Mechanics for Robotics

Course Overview

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Course Structure

- **Duration:** 10 Sessions $\times$ 1.5 Hours = **15 Hours**
- **Mode:** Conceptual Lectures + Interactive Simulations
- **Level:** Minor in AI specialization (Undergraduate/Master)
- **Alignment:** Intelligent Systems $\rightarrow$ Robotics $\rightarrow$ Kinematics and Dynamics (IS.KD)
- **Pedagogy:**
  - Each session includes theory + practical demos
  - Focus on physics foundations applied to real robots
  - Tools: Python, GeoGebra, RoboAnalyzer, PyBullet, Arduino sim, PhET

Key Focus Areas

This course will explore the interplay between physics and robotics:

1. **Foundations of Mechanics**
   - Motion (Kinematics): position, velocity, acceleration
   - Forces (Dynamics): Newton's laws, torque, angular motion
   - Equilibrium (Statics): balance, center of mass, support polygon
2. **Mechanical Behavior of Robotic Systems**
   - Friction, compliance, damping, and energy losses
   - Linkages, joints, actuators, and gear systems
3. **Simulation-Based Learning**
   - Modeling robot motion and forces using physics engines
   - Simulating real-world behaviors in controlled environments
4. **Application-Driven Learning**
   - Understanding mechanical requirements in robotic arms, legs, and mobile platforms
   - Linking physics principles to design constraints and performance

Learning Outcomes

By the end of this course, students will be able to:

- **Understand and apply physics principles** such as motion, forces, torque, energy, and friction to analyze robotic behavior.
- **Model mechanical aspects of robotic systems** using free-body diagrams, torque calculations, and energy equations.
- **Analyze static and dynamic stability** of robots, including balance, center of mass, and compliance.
- **Use simulation tools** like PyBullet, RoboAnalyzer, and GeoGebra to visualize kinematics and dynamics of robots.
- **Evaluate actuator demands and mechanical trade-offs** such as torque-speed balance, energy consumption, and frictional losses.
- **Bridge theory and practice** by relating foundational mechanics to real-world robot components, tasks, and challenges.

Session 1: Introduction to Mechanics for Robotics

Topics Covered:

- What is mechanics? Branches: statics, dynamics, kinematics
- Why study mechanics in the context of robotics?
- From classical mechanics to robot motion
- Overview of robotics applications needing mechanical understanding

Learning Objectives:

- Grasp the foundational role of mechanics in robotic systems
- Recognize key mechanics concepts relevant to motion and control
- Build intuition about robot-environment physical interactions

Hands-on / Demo:

- Interactive Newton's Laws simulator (e.g., PhET or Python)

Session 2: Vectors, Coordinate Frames & Kinematics

Topics Covered:

- Scalars vs. vectors in mechanics
- Position, displacement, velocity and acceleration as vectors
- Coordinate systems: world frame vs local frame
- Transformations: translation, rotation, homogeneous matrices

Learning Objectives:

- Use vector notation to describe motion in space
- Understand how coordinate frames are attached to robot parts
- Perform basic transformations between frames

Hands-on / Demo:

- 3D vector visualization using GeoGebra or matplotlib
- Coordinate frame animation (optional: RoboAnalyzer or Python)

Session 3: Linear and Angular Motion

Topics Covered:

- Linear motion: velocity, acceleration
- Angular motion: angular velocity, angular acceleration
- Relationship between linear and angular quantities
- Torque: definition and physical meaning

Learning Objectives:

- Distinguish between linear and rotational quantities
- Understand torque as the cause of angular motion
- Apply vector relationships between rotation and translation

Hands-on / Demo:

- Fidget spinner demo with webcam tracking angular speed
- Python simulation of rotating arms

Session 4: Statics and Center of Mass

Topics Covered:

- Forces and moments in equilibrium
- Free-body diagrams
- Center of mass (COM) and balance
- Support polygon and static stability

Learning Objectives:

