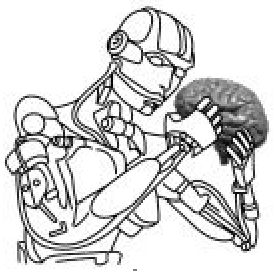
CS 545 Lecture II
Actuators and Sensors

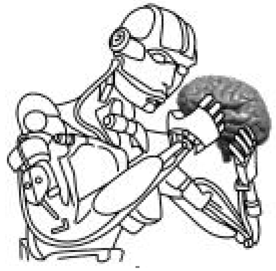
http://robotics.usc.edu/~aatrash/cs545

Actuators and Sensors



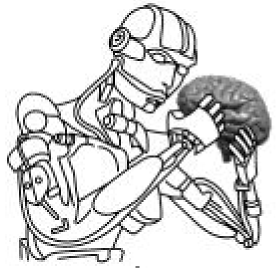
- Actuators
  - Servomotors
  - Transmission
  - Power
- Sensors
  - Proprioceptive
  - Exteroceptive
- Signal Processing

Actuators



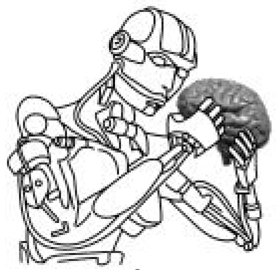
- Pneumatic - compressed air
  - Compressor transforms pneumatic energy into mechanic energy
  - Pistons, turbines
- Hydraulic – compressed liquid
  - Converts hydraulic energy into mechanic energy
- Electric – uses electricity

Desired Properties



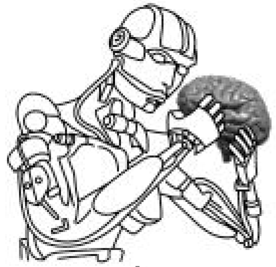
- Low inertia
- High power-to-weight ratio
- High acceleration
- Robust to overload
- Wide velocity range (1 to 1000 revolutions/min)
- Position accuracy (1/1000 of a circle)
- Smooth motion (torque ripples, friction, stiction)

Pneumatic Motors



- Good
  - Light weight
  - Clean
  - Compliant
- Bad
  - Position error due to compression
  - Requires compressor
  - Not strong
- Not used as often as other motors

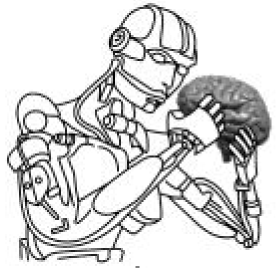
Hydraulic Motors

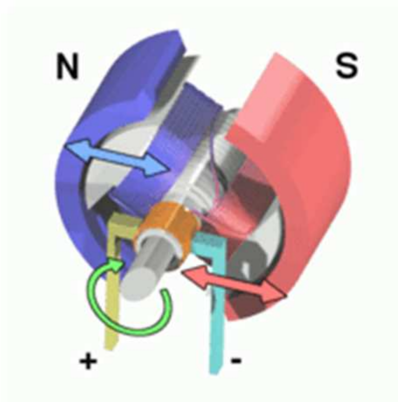


- Good
  - Light
  - Robust to burnout
  - Fewer problems with heat/lubrication
  - Very strong
  - Low speed/high torque
- Bad
  - Requires heavy off-board pump
  - Messy (pollution)
  - Expensive
  - Difficult to miniaturize
  - Can be susceptible to temperature of fluid
- Used in domains with heavy load

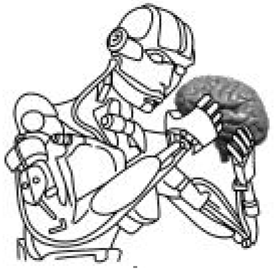
Electric motors

- Good
  - High speed/low torque
  - Cheap
  - Readily available
  - Small
  - Electricity everywhere
  - More predictable
- Bad
  - Heavy
  - Requires amplifier
  - Problems with burnout
- Used in small/mid-size applications
- Brushed/Brushless motors



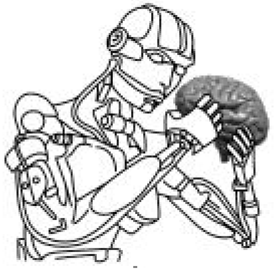


Servo Motors



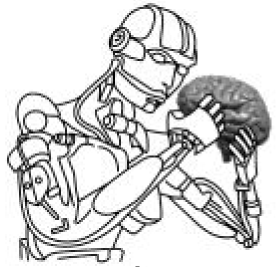
- Need to move motor to specific position
- Servo motors are adapted DC motors
  - Gear reduction
  - Position sensor (potentiometer)
  - Electronic controller
- Range usually 180+ degrees

Transmission



- May not always be able to place motor **at** joint
- Move power from the motor to joint

Transmission Types

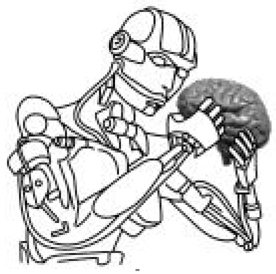


- Spur Gears – basic gear
  - Dish/cylinder with teeth
  - Allows power conversion through ratio of gears

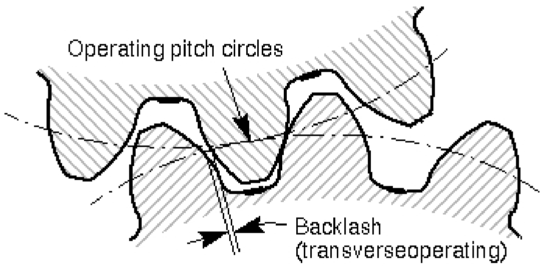
- Lead Screws
  - Used for prismatic joints

- Belts/Chains/Pulleys
  - Locate the motor remotely from the joint
- Direct Drive

Transmission Properties

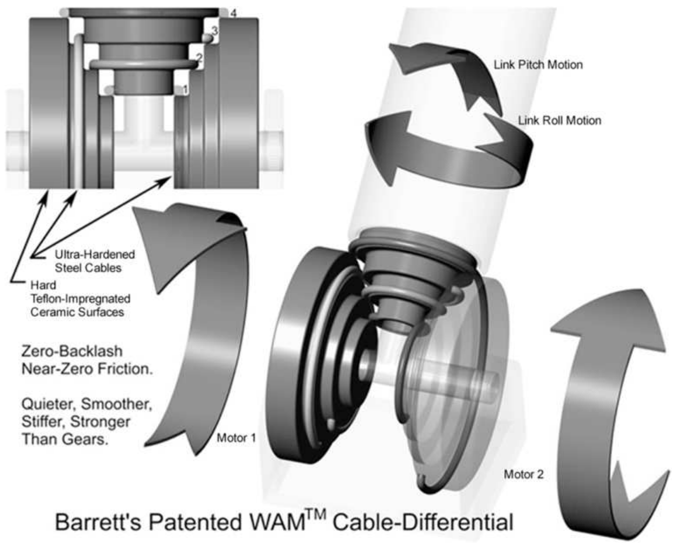


- Allows for conversion of output
  - Velocity and torque through gearing
    - Power = Speed * Torque
  - Convert rotational into translational
  - Differential gears
- Backlash – spacing between contacts
  - Room for lubrication (oil), error in manufacturing, deflection from load, thermal expansion

