Lecture 6 February 05, 2018

Actuators and Sensors

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Announcement

- Outlines of lectures 1-3,4&5 are available in

  http://sksaha.com/courses

Review of Lecture 4&5

- **Coordinate Transformation**
  - **Relation between two coordinate frames**
  - **Homogeneous Transformation Matrix (HTM)**
- **Forward and inverse kinematics**
- **Solved examples**

Questions from Lecture 4?

- What is the size of a HTM?
- How many solution FK has?
- How many solution IK of a 2-DOF arm has?
- How many solutions IK of Kuka KR5 Arc robot has?

Project

(A report on the Exam. Day)

For your plant choose an appropriate robot for painting cylindrical box of 50cm height with 30cm diameter

(Submit a report on the day of exam.)

Outline

- **An actuation system**
- **Electric actuators**
  - **Stepper motors**
  - **DC motors**
  - **AC motors**
  - **Linear actuators**
- **Hydraulic and pneumatic actuators**
- **Selection of motors**
- **Sensors**

An Actuation System

- A power supply
- A power amplifier
- A motor
- A transmission system

Actuator vs. Motor?

(Interchangeably used)

Electric Actuators

- Electric motors

  +

- Mechanical transmissions
- First commercial electric motor: 1974 by ABB

Advantages vs. Disadvantages

- *Advantages*
  - Widespread availability of power supply.
  - Basic drive element is lighter than fluid power.
  - High power conversion efficiency.
  - No pollution
  - ↑accuracy + ↑repeatability compared to cost.
  - Quiet and clean

- Easily maintained and repaired.
- Components are lightweight.
- Drive system is suitable to electronic control.

• *Disadvantages*

- Requires mechanical transmission system.
- Adds mass and unwanted movement.
- Requires additional power + cost.
- Not safe in explosive atmospheres.

Electric Motors

- Stepper motors
  - Variable Reluctance
  - Permanent Magnet
  - Hybrid
- Small/Medium end of industrial range
- Digitally controlled → No feedback
- Incremental shaft rotation for each pulse

- Steps range from 1.8 – 90 deg.
- To know final position, count # of pulses
- Vel. = # of pulse per unit time
- 500 pulses/sec ≡ 150 rpm (1.8^{o}/pulse)
- Pulses cease, motor stops. No brake, etc.
- Max. torque at low pulse rate
- Many steppers from same source. Exact synchronization

DC Motors

- Direct Current: Used in toys etc.
- Electrically driven robots us DC
  - Introduced in 1974 by ABB
  - Powerful versions available
  - Control is simple
  - Batteries are rarely used
  - AC supply is rectified to DC

Principle of a DC Motor

- Magnetic Field → Stator
  - Field coils wound on the stators
  - Permanent magnet
- Conductor (Armature) → Rotor
  - Current via brushes + commutators
- Maximum torque for $\sigma = 90^o$

