Perception and Planning

Week 2

Sensors

Types and Limitations

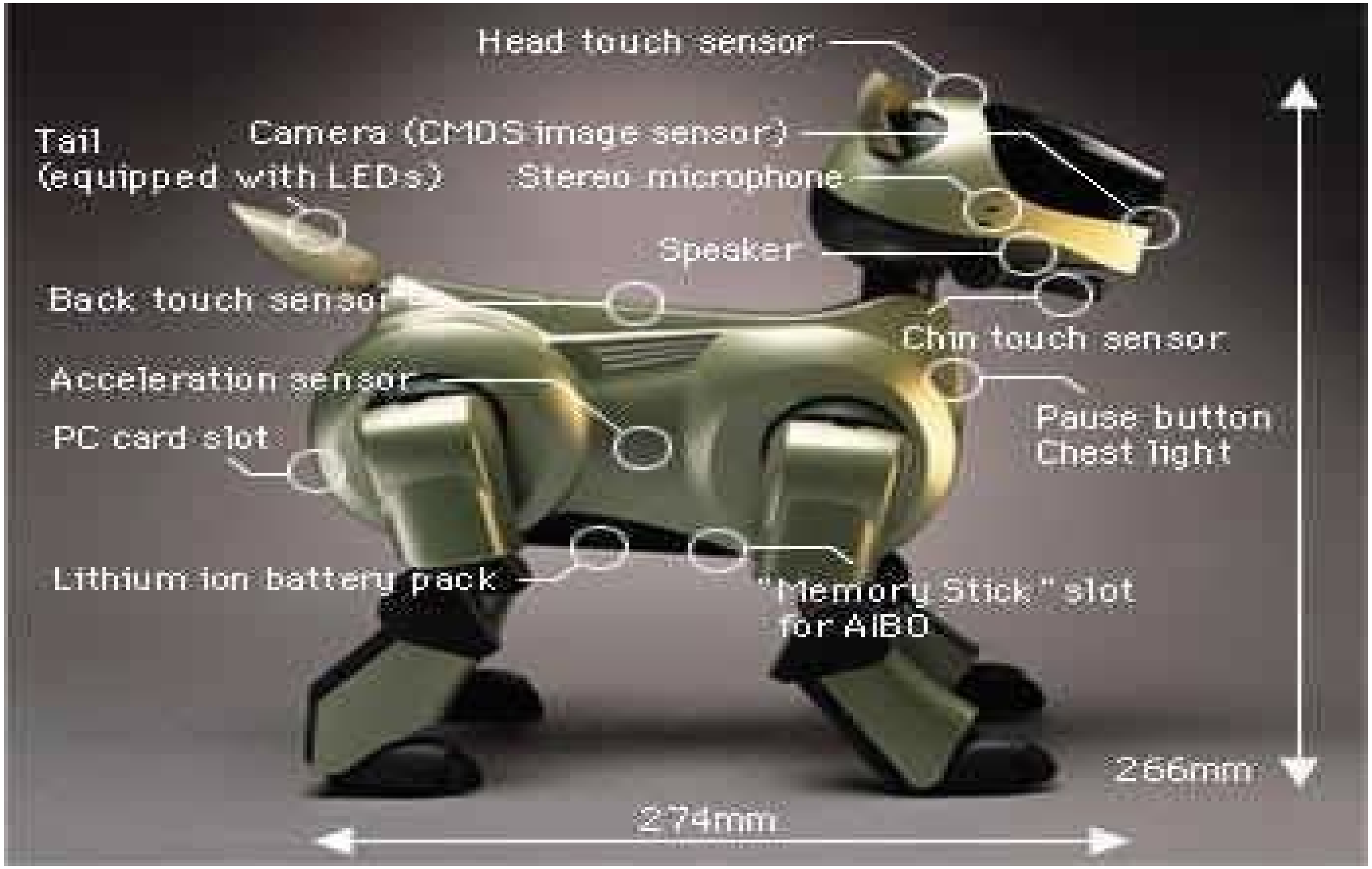
Robot Sensors

- Most robots require sensory feedback to:
  - Localize and navigate its environment
  - Detect objects
  - Protect against dangerous and unexpected situations. (Especially if the robot must work close to humans)
  - Perform “intelligent” recovery from error conditions (e.g. lost)
  - Recognize objects (i.e. humans).
  - Make informed decisions （intelligent decision）.
  - etc. …

- The main objective of incorporating sensors in robotic system is to enable robots to work in non-structured and random environments.

- Sensors can make robots more intelligent, but the associated software must have the ability to receive data from the sensors and to process it in real time.

Robot Sensors - Example



Sony Aibo ERS-210

What is Sensing ?

- Collect information about the world and itself
- Sensor - an electrical/mechanical/chemical device that maps an environmental attribute to a quantitative measurement
- Each sensor is based on a ***transduction principle*** - conversion of energy from one form to another

What is a transduction principle?

In the monitoring and control of processes, a multitude of devices are used to collect or present information in a suitable form; such devices are termed transducers.

A transducer accepts energy from one part of a system and emits it in different form to another part of the system.

The devices that we will consider are those which either, by monitoring the physical world, provide an electrical analogue to be used in the processing or display system, or, by responding to an electrical stimulus in an ordered manner, interact with the physical world.

An accelerometer use a strain gauge to measure the strain in a steel bar as it flexes under the forces of acceleration. Since strain is proportional to stress, that is to force per unit area, this indicated value gives the quantity we really wish to measure.

Transduction to electronics

- Thermistor: temperature-to-resistance
- Electrochemical: chemistry-to-voltage
- Photocurrent: light intensity-to-current
- Pyroelectric: thermal radiation-to-voltage
- Humidity: humidity-to-capacitance
- Length (LVDT: Linear variable differential transformers) : position-to-inductance
- Microphone: sound pressure-to-voltage

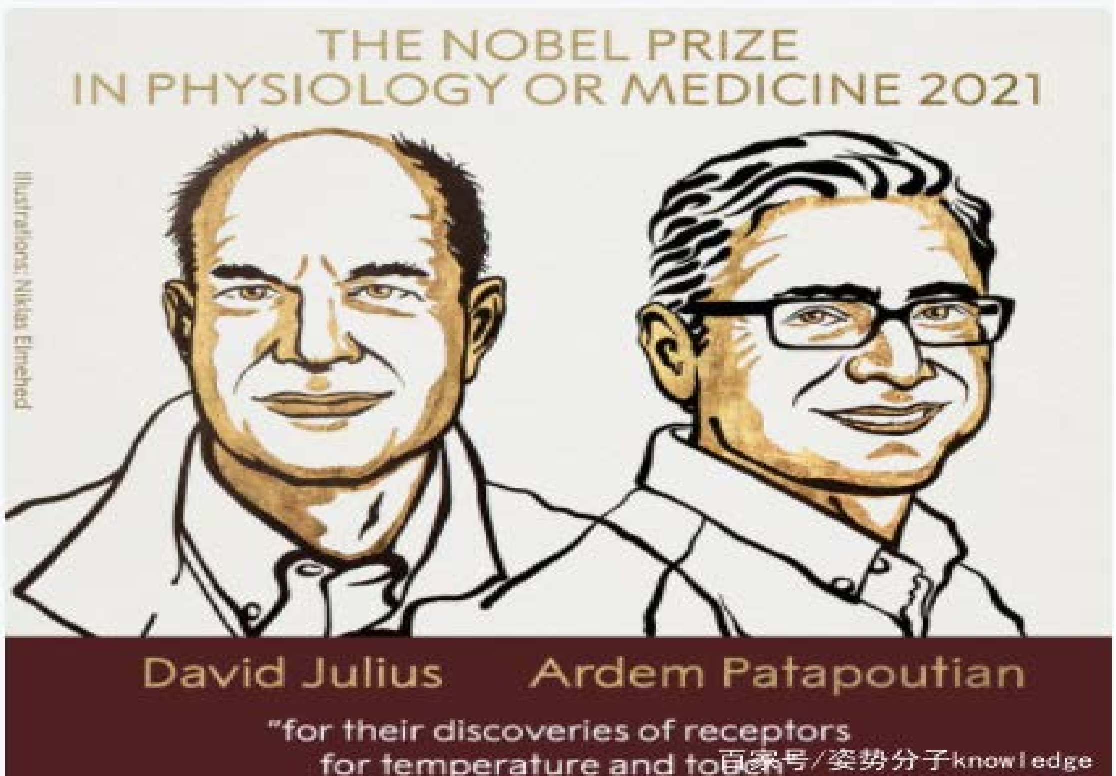
Human sensing and organs

- Vision: eyes (optics, light)
- Hearing: ears (acoustics, sound)
- Touch: skin (mechanics, heat)
- Odor: nose (vapor-phase chemistry)
- Taste: tongue (liquid-phase chemistry)

2021 Nobel Prize in Physiology or Medicine

The Nobel Prize
@NobelPrize

BREAKING NEWS:
The 2021 #NobelPrize in Physiology or Medicine has been awarded jointly to David Julius and Ardem Patapoutian “for their discoveries of receptors for temperature and touch.”



2021 Nobel Prize in Physiology or Medicine

On Oct. 4, Beijing time. David Julius and Adem Patabodtian shared the prize.

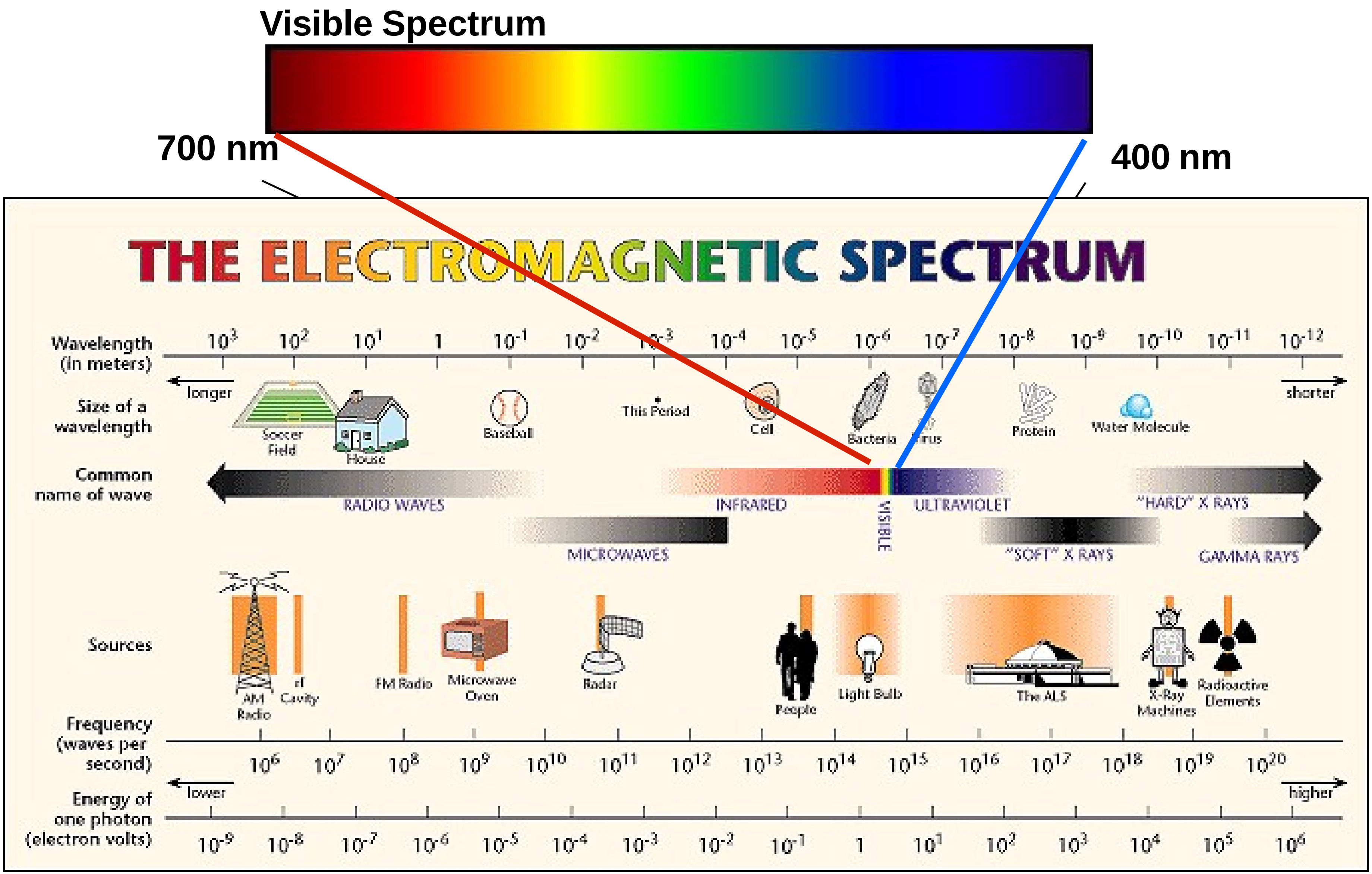
Humans' ability to sense heat, cold and touch is essential for survival and underpins our interaction with the world around us.