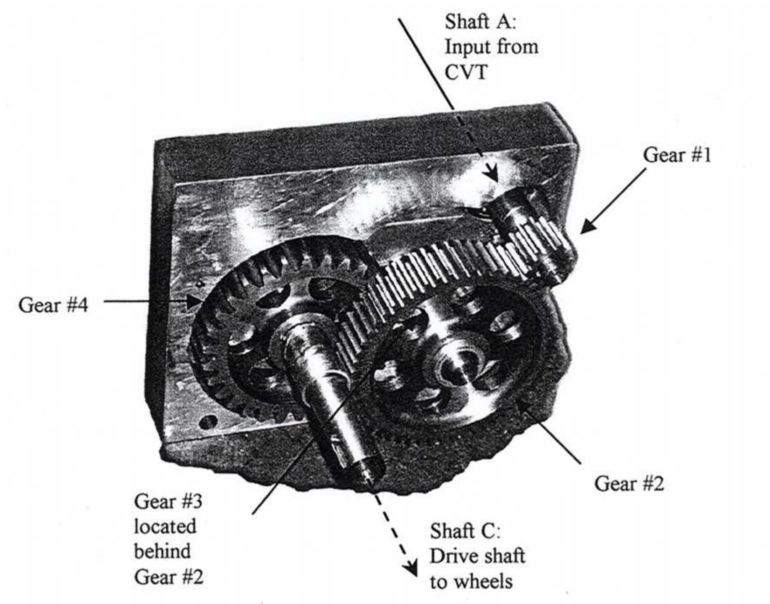


- Properties
  - Impact of backlash
  - Impact of friction
  - Backdrivable (moving motor moves input)
  - Transmission ratios up to 1:300 or more

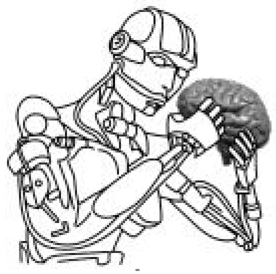
Gears



Barrett's Patented WAM^{TM} Cable-Differential



Gear Fundamentals

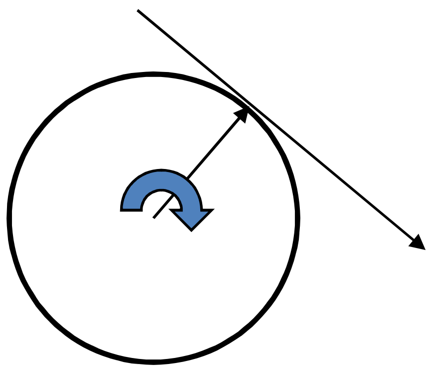


- The force F at the edge of a gear of radius r is given by:

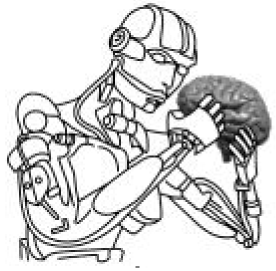
$$F = t / r$$

- The linear speed v at the edge of a gear of radius r is given by:

$$v = \omega r$$

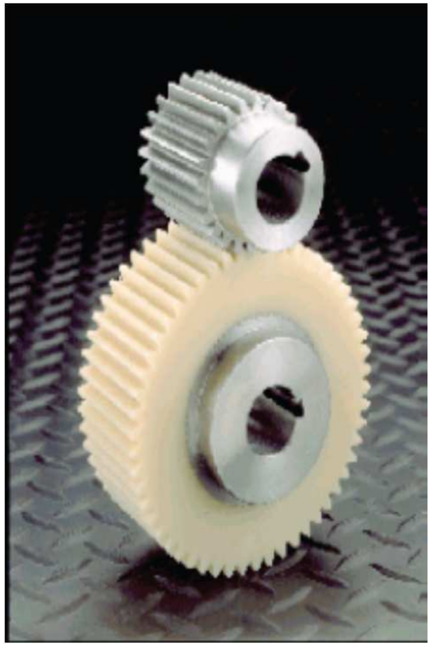


Combining Gears

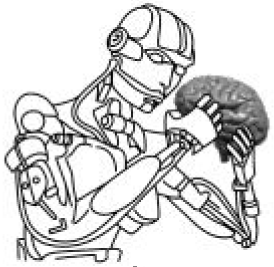


Given ω_1 , what is ω_2 ?

Given t_1 , what is t_2 ?

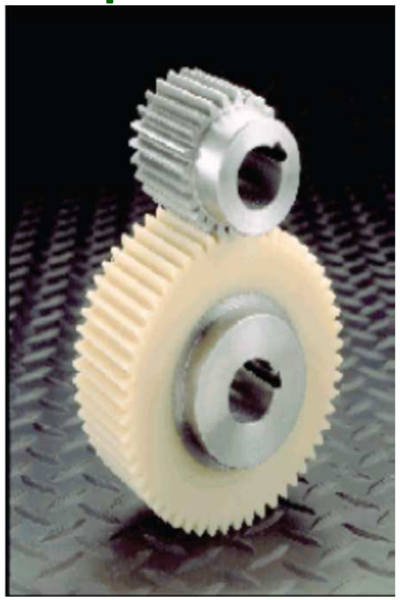


Combining Gears



- Meshing gears have equal linear speeds:

$$v_1 = v_2$$



- Thus the output speed is:

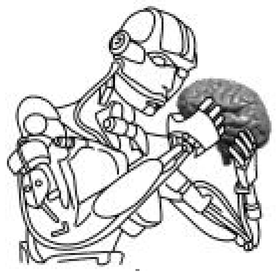
$$\omega_2 = (r_1 / r_2)\ \omega_1$$

- And the output torque is:

$$t_2 = (r_2 / r_1)\ t_1$$

- r_2 / r_1 is known as the *gear ratio*

Examples



- Gearing down:

$$r_1 = 1, r_2 = 2$$

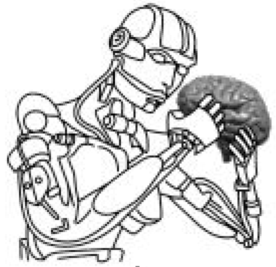
- 2:1 gear ratio doubles the torque and halves speed

- Gearing up:

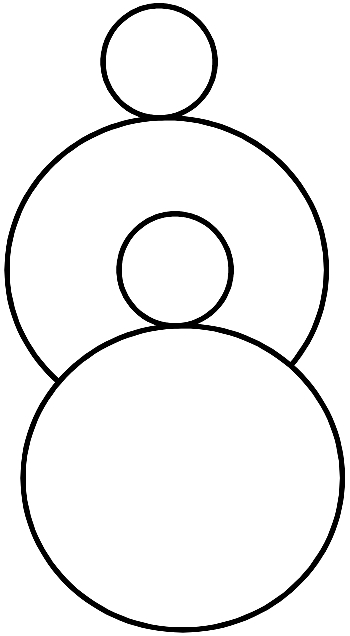
$$r_1 = 2, r_2 = 1$$

- 1:2 gear ratio halves torque and doubles speed

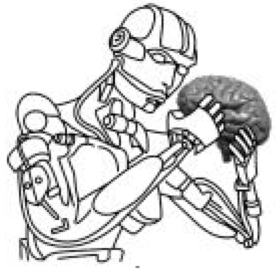
Gear Stages



- Usually it is not possible to achieve sufficient a gear ratio with a single pair of gears
- Gears can be arranged *in stages*
- The total gear ratio is the product of gear ratios for each stage
  - E.g.: 4:1 x 4:1 = 16:1