- Analyze static equilibrium using force balance
- Calculate the COM for a robotic configuration
- Determine stability based on support area

Hands-on / Demo:

- Static analysis of a 2D robotic arm (free-body diagram)
- COM plots for different robot poses (Python)

Session 5: Newton-Euler Dynamics

Topics Covered:

- Newton's second law ($F = ma$) and angular counterpart ($\tau = I\alpha$)
- Moment of inertia and its role
- Newton-Euler formulation of link dynamics
- Link-wise force propagation in robots

Learning Objectives:

- Apply Newton-Euler equations to robotic links
- Understand rotational inertia and torque relationships
- Analyze dynamics of serial manipulators

Hands-on / Demo:

- Simulate forces on a rotating arm (Python)
- Inertia effects with variable link lengths

Session 6: Energy, Work and Power

Topics Covered:

- Kinetic and potential energy in motion
- Work-energy theorem
- Mechanical work by actuators
- Power consumption and efficiency in motors

Learning Objectives:

- Quantify energy involved in robot motion
- Compute work done by and on a robot
- Understand actuator efficiency and power demand

Hands-on / Demo:

- Simulate energy in pendulum motion (Python)
- Power measurement with Arduino motor setup

Session 7: Friction, Compliance and Damping

Topics Covered:

- Sliding and rolling friction in robotics
- Contact modeling and compliant joints
- Hooke's law, springs and dampers
- Mechanical compliance and passive safety

Learning Objectives:

- Model and simulate different frictional forces
- Understand compliance and damping in robotic systems
- Analyze energy dissipation in mechanical interactions

Hands-on / Demo:

- Ball on adjustable incline simulation
- Spring-mass-damper system in Python

Session 8: Linkages, Mechanisms and Drives

Topics Covered:

- 4-bar linkages and crank-slider mechanisms
- Gear trains, belts, and pulleys
- Torque-speed tradeoffs in gear systems
- Transmission design for robotic joints

Learning Objectives:

- Analyze mechanical advantage using gears and linkages
- Understand role of transmissions in actuation
- Design basic drive systems for robotic motion

Hands-on / Demo:

- Simulate linkages in RoboAnalyzer
- Explore gear ratios using virtual lab

Session 9: Inverse Dynamics

Topics Covered:

- From motion to force: Inverse dynamics problem
- Recursive Newton-Euler algorithm
- Torque profiles for trajectory tracking
- Real-time actuation demands in manipulators

Learning Objectives:

- Compute required joint torques for known motion
- Use inverse dynamics to optimize control strategies
- Apply recursive formulations for multi-link robots

Hands-on / Demo:

- Python walkthrough: 2-link arm inverse dynamics

Session 10: Simulation Tools & Robot Case Studies

Topics Covered:

- Overview of simulation tools: PyBullet, Mujoco, RoboAnalyzer
- Building a simulation scene for robot motion
- Real-world case studies: Boston Dynamics, industrial arms
- Review of mechanics applications across the course

Learning Objectives:

- Use simulation tools to test and analyze robot mechanics
- Connect course principles to actual robot design
- Reflect on the mechanical foundations of modern robotics

Hands-on / Demo:

- PyBullet-based interactive robot demo
- Visual walkthrough of Boston Dynamics mechanics

Session 1: Introduction to Mechanics for Robotics

Part A: Motivation and Mechanics Foundations
Part B: Motion, Forces, and Newton's Laws
Part C: Mechanics in Robotics Examples - videos

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Part A – Motivation and Mechanics Foundations

What is Mechanics in Robotics?

Mechanics is the branch of physics that studies how physical bodies behave when subjected to forces or displacements.

- Includes both:
  - **Bodies at rest** (Statics)
  - **Bodies in motion** (Kinematics & Dynamics)
- Provides the physical foundation for:
  - Robotic movement
  - Balance and stability
  - Interaction with the environment
- In robotics, every action is governed by mechanics — from a finger gripping a cup to a drone adjusting flight trajectory...