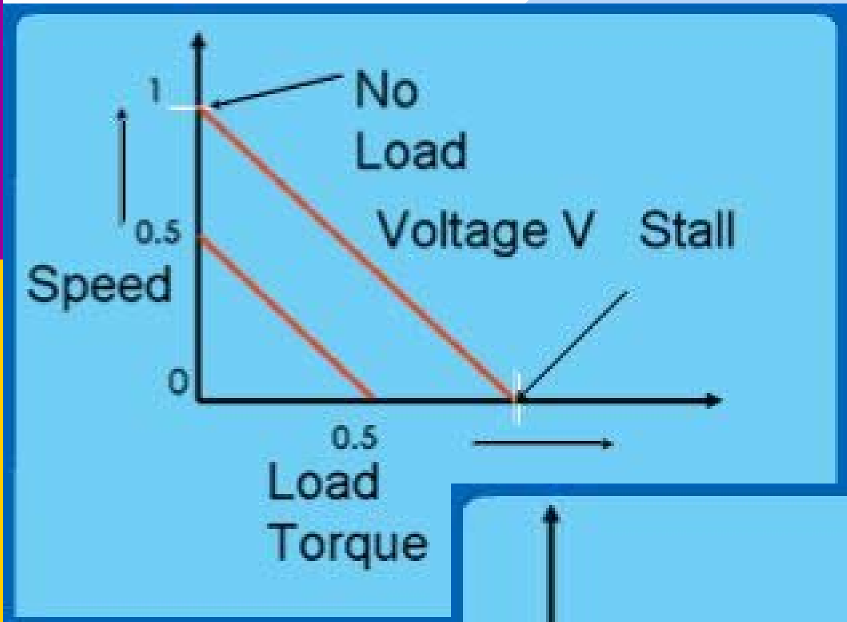
Features of a DC Motor

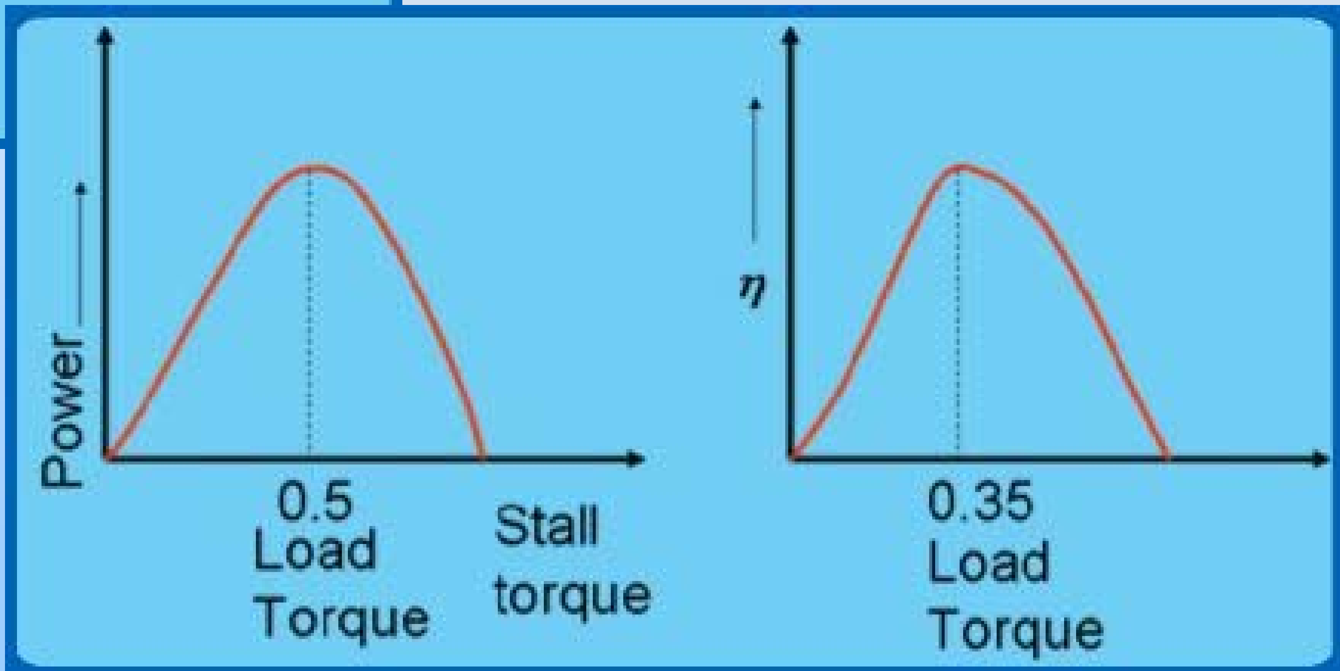
- High voltage in stator coils → Fast speed (simple speed control)
- Varying current in armature → Controls torque
- Reversing polarity → Turns opposite
- Larger robots: Field control DC motor
  - Current in field coils → Controls torque
  - High power@high speed + High power/wt.

Specification & Characteristic

Technical Specifications of DC Motors	
Brand	Parvalux
Manufacturer Part No.	PM2 160W511109
Type	Industrial DC Electric Motors
Shaft Size (S,M,L)	M
Speed (rpm)	4000 rpm
Power Rating (W)	160 W
Voltage Rating (Vdc)	50 V(dc)
Input Current	3.8 A
Height × Width × Length	78 mm ×140 mm × 165 mm

Characteristics





Permanent Magnet (PM) Motor

- Two configurations
  - Cylindrical [Common in industrial robots]
  - Disk
- No field coils
- Field is by permanent magnets (PM)
- Some PM has coils for recharge
- Torque $\propto$ Armature current [Const. flux]

Advantages of PM DC Motors

- No power supplies for field coils
- Reliability is high
- No power loss due to field supply
- Improved Efficiency + Cooling

Brushless PM DC Motor

- Problem with DC motors
  - Commuter and brushes → Periodical reversal of current through each armature coil
  - Brushes + Commutators → Sliding contact → Sparks → Wear → Change brushes + Resurface commuators
- Solution: Brushless motors

Principles of Brushless PM

- Reverse principle than convention DC
- Current carrying conductor (stator) experience a force
- Magnet (rotor) will experience a reaction (Newton's 3rd law)
- Current to stator coils is electronically switched by transistors (Expensive)
- Switching is controlled by rotor position → Magnet (rotor) rotates same direction

Advantages of Brushless PM

- Better heat dissipation
- Reduced rotor inertia
- Weigh less → Less expensive + Durable
- Smaller for comparable power
- Absence of brushes → Reduced maintenance cost
- Electric robots → Hazardous areas with flammable atmospheres (Spray painting)

AC Motors

- Alternating Current: Domestic supply
- 50 Hz; 220 V (India)
- 60 Hz; 110 V (USA)
- Difficult to control speed → Not suitable for robots

Principle of an AC Motor

- External electromagnets (EM) around a central rotor
- AC supply to EM → Polarity change performs the task of mech. Switching
- Magnetic field of coils will appear to rotate → Induces current in rotor (induction) or makes rotor to rotate (synchronous)

Specification & Characteristic

Technical Specifications of AC Motor	
Brand	ABB
Manufacturer Part No.	1676687
Type	Industrial 1-, 3-Phase Electric Motors
Supply Voltage	220 – 240 Vac 50 Hz
Output Power	180 W
Input Current	0.783 A
Shaft Diameter	14 mm
Shaft Length	30 mm
Speed	1370 rpm
Rated Torque	1.3 Nm
Torque Starting	1.3 Nm
Height × Length × Width	150 mm × 213 mm × 120 mm

Features of an AC Motor

- Higher the frequency → Fast speed
- Varying frequency to a number of robot axes has been impractical till recently
- Electromagnetism is used for regenerative braking (also for DC) → Reduces deceleration time and overrun
- Motor speed cannot be predicted (same for DC) → Extra arrangements required

Classification of an AC Motor

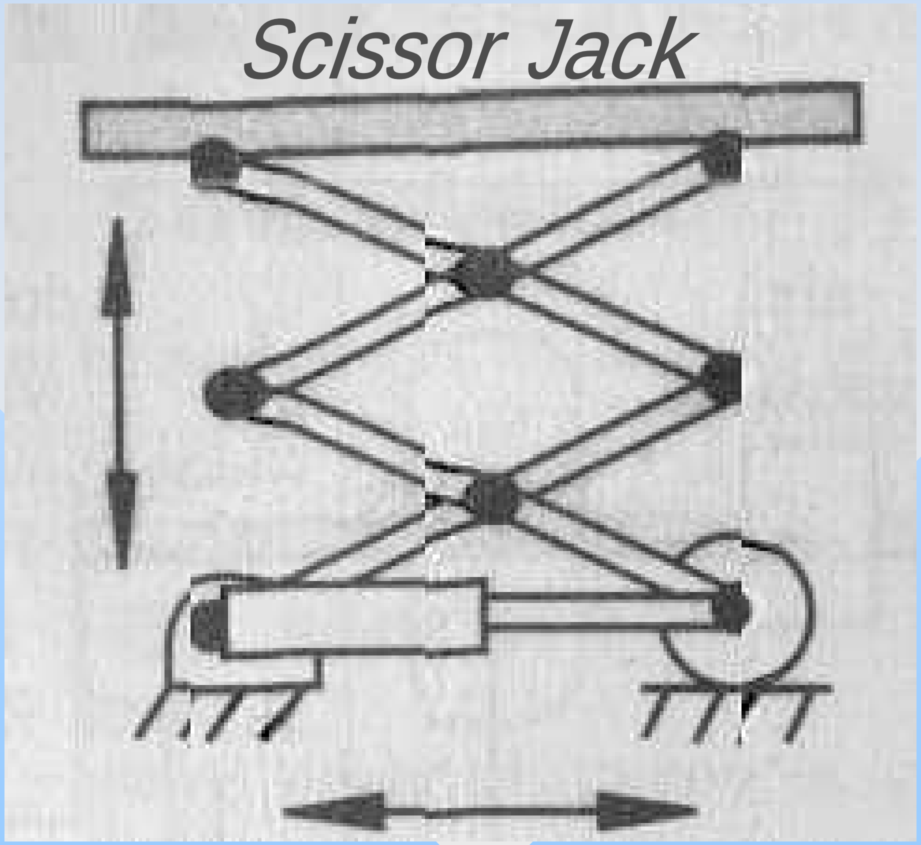
- Single-phase [Low-power requirements]
  - Induction
  - Synchronous
- Poly-phase (typically 3-phase) [High-power requirements]
  - Induction
  - Synchronous
- Induction motors are cheaper → Widely used

