Mechatronic Engineering: The synergistic integration of elements of mechanical, electrical, control and computer engineering.

throught the design and manufacturing process

benefit: shorter development cycles, lower costs, increased quality, increased reliability, increased performance and increased benifits to the customer.

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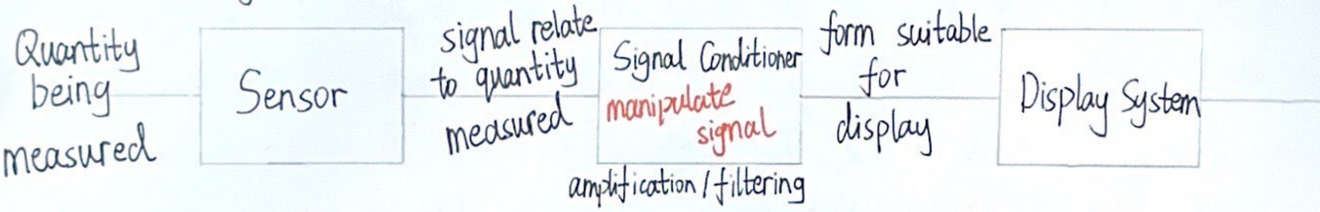
Mechatronic Design: One that uses all the elements of mechatronic ~~design~~ engineering to achieve the design objectives and/or a design that is some way optimal.

Mechatronics involves "systems": one or more input and one or more output
interested in relationship between input & output

Measurement System:

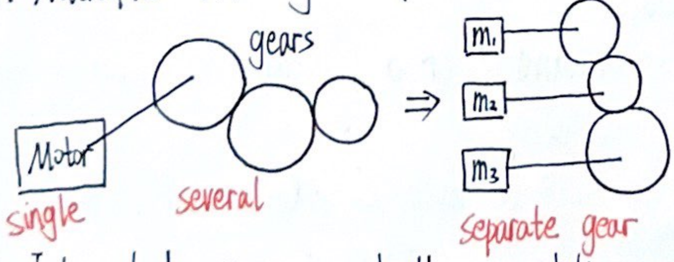


In the past, sequential control ~~&~~ was implemented using cam-operated switches
Today, Programmable Logic Controller (PLC) is used.

Computer Simulation: based on mathematical models, allow preliminary mechatronic designs to be tried out quickly, inexpensively and safely

Mechatronic Systems:

1. Multiple rotating shafts



removing gears reduces cost
removing gears eliminates wear and backlash
failure of a single motor has lower impact

2. Integrated sensor-controller-amplifier-actuator

SmartMotor { DC motor, amplifier, sensor, controller } — integrated

only power and network signal

one Master controller, other follow
no additional hardware
no extensive wiring

3. Hollow integrated motor-gearbox

PowerHub { DC motor, bearing, harmonic drive } twisting of the cables ⇒ make centre hollow

4. Computer hard disk drive

read/write arm motor } reduce inertia, allowing acceleration and velocity of arm to be increased (reduce seek time)

5. Electronic barthroom scale

weight ⟶ $\boxed{\text{mechanical mechanism}}$ ⟶ electromechanical force sensor

6. Artificial hand for small child.

electric motor is used only when hand must be opened to grip an object

spring force is used to close the hand and perform gripping action.

Distributed Control: multiple microprocessors used in mechatronic systems

common controller still required

- greater reliability (less wiring, failure of one μP is less critical)
- improved performance (computing done in parallel, less data transmission delay)
- less expensive

Centralized Control: signal travel through relative long cables ⇒ easy for failure by insulation wear and fracture and wire fatigue.

Control System: keep its output as close as possible to its reference input (setpoint)

cable between controller and actuator fails ⇒ spring-loaded brake

cable between sensor and controller fails:

closed-loop is better {
1. A change in the process dynamics or a disturbance causes the output to change
2. The changes are small enough so that closed-loop is stable.
3. The controller receives correct signal from the sensor

If wrong signal sent from sensor, open-loop controller will be unaffected

Sensor: A device that produces a signal related to the quantity measured.
input is the quantity; output is a Voltage
① Static performance: steady-state ② Dynamic performance: varies over time

Range: The limits between which the quantity being measured can vary
e.g. thermometer range: -20°C to 100°C

Full Scale: Difference between maximum and minimum values that the sensor can measure. $Quantity_{max} - Quantity_{min}$

Resolution: Smallest change in the quantity being measured that is ~~dect~~ detectable by the sensor. Easy to measure but do not truly indicate quality.

Repeatability: The ability of a sensor to produce the same output for repeated applications of the same input, also called precision,
$= \pm 3\sigma_y$, σ_y is standard deviation to 99.7% confidence interval
Random error normally distributed

Accuracy: The maximum extent the output of the sensor may be incorrect over its range. include both random and deterministic error

$$Accuracy = \pm(max(abs(Y_{true} - Y_{sensor})) + 3\sigma_Y)$$

Y_{true}: True value measured, Y_{sensor} mean value of calibrated output

large
Sensitivity: Ratio of the magnitude of the sensor output to the magnitude of the quantity being measured.

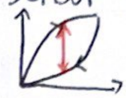
Small
Cross-sensitivity: With directional sensors, the sensitivity of the sensor output to inputs orthogonal to the measurement direction.

Deadband: The band of input values for which there is zero output.

Linearity: The maximum error between the mean values of the sensors outputs and the true value being measured.

$$Linearity = \pm max(abs(Y_{true} - Y_{sensor}))$$

Hysteresis: The maximum difference between the calibrated sensor outputs for continuously increasing and decreasing inputs.



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Response Time: The time the output takes to reach 95% of the input.

Rise Time: Time required for the output to increase from 10% to 90% of its steady-state value.

Settling Time: The time required for the output to settle within ±1% of its steady-state value.

Time Constant: The time required for the output to reach 63.2% of its steady-state

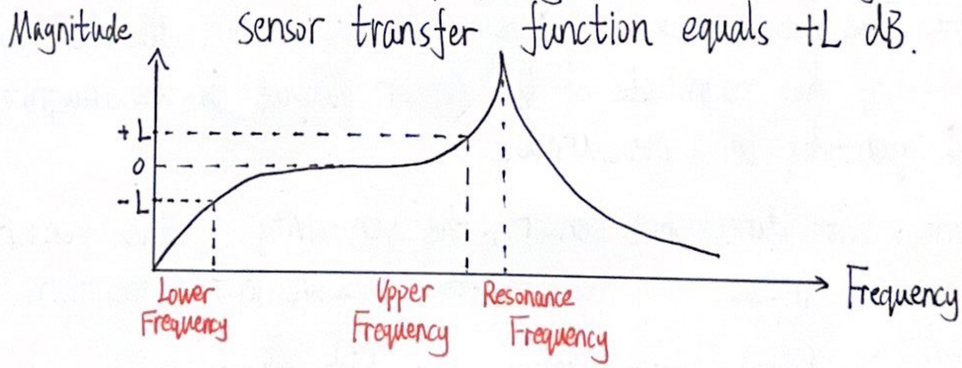
Stability: The ability of a sensor to produce the same output when measuring a constant input over an extended period of time.

drift: a change in output under these conditions.

Bandwidth: The lowest frequency at which the magnitude of the sensor transfer function drops by 3dB.

Lower frequency limit: The lowest frequency at which the magnitude of the sensor transfer function equals −L dB.

Upper frequency limit: The lowest frequency at which the magnitude of the sensor transfer function equals +L dB.