Benefits of electronic sensors

Extended ranges and modalities:

- Vision outside the RGB spectrum
  - Infrared Camera, see at night
- Active vision
  - Radar and optical (laser) range measurement
- Hearing outside the 20 Hz – 20 kHz range
  - Ultrasonic range measurement
- Magnetism
  - Compass
- Chemical analysis beyond taste and smell
- Radiation: α, β, γ-rays, neutrons, etc.

Electromagnetic Spectrum



Transducers

- Many sensors transform one form of energy to another.
- Transducers are devices that convert energy from one form to another.
  - e.g. microphone and speakers convert *between* acoustic and electrical energy.
- Many transducers are bidirectional.
- Some sensors *are* transducers; almost all involve transduction.

Problem with Transduction

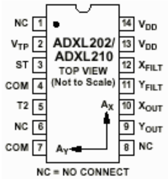
- Most robots are controlled by computer technologies
  - Sensory information needs to be converted to digital representation (i.e. via analog to digital converters).
- Problem:
  - Analog values cover a continuous value range,
  - Digital values are discrete,
  - ADC results in some loss of information or accuracy.
- Solution:
  - Use sufficiently accurate sensors and transducers, or
  - Use algorithms that are insensitive to inaccuracies in sensory information.

What Sensors Are Out There?

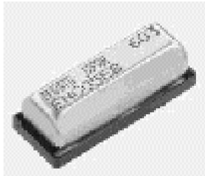
- Visual – Cameras & Arrays (Active & Passive)
- Color Sensors (Active & Passive)
- Magnetic (Active & Passive)
- Orientation (Pitch & Roll)
- GPS (location, altitude)
- Compass (orientation, bearing)
- Voltage – Electric Field Sensors
- Current – Magnetic Field Sensors
- Chemical – Smoke Detectors, Gas Sensors

What Sensors Are Out There?

- Feelers (Whiskers, Bumpers) – Mechanical
- Photoelectric (Visible) – Active & Passive
- Infrared (light) – Active & Passive
- Ultrasonic (sound) – Active & Passive
- Sonic – Active & Passive
- Resistive/Capacitive/Inductive – Active & Passive



Accelerometer

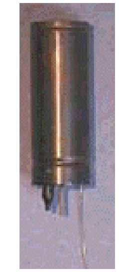

Gyro

Pendulum Resistive Tilt Sensors

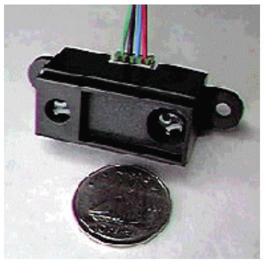

Piezo Bend Sensor


Metal Detector

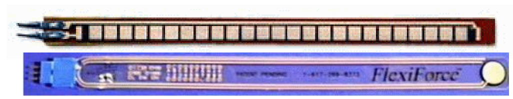
Gas Sensor


Gieger-Muller Radiation Sensor

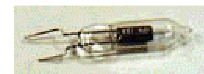

Pyroelectric Detector

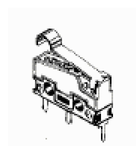

Digital Infrared Ranging


CDS Cell Resistive Light Sensor



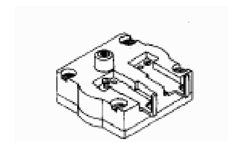
Resistive Bend Sensors

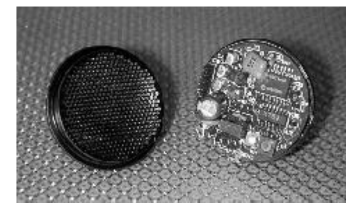

UV Detector

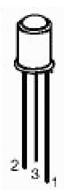

Limit Switch

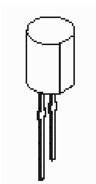

Mechanical Tilt Sensors

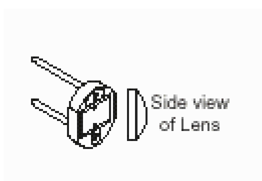

Touch Switch


Pressure Switch

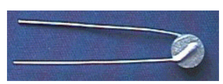

Miniature Polaroid Sensor

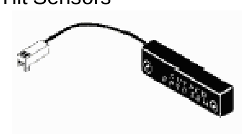


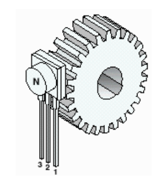

IR Pin Diode

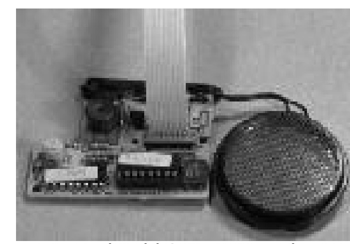


IR Sensor w/lens


Thyristor

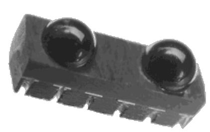

Magnetic Sensor


Hall Effect Magnetic Field Sensors

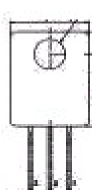

Polaroid Sensor Board

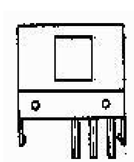

IR Reflection Sensor


IR Amplifier Sensor


IRDA Transceiver

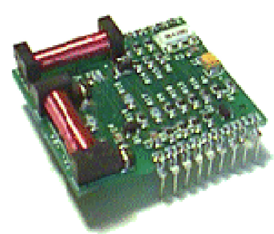

Magnetic Reed Switch

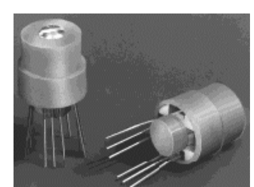

Lite-On IR Remote Receiver

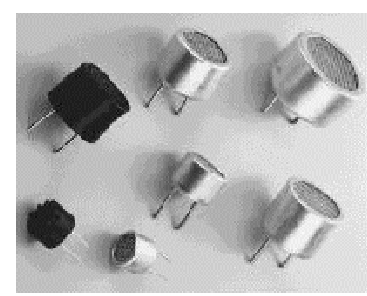

Radio Shack Remote Receiver


IR Modulator Receiver


Solar Cell


Compass


Compass


Piezo Ultrasonic Transducers

Classification of Sensors

- Robotic sensors can be divided into two main classes:
  - Internal state sensors (Proprioceptive Sensors) -
    - Sensors that measure values internal to the robotic system.
    - e.g. battery level, motor speed, wheel position, wheel load, robot heading, velocity and acceleration.
    - Also, included sensors that measure the joint angles of robotic arms and hands.
    - These sensing devices are commonly potentiometers, tachometers, optical interrupters, optical encoders, accelerometers and gyros.
  - External state sensors (Exteroceptive Sensors) –
    - Sensors that detect or observe objects in the environment
    - e.g. distances to objects, intensity of the ambient light, classification of objects.
    - These sensing devices are commonly cameras, sonar sensors, radar, laser scanners, etc.

Classification of Sensors

- How sensors work can de divided into two types:
  - Passive sensors
    - where the energy is coming from the environment and is passively received by the sensor. e.g. camera, sound, room temperature.
  - Active sensors
    - where the sensor emits energy and measures the reflection. e.g., radar, sonar, laser scanner.
    - Better performance, but can suffer from cross-talk, where one sensor picks up the energy emitted from another active sensor.

Classification of Sensors

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

Classification of Sensors

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

A: active; P: passive; P/A: passive/active; PC: proprioceptive; EC: exteroceptive

Sensor Examples

Lets take a closer look. . .

Sensors used in robot navigation

- Tactile sensors
  - contact switch, bumpers…
- Resistive sensors
  - bend sensors, potentiometer, resistive photocells, ...
- Infrared sensors
  - Reflective proximity, distance sensors…
- Ultrasonic Distance Sensor
- Inertial Sensors (measure position)
  - Accelerometer, Gyroscopes,
- Orientation Sensors
  - Compass, Inclinometer
- Laser range sensors
- Vision
- Global Positioning System

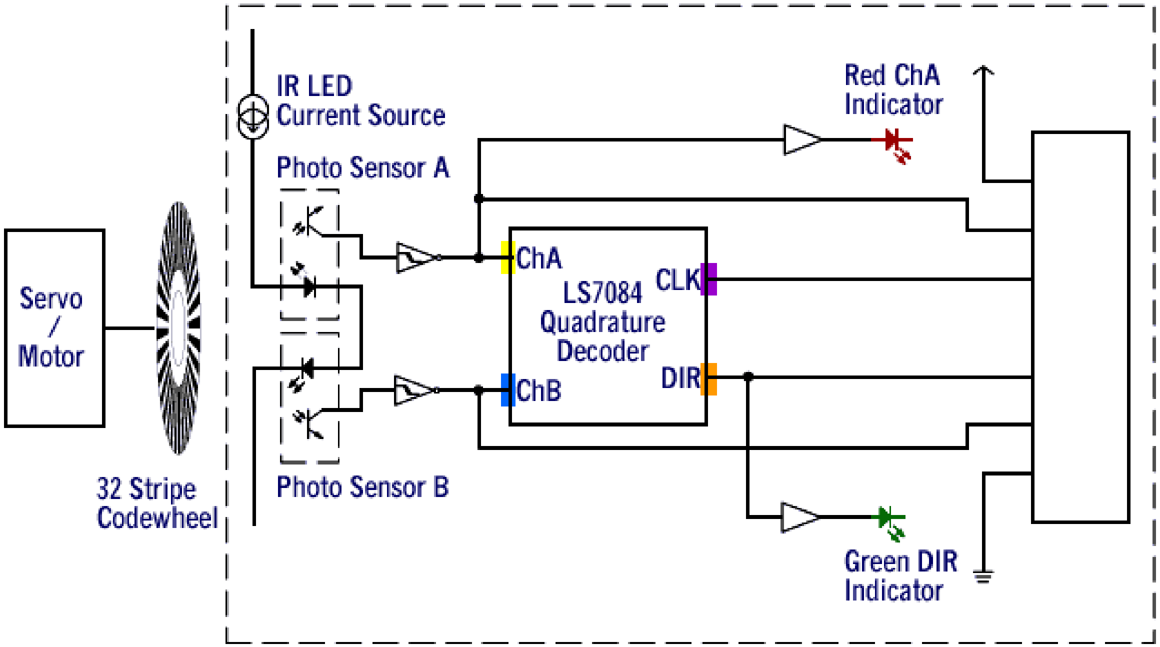
Sensors – Position/Location

- Wheel Encoders
  - Relative position & motion
  - Integrate/Differentiate for other parameters

- Global Positioning System
  - Absolute position/location on earth
  - Local differential error correction
  - Integrate/Differentiate for other parameters

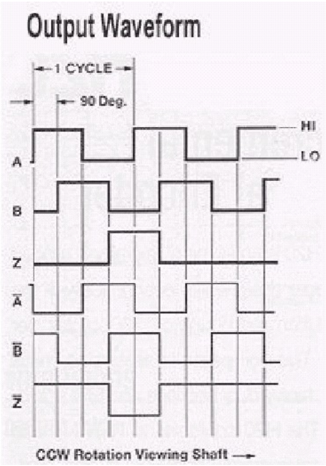
Wheel Encoders

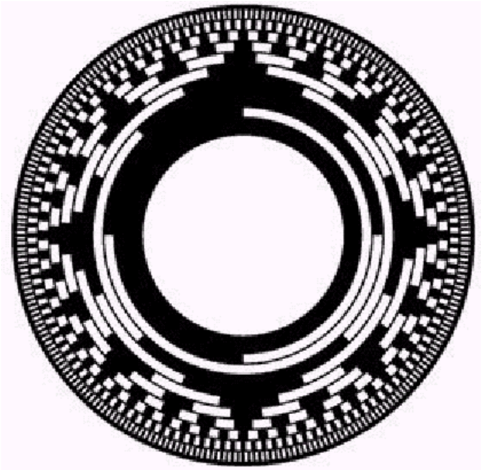
- Nubotics.com, $27
- Jun 98, Oct 2000 Encoder