AC vs. DC Motors

- Cheaper, rugged, reliable, maintenance free
- Speed control is more complex
- Speed-controlled DC drive (stator voltage) is cheaper than speed-controlled AC drive (Variable Frequency Drive)
- Price of VFD is steadily reducing

Hydraulic Actuators

- Other fluid device
- Uses Mineral Oil [at 70 – 170 Bars]
- An Application



Advantages vs. Disadvantages

- *Advantages*
  - High η + power-to-size ratio.
  - Accurate control of speed/pos./dirn.
  - Few backlash prob. ⇐ Stiffness + incompressibility of fluid
  - Large forces can be applied at locations.

Backlash ≡ Unwanted play in transmission components

- Greater load carrying cap.
- No mech. linkage → Mech. simplicity.
- Self lubricating → Low wear + non-corro.
- Due to 'storage' sudden demands can be met.
- Capable of withstanding shock.

- *Disadvantages*
  - Leakages occur → Loss in performance
  - Higher fire risk.
  - Power pack is (70 dBA)
  - Temp. change alters viscosity.
  - ↑Viscosity at ↓temp. causes sluggishness.
  - Servo-control is comples

70 dbA ≡ Noise of heavy traffic

Pneumatic Actuators

- One of fluid devices
- Uses compressed air [1-7 bar; ~.1 MPa/bar]
- Components

  1) Compressor; 2) After-cooler; 3) Storage tank;

  4) Desiccant driers; 5) Filters; 6) Pressure regulators; 7) Lubricants; 8) Directional control valves; 9) Actuators

Advantages vs. Disadvantages

- *Advantages*
  - Cheapest form of actuators.
  - Components are readily available.
  - Compressed air is available in factories.
  - Compressed air can be stored, and conveyed easily over long distances.
  - Compressed air is clean, explosion-proof & insensitive to temp. var. ⇨ Many applns.

- Few moving parts → Reliable + low maint. costs
- Relevant personnel are familiar with the tech.
- Very quick → Fast work cycles
- No mech. transmission is required.
- Safe in explosive areas as no elect. contact
- Systems are compact.
- Control is simple. Mechanical stops.
- Components are easy to connect.

- *Disadvantages*
  - Air is compressible.
  - Precise control of speed/position is not easy.
  - If **no m**echanical stops resetting is slow.
  - Not suitable for heavy loads
  - If moisture penetrates rusts occur.

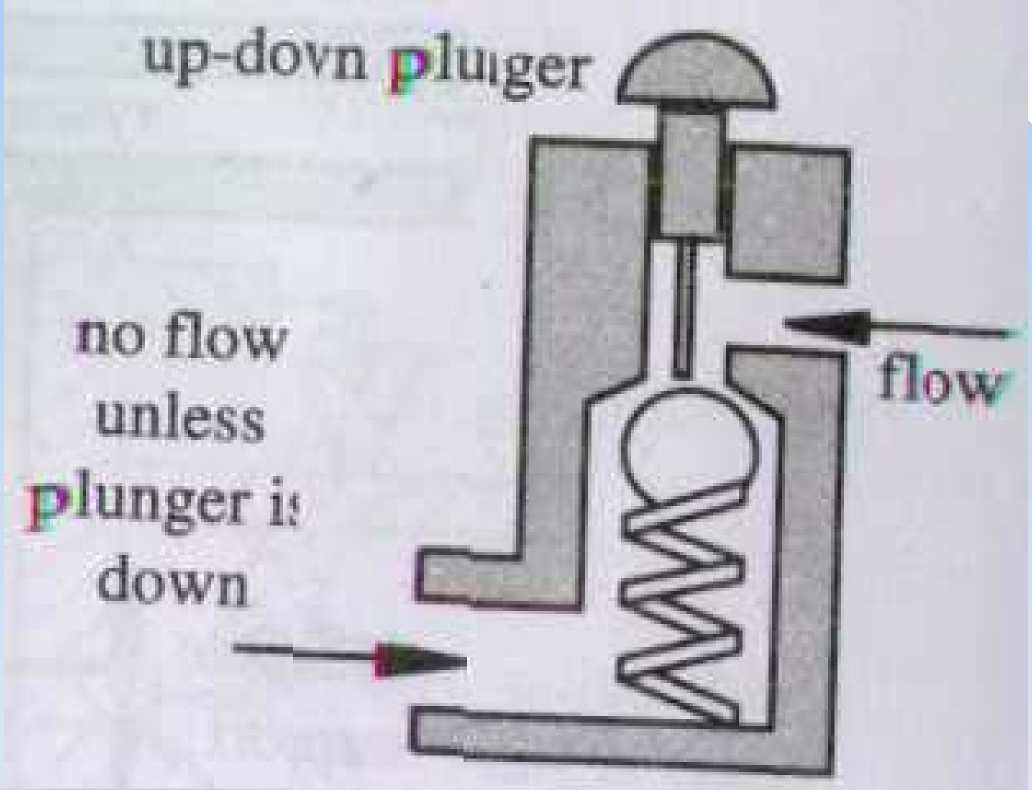
Compressibility of the air can be advantageous.