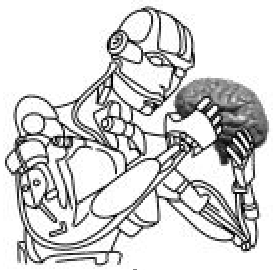


Power

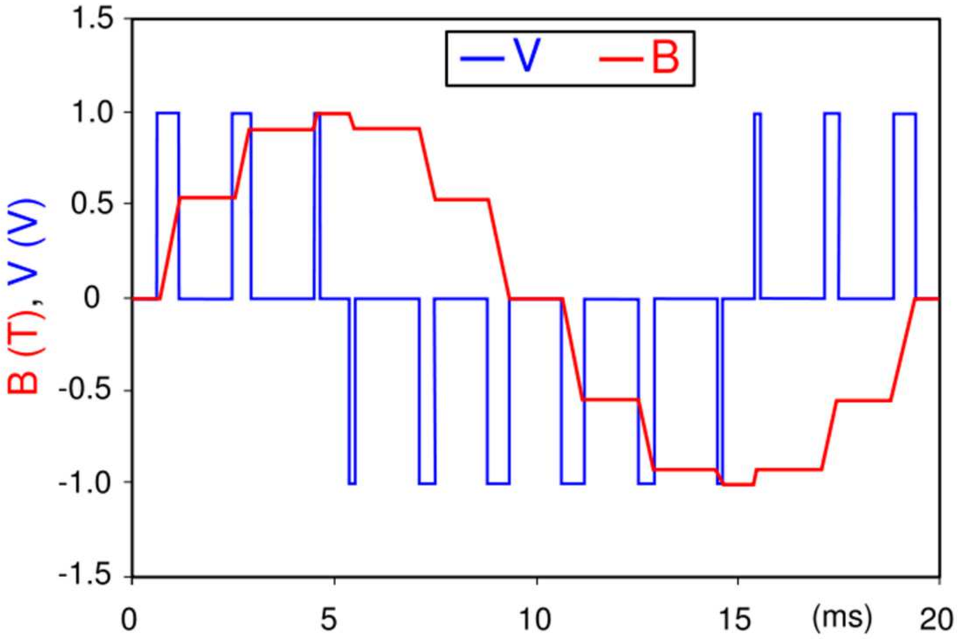


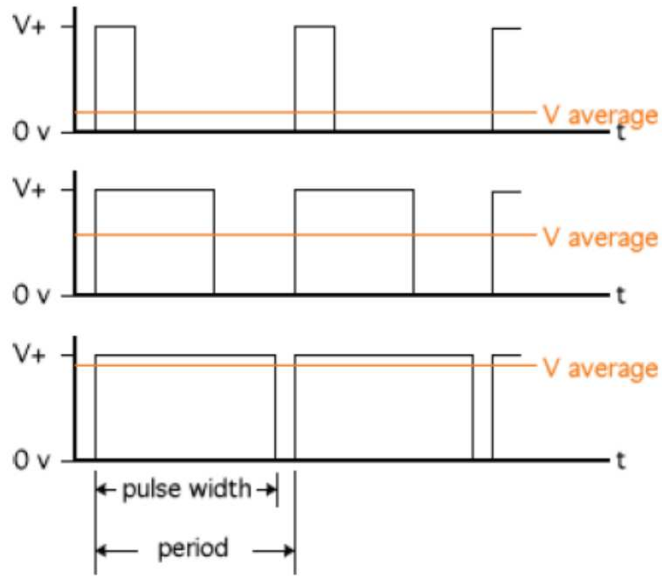
- Power Supplies
  - Electric
    - Transformer
  - Hydraulic/Pneumatic
    - Gear or piston pump compresses medium
    - High pressures
- Power Amplifier
  - Regulars amount of power provided by power supply
  - Electric
    - Usually current control
    - Pulse Width Modulation
  - Hydraulic/Pneumatic
    - Electro-hydraulic (pneumatic) valves

Pulse Width Modulation

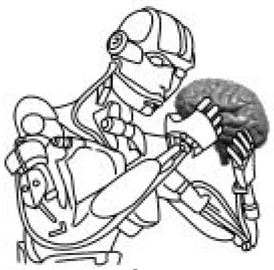


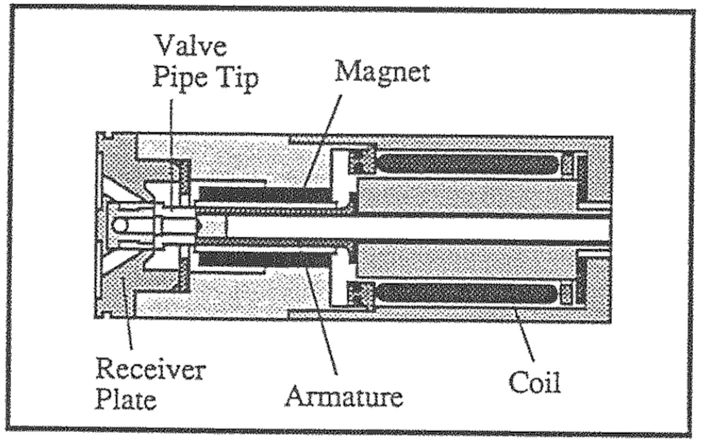
- Control analog device with digital controller
- Apply digital signal with varying frequency to generate analog signal
- 9V battery, 50 ms, 10 HZ = 4.5 V battery



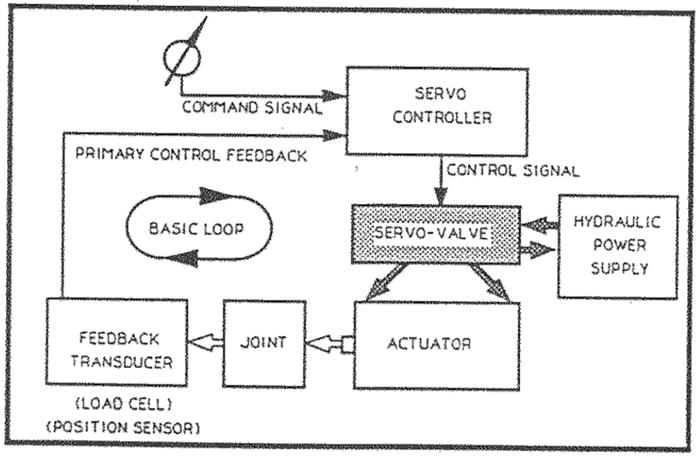


Hydraulic Valves





Cut away view

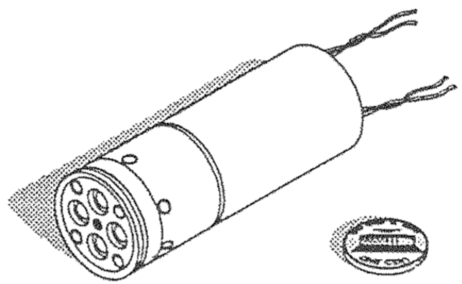


Specifications

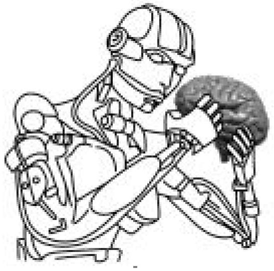
Supply Pressure	0-3000 psi
Size	2.16 cu. in.
Weight	4.96 oz.
Rated Flow	
No load	2.0 gpm @ 3000 psi
Max. internal leakage	
at null	0.2 gpm @ 3000 psi
Rated Current	± 1 amp
Coil Resistance	8 Ω
Electrical Connection	2 wire cable
Working Fluid	Industrial grade hydraulic oil

Manifolding Options:

1) Stand alone unit
2) Mounted to manifold plate
3) As part of integrated actuator