Sensor Calibration:

1. Applying a constant input at the start of the range of the sensor.
2. Measuring the sensor output multiple times (at least 100)
3. Calculating the mean value and standard deviation of the measured outputs
4. Increasing the input and hold it constant
5. Repeat 2 and 3. 6) Repeat 4 and 5 until input is at end of range
7) Fitting a calibration line to mean values of output (measured), using linear regression ⇒ $y = A x$ (y: dependent, x: independent)

$$A = \frac{\sum xy}{\sum x^2}$$

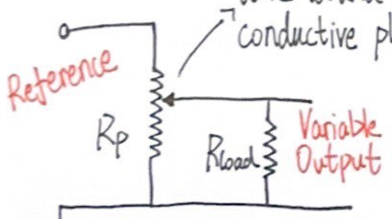
For $y = Ax$: $Y_{sensor} = \frac{Y_{volt}}{A}$

$$A = \frac{n\sum xy - (\sum x)(\sum y)}{n\sum x^2 - (\sum x)^2} \qquad B = \frac{\sum y - A\sum x}{n}$$

For $y = Ax + B$: $Y_{sensor} = \frac{Y_{volts} - B}{A}$

Displacement Sensors

1. Potentiometer: a resistance element with sliding contact that can move



$R_{load} >> R_p$

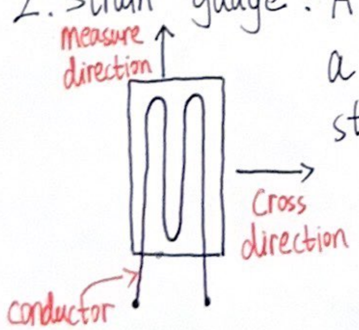
wire-wound { Advantage: not temperature sensitive; Disadvantage: limited resolution (wire diameter) }

plastic resistant { Advantage: unlimited resolution; Disadvantage: temperature sensitive }

Advantage: Low cost, Large range

Disadvantage: Output affected by load resistance, analog out, sensor is affected by dirt and wire

2. Strain guage: A wire, metal foil or semiconductor strip that can be stuck onto a surface to measure its strain. The change in resistance due to strain can be converted into a voltage.



$$\frac{\Delta R}{R} = G\varepsilon$$

$\Delta R / R$: tiny change in resistance → voltage; G: guage factor; ε: strain { positive: tensile; negative: compressive }

Small range (less than 1m) ⇒ Cantilever, Ring Shaped, U shaped (flexible elements)

Temperature Compensation: very sensitive to changes in temperature.

① The temperature of the sensor must be kept constant

② Mount a pair of sensors on opposite side → best approach

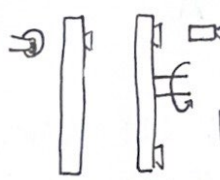
Advantage: no wear

Disadvantage: small range unless mechanical element is added, analog output temperature sensitive

3. Encoders: used in motion control systems of robots and machine tools. produce digital output for angular (or linear) displacement.

	common ← optical	magnetic	capacitive	inductive
Incremental	✓	✓	✓	✓
Absolute	✓	✓		

Incremental Encoder: Output is a measure of relative displacement



rotating: blocked / unblocked => OFF / ON

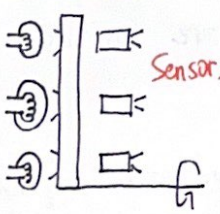
absolute displacement: Channel A and Channel B

half slot width

determine the rotation direction.

improve resolution: quadrature counting

Absolute Encoder: each position gives a unique output (binary number)



problem: range is limited to one revolution.

use an incremental encoder with a counter

Advantage: no wear, digital output is relatively insensitive to noise and easy to interface

Disadvantage: limited resolution, susceptibility to large vibrations

Digital Sensor	Analog Sensor
Advantage: Noise Immunity	Advantage: potentially infinite resolution
Disadvantage: Limited resolution Few purely sensor exists	Disadvantage: sensitive to noise

digitize to analog : often   transmit digitally : long distance (increases noise)

4. Hall Effect Sensor : measure the flux density of a magnet

analog output : linear or employ a threshold → non-contact proximity switch
↳ automotive application

Advantage : non-contact (no wear), immune to the working environment

Velocity Sensors

1. By differentiating displacement or position

   Advantage : low cost

   Disadvantage : Amplifies high frequency noise, numerical differentiation adds time delay

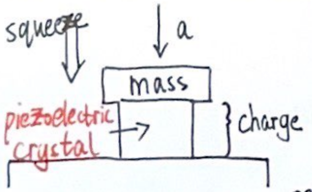
2. Tachogenerator or Tachometer : produces an analog voltage that is proportional to the velocity

   motor as generator, brush / brushless, not used so much

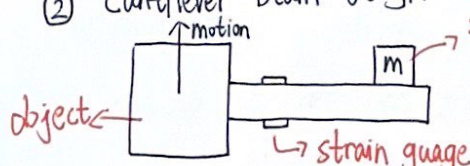
   Disadvantage : brushes create noise, are subject to wear.

Acceleration Sensors (Accelerometers)

① squeeze



② cantilever beam design



small mass (seismic mass)

measure the strain

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

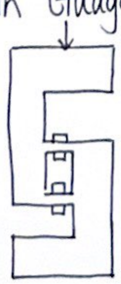
Larger $\frac{m}{k}$, Larger sensitivity of the sensor. will limit the bandwidth.

Advantage : simpler to use than displacement and velocity sensors, no wear
Multiple axis (X-Y-Z) and angular acceleration sensors are avaliable

Force Sensors

① Strain Guage Type

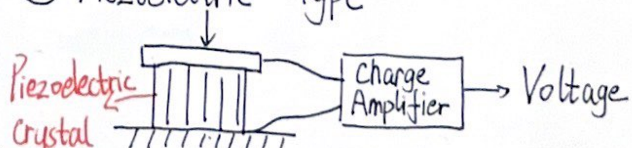
mass of sensor may affect the result



advantage : Low cost

disadvantage : Worse linearity, greater temperature sensitivity.

② Piezoelectric Type



Advantage : Better linearity and temp sensitivity

Disadvantage : Higher cost, amplifier must be designed carefully to prevent stability problems

Design issue: piezoelectric avoids problem with cross-sensitivity
flexible elements must be designed to avoid cross-sensitivity
Both need to be as stiff as possible to maximize natural sensitivity

Pressure Sensors

Employing a tiny diaphragm~~s~~ incorporates strain guages to measure deflection when pressure is applied.

Temperature Sensors

1. Bimetallic Strips: two metal strip bounded back to back having different coefficient of thermal expansion. The different expansions cause strip to band. Used as temperature controlled switch

Issue: fatigue of the metals.

2. Resistance Temperature Detectors: consists coil of wire, resistance changes when temperature changes

Advantage: simplicity, linearity

Disadvantage: small sensitivity to temperature.

Small temperature sensor
1. measure very locally => temp distribution
2. heat up faster => fast response time
3. fit in tight location

3. Thermistors: mixture of metal oxides. the resistance is very sensitive to the temperature.

Advantage: can be easily formed into different shapes, large sensitivity. can be very small

Disadvantage: Very non-linear response so special ~~cab~~ calibration required.

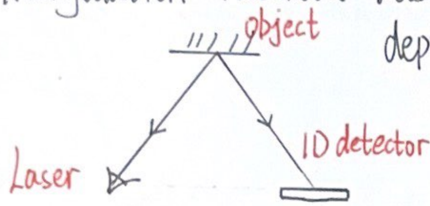
4. Thermocouples: traditional temperature sensors but less popular. Small Voltage produced when two metals joined, function of metals and temperature

Advantage: Large range, Excellent linearity

Disadvantage: Very small sensitivity, small output makes it very susceptible to noise, Special electronics required

Depth Sensors (range-sensing)

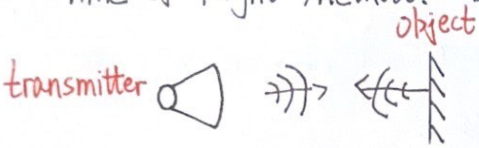
1. ~~Tra~~ Triangulation Method: Laser and 1D detector form a triangle



depth determined by geometry

one of ways humans and animals detect the depth

2. Time of Flight Method: based on distance travelled = speed x time



reflected pulse detected by receiver

lidar sensors used with autonomous vehicles + Ultrasonic

Advantage: Greater range, not affected by optical properties of the object, transmitter can be located close to receiver without affecting performance, not affected by dirt, lower cost.

Disadvantage: Worse accuracy, suspectible to indirect reflections.

Proximity Sensors

used to detect when or whether a location is within a specified proximity

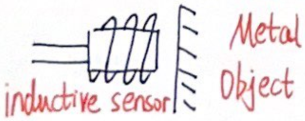
1. Microswitch: spring-loaded mechanical switch.

Disadvantage: Object sensed must come into contact and apply small force

Dynamics of spring (and mass can cause false outputs

Subject to wear.

2. Inductive: used change in magnetic circuit formed by coil, detect presence of a metal object.

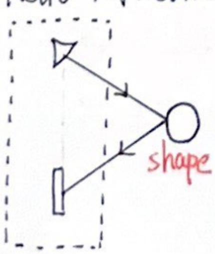


Disadvantage: Can detect presence of metal objects only.

Small range, require power.

3. Photoelectric: consists of light and light detector (phototransister)

Retro-reflective

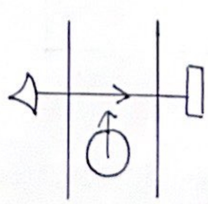


Contained within one sensor

not require separate mounting and alignment

smaller range, greater sensitivity to optical properties

~~Thru~~ Thru-beam

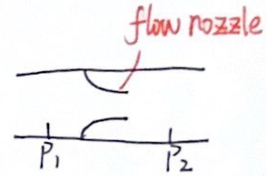


Two parts aligned

Advantage: Both types have a much larger range

Disadvantage: Suitable for opaque objects only, Sensitivre to dirt, sensitive to ambient light, requires power.

