ME 598: Introduction to Robotics

Lecture 6: Sensors and Actuators

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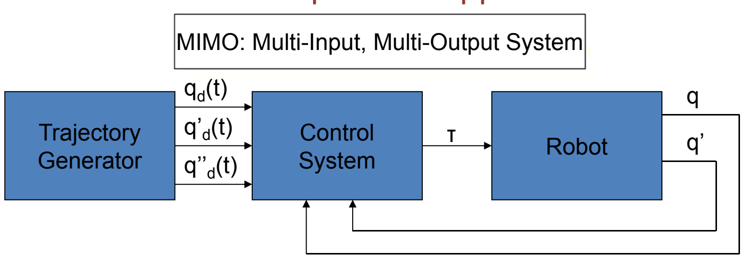
Date:
By:

Slides adapted from Dr. David J. Cappelleri

Review: Control of Manipulators

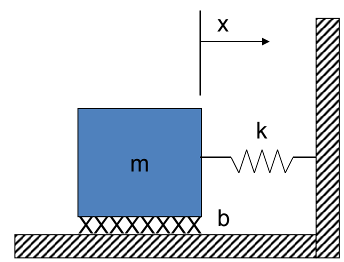
Reference:
J. Craig, Chapter 9: Linear Control of Manipulators, Introduction to Robotics: Mechanics and Control, 2nd Edition, Addison-Wesley Publishing Company, New York, 1989.

Review: Control of Manipulators Approximation



- Approximation:
  - Treat each joint as separate system to be controlled
  - N-jointed manipulator, N-independent single-input, single-output (SISO) control systems

Review: Second-Order Linear Systems



- Equation of motion:

$$m\ddot{x} + b\dot{x} + kx = 0$$

- Find solution: x(t)
  - Form of solution depends on roots of characteristic equation:

$$ms^2 + bs + k = 0$$

Review:
(Stable) Second-Order Linear Systems

- Roots (poles):

$$s_1 = -\frac{b}{2m} + \frac{\sqrt{b^2 - 4mk}}{2m}$$

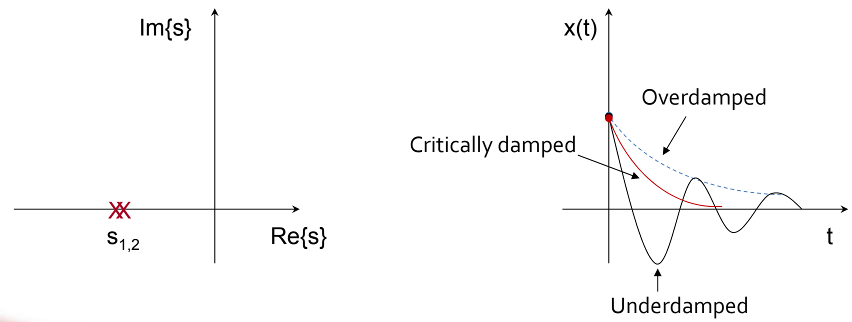
$$s_2 = -\frac{b}{2m} - \frac{\sqrt{b^2 - 4mk}}{2m}$$

- Three cases for roots (if system is stable!):
  1. Real and Unequal: $b^2 > 4mk$, friction dominates, sluggish behavior results → **overdamped**
  2. Complex: $b^2 < 4mk$, stiffness dominates, oscillatory behavior results → **underdamped**
  3. Real and equal: $b^2 = 4mk$, friction and stiffness are balanced, fastest possible nonoscillatory response → **critically damped**

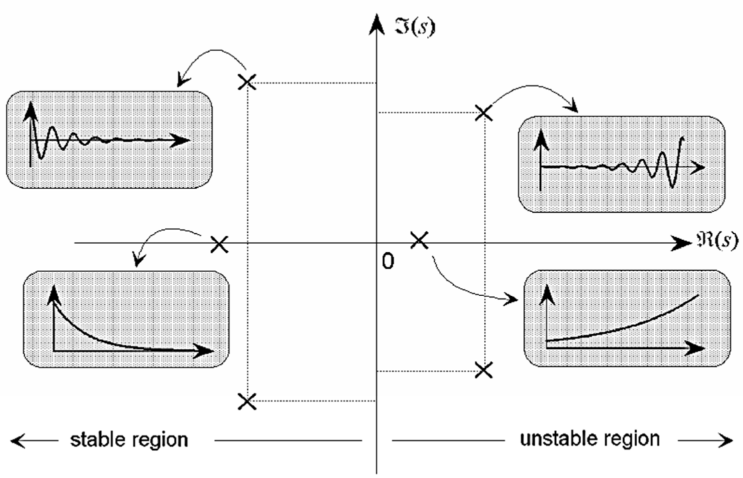
Review:
Case 3- Critically Damped System

$$s_1 = s_2 = -\frac{b}{2m}$$

$$x(t) = (c_1 + c_2 t)e^{-\frac{b}{2m}t}$$



Review:
Second-Order System Response



Review:
Second-Order System

- Alternative representation:
  - Parameterize characteristic equation by:

$$s^2 + 2\varsigma\omega_n s + \omega_n^2 = 0$$
$$\varsigma = \text{damping ratio}$$
$$\omega_n = \text{natural frequency}$$

  - Relationship to pole locations: $s_1 = \lambda + \mu j, \quad s_2 = \lambda - \mu j$

$$\lambda = -\varsigma\omega_n, \quad \mu = \omega_n\sqrt{1-\varsigma^2} = \text{damped natural frequency}$$

  - For this spring-mass-damp system:

$$\varsigma = \frac{b}{2\sqrt{km}}, \quad \omega_n = \sqrt{k/m}$$

No damping: $b = 0$, $\varsigma = 0$

Critically damped, ($b^2=4km$), $\varsigma = 1$

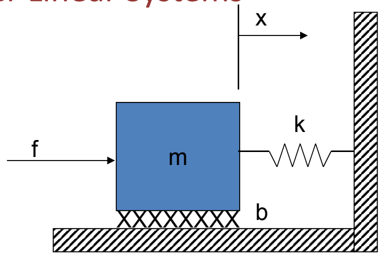
Control of Manipulators:
Control of Second-Order Linear Systems