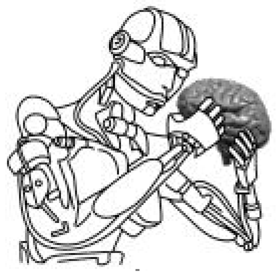


Sensors



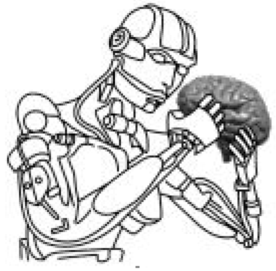
- Types
  - Proprioceptive (internal state)
    - Position, joint angles
    - Velocity
    - Acceleration
  - Exteroceptive (external state)
    - Force
    - Tactile
    - Proximity, range
    - Vision
  - Application specific (sound, humidity, smoke, temperature)
  - Passive (receive energy)
    - Vision, audio
  - Active (emit energy)
    - Sonar, ladar, structured light
- Goal: Extract information characterizing interaction of robot with objects in environment
- Robot as intelligent connection between perception and action

Examples of sensors



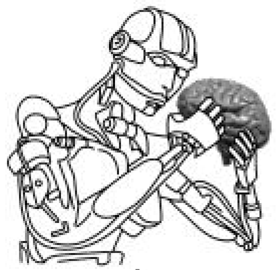
- light level -> photo cells, cameras
- sound level -> microphones
- strain -> strain gauges
- rotation -> encoders
- temperature -> thermometer
- gravity -> inclinometers
- acceleration -> accelerometers
- acceleration -> rate gyroscopes

Levels of Processing



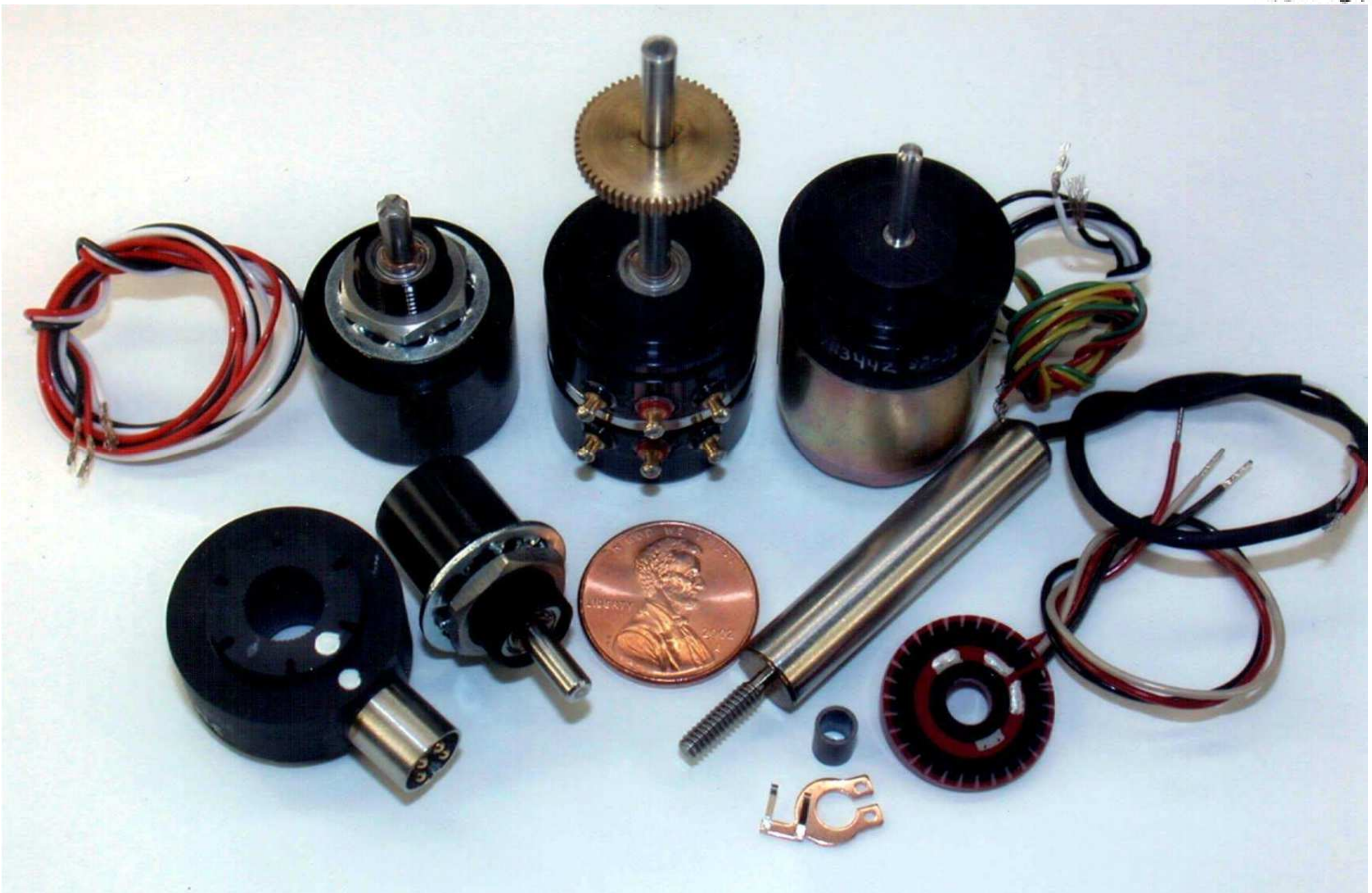
- Determine position of switch from voltage in circuit => electronics
- Using a microphone, separate voice from noise => signal processing
- Using a camera, find people in the image and recognize “persons of interest” => computation

