Robot Sensors and Actuators

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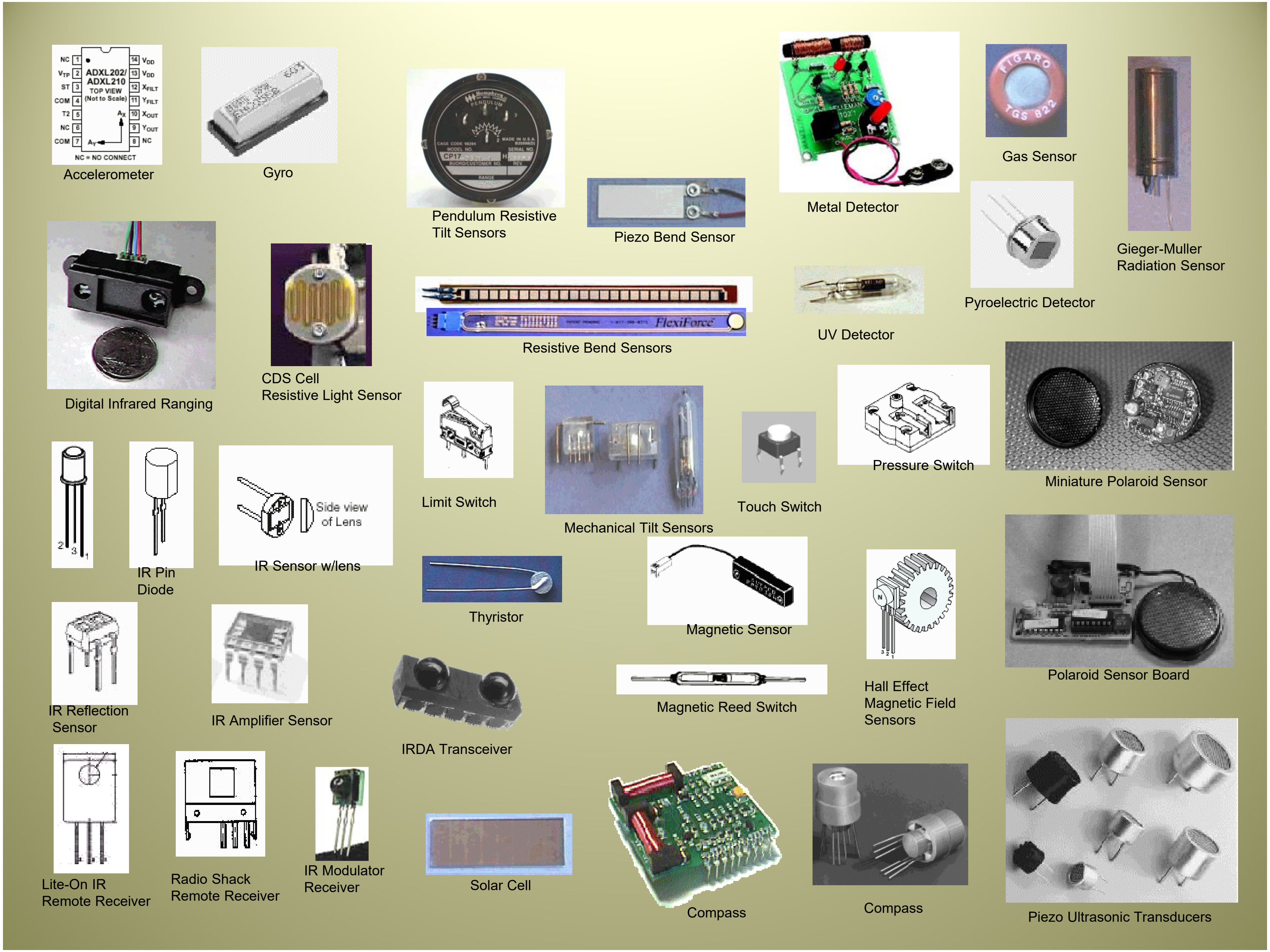
Robot Sensors

- Sensors are devices for sensing and measuring geometric and physical properties of robots and the surrounding environment
  - Position, orientation, velocity, acceleration
  - Distance, size
  - Force, moment
  - temperature, luminance, weight
  - etc.

ultrasonic sensors

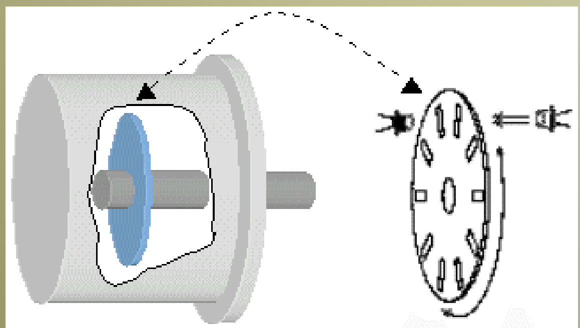
Infra-red sensors

touch sensors


Accelerometer
Gyro
Pendulum Resistive Tilt Sensors
Piezo Bend Sensor
Metal Detector
Gas Sensor
Gieger-Muller Radiation Sensor
Digital Infrared Ranging
CDS Cell Resistive Light Sensor
Resistive Bend Sensors
UV Detector
Pyroelectric Detector
Limit Switch
Mechanical Tilt Sensors
Touch Switch
Pressure Switch
Miniature Polaroid Sensor
IR Pin Diode
IR Sensor w/lens
Side view of 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

Internal Sensors

- Robot sensors can be classified into two groups: Internal sensors and external sensors
- Internal sensors: Obtain the information about the robot itself.
  - position sensor, velocity sensor, acceleration sensors, motor torque sensor, etc.



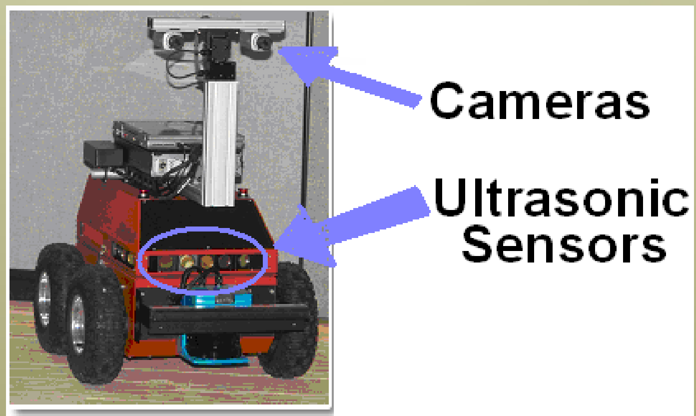
optical encoder

acceleration sensors

velocity sensor

External Sensors

- External sensors: Obtain the information in the surrounding environment.
  - Cameras for viewing the environment
  - Range sensors: IR sensor, laser range finder, ultrasonic sensor, etc.
  - Contact and proximity sensors: Photodiode, IR detector, RFID, touch etc.
  - Force sensors: measuring the interaction forces with the environment,
  - etc

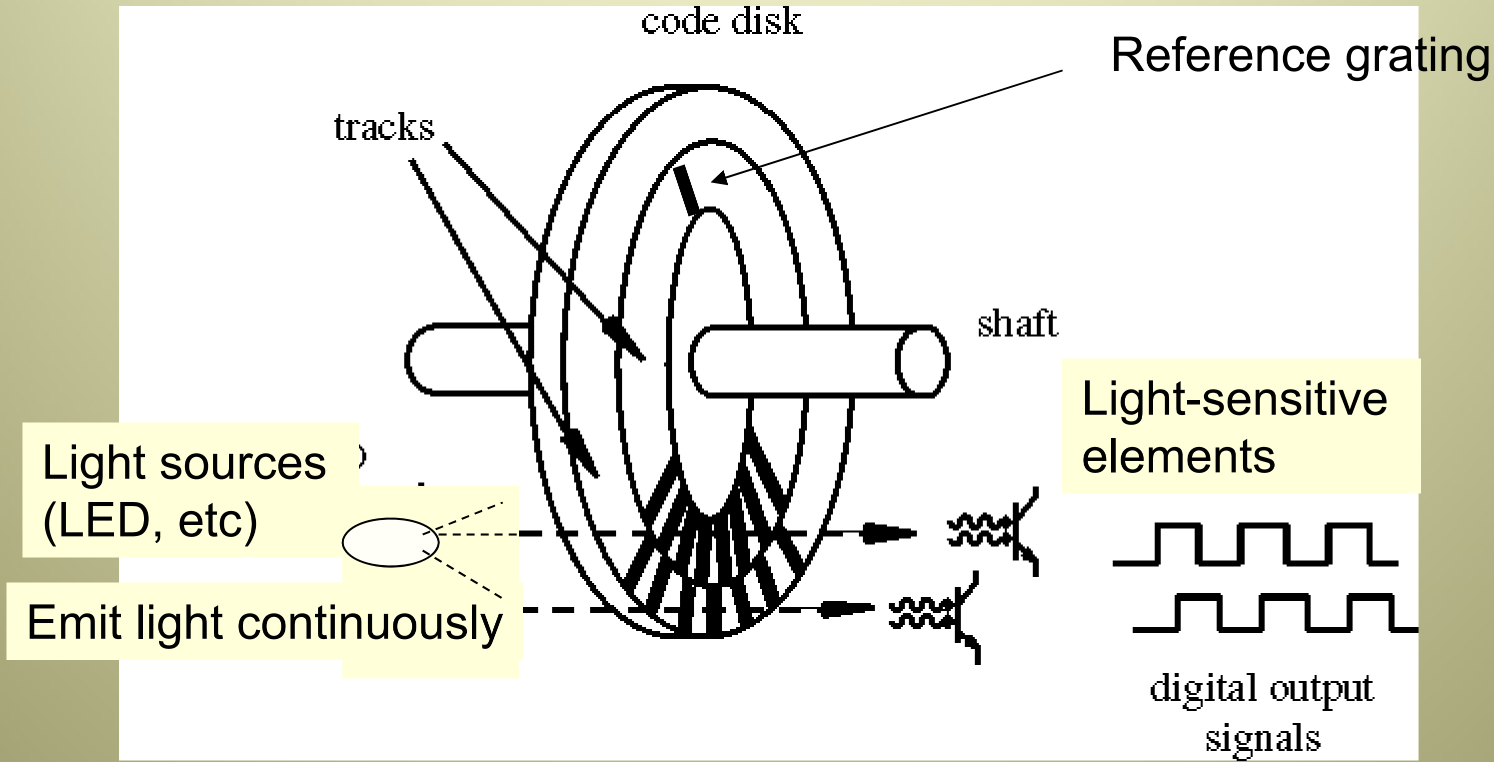


A mobile robot with external sensors

Position Measurement

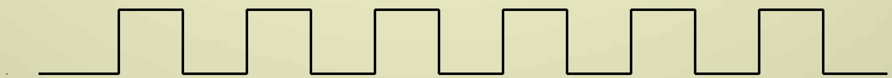
- An optical encoder is to measure the rotational angle of a motor shaft.
- It consists of a light beam, a light detector, and a rotating disc with a radial grating on its surface.
- The grating consists of black lines separated by clear spaces. The widths of the lines and spaces are the same.
  - Line: cut the beam → a low signal output
  - Space: allow the beam to pass → a high signal output
- A train of pulses is generated with rotation of the disc. By counting the pulses, it is possible to know the rotational angle.

Optical Encoder

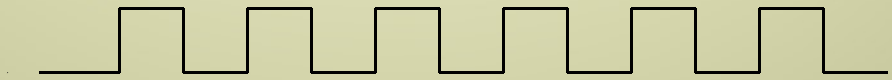


Optical Encoders

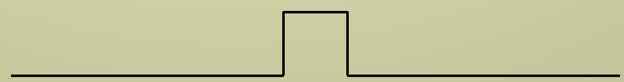
- Three phases of signals:
  - Phase A: A train of pulses



  - Phase B: A train of pulses.



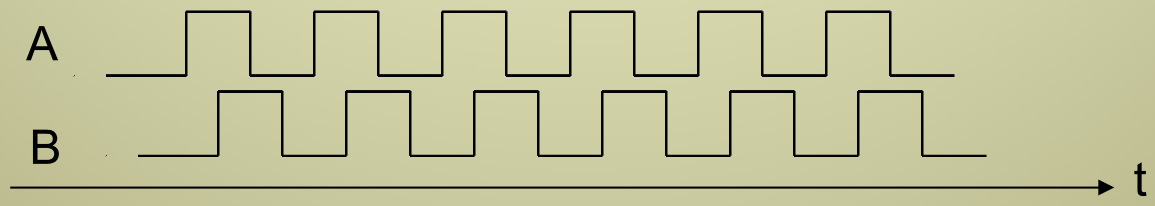
  - Phase Z: A single pulse per turn.