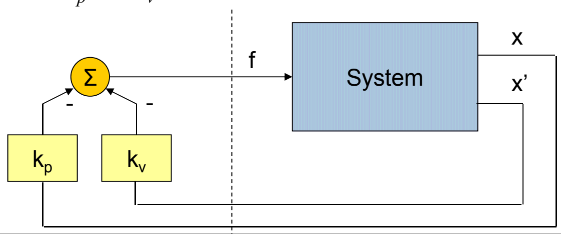
- Equation of motion:

$$m\ddot{x}+b\dot{x}+kx=f$$

- Control law as a function of sensed feedback:

$$f=-k_p x-k_v\dot{x}$$





Position regulation system: maintains the position of the block in one fixed place regardless of disturbance forces applied to the block

Control of Manipulators:
Control of Second-Order Linear Systems

$$(1)\quad m\ddot{x}+b\dot{x}+kx=f$$
$$(2)\quad f=-k_p x-k_v\dot{x}$$

- Plugging (1) into (2):

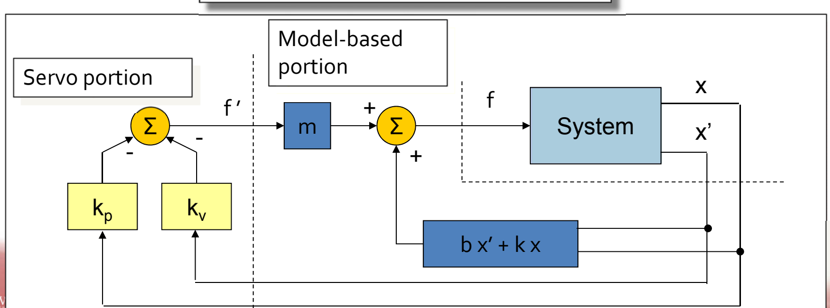
$$m\ddot{x}+b\dot{x}+kx=-k_p x-k_v\dot{x}$$
$$m\ddot{x}+(b+k_v)\dot{x}+(k+k_p)x=0$$
$$m\ddot{x}+b'\dot{x}+k'x=0$$
$$\text{where}\quad b'=b+k_v \text{ and } k'=k+k_p$$

- Choose control gains, k_v and k_p, to cause system to have any second order system behavior that is desired:

$$\text{critically damped}:\ b'=2\sqrt{mk'}$$
$$\text{closed loop stiffness}:\ k'$$

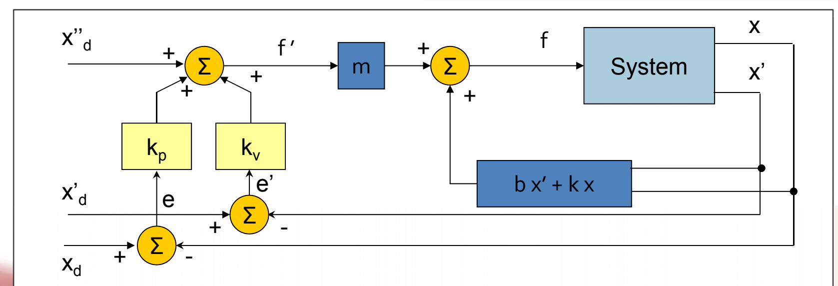
Review:
Control Law Partitioning

$$m\ddot{x}+b\dot{x}+kx=\alpha f'+\beta$$
$$\text{Choose}:\ \alpha=m,\quad \beta=b\dot{x}+kx$$
$$\text{After substitution}:\ \ddot{x}=f' \rightarrow \text{Equation of motion for unit mass}$$
$$\text{Control law}: f'=-k_v\dot{x}-k_p x$$
$$\text{After substitution}:\ \ddot{x}+k_v\dot{x}+k_p x=0$$
$$\text{For critical damping}:\ k_v=2\sqrt{k_p}$$



Review:
Trajectory Following-Control

$$\text{Desired Trajectory}:\ x_d(t)$$
$$\text{Given}: x_d, \dot{x}_d, \ddot{x}_d$$
$$\text{Servo Error}:\ e=x_d-x$$
$$\text{Control law}: f'=\ddot{x}_d+k_v\dot{e}+k_p e$$
$$\text{After substitution}:\ \ddot{e}+k_v\dot{e}+k_p e=0$$
$$\text{For critical damping}:\ k_v=2\sqrt{k_p}$$

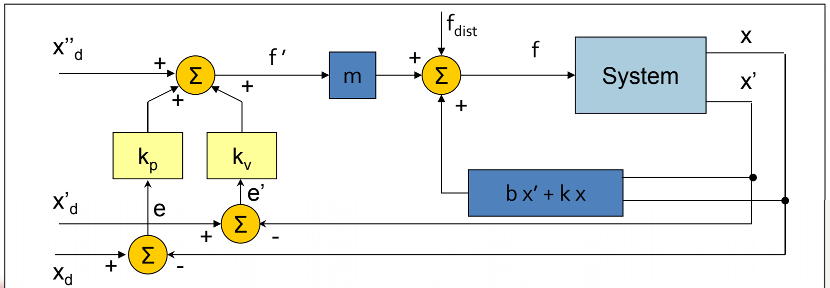


Review: Disturbance Rejection

$$\ddot{e} + k_v \dot{e} + k_p e = f_{dist}$$

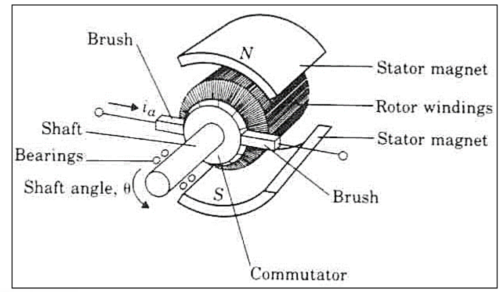
$$\text{Control law}: f' = \ddot{x}_d + k_v \dot{e} + k_p e + k_i \int e\,dt$$

$$\text{At steady-state}: e = 0$$



Review: Modeling and Control of a Single Joint

- Model single rotary joint of manipulator as second-order linear system
- DC torque motor