Potentiometer

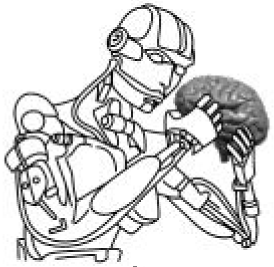


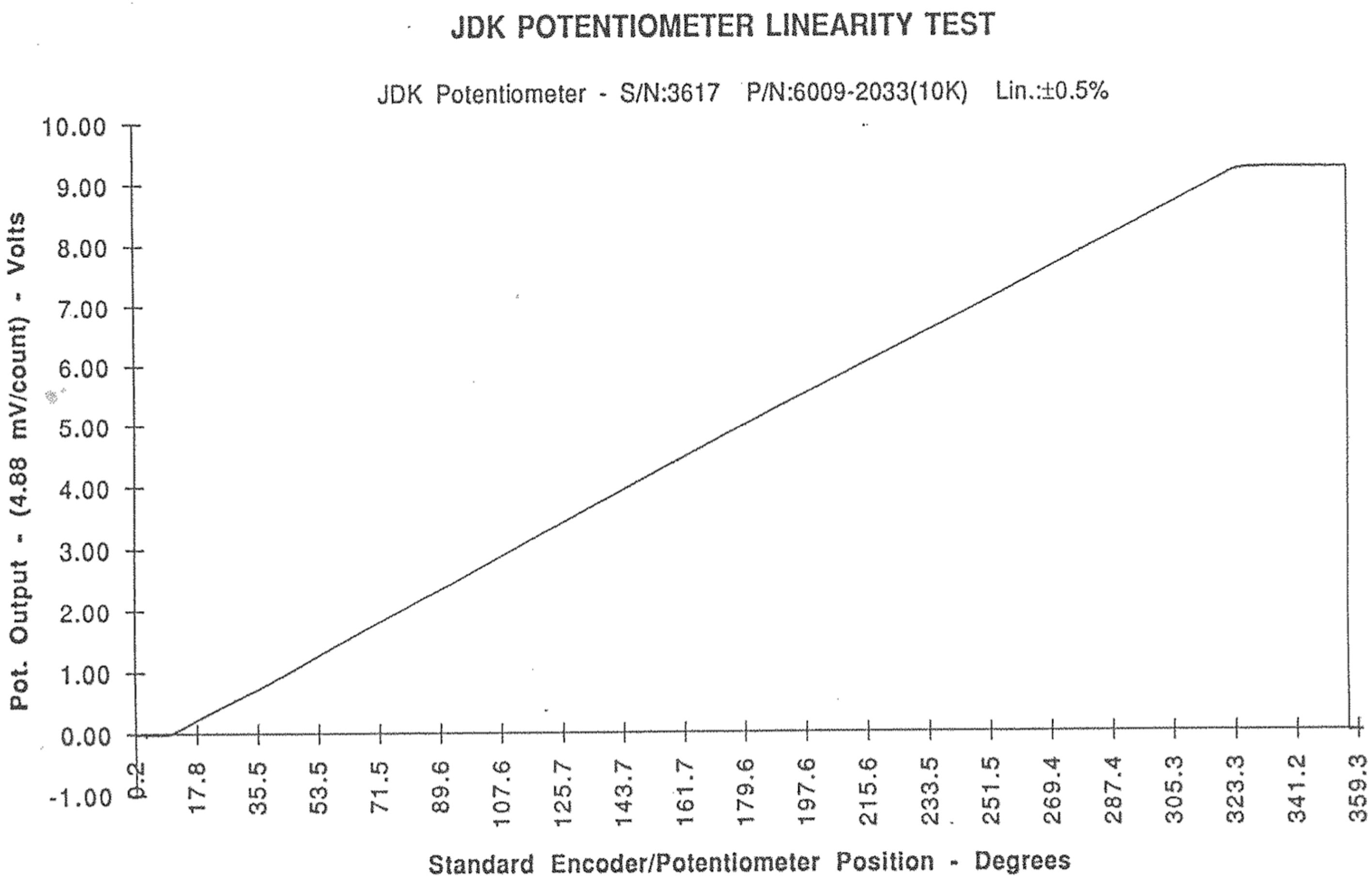
- Output voltage based on rotation
- Good
  - Cheap
  - Small
  - Linear and rotary version
  - Absolute values (continuous)
- Cons
  - Noisy
  - Mechanical interaction (siphons power)
  - Requires analog to digital conversion
  - Medium resolution (12-16 bit)

Potentiometer

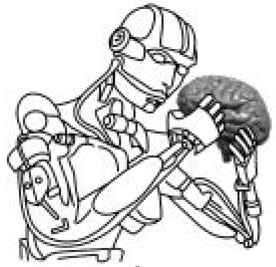


Potentiometer

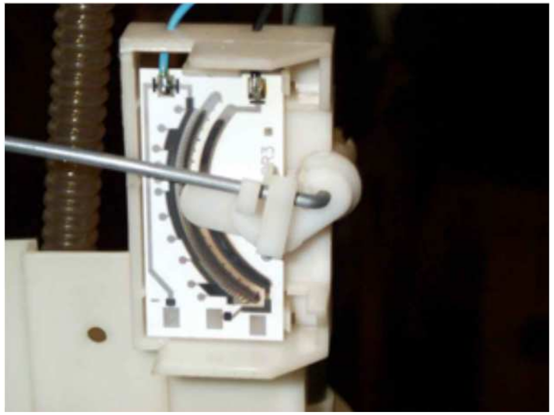




Potentiometer Uses

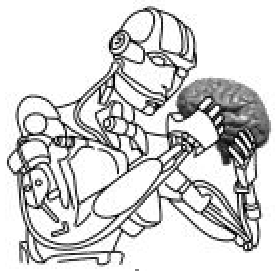


- Position:
  - Joint angle
  - Shaft angle
  - Linear travel



- Proximity:
  - Spring-loaded “whiskers”

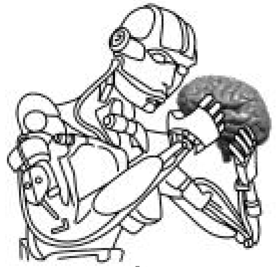
Encoders



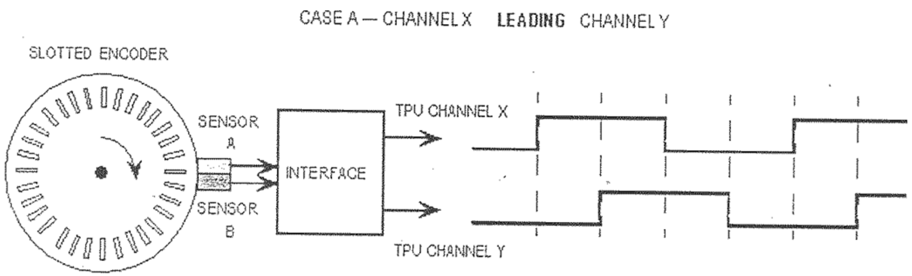
- Count rotations
- Good
  - High resolution (expensive)
  - Low resolution (cheap)
  - Very clean data
  - No A/D conversion
- Bad
  - Expensive or low resolution
  - Bulky
  - Special hardware needed for counting (Quadrature Board)
  - Usual incremental (not absolute. i.e. Continuous)

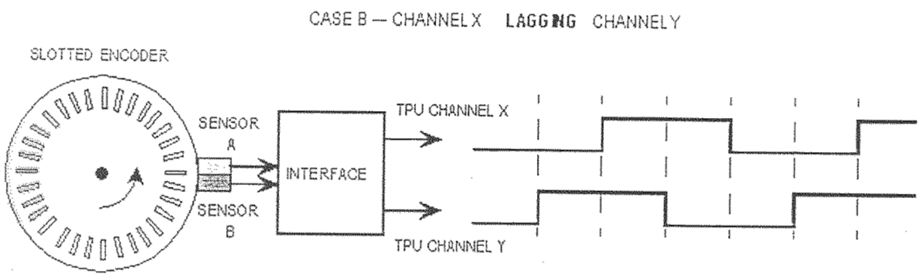
Optical Encoder Examples

Quadrature

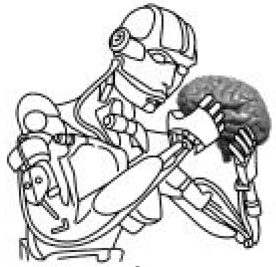


- Required to keep count





Absolute vs. Incremental Encoder



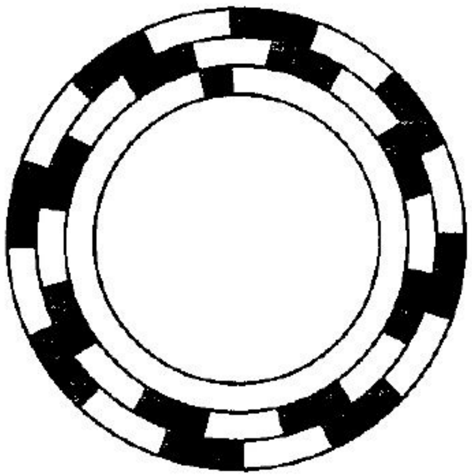
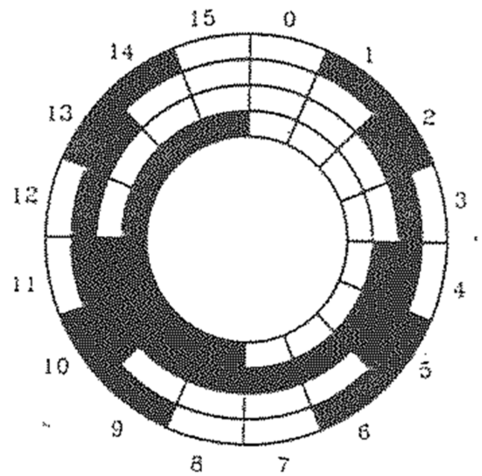


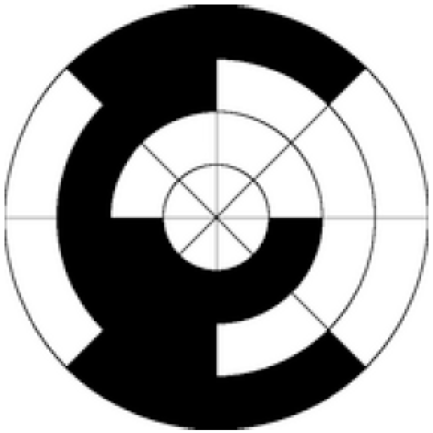
FIGURE 8.8
Schematic representation of an incremental encoder.



