Robotics: Introduction

Minor in AI - IIT ROPAR

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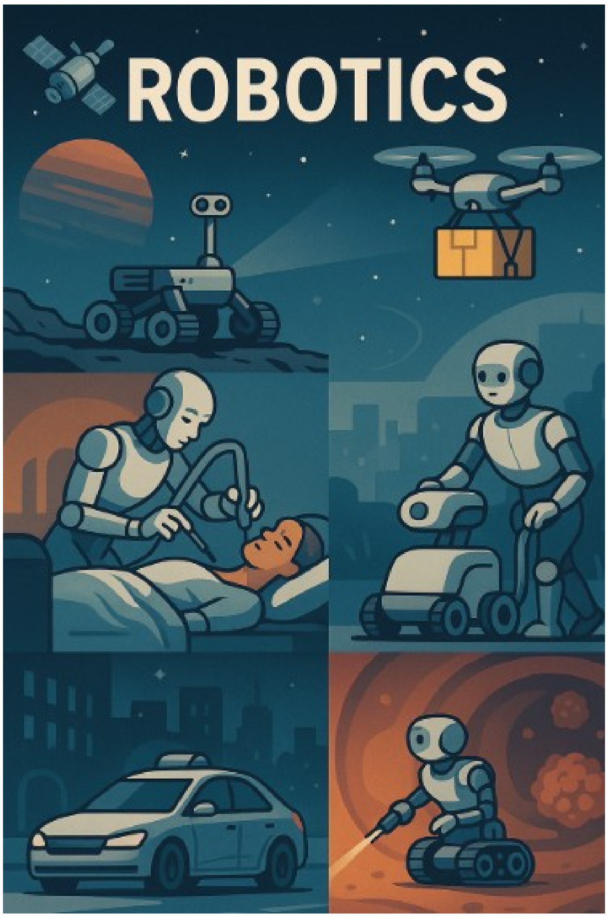
Welcome to the world of Robotics! Imagine a world where machines not only follow instructions but also think, see, and act autonomously—helping humans explore the farthest reaches of space, perform intricate surgeries with unmatched precision, and even assist us in everyday tasks like cleaning our homes or delivering packages.

Robotics is the exciting interdisciplinary field that brings this vision to reality by blending creativity, mechanical design, electronics, and cutting-edge computer intelligence.

It goes far beyond simply building robots; it involves creating intelligent systems that can sense their environment, process vast amounts of data, make complex decisions, and physically interact with the world around them to solve real-world challenges.

Whether it's autonomous cars safely navigating through chaotic city streets, drones monitoring disaster zones, or microscopic medical robots targeting diseases within the human body, robotics is revolutionizing industries, improving quality of life, and expanding the boundaries of technology.

As you embark on this journey into robotics, you step into a dynamic world where innovation knows no limits, and your ideas have the power to shape the future of how humans and machines coexist and collaborate.



What is a Robot?

Definition:
A *robot* is a programmable machine that can execute a sequence of actions either automatically or semi-autonomously. These machines are designed to interact with the physical world and can adapt to their surroundings by processing sensory input and making decisions based on that data. Robots may be mobile or stationary and can be employed in a wide variety of domains such as manufacturing, healthcare, space exploration, and household assistance.

Key Idea:
"A robot senses, thinks, and acts." This encapsulates the three fundamental capabilities of a robot:

- **Sensing**: Gathering information from its environment
- **Thinking**: Processing the information and making decisions
- **Acting**: Executing physical actions based on its decisions

Essential Components of a Robot

To achieve these capabilities, a robot typically consists of the following core components:

1. **Sensors**
   Sensors are the components that allow a robot to perceive its environment. They gather data from the physical world and convert it into signals that the robot can interpret. Types of sensors include:
   - *Cameras* – for visual perception and object recognition
   - *Touch sensors* – to detect physical contact and pressure
   - *Proximity sensors* – to measure the distance to nearby objects
   - *Temperature, sound, and light sensors* – for specific environmental readings
2. **Actuators**
   Actuators are the mechanisms through which a robot interacts with the physical world. They convert commands from the controller into motion or other forms of action. Common types of actuators include:
   - *Electric motors* – to drive wheels or joints
   - *Servos* – for precise angular movement
   - *Hydraulic or pneumatic systems* – for high-force tasks
3. **Controller**
   The controller is often considered the brain of the robot. It is responsible for processing the input from sensors, making decisions based on programmed algorithms or learned behavior, and sending commands to actuators. Controllers can range from simple microcontrollers to advanced embedded computer systems.
   - May include onboard processors, memory, and communication interfaces
   - Can implement decision-making through logic, rule-based systems, or artificial intelligence

What is Robotics?