Review: Mechanical Model of DC Motor Rotor

τ_m = torque applied to rotor

τ = torque applied to load

i_a = armature current

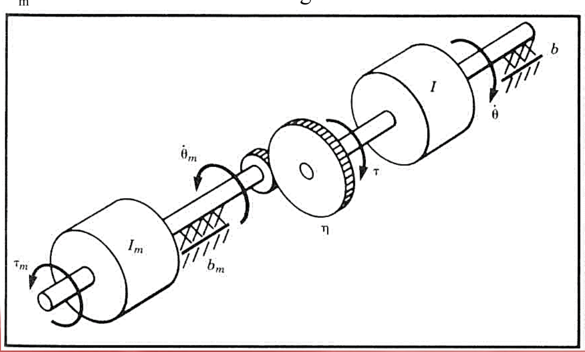
η = gear ratio

I_m and I = motor and load inertias

b_m and b = rotor and load bearings viscous friction coefficients

$$\tau = \eta \tau_m$$

$$\dot{\theta} = (1/\eta)\dot{\theta}_m$$



Review: Second-Order Model for DC Motor

Torque balance:

$$\tau_m = I_m \ddot{\theta}_m + b_m \dot{\theta}_m + (1/\eta)(I\ddot{\theta} + b\dot{\theta})$$

$$\tau = \eta \tau_m$$

$$\dot{\theta} = (1/\eta)\dot{\theta}_m$$

In terms of motor variables:

$$\tau_m = \left(I_m + \frac{I}{\eta^2}\right)\ddot{\theta}_m + \left(b_m + \frac{b}{\eta^2}\right)\dot{\theta}_m$$

In terms of load variables:

$$\tau = \underbrace{(I + \eta^2 I_m)}_{\text{Effective inertia}}\ddot{\theta} + \underbrace{(b + \eta^2 b_m)}_{\text{Effective damping}}\dot{\theta}$$

For highly geared joints (η>>1), I_m dominates → can assume effective inertia term is a constant.

To ensure link motion is never underdamped, set I to I_{max} for application

Review:
Unmodeled Resonances

- Assumption: gearings, shafts, bearings, and link are rigid, not flexible
  - If system is sufficiently stiff, natural freq of these unmodeled resonances are very high and can be neglected compared to influence of the second-order poles
- If lowest structural resonance is ω_{res}, need to limit closed-loop natural frequency:

$$\omega_n \le \tfrac{1}{2}\omega_{res}$$

  - This will limit the magnitudes for some of the gains that we choose in our controller design
  - For k = stiffness of flexible member, m = equivalent mass, estimate ω_{res} as:

$$\omega_{res} = \sqrt{k/m}$$

Review:
Control of a Single Joint

- Assumptions:
  1. Neglect motor inductance L_a
  2. High gearing, effective inertia is constant: $I_{max} + \eta^2 I_m$
  3. Structural flexibilities are neglected; use the lowest one, ω_{res}, to set the servo gains
- Use partitioned controller design:

$$\alpha = I_{\max} + \eta^2 I_m$$
$$\beta = b + \eta^2 b_m$$
$$\text{control law} = \tau' = \ddot{\theta}_d + k_v \dot{e} + k_p e$$

- Closed-loop dynamics: $\ddot{e} + k_v \dot{e} + k_p e = \tau_{dist}$
- Gains: $k_p = \omega_n^{\,2} = \frac{1}{4}\omega_{res}^{\,2}, \quad k_v = 2\sqrt{k_p} = \omega_{res}$

Sensors and Actuators

References:
S. Niku, *Ch 6. Actuators, Ch.7 Sensors*
Introduction to Robotics: Analysis, Systems, Applications.
Prentice Hall, NJ 2001
D.G. Alciatore, M.B. Histand, *Ch. 9 Sensors, Ch.10 Actuators*
Introduction to Mechatronics and Measurement Systems, 4th Ed.
McGraw Hill, NY 2012

Sensors and Actuators:
Introduction

Sensors

- Acquire information from the environment/system
- Rotations, translations, distance, speed, vibration, temperature, etc.
- Used for decision making and control

Actuators

- Induce motion or reaction in the environment/system
- Motors, voice coils, hydraulic pistons, shape-memory-alloys (SMAs), etc.
- Used for making the robot physically do something

Actuators

Sensors and Actuators: Characteristics of Actuating Systems

- Weight, Power-to-Weight
  - Ideal: low weight, high power
- Operating Pressure (hydraulic/pneumatic)
  - Higher pressures, higher power
    - Higher maintenance, more dangerous
- Stiffness vs. Compliance
  - Stiff: won't deform under load
    - Quicker response, more accurate
  - Compliant: can deform under load
    - Prevents damage
- Reduction Gearing
  - Increases torque, decreases speed
    - Increases weight, cost, parts, backlash, inertia
  - Increases resolution

Sensors and Actuators: Hydraulic Actuators

- High power-to-weight ratio
- Large forces at low speeds
- Linear and rotary versions
- Tolerant of extreme environments
- Leakage problems
- High power unit weight, cost
- Large force, small size
  - F = p x A
    - p = 1000 psi, A = 1 in^2: F = 1000 lb

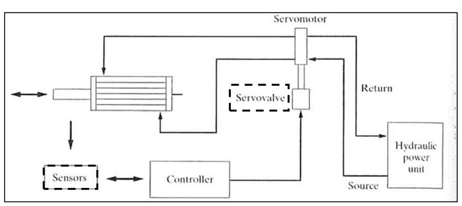
Volume of fluid going into cylinder controls displacement