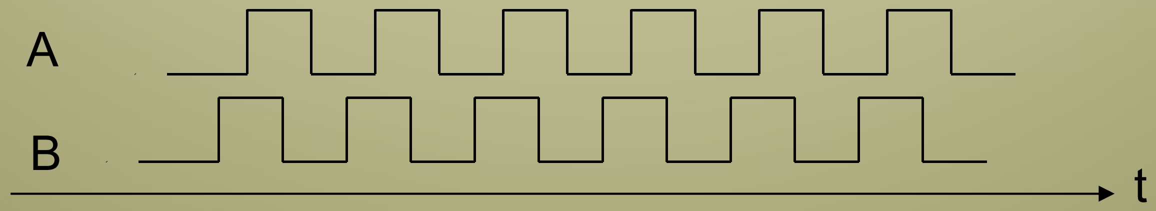
  - The phase difference between Phase A and Phase B is 90 degrees.
  - The Z-pulse is used as a reference angle (zero angle) so that the absolute angle can be detected.

Optical Encoders

- The direction of rotation is determined by checking which phase of signals is leading.
  - If Phase A signals are leading, the rotation is in the clockwise direction.



  - If Phase B signals are leading, the rotation is the counterclockwise direction.



Optical Encoders

- Resolution of measurement

$$s = \frac{360^{\circ}}{\text{number of lines(spaces)}}$$

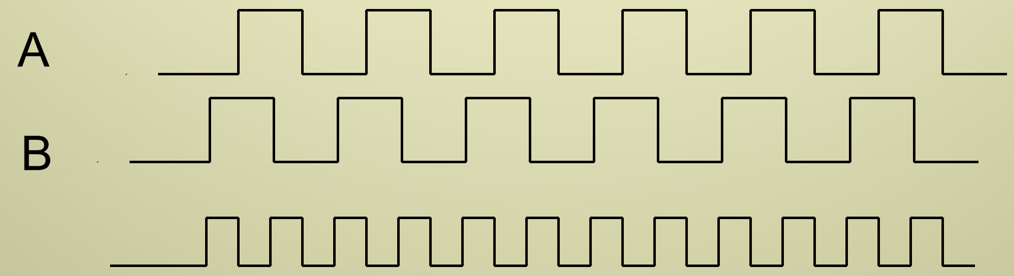
- The smaller is the resolution, the better is the measurement

Optical Encoders

- How to increase the resolution, i.e. to make the value of s smaller.
  - Increase the number of lines/spaces → the manufacturing cost will be increased
  - Evaluate the two trains of pulses. The evaluation means to take set operations, interpolation, etc.

Optical Encoders

- Set operations: Exclusive-or (XOR) operation (low output if the two pulses are the same, otherwise high)

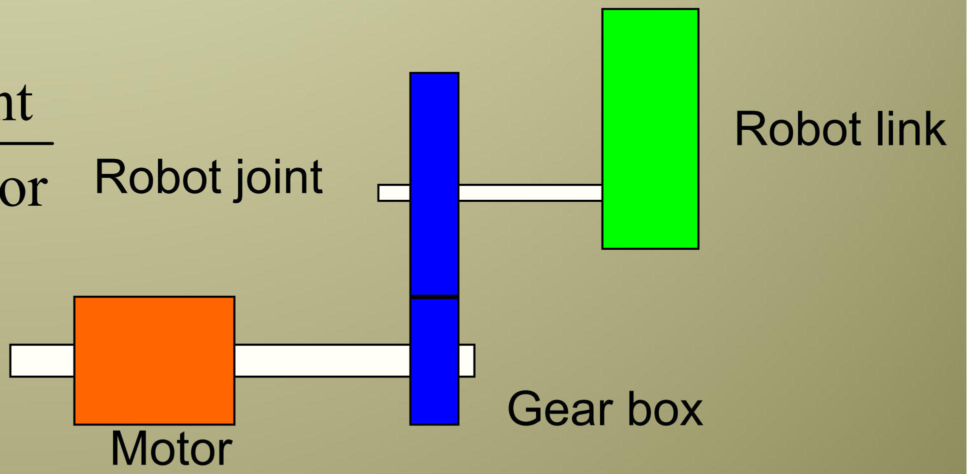


  – The frequency of the pulses train is doubled→ the resolution will be doubled (the value becomes the half of the original one)
- By counting the raising and falling edges, the resolution can be increased 4 times.
- The resolution can be increased by interpolating the pluses, i.e. dividing a pulse into more pulses. Of course, this interpolation means approximation.

Optical Encoders

- In robotics, we are more interested in the measurement of joint angles instead of the angle of the motor shaft.
- By adding a reduction mechanism (gear box, etc), the measurement resolution of the joint angle will be increased n times, where n is the gear ratio (velocity ratio) of the reduction mechanism.
  - One turn of the joint corresponds to n turns of the motor shaft.

$$\text{gear ratio}(n) = \frac{\text{radius of gear on joint}}{\text{radius of gear on motor}} = \frac{\text{motor speed}}{\text{joint speed}}$$



Other position sensor: Potentiometer（电位器）

- Potentiometer = varying resistance

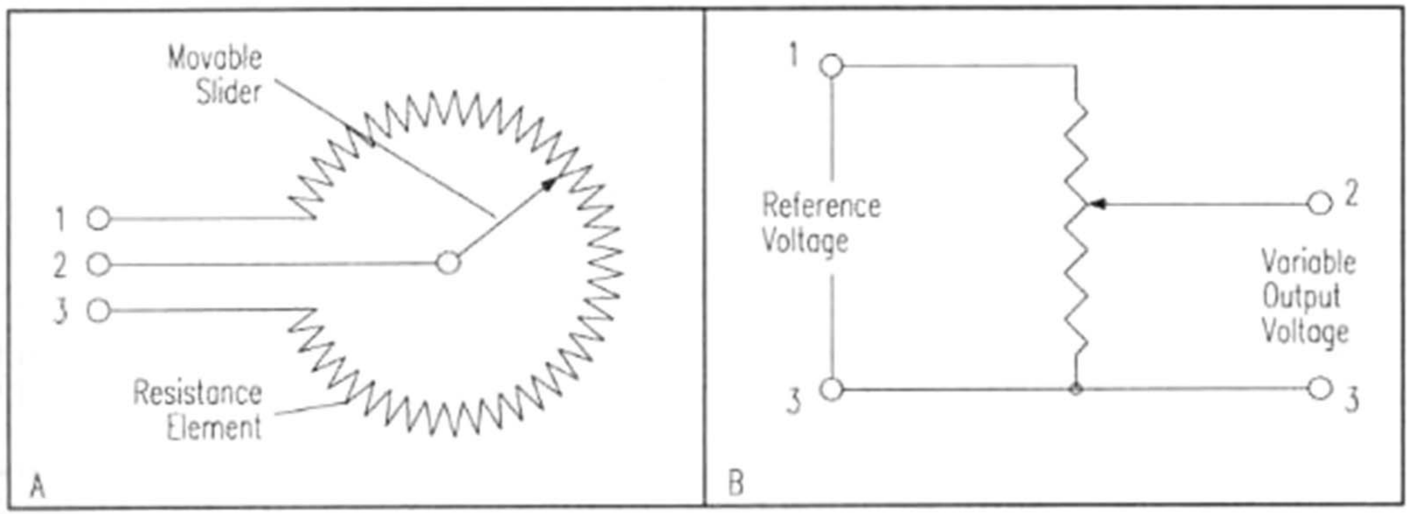


Figure 2-1. For a linear-taper pot, the output voltage V_o is directly related to the ratio of actual to full scale displacement.

Problems:

Frictions

Noisy

Nonlinearity

etc.

Velocity Measurement

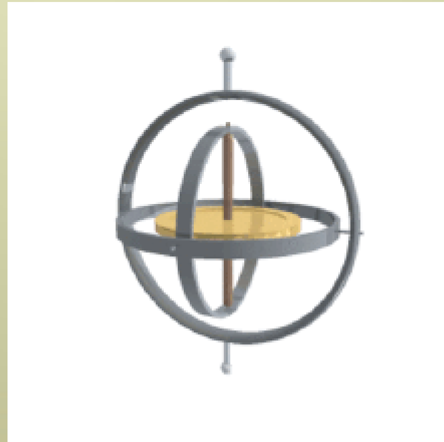
- Differentiate position: Use position sensors.

$$V = \frac{\Delta p}{\Delta t}$$

- Advantages: Simple, without using additional sensors.
- Disadvantages: noisy signals
- Use low-pass filters to improve the accuracy, i.e. look at a few points before the current time, etc.

Inertial Sensors

- **Gyroscopes**
  - Heading sensors, that keep the orientation to a fixed frame
  - absolute measure for the heading of a mobile system.
  - Two categories, the mechanical and the optical gyroscopes
    - Mechanical Gyroscopes
    - Optical Gyroscopes



- **Accelerometers**
  - Measure accelerations with respect to an inertial frame
  - Common applications:
    - Tilt sensor in static applications, Vibration Analysis, Full INS Systems

Applications of Gyroscopes

- Gyroscopes can be very perplexing objects because they move in peculiar ways and even seem to defy gravity.
  - A bicycle
  - an advanced navigation system on the space shuttle
  - a typical airplane uses about a dozen gyroscopes in everything from its compass to its autopilot.
  - the Russian Mir space station used 11 gyroscopes to keep its orientation to the sun
  - the Hubble Space Telescope has a batch of navigational gyros as well

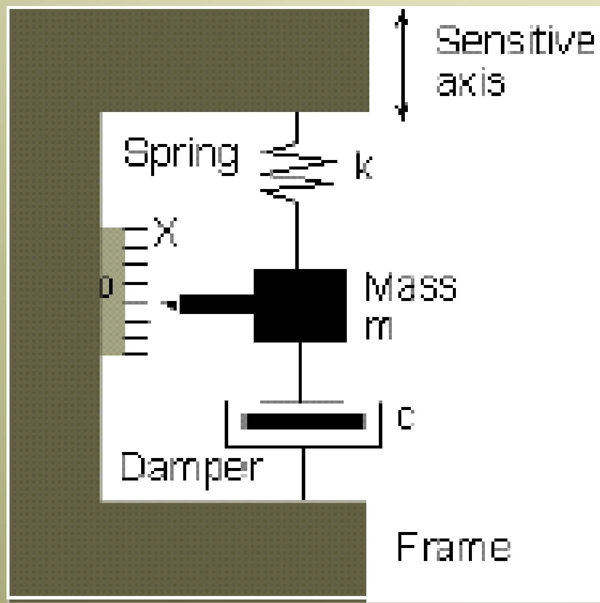
Accelerometers

- They measure the inertia force generated when a mass is affected by a change in velocity.
- This force may change
  - The tension of a string
  - The deflection of a beam
  - The vibrating frequency of a mass

Accelerometer

- Main elements of an accelerometer:

1. Mass 2. Suspension mechanism 3. Sensing element

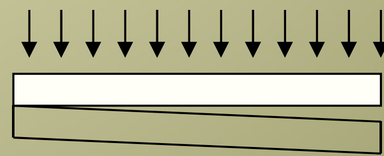


$$F = m\frac{d^2x}{d^2t} + c\frac{dx}{dt} + kx$$

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

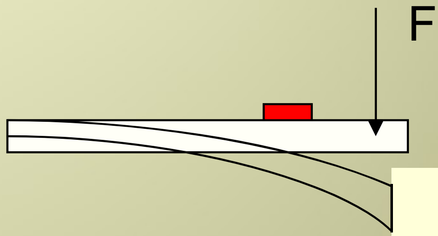
Acceleration Measurement

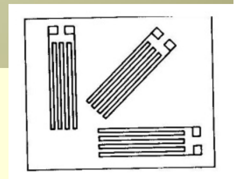
- Differentiation of the velocity signals →noisy results
- MEMs accelerometer: Measurement of bending of a MEMs structure under inertia forces.
  - Gravity force gives output
  - Low measurement accuracy
  - Drifting



Force Sensors

- Forces can be measured by measuring the deflection of an elastic element.