Robot Sensors

- Internal sensors to measure the robot configuration
  - Encoders measure the rotation angle of a joint

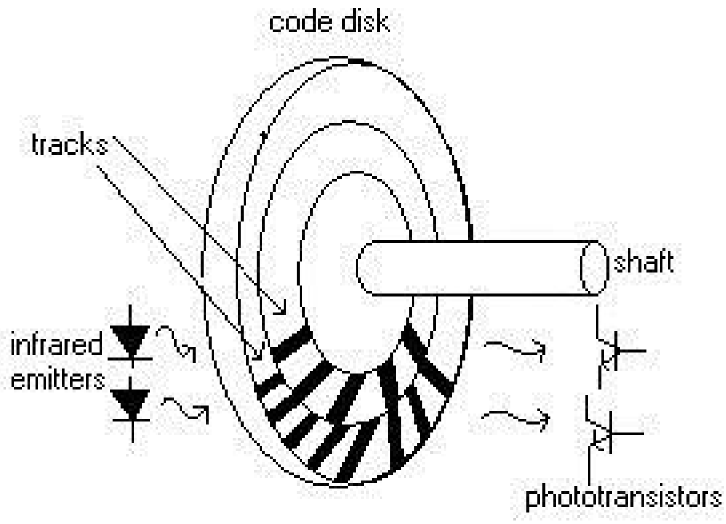




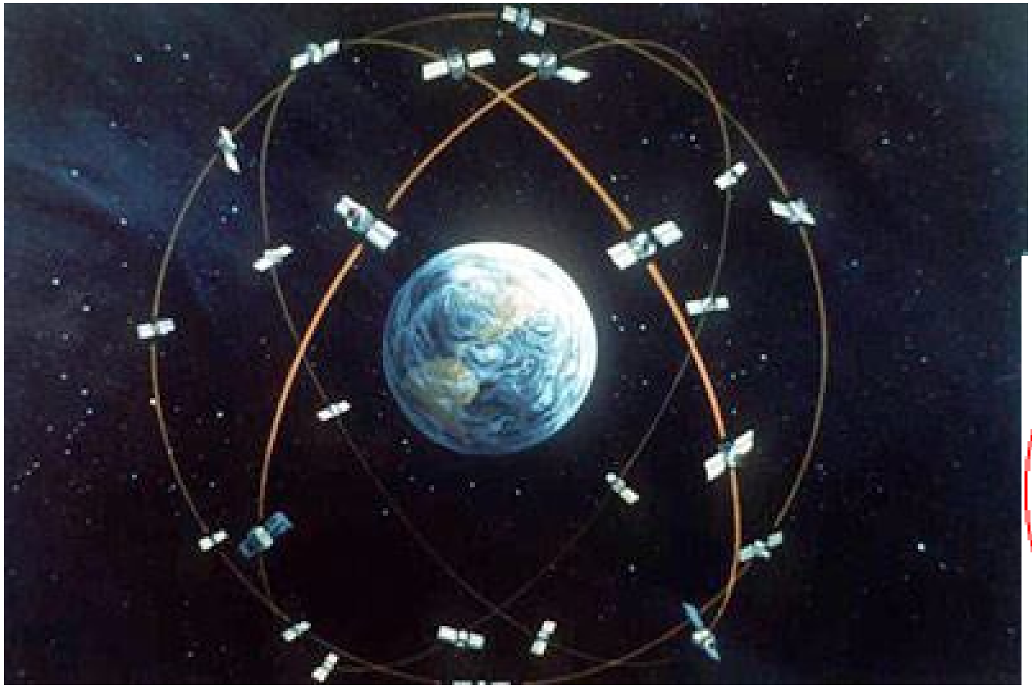
  - Limit switches detect when the joint has reached the limit

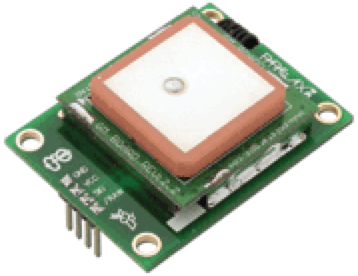
Sensors for dead reckoning

- Typical sensor: optical encoder
- One type found in standard computer mouse
- Quadrature encoding

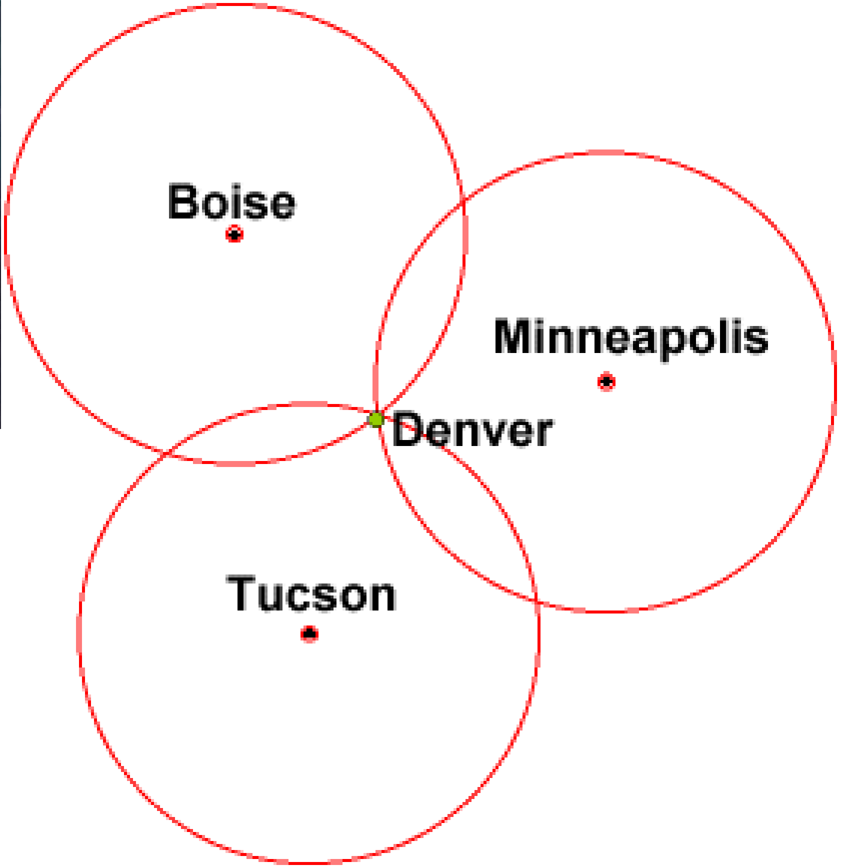


Sensors – Position/Location





- Parallax.com
- $80

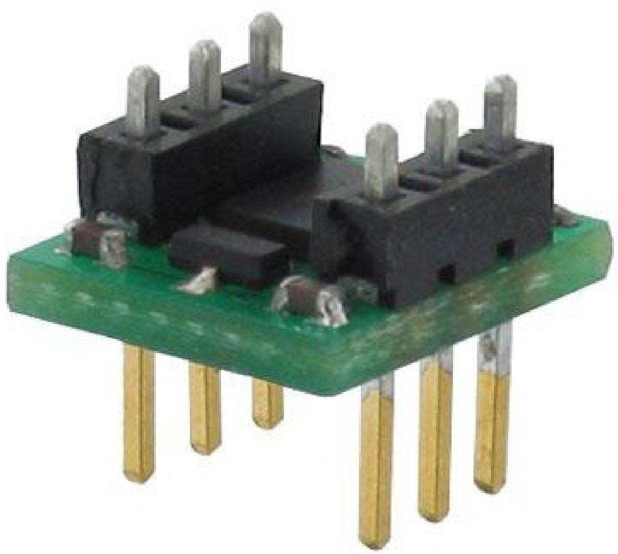


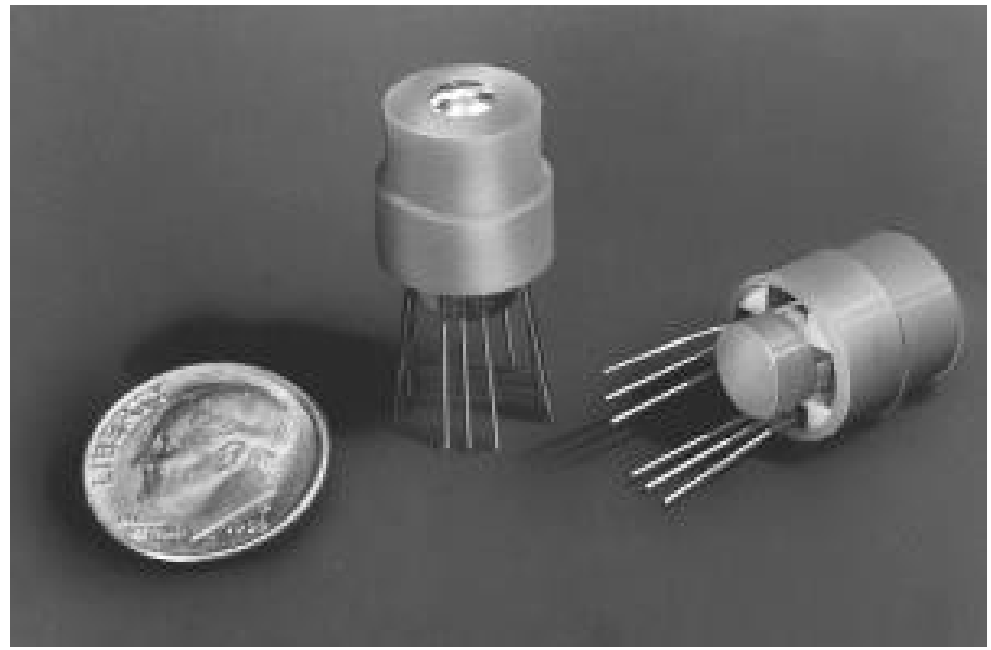
Sensors – Magnetic

- Active (emitting)
  - Metal detectors
  - Follows metallic strips on or under the floor
  - Magnetometer

- Passive (sensors only)
  - Compass
  - Magnetic field sensor ($\rightarrow$oscillating current)

Sensors – Compass (Orientation)



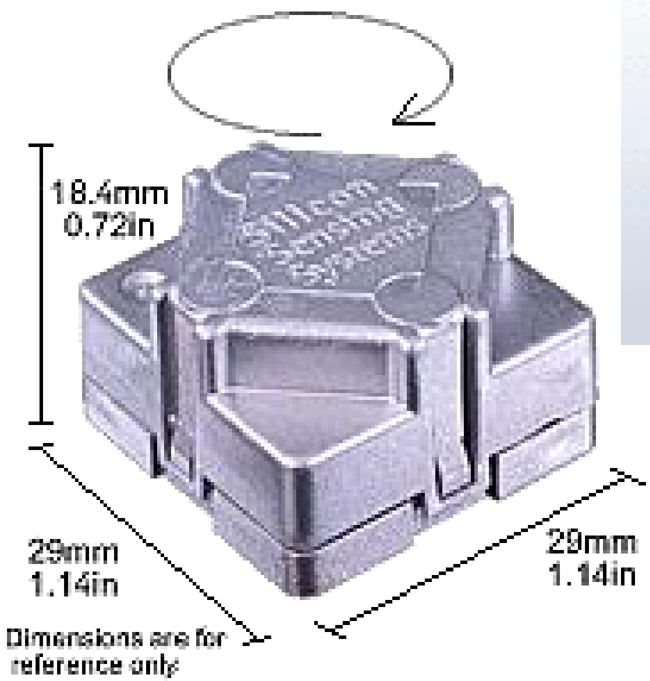


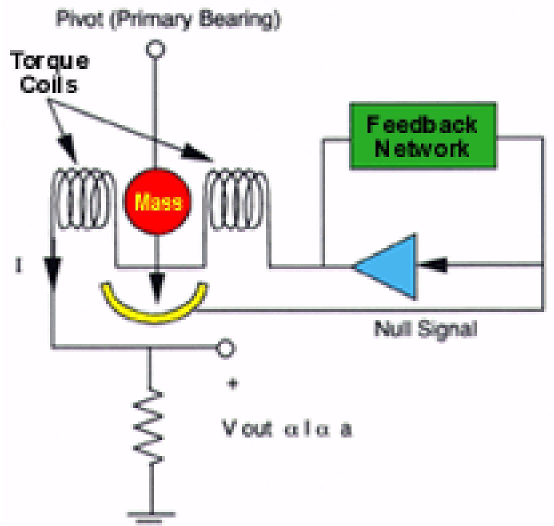
- Track bearing & distance to determine position
- L: Parallax.com, $30
- R: Dinsmoresensors.com, $13-$37

