Lecture 3-2

What's Going On?

Sensors and Perception

Switch on the Light:

Simple Sensors

The Robotics Primer (Ch. 7, 8)

Course Announcements

- Bring a calculator for Monday's Quiz on **Sensors/Perception**
- Bring your laptop and robot everyday
- Lab 2 demo due Thursday, 3/26/09
- Take your robot to the parts room after the Thursday demo to be fitted with wheels
- Lab 2 memo and code due by midnight on Friday, 3/27/09
- Upload memo and code to Angel
- Memo and Code grades on Angel by Friday, 3/27/09

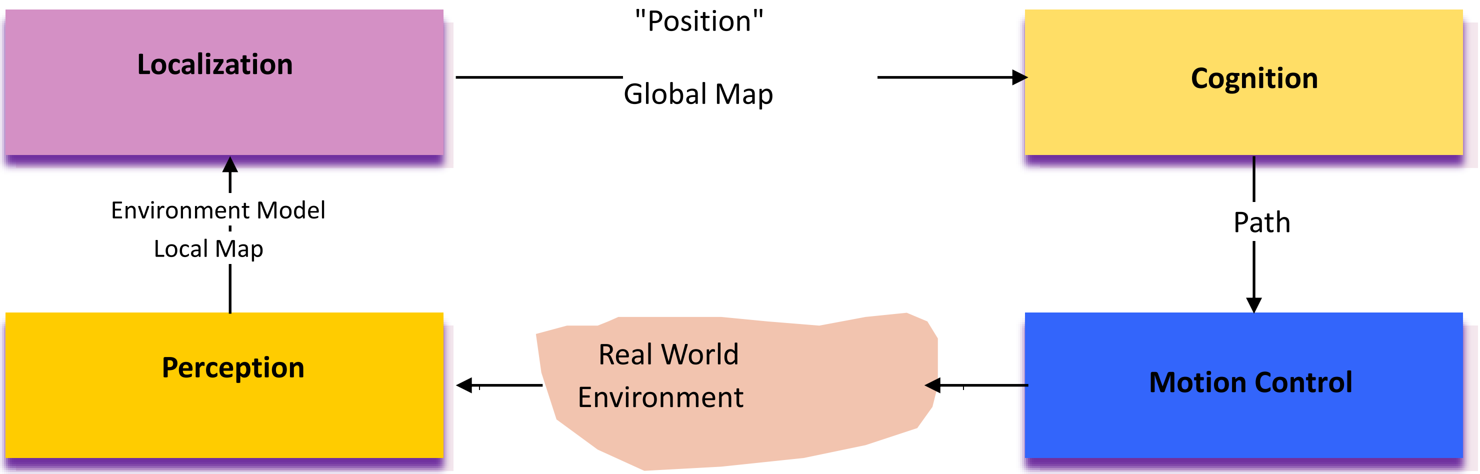
Quote of the Week

"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

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



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 **process** and speed of **processing** sensory input
- The ability of a robot to gain meaningful information about its environment through sensing is **perception**

Sensors

- A robot's intelligence is typically measured by the diversity of its sensor suite.
- **Proprioceptive Sensors** perceive elements in the robot's internal state. For example, encoders on motors for distance or velocity or battery voltage.
- **Exteroceptive Sensors** perceive elements in the state of the external world around the robot. For example, infrared sensors for distance, temperature or light intensity.
- Proprioceptive and Exteroceptive sensors combine to make the robot's **perceptual system**

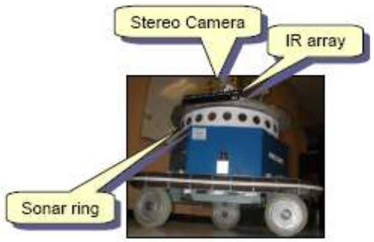
Sensor Diversity

- 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

Signal versus State

- Sensors do not provide state information but rather data or physical quantities. These measurements must be processed in order to be useful
- Because sensors are prone to error, there are several sensors that measure the same quantity and can be used for **sensor redundancy**
- **Sensor fusion** is when multiple sensors are used to create some knowledge or get better information about the robot’s internal and/or external state.