#
0
1
2
3
4
5
6
7

FIGURE 8.7
Schematic representation of an absolute encoder with Gray-code table.

Digital Position Encoder



3-Bit binary code disc

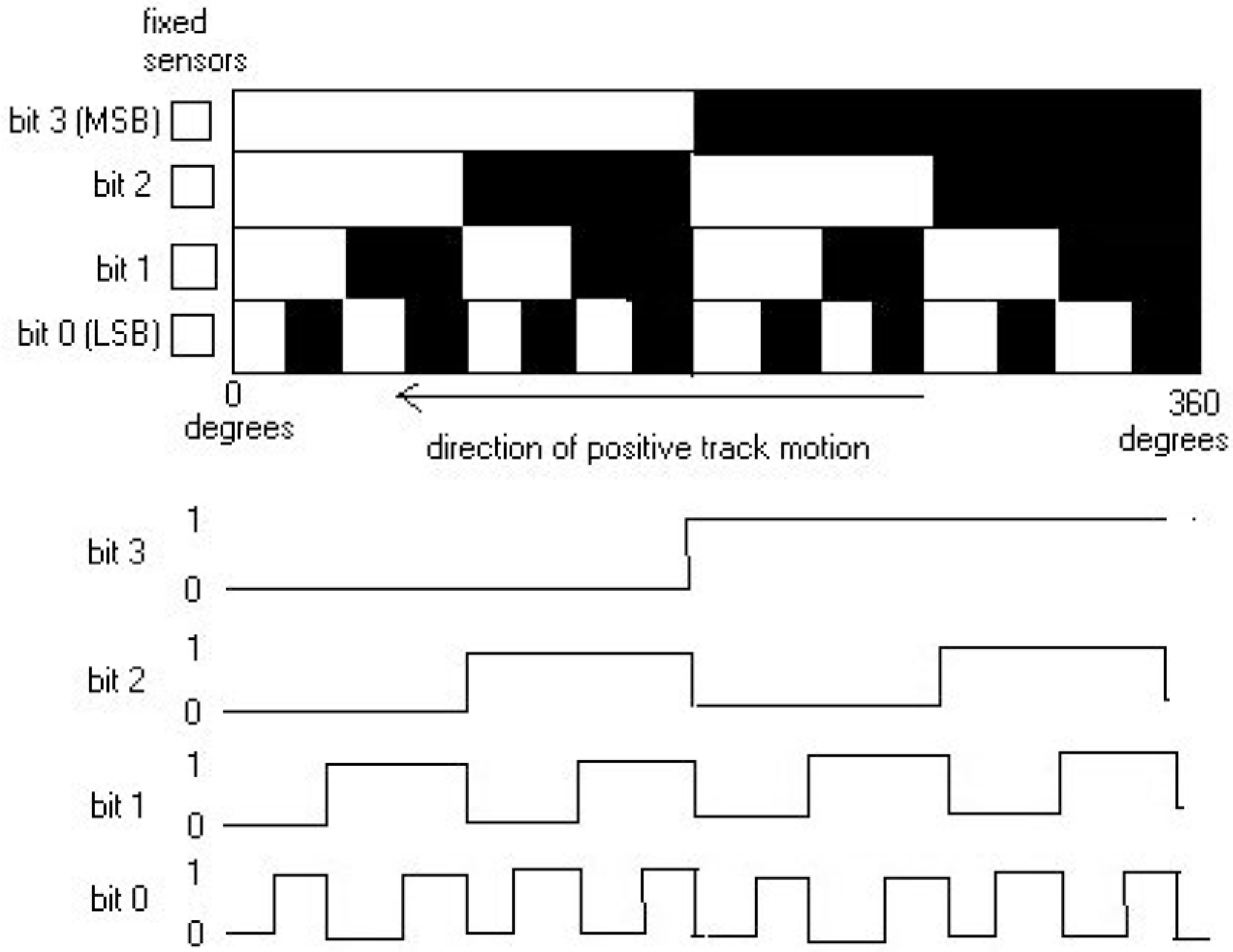
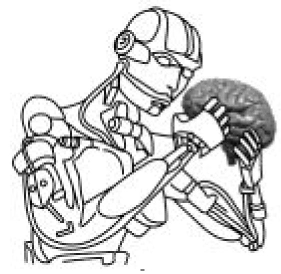


Fig 3 4-Bit binary code absolute encoder disk track patterns

Velocity Encoders

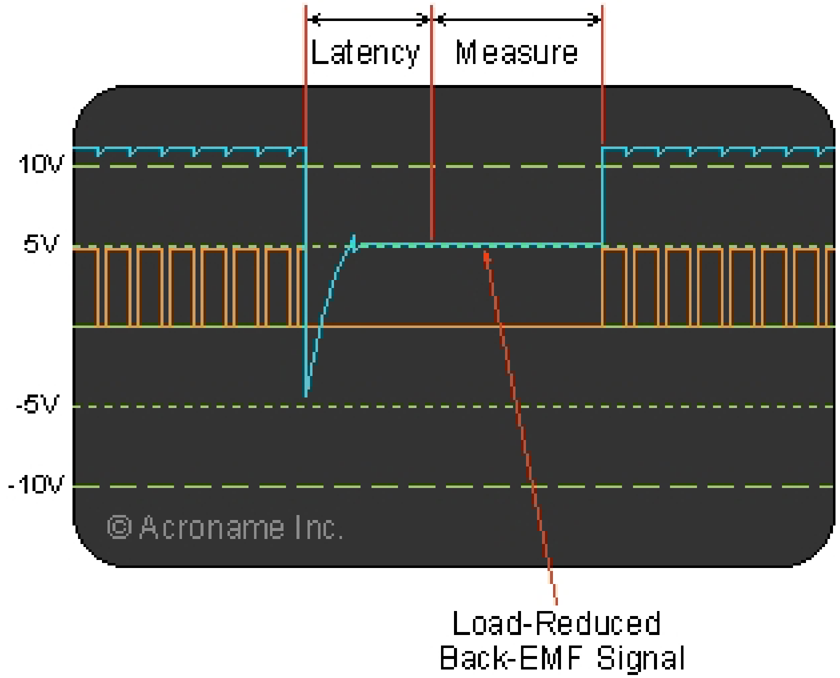
- Analog velocity encoders:
  - Electrical: back-EMF
- Digital velocity encoders:
  - Optical: optosensor + coded disk

Back-EMF



- idea: rotating motor yields induced voltage (dynamo effect)

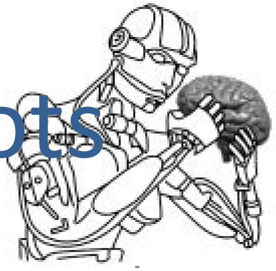
- spin the motor (e.g., PWM), then stop applying driving current for a short while, and measure voltage. Can then infer speed.