Why Study Mechanics in Robotics?

Robotics is not just coding — it's applied physics. Every robotic movement involves:

- **Applying a force**
- **Responding to friction, gravity, and torque**
- **Ensuring balance and stability**

Mechanics helps answer:

- How much force is needed to lift a load?
- How does a robot stay upright?
- What happens when a robot speeds up or slows down?

"Think of a robot as a physical agent obeying the laws of physics. Whether it's moving forward, picking an object, or stabilizing mid-air — mechanics is the invisible framework behind all its motion."

Three Main Branches of Mechanics

Mechanics is divided into three key branches, each addressing different physical questions in robotics:

- **Kinematics**
  - Describes motion *without considering the forces that cause it*
  - Involves position, velocity, acceleration
  - Used for path planning, trajectory design
  - Example: Analyzing how the joints of a robotic arm allow for specific movements and reach.
- **Dynamics**
  - Relates motion to the *forces that cause it*
  - Core equation: $F = ma$, $\tau = I\alpha$
  - Used in control of actuators, calculating torque
  - Example: Analyzing the forces needed to move a robotic arm, including gravity, friction, and external loads.

Three Main Branches of Mechanics

- **Statics**
  - Deals with systems in equilibrium *(no net force or motion)*
  - Focuses on balance, stability, and support forces
  - Used in analyzing stationary robots or balanced poses
  - Example: Calculating the center of mass and support polygon for a robot standing still.

Real-World Robotics Examples

Let's connect mechanics to actual robotic systems:

- **Robotic Arm (Dynamics)**
  - Calculates joint torques to lift or move payloads
  - Applies Newton's second law: $\tau = I\alpha$
  - Dynamics governs how fast and smoothly it moves

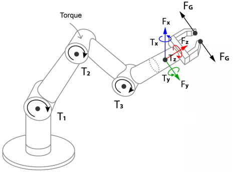

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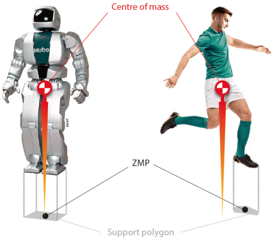
Image Sources:

1. https://reachrobotics.com/blog/force-and-torque-ft-why-are-they-of-interest-in-robotics/
2. https://mail.irjet.net/archives/V10/i1/IRJET-V10I187.pdf

Three Main Branches of Mechanics

- **Humanoid Robot (Statics)**
  - Maintains upright posture while walking or standing
  - Uses Center of Mass (COM) and Support Polygon
  - Statics ensures stability by balancing torques and forces



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- **Mobile Robot or Car (Kinematics + Dynamics)**
  - Uses wheel rotation to navigate and steer
  - Kinematics defines path; dynamics controls acceleration/braking
  - Friction and inertia must be considered for turns and stops


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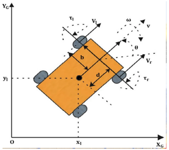
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Image Sources:
1. https://metode.org/issues/monographs/robots-that-look-like-humans.html
2. https://www.mdpi.com/1424-8220/22/21/8101
3. https://www.nature.com/articles/s41598-022-16226-y

Part B – Motion, Forces, and Newton's Laws

Motion Quantities & Physical Concepts

Position $x(t)$**:**
Describes location along a line (1D).

Distance: Total path covered (scalar)

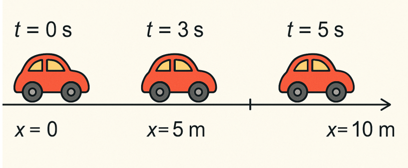
Displacement: Net change in position (vector)

Speed: Rate of distance covered (scalar)

$$\text{Speed} = \frac{\text{Distance}}{\text{Time}}$$

Velocity: Rate of displacement (vector)

$$v(t) = \frac{dx(t)}{dt}$$



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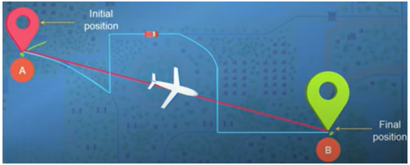