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

Uncertainty

- **Uncertainty** refers to the robot's inability to be certain about the state of itself or the environment.
- Some of the sources of uncertainty are:
  - Sensor noise and errors
  - Sensor limitations
  - Effector and actuator noise and errors
  - Hidden and partially observable state
  - Lack or prior knowledge about the environment
  - Dynamic and changing environment

Sensor Questions

- Given a sensory reading, what should I do?
  - Easy to answer with a simple sensor, i.e. if the bump sensor is triggered, the robot should stop
  - Hard to answer with a complex sensor, i.e. if the camera image contains a wall, the robot should ?
- Given a sensory reading, what was the world like when the reading was taken?
  - May not be easy to answer with simple or complex sensors
  - Simple sensors do not prove enough information for reconstruction of the world. i.e. if the bump sensor is triggered, what did it hit?
  - Complex sensors provide this information but require a great deal more processing

Signal to Symbol Problem

- The ***signal to symbol*** problem involves extracting useful information from a sensor signal. This is an enduring challenge in robotics
- ***Sensor preprocessing*** must be done before the robot can use the data to make any decisions or take any actions.

Levels of Processing

- ***Electronics*** can be used to identify an obstacle based upon voltage going through a circuit from a bump sensor
- ***Signal processing*** can be used to recognize a voice heard through a microphone sensor. This method also uses electronics to filter out noise.
- ***Computation*** can be used to find a known object in an image from a camera sensor by comparing it to a database. This will also use electronics and signal or image processing.

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)

Effective Perception

- **Action-oriented perception** involves using knowledge of the task to look for particular stimuli and respond. For example, a robot over a conveyor belt uses the whisker switch to indicate arrival of a part.
- **Expectation-based perception** involves using knowledge about the environment to constrain the interpretation of sensor data. For example, triggering a motion sensor sets off a burglar alarm but it is not necessary to reconstruct the burglar or world at that point

Effective Perception

- **Task-driven** involves using knowledge of the task to move the robot in the direction of the required sensory data. For example, a robot camera faces the door to recognize visitors.
- **Perceptual-classes** divide the world or sensory data into perceptual categories that are useful for the task. For example, an IR sensor data can be categorized into classes of too close, too far, just right for wall following.

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

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

The Robotics Primer, Matarić, Chapter 8

Simple Sensors

Passive vs. Active Sensors

- **Passive Sensors** measure a physical property from the environment.
- They consist of a detector which perceives the property to be measured. (i.e. bumper)

- **Active sensors** provide theory own signal and use the interaction of that signal with the environment as the property they measure. (i.e. sonar)
- They consist of an emitter that produces the signal and a detector

General Classifications

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 geometric 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 analysis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

General Classifications Cont.

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	EC	P
	Optical barriers	EC	A
	Noncontact proximity sensors	EC	A
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders	PC	P
	Potentiometers	PC	P
	Synchros, resolvers	PC	A
	Optical encoders	PC	A
	Magnetic encoders	PC	A
	Inductive encoders	PC	A
	Capacitive encoders	PC	A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass	EC	P
	Gyroscopes	PC	P
	Inclinometers	EC	A/P

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

Simple vs. Complex Sensors

- Recall that simple sensors do not require a great deal of processing or computation but the information they provide is simple or limited (i.e. light levels, presence or absence of objects, distance to objects)
- Whether a sensor is simple or complex is determined by the amount of **processing** its data require
- Whether a sensor is active or passive is determined by the **mechanism** used to extract data

Simple vs. Complex Sensors

- Passive sensors can be simple or complex
  - For example, reflectance and break beam sensors are simple active sensors
- Active sensors are not necessarily complex
  - For example, the camera is a complex passive sensor

Sensor Characteristics

- *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

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

In Situ Sensor Performance cont.

