Sheikh Hasina University, Netrokona

Department of Computer Science and Engineering

CSE-2205: Introduction to Mechatronics

Lec-6: Basic Mechanical Engineering

Md. Ariful Islam

Assistant Professor

Dept. of Robotics and Mechatronics Engineering

University of Dhaka

&

Adjunct Faculty

Sheikh Hasina University, Netrokona

Department of Computer Science and Engineering

Contents

Mechanics fundamentals

Newton's Law of Motion

Newton's First Law of Motion (The Law of Inertia):

"An object at rest tends to stay at rest, and an object in motion tends to stay in motion with the same speed and in the same direction unless acted upon by an unbalanced external force."

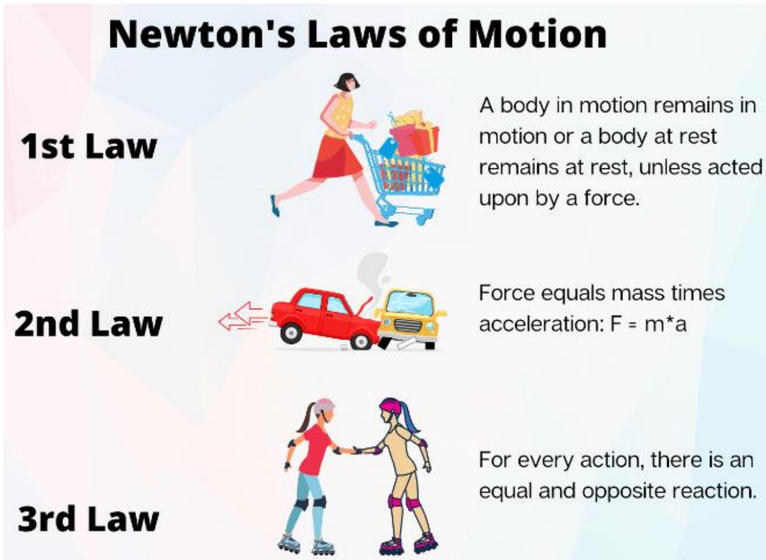
This law describes the natural tendency of objects to maintain their state of motion or rest unless an external force is applied to change that state. In mathematical terms, it can be summarized as:

$$F=0$$

Where:

- *F represents the net force acting on the object.*
- *0 indicates that the net force is zero, meaning there is no acceleration or change in motion.*

Suppose you have a robotic arm that is holding a tool in a fixed position. According to Newton's first law, the tool will remain in place unless an external force is applied. When the robotic arm starts moving the tool, it continues to move until the robotic control system applies a force to stop it. This law is essential for programming and controlling the motion of robotic systems.



Newton's Second Law of Motion (Law of Acceleration):

Newton's second law of motion, also known as the law of acceleration, relates the net force acting on an object to its mass and the resulting acceleration. The mathematical formula for Newton's second law is expressed as:

$$F=ma$$

Where:

- *F represents the net force acting on the object (in newton's, N).*
- *m is the mass of the object (in kilograms, kg).*
- *a is the acceleration of the object (in meters per second squared, m/s²).*

In this formula, the force (F) applied to an object is directly proportional to the product of its mass (m) and the acceleration (a) it experiences. This law states that when a force is applied to an object, it will accelerate in the direction of the applied force, and the acceleration is directly proportional to the force and inversely proportional to the mass of the object.

Consider a mechatronic system with a conveyor belt carrying objects. To change the speed of the conveyor, you need to adjust the force applied by the motor (the control system). If you increase the force, the acceleration of the conveyor increases, and objects move faster. This demonstrates the relationship between force, mass, and acceleration, as described by Newton's second law.

Newton's Third Law of Motion (Action-Reaction):

Newton's third law states that for every action, there is an equal and opposite reaction. In other words, when one object exerts a force on another object, the second object exerts an equal force in the opposite direction.

The concept can be expressed using vectors, with forces represented as vectors. If we have two objects, A and B, interacting with each other, the law can be stated as follows:

$$F_{A\rightarrow B}=-F_{B\rightarrow A}$$

Where:

- $F_{A\rightarrow B}$ represents the force exerted by object A on object B.
- $F_{B\rightarrow A}$ represents the force exerted by object B on object A.
- The minus sign (-) indicates that the forces are equal in magnitude but opposite in direction.

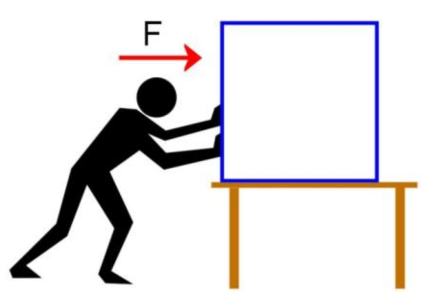
In practical terms, if object A exerts a force of 10 newtons to the right on object B, according to Newton's third law, object B exerts a force of 10 newtons to the left on object A. This law helps explain the behavior of objects in contact or interacting through forces, such as the propulsion of a rocket (action) resulting from the expulsion of exhaust gases (reaction).

Think about a drone hovering in the air. The propellers of the drone push air downward (action). According to Newton's third law, the air exerts an equal and opposite force upward on the drone (reaction). This reaction force allows the drone to stay airborne and maintain its position. Understanding this law is crucial when designing and controlling drones and other aerial mechatronic systems.

Force and Moment

Force:

- **Definition:** A force is a vector quantity that represents a push or pull acting on an object. It is characterized by its magnitude, direction, and point of application.



- **Units:** The standard unit of force in the International System of Units (SI) is the newton (N), which is equivalent to 1 kilogram-meter per second squared (kg·m/s²).
- **Symbol:** In equations, force is often represented by the symbol "F."

The formula to calculate force (F) is derived from Newton's second law of motion, which relates force to the mass (m) of an object and its acceleration (a). The formula for force is:

$$F=ma$$

Where:

- F represents the force applied to the object (in newtons, N).
- m is the mass of the object (in kilograms, kg).
- a is the acceleration of the object (in meters per second squared, m/s²).

This formula states that the force applied to an object is directly proportional to the product of its mass and acceleration. In other words, it quantifies how an object's motion changes in response to an applied force.

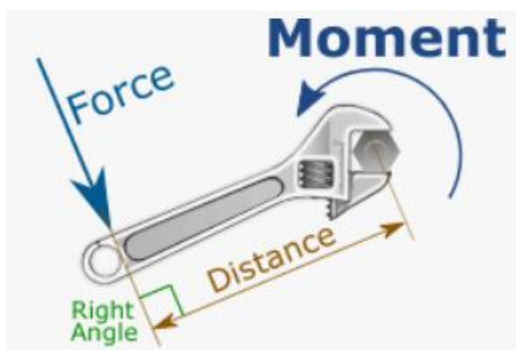
If you know the mass of an object and the acceleration it experiences, you can use this formula to calculate the force acting on that object. Conversely, if you know the force and mass, you can calculate the acceleration using the rearranged formula:

$$a=F/m$$

This formula is fundamental in physics and engineering for analyzing the motion of objects under the influence of forces.