Flow Rate Sensors

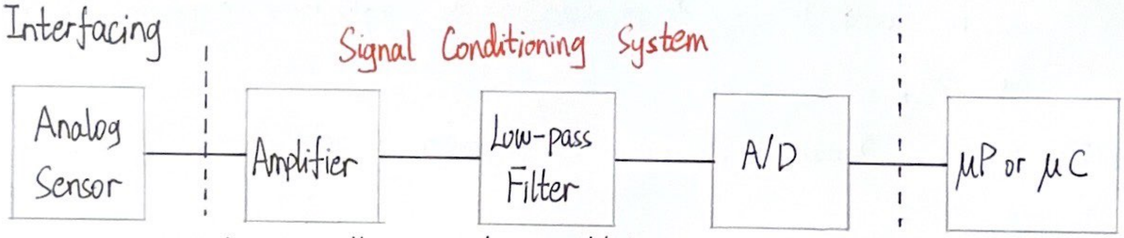


1. Flow Nozzle: restricts the flow causing a pressure drop ($P_1 - P_2$)
2. Turbine Flow Meter: propeller attached to a tachogenerator, less pressure drop

Advantage: Less expensive, Less susceptible to wear.

Disadvantage: Less accurate

Sensor Interfacing



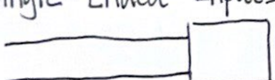
increase voltage to suitable value

reduce amplitude of high frequency noise

analog -> ditigital

long cable more negative effect

Single-Ended Inputs



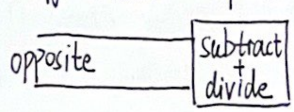
0.3V => noise +0.5V => Input 0.8V.

↳ relative common ground

noise added

send three signals, need four lines

Differential Inputs



+0.3V, -0.3V => noise +0.05V => Input $\frac{0.35-(-0.25)}{2} = 0.3V$

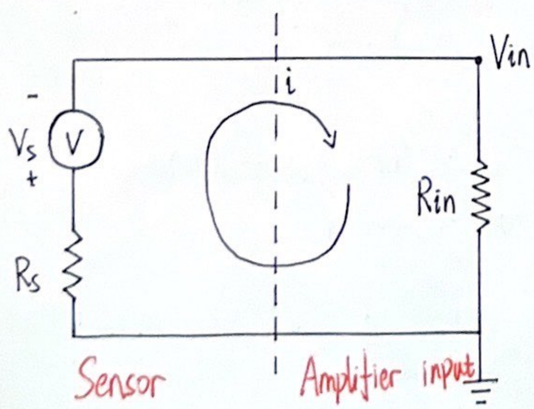
greatly reduce common noise

Better

used analog and digital

Differential disadvantage: added cost (more complex input circuitry & extra wire needed)

Loading Effect



Sensor gives output voltage, received by Amplifier

$$V_{in} = V_s\left(\frac{R_{in}}{R_{in}+R_s}\right)$$ ideally want ≈ 1

Each hardware element must have a small output impedence and large input impedence for loading effects to be minimized

happen between any connections of input & output

Error of resolution of an ADC

$$a_{ADC} = \pm \frac{V_{FS}}{2^{ENOB}}$$

ADC accuracy in volts ← a_{ADC}

V_{FS} → ADC's full scale Voltage

$ENOB$ → ADC's Effective number of bits

Propagation of Error

When uncertain quantities are multipled or divided, the total uncertainty can be calculated by summing relative uncertainties.

if

$$R = \frac{XYZ}{P} \Rightarrow \Delta R = |R|\left(\left|\frac{\Delta X}{X}\right| + \left|\frac{\Delta Y}{Y}\right| + \left|\frac{\Delta Z}{Z}\right| + \left|\frac{\Delta P}{P}\right|\right)$$

uncertainty of R   Relative uncertainties of each element

When uncertain quantities are added or subtracted, the total uncertainty can be calculated by summing absolute uncertainties

if

$$R = X + Y - Z \Rightarrow \Delta R = |\Delta X| + |\Delta Y| + |\Delta Z|$$

Errors Due to Time Varying Inputs

approximate the measurement system's transfer function first order

$$\frac{Y_{out}(s)}{Y_{true}(s)} = \frac{K_s}{\tau_s s + 1}$$

K_s → steady state gain, usually 1

τ_s → dominant time constant

$$\tau_s = 0.455 t_r \rightarrow \text{rise time}$$

$$= \frac{1}{\omega_b} = \frac{1}{2\pi f_b} \rightarrow \text{bandwidth}$$

A step input applied at $t = 0$

$$y_{out}(t) = y_{out}(0) e^{-\frac{t}{\tau_s}} + K_s\left(1 - e^{-\frac{t}{\tau_s}}\right) y_{true}$$

Rule of thumb: Wait until the effect of the trasient on y_{out} drops to $\frac{1}{10}$ of accuracy

How long should system wait to read output ←

$$t \geq -\tau_s \ln\left(\frac{0.1|a_y|}{\max(y_{max} - y_{out}(0),\ y_{out}(0) - y_{min})}\right)$$

a_y → accuracy

y_{max}, y_{min} → upper and lower limit of the sensor's range

Worst case error

$$\Delta y_{out}(t) = |a_y| + \max(y_{max} - y_{out}(0),\ y_{out}(0) - y_{min}) e^{-\frac{t}{\tau_s}}$$

An input consisting one or more sinusoids

$$\underbrace{y_{true}(t) = A_{true} \sin(\omega t)}_{\text{Input}} \Rightarrow y_{out}(t) = A_{out}(t) \sin(\omega t + \phi(\omega))$$

$$= K_s M(\omega) A_{out} \sin(\omega t + \phi(\omega))$$

$M(\omega) = \frac{1}{\sqrt{1+\omega^2\tau_s^2}}$ magnitude

$\phi(\omega) = -\tan^{-1}(\omega\tau_s)$ phase shift in radians = error in phase input & output

$t_d = -\frac{\phi}{\omega}$ time delay due to shift

$\Delta A_{out}(\omega) = |a_y| + \left(\sqrt{1+\omega^2\tau_s^2} - 1\right) A_{out}(\omega)$ Worst case error

Error Caused by Numerical Differentiation

estimate velocity $V_{est}(kT) = \frac{P(kT)-P((k-1)T)}{T} = \frac{P_{true}(kT)-P_{true}(k-1)T}{T} + \frac{e_p(kT)-e_p(k-1)T}{T}$ → measurement error

form of amplified noise

Worst case velocity error $\Delta V_{est} = \frac{T}{2}\max(|a_{true}|) + \frac{2\Delta P}{T}$

Smaller T ⇒ smaller truncation + larger amplification of position measurement noise

phase lag ← truncation backward differencing

$T_{opt} = \sqrt{\frac{4\Delta P}{\max(|a_{true}|)}}$ → position

Optimal sampling period value

$\Delta V_{est} = \frac{T}{2}\max(|\cancel{a}\, a_{true}|) + \frac{2\Delta P}{T}$ sensed by an ~~[illegible]~~ incremental encoder

$= \frac{T}{2}\max(|a_{true}|) + \frac{\text{encoder position resolution}}{T}$

need to consider the frequency of noise

Sensed by a position sensor with analog output

99.7% conf $\Delta V_{est} = \frac{T}{2}\max(|a_{true}|) + \frac{6\sigma_P}{T}$ → standard deviation

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Actuator: a device that converts energy into a force or torque that produces motion.

e.g. motor applies torque to robot, furnance heats the air

Mechanism: commonly used in mechatronic designs to transform motion or to provide a mechanical advantage

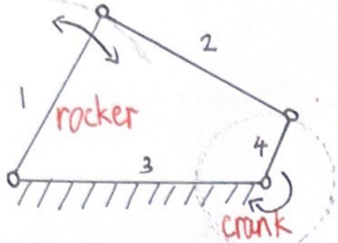
$\boxed{\text{actuator}} \xrightarrow{\text{input}} \boxed{\text{mechanism}} \longrightarrow$ larger force or torque

increase in force ⇒ decrease in speed

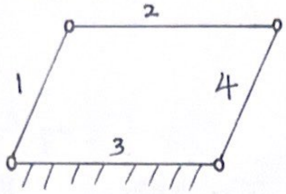
link: a rigid body used to connect two joints

crank: a link that is capable of making full rotation four-bar mechanisms ① crank-rocker ② double-crank ③ slider-crank