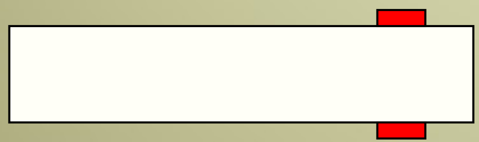


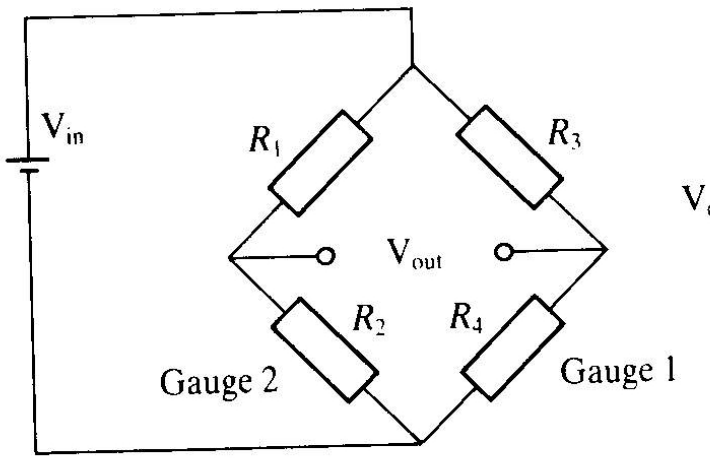
$$\varepsilon = \frac{\Delta l}{l} = strain$$

  - the strain we measure is about 0.005mm/mm
- Strain gauges: Most common sensing elements of force. It converts the deformation to the change of its resistance.
- Gauge resistance varies from 30 to 3K, corresponding to deformation from $30\mu m$ to $100\mu m$

Force Sensors

- Detect the resistance changes of the strain gauge using the Wheatstone bridge circuit.



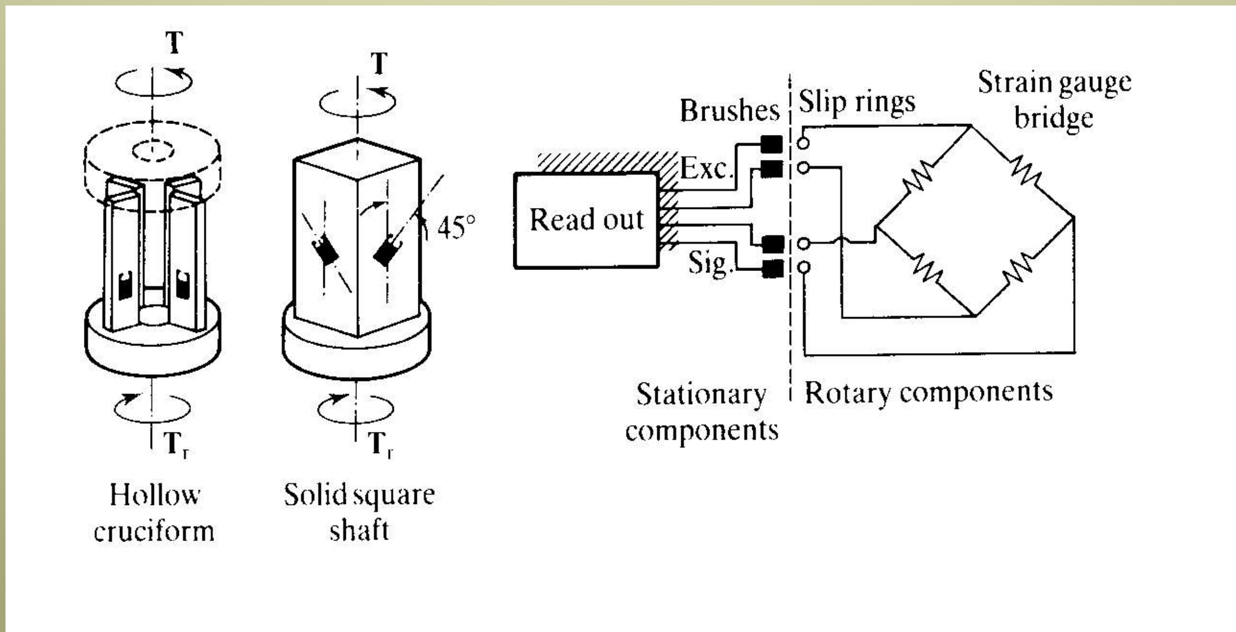


$$V_{out} = \left(\frac{R_2}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right) V_{in}$$

Using two gauges is to cancel the drift due to temperature change.

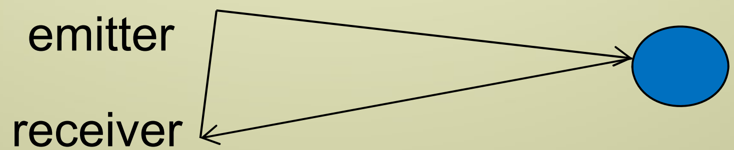
Torque Sensor

- Shaft torque is measured with strain gauges mounted on a shaft with specially designed cross-section.



Range Sensors

- To measure the distance from the sensor to a nearby object
- Working principles
  - Triangulation: Use the triangle formed by the traveling path of the signal to calculate the distance

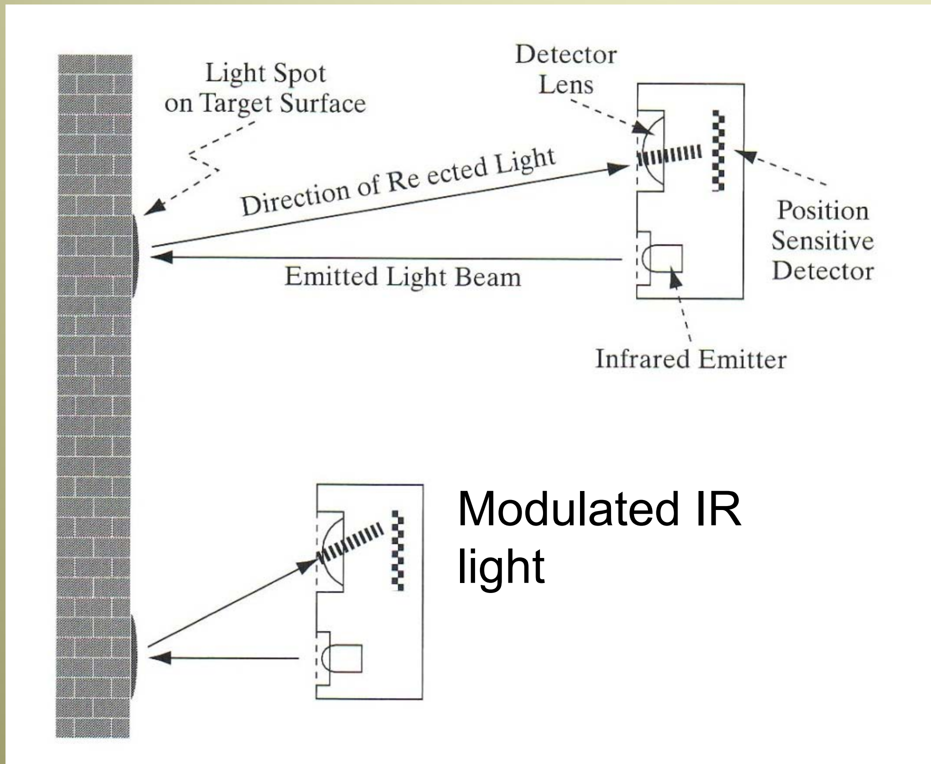


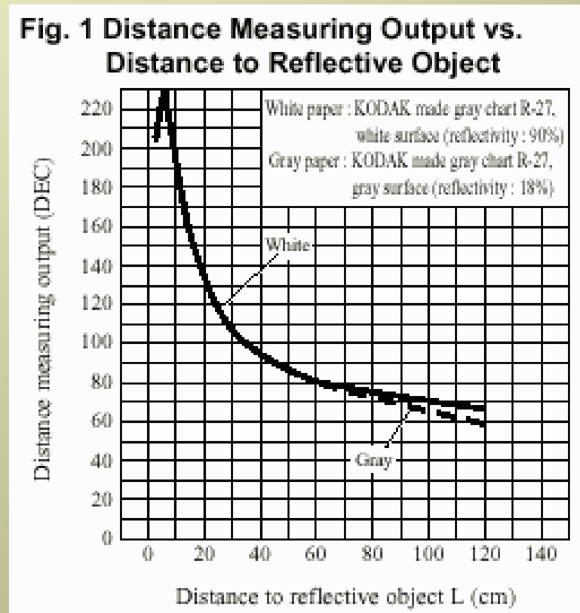
  - Time-of-flight: Use the time of flight of the signals to measure the distance

- Typical range sensors
  - Infra-red range sensor (triangulation)
  - Ultrasonic sensors (time-of-flight)
  - Laser range sensor (triangulation)
  - etc

IR Range Sensors

- Principle of operation: triangulation
  - IR emitter + focusing lens + position-sensitive detector





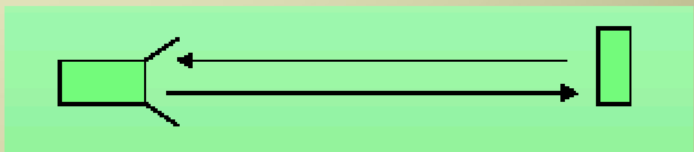
Location of the spot on the detector corresponds to the distance to the target surface.

Limitations of Infrared Sensors

- Poor reflection of IR signals: Certain dark objects cannot reflect the IR signals well.
  - The absence of reflected IR signals does not mean that no object is present!
- Background noises: The sensor fails to work if there are similar IR signals sources in the environment.
- IR sensors measure objects in short range.
  - typical maximum range is 50 to 100 cm.

Time of Flight Range Sensors

- Time of Flight
- The measured pulses typically come form ultrasonic, RF and optical energy sources.
  - **D = v * t**
  - D = round-trip distance
  - v = speed of wave propagation
  - t = elapsed time



- Sound = 0.3 meters/msec
- RF/light = 0.3 meters / ns (Very difficult to measure short distances 1-100 meters)

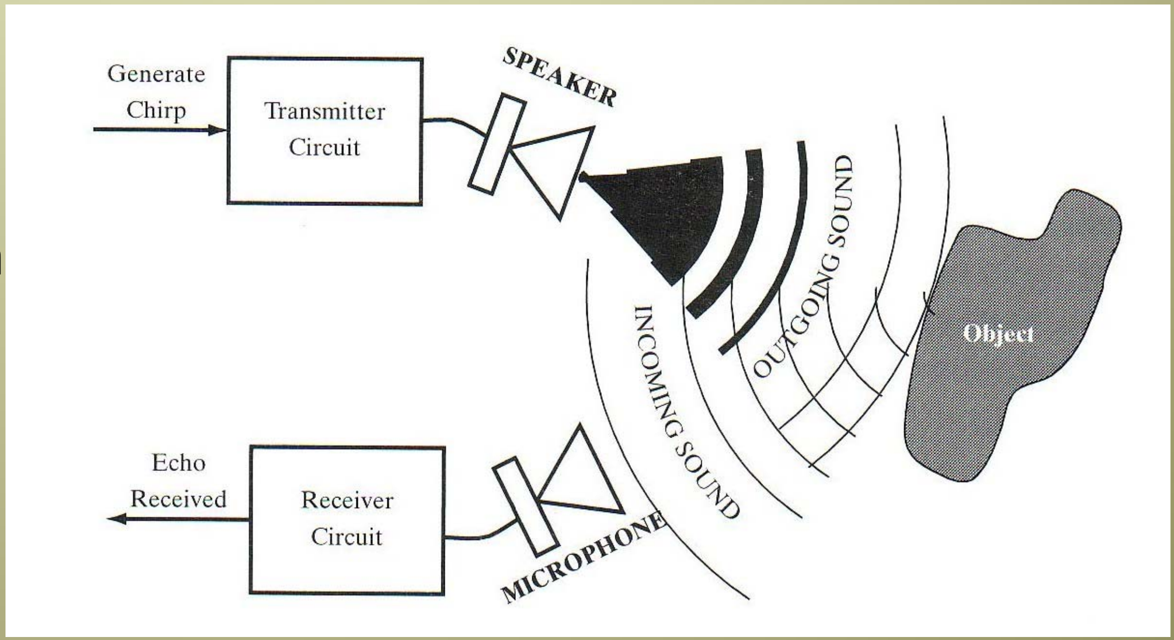
Ultrasonic Sensors

- Basic principle of operation:
  - Emit a quick burst of ultrasound (50kHz), (human hearing: 20Hz to 20kHz)
  - Measure the elapsed time until the receiver indicates that an echo is detected.
  - Determine how far away the nearest object is from the sensor