Moment (Torque):

- **Definition:** A moment, also known as torque, is a turning force that tends to cause an object to rotate around an axis or pivot point. It is characterized by its magnitude, direction, and the point at which it is applied.



- **Units:** The standard unit of moment or torque in SI is the newton-meter (N·m).
- **Symbol:** In equations, torque is often represented by the symbol "τ" (tau).

Torque is defined as the product of the force (F) applied to an object and the lever arm (or moment arm, r) at which the force is applied. Mathematically, torque (τ) is expressed as:

$$\tau=Fr$$

Where:

- τ represents torque (in newton-meters, N·m).
- F is the force applied (in newtons, N).

- *r* is the lever arm or moment arm (in meters, m) at which the force is applied.
- **Direction:** Torque is a vector quantity with both magnitude and direction. It follows the right-hand rule, meaning the direction of the torque vector is perpendicular to the plane formed by the force vector and the lever arm. The direction is determined by the direction of rotation produced by the force.

Types of forces and moments

Tensile Force:

- **Description:** Tensile forces act to stretch or pull an object, trying to make it longer.
- **Mechatronics Application:** Tensile forces can be found in the cables and wires used in robotics, conveyor systems, and mechatronic systems that involve lifting or pulling.

  Direction: Tensile force acts along the length of the object and tries to stretch it. It is directed outward from the center of the object, causing it to elongate.

  Causes of Tensile Force: Tensile forces can result from various situations, such as:

  - Applying a pulling force to a rope, cable, or wire.
  - Stretching a spring.
  - Subjecting a material specimen to a tensile test in a materials testing laboratory to determine its tensile strength and other mechanical properties.
  - The force exerted by a load hanging from a support, such as a weight suspended from a ceiling.

Tensile force is the stretching forces acting on the material and has two components namely, tensile stress and tensile strain. This means that the material experiencing the force is under tension and the forces are trying to stretch it.

When a tensile force is applied to a material, it develops a stress corresponding to the applied force, contracting the cross-section and elongating the length.

The tensile strain ε is expressed as $\varepsilon = \Delta L/L$. If a compressive force is applied, the compressive strain is expressed as $\varepsilon = -\Delta L/L$. Based on Hooke's law, the relation between stress and strain is expressed as $\sigma = E\varepsilon$, where σ – stress, E – Young's modulus and ε – strain.

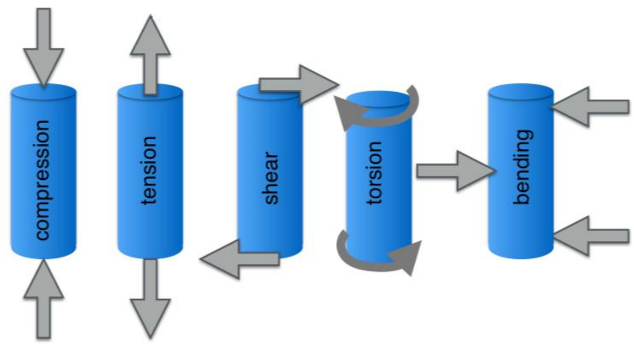
On receiving a tensile force, the material expands in the axial direction (longitudinal strain) while contracting in the transverse direction (transverse strain).

Stress is calculated as:

$$\text{Stress } (\sigma) = \text{Force } (F) / \text{Area } (A)$$

Strain is calculated as:

$$\text{Strain } (\varepsilon) = \text{Extension in length } (\Delta L) / \text{Length } (L)$$



2. Compressive Force:

- **Description:** Compressive forces push or squeeze an object, trying to make it shorter.
- **Mechatronics Application:** Compressive forces are relevant in mechatronic systems that involve structures and supports, such as the frames of machines or the legs of a robot.

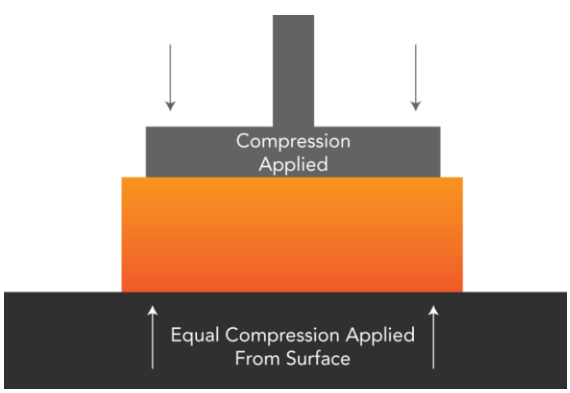
Compression force (or compressive force) occurs when a physical force presses inward on an object, causing it to become compacted. In this process, the relative positions of atoms and molecules of the object change. This change can be temporary or permanent depending on the type of material receiving the compressive force. There can also be different results depending on the direction or position on the object that the compressive force is applied.

How is Compression Force Measured?

Compression force is usually captured in Newtons (N); defined as a unit of force that give to a mass of one kilogram an acceleration of 1 meter per second squared (m/s^2, commonly represented as "a").

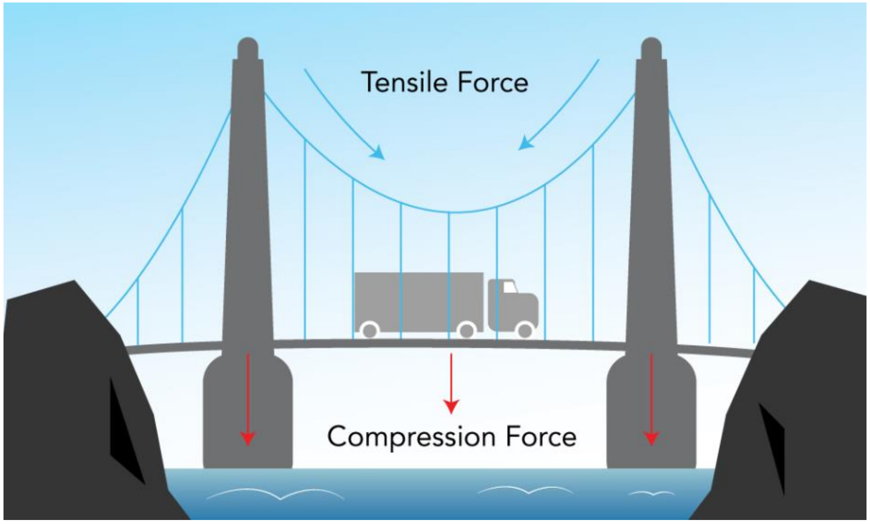
$$N = m * a$$

Compression Force Applied to an Object on a Solid Surface



Newton's Third Law of Motion states that for every action force, there is an equal opposite reaction force. This is depicted in **Figure:** When compression force is applied to an object resting on a surface, both ends of the object receive the same amount of force.