① rotatory => oscillatory



② double-crank



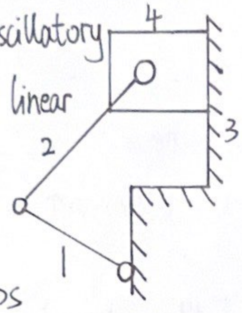
1 = 4 , 2 = 3

all in parallel

inputs and outputs links will both rotate fully and at the same speed

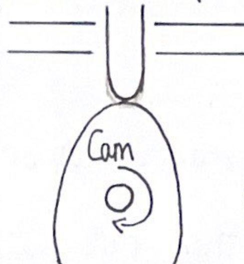
③ oscillatory

rotatory => linear



application: pumps

Cam and Cam follower



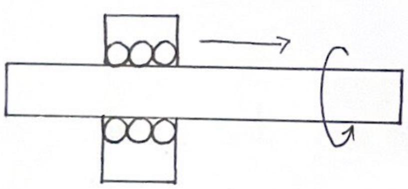
rotatory => oscillatory motion

shape of cam can be used to produce different output motion

Mechanisms for Conversion of Rotatory to linear and linear to Rotatory

1. Linear screws and ball screws

a combination of a precisely made screw and nut (prevented from rotating)



ball bearing: convert sliding contact between screw and nut into rolling contact

reduce wear and power loss to friction

Advantage: Ball screws have very good accuracy and large motion range

Disadvantage: High cost, typically cannot be used to convert linear to rotatory

Example Application: CNC machine tools and robots

$$\tau = \frac{F\,l}{(2\pi/\text{rev})\,\eta_s}$$

load (F); amount of linear motion per revolution (lead) (l)

input torque (τ)

efficiency of the screw (η_s) =1 if no friction

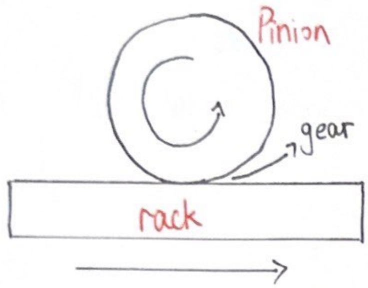
$$J = M\left(\frac{l}{(2\pi/\text{rev})}\right)^2$$

mass (M); lead (l)

equivalent rotational inertia (J)

Assume: Torque to accelerate the screw is negligible

2. Rack and Pinion



linear motion per revolution $= (2\pi/\text{rev})\, r_p$ → radius of the pitch circle

torque

force output ← $F = \frac{\tau_{in}}{r_p}\eta_{rp}$ → efficiency, =1 if no friction

radius

if rack attached to actuator

$\tau_{out} = F_{in} r_p \eta_{rp}$

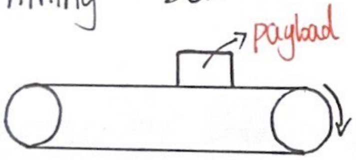
$J = M r_p^2$

inertia   mass

Advantage: Large motion range, less expensive than ball screw. Can be used to convert rotatory to linear motion and vice-versa.

Disadvantage: Less accurate than ball screw due to wear and backlash.

3. Timing Belt



belt with teeth, prevent from slipping

typically one of pulleys is driven by a rotatry actuator

Advantage: Low cost solution

Disadvantage: Only suitable for driving small loads due to the flexibility of the belt. The rubber belt teeth are sensitive to wear.
Less accurate than ball screw and pinion

Example Application: Photo copiers and ~~desk~~ desktop scanners

4. Cam and Cam follower

Advantage: Compact. Suitable for very high speed motion

Disadvantage: Small motion range. Cannot be used to convert linear to rotatry motion

Example Application: Used in some robot grippers to open / close the jaws

Electric motor: the most common actuators used in mechatronic designs.

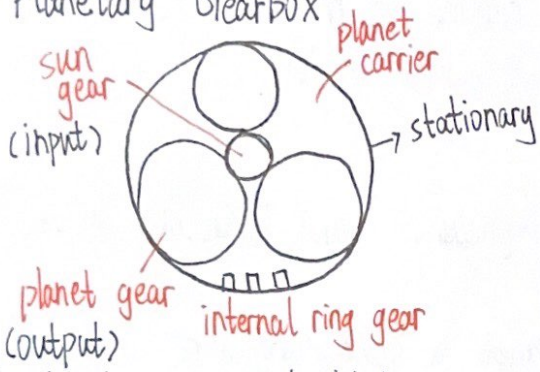
Do not produce high torques at low speeds

compact, low weight

gearbox: most common solution ① Planetary gearbox ② harmonic drive reducers

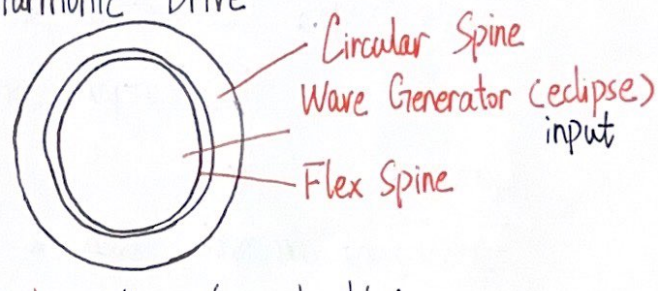
low inertia

Planetary Gearbox



Disadvantage: gear backlash introduces position errors

Harmonic Drive



Does not suffer from backlash

But the flexibility of the flex spine does lead to position error.

Gearbox Equation

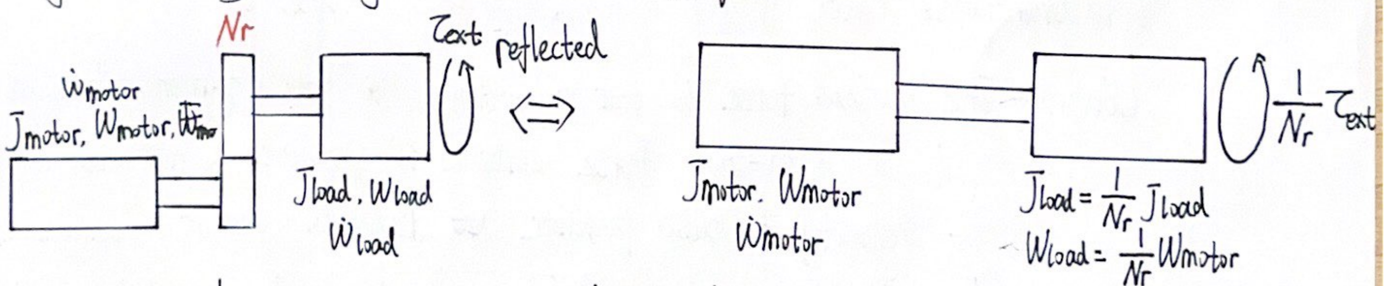
$\omega_{out} = \frac{1}{N_r}\omega_{in}$ angular velocity

$\dot{\omega}_{out} = \frac{1}{N_r}\dot{\omega}_{in}$ angular acceleration

$\tau_{out} = N_r \tau_{in} \eta_g$ torque

N_r: gear ratio

η: efficiency



$$\tau_{reflected} = \frac{1}{N_r} J_{load}\dot{\omega}_{load} + \frac{1}{N_r}\tau_{ext} = \frac{1}{N_r} J_{load} \frac{1}{N_r}\dot{\omega}_{motor} + \frac{1}{N_r}\tau_{external}$$

$$= \frac{1}{N_r^2} J_{load}\dot{\omega}_{motor} + \frac{1}{N_r}\tau_{ext}$$

$$\tau_{motor} = J_{motor}\dot{\omega}_{motor} + \tau_{reflected}$$

$$= J_{motor}\dot{\omega}_{motor} + \frac{1}{N_r^2} J_{load}\dot{\omega}_{motor} + \frac{1}{N_r}\tau_{ext}$$

Electrical Actuators

1. Solenoids: Consists of a coil and a soft iron core. When current flows through the coil the core is pulled inwards.

   Advantage: Fast response, simple design and do not wear

   Disadvantage: The output force and range of motion are small. The output force is ~~unidirect~~ undirectional

   Control: on / off

   Application: Commonly used to actuate pneumatic and hydraulic valves.

2. Voice Coils: consist of a permanent magnet, a stationary iron core and a movable coil. The iron core intensifies the magnetic field produced by the PM.