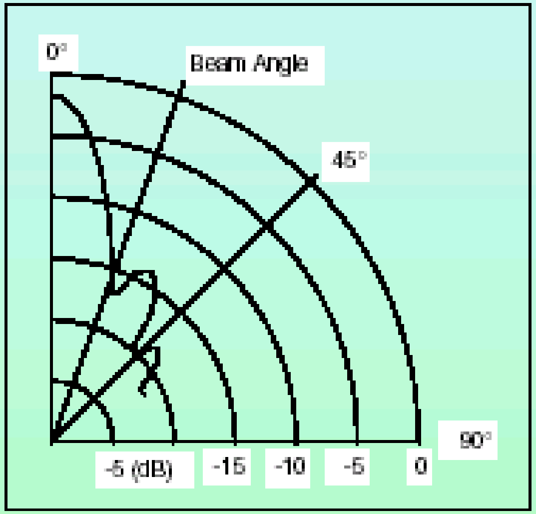
- $D = v * t$

D = round-trip distance
v = speed of propagation (340 m/s)
t = elapsed time

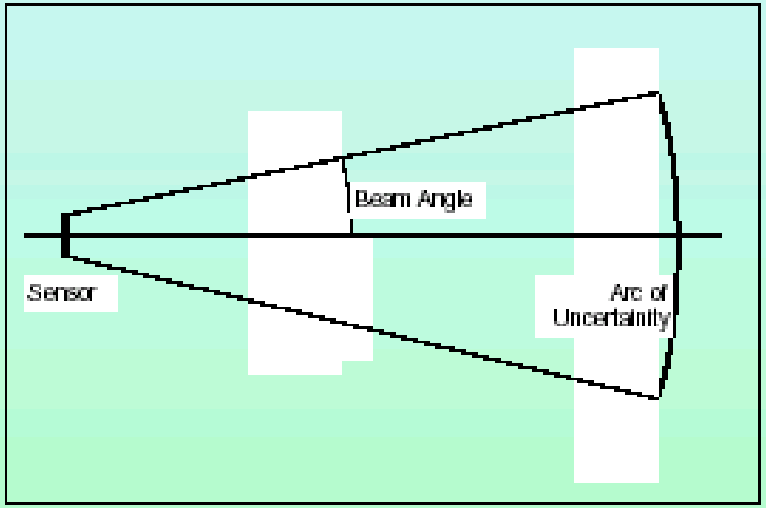
Bat, dolphin, …



Ultrasonic Sensors



Sensor Specification

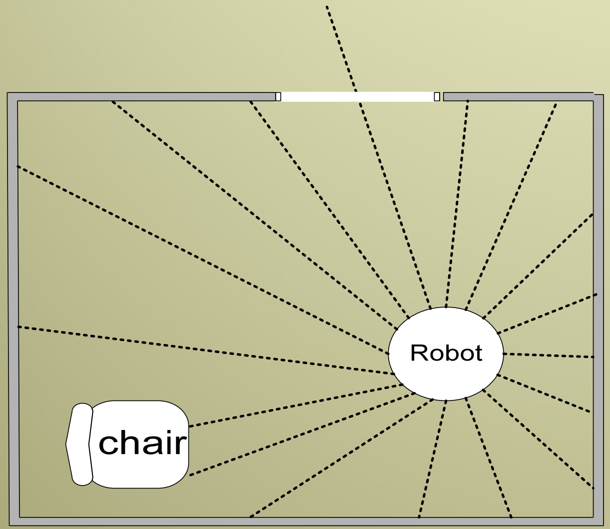


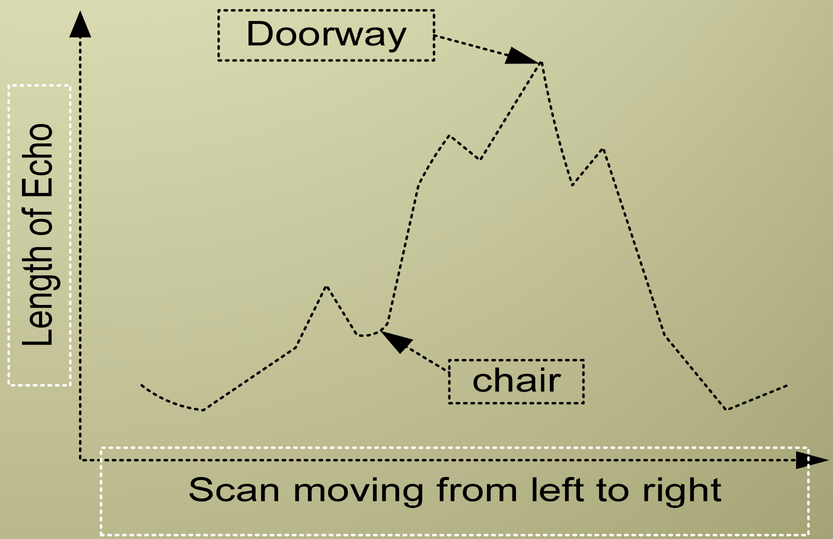
Sensor Model, angle = 15 degrees

- Ranging is accurate but bearing has a 30 degree uncertainty. The object can be located anywhere in the arc.
- Typical ranges are of the order of several centimeters to 30 meters.
- Another problem is the propagation time. The ultrasonic signal will take 200 msec to travel 60 meters. (30 meters roundtrip @ 340 m/s)

Ultrasonic Sensors

- Applications:
  - Distance Measurement
  - Mapping: Rotating proximity scans (maps the proximity of objects surrounding the robot)





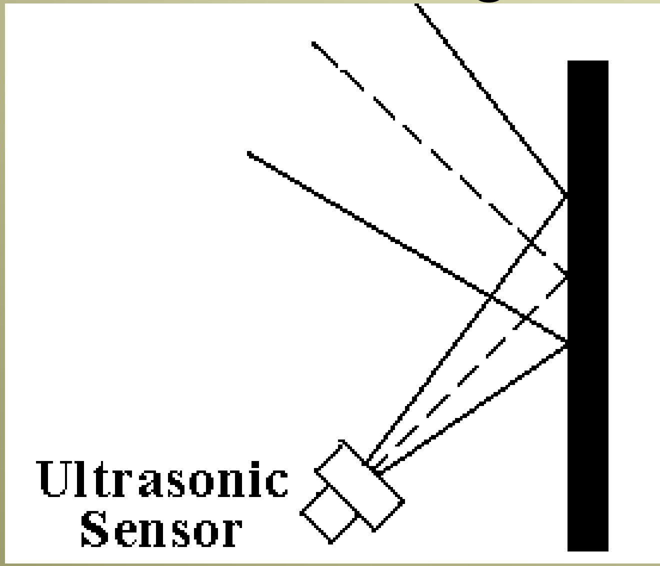
Scanning at an angle of 15º apart can achieve best results

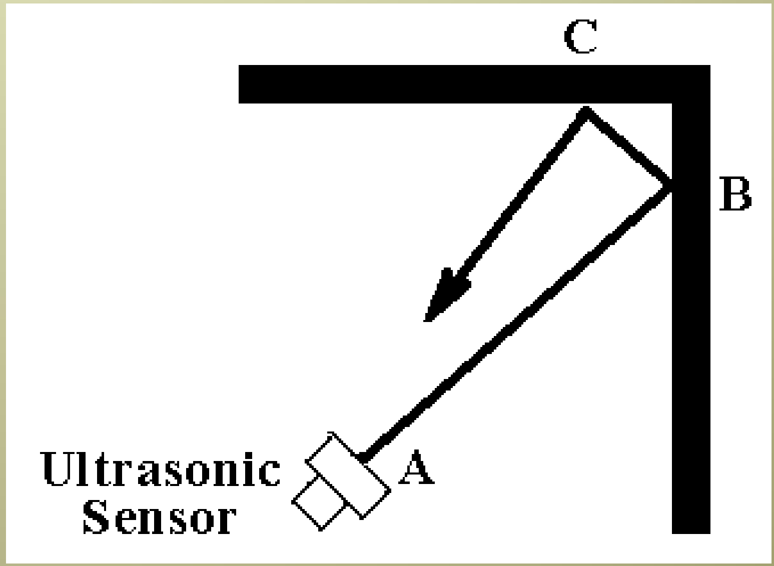
Limitations of Ultrasonic Sensors

- Background noises: If there are other ultrasonic sources, the sensor may detect signals emitted by another source.
- The speed of sound varies with air temp. and pressure
  - a 16℃ temperature change can cause a 30cm error at 10m!
- Cross-talk problem: If a robot has more than one ultrasonic sensors who measurement ranges intersect, a sensor may receive signals emitted by others

Limitations of Ultrasonic Sensors

- Poor surface reflection: Surface materials absorb ultrasonic waves.
- Surface orientation affect the reflection of ultrasonic signals.





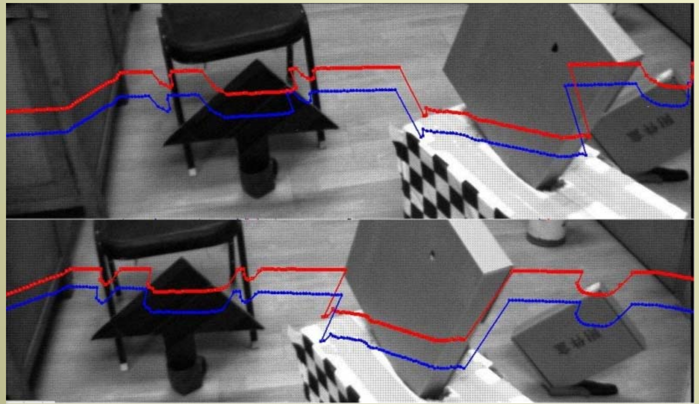
Surface orientation affects the performance

Laser Ranger Finder

- The working principle: Triangulation.
  - Spin the laser strip and detect the reflected light
- Range 2-500 meters
- Resolution : 10 mm
- Field of view : 100 - 180 degrees
- Angular resolution : 0.25 degrees
- Scan time : 13 - 40 msec.
- These lasers are more immune to Dust and Fog

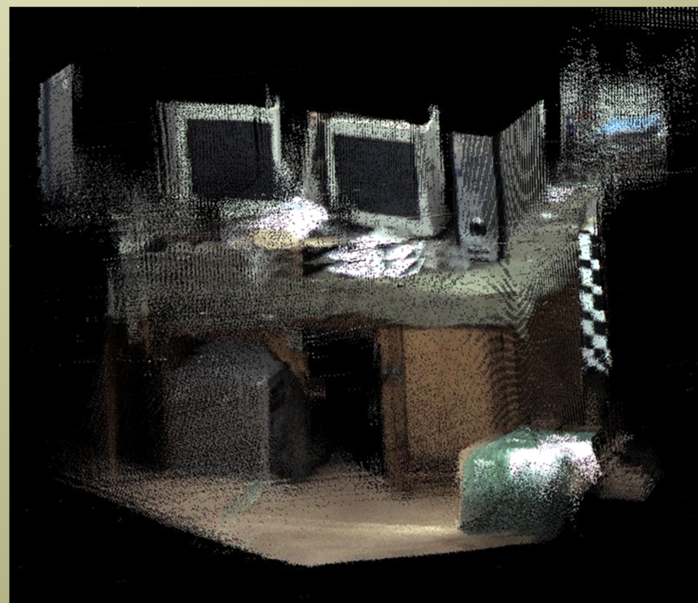
http://www.sick.de/de/products/categories/safety/

Example (Laser Range Finder)



Measurement slice

A scene



3D model constructed

Vision

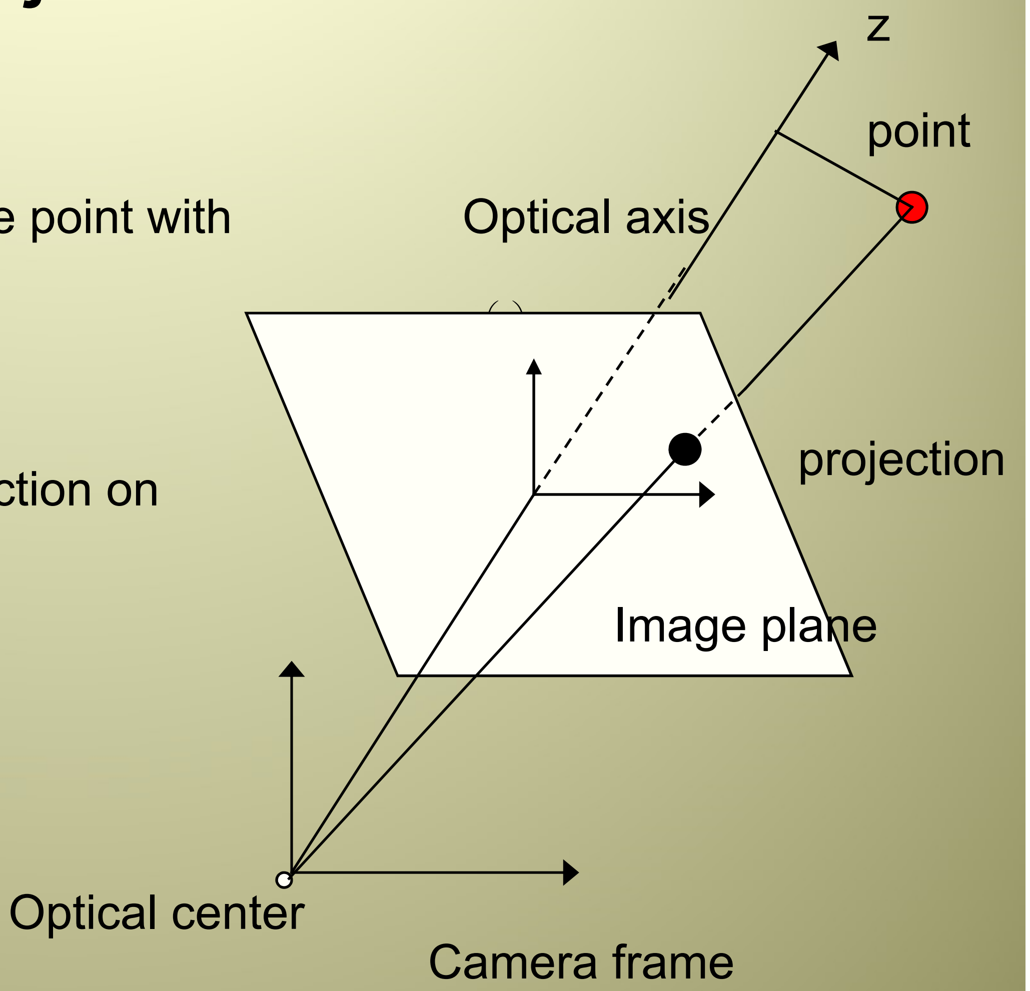
- Vision provide the richest information
  - Geometric information
  - Texture
  - Color
  - Etc
- Many applications in robotics
  - Distance measurement
  - Object/person recognition
  - Control
  - …..
- Vision systems
  - Single camera, stereo camera
  - Active vision, passive vision