Prevents damage due to overload.

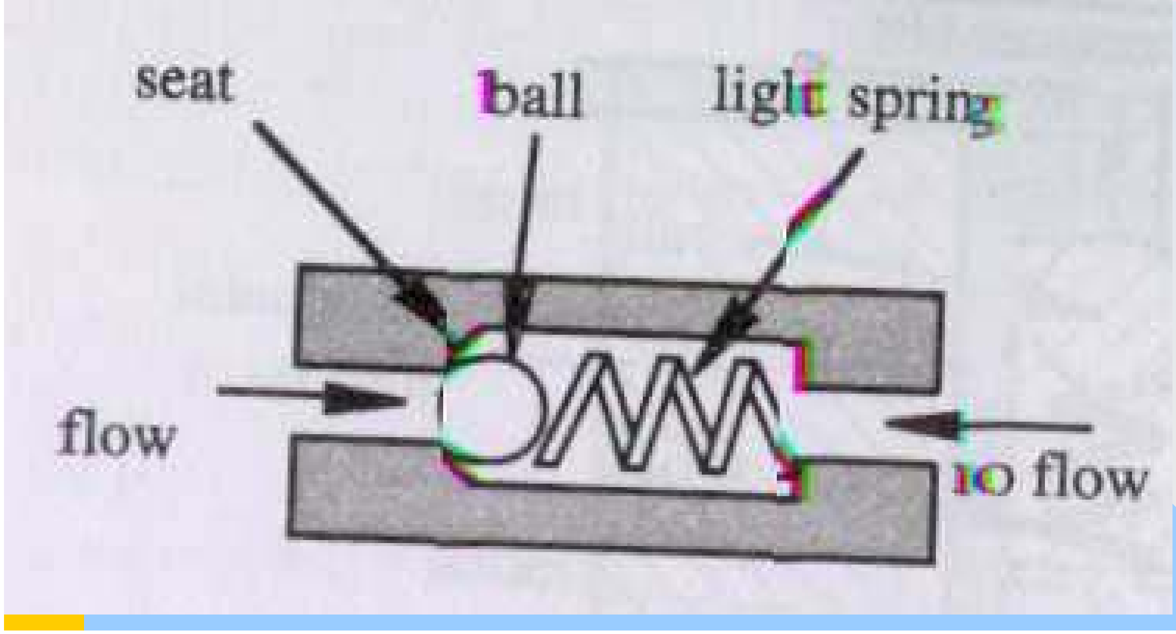
Major Components

- Compressor: Compresses air
- After-cooler: Cools air after compression as hot air contains vapor
- Storage tank: Provides const. high press.
- Desiccant Drier: Air passes through chemicals to remove moisture
- Filters: Removes water droplet
- Pressure Regulator: Poppet valve