Sensors – Motion

Rate Gyro – Silicon Sensing Systems

Servo Accel – Sensorland.com





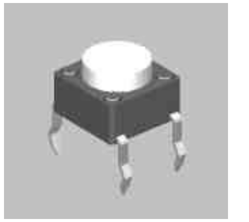
Sensors – Orientation

- Rate Gyros
  - Output proportional to angular rotation speed
  - Integrate to get position
  - Differentiate to get acceleration
- DC Accelerometer
  - Output proportional to sine of vertical angle

Sensors for orientation/heading

- Use: orientation/heading
- Options: gyroscope, geomagnetic sensors
- Issues: gyro drift, B-field distortion

Tactile Sensors

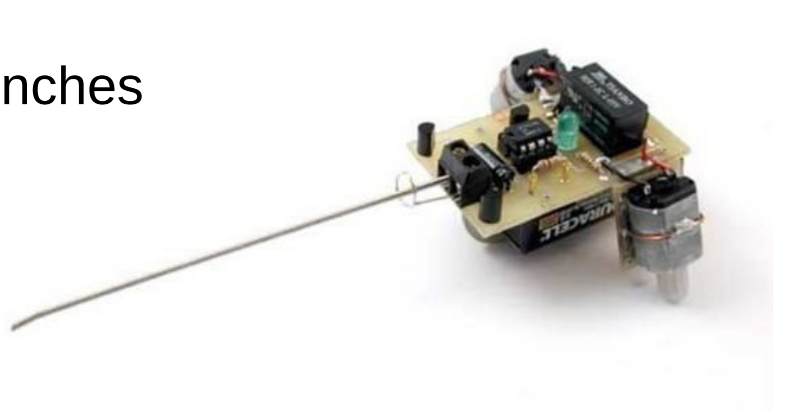


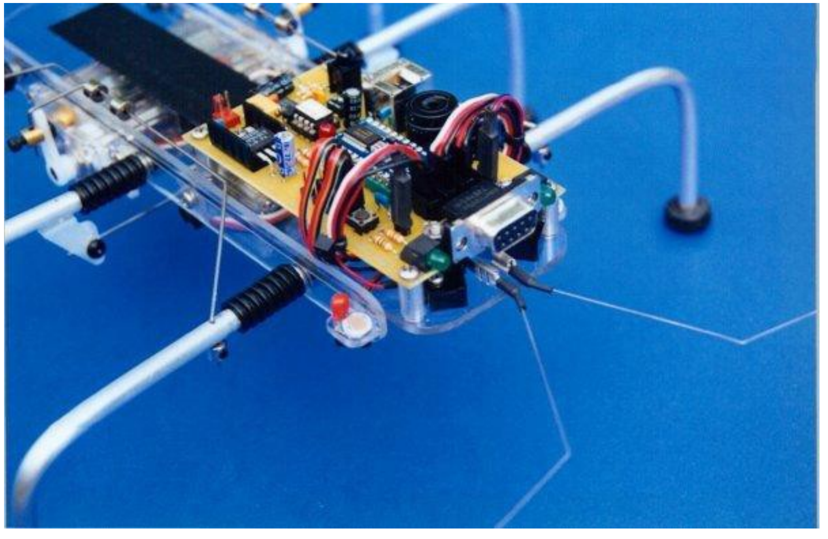
Touch Switch

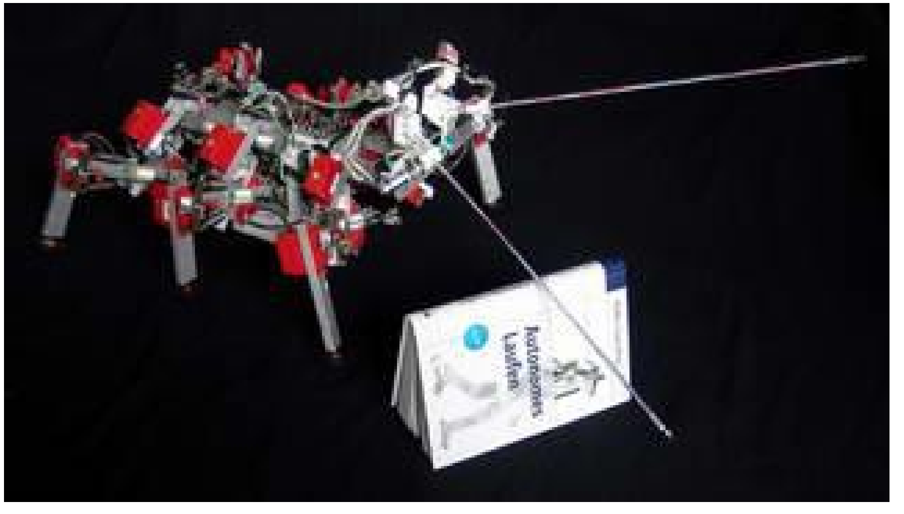
- Tactile sensing includes any form of sensing which requires physical touching between the sensor and the object to be sensed.
- The need for touch or tactile sensors occurs in many robotic applications, from picking oranges to loading machines. Probably the most important application currently is the general problem of locating, identifying, and organizing parts that need to be assembled.
- Tactile sensors can be binary (on/off) or analog e.g. whiskers, bumpers, pressure sensors.

Feelers - Whiskers

- Piano wire suspended through conductive “hoop”
- Deflection causes contact with “hoop”
- Springy wire that touches studs when deflected
- Simple, cheap, binary output
- Disadvantage: Reaches only a few inches

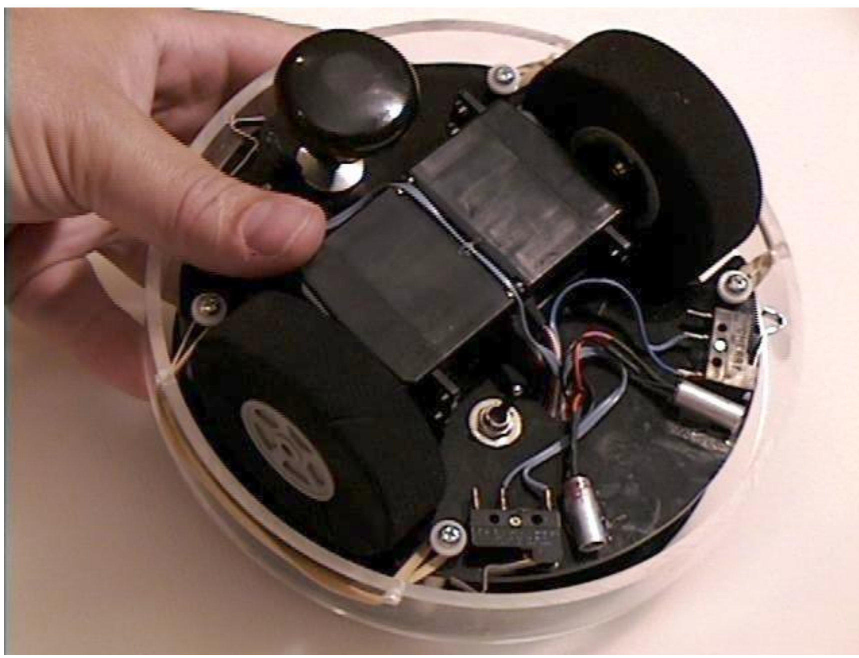


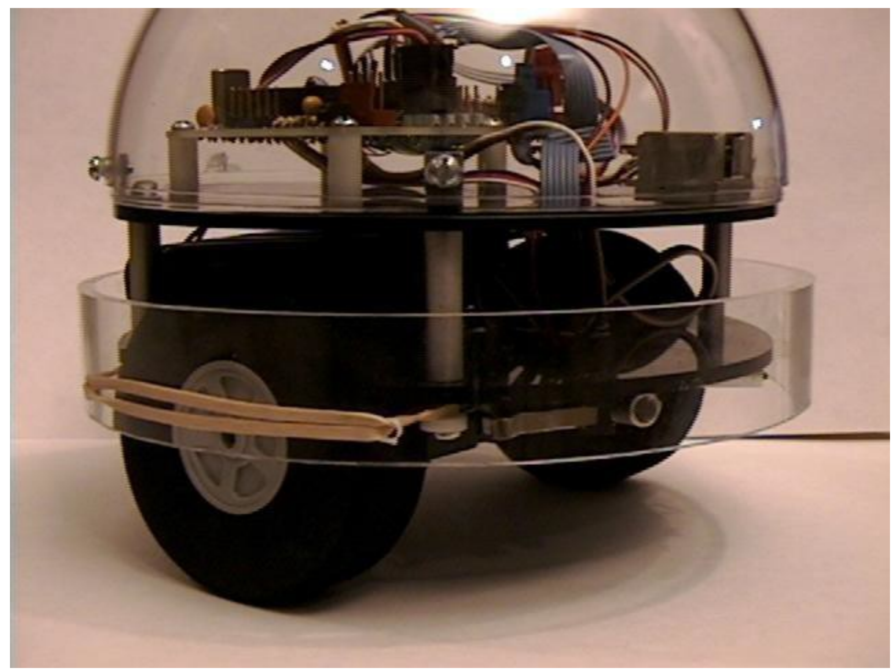




Bumpers & Guards

- Impact/Collision sensor, senses pressure/contact
- Micro-switches & wires or framework that moves
- Simple, cheap, binary output, easy to read



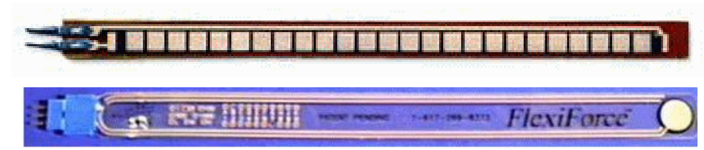


From Kevin Ross's "Getting Started Article (SRS Website)

Resistive Analog Tactile Sensors

Bend Sensors

- Resistance: 10kΩ to 35kΩ
- As the strip is bent, resistance increases



Resistive Bend Sensor

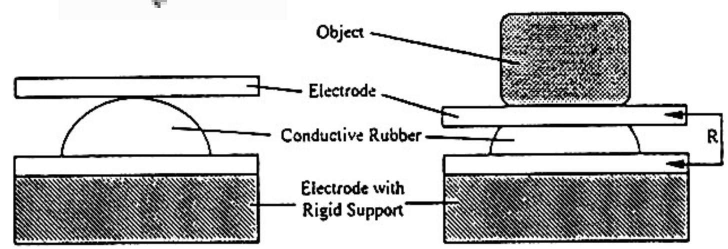
Potentiometers

- Can be used as position sensors for sliding mechanisms or rotating shafts
- Easy to find, easy to mount

Potentiometer

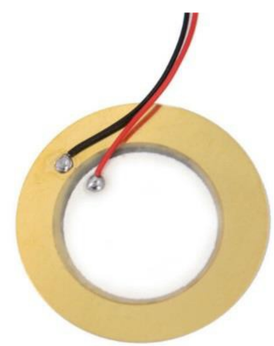
Resistive conductive rubber sensor

- Good for detecting impact or pressure
- Non-linear resistance dependent on force.