Perspective Projection of Camera

$\begin{pmatrix} x \\ y \\ z \end{pmatrix}$ 3-D position of the feature point with the camera frame

$\begin{pmatrix} u \\ v \end{pmatrix}$ Coordinates of the projection on the image plane

$$\begin{pmatrix} u \\ v \end{pmatrix} = \frac{f}{z} \begin{pmatrix} x \\ y \end{pmatrix}$$



f: the focal length of the camera

Stereo Vision

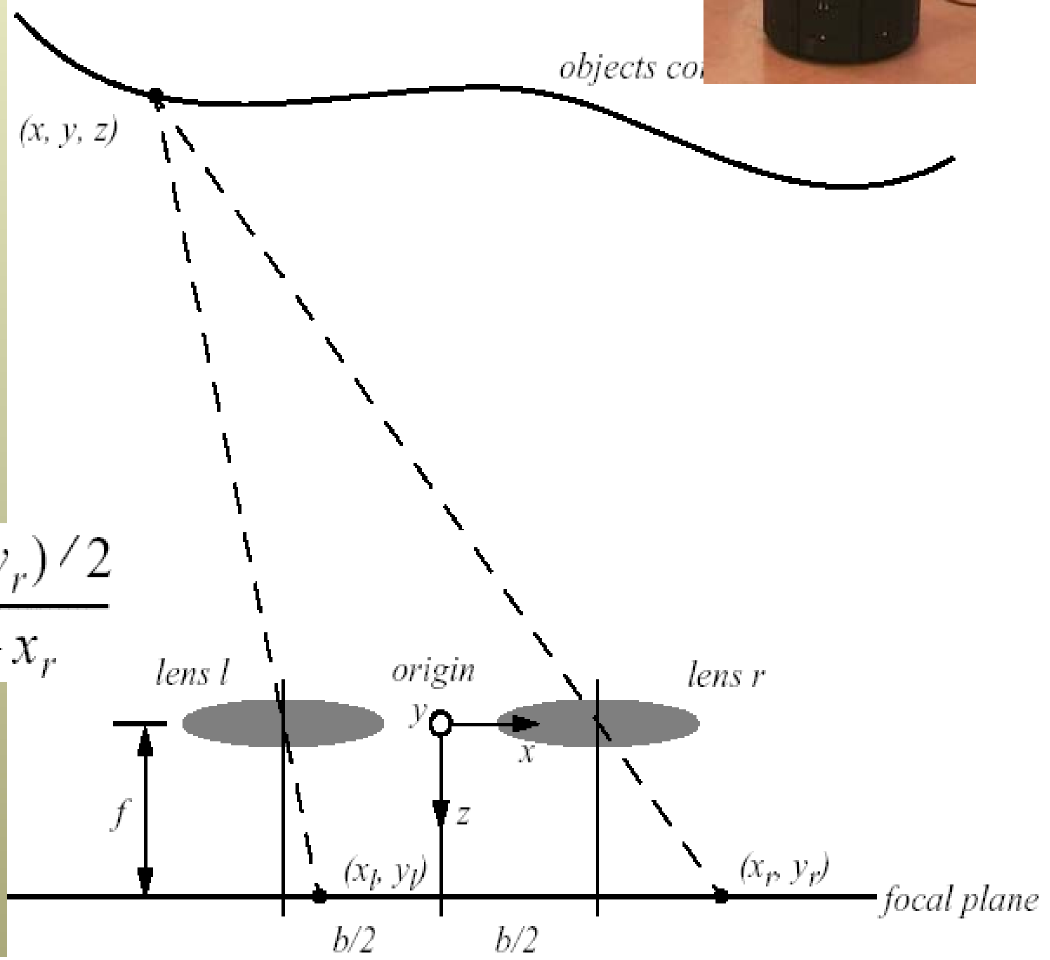
- Use two cameras to measure the depth
- Idealized camera geometry for stereo vision
  - Disparity between two images -> Computing of depth
  - From the figure it can be seen that

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

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

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

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

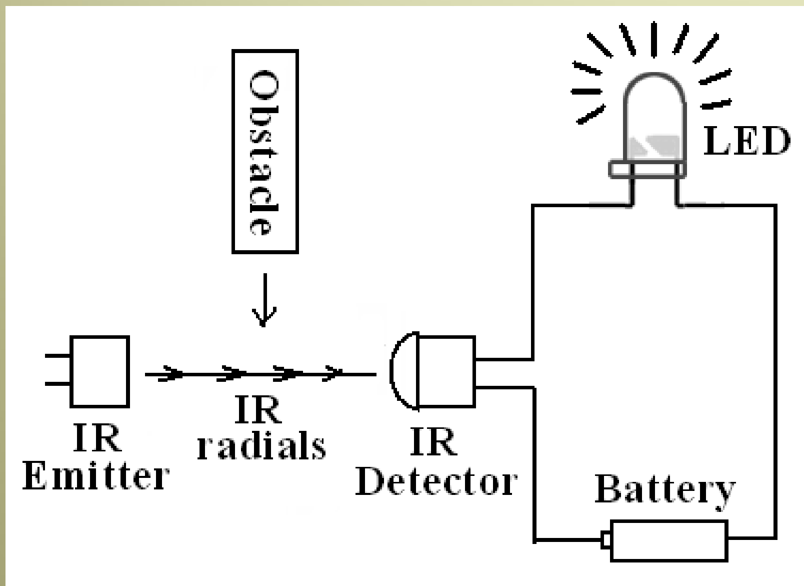


Touch and Proximity Sensors

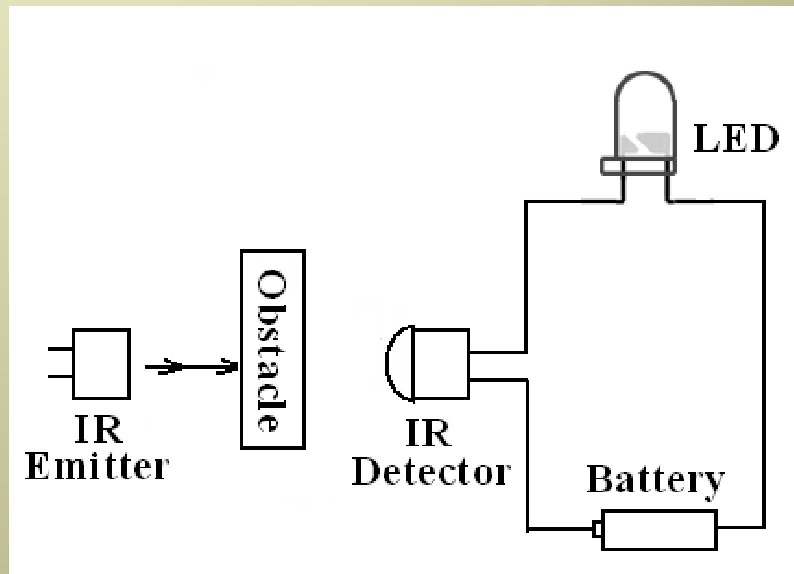
- To detect whether any object is close to a robot or touches a robot.
- Proximity sensor does not give distance, but only tells the existence of an object.
- Typical sensors
  - IR proximity sensors
  - Photodiodes
  - Touch sensors
  - RFID detector
  - etc

Infrared (IR) Detector

IR detector: To detect existence of an object.



(a) LED is on when there is no obstacle



(b) LED is off when there is an obstacle

Photodiodes （光电二极管）

- Photodiodes generate a current or voltage when illuminated by light.
- Their working principle is the same as that of IR sensors
- The differences lie in the wavelength of the lights they sense.

Touch Sensors

- Working principle:
  - A force sensing resistor changes its resistance when it is pressed or bent.
  - When the button is pressed, the circuit is connected.

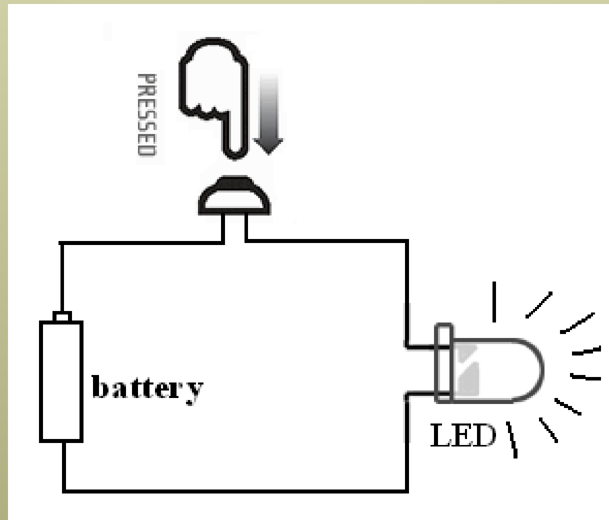
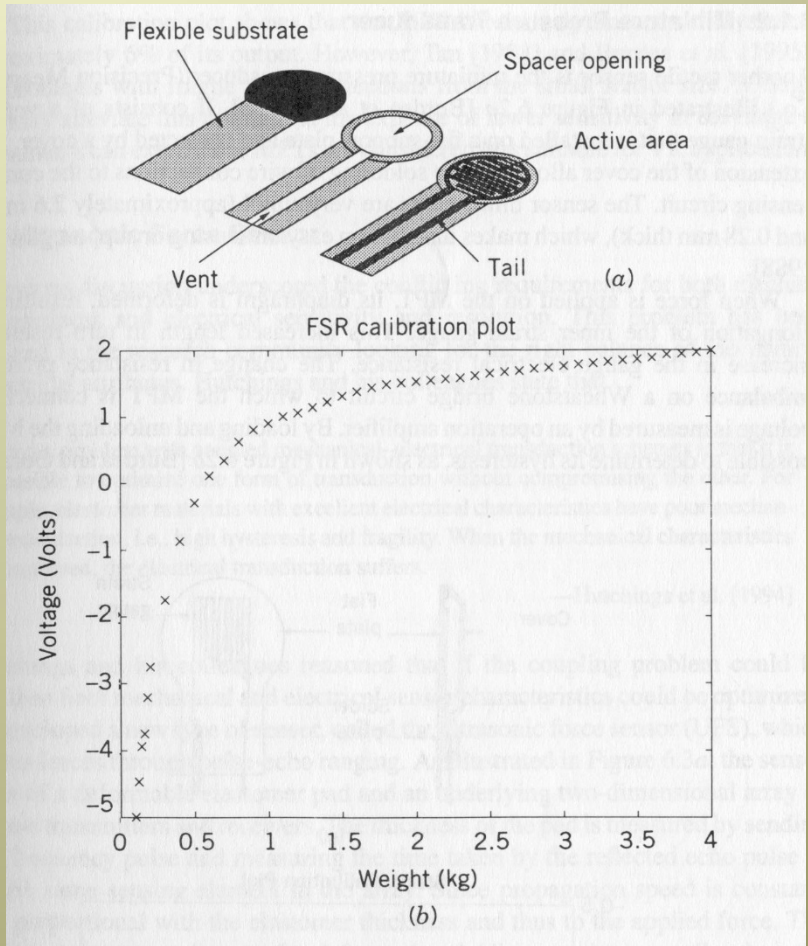


Figure. Working principle of touch sensors

Tactile Sensors（触觉）

- Force-Sensitive Resistor (FSR)
  - Principle: Change pressure force to resistance change
  - Structure: an active area, a spacer, and a flexible substrate