Rate at which fluid sent to cylinder controls velocity

Hydraulic linear/rotary cylinder and ram

Safety valves

Connecting hoses



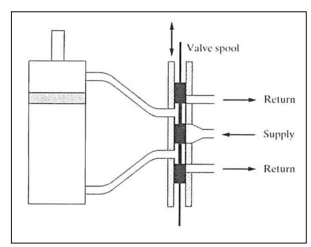
Cooling system

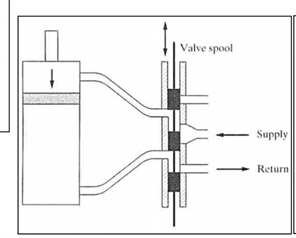
Reservoir of fluid supply

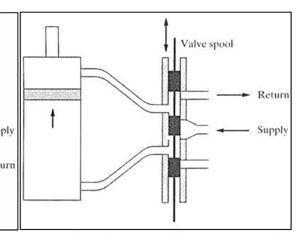
Hydraulic pump; motor

Sensors and Actuators: Hydraulic Actuators

- Spool valve for cylinder
  - Size of opening controls flow rate → velocity
  - Length of time port is open controls travel
- Controller calculates required joint movement/speed
- Sets current and duration of servomotor
- Servomotor controls position and rate of movement of valve
- Valve controls flow of fluid and rate to cylinder that moves joint

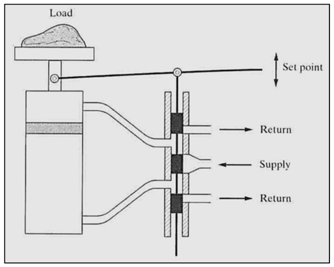


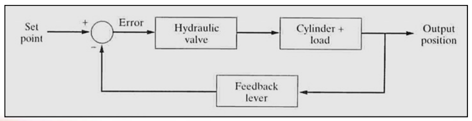




Sensors and Actuators: Hydraulic Actuator Control

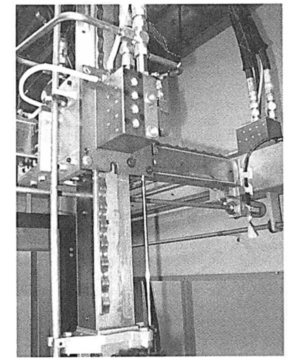
- Mechanical, proportional, feedback



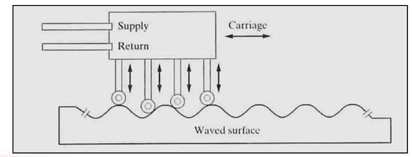


Sensors and Actuators: Hydraulic Actuators

- Linear hydraulic motor
  - 4 small linear hydraulic cylinders
  - Sequentially move in/out against waved surface
  - Cylinders forced into desired position on surface, causing carriage to move sideways
  - For more travel, add more waved surface



IBM 7565 robot

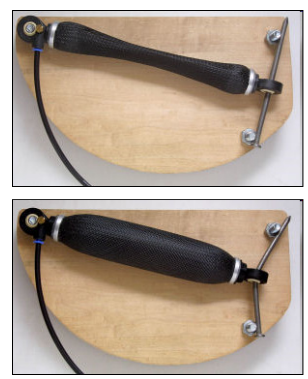


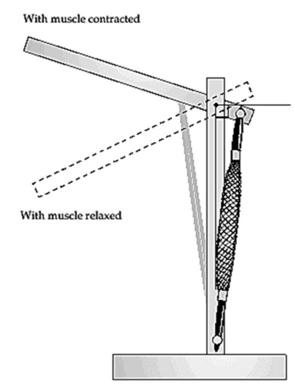
Sensors and Actuators: Pneumatic Actuators

- Same principle as hydraulic actuators
  - Use pressurized air instead of hydraulic fluid
  - Controlled by solenoid valves
- Lower power-to-weight ratio
  - Decreased weight since air source is separate from actuator
  - Much lower pressures than hydraulic (100 – 120 psi)
- Air is compressible; hydraulic fluid is incompressible
  - Typically used with actuator all the way forward or backward; fully on/fully off
  - Controlling exact position is difficult

Sensors and Actuators: Pneumatic Actuators

- Bio-inspired, air muscle actuators

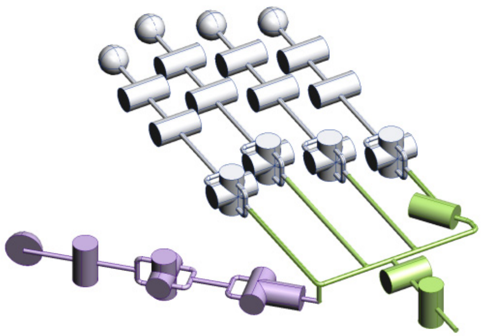




www.shadowrobot.com

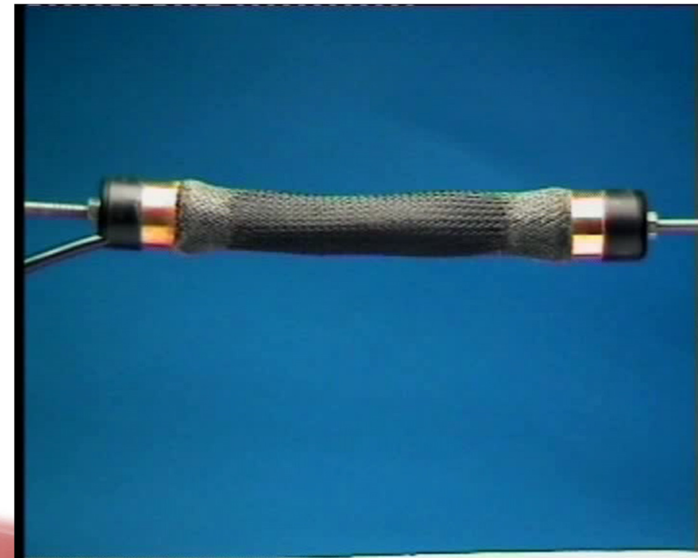
Sensors and Actuators: Pneumatic Actuators