   Advantage: Bidirectional force output, fast response, simple design, compact and do not wear

   Disadvantage: Small motion range, Higher cost due to PM

   Control: The output force is ~~por~~ proportional to the current through the coil so open-loop force control is possible. Continuous control of velocity is also possible but requires sensor feedback.

   Application: Positioning of read/write head of hard disk, control of the spool position with hydralic or pneumatic servo valves.

3. DC Motors: PM DC brush & PM DC brushless motors

   in the past rotor windings needed to generate magnetic field strength

   nowadays replace windings with PMs, eliminates heat generated by rotor windings stationary stator (PMs), rotating rotor (several coils)

commutator: uses split ring and metal or graphite brushes to switch direction.

Brush:

Advantage: Relatively easy to control and interface

Disadvantage: Relatively low torque output, the brushes wear, cause friction losses, and can ~~ca~~ cause arcing ⇒ create electric noise and can be a safety problem in some application.

Brushless: rotor (permanent magnets) stator (~~sevrd~~ several coils)

Advantage: ~~Relu~~ Relatively easy to control and interface, No problems due to brushes, greater reliability, better communication, can produce higher continuous torque, better heat dissipation

Disadvantage: More expensive, more difficult to produce constant torque output at high speeds increased momentum less sensitive to torque ripple

Control: easy to control because output torque is proportional to input current for a constant load torque, speed is roughly proportional to input voltage Continuous control of torque, velocity and position is possible.

Application: positioning in numerous mechatronic devices. such as robots, machine tools, and vedio cameras

Mathematical Modelling

$$V_a = K_b W + L_a \frac{di}{dt} + R_a i_a$$

$$J \frac{dw}{dt} = K_t i_a - K_d W - \tau_{load}$$

V_a: armature voltage R_a: armature resistance

K_b: back emf constant i_a: armature current

L_a: armature inductance

J: moment of inertia of the motor

τ_{load}: torque due to load

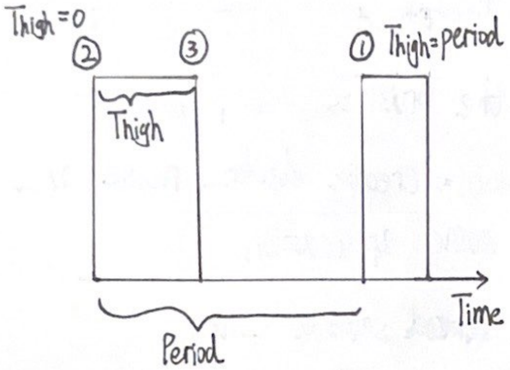
K_d: damping constant

K_t: torque constant

Position control of PM DC motor is only possible using closed-loop control.

incremental encoder is the most common source of position feedback

control algorithm executed on $\mu C \xRightarrow{\text{output}}$ Pulse - Width - Modulated signal



① output voltage = V_{high}

② output voltage = V_{low}

③ $V_{out} = V_{average}$ + High frequency signal

$= \frac{T_{high} V_{high} + (Period - T_{high}) V_{low}}{Period}$ + High frequency signal

filter out high frequency component

Advantage: Inexpensive. May be used to switch the transistors in a "switching amplifier"

Switching transistors on/off is more energy efficient than in linear region

Disadvantage: high frequence component is actually high frequency noise. can be picked up by other elements and affect control performance

4. Linear Motors: DC, AC or stepper motor whose stator has been unwrapped into a linear form.

Advantage: Capable of achieving very high acceleration and range of speeds

Can be made no contact, can be 2-D, no backlash, smaller size, Better reliability

Disadvantage: High cost, Sensitive to dirt, to increase range of motion the size should be increased => increased cost, no machnical advantage for ball screw (or other mechanism) to help provide force

5. Stepper Motor: moves in small angular increments

① PM stepper Motor

accompolished by electronically switching the polarity of the stator windings.

Full stepping mode: reverse the polarity of a pair of poles. step angle $=90°$

Half stepping mode: one of pair is shutting off. step angle $=45°$

disadvantage: average torque output is reduced.

Microstepping: position is incremented by decreasing the current in one pair.

dis advantage: more complex and expensive controller required.

② VR Stepper Motor

rotor and stator are cut with small grooves to form teeth

rotor moves the position of lowest reluctance.

step angle $= 360° /$ rotor teeth $*$ num of pair of poles (phase)

③ Hybrid stepper Motor

combines the best features of the two above

Advantage: less expensive, less complex, no potential for closed-loop instability

Disadvantage: less torque than DC motor of small size, care must be taken so that controller and motor remain synchronised, small acceleration and payloads, no useful in presence of large disturbance, less ~~no~~ smooth & low efficiency

Control: performed open-loop, control position, velocity and acceleration

Application: Any positioning application that does not involve large loads or accelerations

Under steady state, $\frac{d\omega}{dt}=0$, $\frac{di_a}{dt}=0$, no friction

$V_a = K_b\omega + R_a i_a$

$\tau_{load} = K_t i_a - K_d\omega$ } input

$\tau_{load} = K_t i_a$ => output

$$\eta_{motor} = \frac{\text{mechanical output}}{\text{electrical input}} = \frac{\tau_{load}\,\omega}{V_a i_a} = \frac{K_t i_a \omega}{K_b \omega i_a + R_a i_a^2}$$

maximized at max speed

$$\eta_{motor+gear} = \eta_{motor}\,\eta_g = \frac{K_t i_a \omega}{K_b \omega i_a + R_a i_a^2}\,\eta_g$$

$$N_{r,opt} = \sqrt{\frac{J_{load}}{J_{motor}}}$$

closest smaller avaliable gear ratio should selected

α will be maximized when gear ratio is above

$$\text{Ratio}_J = \frac{J_{load}/N_r^2}{J_{motor}}$$

$= 1$

1 will maximize power

inertia matching: keep inertia ratio as close to 1 as possible, with 1 to 10. Larger than 10 will be unstable.

$$\tau_{motor,RMS} = \sqrt{\frac{\sum_{i=1}^{n} \tau_{motor,i}^2 t_i}{\sum_{i=1}^{n} t_i}}$$

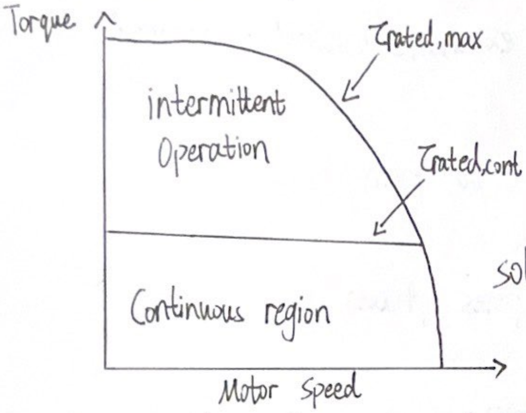
$\tau_{motor,i}$: the torque for the i^{th} period

t_i : duration of the i^{th} period

n : number of periods

a motor can operate at it maximum rated torque $\tau_{rated,max}$ intermittently — thermally damaged if work too long

motor can also produce a smaller torque $\tau_{rated,cont}$ continuously



acceptable: $\omega_{motor,max}$ & $\tau_{motor,RMS}$ lies within the region of continuous region.

$\omega_{motor,max}$ & $\tau_{motor,max}$ is below the boundary of intermittent region

solution: ① changing N_r (increase N_r decrease torque)

② increasing $\omega_{motor,max}$

Selection procedure for a DC motor and gearbox

1. Calculate desired motion profiles if not provided
2. Based on the load, motor data and ~~mech~~ mechanisms used, select gear ratio maximizes acceleration, or let inertia ratio closest to 1.
3. Based on velocity profile. find ω_{max}. Compare $\omega_{motor,max} = N_r \omega_{max}$ to $\omega_{rated,max}$. Until a suitable one is found.
4. Based on the material provided, calculate $\tau_{motor,max}$.
5. Check if $\tau_{motor,max} < \tau_{rated,cont}$
6. Compute $\tau_{motor,RMS}$. check if $\tau_{motor,RMS} < \tau_{rated,cont}$

yes

7. Select a higher gear ratio if possible, or select a more powerful motor.
8. Check if temp rise is acceptable. If not then try increase gear ratio. If no sufficient then ~~eth~~ either try additional cooling, or select a more powerful motor.

$$P_j = I^2 R_{Hot}$$

Power loss — P_j; current — I; R_{Hot} — motor thermal resistance

increases as the temperature increases

typically gives at 25°C

copper winding resistance: $R_{Hot} = R_{25}(1 + 0.00392(T_{Hot} - 25))$ — T_{Hot}: desired operating temperature