Compression & Tensile Force on a Suspension Bridge



Suspension bridges are an example of a rigid structure that is designed to withstand compression forces over a long distance. As **Figure** shows, when vehicles drive over the bridge, the columns and beams used to support the bridge experience the compression force. Meanwhile, the anchorages and suspension cables are put under tension. These two facets working together essentially transfer the compressive force load across the entire bridge to maintain a sound, stable driving surface. This is a key principle that allows suspension bridges to cover longer distances than other bridge types.

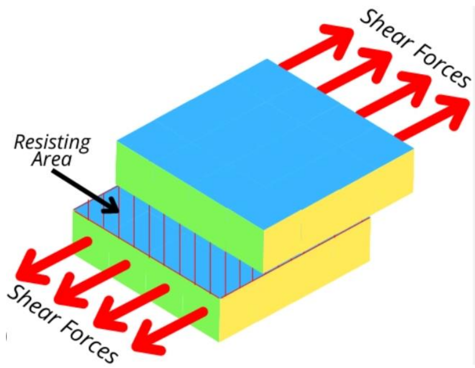
3. Shear Force:

- **Description:** Shear forces act parallel to the surface of an object, causing one part of the object to slide or deform relative to another part.

Example: Cutting Through an Object with a Knife

Imagine you have a knife, and you want to cut through a piece of fruit, like an apple. When you apply a downward force to the knife, the blade comes into contact with the apple's surface. Now, let's analyze the forces involved:

1. **Normal Force (Compression):** The knife's blade exerts a downward normal force on the apple. This force is perpendicular to the surface of the apple and is responsible for compressing the apple slightly.
2. **Shear Force:** As you continue to apply the force while maintaining the knife's orientation parallel to the apple's surface, a shear force is generated. This shear force acts parallel to the surface and is directed horizontally along the blade of the knife.



$$\tau = \frac{F}{A}$$

τ = shear stress

F = applied force

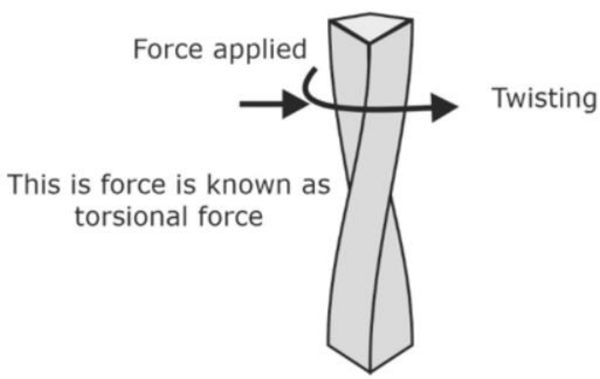
A = cross-sectional area

3. **Resulting Effect:** The shear force causes the knife to slice through the apple. It's the shear force that allows the blade to move through the material, effectively separating one part of the apple from the other. This is why we describe the force involved in cutting as a shear force.

- **Mechatronics Application:** Shear forces can occur in the joints and connections of mechanical components in mechatronic systems, affecting the stability and motion of these systems.

4. Torsional Moment (Torque):

- **Description:** Torsional moments, or torques, cause an object to twist or rotate about an axis.
- **Mechatronics Application:** Torques are essential in mechatronic systems with rotating components, such as motors, gears, and shafts. Controlling torque is crucial for precise motion control.



The formula for torsional moment can be expressed as:

$$T=k\cdot\phi\cdot L$$

Where:

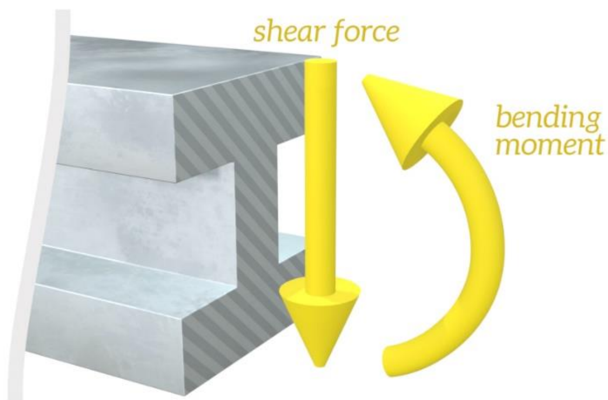
- T represents the torsional moment or torque (in newton-meters, N·m).
- k is the torsional stiffness or torsional spring constant (in newton-meters per radian, N·m/rad).
- ϕ (phi) is the angle of twist in radians (rad).
- L is the length of the object that is undergoing torsion (in meters, m).

This formula relates the torsional moment to the angular displacement (ϕ) of the object undergoing torsion and its length (L), as well as the torsional stiffness (k) of the material or structure.

It's important to note that the value of the torsional stiffness (k) depends on the material properties (such as the shear modulus) and the geometry of the object. The angle of twist (ϕ) represents the amount by which the object has rotated or twisted from its original position.

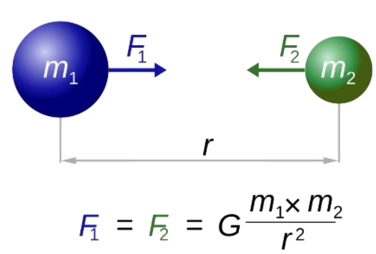
5. Bending Moment:

- **Description:** Bending moments induce bending or flexural deformations in a structure.
- **Mechatronics Application:** Bending moments are relevant in mechatronic systems with beams, arms, or cantilevers, such as robotic arms and manufacturing equipment.

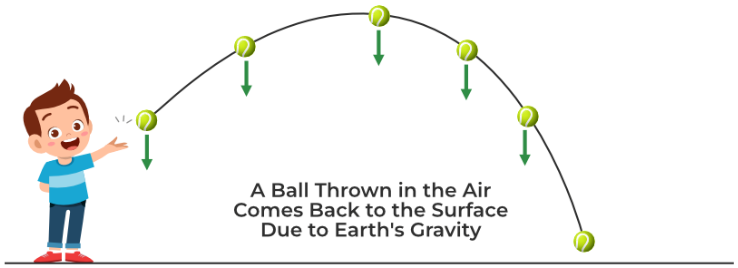


6. Gravity Force:

- **Description:** Gravity is a force that pulls objects downward toward the center of the Earth or any other massive body.



- **Mechatronics Application:** Gravity is a constant consideration in mechatronic systems, affecting the weight of objects and the stability of structures. It plays a role in designing suspension systems, load-bearing components, and balance control in robots and drones.