- Shadow Dextrous Hand

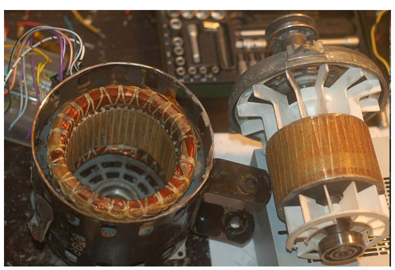


The Muscle Types	
Single with Spring	One muscle with an opposing return spring.
Coupled pair	The two joints are coupled such that the angle of Joint 2 is less than the angle of Joint 1. Two muscles drive these joints.
Pair	Two antagonistic muscles drive this joint. The distal and middle joints are coupled in a manner similar to a human finger, such that the angle of the middle joint is always greater than or equal to the angle of the distal joint. This allows the middle phalange to bend while the distal phalange is straight. The movement from 0 to -20 of the distal joint is a purely passive movement. The little finger has an extra joint in the palm. All joints except the finger distal joints are controllable to +/- 1° across the full range of movement.

Sensors and Actuators: Pneumatic Actuators- Air Muscle

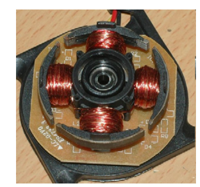


Sensors and Actuators: AC Electric Motors



- AC Motors
  - Same as DC except rotor is permanent magnet, stator houses windings, no commutators or brushes
  - As flux generated by AC current changes, rotor follows it and rotates
  - Fixed nominal speeds:
    - Functions of number of poles on rotor and line frequency (60 Hz)
  - Better at dissipating heat than DC motors

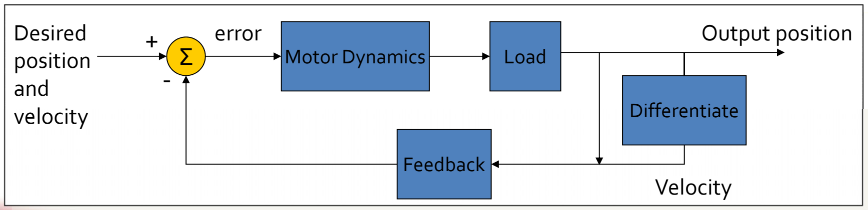
Sensors and Actuators: Brushless DC Electric Motors



- Brushless DC Motors
  - Hybrid between AC and DC motors
  - Similar construction as AC
  - Operated with switched DC waveform that mimics an AC current, not limited to 60 Hz
    - Can operate at any speed
  - Needs a controller circuit
    - Feedback needed to determine when to switch direction of current to rotor (sensor on rotor)
    - Rotor usually has 3 phases → 3 currents, with 120° phase shift

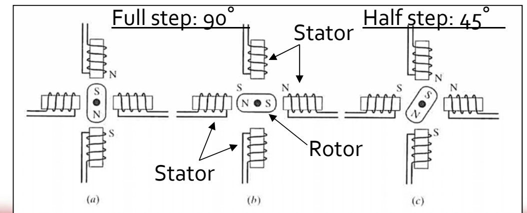
Sensors and Actuators: Electric Servomotors

- Servomotors
  - A motor (DC, AC, brushless) with feedback that can be controlled to move at a desired speed (torque) and/or a desired angle of rotation
  - Velocity feedback:
    - For higher/lower loads
      - Velocity lower/higher than desired value
      - Current is increased/decreased until desired speed reached
  - Position feedback:
    - Motor shuts off as rotor approaches desired angular position



Sensors and Actuators: Electric Stepper Motors

- Stepper Motors
  - Permanent magnet rotors; stators have multiple windings
  - Will not rotate when connected to power
    - Require drive electronics/microcontroller/microprocessor
  - Typically not used in industrial robots, used extensively in nonindustrial robots and devices
  - Repeatable open-loop performance
    - Do not require feedback



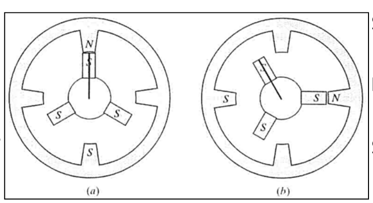
Sensors and Actuators: Electric Hybrid Stepper Motors

- Hybrid stepper motors
  - Rotor and stator poles all have teeth (different)
  - Teeth on one half of rotor is offset by half-tooth from other half of rotor
  - Since rotor and stator have different # of teeth, rotor will rotate an angle equal to the difference between the divisions

Stator = 4 teeth
division = 360° /4 = 90°

Rotor = 3 teeth
division = 360° /3 = 120°

Step size = 120° – 90° = 30°



Stator = 40 teeth
division = 360° /40 = 9°

Rotor = 50 teeth
division = 360° /50 = 7.2°

Step size = 1.8°

Full step / half step / reverse

Sensors and Actuators: Electric Microstepping Stepper Motors

- Microstepping Stepper Motors
  - Gradual power up/power down of each coil
  - Divides changes into smaller divisions

<u>Traditional Stepper Motor</u>

1. Coil A – On, Coil B – Off
2. Coil A – Off, Coil B – On

Full step → 100 small steps

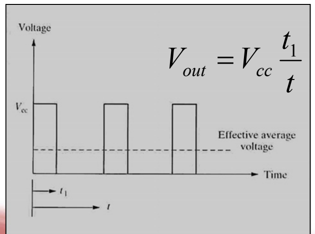
For 200-step 1.8° motor, microstepping produces 20,000 steps/revolution

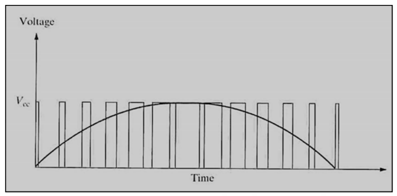
<u>Microstepper Stepper Motor</u> (divisions = 100)

1. Coil A – On, Coil B – Off
2. Coil A – 99% On, Coil B – 1 % On
3. Coil A – 98% On, Coil B – 2 % On
4. Coil A – 97% On, Coil B – 3% On
5. …
6. Coil A – Off, Coil B – 100% On