Pressure Regulators

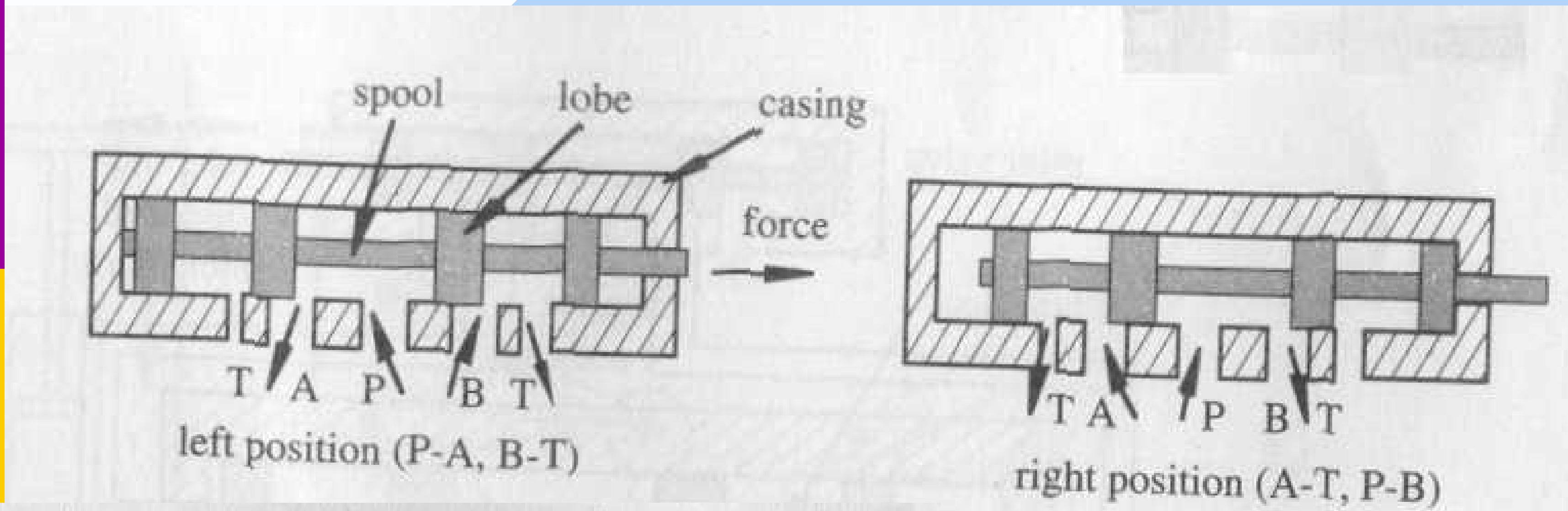


Poppet Valve

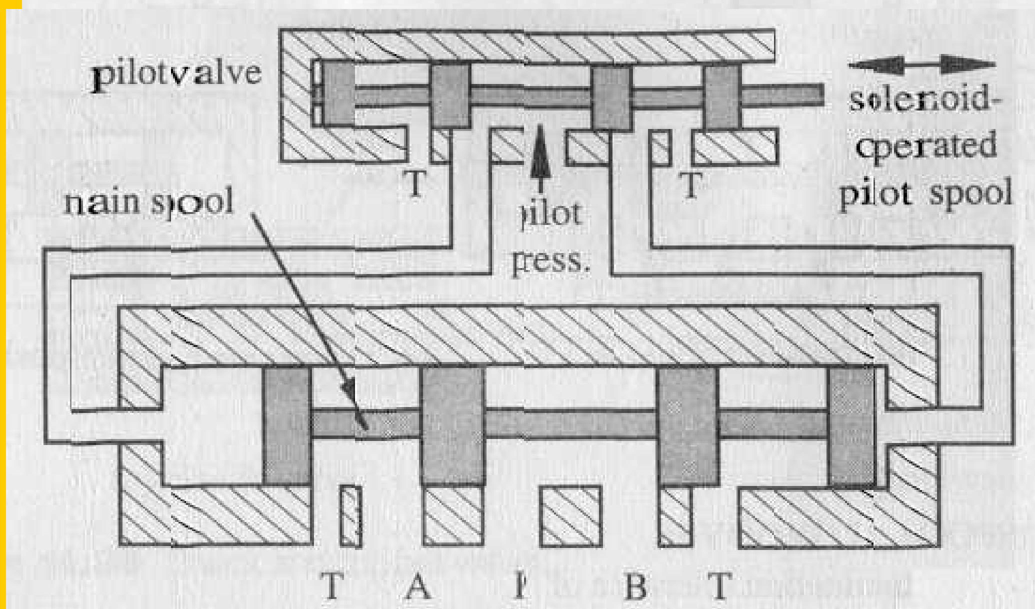


<-- Check Valve

Directional Control Valves: Spool Valve



Spool valve



<-- Pilot operated spool valve

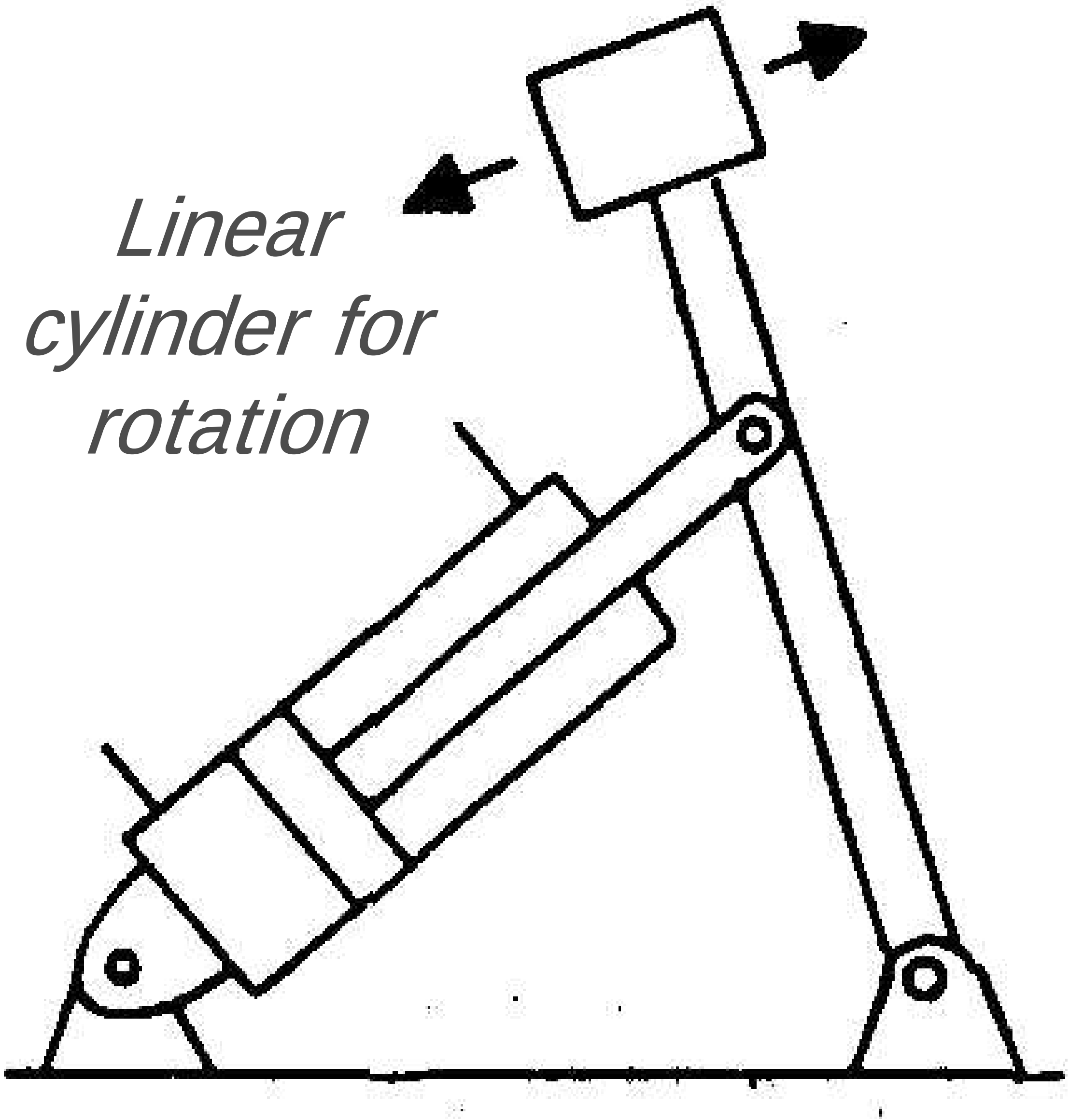
Actuators

- Actuators: Linear or Rotary

Linear: Air is returned; Rotary: Air is exhausted to atm.

An Application

Linear cylinder for rotation



Motor Selection

- For robot applications
  - Positioning accuracy, reliability, speed of operation, cost, etc.
- Electric is clean + Capable of high precision
- Electronics is cheap but more heat
- Pneumatics are not for high precision for continuous path

Motor Selection (contd.)