7. Aerodynamic Forces:

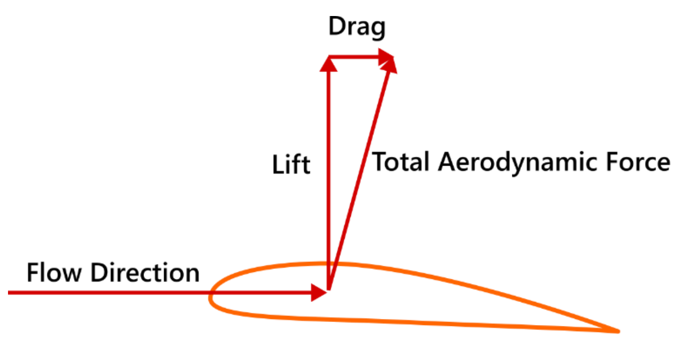
- **Description:** Aerodynamic forces, including lift and drag, result from the interaction of objects with the surrounding air or fluid.

Aerodynamic forces refer to the forces generated on an object as it moves through a fluid, such as air. These forces include lift, drag, and sometimes thrust and weight. The specific formulas for these aerodynamic forces can vary depending on the shape of the object, its velocity, and the fluid properties. Here are some basic formulas:

1. **Lift (L):**
    - Lift is the force that acts perpendicular to the relative wind and is responsible for keeping an aircraft aloft.
    - The formula for lift can be approximated by: $L=0.5\times C_L\times \rho\times A\times V^2$
    - Where:
        - L is the lift force (in newtons, N).
        - C_L is the coefficient of lift, which depends on the shape of the airfoil or object.
        - ρ is the air density (in kilograms per cubic meter, kg/m³).
        - A is the reference area (in square meters, m²).
        - V is the velocity of the fluid (in meters per second, m/s).
2. **Drag (D):**
    - Drag is the force that opposes the motion of the object through the fluid.
    - The formula for drag can be approximated by: $D=0.5\times C_D\times \rho\times A\times V^2$
    - Where:
        - D is the drag force (in newtons, N).

- C_D is the coefficient of drag, which depends on the object's shape.
- ρ is the air density (in kg/m³).
- A is the reference area (in m²).
- V is the velocity of the fluid (in m/s).

These formulas are simplified representations of lift and drag forces. The coefficients of lift (C_L) and drag (C_D) are determined experimentally for specific objects or airfoils and are essential for calculating these forces accurately. The reference area (A) is the projected area of the object in the direction of the fluid flow.



- **Mechatronics Application:** Aerodynamic forces are critical in mechatronic systems like drones and aircraft, where they affect flight dynamics and stability.

8. Frictional Force:

- **Description:** Frictional forces oppose the relative motion between two surfaces in contact.

The frictional force formula depends on whether you are referring to static friction (force required to overcome initial resistance to motion) or kinetic friction (force opposing motion once it has started). The general formula for both types of friction is as follows:

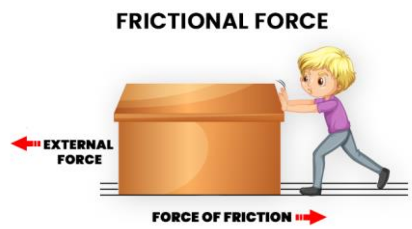
$$F_{\text{friction}}=\mu \cdot N$$

Where:

- F_{friction} is the frictional force (in newtons, N).
- μ (mu) is the coefficient of friction, a dimensionless constant that depends on the materials in contact and whether it's static or kinetic friction.
- N is the normal force (in newtons, N), which is the force exerted perpendicular to the surface of contact between the two objects.

The coefficient of friction (μ) can take on different values depending on the specific materials and conditions. There are two common cases:

1. **Static Friction:** This is the frictional force that opposes the initiation of motion when an object is at rest. The maximum static frictional force (F_{static}) is the force required to overcome the initial resistance to motion. In this case, μ represents the coefficient of static friction.
2. **Kinetic Friction:** Once an object is in motion, it experiences kinetic friction. The kinetic frictional force ($F_{kinetic}$) opposes the object's motion and is typically less than the maximum static frictional force. In this case, μ represents the coefficient of kinetic friction.



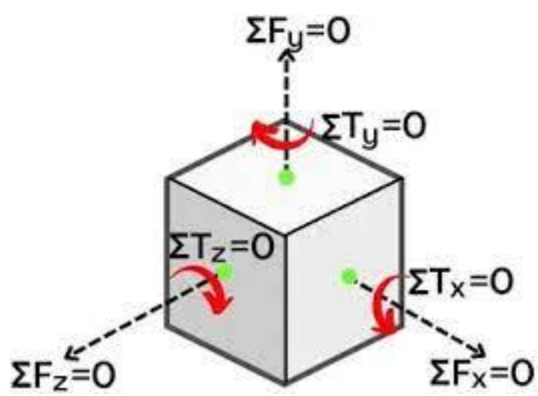
- **Mechatronics Application:** Frictional forces are present in mechatronic systems with moving parts, such as bearings, gears, and sliding mechanisms. Engineers must account for friction to optimize system performance and energy efficiency.

Equilibrium

Definition: Equilibrium is a state in which an object or system experiences no net change in its motion. In other words, the net force acting on the object is zero, and the net torque (rotational force) about any point is zero.

Conditions for Equilibrium:

1. **Translational Equilibrium:** The vector sum of all external forces acting on the object is zero ($\Sigma F = 0$), which means there is no linear acceleration.



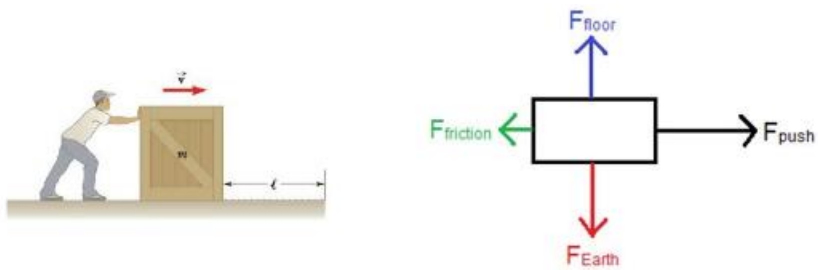
2. **Rotational Equilibrium:** The vector sum of all external torques (moments) acting on the object is zero ($\Sigma\tau = 0$), which means there is no angular acceleration.

Equilibrium in Mechatronics:

- **Purpose:** Equilibrium principles are essential for ensuring the stability and balance of mechatronic systems, which often involve complex mechanical structures and components.
- **Example:** When designing a robotic arm, engineers need to ensure that the arm is in equilibrium at different positions and under various loads. This ensures that the arm can support its own weight and any additional weight it may carry, while remaining stable and not toppling over.

Free-Body Diagram (FBD)

Definition: A free-body diagram is a simplified visual representation of an object with all the forces and moments acting on it shown as vectors. It helps in analyzing the forces and moments acting on an object in equilibrium or during motion.