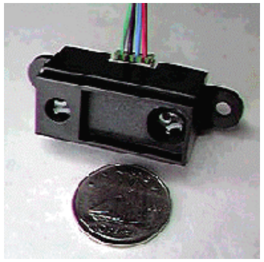
Piezoelectric sensor

- A piezoelectric element generates a voltage when deformed
- Measures changes in pressure, acceleration, strain, or force



Sensors – IR

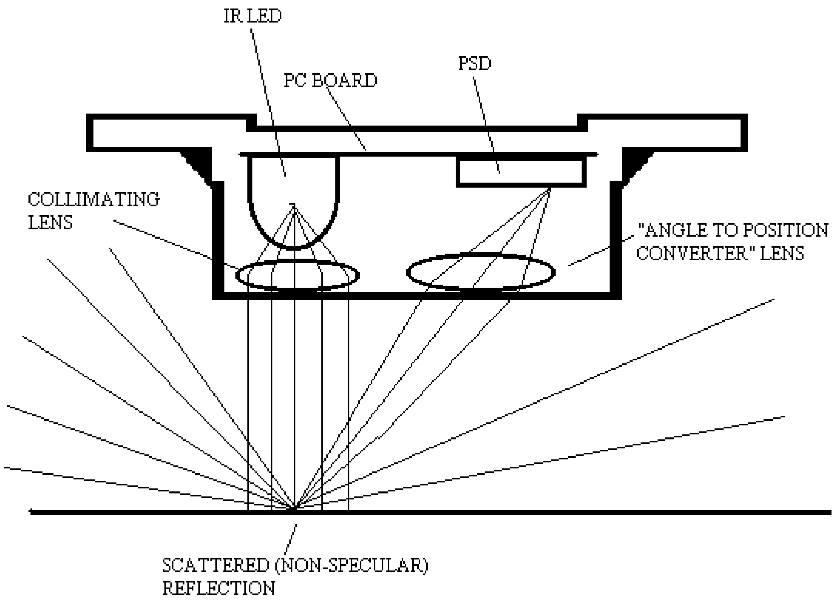
- Active (IR emitting & receiving)
  - Oscillator generates IR reflections off objects
  - Filtered receiver looks for “reflections”
  - Pulses may be encoded for better discrimination
  - Typically frequencies around 40KHz
  - Doesn’t work well with translucent (i.e. silicon) or dark, flat colored objects



- Passive (sensor only)
  - Pyro-electric (heat sensor)
  - Look for IR emissions from people & animals
  - Used in security systems & motion detectors

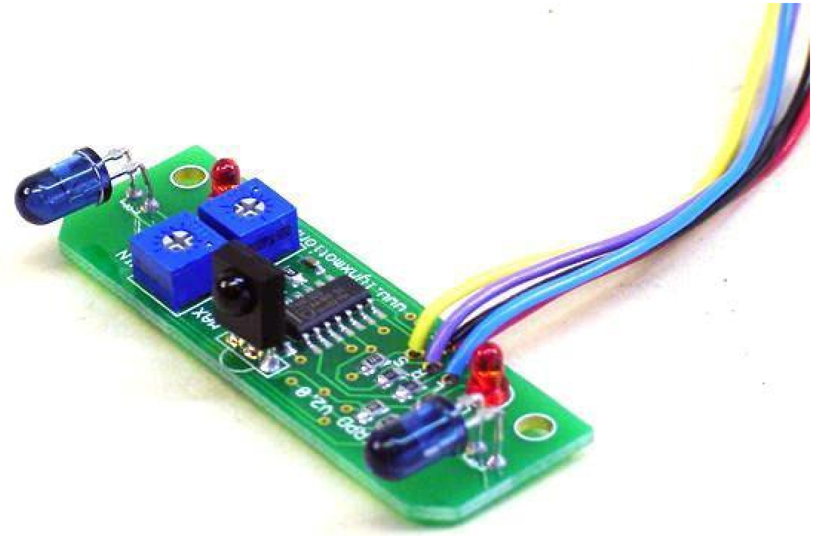
Linear Array IR Range Sensors

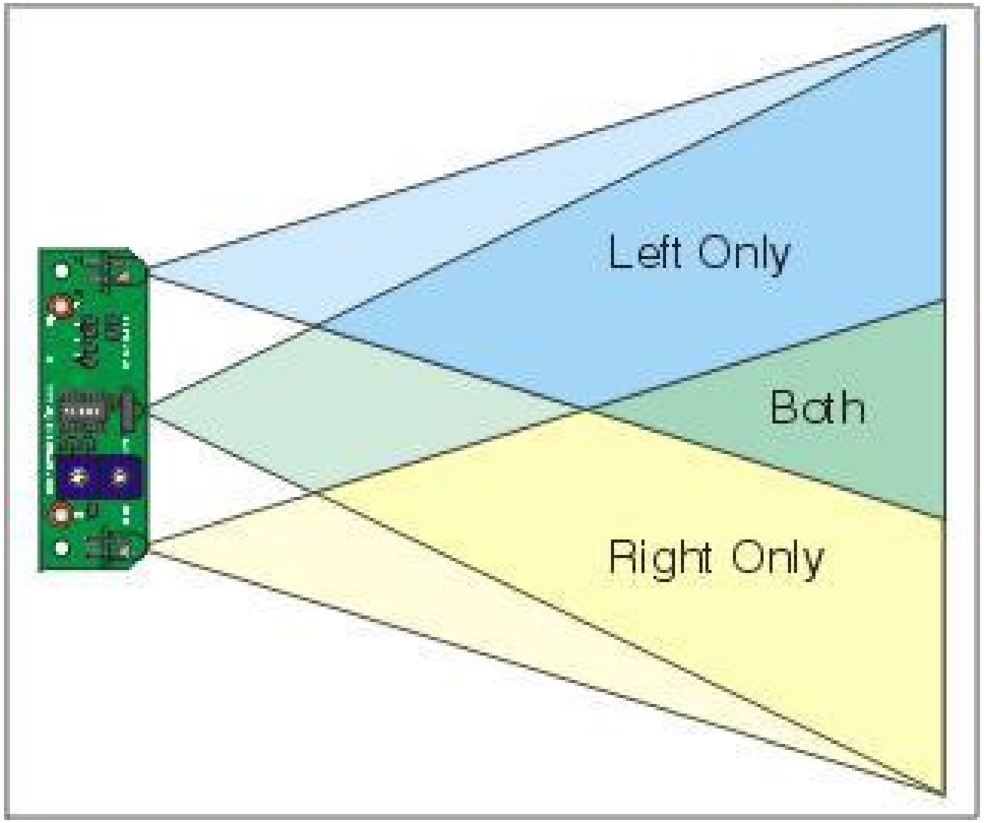
- Sharp GP2Dxx (one of many)
- 30cm – 6m Range
- Fixed Range with Discrete Output
- Analog or Digital Output
- Easy to Use



Infrared – Range and Position

Infrared sensors determine the distance to an object by measuring the amount of infrared light the object reflects back to the robot

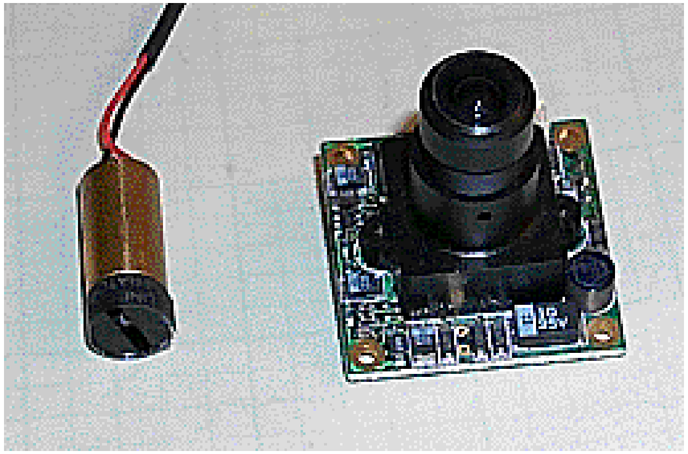


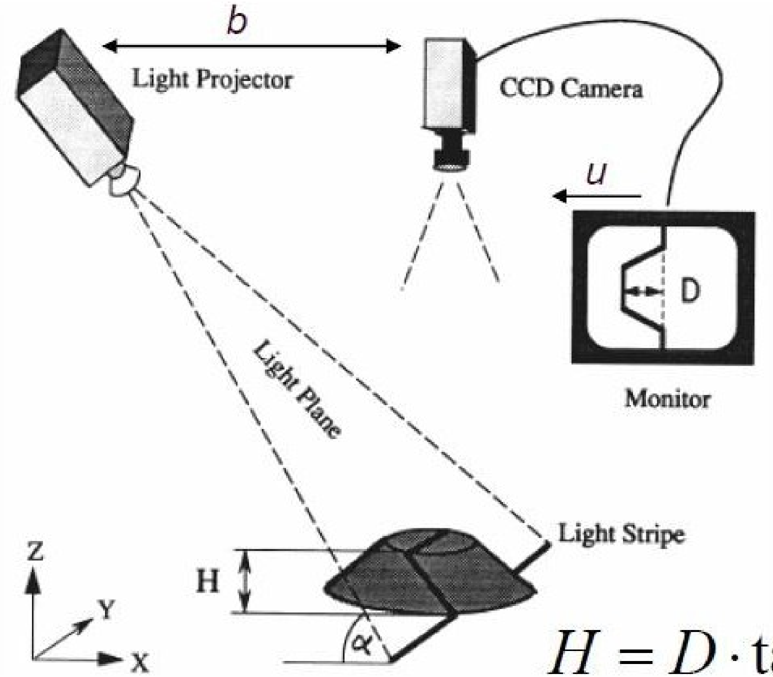


Position and range IR sensor from Lynxmotion

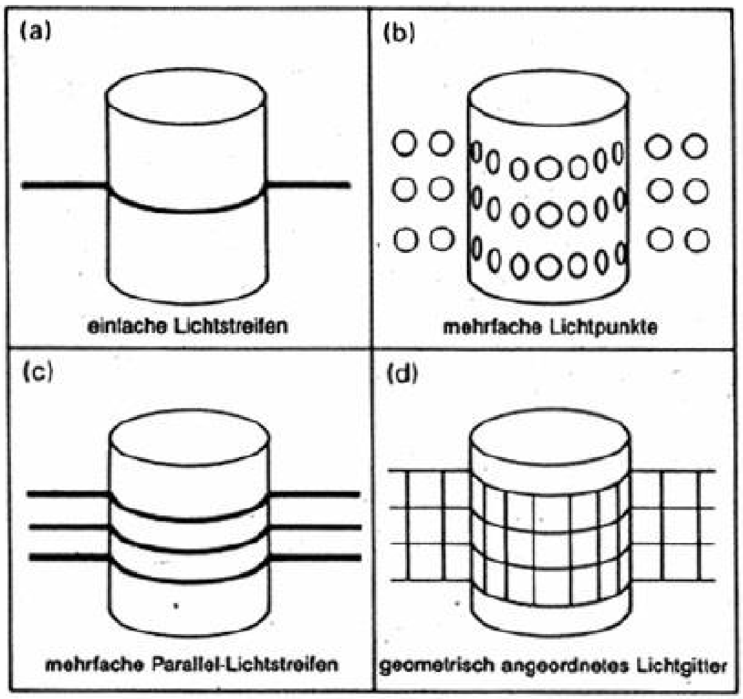
Laser Line Sensors

- Laser line stripe emitted from a collimating lens is perceived by offset camera.
- Range to any illuminated point along the line can then be determined via triangulation.





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



Laser Range Sensors (time of flight)

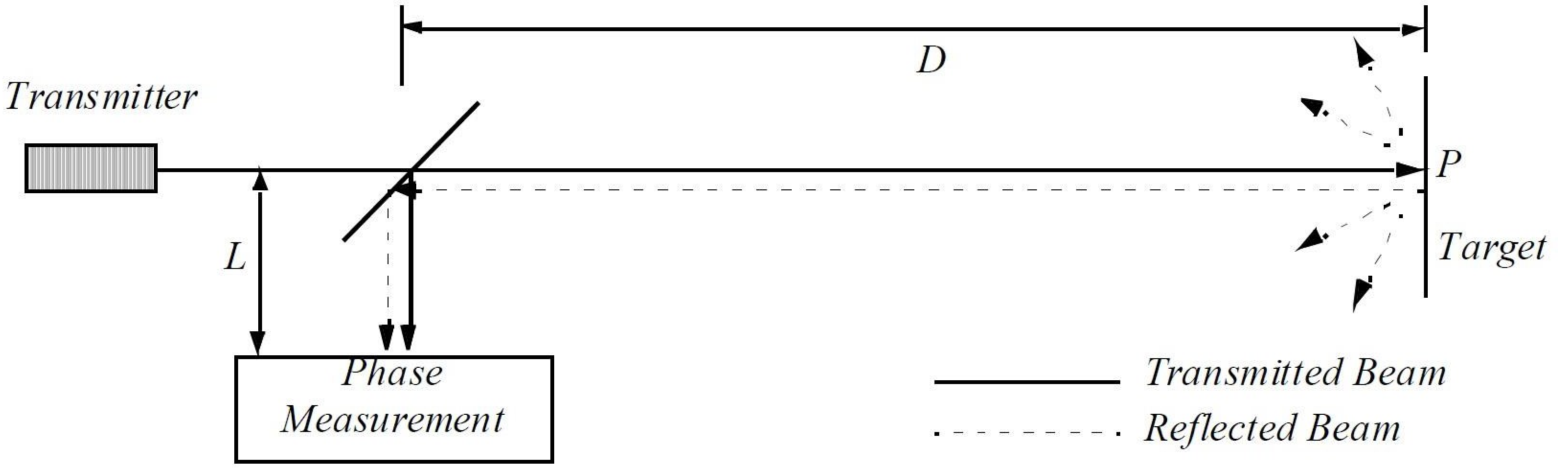
Laser range finders determine distance by measuring either the time it takes for a laser beam to be reflected back to the sensor.