- Hydraulics can generate more power in compact volume
- Capable of high torque + Rapid operations
- Power for electro-hydraulic valve is small but expensive
- All power can be from one powerful hydraulic pump located at distance

Thumb Rule for Motor Selection

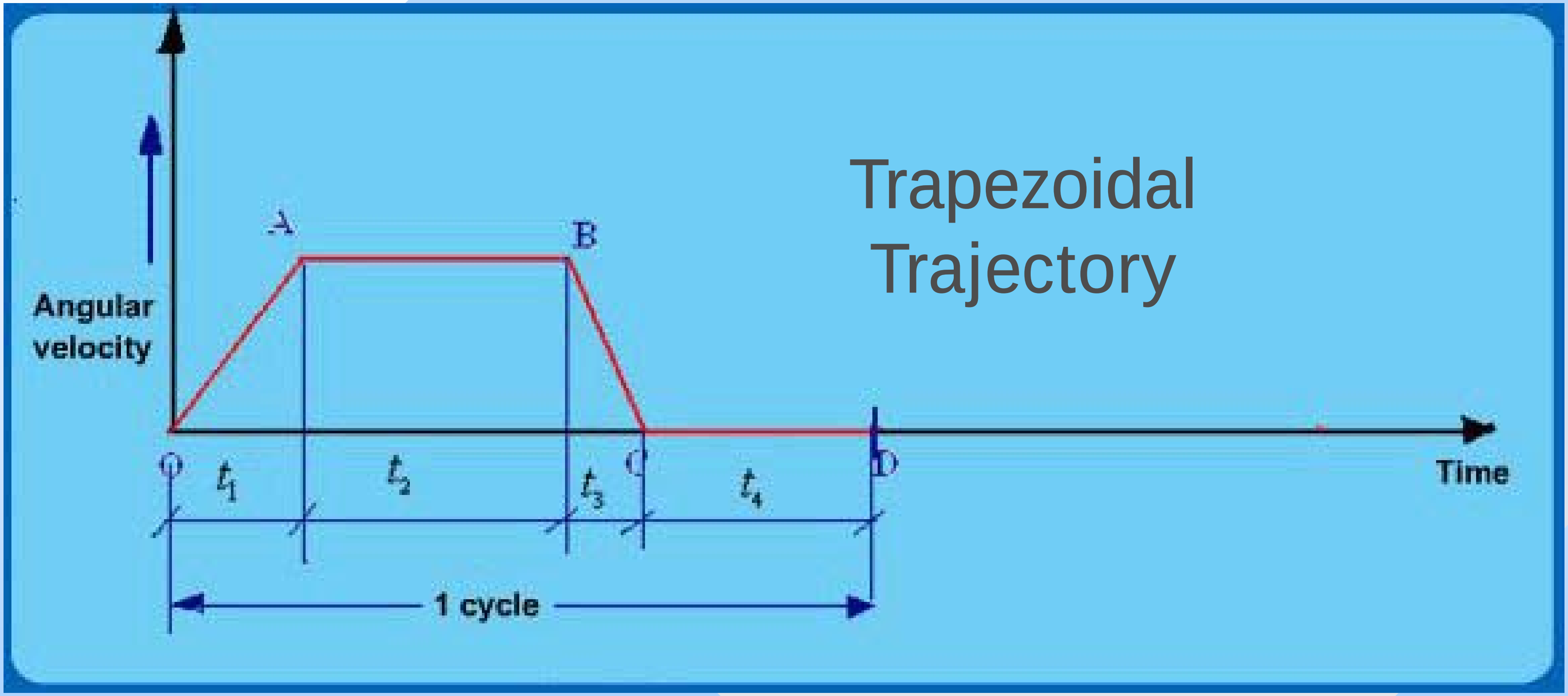
- Rapid movement with high torques (> 3.5 kW): Hydraulic actuator
- < 1.5 kW (no fire hazard): Electric motors
- 1-5 kW: Availability or cost will determine the choice

Simple Calculation

2 m robot arm to lift 25 kg mass at 10 rpm

- Force = 25 x 9.81 = 245.25 N
- Torque = 245.25 x 2 = 490.5 Nm
- Speed = 2π x 10/60 = 1.047 rad/sec
- Power = Torque x Speed = 0.513 kW
- Simple but sufficient for approximation

Practical Application



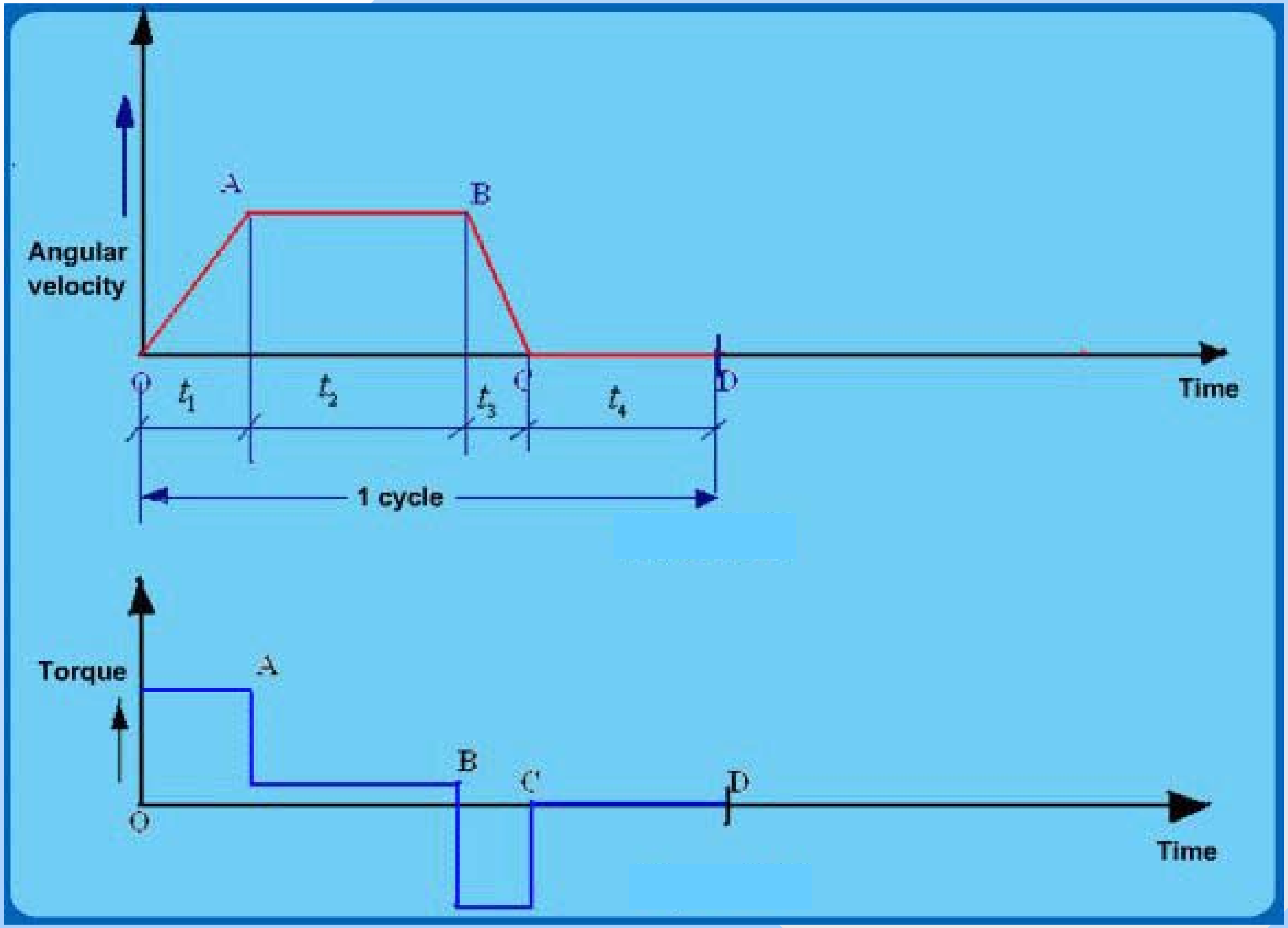
Subscript *l* for load; *m* for motor;