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

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

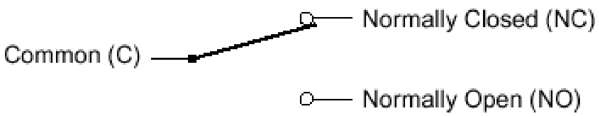
Characterizing Error

The 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)

Specific Sensors

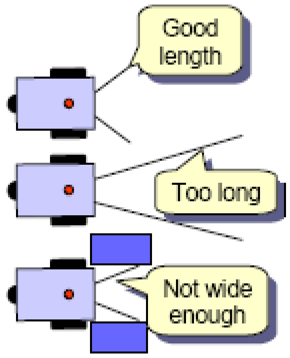
Switches



- Switches are the simplest sensor of all
- They provide data on the electronics (circuit) level because they work on the principle of open vs. closed
- A switch can be normally closed or open and state is detected by measuring current flow
- **Contact sensors** detect when the sensor touches an object
- **Limit sensors** determine when a mechanism has moved to the end of its range
- **Shaft encoders** detect how many times a motor shaft turns

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



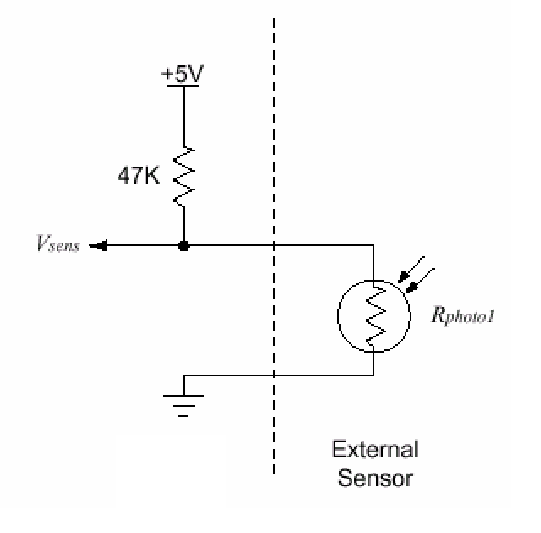
- Advantages
  - Simple
  - Reliable
- Disadvantages
  - Course resolution
  - Solid contact (dangerous for obstacles, may damage robot)
  - Whiskers can become tangled
  - Whiskers oscillate when released, spurious readings
  - Whiskers may require mechanical adjustment or repair

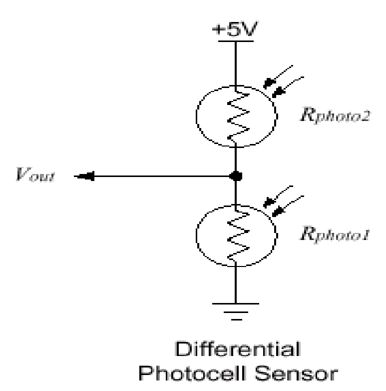
Proximity Sensors

- 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

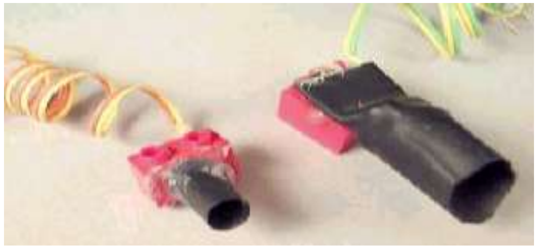
Light Sensors

- It is also useful for a robot to be able to detect areas of light and dark
- Light sensors measure the amount of light impacting a photocell.
- The photocell changes resistance based upon illumination
- This variability in resistance can be used in an electronic circuit.
- The resistance of the photocell is low when illuminated. Thus a photocell is really a 'dark sensor'
- They can be used as passive or active sensors can can measure:
  - Light intensity
  - Differential intensity
  - Break in continuity





Types of Light Sensors



- **Polarized light** is used to create an active light sensor and involves a light source with a polarizing filter that only lets waves with the direction of the filter pass through. It is active because of the introduction of the light source and filter
- **Reflective optosensors** operate on the principle of reflected light. They are active sensors that consist of an emitter and detector. The emitter is usually made with an LED (light-emitting diode). The detector is a photodiode/phototransistor. Photocells have a slow change in resistance based upon light incidence. Photodiodes and phototransistors are faster and preferred in robotics

Reflective Optosensors

- There are two basic arrangements for reflective optosensors:
  - **Reflectance sensors** have the emitter and detector are side by side and separated by a barrier. The presence of an object is detected when the light reflects back into the detector
  - **Break beam sensors** have the emitter and detector face one another and the presence of the object is detected if the beam of light between the emitter and detector is interrupted or broken.