Sensors and Actuators:
Electric Motor Speed Control

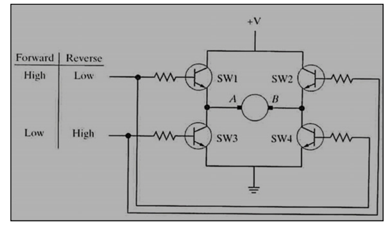
- Electric Motor Speed Control with microprocessors
  - DC motor speed control: voltage increase/decrease, speed increase/decrease
  - Continuous voltage signal at different levels: large number of output ports/bits to get good resolution, expensive
  - Pulse-width-modulation (PWM): Creates many different voltage levels with one single-level input voltage (e.g. 5 V) and one output bit
    - Turn voltage on/off repeatedly (pulse), varying length of time (width) to vary (modulate) the effective voltage

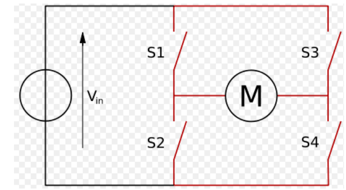


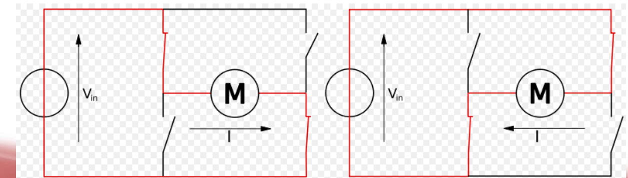


Sensors and Actuators:
Electric Motor Direction and Speed Control

- Direction Control with H-Bridge
  - Change polarity = change motor direction
  - Instead of changing physical polarity, change direction of current flow
  - H-bridge circuit changes current flow with two bits of information







[Wikipedia]

Summary of Actuator Characteristics

Hydraulic
- Good for large robots, heavy payloads
- Highest power/weight ratio
- Stiff system, high accuracy, better response
- No reduction gear needed
- Can work in wide range of speeds w/o difficulty
- Can be left in position w/o any damage
- May leak, not fit for clean room applications
- Requires pump, reservoir, motor, hoses, etc.
- Can be expensive and noisy. Requires maintenance.
- Viscosity of oil changes with temperature
- Very susceptible to dirt and other foreign material in oil
- Low compliance
- High torque, high pressure, large inertia

Electric
- Good for all sizes of robots
- Better control, good for high precision robots
- Higher compliance than hydraulics
- reduction gears used reduce inertia on the motor
- Does not leak, good for clean room
- Reliable, low maintenance
- Can be spark-free, good for explosive environments
- Low stiffness
- Needs reduction gears, increased backlash, cost, weight, etc.
- Motor needs braking device when not powered, otherwise, the arm will fall

[Pros]
[Cons]

Pneumatic
- Many components are usually off-the-shelf
- Reliable components
- No leaks or sparks
- Inexpensive and simple
- Low pressures compared to hydraulics
- Good for on-off applications and pick and place
- Compliant systems
- Noisy systems
- Require air pressure, filter, etc.
- Difficult to control linear position
- Deform under load constantly
- Very low stiffness. Inaccurate response
- Lowest power to weight ratio

Sensors

Sensors and Actuators: Sensor Characteristics

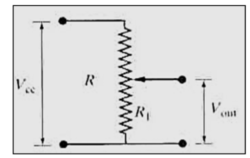
- Cost, Size, Weight
- Type of output (digital or analog)
- Interfacing
  - Compatible with controller, microcontroller, microprocessor
- Resolution
  - Minimum step size within measurement range
- Sensitivity
  - Ratio of change in output to change in input
- Linearity
  - Relationship between input and output variations
- Range
  - Difference between smallest and largest outputs
- Response time
  - Required time for output to reach a certain percentage of total change (~95%); time required to observe change
- Frequency response
  - Ability of the sensor to respond to varying inputs (operating conditions)
- Reliability
  - Ratio of how many times a sensor operates properly to how many times it is tried
- Accuracy
  - How close sensor output is to expected value
- Repeatability
  - For the same input, a measure of how varied sensor outputs are relative to each other

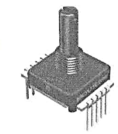
Sensors and Actuators: Position Sensors- Potentionmeters

Potentiometers

- Convert position information into a variable voltage through a resistor
  - Acts a voltage divider circuit
- Linear or rotary versions
- Generally used as internal feedback sensors to report joint/link positions

$$V_{out} = V_{cc}\frac{R_1}{R}$$





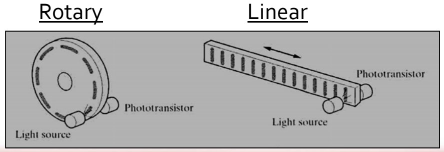
Sensors and Actuators: Position Sensors- Encoders

Encoders

- Device that can output a digital signal for each small portion of a movement
- Two types of encoders
  - Incremental- only reports change in position, not what actual position is
  - Absolute– can report the actual position
- Resolution depends on # of slits/arcs/markings
  - Typically 512 to 1024 arcs, resolution of 0.7 to 0.35

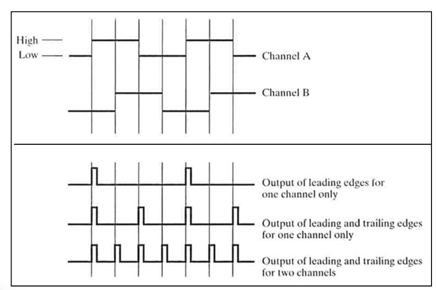
[Wikipedia]

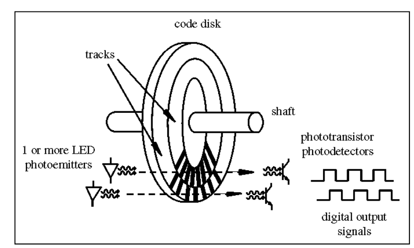
Rotary Linear



Sensors and Actuators: Position Sensors- Incremental Encoders

- Incremental encoders – determining direction
  - Two sets of arcs (two channels) on wheels, ½ step out of phase
  - Controller can compare signals to see which one changes first to determine direction
- Count changes of signals at both leading and trailing edges to increase resolution
  - 2 channels, both edges → 4X resolution



