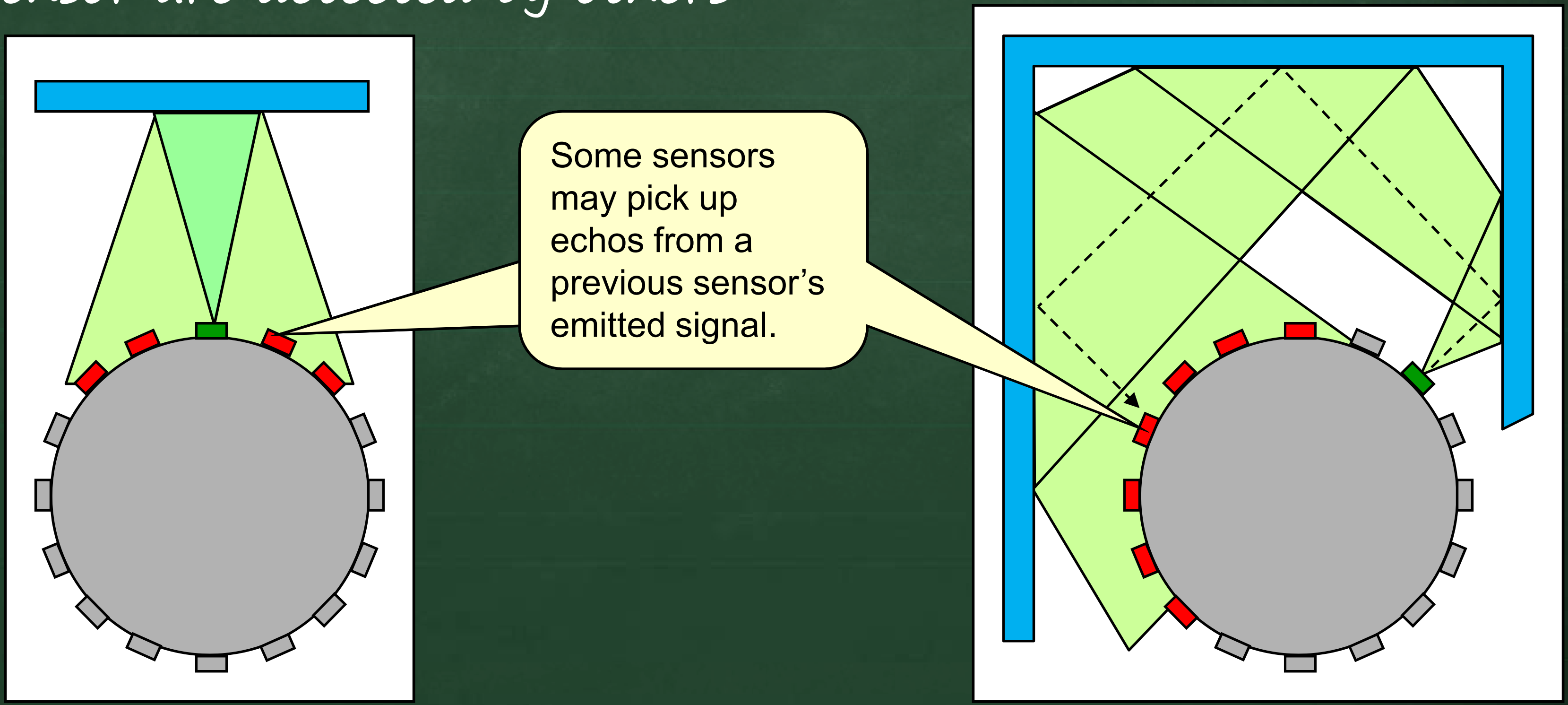
- To perform mapping, sonars (a.k.a. ultrasonic sensors) must take multiple readings:
  - can simply rotate the robot body
  - can rotate some kind of head device
  - can use multiple sensors at fixed positions around robot body





Ultrasonic Range Sensors

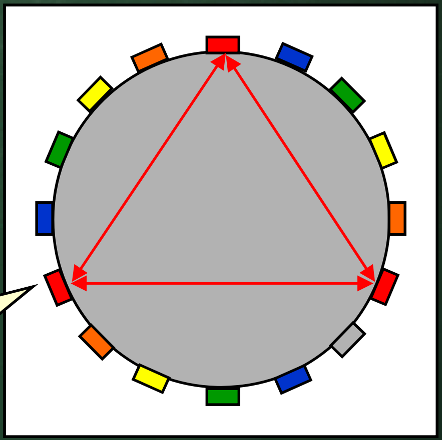
- Using multiple fixed position sensors can lead to another problem called ***crosstalk***:
  - A form of interference in which echoes emitted from one sensor are detected by others



Ultrasonic Range Sensors

- Crosstalk signals are impossible to detect
  - unless signals are somehow unique (e.g., 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 will "likely" have no interference (although there are no guarantees)

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



Ultrasonic Range Sensors

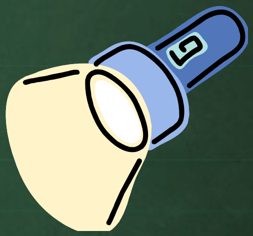
- Advantages of ultrasonic range sensors:
  - + reliable with good precision
  - + not as prone to outside interference
  - + good maximum range
  - + inexpensive

- Disadvantages:
  - – sensitive to smoothness & angle to obstacles
  - – poor resolution
  - – prone to self-interference from echos
  - – cannot detect obstacles too close

Infrared (IR) Range Sensors

IR Range Sensors

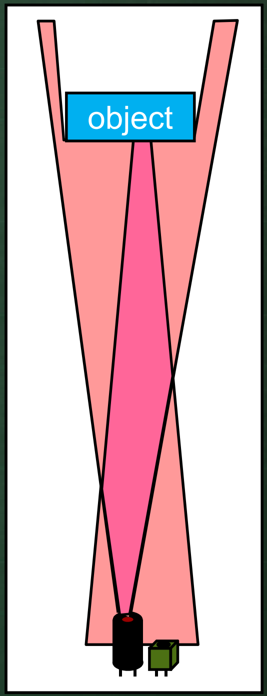
- ***Infrared Range Sensors*** emit a beam of infrared light and measure the amount of light being reflected from the obstacle.

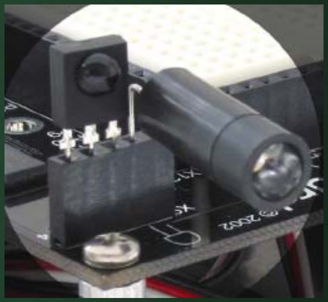


- IR light beam is not visible
- There are four main operational techniques:
  - Reflective (measures strength of light reflected from object)
  - Transmissive (detects presence of object between emitter/detector)
  - Modulated (modulates beam to reduce noise)
  - Triangulation (measures angle that light is reflected from object)

IR Range Sensors

- Basic IR proximity detection is simple
  - Turn on an IR diode (i.e., light)
  - Light is reflected off obstacle, some light returns
  - Receiver measures strength of light returned.
- As with sonars, signal is highly dependent on reflective characteristics of the object.
  - shiny obstacles (e.g., metal) cause problems
- Range depends on color of obstacle
  - white/black surfaces report different ranges
  - cannot detect glass





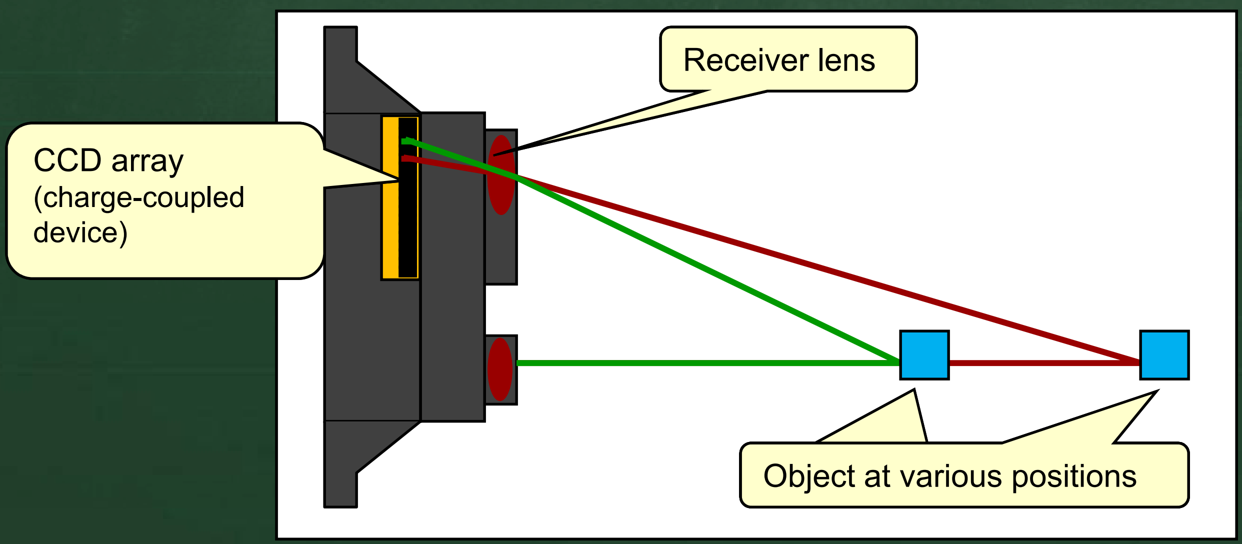
IR Range Sensors

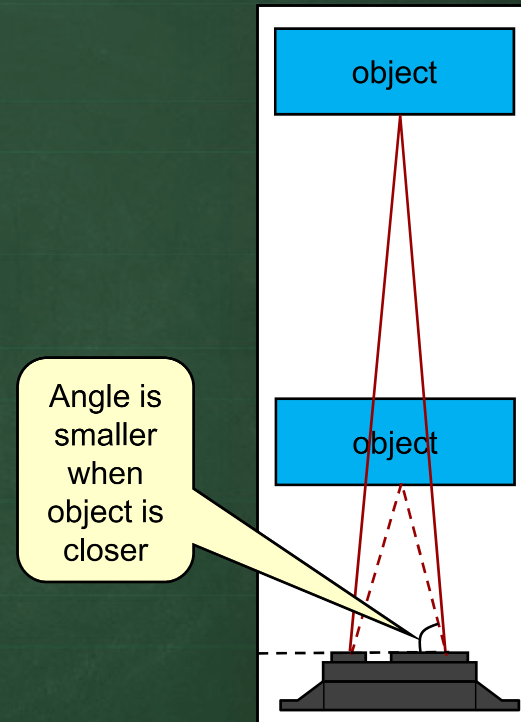
- Modulated IR
  - Signal is rapidly-varied IR, usually via flashing or pulsing (e.g., 40khz)
  - Receiver has additional circuitry so that it only responds to a matching modulated IR signal.

- Helps reduce 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.