Reflectance Sensors

- Uses:
  - Detect the presence of an object (is there a wall?)
  - Detect the distance to an object (how far to the wall?)
  - Detect some surface feature (is there a line?)
  - Decode a bar code
  - Track the rotations of a wheel
- Light reflectivity is affected by color, texture, and other properties of the surface it hits
- No sensor is perfect and all sensors are prone to error and noise interference from the environment

Ambient Light

- Light sensors most ignore the **ambient light** that naturally exists in the environment
- **Calibration** is the process of adjusting a mechanism so as to maximize its performance
- Calibration may need to be done continuously for example dependent upon the time of cay for light sensors
- To avoid interference, typically encode a detector so that it can easily separate ambient light from signal light (i.e. polarization filters or adjust the wavelength of the emitted light)

Infrared Light

- Visible light is in the frequency band that the human eye can perceive
- Infrared (IR) light has a wavelength that is not in the visible spectrum
- IR sensors are used for reflectance and break beam sensor
- IR sensors are typically used as active sensors because it is not necessary to detect IR light unless it is used for “night vision”
- IR can be easily modulated and is less prone to interference and can be used for communication

Modulation and Demodulation

- Light is **modulated** by rapidly turning the emitter on and off, pulsing it.
- The light signal is detected by a **demodulator** that is tuned to the particular frequency of the modulation
- Strobe light is an example of modulated visible light
- Most household remote controls are based on modulated IR

Active Ranging

- *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.

Common 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

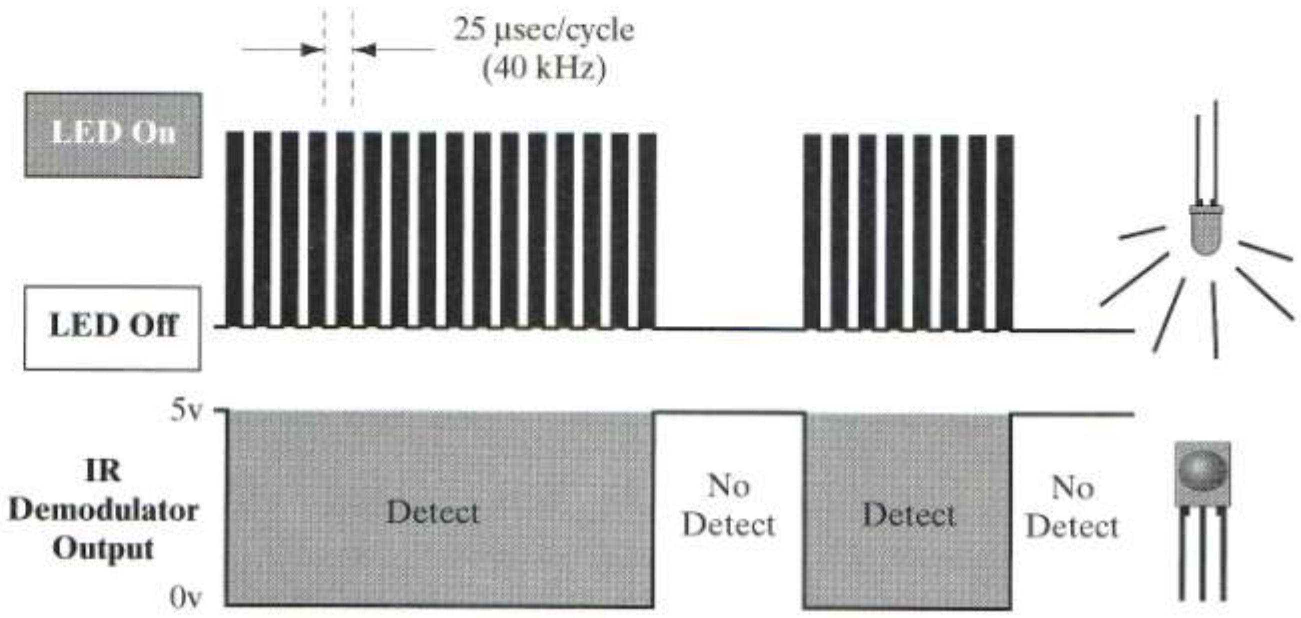
Range Sensor Quality

- 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)