$G = \omega_l / \omega_m (< 1)$; η: Motor + Gear box efficiency

Accelerations & Torques

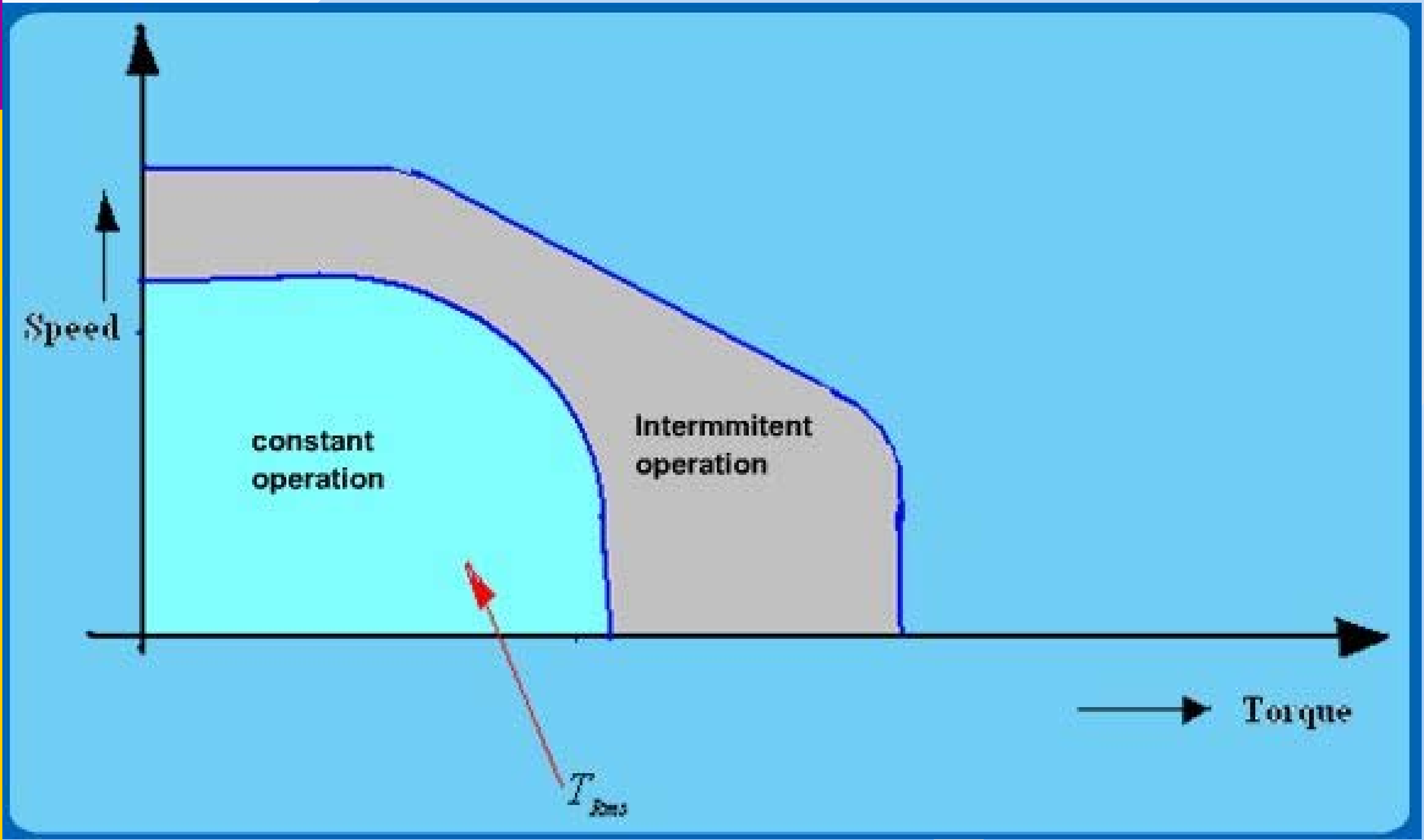
- Ang. accn. during t_1: $\alpha_1 = \dfrac{\omega_a - 0}{t_1}$
- Ang. accn. during t_2: Zero (Const. Vel.)
- Ang. accn. during t_3: $\alpha_3 = \dfrac{\omega_b - 0}{t_3}$
- Torque during t_1: $T_1 = (I_m + \dfrac{G^2}{\eta} I_l)\alpha_1 + T_f \dfrac{G}{\eta}$
- Torque during t_2: $T_2 = T_f \dfrac{G}{\eta}$
- Torque during t_3: $T_3 = (I_m + \dfrac{G^2}{\eta} I_l)\alpha_3 - T_f \dfrac{G}{\eta}$

RMS Value



$$T_{Rms} = \sqrt{\frac{(T_1^2 \times t_1) + (T_2^2 \times t_2) + (T_3^2 \times t_3) + (zero)t_4}{t_1 + t_2 + t_3 + t_4}}$$

Motor Performance



Final Selection

- Peak speed and peak torque requirements , where T_{Peak} is max of (magnitudes) T_1, T_2, and T_3
- Use individual torque and RMS values + Performance curves provided by the manufacturer.
- Check heat generation + natural frequency of the drive.