Definition:
Robotics is an interdisciplinary field concerned with the design, construction, operation, and application of robots. These are machines capable of perceiving their environment, making decisions, and executing actions in the physical world. Robotics combines principles from multiple engineering and scientific disciplines to create intelligent systems that can perform tasks autonomously or semi-autonomously.

The field encompasses both the theoretical and practical aspects of robotic systems, ranging from their mechanical structure to their cognitive capabilities.

Core Disciplines Involved in Robotics

Robotics draws upon knowledge from several foundational fields:

1. **Mechanical Engineering**
   Focuses on the physical structure and movement of robots, including:
   - Kinematics and dynamics
   - Design of joints, arms, and mobile platforms
   - Mechanical strength and structural integrity
2. **Electrical and Electronics Engineering**
   Provides the essential electronic systems required for sensing and actuation, such as:
   - Design of electrical circuits and power systems
   - Integration of sensors and actuators
   - Signal processing and interface electronics
3. **Computer Science**
   Enables the programming and intelligence of robots, including:
   - Software development and embedded programming
   - Artificial intelligence and machine learning
   - Computer vision and path planning
4. **Control Systems Engineering**
   Ensures accurate and stable behavior of robots through feedback mechanisms:
   - Closed-loop control and automation
   - PID controllers and system stability
   - Real-time decision-making and error correction

Goal of Robotics

The ultimate objective of robotics is to develop autonomous or semi-autonomous systems that can:

- **Assist** humans in performing repetitive, dangerous, or precision-demanding tasks
- **Augment** human capabilities by enhancing strength, precision, or perception
- **Replace** human labor in hazardous or inaccessible environments

These goals are applied across diverse industries, including manufacturing, healthcare, agriculture, space exploration, and domestic services.

Characteristics of a Robot

Robots possess a set of core capabilities that distinguish them from conventional machines. These capabilities allow robots to operate intelligently and interact with the real world:

1. **Perception**
   The ability to sense and interpret the surrounding environment using various sensory technologies. Examples include:
   - *Cameras* – for visual information and object recognition
   - *Proximity sensors* – to detect nearby obstacles
   - *LIDAR* – for high-precision 3D mapping and navigation

2. **Computation**
   The capability to process sensory data, execute algorithms, and make decisions. This includes:
   - *Microcontrollers and embedded systems* – for low-level control
   - *Processors and computing units* – for real-time data handling
   - *Artificial intelligence models* – for learning and adaptive behavior
3. **Actuation**
   The means through which a robot physically interacts with its environment by executing tasks. Common actuators include:
   - *Motors and servos* – for joint or wheel movement
   - *Grippers* – to manipulate objects
   - *Legs or wheels* – for locomotion
4. **Autonomy**
   The degree to which a robot can operate independently without human intervention. This includes:
   - *Automated navigation systems*
   - *Obstacle detection and avoidance*
   - *Decision-making under uncertainty*
5. **Embodiment**
   Refers to the robot's physical presence and ability to act within the real, physical world. Unlike virtual agents, robots:
   - Occupy space and have a tangible form
   - Interact directly with physical objects and environments
   - Must manage real-world constraints such as friction, gravity, and terrain

Types of Robots

Robots are developed for a wide range of environments and functions. They can be broadly categorized according to their design, functionality, and area of application: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1. **Industrial Robots**
   These robots are typically stationary and used in structured manufacturing environments. They are designed for high precision, repeatability, and speed in tasks such as:
   - *Welding* – joining materials in automotive or aerospace industries
   - *Painting* – automated spray coating to ensure uniformity
   - *Assembly and packaging* – placing components or products in desired configurations

   Industrial robots often consist of multi-jointed robotic arms with high degrees of freedom.

   Examples: KUKA KR series, ABB IRB series, FANUC robots


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2. **Service Robots**
   Designed to perform tasks that directly assist or benefit humans, these robots operate in homes, offices, warehouses, and public spaces. Their functions include:

   - *Domestic help* – cleaning, lawn mowing, personal assistance
   - *Hospitality* – concierge robots in hotels, room service delivery
   - *Logistics* – automated carts or robots for goods handling

   Service robots often require interaction with unstructured environments and humans.