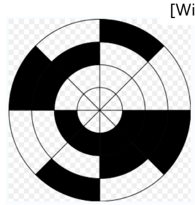


Sensors and Actuators: Position Sensors- Absolute Encoders

- Absolute– each portion of encoder wheel has unique combo of clear and opaque arcs to give unique signature
  - Can get exact position of wheel at any time w/o need of starting position
  - Multiple rows of arcs, all different
  - Each row needs own light source and light sensor
  - Encoder with 4 sets or arcs can have 2^4=16 distinct combinations, each section covering 22.5°
    - Within 22.5° section, controller doesn't know where it is
    - Increase # arcs to increase resolution
    - Many more bits of info, much more expensive

[Wikipedia]

Row 1 - 2 arcs
Row 2 – 4 arcs
Row 3 – 8 arcs

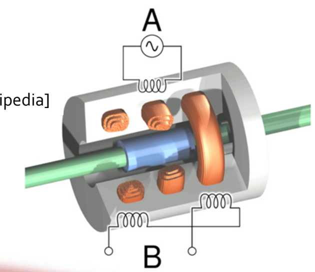


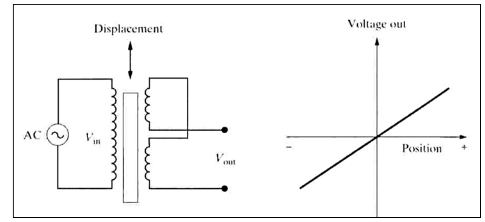
Sensors and Actuators: Pos. Sens.- Linear Variable Differential Transformer (LVDT)

Linear Variable Differential Transformers (LVDT)

- Transformer whose core moves along with the distance being measured and outputs a variable analog voltage as a result of displacement
- Transformer- converts an electrical energy into the same form but changes the voltage-current ratio
- Very linear response in specified range, proportional to the input position of the core

[Wikipedia]



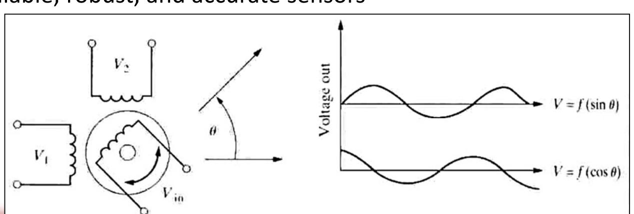


Displacement of iron core changes magnetic field → voltage through coils

Sensors and Actuators: Position Sensors- Resolvers

Resolvers

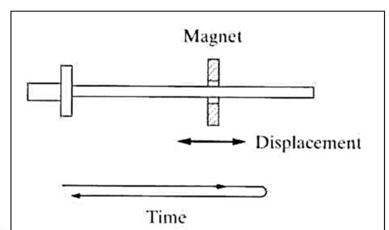
- Similar in principle to LVDT's, used to measure angular motion
- Transformer with primary coil connected to rotating shaft; carries an alternating current
- When primary coil parallel to a secondary coils, voltage in that secondary coil is at max while in other is zero
- For all other angles in between, voltage in secondary coils is proportional to sine and cosine of the angle between the primary coil and two secondary coils
- Reliable, robust, and accurate sensors

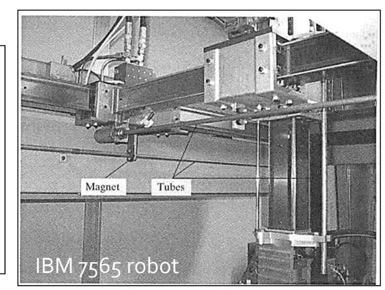


Sensors and Actuators: Pos. Sens.- Magneto Reflective Displacement Sensor

Magneto Reflective Displacement Sensor

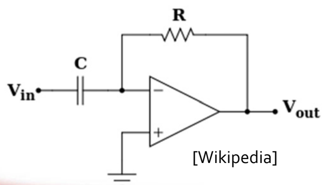
- Pulse is sent out through a conductor that bounces back after it hits a magnet
- The time of travel to the magnet and back is converted to the distance if the speed of travel is known
- Moving part is attached to magnet or conductor to measure displacement





Sensors and Actuators: Velocity Sensors

- Dependent on the type of position sensor used
- No need for velocity sensor if using encoders
  - Count # of signals in given length of time
  - Velocity = (change in position) / (change in time)
- Tachometers- generator that converts mechanical energy into electrical energy
  - Output = analog voltage proportional to angular speed
  - Used with potentiometers to estimate velocity
- Clean, continuous position signals can be differentiated with circuits to convert position signal into velocity signal

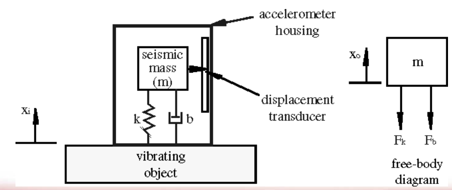


[Wikipedia]

$$V_{out} = -RC\frac{dV_{in}}{dt}$$

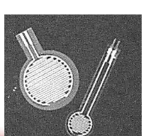
Sensors and Actuators: Acceleration/Vibration Sensors- Accelerometers

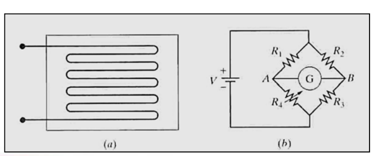
- Accelerometers
  - Accelerations are generally ***not*** measured on industrial robots
  - Quasi-steady-state vibrations and orientations can be measured using accelerometers
  - Mechanically attached to object being measured
  - Detects acceleration along on axis, insensitive to other axes
  - Strain gages or piezoelectric elements are used to convert vibration into voltage signal
  - Design based on inertial effects associated with mass connected to moving object through spring, damper, and displacement sensor