Self-learning Resources

- http://en.wikipedia.org/wiki/Infrared_detector
- http://robotics.ee.uwa.edu.au/courses/embedded/tutorials/tutorials/tutorial_8/Tutorial%208.htm
- http://www.societyofrobots.com/robot_tutorial.shtml#sensors
- http://www.sensorcentral.com/photoelectric/ultrasonic01.php
- http://www.sensorsmag.com/sensors/article/articleDetail.jsp?id=178903&pageID=1&sk=&date

Self-learning Resources

- http://ccrma.stanford.edu/CCRMA/Courses/252/sensors/node8.html
- http://sales.hamamatsu.com/assets/html/ssd/si-photodiode/index.htm
- http://www.andrew.cmu.edu/user/rjg/websensors/robot_sensors2.html

Robot Actuators

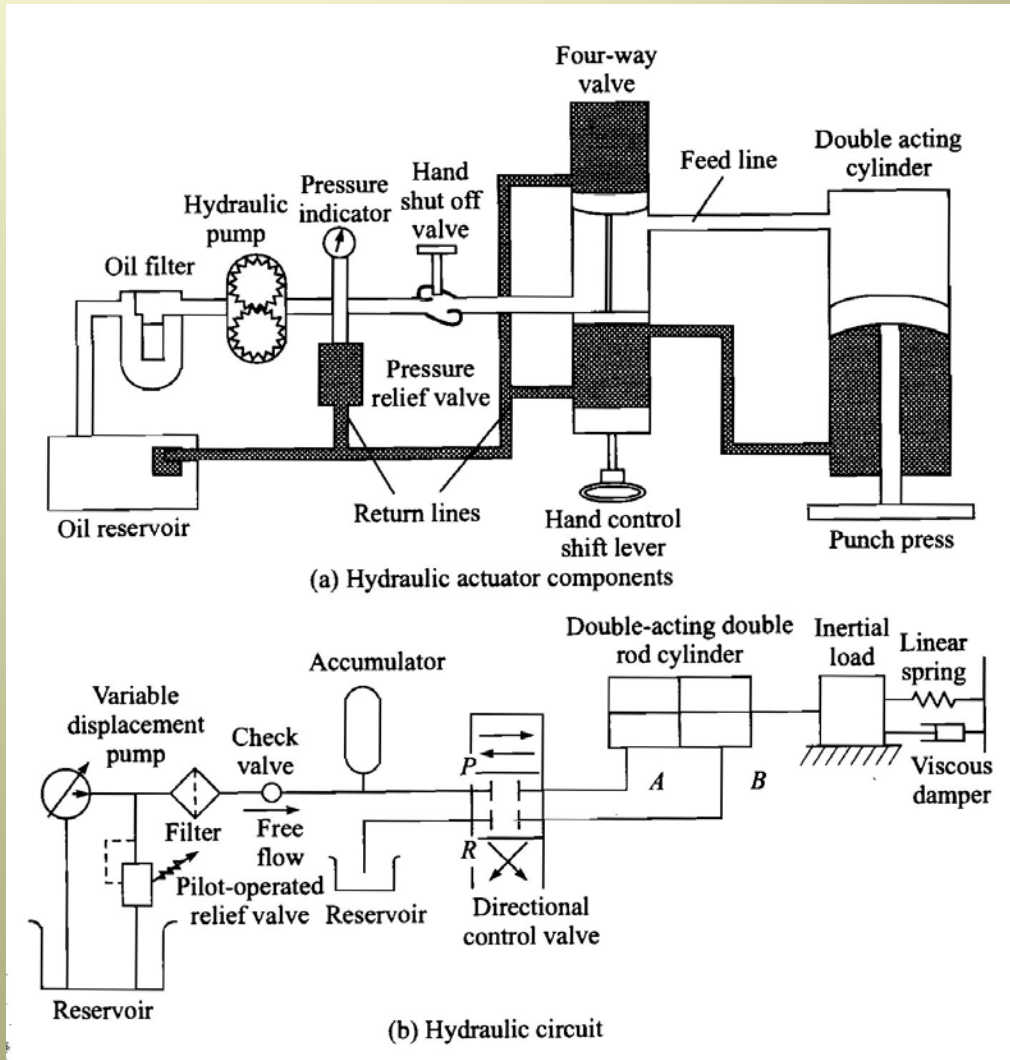
- Electrical actuators
- Hydraulic actuators
- Pneumatic actuators
- Others (SMA, heat, etc)

Hydraulic Actuation

- Drive robot joints by using the pressure of oils, water, etc.
- Advantages: High power output
- Disadvantage:
  - Difficult to control -->low accuracy
  - Slow response
  - Big size
  - Dirty
- Early robots used hydraulic actuation

Hydraulic Actuation

- Use liquid pressure to drive a cylinder
- Use valve to control the flow of the liquid.
- Can be modled as mass, spring, damper system

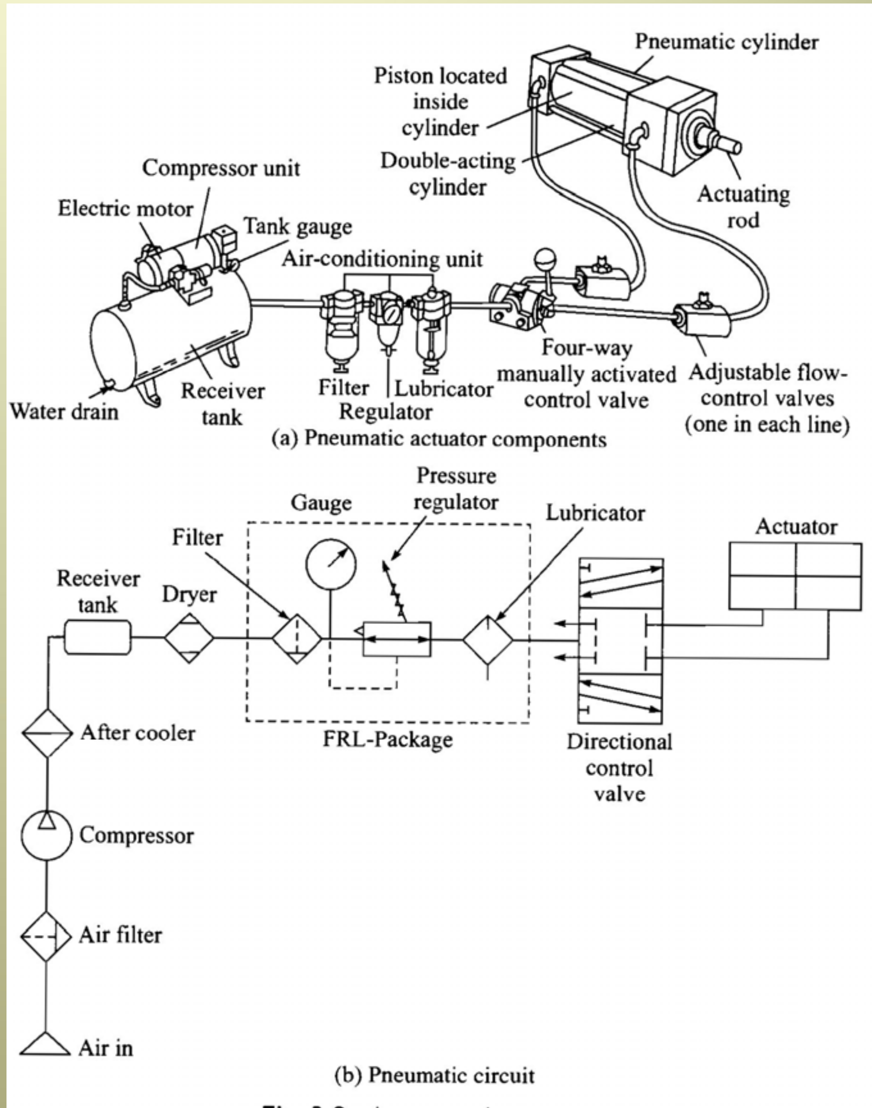


Pneumatic Actuation

- Drive robot joints by the pressure of air.
- Advantages:
  - clean and small.
  - cheap
- Disadvantage:
  - difficult to control position precisely
- Mainly used in opening control of robot grippers.

Pneumatic Actuation

- The structure is similar to that of hydraulic actuator
- Use air pressure to drive the pneumatic cylinder



Electrical Actuators

- Stepping motors, DC motors, AC motors and Servo motors
- Advantages:
  - small size
  - easy to control, high control accuracy
  - fast response
  - clean
- Disadvantages:
  - low power output compared to hydraulic actuators

Power/Weight Ratio

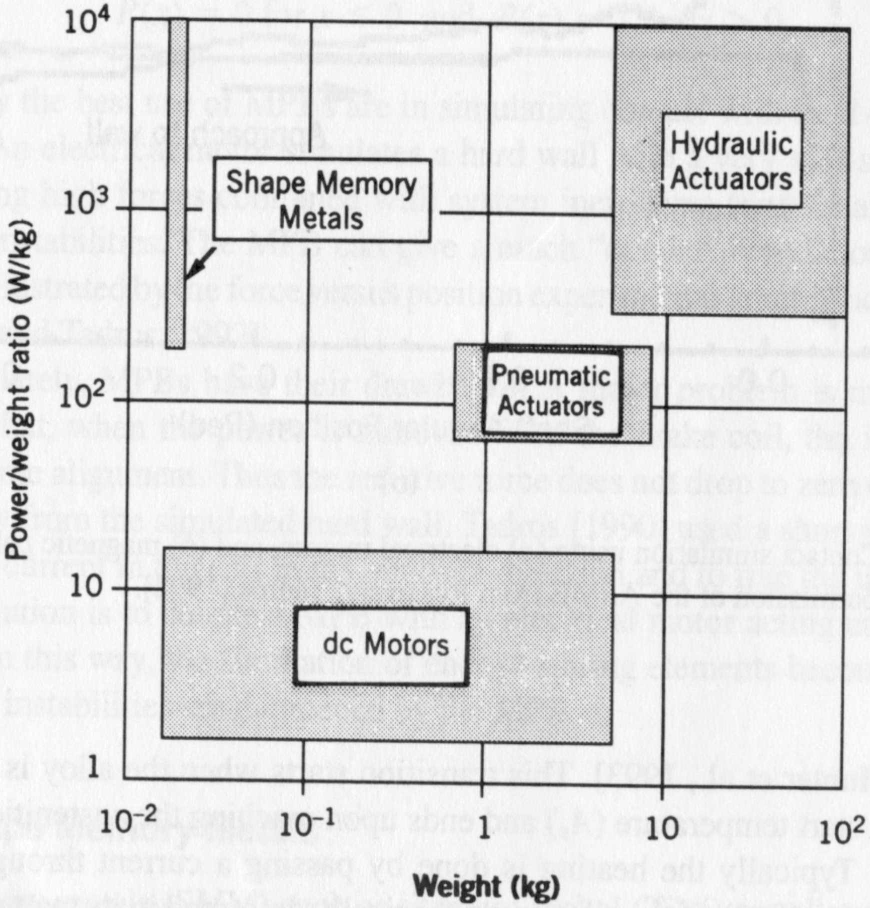
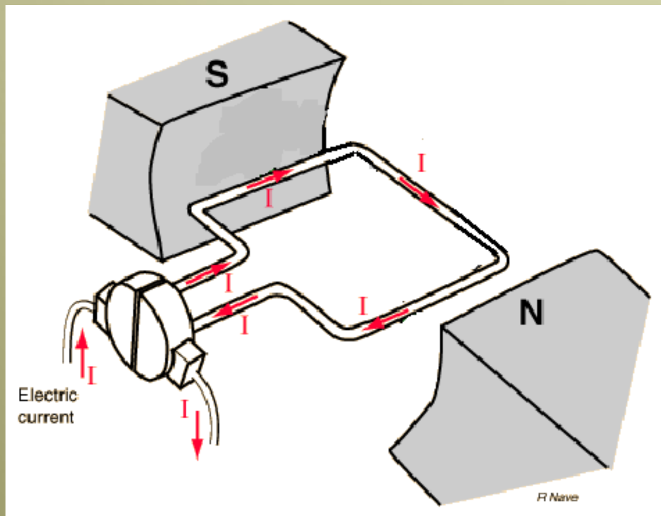
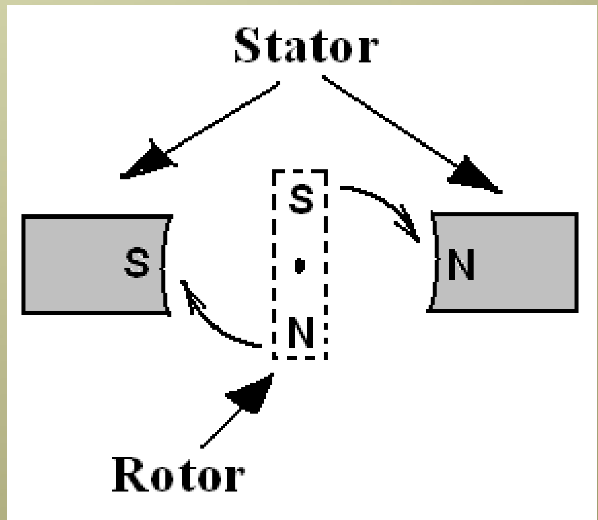


Figure 3.8 Shape memory metal (SMM) power density vs. other actuators. Adapted from Hirose et al. [1989] and Hollerbach et al. [1992]. Reprinted by permission of the MIT Press.