Thermal resistance $R_{th} = R_{th_1} + R_{th_2}$ — R_{th_2}: indicator of heat transfer from housing to ambient

↳ ~~热~~ characterizes heat transfer from windings to housing

Winding Temperature:

$$T_w(t) = T_{initial} + (P_j R_{th} + T_a - T_{initial})(1 - e^{\frac{-t}{\tau_w}})$$

T_a: ambient temp

τ_w: amount of time to reach 63.2% of steady state temp

if t is greater than $7\tau_w$, can be simplified: $T_w = T_a + P_j R_{th}$

if motor is turned off when $T_w > T_a$, the temperature falls:

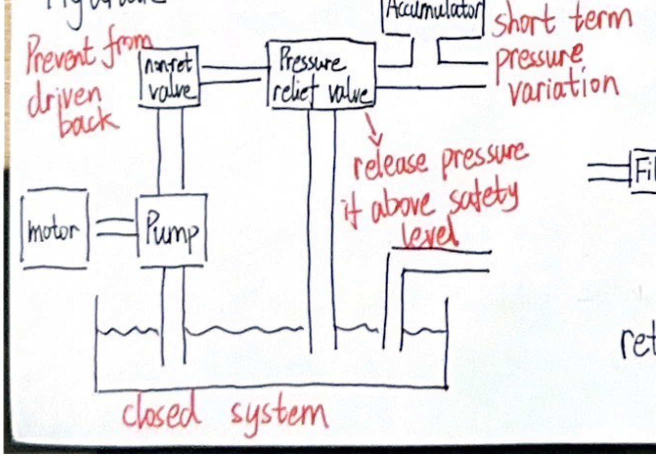
$$T_w(t) = T_{initial} + (T_a - T_{initial})(1 - e^{\frac{-t}{\tau_w}})$$

Pneumatic and Hydralic Actuators

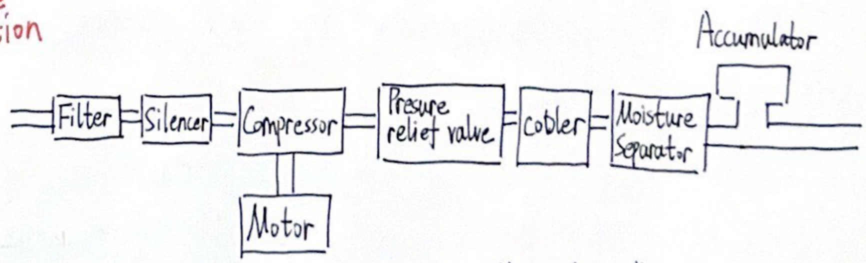
Advantage: provide much higher ratios of (force or torque) to (mass and size) than electromechanical actuators. Less expensive when accurate control not required. Mechanically stiffer than electrical actuators. Many companies have a factory wide high pressure air supply.

Disadvantage: The compressibility of air makes continuous position control very difficult. Hydralic actuators are more expensive than pneumatic actuators. Hydralic oil is toxic and flammable. Hydralic actuators operate at high pressures. Pneumatic and hydralic are much larger and more complex than electrical ones.

Hydralic



Pneumatic: operate at lower pressure



reture air are exhausted into the atmosphere

Pneumatic and Hydralic Cylinders: Two types. Double acting & Single acting with spring return

Double acting: has two bidirectional ports, possible to continuously control

Single acting: a single hose and simpler valve. Disadvantage of only supply unidirectional force, not suitable for position or force control applications.

Output force in the extend direction

$$F_{extend} = \underbrace{P_{extend}}_{\text{gauge pressure}} A_{extend} - P_{retract} A_{retract}$$

Output velocity $V = \dfrac{Q}{A}$ $Q \rightarrow$ volume flow rate

$$A_{extend} = \frac{\pi D_{bore}^2}{4}, \quad A_{retract} = \frac{\pi (D_{bore}^2 - D_{rod}^2)}{4}$$ for single acting cylinder

Control Valves: used to direct the flow, and/or to change the flow rate, and/or to change the pressure

finite position if valves can either be open or closed.

continuous (infinite) valves: proportional valve allows orifice area to be adjusted in proportional to an input voltage.

higher cost ← servo valve has built in colsed-loop control system give faster and more accurate response.

Valve sizing equation

$$C_v = 4.22 \times 10^4 Q \sqrt{\frac{\rho}{\Delta P}} \quad \text{or} \quad Q = 2.37 \times 10^{-5} C_v \sqrt{\frac{\Delta P}{\rho}}$$

Q: required volume flow rate

ΔP: pressure drop

ρ: density

ρ for air:

$$\rho = \frac{P_2}{R_g T} = \frac{P_1 - \Delta P}{R_g T}$$

P_2: absolute outlet pressure

T: air temperature

R_g: gas constant

P_1: absolute inlet pressure

Piezoelectric Actuators

Applied ~~force~~ electric charge parallel to the direction of polarization of the crystal causes expansion and force output.

made of several layers (each < 1mm)

Advantage: Better energy efficiency, suitable for miniaturization, capable of nanometre resolution, capable of response times < 1ms, capable of large output force, large stiffness when pushing, no wear

Disadvantage: very small range of motion, low polling force unless preloading is used, large displacements require large voltages. Sensitive to temperature changes. Requires complex form of closed-loop control to achieve low frequency displacements. Subject to fatigue failure

Application: Inkjet printer heads, piezoelectric valves, vibratory feeders, optical alignment, precision assembly and precision ~~etching~~ machining.

Shape Memory Alloy Actuators

at low temperature, pushed and the ~~shapes~~ shape is changed; at high temperature, SMA spring recovers its original shape and push back the shaft.

Advantage: Simple one piece design, material can be shaped for the application. Large force per unit area, no wear.

Disadvantage: Slow response speed, small range of motion, operating temperature is approximately 90°C, subject to fatigue failure, large hysteresis, unidirectional, low energy efficiency.

Control: Typically by controlling the electric current flowing through the actuator, this allows the temperature and resulting displacement to be altered.

Applications: valves, electronic locks, safety devices.

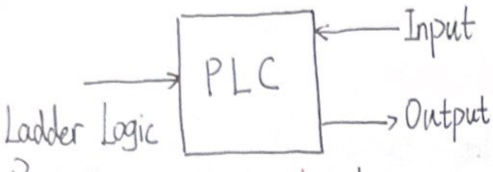
Ultrasonic Motors

a special type of piezoelectric actuator, can be linear or rotary. electric driven

Advantage: provide high torque at low speed. Small and lighter, can produce large acceleration due to small rotor inertia. Rotor is locked when power is off. Suitable for miniaturization.

Disadvantage: Relies on friction to provide torque. Subject to fatigue and wear. Driven by large voltages relative to DC motors. Torque is not controller

Application: lens motors in autoforcus cameras.



Ladder Logic: most common programming language

Consists of a series of groups of instructions / rungs

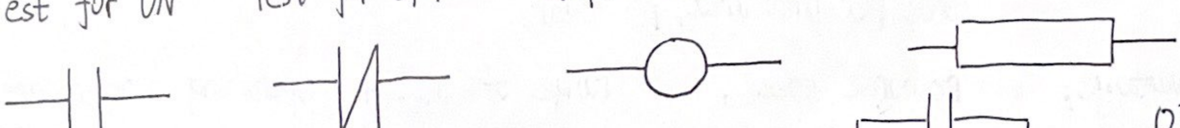
never wait at a rung, starts again when running at the end of system

1. Each rung must begin with one or more "Test for ON" or "Test for OFF" and end with an output instruction or a special instruction.
2. Each output instruction should occur once in a program.

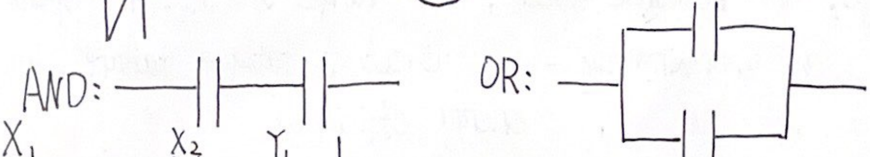
normally open pushbutton: press provides ON, not press provides OFF

normally closed pushbutton: press provides OFF, not press provides ON

Test for ON   Test for OFF   Output instruction   Special instruction



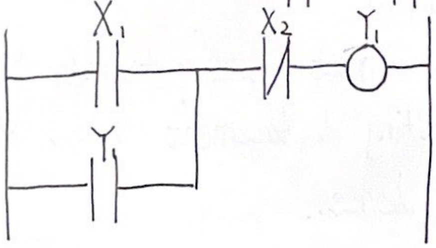
Logic Function:



OFF = 0

ON = 1

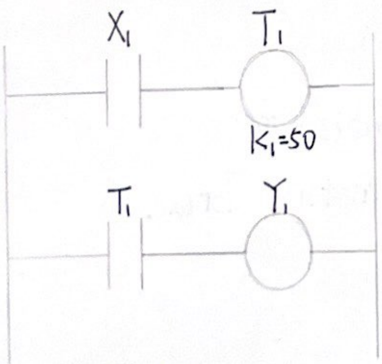
Latching:



when X_1 pressed, Y_1 is on. After that X_1 OFF, Y_1 still ON. Only when X_2 pressed to make Y_1 stop.