- 240º Field of View
- 0.36º Angular Resolution
- ~10Hz Refresh Rate
- Accuracy up to 0.3mm
- Range up to 500 meters
- Accuracy decreases with distance.
- ~$2000 (cool but pricey)

Laser Range Sensors (time of flight)

- Time of flight measurement achieved by either:
  - Pulsed laser (today’s standard)
    - measurement of elapsed time directly
    - resolving picoseconds
  - Pulse frequency between a frequency modulated continuous wave and its received reflection
  - Phase shift measurement to produce range estimation
    - technically easier than the above two methods.

Laser Range Sensors (time of flight)



- Transmitted and received beams are coaxial
- Transmitter illuminates a target with a collimated beam (laser)
- Receiver detects the time of the round-trip
- A mechanical mechanism with a mirror sweeps the beam
- Can achieve 2D (plane) or 3D (volume) measurement

Range Sensors (time of flight)

- TOF laser and ultrasonic (sonar) sensors make use of the propagation speed of light or sound waves, respectively.

- The travelled distance of a electromagnetic or sound wave is given by:

$$d = c \cdot t$$

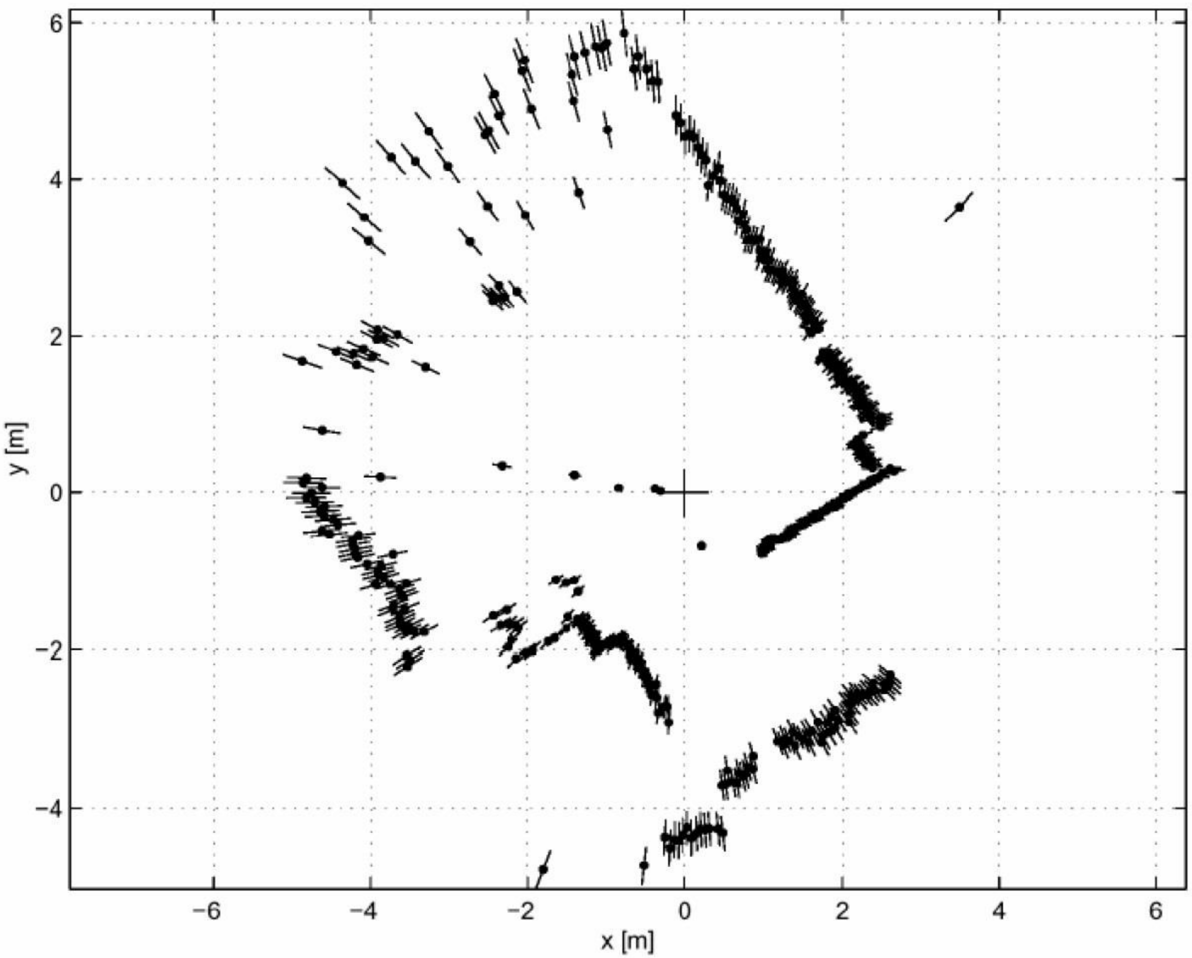
- Where
  - d = distance travelled (usually round-trip)
  - c = speed of wave propagation (light or sound)
  - t = time of flight.

Range Sensors (time of flight)

- It is important to point out
  - Propagation speed (v) of sound: 0.3 m/ms
  - Propagation speed (v) of electromagnetic signals: 0.3 m/ns,
    - one million times faster.
  - 3 meters
    - is 10 ms for an ultrasonic system
    - only 10 ns for a laser range sensor
    - time of flight with electromagnetic signals is not an easy task
    - laser range sensors expensive and delicate
- The quality of time of flight range sensors mainly depends 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 (especially 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)

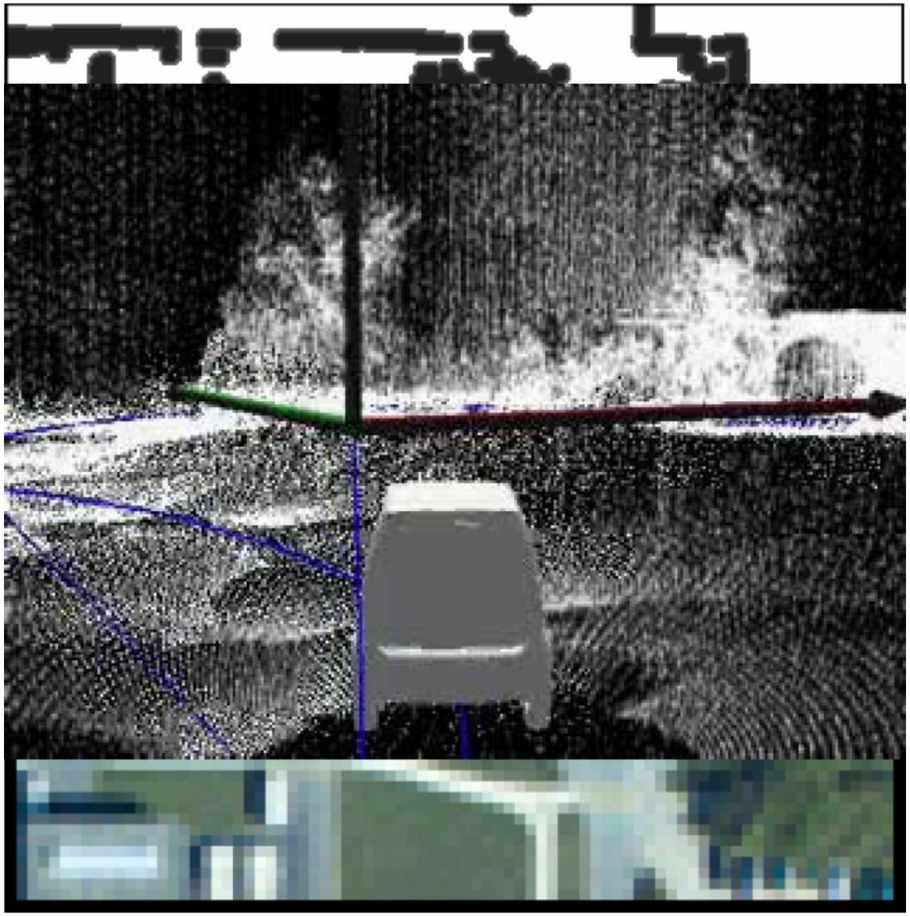
Laser Range Sensors (time of flight)

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 Sensors (time of flight)

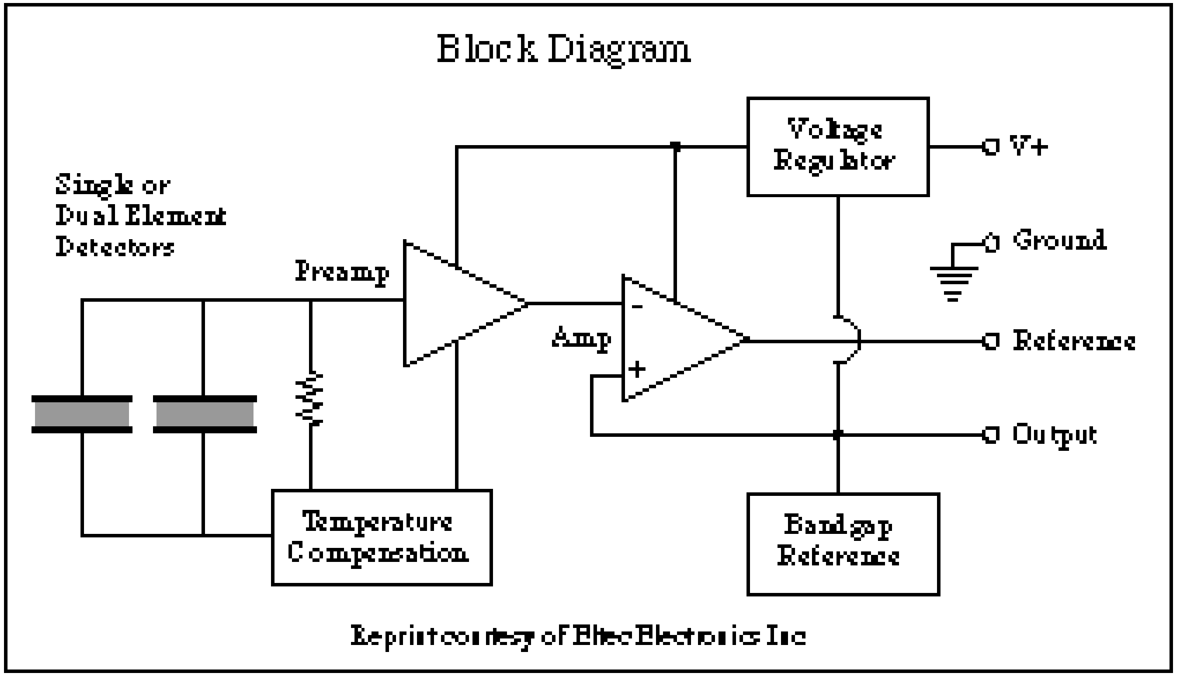
Laser Range Sensor for Autonomous Driving.



Passive IR – Pyro-Electric

$66 from Acroname

Dec 2000, Sept 2001 Encoder



The Model 442-3 IR-EYE is a Lithium Tantalate pyroelectric parallel opposed dual-element high-gain detector with complete integral analog signal processing.

Sensors for detecting humans

- Options:
  - computer vision or
  - pyroelectric sensors

- Pyroelectric sensors
  - detect far-IR radiation emitted from humans
  - Can also detect heat and fire

- Standard alarm sensor are cheap

Ultrasonic Sensors

- Ultrasonic sensors can be active or passive
- Active
  - Emit pulses and listen for echos
  - Times round trip sound travel (~1ft/mS)
  - Reaches up to 50 ft (15 meters)
  - Relatively simple and cheap, analog output
  - Directional, but not everything reflects sound
- Passive (listens only)
  - Sensor listens for ultrasonic sounds
  - Electronics may translate frequency or modulation
  - Software may perform signal analysis (FFTs, etc.)

Ultrasonic Sensors (active)

$27

$49

$134

Visit http://www.acroname.com for more information about these & other products.