Infrared Range Sensors

- 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

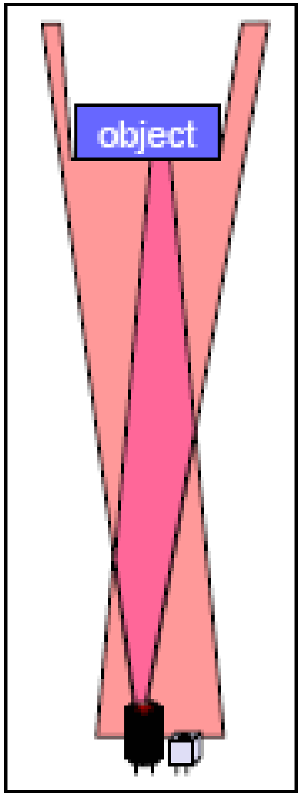
Modulated Infrared



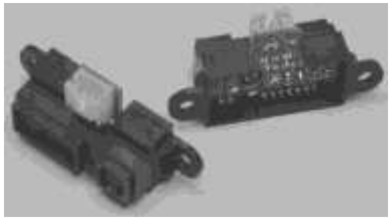
Negative "True" Logic
Detect = 0V
No Detect = 5V

Infrared Range Sensors

- 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 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

Time of flight

- ***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

Infrared 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

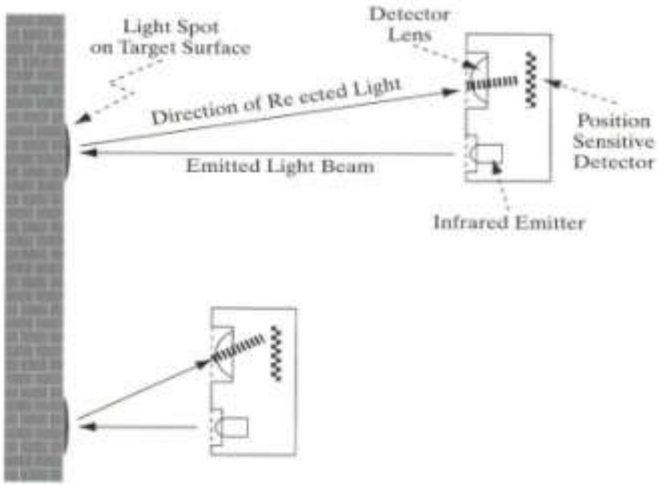
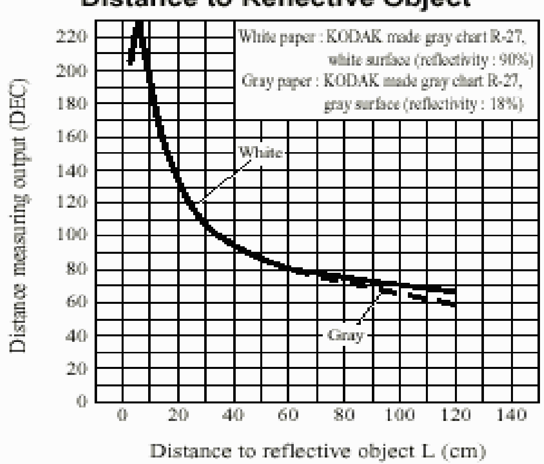
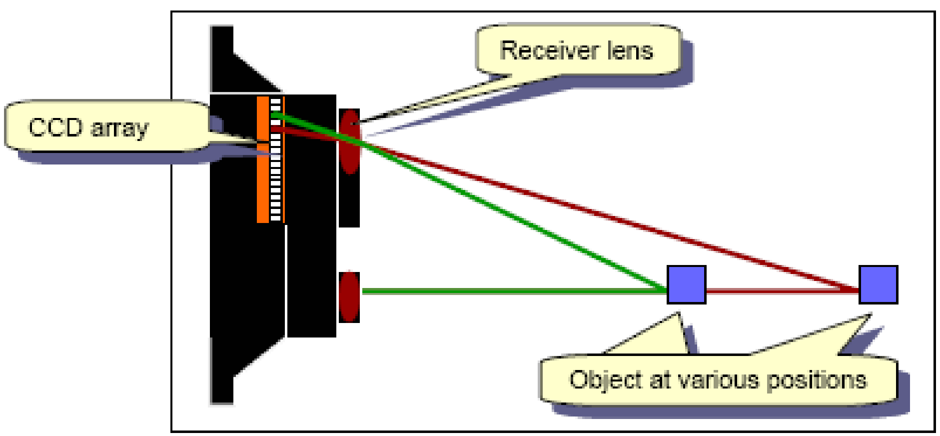