Sensors: Purpose

- Sensors are like
  - Eyes, Skin, Nose, Ears, and Tongue
  - Terms like vision, tactile, etc. have cropped
- Gather information → To function effectively
  - During pick-n-place obstacles are to be avoided
  - Fragile objects not to be broken
- End-effector, sensor, controller work together

Capabilities

- Simple Touch
  - Presence/absence of an object
- Taction or Complex Touch
  - Presence of an object
  - Size and shape
- Simple Force
  - Force along a single axis
- Complex Force
  - Along 2 or more axes

Capabilities ...

- Proximity
  - Non-contact detection
- Simple Vision
  - Detects edges, holes, corners, etc.
- Complex Vision
  - Recognize shapes

Classification

Internal Sensors

- Used to measure the internal state of a robot
  - Position
  - Velocity
  - Aceleration, etc
- Based on above info. control command is decided by controller

Position Sensors

- Measures position (angle) of each joint
- Joint angles → End-effector configuration
- Encoder
  - Digital optical device
  - Converts motion → Sequence of pulses
  - Pulses can be converted to rel./abs. meas.
  - Incremental or Absolute
  - Linear and Rotary

Incremental Absolute Linear Encoders

- Transparent scale with opaque grating
- Equal grating line thickness, and gap, μm
- One side light source + condenser lens
- Other side light sensitive cells
- Cell resistance (photodiodes) decreases when light falls → Pulse is generated
- Pulse (digital) is fed to controller

Incremental and Absolute Rotary Encoders

- Similar to incremental encoder
- Gratings are on circular disc
- Common value of transparent space width = 20 μm
- Two sets of grating lines on two different circles
  - Detects the direction of motion
- Mounted on motor shaft or with some gearing (to enhance accuracy)

Potentiometer

- Also referred as ‘pot’
- Variable resistance device
- Expresses lin./ang. disp. in terms of voltage
- Consists of a wiper → Makes contact with resistive element
- When pt. of contact moves → Resistance betn. wiper & end leads change ∝ disp.

LVDT

- Linear Variable Differential Transformer
- Most used disp. transducer (?) when high accuracy is reqd.
- It generates AC signal. Magnitude is related to the moving core disp.
- Ferrous core moving a magnetic field
- Field is created similar to transformer
- A RVDT uses same principle

Synchros and Resolvers

- Encoders provide digital output
- Synchros/Reolvers give analog signal as output
- Consist of a rotor + stator: Must be converted to digital signal
- Single winding rotor inside fixed stators

Velocity Sensors

- All position sensors with certain time bounds
- Velocity = No. of pulses for an inc. encoder divided by time consumed in doing so
- This scheme puts some computational load on controller

Tachometer

- Finds speed directly without any computational load
- Based on Fleming's rule: Voltage produced $\propto$ Rate of change of flux linkage
- Voltage produced $\propto$ Speed of shaft rotation
- Info. to be digitized using ADC before passing it to the controller computer

Hall-Effect Sensor

- Flat piece of conductor material (called Hall chip) is attached to a potential diff., voltage across ⊥ faces is zero
- If a magnetic field is imposed, voltage is generated
- With ring magnet on shaft, voltage ∝ speed of shaft

Acceleration Sensors

- Time-rate of change of velocities or double time-rate of change of positions
- Heavy computational load on the computer → Not efficient
- Speed of robot operation will be hampered
- Alternate way: Measure force (F) = mass (m) x acceleration (a)

Acceleration Sensors ...

- Force can be measured using strain gauges

$$F = \Delta R\ A\ E\ /(R\ C)$$

F: Force; ΔR: Change in resistance of strain gauge (SG); A: Area; E: Elastic modulus of SG material; R: Original resistance of SG; C: Deformation constant of SG

Acceleration, $a = \Delta R\ A\ E\ /(R\ C\ m)$

Differentiation vs. Integration

- Velocity and acceleration using a position sensor requires differentiation → Not desired
- Any noise is amplified upon differentiation
- Velocity and position from acceleration require integration → Recommended
- Integrators tend to suppress noise

Force Sensors

- A spring balance is a force sesnsor
- Force (weight) is applied on scale pan → Displacement (spring stretches)
- Strain Gauge based, Piezoelectric, etc.

Strain Gauge

- Principle: Elongation of a conductor increases its resistance. Due to
  - Increase in length
  - Decrease in area
- Typical resistance 50-100 Ω
- Made of electrical conductors (wire or foil etched on base material

Strain Gauge …

- Glued on surfaces where strains are measured, R_1 and R_2
- Resistances are measured by attaching them to the Wheatstone bridge circuit
- Cheap and accurate method
- Care should be taken for the temp. change
- To enhance output + temperature compensation 2 SGs are used

Piezoelectric Sensor

- Based on Piezoelectric effect
  - When asymmetrical, elastic crystals are deformed by a force → Electrical potential will be developed
  - Reversible, i.e., if a potential is applied betn. the surfaces of the crystal, it will change physical dimension
  - Magnitude and polarity of induced charges $\propto$ Magnitude and direction of applied force

Piezoelectric Sensor ... / Current-based Sensing

- Materials: Quartz, Tourmaline, Rochalle salt, and others
- 1 to 20 kN
- Used for instantaneous change in force (dynamic force)
- Current-based sensing: Uses the principle of electric motor, i.e., torque $\propto$ current drawn (motor characteristics are known)

Summary

- Advantages and disadvantages of various motors and actuators are explained.
- How to select an electric motor is shown.
- Purpose of sensors explained
- Classification of sensors is provided

Thank You

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