Introduction to Motors

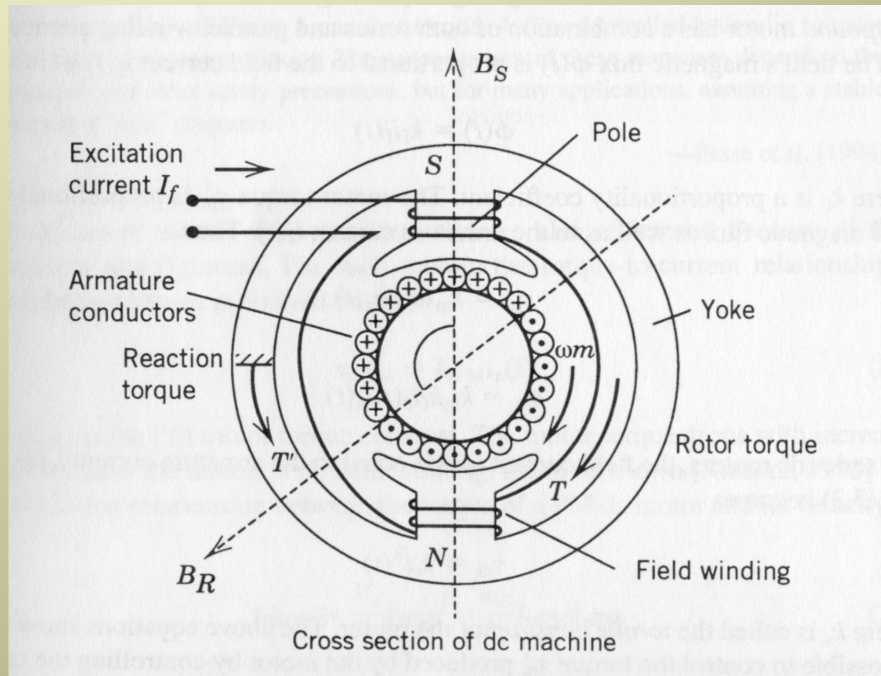
- Motors convert electrical energy to mechanical energy , i.e. rotation of motor shaft.
- The magnetic force turns the rotor of a motor.
- The speed of the motor can be controlled by changing the supplying voltage.





DC Motors

- Input: Direct current (DC) or voltage
- Field winding on the stator
- Armature winding on the rotator.
- By changing the excitation currents to control the rotational speed.

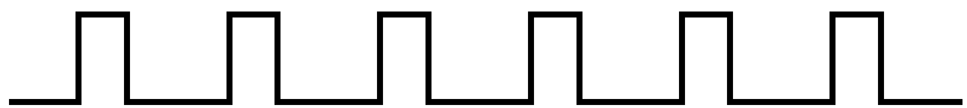


AC Motors

- Input: Continuous alternating current (AC) or voltage.
- Working principle: Similar to that of DC motors.

Stepping Motors

- A stepping motor converts electrical pulses into specific rotational movements.
  - Input: a pulse train
  - Output: rotation of the motor shaft. Output: rotation of the motor shaft.



The input pulse of a stepping motor

Working Principle of Stepping Motors

- Rotator is a permanent magnet
- Coils in the stator are turned on and off to rotate the stator

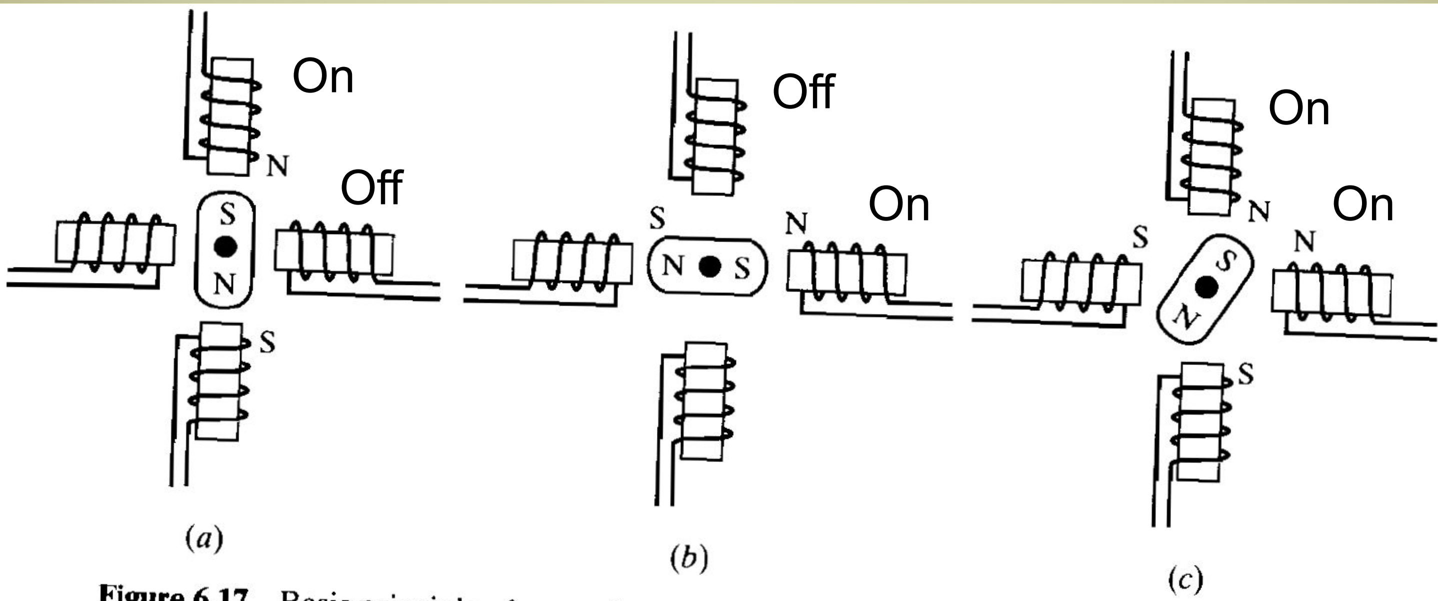
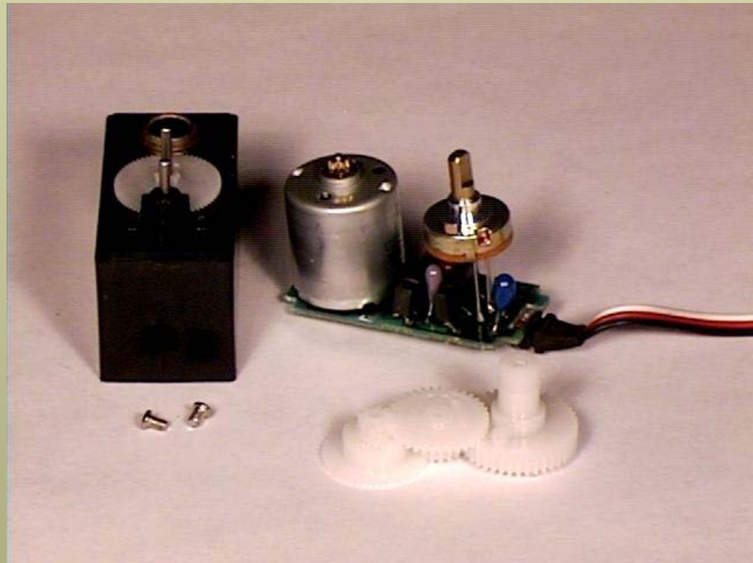


Figure 6.17 Basic principle of operation of a stepper motor. As the coils in the stator are turned on and off, the rotor will rotate to align itself with the magnetic field.

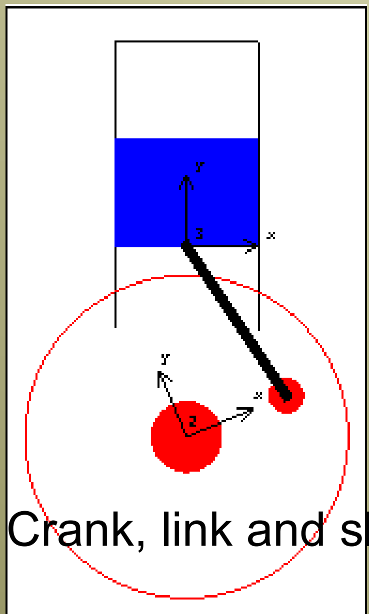
Servo Motors

- Servo motors: Can rotate the motor shaft to a specified angular position.
    - Input: coded signals
    - Output: a specific angular position.

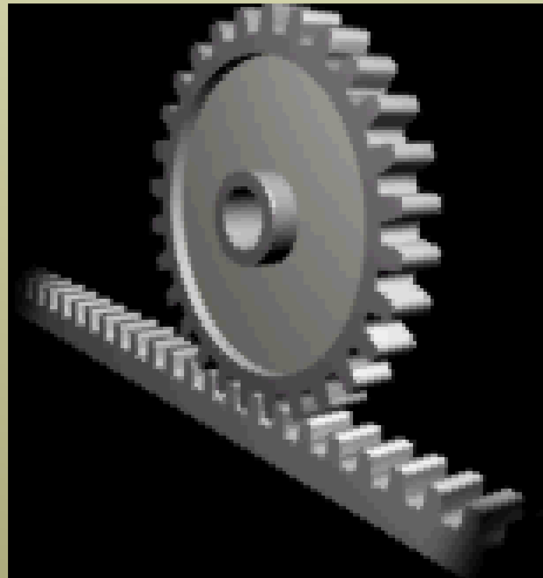


Motion Transmission

- Why do we need a motion transmission mechanism?
  - transfer motion from one type to another
  - Change direction
  - Change speed of motion
  - Deliver big force



Crank, link and slider

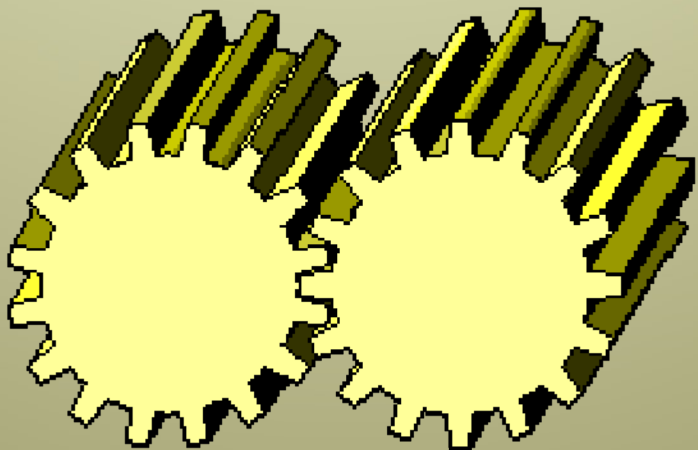


Rack and pinion

Gears

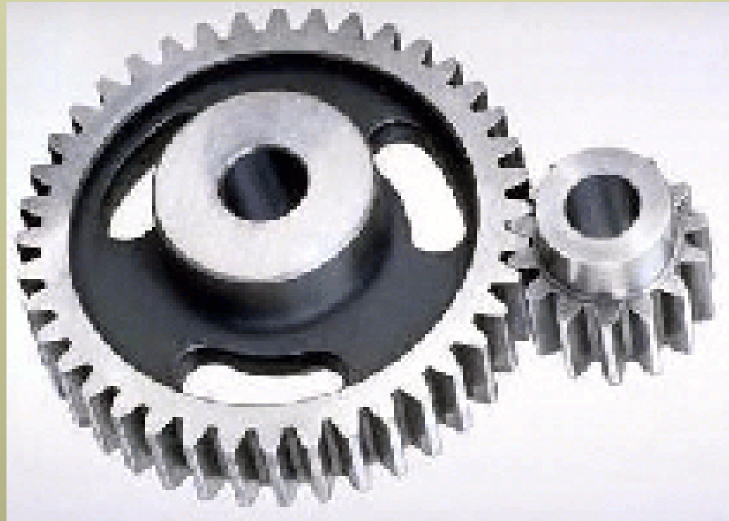
Motion Transmission

- Gears are most commonly used transmission devices in robots
- Gears are wheels with teeth.
- Gears are used to transfer motion or power from one moving part to another.



Motion Transmission with Gears

- Spur gears: Change speed of rotation. Spur gears are the most common type of gears. They connect parallel shafts.