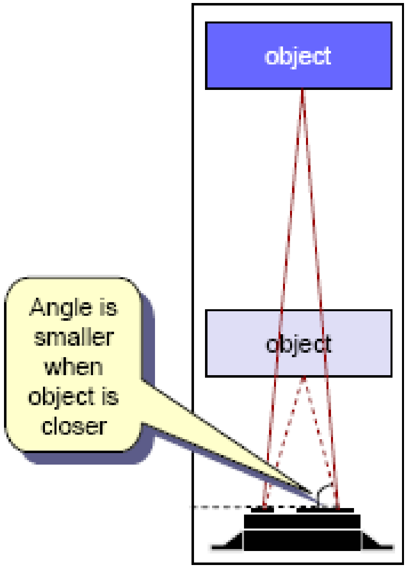
Fig. 1 Distance Measuring Output vs. Distance to Reflective Object



Triangulation

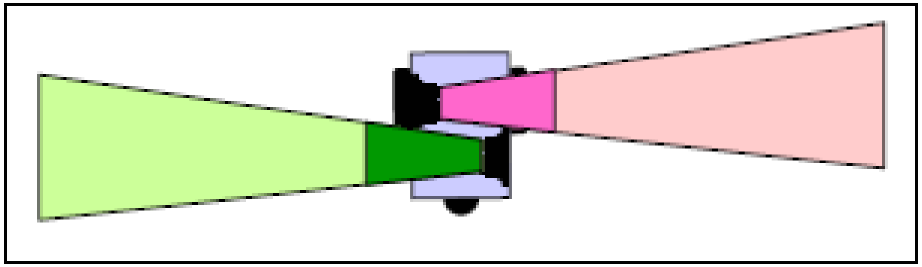
- Senses the angle at which the reflected light is returned to the sensor
- Receiver has a lens that projects the returned light onto a CCD array