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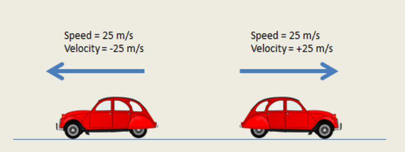

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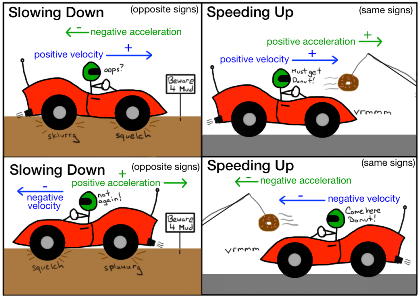
Motion Quantities & Physical Concepts

Acceleration

Change in velocity, $a(t) = \frac{dv(t)}{dt}$



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Force

Push or pull causing motion/change

Measured in Newtons (N), vector quantity

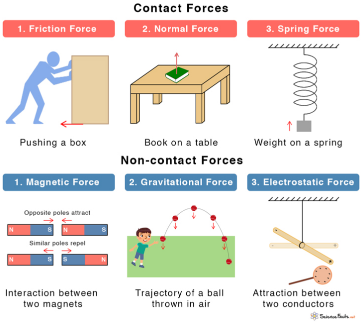

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Image Sources:

1. `https://chatgpt.com/`
2. `https://youtu.be/ytKBxscSni0`
3. `https://examvictor.com/difference-speed-velocity/`
4. `https://www.khanacademy.org/science/mechanics-essentials/`
5. `https://www.sciencefacts.net/types-of-forces.html`

Balanced vs Unbalanced Forces

Balanced Forces:

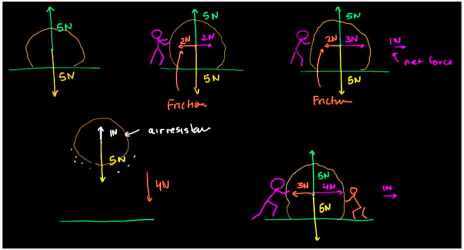
- Equal in magnitude and opposite in direction
- **Net force = 0** $\rightarrow$ no change in motion
- Object remains at rest or moves with constant velocity

Example: Balanced and unbalanced forces acting on a rock:

- A rock at rest experiences balanced vertical forces (gravity and normal force).
- When external pushes exceed friction, the net force becomes non-zero and the rock moves or accelerates.

Unbalanced Forces:

- Forces do not cancel out
- **Net force** $\neq 0 \rightarrow$ object accelerates
- Can change an object's speed, direction, or both



Source:
`https://www.khanacademy.org/science/physics/forces-newtons-laws/newtons-laws-of-motion/v/balanced-and-unbalanced-forces`

Newton’s First Law: Inertia

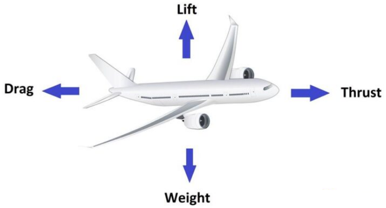
“An object at rest remains at rest, and an object in motion remains in motion at constant speed and in a straight line unless acted on by an unbalanced force.”

What does it mean?

- Motion only changes when a net force is applied
- This tendency to resist change is called **inertia**

Example: Forces Acting on an Aircraft

- An airplane is subject to two opposing sets of external forces:
  - **Thrust vs Drag**
  - **Lift vs Weight**
- If one force becomes stronger than its counterpart:
  - The airplane may speed up, slow down, change direction or altitude.



Source:
`https://www.aviationfile.com/newtons-laws-of-motion-and-aviation`

Newton's Second Law: Force Causes Acceleration

"When an unbalanced force acts on an object, it causes the object to accelerate in the direction of the net force."