- **Purpose:** FBDs are used to isolate an object of interest and identify all the external forces and moments acting on it. This simplifies the problem-solving process by breaking down complex systems into individual components.
- **Components of a Free-Body Diagram:**
    - **Object of interest:** Typically represented as a point or a simple shape.
    - **Forces:** Arrows representing the magnitude and direction of all external forces acting on the object.
    - **Moments (Torques):** Arrows representing the magnitude and direction of all external moments acting on the object.
    - **Labels:** Each force and moment vector should be labeled for clarity.

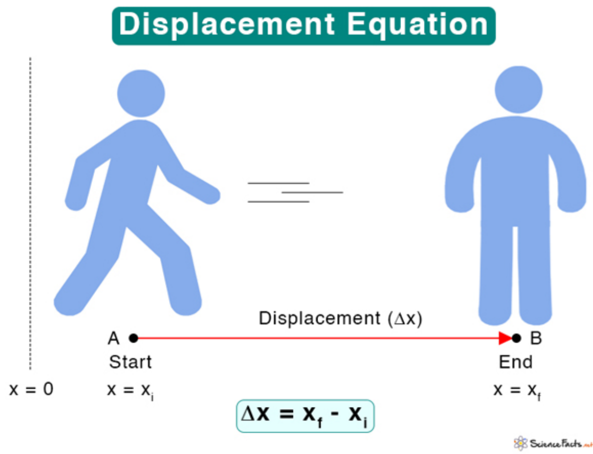
Free-Body Diagrams in Mechatronics:

- **Purpose:** Free-body diagrams are indispensable tools for isolating and analyzing the forces and moments acting on individual components within mechatronic systems.
- **Example:** Consider a mechatronic system with a conveyor belt. To design the belt's support structure, you'd create a free-body diagram for each support point. This diagram would include forces such as the weight of the belt and any external loads, allowing you to calculate the forces and moments that the support structure must withstand.

Kinematics and dynamics

Displacement:

- **Definition:** Displacement is the change in position of an object or system in a specific direction. It is typically measured in units of length (e.g., meters).



- **Application in Mechatronics:** In mechatronics, displacement is crucial for understanding how objects or components move within a system.

- **Example:** Imagine a mobile robot in a warehouse. Its displacement is the change in position from one location to another as it navigates the warehouse floor to pick and transport items. Accurate measurement of displacement helps the robot determine its position and plan its path.

Velocity:

- **Definition:** Velocity is the rate of change of displacement with respect to time. It is a vector quantity, meaning it has both magnitude and direction. Velocity is measured in units of length per unit time (e.g., meters per second, m/s).

$$\text{Velocity} = \frac{\text{Displacement}}{\text{Time}}$$

or

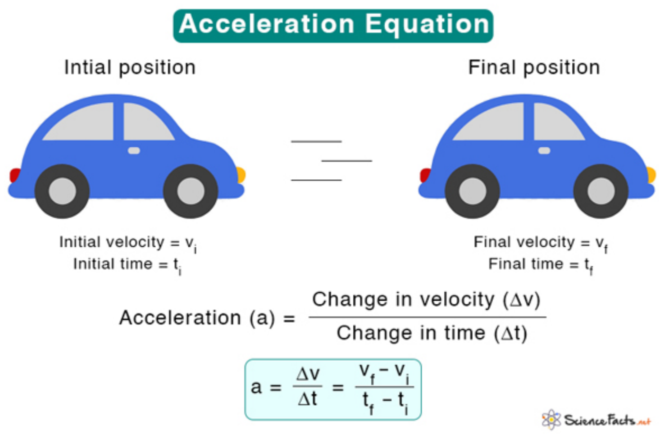
$$v = \frac{s}{t}$$

- **Application in Mechatronics:** Velocity is essential for describing the speed and direction of motion in mechatronic systems.

- **Example:** In a mechatronic conveyor system used in manufacturing, the velocity of the conveyor belt is crucial. It determines the speed at which items are transported along the assembly line. Accurate control of velocity ensures efficient and consistent production.

Acceleration:

- **Definition:** Acceleration is the rate of change of velocity with respect to time. Like velocity, acceleration is a vector quantity. It is measured in units of length per unit time squared (e.g., meters per second squared, m/s²).

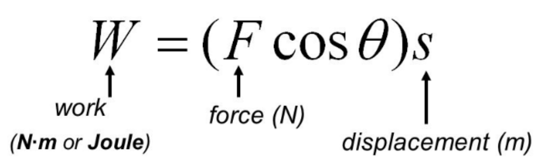


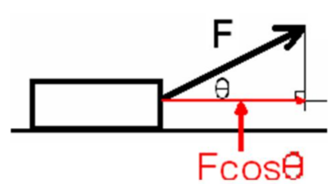
- **Application in Mechatronics:** Acceleration is vital for describing how quickly the velocity of an object or component changes.

- **Example:** Consider a mechatronic robotic arm used for pick-and-place tasks in a factory. The arm's acceleration determines how fast it can change the direction and speed of its end effector (the tool it uses for picking and placing objects). Precise control of acceleration ensures efficient and accurate manipulation of objects.

Work:

- **Definition:** Work is done when a force acts on an object and causes a displacement in the direction of the force. Mathematically, work (W) is calculated as the product of the force (F) and the distance (d) over which the force is applied, multiplied by the cosine of the angle (θ) between the force and displacement vectors.





- **Units:** The SI unit of work is the joule (J), which is equivalent to one newton-meter (N·m).

- **Mechatronics Application:** In mechatronics, work is often associated with the movement of mechanical components. For example, when a robotic arm lifts an object, work is done against the force of gravity. Understanding the work involved in various tasks is essential for energy management and efficiency in mechatronic systems.

Energy:

- **Definition:** Energy is the ability to do work. It comes in various forms, such as kinetic energy (associated with motion), potential energy (associated with position or height), and electrical energy (associated with electrical systems). The law of conservation of energy states that energy cannot be created or destroyed but can change from one form to another.

$$\begin{aligned}
\text{Energy} &= \text{Work Done} \\
&= \text{Force} * \text{displacement} \\
&= \text{mass} * \text{acceleration} * \text{displacement} \\
&= \text{mass} * \frac{\text{distance}}{\text{time}^2} * \text{displacement} \\
&= \text{mass} * \text{distance} * \text{displacement} * \text{time}^{-2}
\end{aligned}$$

$$\text{Energy} = [M]\,[L]\,[L]\,[T^{-2}]$$

$$\textbf{Dimensional Formula of Energy} = [M^1\ L^2\ T^{-2}]$$

- **Units:** Energy is measured in joules (J).
- **Mechatronics Application:** Mechatronic systems often involve the conversion and transfer of energy between different forms. For example, in an electric vehicle, energy from the battery is converted into kinetic energy to propel the vehicle forward. Understanding energy transfer is vital for designing efficient mechatronic systems.