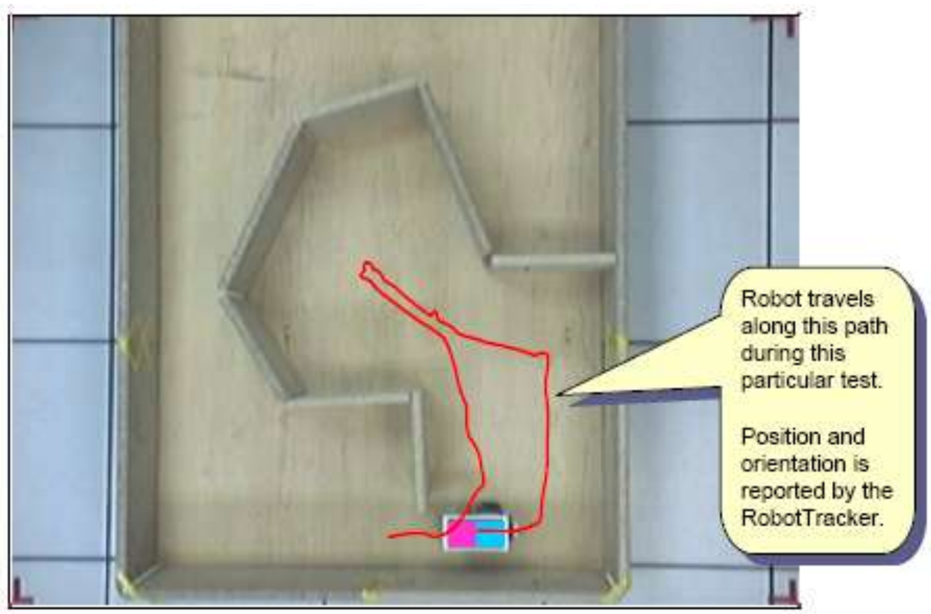
Collision Avoidance Range

- 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*)