Sensors and Actuators: Force and Pressure Sensors

- Piezoelectric sensors
  - When compressed, piezoelectric material produces a voltage → forces and pressures
- Force sensing resistor
  - Polymer thick-film that exhibits decreasing resistance with increasing force applied normal to its surface
- Strain gauges
  - Exhibits a variable resistance, proportional to strain, that a is function of applied forces
    - Used to measure forces at the end-effector and wrist

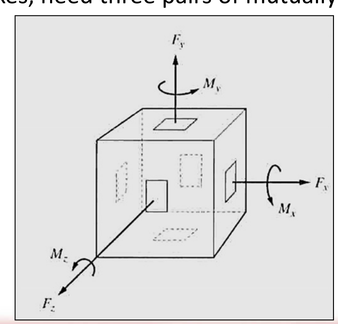




$$\frac{R_1}{R_4} = \frac{R_2}{R_3}$$

Sensors and Actuators: Torque Sensors

- Measure torques with a pair of strategically placed force sensors
  - Two force sensors on a shaft, opposite of each other, on opposite sides
  - Torque on shaft generates two opposing forces on shaft, causing strains in opposite directions
  - To measure torques about different axes, need three pairs of mutually perpendicular sensors



Sensors and Actuators: Miscellaneous Sensors

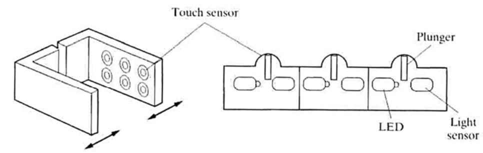
- Microswitches, limit switches
  - Used to cut off electrical current through a conductor
  - Used for contact sensors, sending signals based on displacements, + many other uses

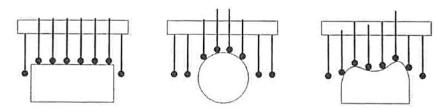
Limit Switch

- Light and infrared sensors
  - Change resistance or conductance based on intensity of light projected on them
    - Infrared sensors – sensitive to infrared light frequencies
    - Light sensors – sensitive to visible light
      - Phototransistors: turns on with light, off otherwise → used with LED's

Sensors and Actuators: Touch and Tactile Sensors

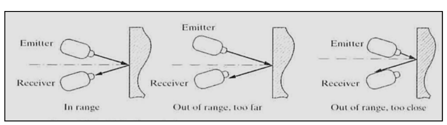
- Touch sensors
  - Send signals when physical contact has been made → Microswitches, limit switches, force sensors
- Tactile sensors
  - Collection of touch sensors that provide additional information about object besides touch → Shape, size, type of material



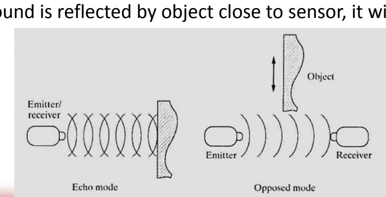


Sensors and Actuators: Proximity Sensors

- Used to determine that an object is close to another before contact is made
  - Optical- consist of light source (LED) and receiver (phototransistor) – LED reflection only detected if object is at correct distance

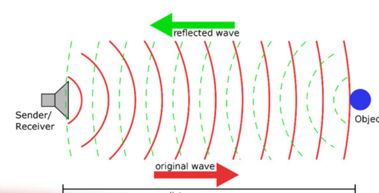


  - Ultrasonic- ultrasonic emitter emits high frequency sound waves
    - Opposed mode- receiver in front of emitter
    - Echo mode- receiver next to, or integrated into, emitter
    - If receiver is within range or if sound is reflected by object close to sensor, it will be sensed and signal produced



Sensors and Actuators: Range Finders

- Used to find larger distances to objects
  - Detect obstacles and map surfaces to objects → advanced information to system
- Based on light (visible, infrared, laser) and ultrasonics
- Time-of-flight method:
  - Send signal from transmitter that bounces back from object and is received by receiver
  - Distance between object and sensor is half the distance traveled by signal
  - Calculated by measuring the time-of-flight of signal and by knowing its speed of travel



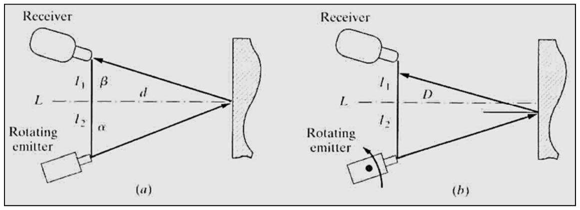
[http://www.kerrywong.com]

Sensors and Actuators: Range Finders

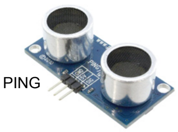
- Triangulation method:
  - Illuminate object to form a spot on it
  - The spot is seen by a receiver
  - Depth or range is calculated from the triangle formed between the receiver, light source, and spot on object
  - L and β are known, α is measured, d is calculated

$$\tan\beta = \frac{d}{l_1}, \quad \tan\alpha = \frac{d}{l_2}, \quad L = l_1 + l_2$$

$$d = \frac{L\tan\alpha\ \tan\beta}{\tan\alpha + an\beta}$$



Sensors and Actuators: Range Finders



Parallax PING

- Ultrasonic
  - Time-of-flight technique using pulse of high frequency ultrasound waves
  - Rugged, simple, inexpensive, low powered
  - Limited resolution, limited range → affected by temperature, type of medium operating in

Sharp GP2Y0A21YK0F

- Light-based (including laser-based)
  - Use 3 different methods
    - Direct-time-delay: measures time for light beam to travel to object and back (speed of light)
    - Indirect amplitude modulation: send out burst of light with low frequency sinusoidal wave, measure phase difference between it and backscattered light (slows down wave speed to measurable scales)
    - Triangulation

Sensors and Actuators: Vision Systems

"A picture is worth a thousand words."

- Extremely sophisticated sensor for robotics
- Used for a sensing a variety of things
- More on this later…