75% Duty Cycle with High Load Simulated Scope

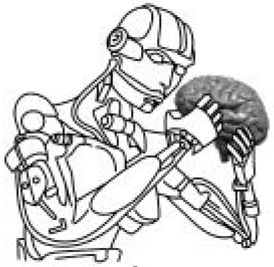
http://www.acroname.com/robotics/info/articles/back-emf/back-emf.html

Odometry for Wheeled Robots



- Common application: odometry for wheeled robots
- Integrate velocities from each wheel through kinematic model
- Estimate robot position (x, y) and orientation θ
- More details later

Force Sensors



- Strain gauge
  - Wire which changes resistance when deformed
  - Measured using Wheat-Stone bridge

568 · *Sensors, Measurement and Perception*

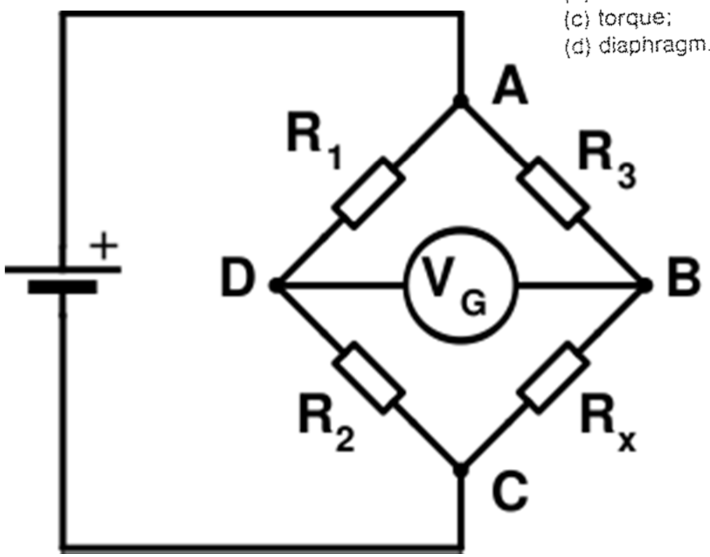
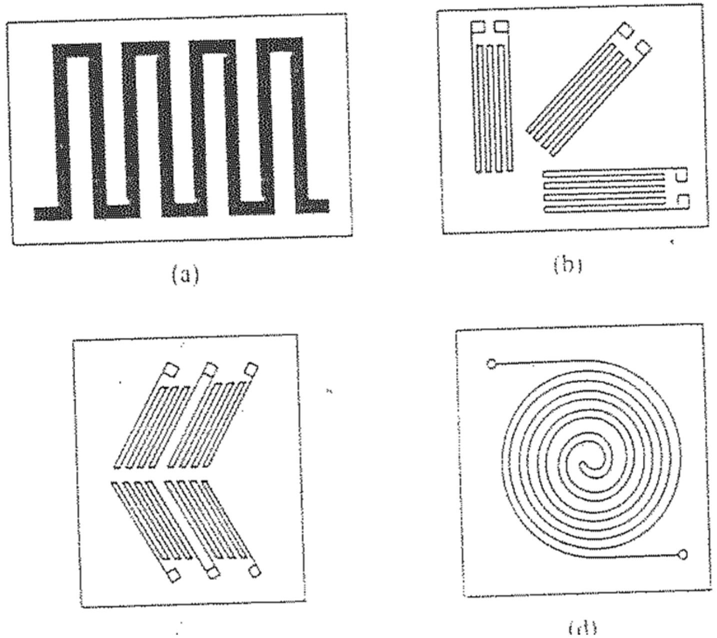
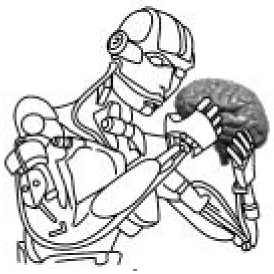


Figure 10.16
Standard patterns for metal foil strain gauges.
(a) Linear;
(b) rosette;
(c) torque;
(d) diaphragm.

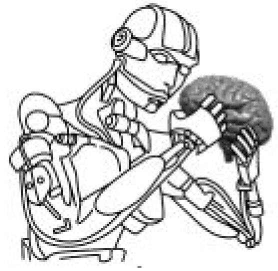


Force Sensors



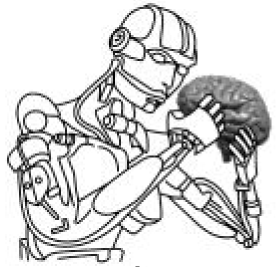
- Properties
  - Noisy
  - Requires special hardware (material that "stretches")
  - Requires careful mounting techniques
  - Multiple strains needed to make sensor resistant to noise and temperature (see previous layouts)

Range Sensors

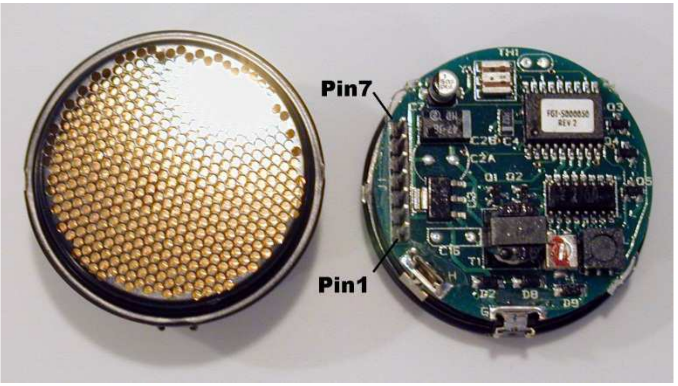


- Measures distance to object in a direction
- Used for obstacle avoidance, mapping and localization, object recognition

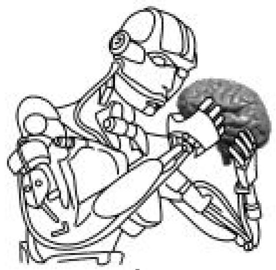
Sonar



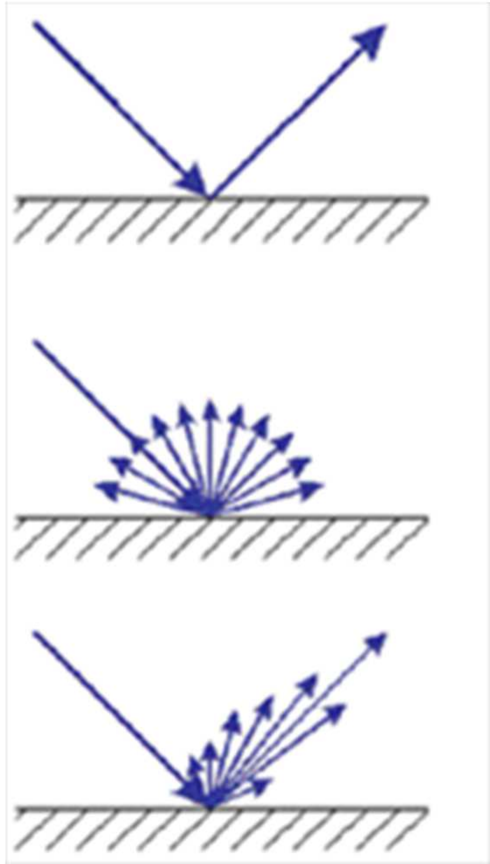
- **SO**und **NA**vigation and **R**anging
- Measure time of flight of acoustic wave
- Mobile and aquatic robots
- Low cost, light, low power, low computation
  - Sometimes only viable option (small robots)
- Very noisy
  - Several failure situations