Timer: Delay-On Timer: The logic input must be held for ON for greater than delay period for the timer output to turn ON.

Timer resets and turned OFF is OFF signal is passed.



When X_1 is ON and stays ON, timer T_1 starts counting until $50 * a_s$ has passed. The T_1 will be ON and put output Y_1 work.

timer resolution: a_s

Marker: internal signals that are not connected to an external input or output device. OFF/ON state is not lost when PLC temporarily loses power.

Counter:

Reset
C_1 $k_1 = k$
Count

will not count when the Reset is ON, and will reset the accumulator to zero.
Count until k rising edge to make C_1 ON.

Data Handling Instructions: operate data (bits ~~work~~ word)

Move: | MOV | S | D |
move S to D storage

Compare: | ? | S | D |
ON ~~is~~ if S ? D

Add: | + | D_0 | D_1 | Can also sub
$D_1 = D_0 + D_1$

Retentive Timer:

Start/Stop
RT_1 K = ?
Reset

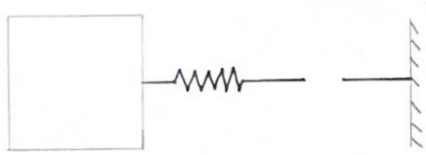
works only when Start/Stop is ON. Stops if the signal is OFF. Set RTA_1 to zero if Reset is ON.

Up Down Counter (Reversible Counter)

UDC1 K=?
UP
DOWN
RESET

Let $UDCA_1$ to increment or decrement.
Make $UDCA_1$ zero if the RESET is ON.

Mechanical System



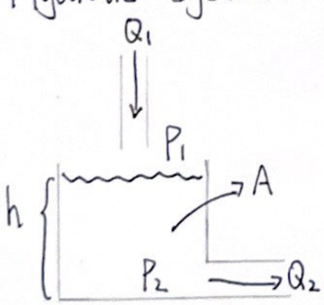
Spring Force: $F = Kx$ deflection
Damping Force: $F = Cv = C\dot{x}$ velocity
Newton's Second Law: $\sum F = ma = m\ddot{x}$

Electrical System

Inductor: $V = L\frac{di}{dt}$ Capacitor: $i = C\frac{dV}{dt}$ Resistor: $V = iR$

Kirchhoff's Law
1. The sum of currents at a junction must equal to zero
2. The sum of voltage drops in a loop must equal to voltage supply

Hydralic System

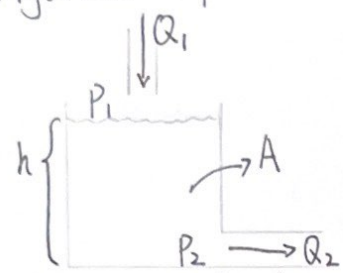


Hydralic resistance: a liquid flow through a valve or a decrease in pipe diameter

$P_1 - P_2 = RQ \rightarrow$ Volume flow rate
$P_1 - P_2$: Pressure Drop
R: Hydralic Resistance

dissipates energy

Hydralic Capacitance



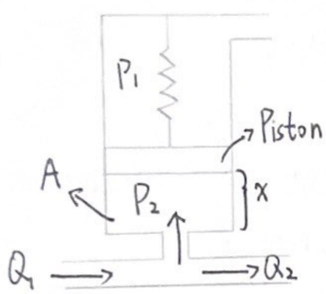
pressure head

$$Q_1 - Q_2 = \frac{dV}{dt} \text{ change in volume} \qquad V = A h \quad (A \to \text{cross-section area})$$

$$Q_1 - Q_2 = A\frac{dh}{dt} \qquad P_2 - P_1 = \rho g h \text{ change in pressure}$$

$$\underbrace{C = \frac{A}{\rho g}}_{\text{Capacitance}} \Rightarrow Q_1 - Q_2 = C\frac{d(P_2-P_1)}{dt} \qquad P_2 - P_1 = \frac{1}{C}\int (Q_1 - Q_2)\,dt$$

$P_1 = 0$ if the tank is open at top and gauge pressure is used.



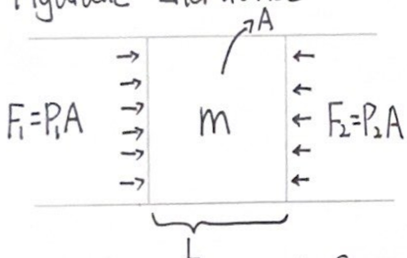
Accumulator

$$Q_1 - Q_2 = A\frac{dx}{dt} \qquad x = \frac{F}{k} = \frac{(P_2-P_1)A}{k} \text{ displacement of the piston}$$

$$\underbrace{C = \frac{A^2}{k}}_{\text{Capacitance}} \Rightarrow Q_1 - Q_2 = C\frac{d(P_2-P_1)}{dt} \qquad P_2 - P_1 = \frac{1}{C_*}\int (Q_1 - Q_2)\,dt$$

$P_1 = 0$ if open at top and gauge pressure is used

Hydralic Inertance



$$\Sigma F = (P_1 - P_2)A = ma = AL\rho\frac{dv}{dt} \quad (v \to \text{Velocity}) \qquad v = \frac{Q}{A}$$

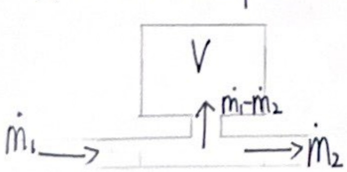
$$\underbrace{I = \frac{L\rho}{A}}_{\text{Inertance}} \qquad \rho: \text{density of the block} \qquad P_1 - P_2 = I\frac{dQ}{dt}$$

Kirchhoff's law
1. Sum of flow rates at a junction $= 0$
2. Sum of pressure drops around loop = supply pressure

Pneumatic Systems

mass flow rate is used $P_1 - P_2 = R\dot{m}$ ($R \to$ Pneumatic Resistance)

Pneumatic Capacitance : the same as hydralic accumulator



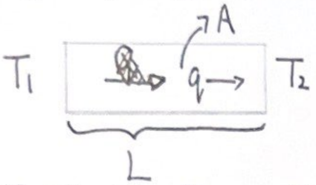
$$\dot{m}_1 - \dot{m}_2 = V\frac{d\rho}{dt} \qquad PV = mR_gT$$

$$C = \frac{V}{R_gT} \Rightarrow \dot{m}_1 - \dot{m}_2 = C\frac{dP}{dt} \text{ change of pressure}$$

Pneumatic Inertance : $\underline{I} = \frac{L}{A} \qquad P_1 - P_2 = \underline{I}\frac{d\dot{m}}{dt}$

Thermal System

thermal resistance: $T_1 - T_2 = Rq$ → rate of heat flow



unidirectional conduction through solid: $R = \frac{L}{AK}$ → K: thermal conductivity

liquid and gas: $R = \frac{1}{Ah}$ → h: coefficient of heat transfer

if $T_1 > T_2$, flow right

thermal capacitance: $q_1 - q_2 = mc\frac{dT}{dt} = C\frac{dT}{dt}$

C: specific heat capacity
m: mass
T: temperature

Non-linear Elements

approximate non-linear to linear

1. elements that having an operating region over which linearity may be assumed
2. elements that may be approximated by a linear system at particular condition

if $y = f(x) \Rightarrow \Delta y = \left(\left.\frac{df}{dx}\right|_{x=x_0}\right)\Delta x$. for multiple input, just add all

Dead Time (Time Delay)

$$out = \begin{cases} 0 & t < \tau_d \\ in(t-\tau_d) & t \geq \tau_d \end{cases}$$

τ: period of dead time

$\frac{Out(s)}{In(s)} = e^{-\tau_d s}$ in Laplace transform

minimize dead time:

1. make actuator and sensor are close together ⇒ transport delay
2. send high-level command and let it perform locally.