Search the web for “polaroid ultrasonic sensor”

Ultrasonic Sensor (active)

- transmit a packet of (ultrasonic) pressure waves
- distance d of the echoing object can be calculated based on the propagation speed of sound c and the time of flight t.

$$d = \frac{c \cdot t}{2}$$

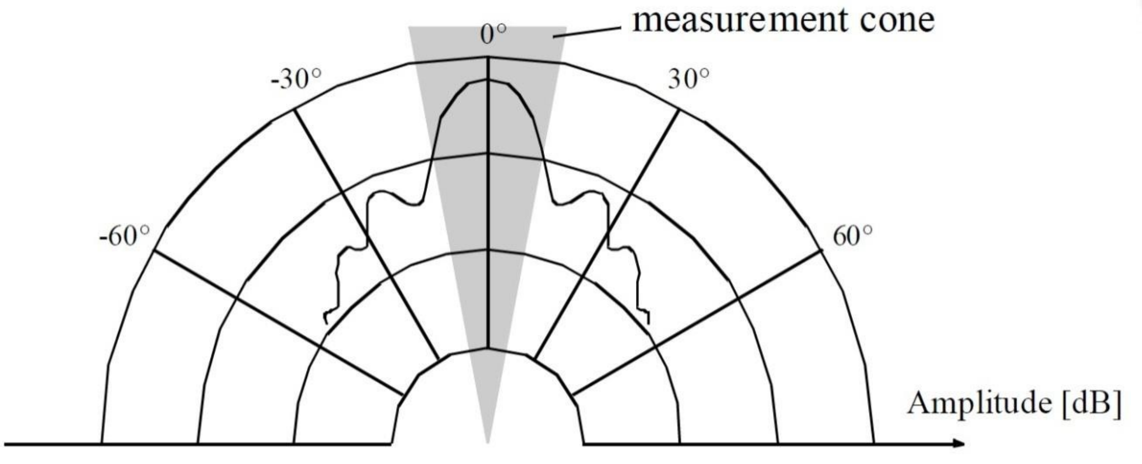
- The speed of sound c (340 m/s in air at sea level) is given by

$$c = \sqrt{\gamma \cdot R \cdot T}$$

  - where
  - γ : ration of specific heats
  - R: gas constant
  - T: temperature in degree Kelvin

Ultrasonic Sensor (active)

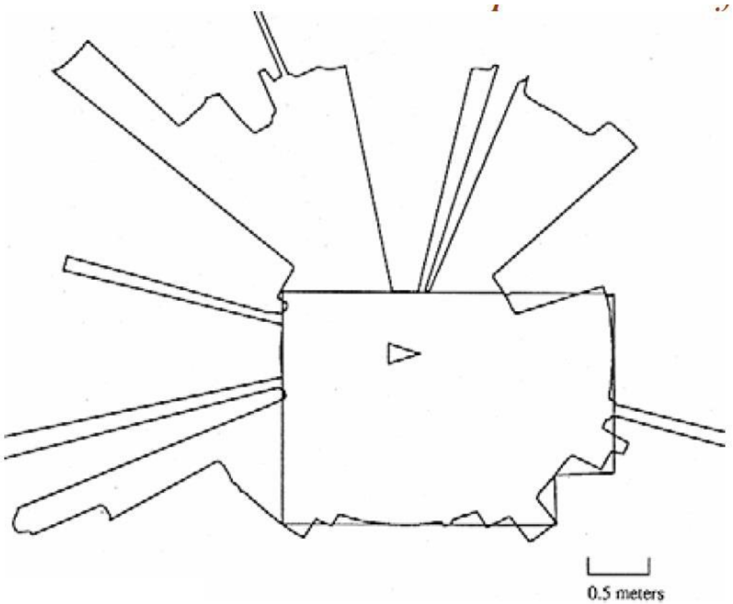
- typical frequency: 40 - 180 kHz
- generation of sound wave: piezo transducer
  - transmitter and receiver separated or not separated
- sound beam propagates in a cone (approx.)
  - opening angles around 20 to 40 degrees
  - regions of constant depth
  - segments of an arc (sphere for 3D)



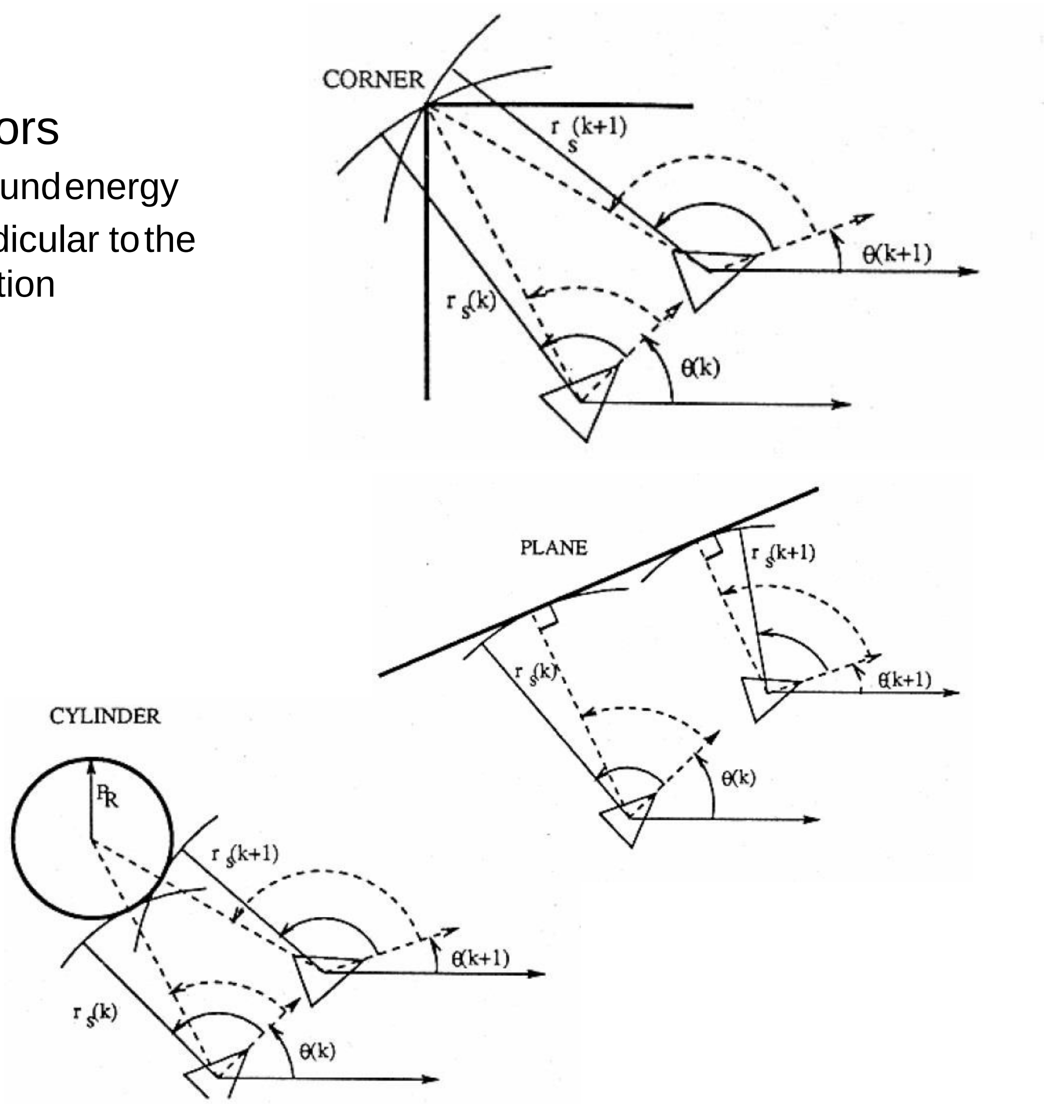
Typical intensity distribution of a ultrasonic sensor

Ultrasonic Sensors (active)

- Other problems for ultrasonic sensors
  - soft surfaces that absorb most of the sound energy
  - surfaces that are far from being perpendicular to the direction of the sound -> specular reflection



a) 360 deg scan



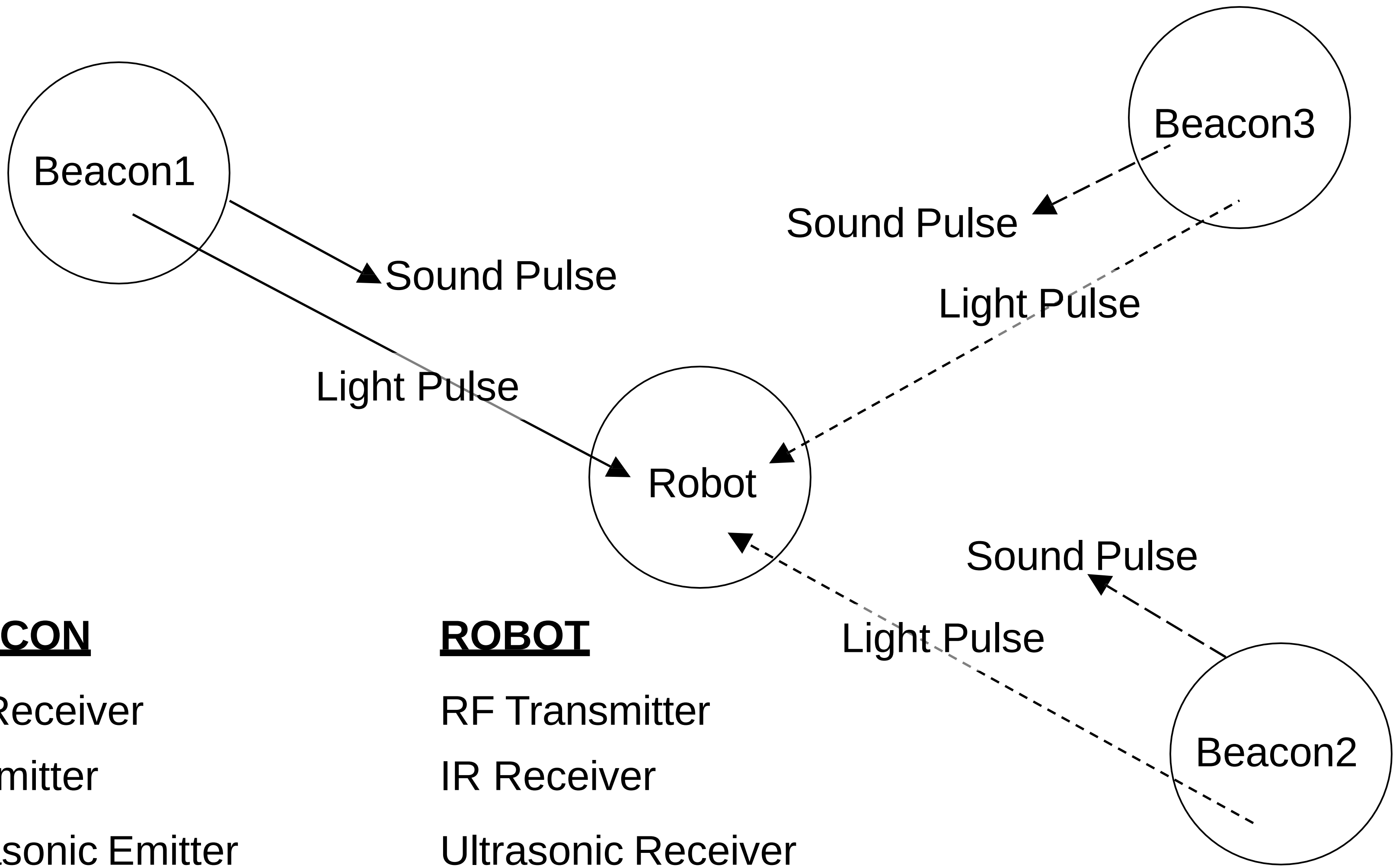
b) Results from different geometric primitives

Ultrasonic Sensors (passive)

- Passive - Beacons & Sensors
  - Beacons listen: RF command to broadcast
    - Beacons can send light & sound pulses
    - Robot looks & listens for each beacon
    - Light pulse starts timer, sound pulse stops it
    - Robot triangulates its location from 2 beacons
    - Compass on robot can provide orientation
    - But compass is unreliable indoors
    - When robot moves, can work of orientation

(Speed of Light=1 ft/nS, Speed of Sound=1ft/mS)

Ultrasonic Sensors (passive)