Mathematical Form:

$$\sum \vec{F} = m\vec{a} \quad \text{or} \quad \vec{a} = \frac{\sum \vec{F}}{m}$$

- $\sum \vec{F}$ = Net force (sum of all forces), in Newtons (N)
- m = Mass (kg)
- $\vec{a}$ = Acceleration (m/s²)

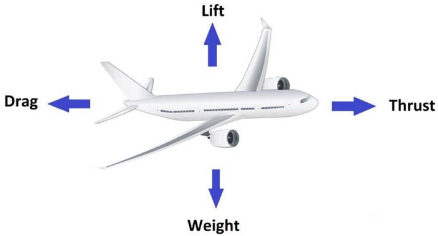
Key Ideas:

- More force → more acceleration (if mass is constant)
- More mass → less acceleration (if force is constant)
- Acceleration always happens in the direction of the net force

Newton's Second Law: Force Causes Acceleration

Example – Aircraft in Motion:

- **Climbing:**
  Thrust + Lift > Weight + Drag
- **Cruising:**
  Thrust + Lift = Weight + Drag
- **Descending:**
  Thrust + Lift < Weight + Drag



Newton's Third Law: Action–Reaction Pairs

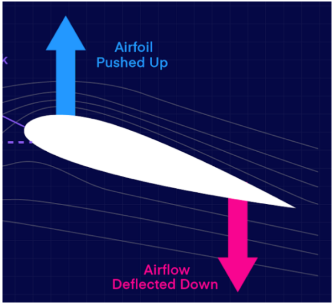
"Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first."

Key Ideas:

- These force pairs happen simultaneously and do not cancel each other
- Both objects experience force regardless of their mass

Forces Come in Pairs: Fundamental to How Airplanes Work

- Wings push air downward → air pushes wings upward with equal force (lift)
- On the ground, the aircraft pushes down → the ground pushes up
- To fly, lift must balance or exceed the weight of the aircraft



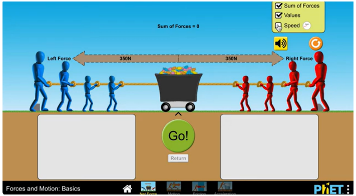
Source: `https://pilotinstitute.com/newtons-third-law/`

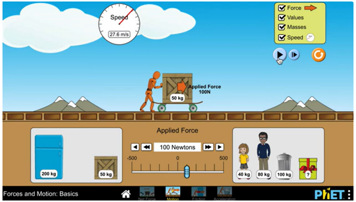
PhET Simulation: Demonstrating Newton's Laws and Friction

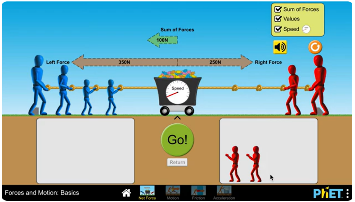
Interactive Link: [PhET: Forces and Motion Basics]

Demonstrations:

- **Newton's First Law – Balanced Forces in Tug of War:** Equal teams $\rightarrow$ object stays still or moves at constant velocity
- **Friction – Resistance to Motion** Force $=$ friction $\rightarrow$ no motion. Force $>$ friction $\rightarrow$ motion. Remove force $\rightarrow$ object slows due to friction
- **Newton's Second Law – Unbalanced Forces in Tug of War** Unequal teams $\rightarrow$ net force causes acceleration. More force $=$ more acceleration







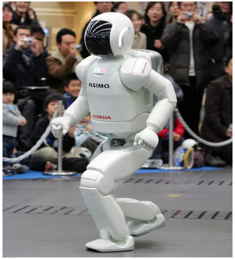
Applying Newton's Laws in Robotics

Mechanics explains how robots lift, move, stop, and balance in the real world.

Robotic Arm (Torque)

Forces at joints to lift objects.

Watch Video



Humanoid Robot (Balance)

Maintaining stability using center of mass.

Watch Video

Autonomous Car (Braking)

Uses acceleration, friction, and deceleration.

Watch Video