State Space Method

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) + Du(t) \end{cases}$$

usually zero

$\left.\begin{array}{l} x(t) = [x_1(t), x_2(t), \ldots, x_n(t)]^T \\ \dot{x}(t) = [\dot{x}_1(t), \dot{x}_2(t), \ldots, \dot{x}_n(t)]^T \end{array}\right\}$ states

$u(t)$: input
⇓
$[u_1(t), u_2(t), \ldots, u_m(t)]^T$

$y(t) = [y_1(t), y_2(t), \ldots, y_p(t)]$ output

advantage:

1. Matrix form of state space makes very well suited for computer simulations
2. Much simpler to use with multiple input & output systems
3. The conversion of a transfer function into state space is straightforward

approximate $\dot{x}(t)$: $x(t+\Delta t) = x(t) + \Delta t * \dot{x}(t)$ at small time change

Discrete Time Model:

signals are measured at each sampling period / interval T

Objective of control system:

1. Regulating: Keeping the process output close to a constant value of the reference input in the presence of external disturbance.
2. Servoing: Making the process output respond to changes in the reference input in a specific way.

Control Algorithms

ON-OFF Control: output is binary (either ON or OFF)

rapid switching causes rapid actuator wear and fatigue

Advantage: Extreme simple to implement. Cannot go unstable

Disadvantage: Output oscillations are unavoidable.

PID Control: most popular. $\frac{U(s)}{E(s)} = K_P(1 + \frac{1}{s}K_I + sK_D) \Rightarrow \frac{U(z)}{E(z)} = K_P(1 + K_I\frac{Tz}{z-1} + K_D\frac{z-1}{Tz})$

tuning: selection of controller gains or other parameters to achieve a desired closed-loop performance.

K_P improves speed of response

K_I eliminates steady state error but also add phase lag to the system

K_D adds damping and phase lead to the ~~respon~~ response

Set all gains equal to zero

Increase K_P until step response has excessive overshoot.

Increase K_D until the overshoot of step response has the desired value

Increase K_I until steady state error is eliminated.

Model-Based Digital Control

Digital control system stable if all poles are all inside the unit circle

Ragazzini's Method: if $Q(z) = \frac{D(z)G(z)}{1+D(z)G(z)}$ is a digital transfer function

$H(z)$ is the desired closed-loop function $\Rightarrow$ $D(z) = \frac{U(z)}{E(z)} = \frac{1}{G(z)} \frac{H(z)}{1-H(z)}$

1. Causality Rule: the dead time of $H(z)$ must be greater than or equal to the dead time of $G(z)$. Normally pick $H(z) = G(z)$ dead time

dead time = (highest power z denominator − lowest power z numerator) * T

in sampling period of the digital system.

2. Stability Rule: 1) Poles of $H(z)$ must not lie outside unit circle

2) $H(z)$ must contain as zeros all of the zeros of $G(z)$ that lie out of the unit circle.

3) ~~$H(z)$~~ $1-H(z)$ must contain as zeros all of the poles of $G(z)$ that lie outside the unit circle

3. Steady-State Error: $E(z) = R(z)(1-H(z))$ final value when $z=1$

$H(1)=1$ to have zero error for step input and finite error to ramp input.

error in ramp input: $e(\infty) = \underbrace{\sum_{i=1}^{n} \frac{T}{1-p_i}}_{\text{poles}} - \underbrace{\sum_{j=1}^{m} \frac{T}{1-q_j}}_{\text{zeros}}$

4. Transient Response: $z = e^{Ts} = e^{aT+jbT} = e^{aT}(\cos(bT) + j\sin(bT))$

5. Sensitivity to Modeling Errors: closer of poles to origin, faster response.

greater difference between poles of $H(z)$ and $G(z)$, more sensitive the controller will be to modeling errors.

inverse z transform: multiplying $z^{-n} \Rightarrow x(k-n)$

$D(z) = \frac{U(z)}{E(z)} \Rightarrow \underbrace{u(k)}_{\text{output at } kT} = ?\ \underbrace{e(k)}_{\text{error}}\ \&\ \underbrace{u(k-n)}_{\text{previous output at } (k-1)T}$

Designing for Safety

Risk Assessment and Risk Reduction: identifying all of the risks faced by anyone who may harmed by the mechatronic system, and changing the design until all risks are reduced to an acceptable level.

1) Determination of the limits of the mechatronics system. ※ must.
2) An analysis to identify potentially hazardous phenomena.
3) Evaluation of the degree of risk

System Faults and Fault Management

- Random hardware component failures, analyzed statistically
- Systematic faults due to the design of the system. not random
- Errors in the design specifications

Fault Avoidance: prevent faults due to the design of the system or errors in the design specifications.

Fault Removal: finding and correcting faults before system enters service

Fault Detection: detect faults during service, allow appropriate actions

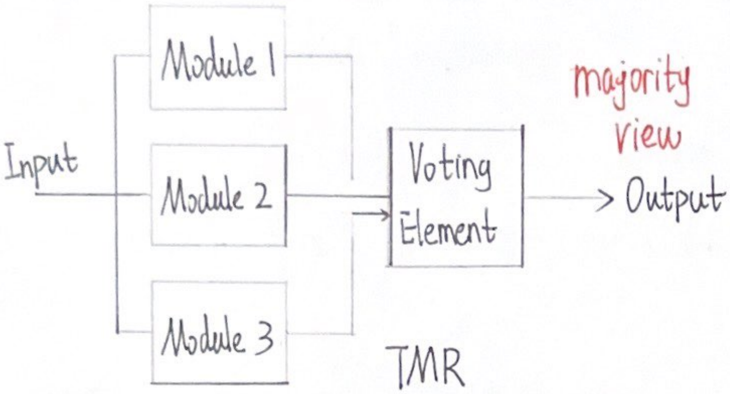
Fault Tolerance: allow system to operate properly with faults.

Fault management categories:

System architecture: main approach, provides protection against random component failure and some types of systematic faults

Reliability engineering: techniques for predicting the probability of failure and altering design until meets required reliability.

Quality management: maintaining high quality standards throught design, manufacturing and testing processes.



TMR

failure of single module ⟶ correct output

assume independent module faults

common-mode faults => design diversity

redundant module have same functionality but design independently

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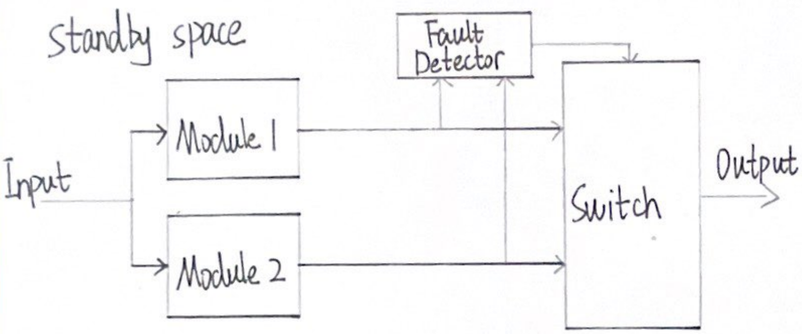
no improve reliability

Watchdog timer: common fault detection technique. A hardware timer will turn on an output if not reset before timing period finishes.

standby space



Fault Detector detect failure

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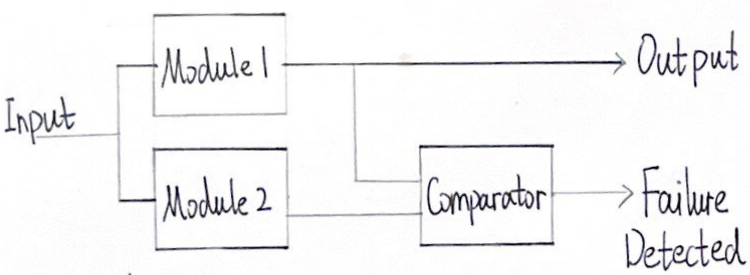
Switch choose good module

disadvantage: reliance on reliable fault detection, and disruption that occurs during detection & reconfiguration



Self-checking pair

Outputs of two modules are compared using hardware / software

failure detected if not same

Module 2 => digital twin

partitioning a system => desired design approach

aids the comprehension of the system, provides isolation between modules such that the effects of faults are localized as much as possible, reliability of modules is easier to test and verify

cares must be taken for hierarchy partitioning to prevent unsafe design

High level → command: operate if safe → lowest level: check state of safety switch and control actuators.

not practical for all systems

self-testing: done when system is in service

Safety critical elements of a system should use components that have an extensive record of reliable operation.

Proper signage. manuals, and training procedures is needed. also safety systems.

Systems should be designed for ease of maintenance