IR Range Sensors

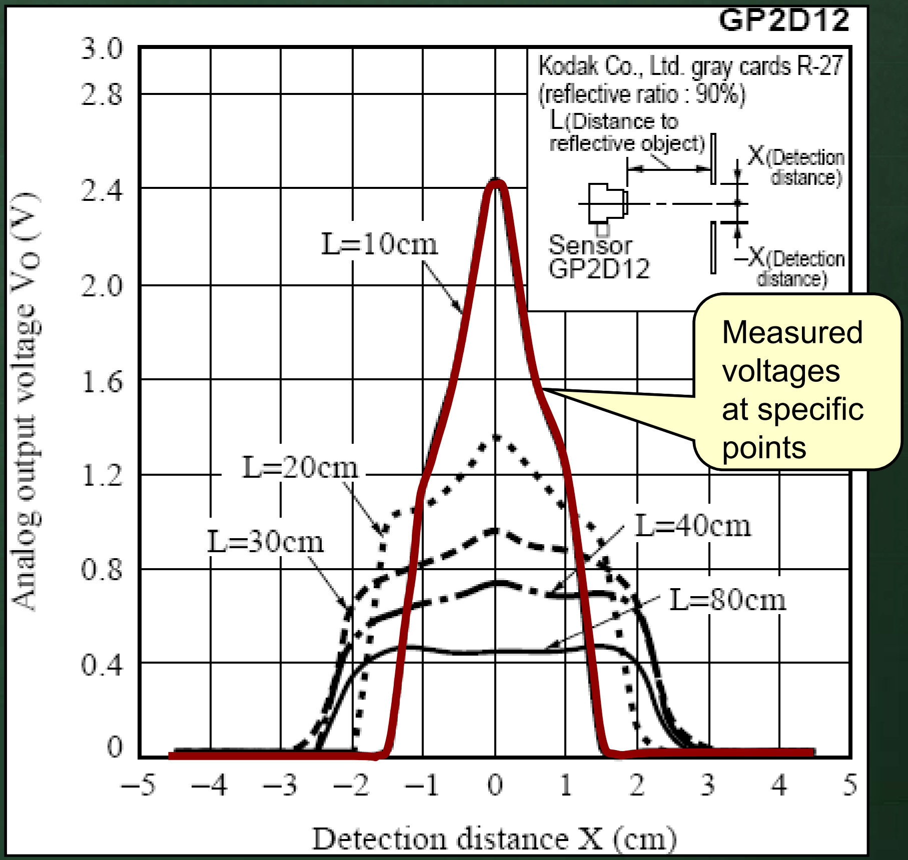
- Triangulated IR (e.g., Sharp GP2D12)
  - senses the angle at which the reflected IR is returned to the sensor.
- Receiver has lens that projects returned IR light onto a CCD array





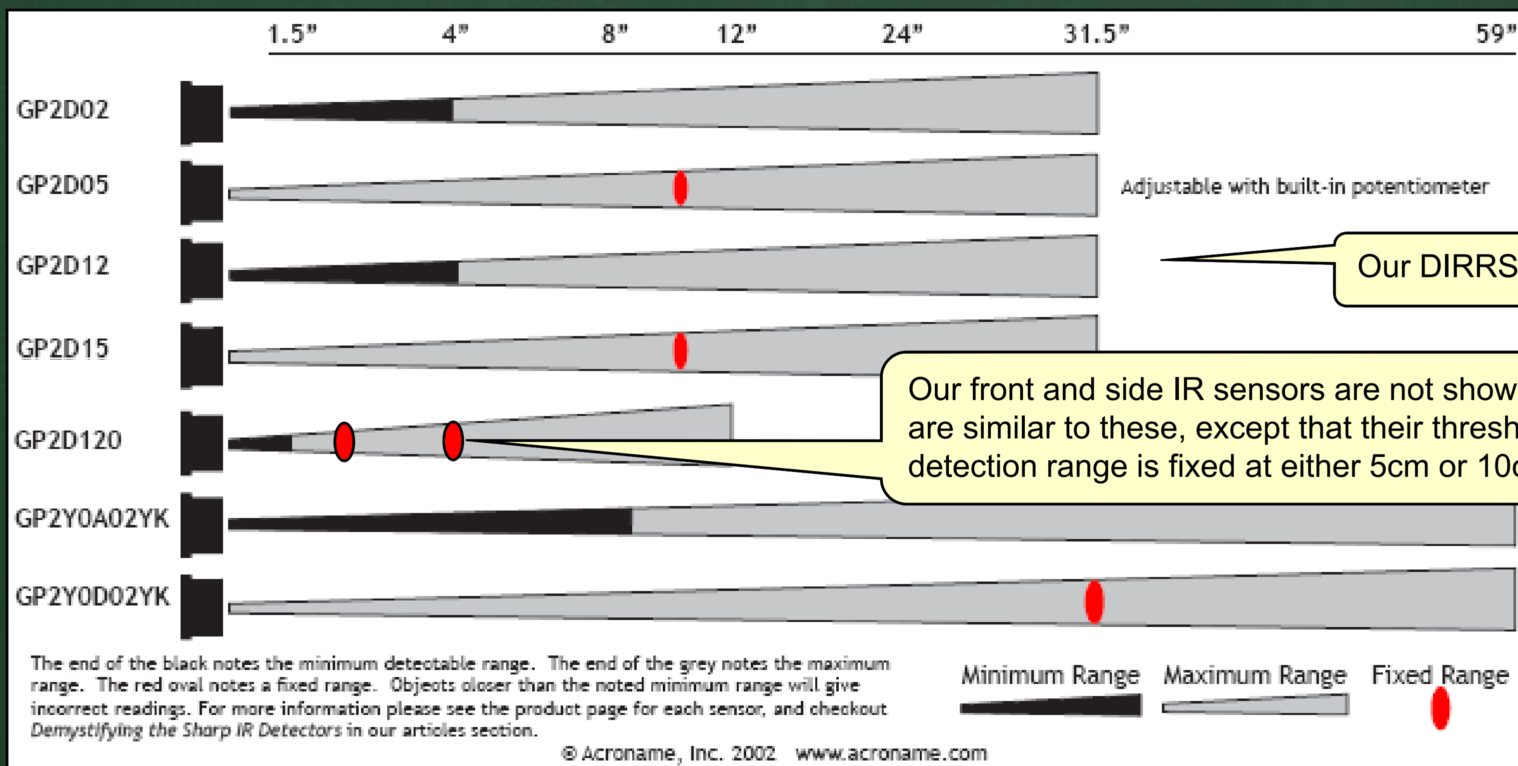
IR Range Sensors

- As with sonars, the Sharp GP2D12 sensor cannot always distinguish features at far distances.
- Consider test done by Sharp as shown on their datasheets:



IR Range Sensors

- Sharp produces many popular proximity detectors that vary according to their maximum and minimum distance ranges:

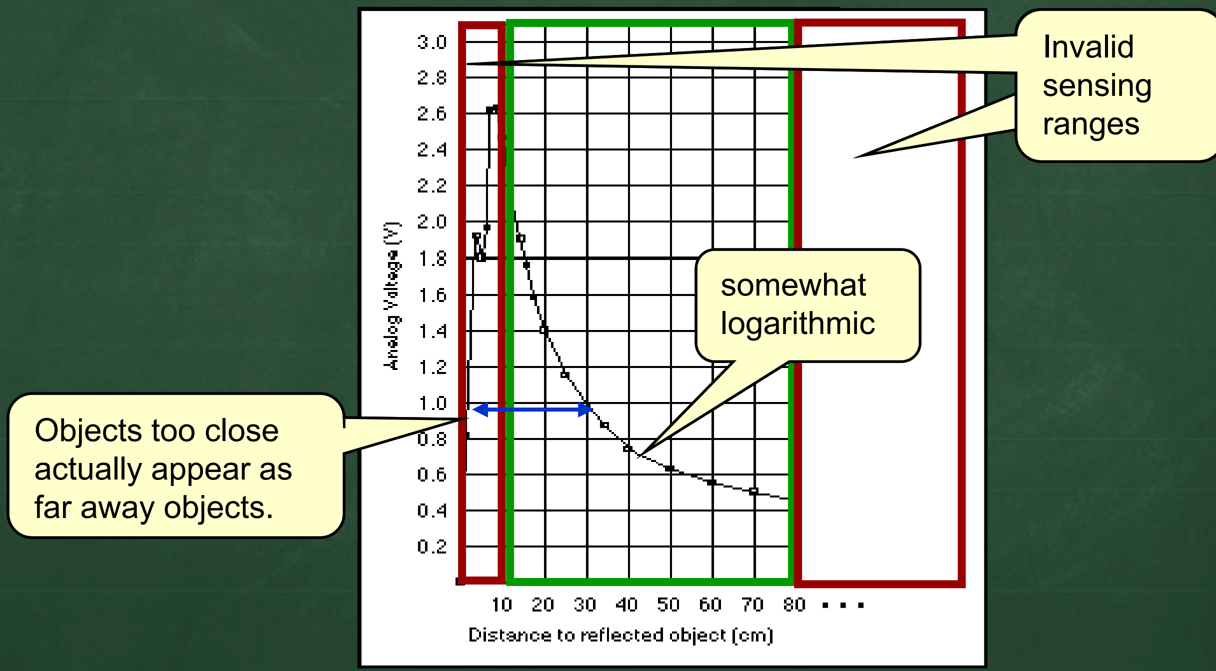


Our DIRRS+ sensor

Our front and side IR sensors are not shown here but are similar to these, except that their threshold detection range is fixed at either 5cm or 10cm.

IR Range Sensors

- The distance vs. voltage graph shows non-linearity

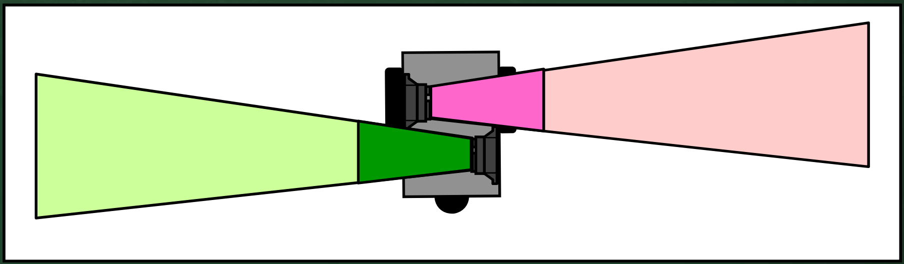


- Logarithmic shape varies slightly from one detector to another.

IR Range Sensors

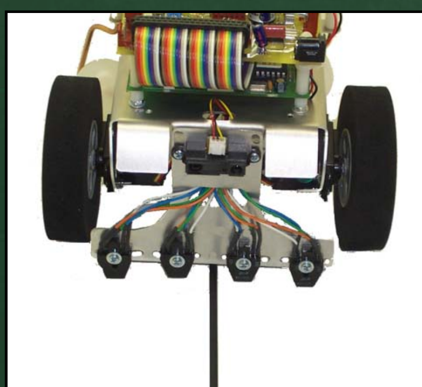
- Close objects (within 8_{cm}) are within a dangerous collision range.
  - Object may be detected at 12_{cm}, but by the time the robot stops, the object is in the 6_{cm} range…
  - The robot would then detect it at 12_{cm} again and think it is still far enough away from it.
- Can reduce this problem by pushing sensors further back on the robot

(called ***cross-firing***)



IR Range Sensors

- Triangulation technique provides improvements:
  - *better immunity to ambient light noise*
  - *indifferent to color variations*
- As with ultrasonic sensors, multiple IR sensors are often used in an array or circular pattern to speed up gathering of range data



IR Range Sensors

- Advantages of IR range sensors:
  - + reliable with good precision
  - + small beam angle
  - + inexpensive

- Disadvantages:
  - – sensitive to smoothness & angle to obstacles
  - – short range
  - – prone to interference from ambient IR (e.g., outdoors)
  - – can't detect distance to glass, mirrors or shiny surfaces

Laser Range Finders

Laser Range Finders

- Laser Range Finders are perhaps the most accurate sensors for measuring distances.