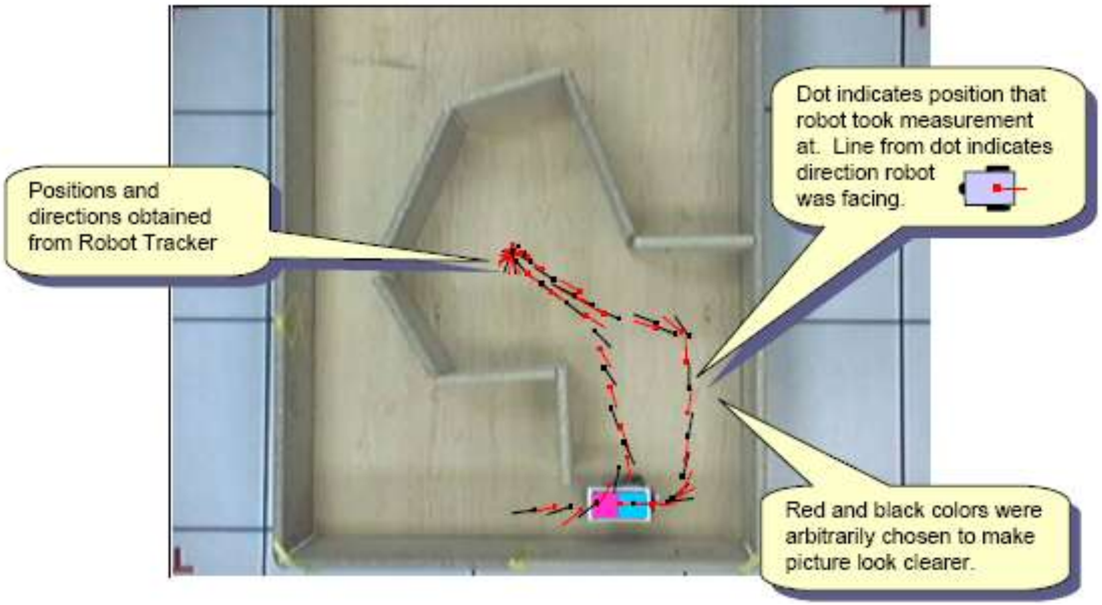
Infrared Sensors: Mapping Example

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



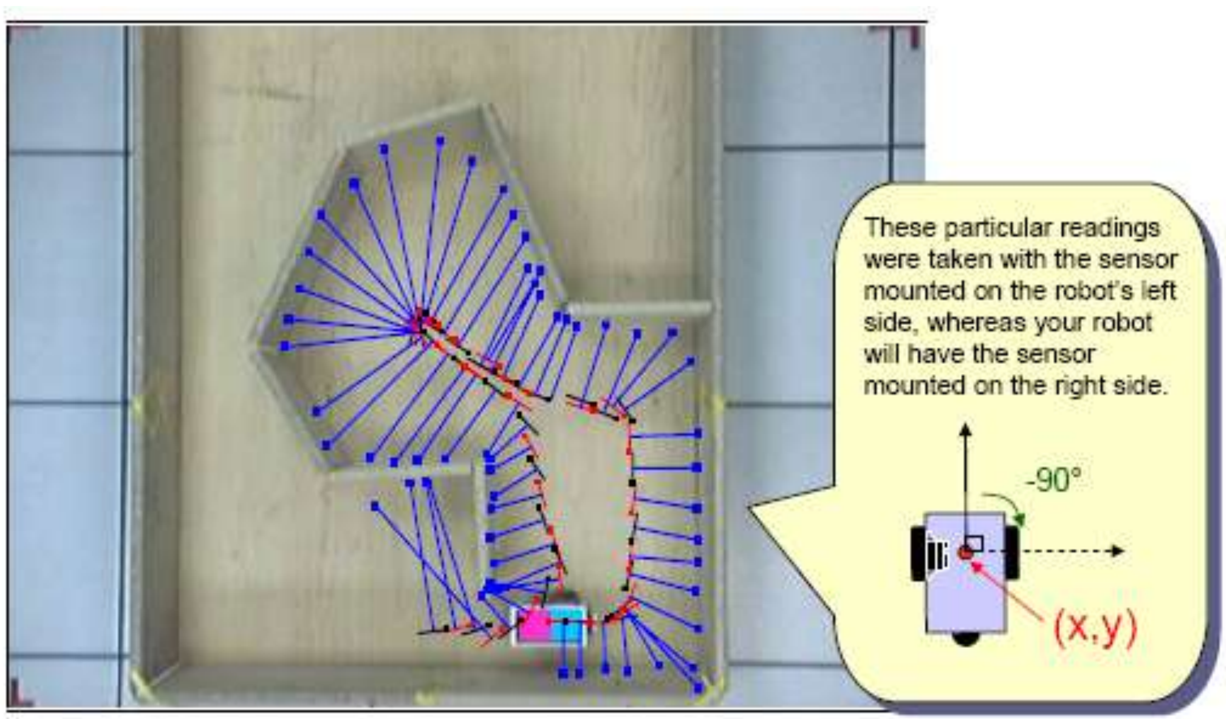
Infrared Sensors: Mapping Example

Take measurements along the path at particular locations



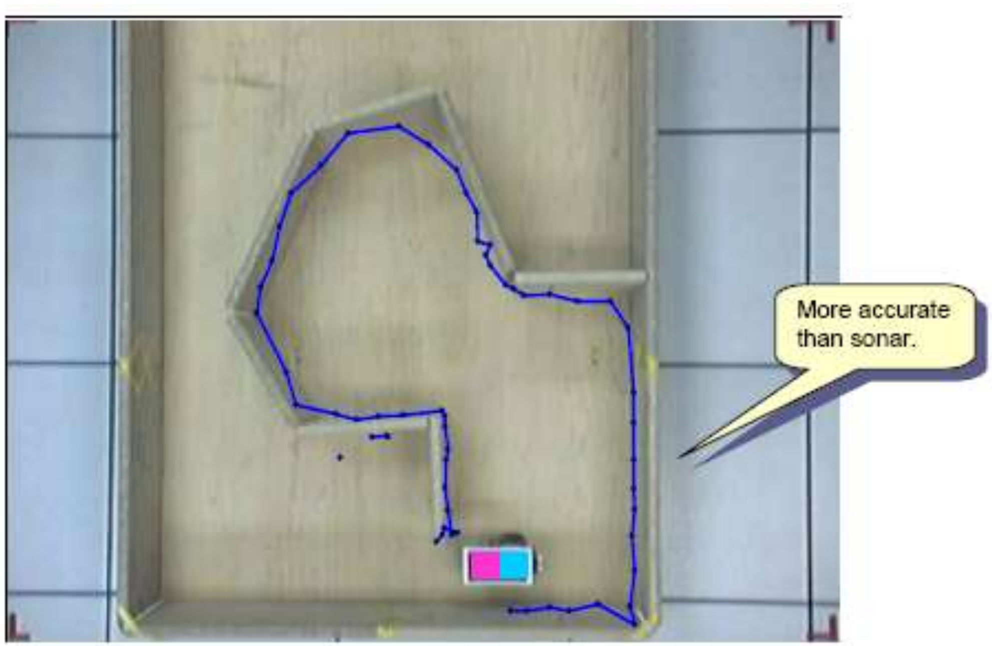
Infrared Sensors: Mapping Example

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



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