Spur gear

Motion Transmission with Gears

- Pinion and worm gear: Change the rotation direction by 90 degrees; deliver big torque.

Worm gear

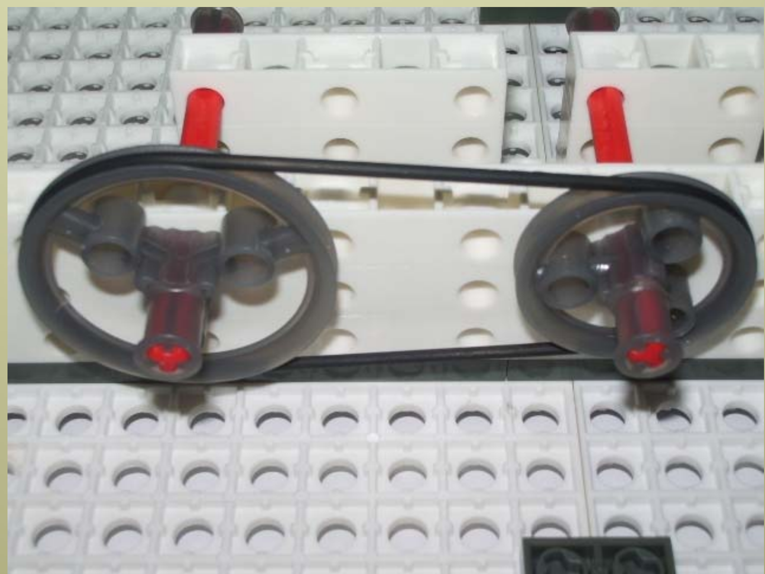
Motion Transmission with Gears

- Bevel gears: Change in the axes of rotation of the respective shafts, commonly 90°.

Bevel gear

Motion Transmission with Belt

- Belt drive: Enable the transmission of power between shafts by means of a belt connecting pulleys on the shafts. Belt drive is simple, quiet and economical.

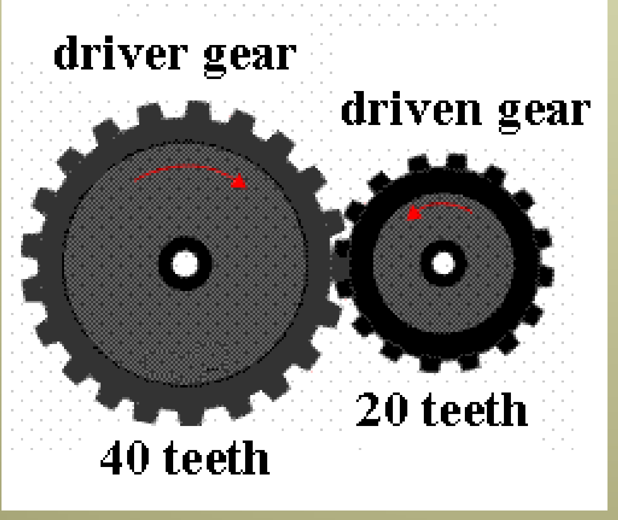


Belt drive

Gear Ratio

- Gear ratio (velocity ratio) is the ratio between the rotational speeds of the meshing gears.

$$Gear\,Ratio = \frac{number\,of\ teeth\,on\,driven\,gear}{number\,of\ teeth\,on\,driver\,gear} = \frac{Radius_{driven}}{Radius_{driver}}$$



$$gr = \frac{20}{40} = \frac{1}{2}$$

Rotation Speed vs Gear Ratio

- Relationship between rotation speed and gear ratio

$$\frac{speed_A}{speed_B} = gear\ ratio = \frac{Radius_B}{Radius_A}$$

- If the gear B is revolving at 200 rpm (revolutions per minute), the output speed of gear A is:

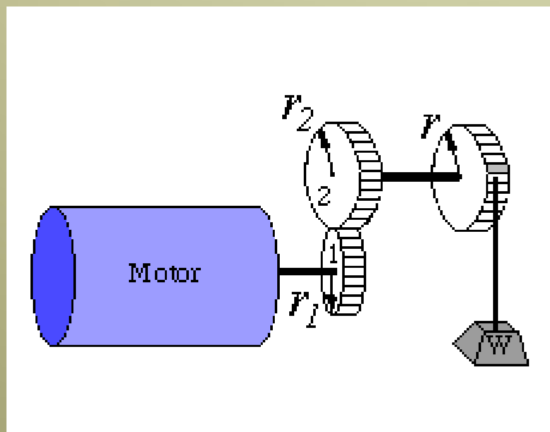
$$speed_A = \frac{Radius_B \times speed_B}{Radius_A} = 50\ rpm$$

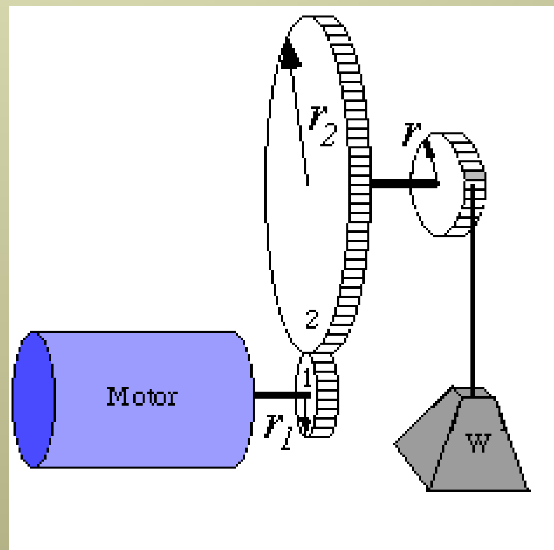
Torque vs Gear Ratio

- Relationship between torque and gear ratio

$$\frac{torque\_load}{torque\_motor} = gear\ ratio = \frac{Radius_2}{Radius_1}$$

  – For a motor with a larger gear ratio, it can lift larger object.

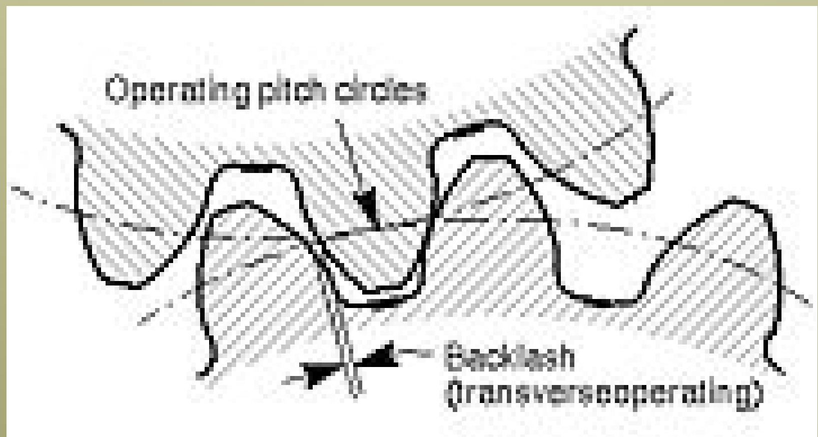




r, r_1, r_2 represent the radius of the corresponding gear

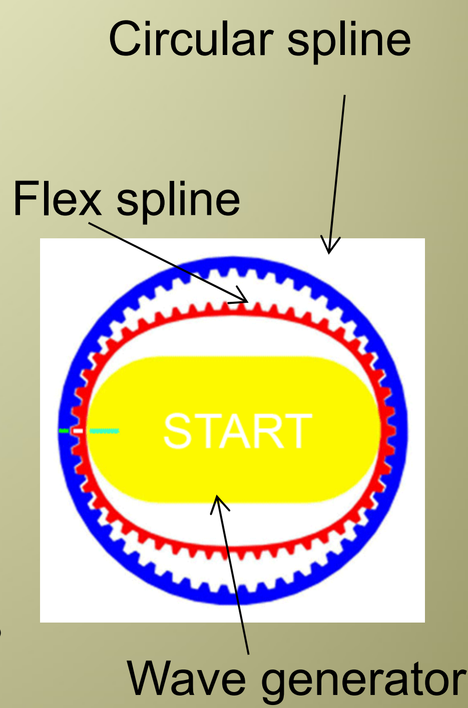
Problems with Gear Transmission

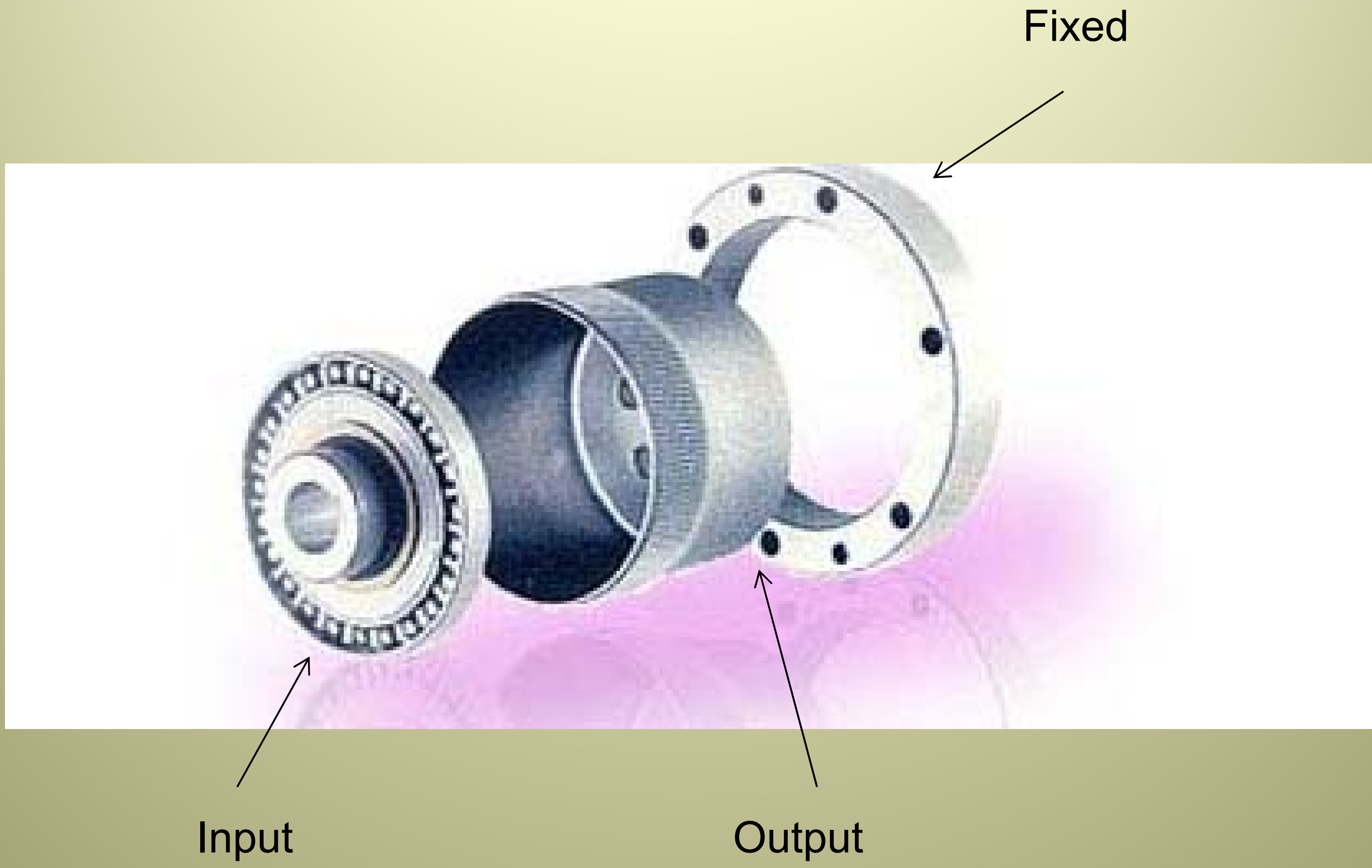
- Backlash
  - Since there exist a small gap, the power transmission will be lost for a very short period if the rotation is reversed
- Big system for big reduction ratio
- Input & output rotations are not coaxial



Harmonic Drive

- Components
  - A flex spline which can deform
  - A wave generator with a plug pushing the flex spline
  - A circular spline
- Design: There are fewer teeth on the flex spline than the circular spline
- Working principle
  - As wave generator plug rotates, the plug deforms the spline flex and the flex spline teeth which are meshed with those of the circular spline change.
  - The difference in teeth will make the circular spline rotate by the angle corresponding to the difference of the teeth in the inverse direction




Fixed
Input
Output

Harmonic Drive

- Reduction ratio:

  (flex spline teeth - circular spline teeth) /flex spline teeth
- Advantages:
  - Zero backlash
  - High reduction ratio with single stage
  - Compact & light weight
  - High torque compaibility
  - Co-axial input & output shaft