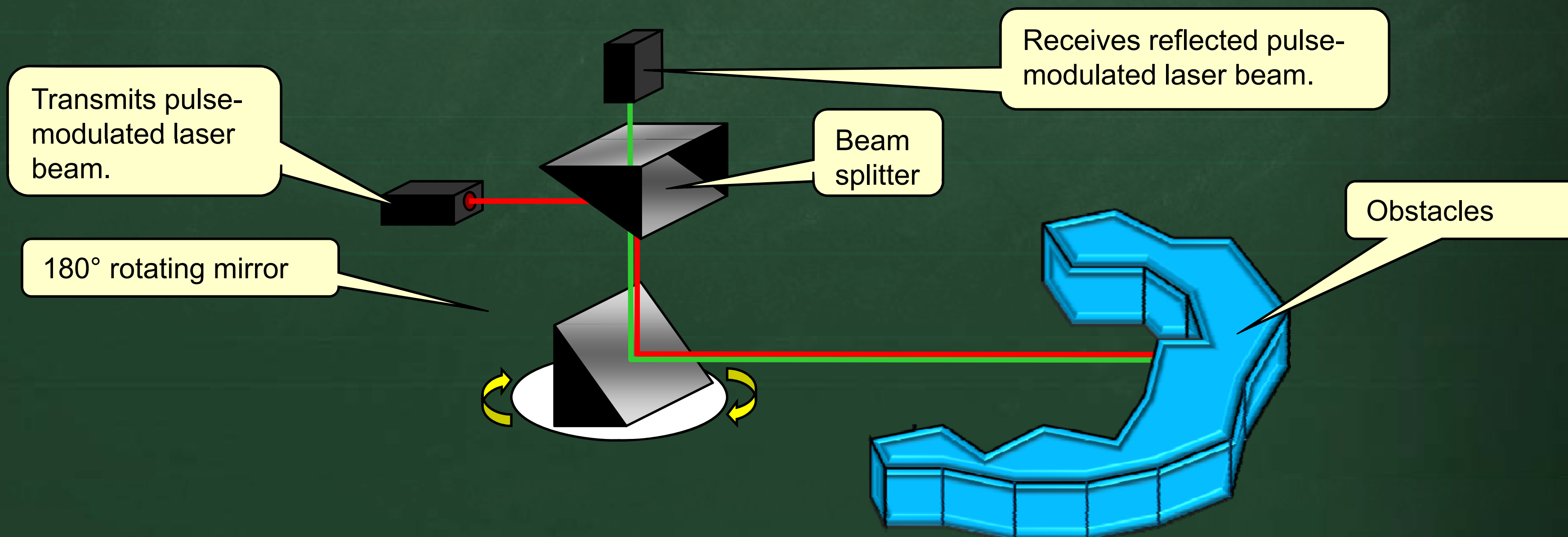
- Similar concept to IR range finder in that IR light is emitted and detected.

- These sensors are ***Lidar*** (Light Detection and Ranging) systems

- Lidar systems use one of three techniques:
  - *Pulsed Modulation*
  - *Amplitude Modulation Continuous Wave* (AMCW)
  - *Frequency Modulation Continuous Wave* (FMCW)

Laser Range Finders

- Pulsed Modulation lidar system (e.g., Sick sensor)
  - emits a pulsed laser light beam
  - reflected light is returned to detector
  - rotating mirrors are used to direct outgoing and incoming light to perform up to 240° scan



Laser Range Finders

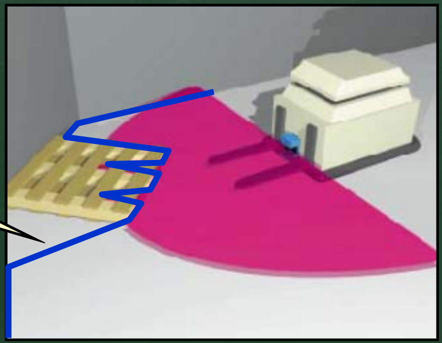
- Range calculated as $r = t \times c / 2$ where
  - t = time taken for light to return from when it was sent out
  - c = speed of light ~= 300,000,000 $_{m/sec}$
- Must have VERY fast processing since return times are very small.
- This leads to high expense of sensor (> $6k US)
- Tradeoff is high resolution … sometimes worth it.
  - "Sick" sensor can scan 180° at 0.5° resolution with accuracy ±1.5$_{cm}$ in short range (1$_m$ - 8$_m$) and ±4$_{cm}$ in long range (8$_m$ - 20$_m$)

Laser Range Finders

- "Hokuyo" sensor can scan 240° at 0.36° resolution with accuracy ±1_{cm} in range (2_{cm} - 4_m)

- Typically measure ranges up to 50_m
- Scanning at multiple heights produces a set of contour lines that can be stacked together to form model

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

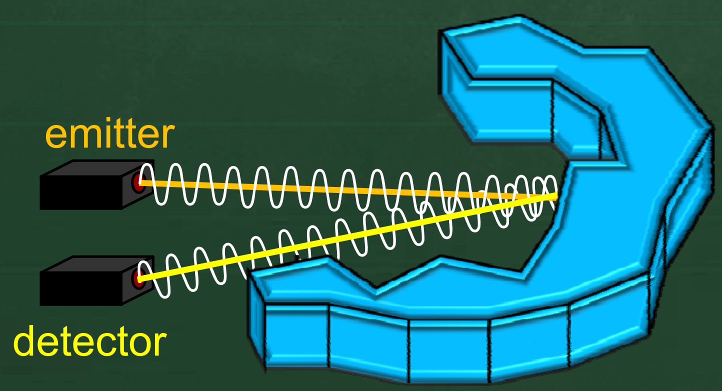


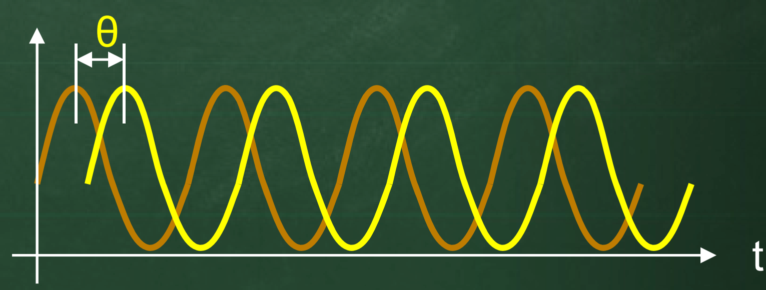
Laser Range Finders

- Full 3D scenes are usually scanned in one shot:
- Typically 180° scan taken at various heights with device mounted on pivoting "head".
- Can be very accurate.

Laser Range Finders

- AMCW sensors
  - emitter sends out a continuous modulated laser signal (i.e., intensity of beam is modulated using some wave pattern (e.g., sin wave).
  - detected light has same amplitude but phase shifted
  - difference in phase shift indicates range

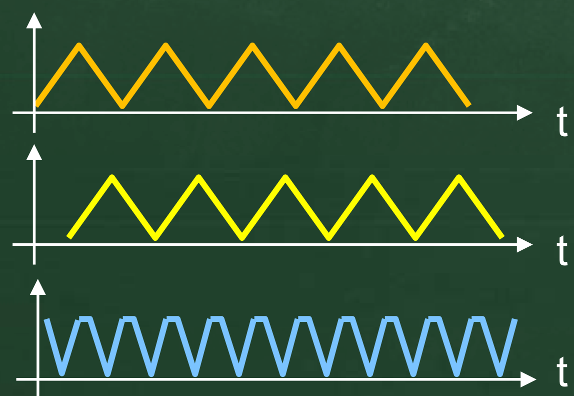


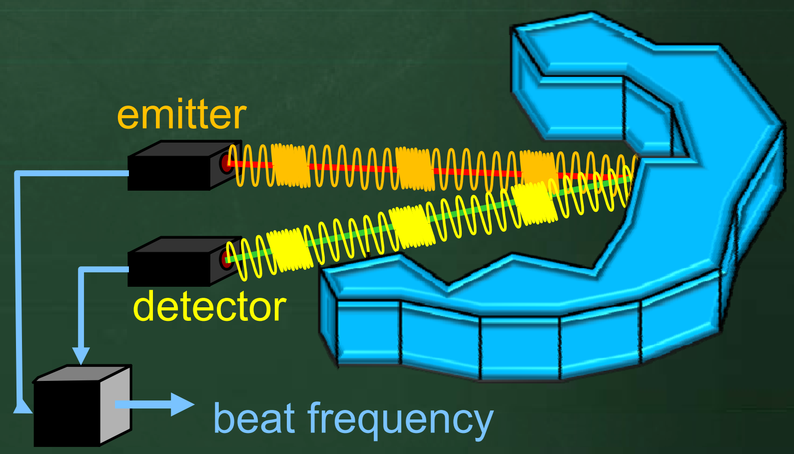


Range calculated as $r = \theta c / 4\pi f$ where
θ = phase shift
f = frequency of modulated signal

Laser Range Finders

- FMCW technique is simpler and hence lower cost
- Resolution is limited by modulating frequency
- FMCW sensors similarly emit a continuous laser beam, but modulated now by frequency.
  - emitted signal is mixed with reflected signal.
  - Result is difference in frequency





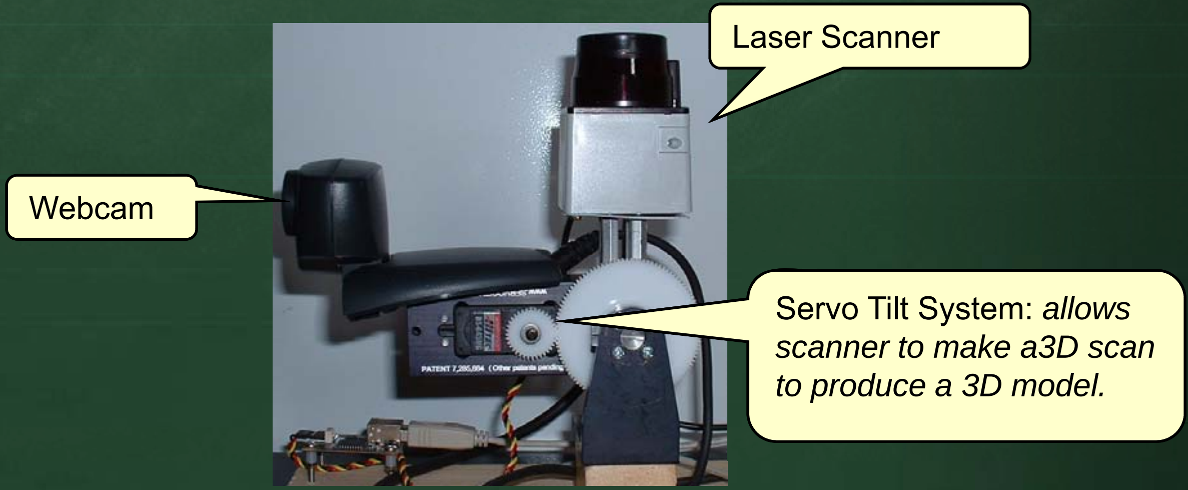
Laser Range Finders

- Advantages:
  - + better resolution than ultrasonic, IR, cameras
  - + very reliable
  - + not as sensitive to lighting conditions as cameras