Power:

- **Definition:** Power is the rate at which work is done or the rate at which energy is transferred or converted. Mathematically, power (P) is calculated as the work done (W) divided by the time (t) it takes to do that work.

$$P_{av} = \frac{W}{t}$$

- **Units:** The SI unit of power is the watt (W), which is equivalent to one joule per second (J/s).
- **Mechatronics Application:** Power is critical in mechatronic systems for assessing performance and efficiency. For example, the power output of a motor determines how quickly it can perform tasks. In robotics, power considerations are essential for optimizing the speed and precision of movements.

Mechatronics Example: Electric Actuator in a Robotic Arm

- Let's consider a mechatronics application involving an electric actuator in a robotic arm:
- **Work:** When the electric actuator extends or retracts to move a robotic arm, it performs work against external forces such as gravity or friction. The work done depends on the force applied and the distance the actuator moves.
- **Energy:** The electric actuator converts electrical energy from the power source into mechanical energy to perform work. The energy is transferred and stored in the system's mechanical components.
- **Power:** The power output of the electric actuator determines how quickly it can move the arm. It is calculated as the rate at which work is done, allowing engineers to assess the actuator's performance and select the appropriate motor and control strategy for the robotic arm.

Mechanical materials

Properties of materials

1. **Mechanical Properties:**

- **Strength:** The strength of a material measures its ability to withstand applied loads without failure. Mechatronics applications often require materials with specific strength properties to ensure the structural integrity of components. For example, in robotics, the materials used for robot arms and joints must have sufficient strength to carry loads and perform tasks accurately.
- **Stiffness:** Stiffness refers to the material's resistance to deformation when subjected to an applied force. In mechatronics, stiffness is crucial in applications like precision mechanisms, where components need to maintain their shape and resist bending or deflection.
- **Elasticity:** Elasticity is the property that allows a material to return to its original shape and size when the applied force is removed. Materials with good elasticity are essential for springs and compliant mechanisms used in mechatronics systems.

2. Thermal Properties:

- **Thermal Conductivity:** Thermal conductivity measures a material's ability to conduct heat. In mechatronics, this property is relevant for components that dissipate heat, such as electronic devices and motors. Effective thermal management ensures that mechatronic systems operate within temperature limits.
- **Coefficient of Thermal Expansion (CTE):** CTE quantifies how much a material expands or contracts with changes in temperature. Matching the CTE of different materials is important in mechatronic systems to prevent unwanted stress or deformation at material interfaces.

3. Electrical Properties:

- **Electrical Conductivity:** Electrical conductivity determines a material's ability to conduct electrical current. In mechatronics, materials with high electrical conductivity are used for wiring, connectors, and conductive pathways in electronic circuits.

- **Dielectric Strength:** Dielectric strength measures a material's ability to withstand electric fields without breaking down. Insulating materials with high dielectric strength are essential for mechatronic systems to prevent electrical short circuits.

4. Corrosion Resistance:

- Corrosion resistance is the ability of a material to resist degradation due to chemical reactions with environmental factors such as moisture or chemicals. In mechatronics applications, materials exposed to harsh conditions, such as outdoor robotics or marine equipment, must have good corrosion resistance to ensure long-term reliability.

5. Wear Resistance:

- Wear resistance measures a material's ability to withstand surface wear and friction. In mechatronics, this property is important for components like gears, bearings, and sliding mechanisms to ensure longevity and reduce maintenance requirements.

6. Weight and Density:

- The weight and density of materials affect the overall weight of mechatronic systems. Lightweight materials are often preferred to reduce energy consumption, increase mobility (e.g., drones), and optimize the performance of robotic systems.

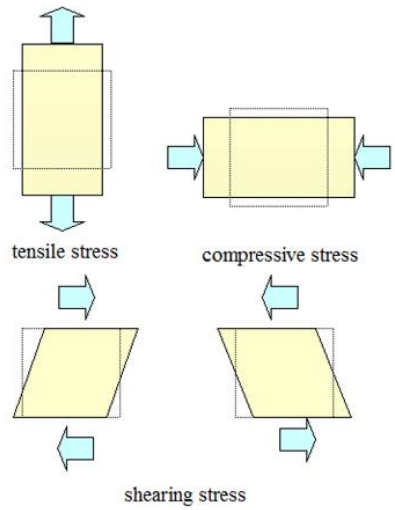
Mechatronics Example: Selection of Materials for a Robotic Gripper

- When designing a mechatronic robotic gripper, engineers need to consider various material properties:
- **Strength and Stiffness:** The gripper's fingers must have sufficient strength and stiffness to securely hold objects of varying weights and shapes.
- **Elasticity:** If the gripper's fingers are designed to adapt to different object shapes, they should exhibit some degree of elasticity to maintain a firm grip.
- **Thermal Conductivity:** If the gripper includes embedded sensors or heating elements, materials with appropriate thermal properties must be chosen.
- **Corrosion Resistance:** In applications where the gripper is exposed to moisture or chemicals, corrosion-resistant materials may be necessary.
- **Weight:** Lightweight materials can reduce the overall weight of the gripper, enhancing its mobility and efficiency in robotics applications.

Stress

Definition: Stress is a measure of the internal resistance of a material to deformation when subjected to an external force. It quantifies the force per unit area acting on a material and is a measure of the intensity of the internal forces within the material.

Units: Stress is typically measured in pascals (Pa), which is equivalent to one newton per square meter (N/m^2).



Types of Stress:

Stress is a measure of the internal resistance of a material to deformation when subjected to an external force. The formula for stress (σ) is typically expressed as:

$$\sigma = F/A$$

Where:

- σ represents the stress (in pascals, Pa), which is the unit of measurement for stress in the International System of Units (SI).
- F is the force applied to the material (in newtons, N).
- A is the cross-sectional area over which the force is applied (in square meters, m^2).

This formula relates the force applied to a material to the resulting stress it experiences. Stress is a measure of force per unit area and is expressed in pascals, which are equivalent to one newton per square meter (1 Pa = 1 N/m^2).

There are different types of stress, including:

1. **Normal Stress (σN):** This occurs when the force is applied perpendicular to the cross-sectional area. The formula for normal stress is the same as the general formula mentioned above.
2. **Shear Stress (τ):** Shear stress occurs when the force is applied parallel to the cross-sectional area. The formula for shear stress is also similar but may involve a different cross-sectional area depending on the geometry and orientation of the material.
3. **Hoop Stress:** This type of stress occurs in cylindrical objects like pipes and pressure vessels when they are subjected to internal pressure. The formula for hoop stress depends on the material properties and the geometry of the object.
4. **Axial Stress:** Axial stress is a type of normal stress that occurs along the axis of a structure, such as a column or beam.