   Examples: Boston Dynamics Spot, Starship delivery bots, Whiz cleaning robot


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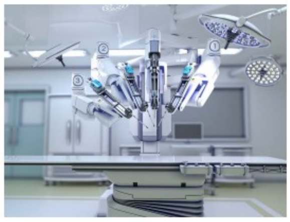
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3. **Medical Robots**
   Used in healthcare to improve accuracy, minimize invasiveness, and enhance patient outcomes. These robots function in:

   - *Surgical assistance* – enhancing precision and control in operations
   - *Rehabilitation* – assisting patients with mobility recovery
   - *Diagnostics and telepresence* – enabling remote diagnosis or surgery

   They must meet stringent safety and sterility standards.

   Examples: da Vinci Surgical System, ReWalk exoskeleton, CyberKnife

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4. **Humanoid Robots**
   These robots are designed to resemble the human body in structure and/or behavior. Their key features include:

   - *Bipedal locomotion* – walking like humans
   - *Facial expression and speech* – for natural social interaction
   - *Gesture-based communication* – useful in education, caregiving, or companionship

   Used extensively in human-robot interaction research and as social robots.

   Examples: Honda ASIMO, SoftBank Pepper, Hanson Robotics' Sophia, Boston Dynamics ATLAS

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5. **Exploration Robots**
   Built to function in extreme, dangerous, or inaccessible environments where human presence is impractical. Applications include:

   - *Space exploration* – navigating alien terrains and collecting samples
   - *Underwater missions* – inspecting pipelines, shipwrecks, marine research
   - *Hazardous zones* – volcanic areas, radiation zones, disaster relief

   These robots require rugged designs, autonomy, and remote operability.

   Examples: NASA Mars rovers (Spirit, Opportunity, Perseverance), OceanOne deep-sea robot, VolcanoBot


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6. **Defense Robots**
   Developed for military, security, and tactical purposes. They may be armed or unarmed and are used for:

   - *Surveillance and reconnaissance* – gathering intelligence in real-time
   - *Combat support and engagement* – armed ground robots or aerial drones
   - *Search and rescue* – identifying and assisting wounded personnel in combat zones
   - *Explosive ordnance disposal* – safely handling or disabling bombs

   They must be durable, reliable, and capable of mission-critical tasks.

   Examples: MAARS (Modular Advanced Armed Robotic System), DOGO robot, iRobot PackBot, MQ-9 Reaper UAV

What are Sensors and Actuators?

In robotics, interaction with the physical world is achieved through two essential components: **sensors** and **actuators**. These elements form the sensory and motor systems of a robot.

Sensor: The Sensory System

A **sensor** is a device that detects or measures a specific physical property and converts it into a signal that can be processed by the robot's control system.

- **Function:** Gather real-time data from the robot's surroundings or internal systems.
- **Output:** Typically an analog or digital electrical signal.
- **Role:** Enables perception — the robot's ability to "sense" the world.

Common Measured Properties: Distance, light intensity, temperature, pressure, motion, force, orientation.

Actuator: The Motor System

An **actuator** is a component that takes control signals (usually electrical) and produces mechanical movement or physical action.

- **Function:** Execute movement or interaction tasks as commanded by the controller.
- **Types of Motion:** Linear (e.g., pistons), rotational (e.g., motors), gripping, or multi-axis motion.
- **Role:** Provides the robot with the ability to act on and alter its environment.

Examples: DC motors, stepper motors, servo motors, pneumatic actuators, robotic arms, grippers, legs.

Robotic Interaction Cycle

The fundamental interaction cycle in robotics can be visualized as:

Environment $\rightarrow$ **Sensor** $\rightarrow$ **Controller** $\rightarrow$ **Actuator** $\rightarrow$ **Environment**

This feedback loop enables adaptive and responsive behavior.

Types of Sensors in Robotics

Sensors in robotics are essential for perception and internal awareness. They are broadly categorized into:

1. External Sensors (Exteroceptive)

These sensors monitor the external world — what is outside the robot.

- **Purpose:** To understand and interpret the environment.
- **Applications:** Obstacle detection, navigation, mapping, environmental interaction.

Examples:

- **Proximity Sensors:**
  - *Infrared (IR):* Detect nearby objects using reflected light.
  - *Ultrasonic:* Emit sound waves and measure echoes to estimate distance.
  - *LIDAR:* High-precision laser-based distance sensing for mapping and SLAM.
- **Vision Sensors:**
  - *Cameras:* Capture 2D or 3D images for object recognition, tracking, etc.
  - *Depth Sensors:* Combine IR and visual data to perceive 3D depth.
- **Tactile Sensors:**
  - *Touch Pads:* Detect contact or pressure.
  - *Force Sensors:* Quantify applied force or strain.
- **Environmental Sensors:**
  - *Light, Gas, Humidity, Temperature sensors:* For adaptive behavior in changing conditions.