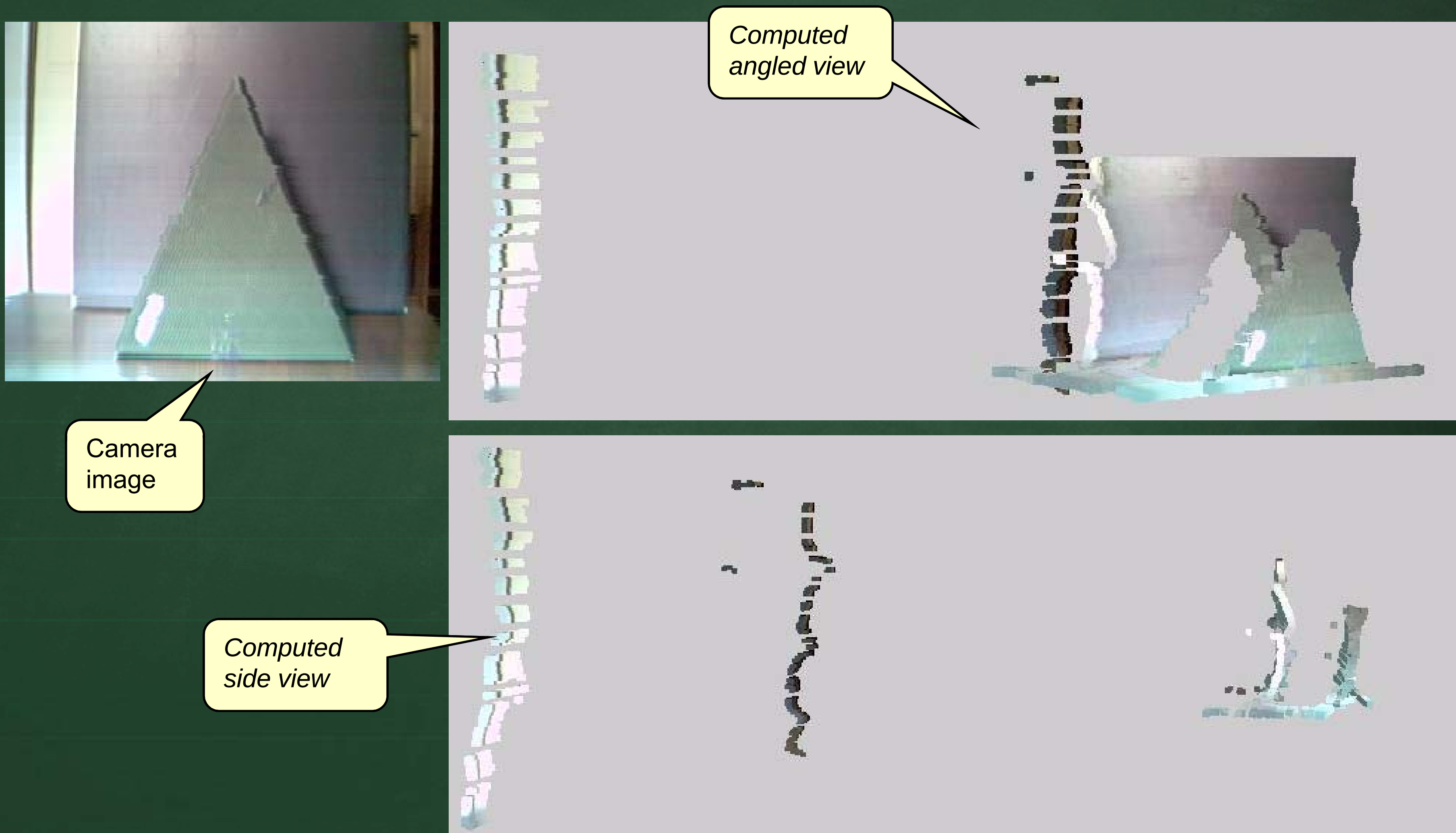
- Disadvantages:
  - – cannot identify mirrors and/or glass
  - – more expensive than all other sensors
  - – larger and heavier than all other sensors

Laser Range Finder Experiments

- Experiments were done using the Hokuyo scanner combined with a webcam
- Objective: to add depth to a camera image by finding surfaces and separating them like cardboard cutouts



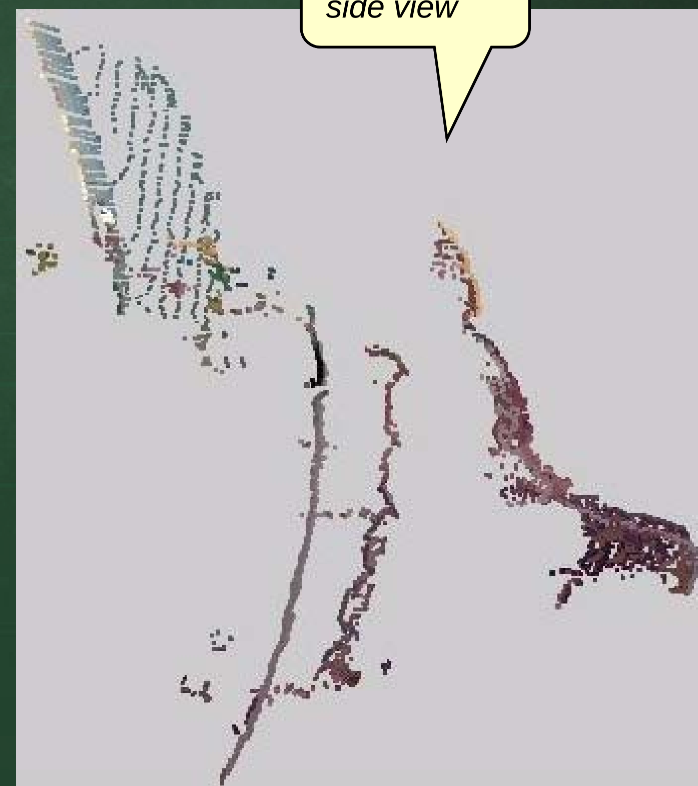
Experiment 1



Experiment 2

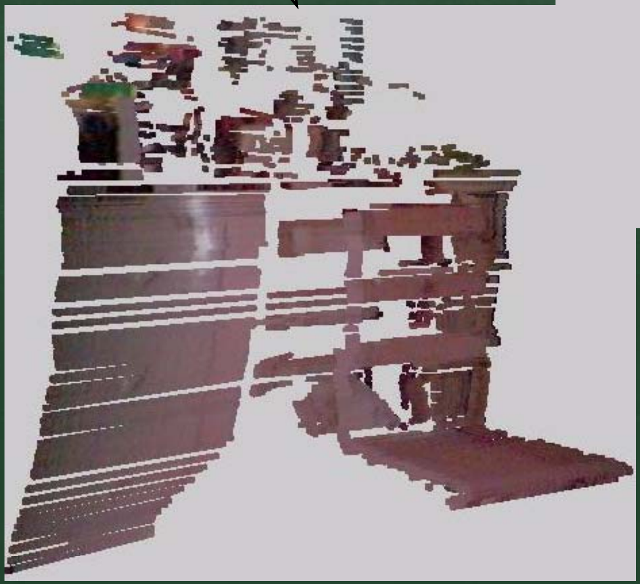
Camera image

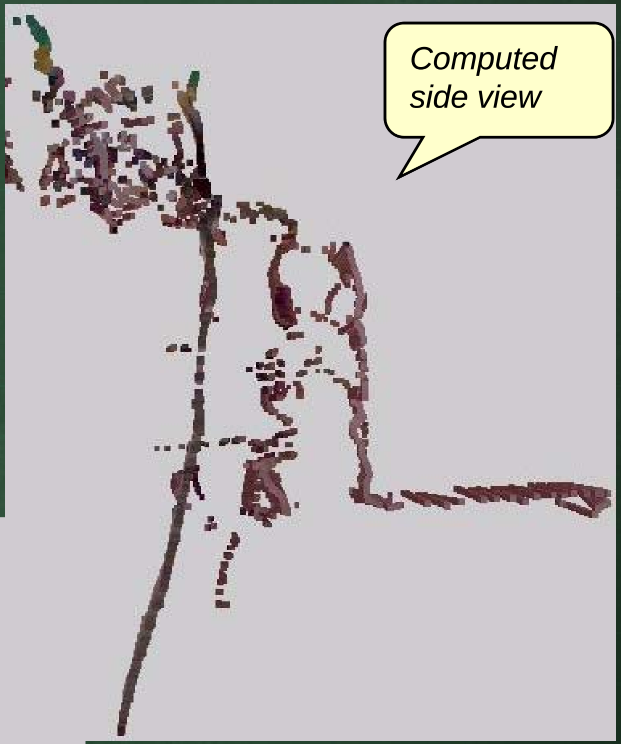
Computed angled view



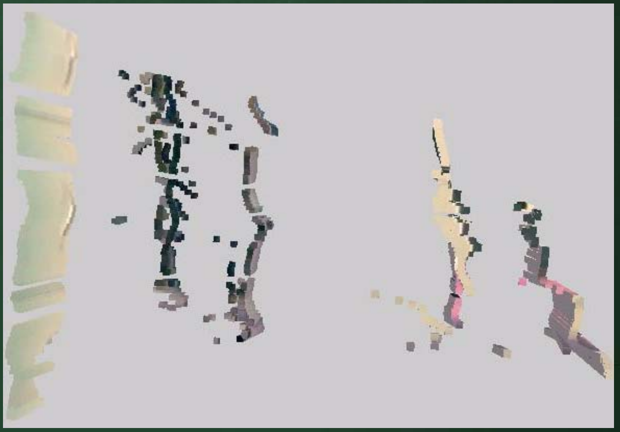
Computed side view

Experiment 3





Experiment 4



Camera image

Computed angled view

Computed side view

Laser Range Finders

- We will not discuss laser range finders any more in this course.
- In terms of mapping, laser range finders are just high quality 3D versions of our simple IR sensors.
- For the PropBot, we do not have the processing speed, power or size to accommodate such a sensor.

Stereo Camera Ranging Systems

Stereo Ranging Systems

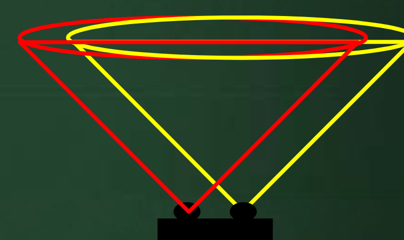
- As with laser range finders, robots equipped with Stereo cameras can obtain 3D range maps of the environment.

- Usually 2 cameras used, although one can be used from multiple locations.

A ~$2k stereo camera from **ptgrey.com**

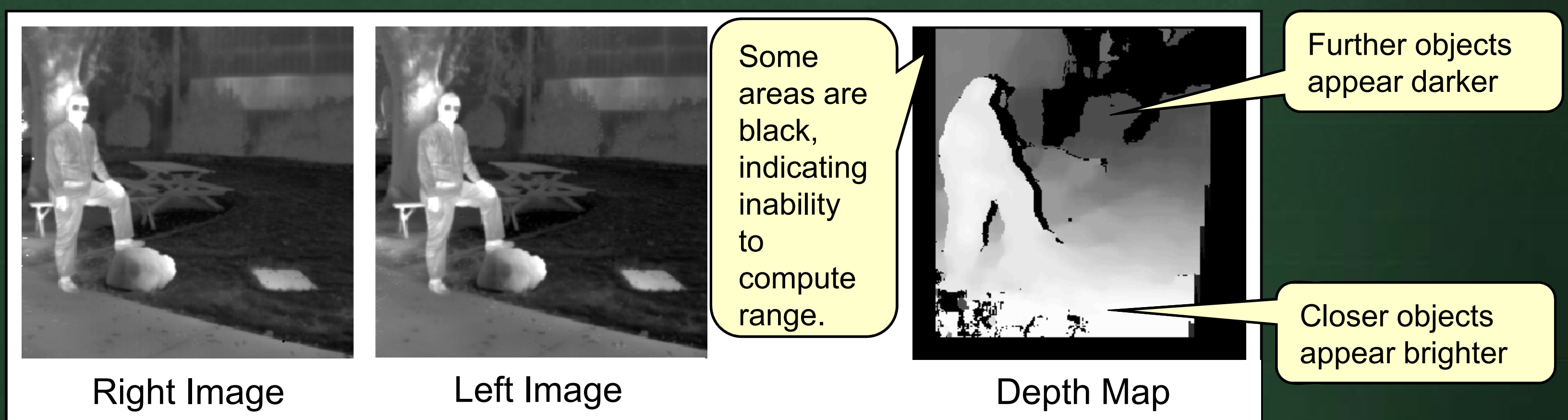
- Typical resolutions:
  - 640 x 480 at 30 frames per second
  - 1024 x 768 at 30 frames per second

- Cameras cover roughly a 45° cone.