Mechatronics Applications of Stress:

1. Material Selection:

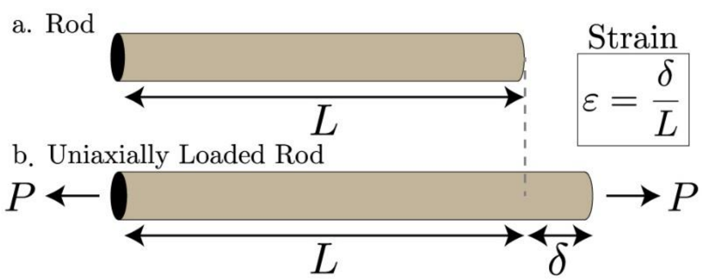
- **Application:** In mechatronics, engineers must choose materials for various components and structures based on their mechanical properties, including stress tolerance.
- **Example:** When designing a robotic arm, engineers select materials that can withstand the tensile and compressive stresses generated during the arm's operation. The choice of materials ensures that the arm can carry out its tasks safely and reliably.

2. Structural Analysis:

- **Application:** Stress analysis is essential for assessing the structural integrity of mechatronic systems, especially those involving complex mechanical components.
- **Example:** In mechatronics, finite element analysis (FEA) software is commonly used to simulate and analyze the stresses within a mechanical structure. Engineers can identify areas of high stress concentration and make design modifications to reduce stress and prevent failures.

Strain

- **Definition:** Strain is a measure of the deformation or elongation of a material in response to stress. It quantifies the relative change in size or shape of a material compared to its original state.
- **Units:** Strain is typically expressed as a dimensionless ratio or as a percentage.



- **Types of Strain:**
  - **Tensile Strain:** Occurs when a material elongates in response to tensile stress.
  - **Compressive Strain:** Occurs when a material shortens in response to compressive stress.
  - **Shear Strain:** Occurs when a material undergoes angular deformation in response to shear stress.

Mechatronics Applications of Strain:

1. Deformation Sensing:

- **Application:** Strain sensors and strain gauges are commonly used in mechatronics to measure deformations and provide feedback on the structural integrity of components.
- **Example:** Strain gauges are used in load cells to measure the strain induced by applied loads. This information is vital in robotic systems for monitoring forces and ensuring safety during operation.

2. Feedback Control:

- **Application:** In mechatronic systems, strain measurements can be used as feedback signals to control and adjust the behavior of mechanical components.
- **Example:** In automated manufacturing, strain sensors in robotic arms can detect variations in material properties and adjust the grip force accordingly to prevent damage or slippage.

Material Selection for a Mechatronic Robotic Arm

1. Mechanical Properties:

- **Strength:** Consider the required load-bearing capacity of the robotic arm. If the arm needs to carry heavy payloads, materials with high tensile and compressive strength, such as aluminum alloys or steel, may be suitable.
- **Stiffness:** Depending on the application, you may require materials with high stiffness to maintain precision and minimize deflection. Carbon fiber composites or titanium alloys are known for their stiffness.

2. Thermal Properties:

- **Thermal Conductivity:** In cases where the robotic arm generates or encounters heat, consider materials with good thermal conductivity to dissipate heat effectively. Aluminum is a common choice for heat dissipation due to its high thermal conductivity.
- **Coefficient of Thermal Expansion (CTE):** Matching the CTE of materials is important to prevent thermal stress and deformation at material interfaces when the arm is exposed to temperature variations.

3. Electrical Properties:

- **Electrical Conductivity:** If the robotic arm requires electrical conductivity for signal transmission or grounding, materials like copper or certain alloys may be needed.
- **Dielectric Properties:** In applications where electrical insulation is crucial, materials with high dielectric strength, like ceramics or certain plastics, should be considered.

4. Weight and Density:

- **Weight:** Consider the overall weight of the robotic arm. Lightweight materials like aluminum, magnesium, or composites are often preferred to reduce the energy required for motion and improve system efficiency.
- **Density:** Calculate the density of materials to determine the arm's mass distribution and its effect on stability and control.

5. Corrosion Resistance:

- **Environmental Conditions:** Assess the operating environment of the robotic arm. If it will be exposed to corrosive substances or moisture, materials with good corrosion resistance, such as stainless steel or corrosion-resistant coatings, should be chosen.

6. Cost and Availability:

- Consider the cost of materials and their availability in the required form. Some advanced materials may be expensive or challenging to procure.

7. Manufacturing Considerations:

- Evaluate the ease of manufacturing with the chosen materials. Some materials may require specialized processes, while others can be readily machined or formed.

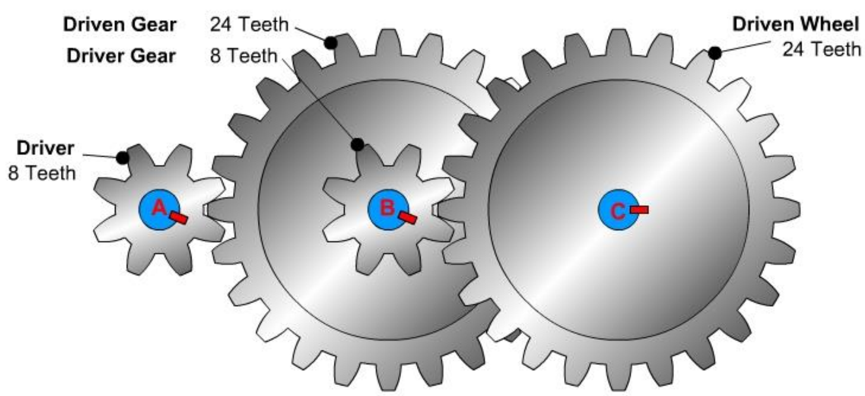
8. Application-Specific Requirements:

- Tailor the material selection to the specific application and operational requirements. For example, in a cleanroom environment, materials with low particle generation may be necessary.

Mechanical components and mechanisms

Gears and Gear Trains

Gears: Gears are mechanical components with toothed wheels that transmit motion and power from one shaft to another. They are used to change the speed, torque, and direction of rotation in mechatronic systems.



Gears and gear trains are mechanical systems used to transmit motion and power between rotating shafts. The key parameters involved in gears and gear trains include gear ratio, rotational speed, and torque. Here are some essential formulas related to gears and gear trains:

1. Gear Ratio (GR):

- The gear ratio represents the ratio of the number of teeth on the driver gear (the one providing input motion) to the number of teeth on the driven gear (the one receiving output motion). It determines the speed and torque relationship between the gears.
- Formula: $GR=N1/N2$
    - GR is the gear ratio.
    - $N1$ is the number of teeth on the driver gear.
    - $N2$ is the number of teeth on the driven gear.

- The gear ratio can also be used to calculate the ratio of angular velocities (rotational speeds) between the gears.