BEACON

RF Receiver

IR Emitter

Ultrasonic Emitter

ROBOT

RF Transmitter

IR Receiver

Ultrasonic Receiver

Sensors – Sonic (Acoustic)

- Active
  - Emit pulses & listen for echos
  - Times round trip sound travel (~1ft/mS)
  - Reaches far beyond robot (30-50 ft)
  - Relatively simple, not cheap, analog output
  - Directional, not everything reflects sound
  - Noisy!!!!
- Passive (sensor only)
  - Sensor listens to ambient sounds
  - Filters or scans selected frequencies
  - ADC measures conditioned signal amplitude
  - CPU performs signal analysis on what it hears

Sonic (Acoustic) - Passive

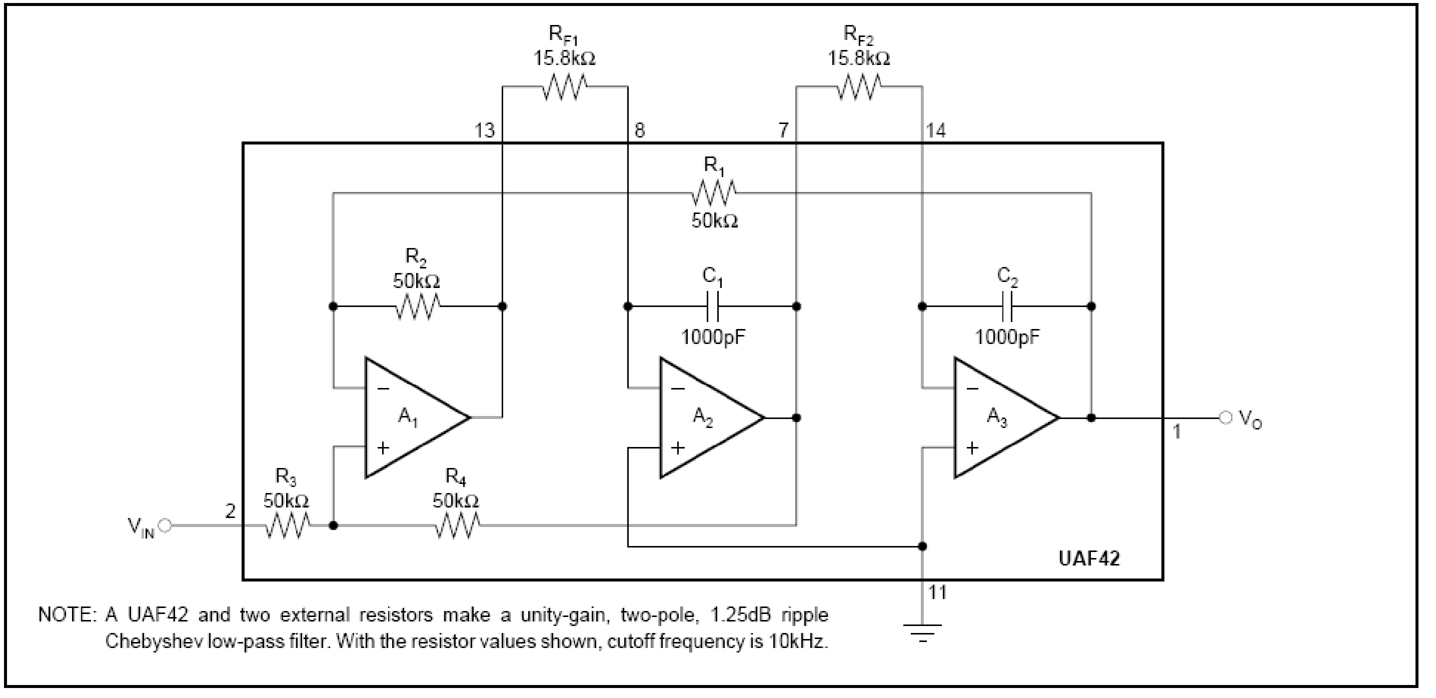


FIGURE 1. Two-Pole Low-Pass Filter Using UAF42.

TI (Burr-Brown) UAF42 Universal Active Filter

http://focus.ti.com/lit/an/sbfa002/sbfa002.pdf

Light / Color Sensors

- Active (emitting)
  - Selective field illumination (specific color(s))
  - Sensor filter removes extraneous light sources
  - Output can be analog (prop.) or digital (on/off)

- Passive (sensors only)
  - Different sensors for different colors
  - Color filter removes extraneous light sources
  - Output can be analog (prop.) or digital (on/off)

Light / Color Sensors

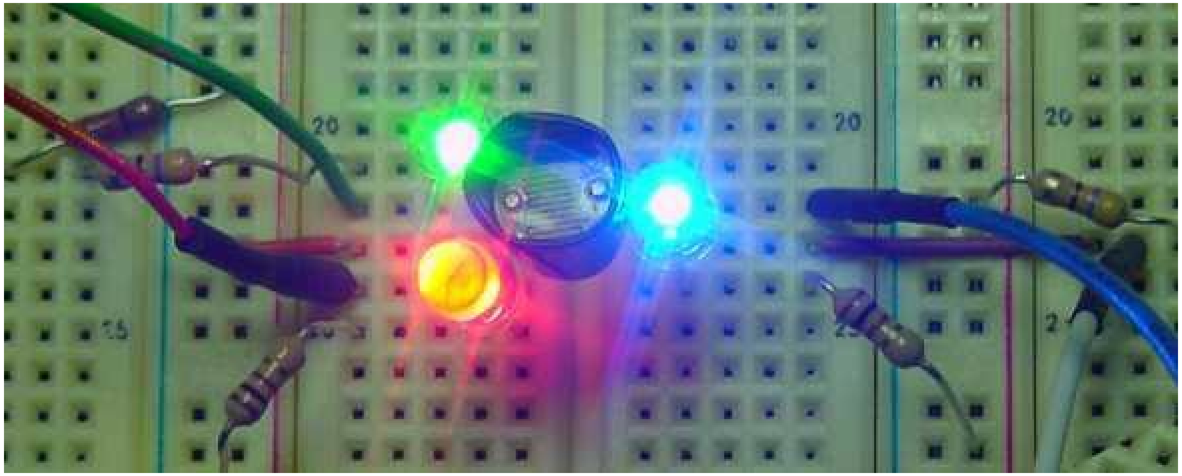
Light Sensor (Photocell)

Resistance is small when brightly illuminated

Good for detecting direction/presence of light

Non-linear resistance

Slow response to light changes



Sensors – Visual

- Active (emitting)
  - Camera with field of view illumination
  - Looks for particular reflections
  - Filter removes non-significant light sources
  - Linear array senses single axis of motion

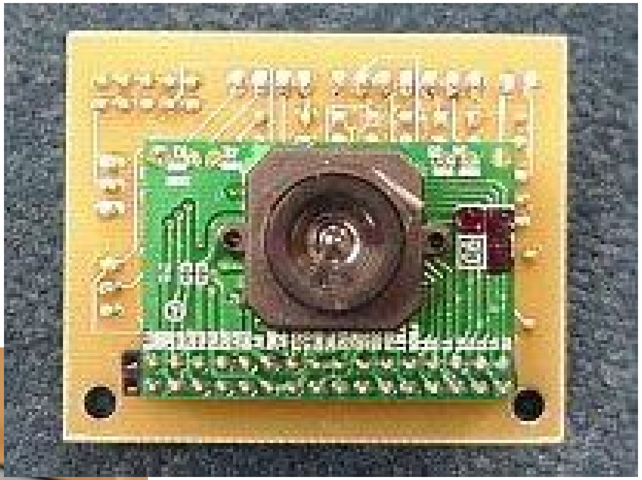
- Passive (camera only)
  - Scans field of interest
  - Looks for objects, artifacts, features of interest
  - Processes digital data to simplified interpretation
  - Can produce a lot of data requiring considerable processing power.

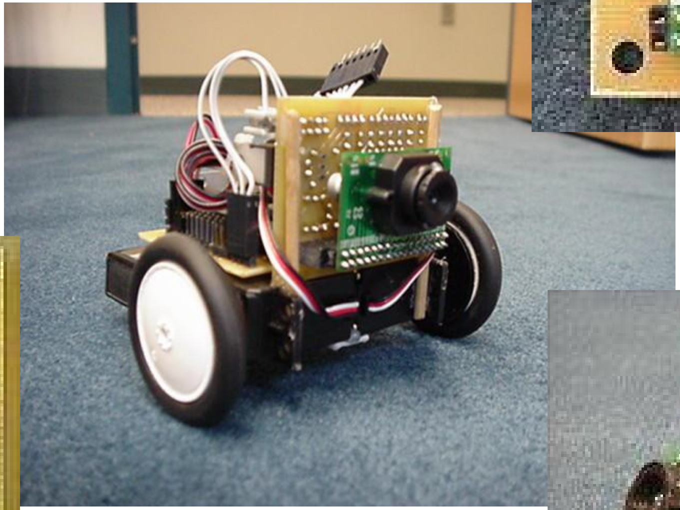
Sensors – Visual

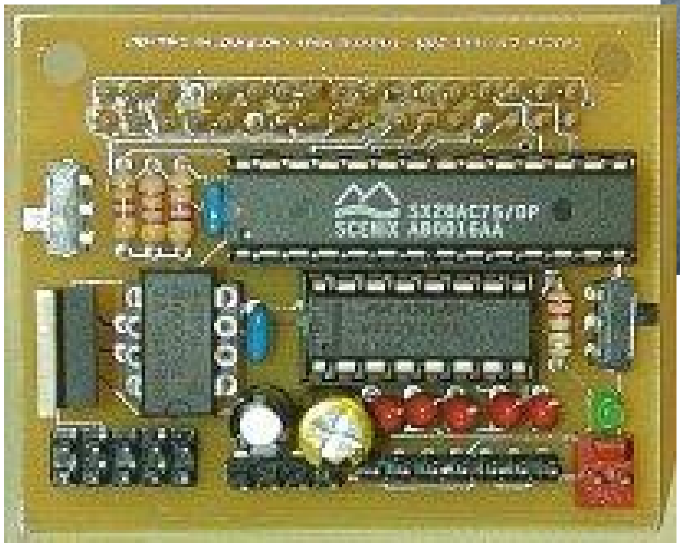
- CMUCam

  consist of a small video camera and a microcontroller

- Linear Optical Array

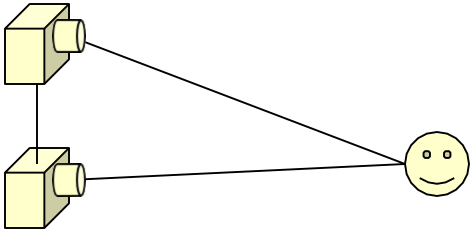






Sensors - Stereo vision

- Computer Vision provides robots with the capability to passively observe the environment
  - Stereo vision systems provide depths and complete location information using triangulation



  - However, computer vision is very complex
    - Correspondence problem makes stereo vision more difficult

Sensor Performance

Characteristics that are especially relevant for real world environments

- Sensitivity
  - ratio of output change to input change
  - however, in real world environment, the sensor very often has high sensitivity to other environmental changes, e.g. illumination
- Cross-sensitivity (cross-talk)
  - sensitivity to other environmental signals
  - influence from other active sensors
- Error / Accuracy
  - difference between the sensor's output and the true value

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

$m = measured\ value$

$v = true\ value$

  - Problem: the robot does not normally know the true value and hence cannot determine the accuracy of a measurement.
  - Size of error can depend on other factors (changes in temperature, air moisture, age of sensor, manufacture variations, etc.)
  - Sensors can fail arbitrarily and at arbitrary times.

Sensor Performance

Characteristics that are especially relevant for real world environments

- Systematic error -> deterministic errors
  - caused by factors that can (in theory) be modelled -> prediction
  - e.g. calibration of a laser sensor or of the distortion cause by the optics of a camera
- 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
  - e.g. resolution of sensor

Dealing with sensor errors

Masking sensor errors:

- Use multiple sensors
  - At different locations
  - From different manufacturers
  - Of different age
- Use sensors of different type to measure the same entity.
- Use fault tolerant algorithms:
  - Triple Modular Redundancy (TMR) methods
  - Byzantine methods

Sensors – Conclusion

- Robot sensors
  - vary greatly in cost and performance
  - can be active or passive
  - can be proprioceptive (internal) or exteroceptive (external)
  - enable robots to navigate their environment
  - range sensors are common in robotics
  - vary in difficulty with respect to processing the sensor data
  - all have pros and cons and need to be chosen carefully