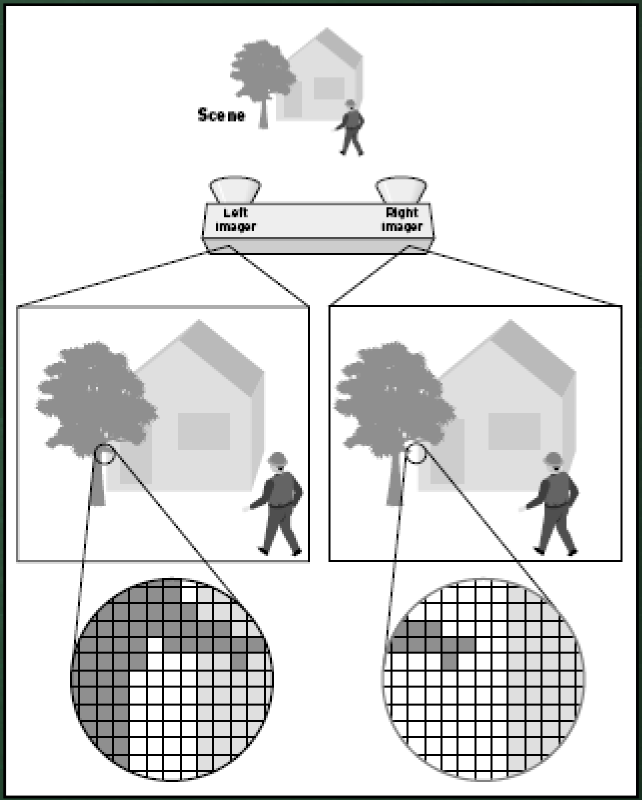
Stereo Ranging Systems

- Goal of stereo vision:
  - to calculate the depth or distance of features relative to the sensor (i.e., to construct a *depth map*).
    - Uses images from dual cameras aimed at the same object.
    - Need to locate the "same" features in both images.
    - Using the geometrical relationship between the two cameras and the location of the feature in each image, the depth of each feature can be triangulated and a depth map constructed.



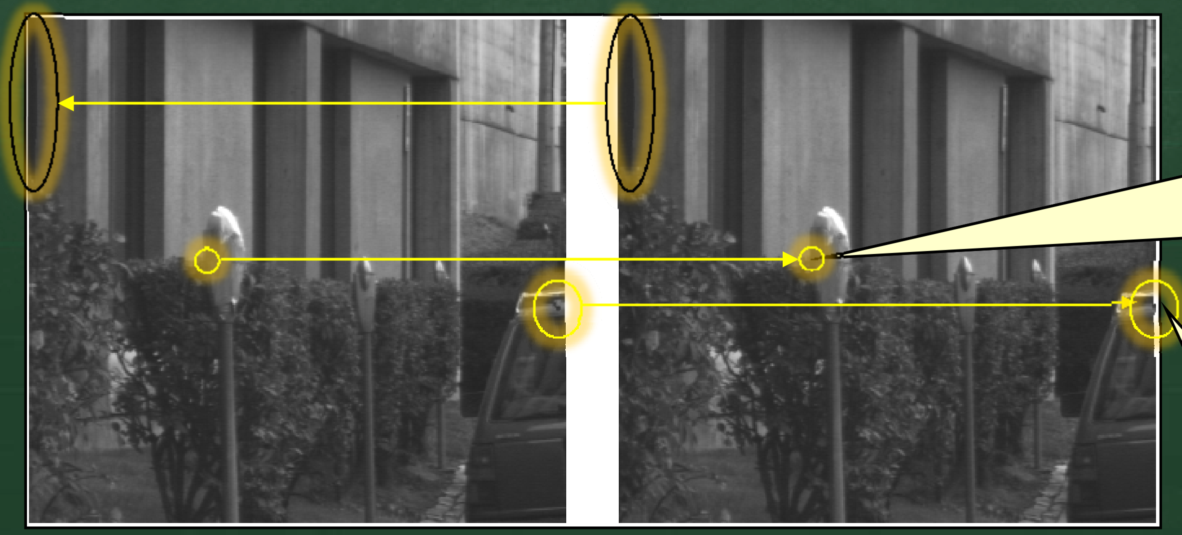
Stereo Ranging Systems

- Principle behind stereo vision:
  - Objects seen in left camera appear horizontally shifted from objects seen in right camera.
  - Size of shift, called the *disparity*, varies with object's distance from the cameras.
  - Central idea is to find a *correspondence* (or match) between points in one image with points in other image (not easy to get right).



Stereo Ranging Systems

- For each pixel in one image, finding the corresponding pixel in the other image is difficult
  - Instead, find similarity (most likely ***match***).
- In some cases, pixels in one image may simply not be visible in the other. This is called ***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

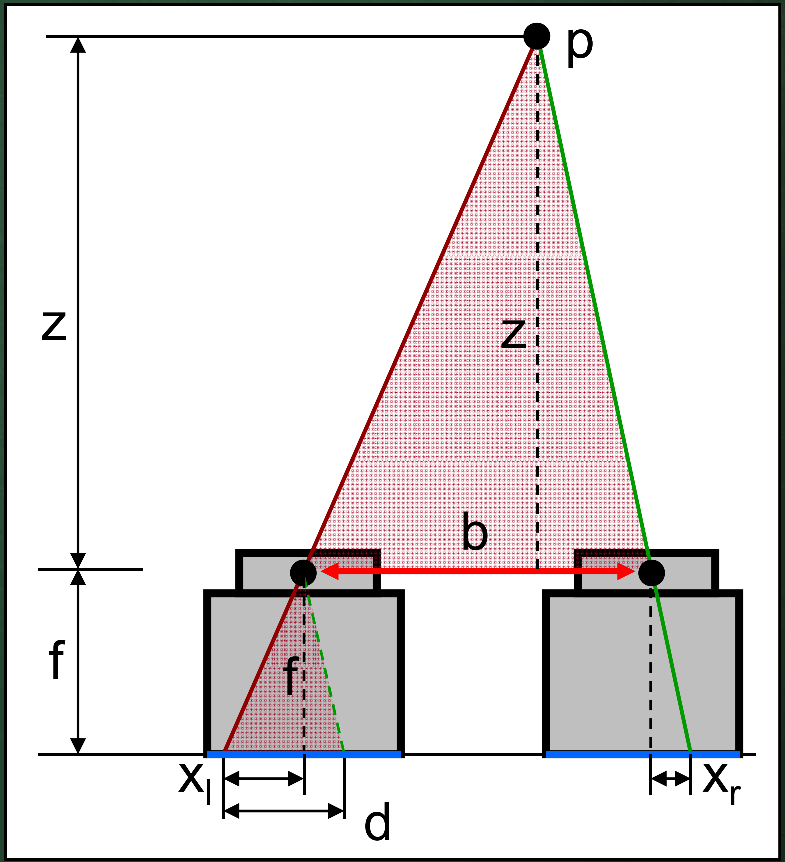
- If cameras pointing in same direction and aligned, can use simple geometry:

  b = baseline of camera system
  (i.e., a fixed value)

  z = depth of point **p**

  d = disparity = $x_l - x_r$

  f = focal point of cameras
  (i.e., a fixed value)



- The two shaded triangles are *similar*, and so $z = \frac{f\,b}{d}$

Stereo Ranging Systems

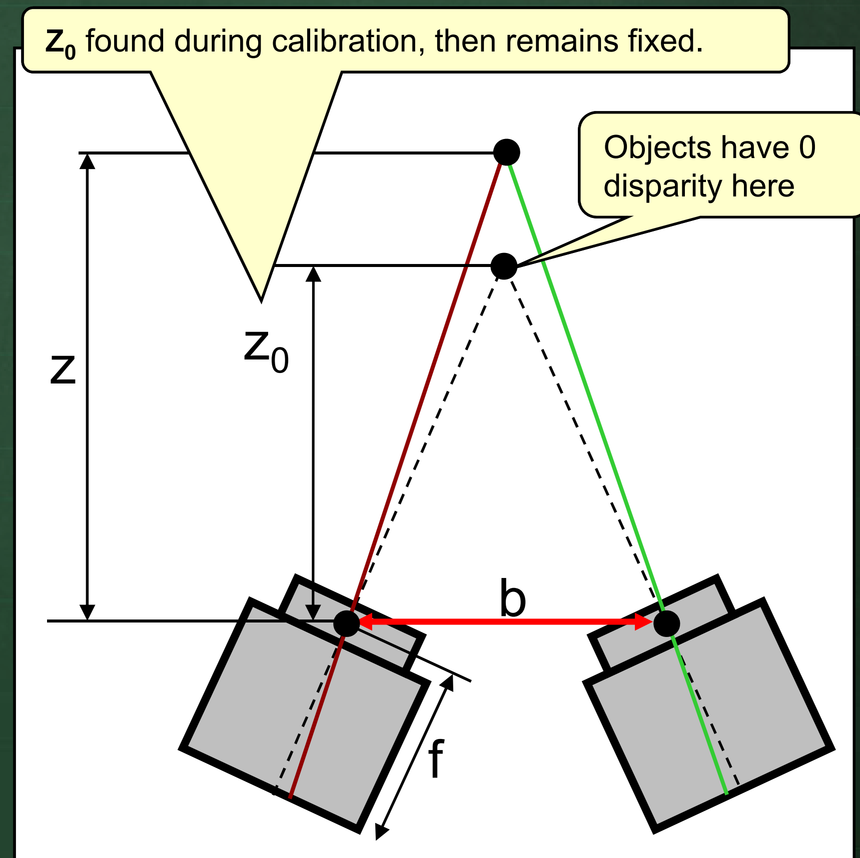
- So, the depth is inversely proportional to disparity
  - stereo is most accurate for close objects
- Disparity is always an integer value since it is difference in x values of pixels.
- Accuracy of depth can be increased by increasing baseline distance (i.e., distance between cameras)
  - but reduces overlap of cameras and hence scene width
  - more difficult to identify matching pairs of points since left/right images have less in common due to larger difference in viewing angle

Stereo Ranging Systems

- More realistic scenario is when cameras are not lying on the same plane:

- Here

$$z \approx \frac{f\,b}{(d + (fb / z_0))}$$



Stereo Ranging Systems

- So how do we compute correspondence ?