2. Rotational Speed (Angular Velocity) Relationship:

- The rotational speed (n) of a gear is inversely proportional to its radius (r) and directly proportional to the gear ratio (GR) and the rotational speed of the driver gear ($n1$).
- Formula: $n=n1/\mathrm{GR}=r1/r2$
  - n is the rotational speed of the driven gear.
  - $n1$ is the rotational speed of the driver gear.
  - $r1$ is the radius of the driver gear.
  - $r2$ is the radius of the driven gear.

3. Torque (Rotational Force) Relationship:

- The torque (T) transmitted by gears is inversely proportional to the gear ratio (GR) and directly proportional to the torque applied to the driver gear ($T1$).
- Formula: $T=T1\cdot GR$
  - T is the torque of the driven gear.
  - $T1$ is the torque of the driver gear.

4. Compound Gear Trains:

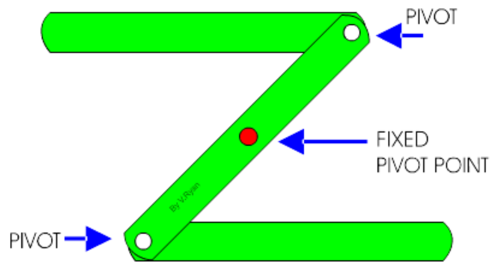
- In compound gear trains, where multiple gears are interconnected, you can calculate the overall gear ratio by multiplying the individual gear ratios.
- For a compound gear train with gears in series (connected end to end), the overall gear ratio (GR_{total}) is the product of the individual gear ratios.
- For a compound gear train with gears in parallel (connected side by side), the overall gear ratio (GR_{total}) is the ratio of the sum of the driver gear teeth to the sum of the driven gear teeth.

These formulas are fundamental for analyzing and designing gear systems and understanding how they affect rotational speed and torque in mechanical systems. They are useful in various applications, including machinery, vehicles, and industrial equipment.

- **Mechatronics Application:** In mechatronics, gears are commonly used in various applications, including robotics, manufacturing, and automation. For instance:
  - **Robotic Joints:** Gears are used in the joints of robotic arms to control and coordinate their movements, allowing for precise positioning and manipulation of objects.
  - **Gear Reduction Systems:** Gear trains are used in mechatronic systems to achieve speed reduction or amplification. For example, in a mechatronic conveyor system, gear trains can be used to control the speed of the conveyor belt.

Linkages and Cams

- **Linkages:** Linkages are mechanical systems composed of rigid rods and pivot points that create specific motion paths or transformations between input and output.



- **Cams:** Cams are eccentric rotating components that convert rotational motion into linear or oscillatory motion.
- **Mechatronics Application:** Linkages and cams are used in mechatronics for various purposes, including:
  - **Valve Actuators:** Linkages and cams are used in engine mechatronic systems to control the opening and closing of intake and exhaust valves for combustion engines.
  - **Printing Machines:** In printers, linkages and cams control the movement of print heads, ensuring precise positioning of ink nozzles during printing.

Bearings and Couplings:

- **Bearings:** Bearings are components used to support and reduce friction between moving parts. They come in various types, including ball bearings, roller bearings, and plain bearings.
- **Couplings:** Couplings are mechanical devices that connect two shafts and transfer torque while accommodating misalignment or shock loads.
- **Mechatronics Application:** Bearings and couplings are essential for maintaining smooth and reliable operation in mechatronic systems, such as:
  - **Robot Joints:** Bearings are used in robotic joints to reduce friction and ensure smooth and precise motion. Couplings are employed to connect the motor shaft to the joint shaft while accommodating any misalignment.
  - **Precision Machinery:** In precision mechatronic systems like CNC machines, bearings are used to support and guide moving components, such as the tool spindle. Couplings connect the motor and the spindle while compensating for misalignment and vibrations.

Design considerations for mechatronic systems

1. Material Selection:

- **Mechanical Properties:** Choose materials that meet the required mechanical properties, such as strength, stiffness, and thermal conductivity, based on the specific application. For example, select materials with high tensile strength for load-bearing components in robotic systems.

- **Thermal Properties:** Consider the thermal properties of materials, including thermal conductivity and coefficient of thermal expansion, to ensure that the materials can handle temperature variations and dissipate heat effectively, especially in components with motors or electronic elements.

- **Electrical Properties:** In mechatronics, electrical properties like electrical conductivity or dielectric strength may be crucial, especially in components that involve electrical connections or insulation.

- **Weight and Density:** Optimize the material selection to achieve the desired weight, density, and mass distribution for the mechatronic system. Lightweight materials can enhance system mobility and efficiency, as seen in drones and mobile robots.

- **Corrosion and Wear Resistance:** Assess the environmental conditions the system will operate in and select materials that resist corrosion and wear, particularly in applications exposed to moisture, chemicals, or abrasive environments.

- **Cost and Availability:** Consider the cost and availability of materials, as well as their ease of procurement and manufacturing. Balancing performance with cost constraints is essential in many mechatronic applications.

2. Design for Manufacturability:

- **Simplicity and Modularity:** Aim for designs that are as simple and modular as possible. Modular designs allow for easier assembly, maintenance, and scalability, which is important in mechatronics, where systems often consist of multiple interconnected components.

- **Standardization:** Use standardized components and interfaces whenever possible. This simplifies procurement, reduces lead times, and ensures compatibility between parts. Standardization is particularly valuable in mechatronics systems that incorporate various sensors, actuators, and control units.

- **Tolerances and Fits:** Define appropriate tolerances and fits for mating parts to ensure proper assembly and minimize the risk of misalignment or interference.

- **Design Validation:** Perform design validation through simulation and prototyping to identify and address any manufacturability issues before production. This can save time and resources in the long run.

- **Design for Assembly (DFA):** Optimize the design for ease of assembly by minimizing the number of parts, reducing fastener complexity, and providing clear assembly instructions. Efficient assembly is critical for reducing production costs.

3. Design for Reliability:

- **Redundancy:** Consider incorporating redundancy in critical components or systems to enhance reliability. For instance, in aerospace mechatronics, redundant sensors and control systems are often used for safety-critical functions.
- **Testing and Validation:** Implement comprehensive testing and validation procedures throughout the design and manufacturing process. This includes stress testing, reliability testing, and failure mode analysis.
- **Serviceability:** Design components and systems with serviceability in mind. Ensure that routine maintenance, repairs, and replacements can be carried out with minimal downtime and cost.
- **Fault Tolerance:** Develop strategies for fault detection and recovery. In mechatronic systems, robust control algorithms and sensor redundancy can help detect and mitigate faults in real-time.
- **Environmental Considerations:** Account for the operating environment and conditions, such as temperature extremes, humidity, and vibration, when designing for reliability. Select materials and components that can withstand these conditions.