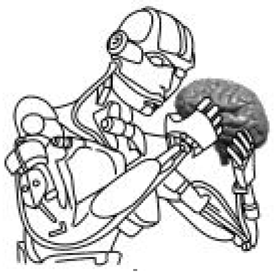
Specularity v. Diffusion

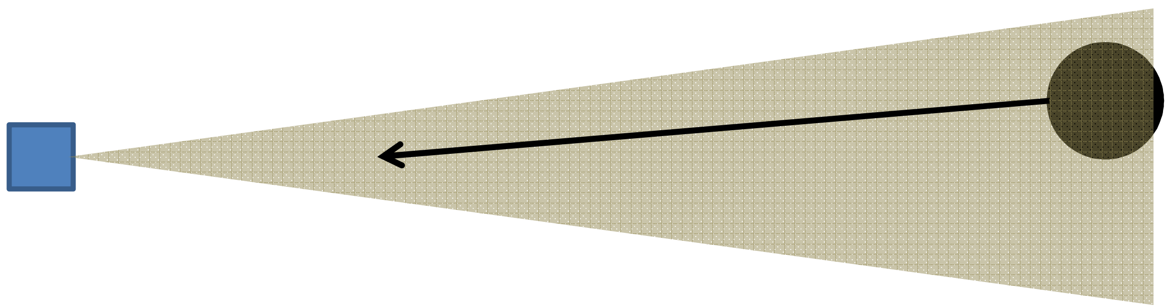


- Surfaces generate two forms of reflection:
  - Specular: angle of incidence = angle of reflection
  - Diffuse: energy absorbed and re-emitted at a broad range of angles
- Specular reflections are strong, but unlikely to return to detector
- Diffuse reflections are weak, but likely to return to detector

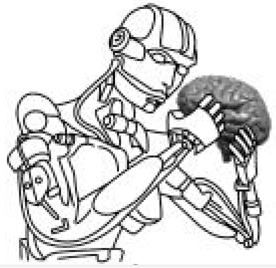


Sonar



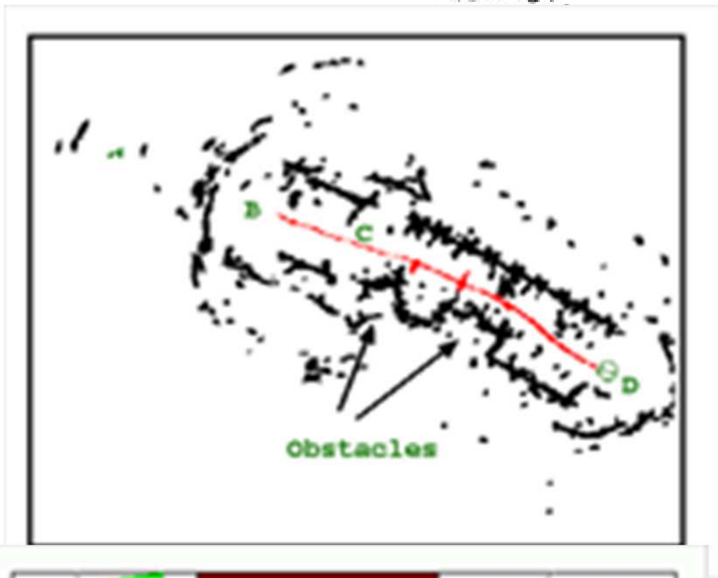


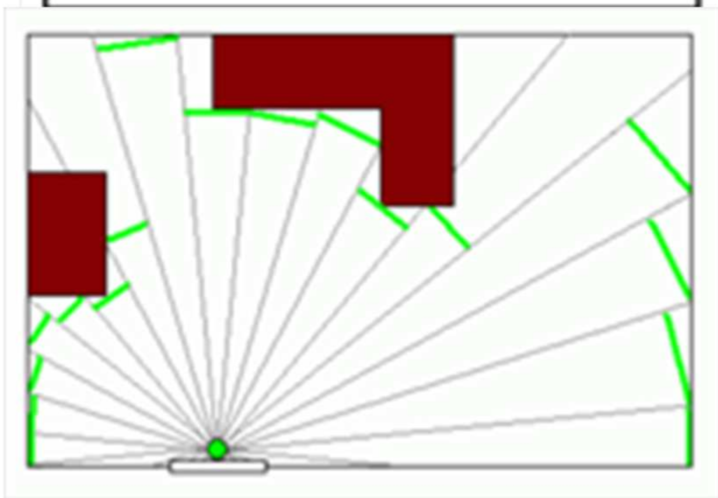
Uses of Sonar Sensors



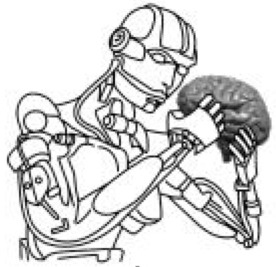
- In spite of specular reflection, ultrasound/sonar sensors are used very successfully

- Robotics applications:
  - obstacle avoidance
  - mapping



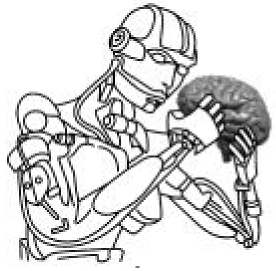


Laser



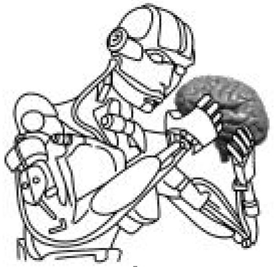
- Similar to sonar
- Uses beams of (non-visible) light
- Narrow beams
  – More accurate
  – More resolution
- Time of flight of light
- Expensive

Vision (Cameras)



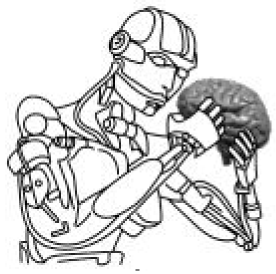
- CCD – Charge Couple Device
- CMOS – Complementary Metal Oxide Semiconductor
- Camera
  - Lens which focuses light onto image plane (CCD or CMOS)
- Versatile, but requires specialized computation

Data Filtering



- Noisy data needs to be processed before used to control robot
- Analog filtering
  – Requires special hardware
- Digital filtering
  – Can be done with computer

Digital Filtering

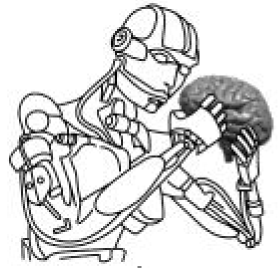


- Mostly done with linear filtering

$$y_n = \sum_{k=0}^{M} c_k x_{n-k} + \sum_{j=1}^{N} d_j y_{n-j}$$

- “Smoothing” (Convolution)
- Two special cases
  - Finite Impulse Response Filter (FIR)
    - N=0, no recursive inputs
    - More easy to design
    - More robust
  - Infinite Impulse Response Filter
    - N!=0
    - Can be unstable
    - More complex design
    - Less robust
    - Better filtering properties

Digital Filtering



- Typical Filters
  - Butterworth (MATLAB: “butter”)
  - Chebyshev (MATLAB: “cheby1” “cheby2”)
  - Elliptic (MATLAB: “ellip”)