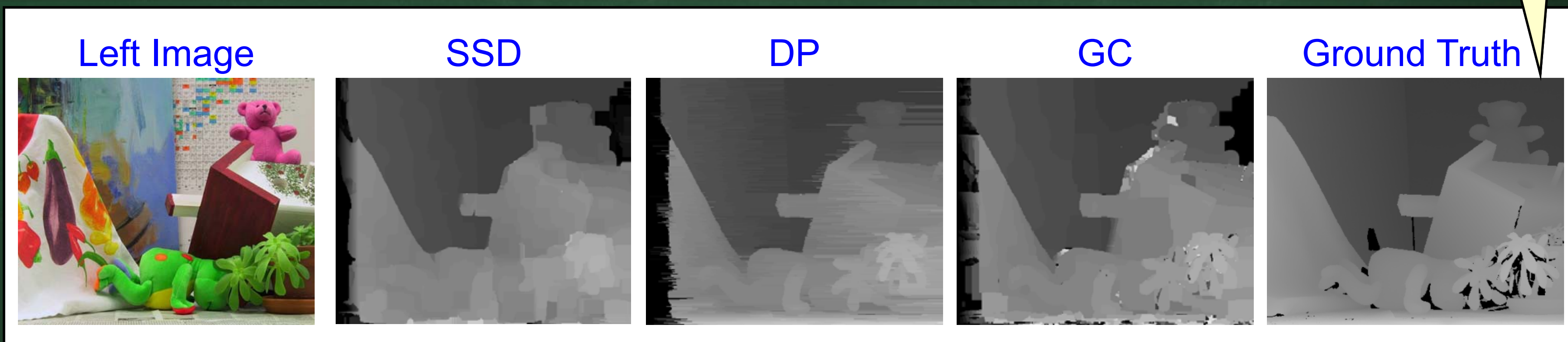
- Some desired characteristics:
  - Corresponding image regions are similar
  - Each point matches a single point in the other image
    - unlikely for low feature scenes (e.g. blank walls)
- Many matching methods, 2 main types:
  - Feature-based - start from image structure (e.g., edges)
  - Correlation-based - start from grey levels
- We will look a little at correlation-based methods

Correlation

- There are many approaches to doing correlation, each providing different results:
  - Sum of Squared Differences (SSD)
  - Dynamic Programming (DP)
  - Graph Cut (GC)
  - Belief Propagation (BP)
  - Markov Random Fields (MRF)

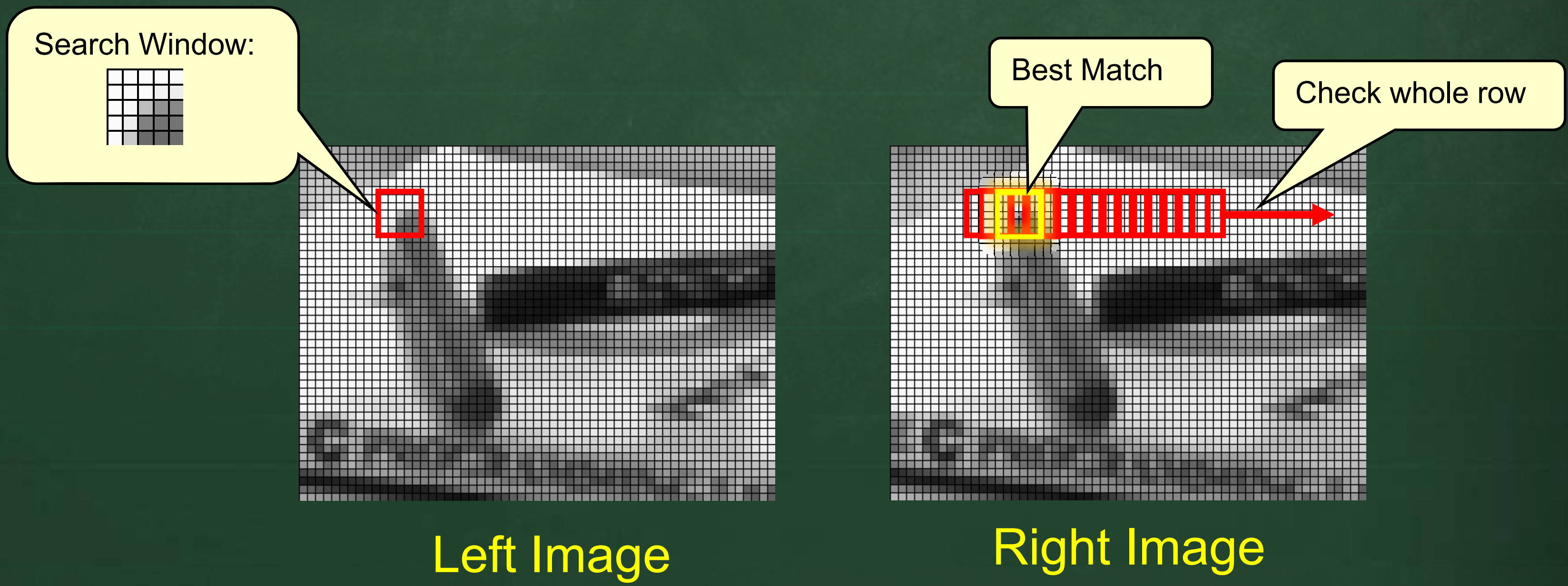
We will look more at this one only.

Ideal solution, manually computed



SSD Correlation

- Idea:
  - Take a small area of data in left image and compare it with similar-sized areas in the right image along the same epipolar line (e.g., at the same height in the image if the cameras are horizontally level).



SSD Correlation

- Comparison is done by finding the sum of squared differences between left and right window areas.

```
FOR x = 0 to width DO {
     FOR y = 0 to height DO {
          bestSSD = MAXINT
          FOR d = 0 to MAXRANGE DO {
             ssd = 0
             FOR xx = x -WINDOW_SIZE/2 to x+WINDOW_SIZE/2 DO {
                FOR yy = y -WINDOW_SIZE/2 to y+WINDOW_SIZE/2 DO {
                   diff = leftImage[xx, yy] - rightImage[xx+d, yy]
                   ssd = ssd + (diff * diff)
                }
             }
             IF (ssd < bestSSD) THEN {
                bestSSD = ssd
                bestDisparity = d
             }
          }
          disparityMap[x, y] = bestDisparity
     }
}
```

Maximum difference allowed during window comparison phase.

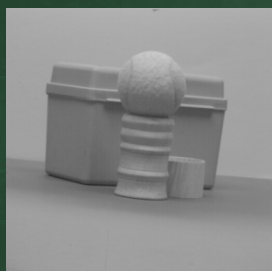
(x,y) position with least squared-difference gives the best match, and hence the disparity of the best match.

Window size is adjustable parameter. Large window means slower, but eliminates more noise.

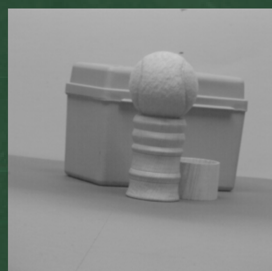
SSD Correlation

Window size

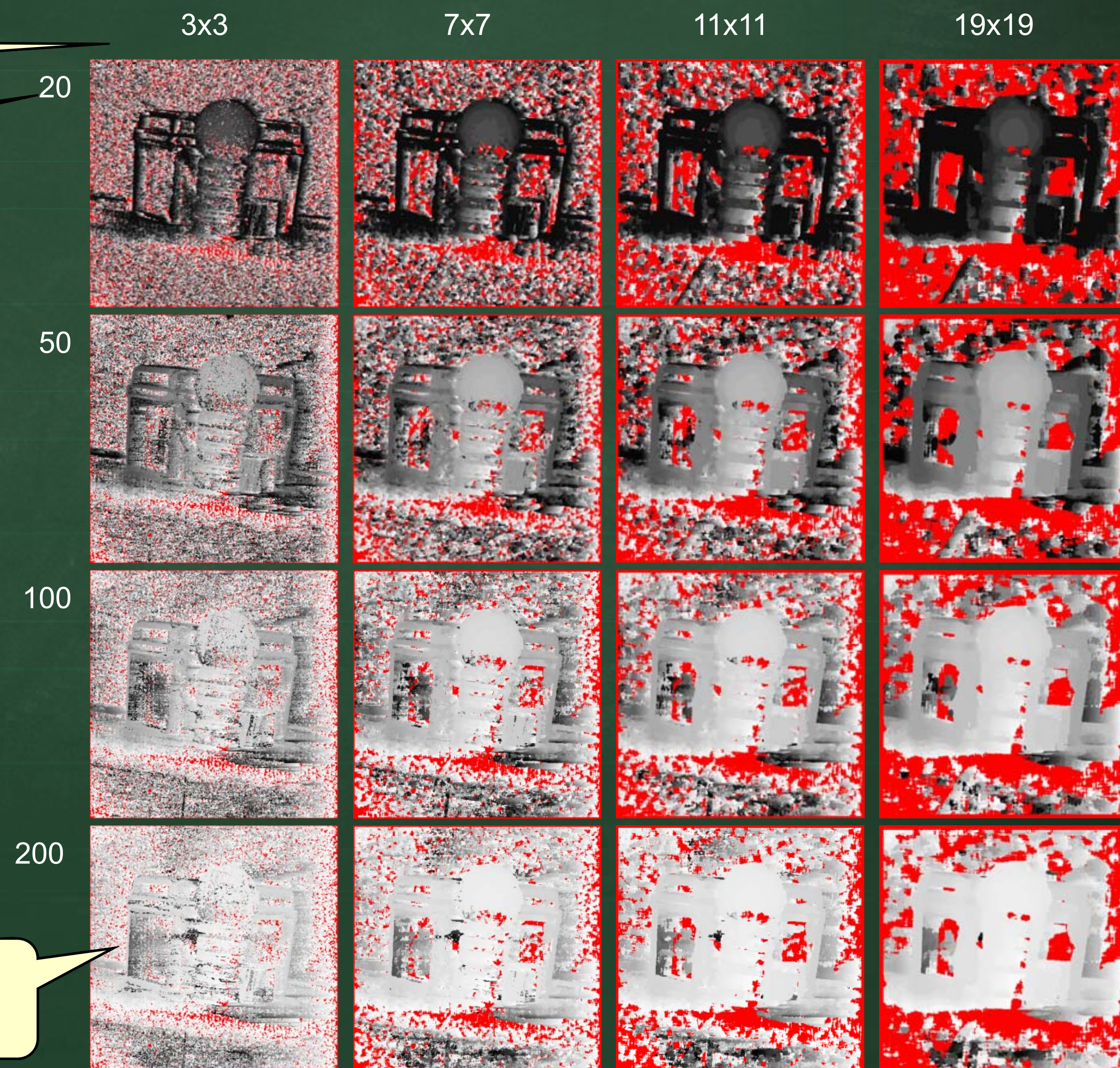
Maximum disparity



left



right

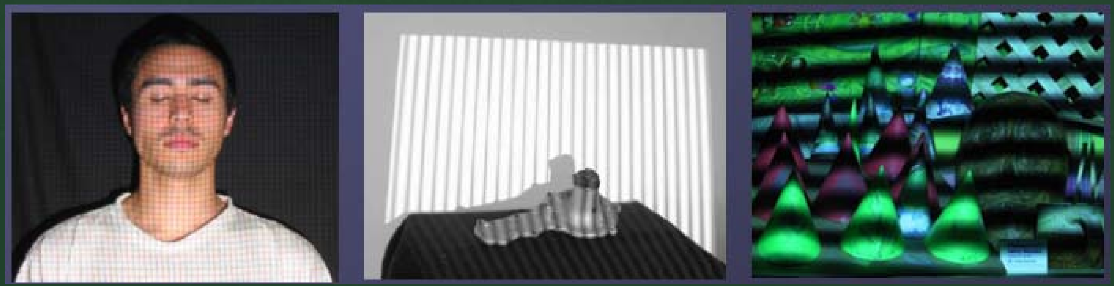


Red indicates no match

Smaller windows = more noise

Correlation

- There are many strategies to improve matching:
  - Apply various image filters before and after processing
  - Identify corners and edges, hence planes (can help to fill-in areas in which no data is available).
  - Use sensor fusion (i.e., data from other sensors) to fill-in missing gaps.
  - Project structured light onto objects to improve matches:



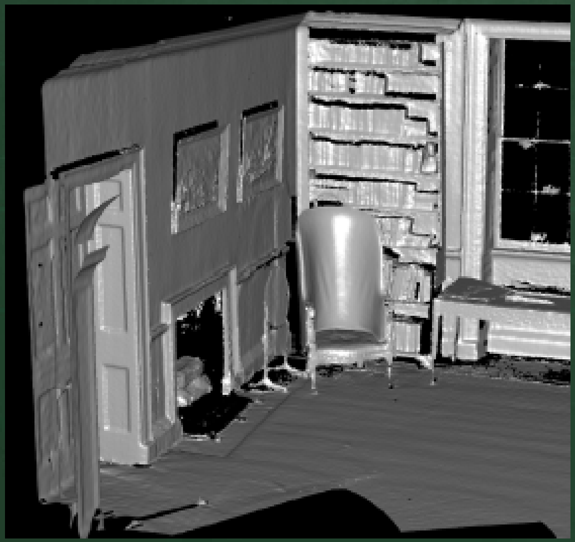
Stereo Ranging Systems

- Advantages:
  - + better resolution than ultrasonic and IR
  - + very reliable when environment is sufficiently cluttered.
  - + often packaged with software to calculate depth

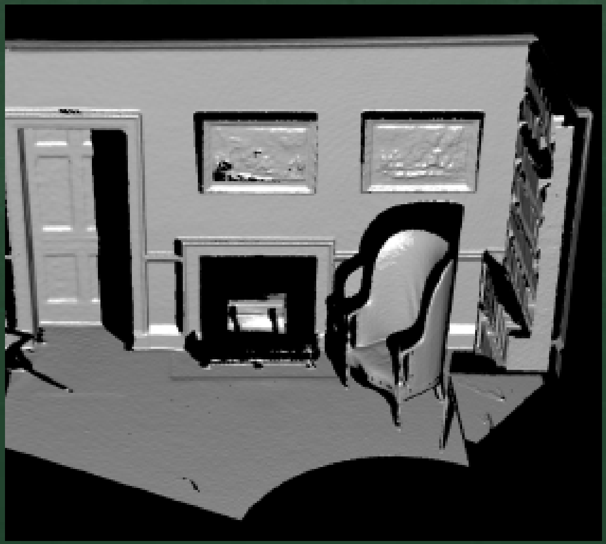
- Disadvantages:
  - – cannot identify mirrors and/or glass
  - – sensitive to lighting conditions
  - – poor performance when environment lacks features
  - – more expensive than ultrasonic and IR
  - – larger that ultrasonic and IR
  - – difficult to calibrate (depending on sensor packaging).

Scene Reconstuction

- From depth maps, 3D models are often constructed by creating a triangular mesh.
- Here is one with 2,860,000 vertices and over 5,000,000 triangles:



3D model from one angle

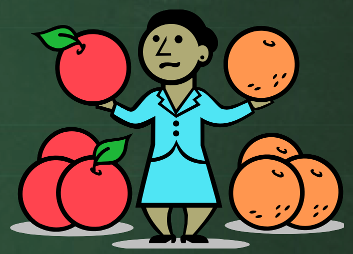


3D model from different angle

Completed model

Sensor Selection

Sensor Selection



- As mentioned, range sensors each have their own advantages and disadvantages.
- Certain factors must be considered when choosing an appropriate sensor:
  - cost and physical size of sensors
  - processing power required
  - environment (obstacle types, features, density, size…)
- Certainly, different kinds of sensors can **compliment** one another

Popular Choice

- The most popular choice for average-sized robots is the laser range finder, due to its high accuracy.
- Vision-based sensors are also quite popular and share advantages with laser range finders:
  - high accuracy and low cost/performance ratio
  - 3D distance information
  - high speed data acquisition
  - rich in information

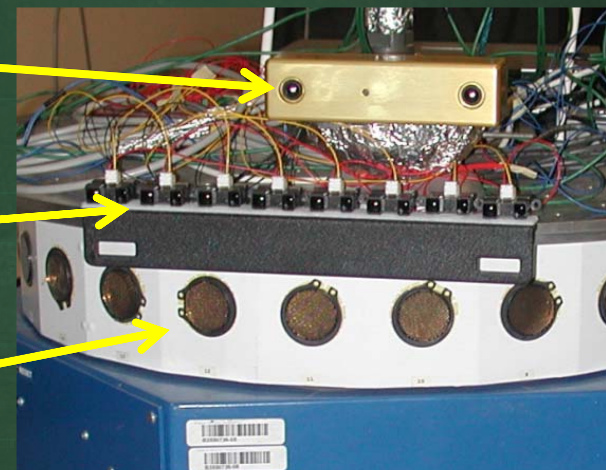
Sensor Tests

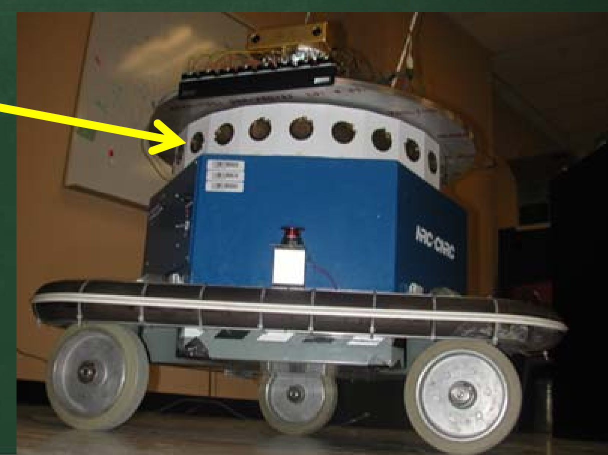
- Tests were performed on our K2A robot platform:
  - Stereo camera

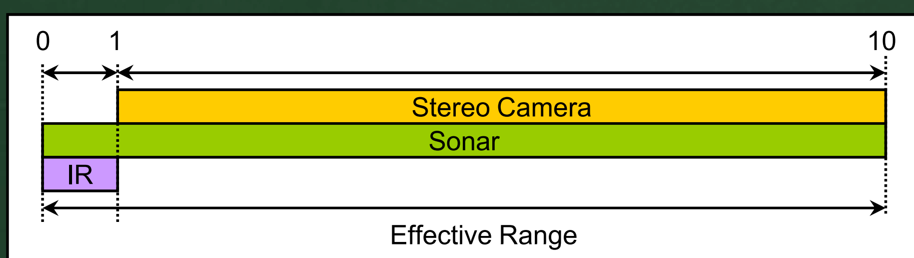
    (Bumblebee camera from Point Grey®)
  - IR proximity sensor array

    (Sharp® GP2Y0A02YK proximity sensors)
  - 24-sensor sonar ring

    (Polaroid® 6500 ultrasonic transducers)





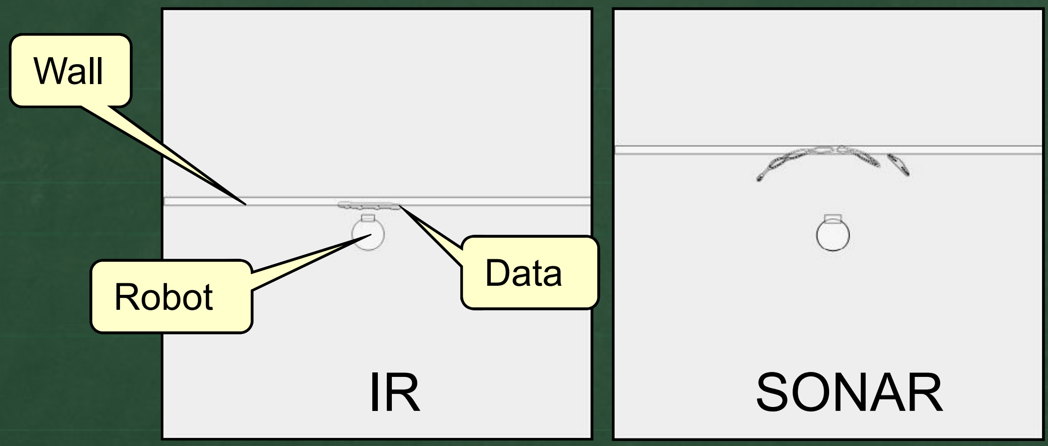


Sensor Tests

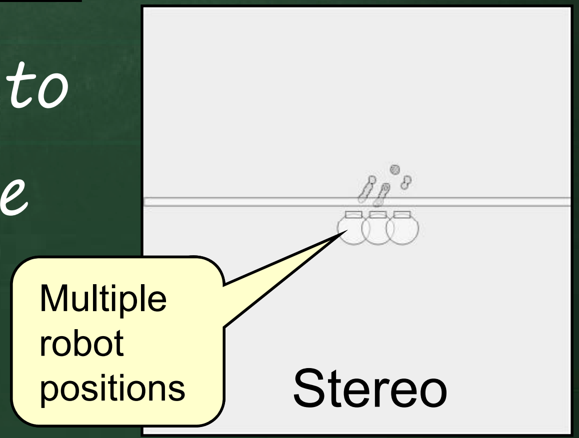
- Tests were aimed at
  - determining the pitfalls of stereo cameras
  - investigating ways to merge 3 types of sensors to produce more accurate obstacle detection
- 5 Tests were performed:
  - Blank Wall – sensors aimed at a blank yellow wall
  - Low Lighting – sensors used in dark setting
  - Low Contrast – sensors try to detect low contrast scene
  - Transparency – sensors try to detect glass
  - Full Lab – sensors operate around a typical lab

Tests – Blank Wall

- Stereo Camera was unable to detect a featureless wall, whereas the IR and Sonar did detect them:

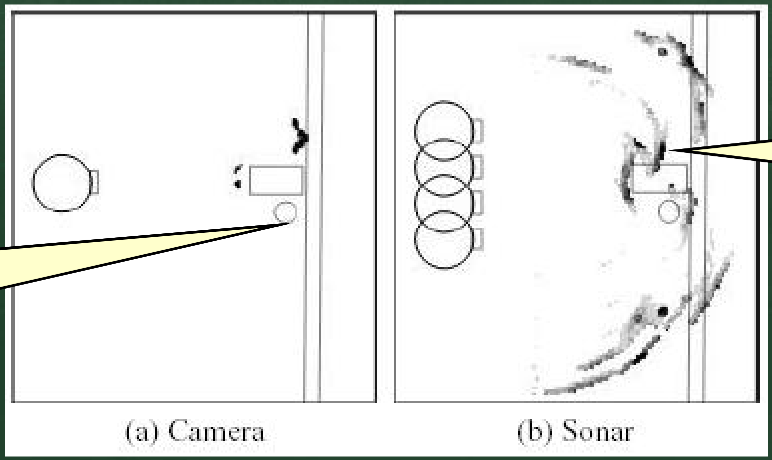


- When sufficient features were added to the environment (a newspaper on the wall), the stereo camera did a little better:



Tests – Low Lighting

- Similarly, stereo cameras performed poorly under low lighting:

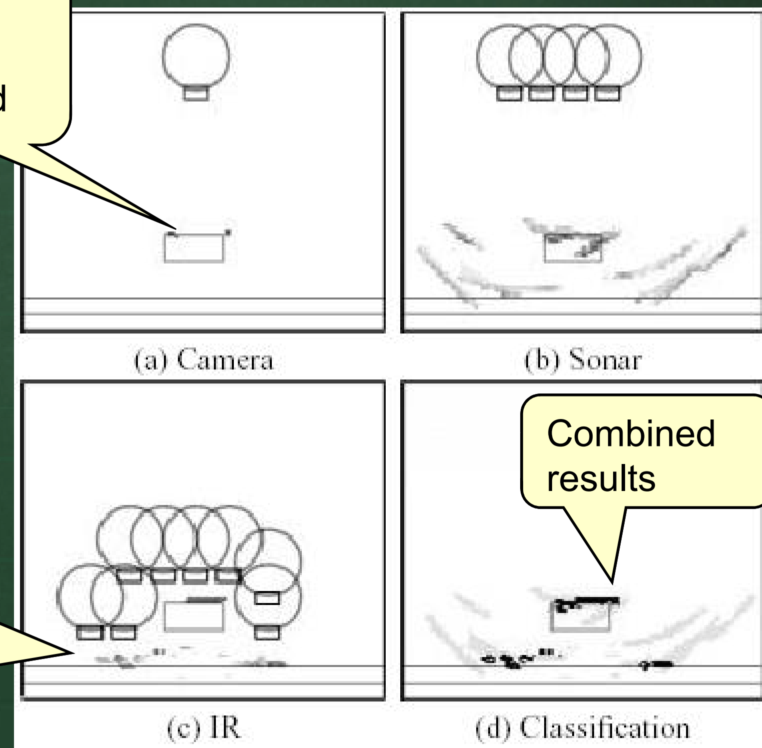


Sonar detected many obstacles, but with coarse readings.

Stereo camera could not detect garbage can, nor walls.

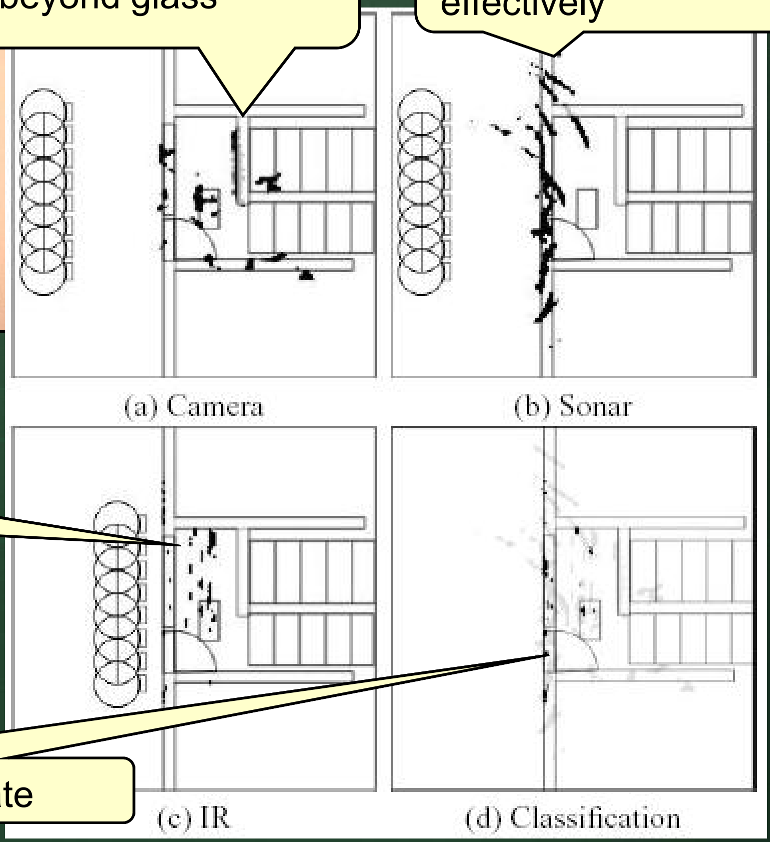
Tests – Low Contrast

- Stereo camera had difficulty identifying range to uniform-color cabinet:



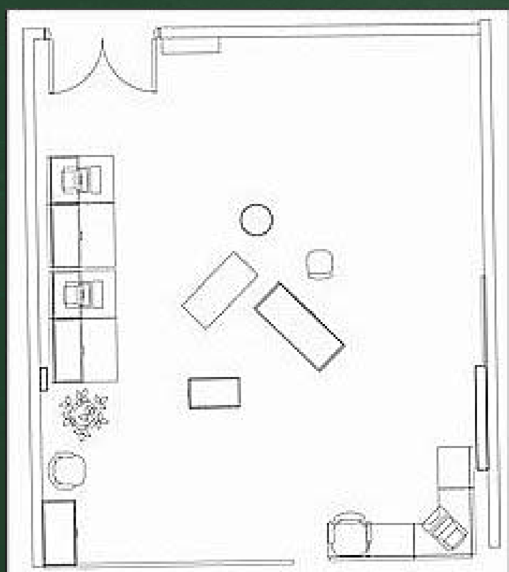
Tests - Transparency

- Both stereo camera and IR had difficulty with glass:



Tests – Full Lab

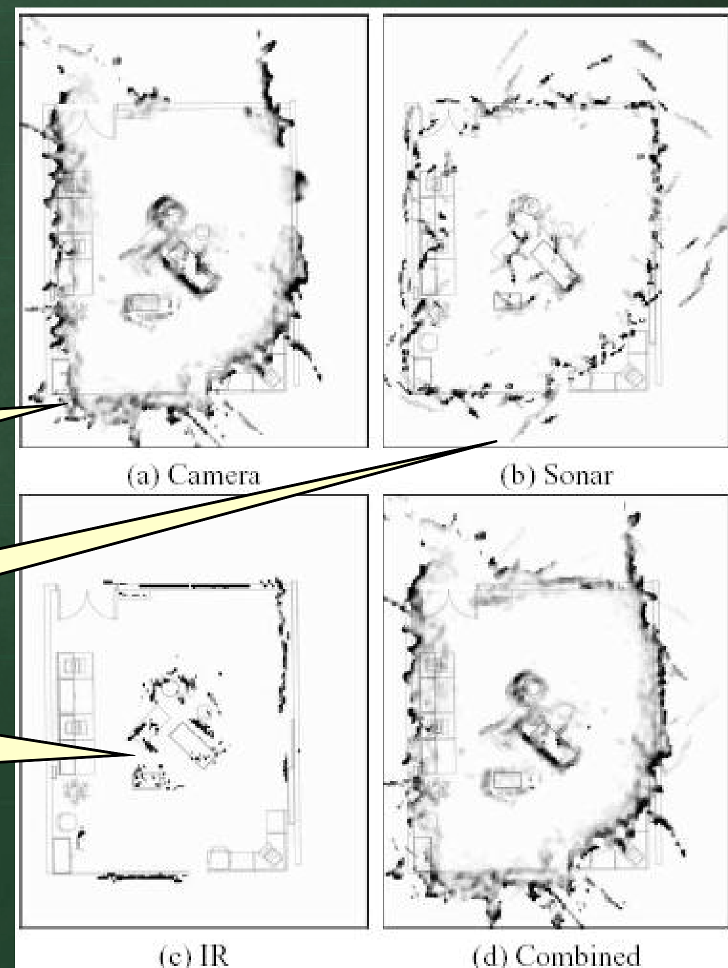
- A more thorough test was done in our full lab:



Much noise from stereo camera

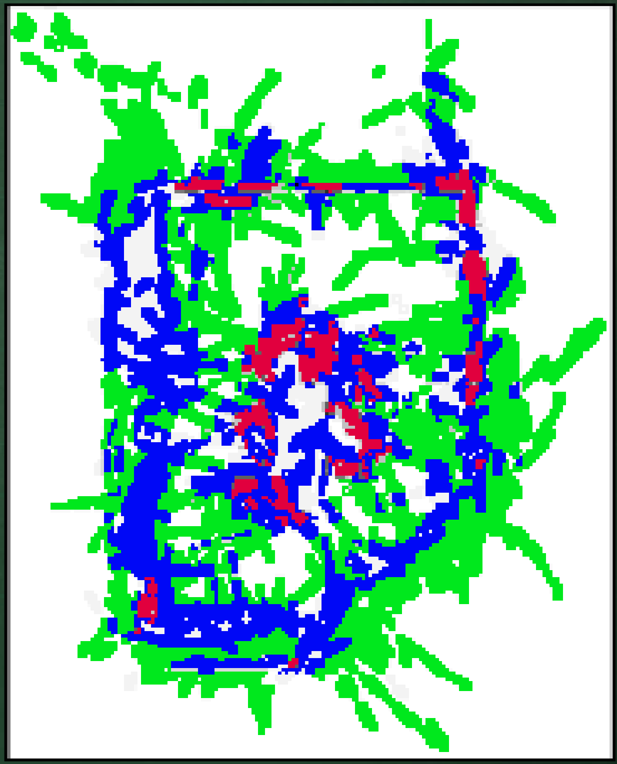
Sonar correct but coarse

IR has less readings due to short range



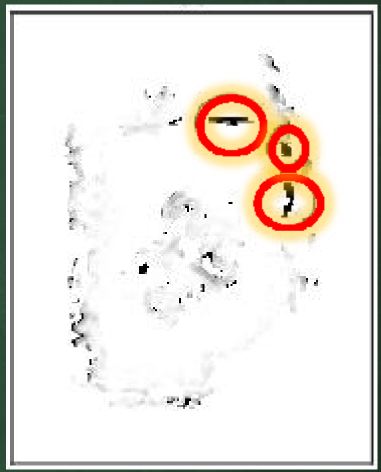
Data Fusion

- 59.7% of data comes from a single sensor
  - considered to be noise
- 34.2% of data from 2 sensors
  - considered to be valid readings
- 6.2% of data from all 3 sensors
  - may be considered "feature points"

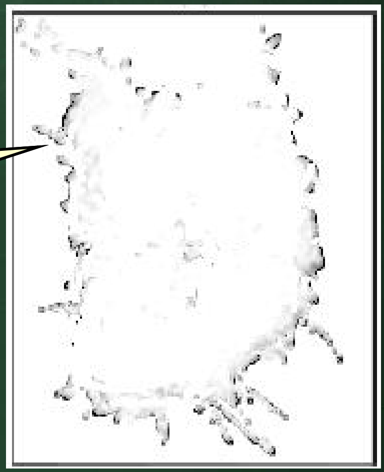


Data Fusion

- Data fusion improves the *quantity* of valid sensor readings:
  - 12% of missing environmental border data is "filled-in" through data fusion process.



- Data fusion improves the *quality* of sensor readings:
  - 48.8% of "noise" from stereo camera data is eliminated through sensor data fusion.



Dynamic Sensor Selection

- No sensor outperforms any other in all situations
  - cameras usually used to model complicated scenes
  - sonar often used for rough/dynamic collision avoidance on larger robots
  - IR typically used for collision avoidance, wall-following, mapping, etc… on smaller robots

- Some work has been done to dynamically select sensors over time:
  - can be based on learned information, known obstacle types or known lighting conditions

Summary

- You should now know about:
  - characteristics of various sensors
  - advantages and disadvantages of various kinds of range and proximity sensors
  - how ultrasonic and IR sensors work
  - the concept behind laser range finders
  - how to use a simple stereo vision algorithm
  - the issues behind choosing sensors