2. Internal Sensors (Proprioceptive)

These sensors provide feedback about the robot's own state and motion.

- **Purpose:** To monitor internal systems for localization, movement control, and diagnostics.
- **Applications:** Feedback control, stabilization, motion tracking, energy management.

Examples:

- **Encoders:**
  - *Rotary Encoders:* Measure rotational motion of wheels or joints.
  - *Linear Encoders:* Measure linear displacement.
- **IMU (Inertial Measurement Unit):**
  - Combination of gyroscope (angular velocity) and accelerometer (linear acceleration).
  - Used for balancing (e.g., self-balancing robots) and navigation (e.g., drones).

- **Potentiometers:**
  - Measure angular displacement in robot joints.
- **Power and Health Monitoring:**
  - Sensors for battery voltage, motor current, and temperature.
  - Critical for managing power and avoiding system failure.

Proximity Sensors: Overview

Proximity sensors detect the presence, absence, or distance of nearby objects **without physical contact**. They are vital for real-time decision-making and safety in mobile robots.

- **Function:** Detect objects within a certain range and provide distance-related feedback to the robot's controller.
- **Significance in Robotics:**
  - *Obstacle avoidance:* Prevent collisions in mobile navigation.
  - *Environment mapping:* Support SLAM (Simultaneous Localization and Mapping).
  - *Behavioral control:* Trigger responses like stopping, turning, or reversing.

Infrared (IR) Proximity Sensors

IR proximity sensors are among the most common and affordable types used in small to medium robotic platforms.

Working Principle

1. **Emission:** The sensor emits a narrow beam of infrared light (invisible to the human eye), usually using an IR LED.
2. **Reflection:** When an object is within range, the IR beam reflects off its surface.
3. **Detection:** A photodiode or phototransistor measures the intensity of the reflected IR light.
4. **Distance Estimation:** The sensor estimates the distance to the object based on the amount of reflected light received—more light indicates a closer object.

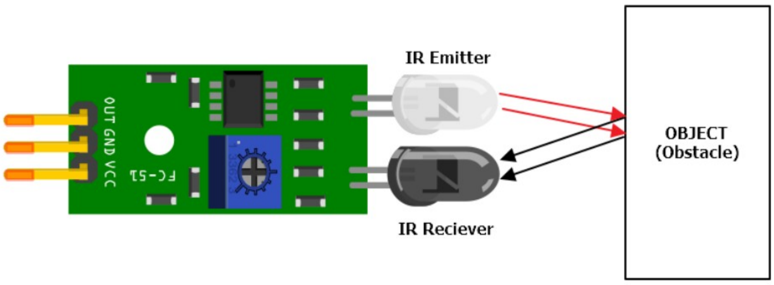
Note: IR reflection is highly sensitive to the surface properties of the object (e.g., shiny surfaces reflect better than matte surfaces).

Features and Characteristics

- **Short Range:**
  - Typical detection range is between **10 to 80 cm**, making IR sensors suitable for near-field applications.
- **Compact and Cost-effective:**
  - Small in size, low in cost, and easy to integrate with microcontrollers.
  - Widely used in beginner and educational robotics kits.
- **Environmental Sensitivity:**
  - Performance can degrade under **bright ambient light** (e.g., direct sunlight may interfere).
  - Detection accuracy is influenced by **object color and texture**; dark or absorbent surfaces may reflect less IR light.

Applications in Robotics

- **Line-following Robots:**
  - IR sensors are used to distinguish between black and white surfaces.
  - Commonly used to follow tracks or paths printed on floors.
- **Cliff or Edge Detection:**
  - Robots use downward-facing IR sensors to detect a sudden drop (e.g., stairs or table edges).
  - Essential for safety in vacuum robots and wheeled platforms.
- **Basic Obstacle Avoidance:**
  - Mounted on the front or sides of mobile robots to detect nearby walls or objects.
  - Enables simple reactive behaviors like turning away or stopping when an object is detected.



IR Reflection [1]

Image Sources:
1. https://www.electronicwings.com/nodemcu/ir-sensor-module

Limitations:

- Inaccurate over longer distances or uneven surfaces.
- Susceptible to interference from other IR sources (e.g., remote controls, sunlight).
- Limited field of view unless combined with multiple sensors.

Ultrasonic Proximity Sensors

Ultrasonic sensors use sound waves to detect the distance to objects. They are commonly used in mobile robotics for detecting obstacles and measuring distances accurately over a wide range.

Working Principle

Ultrasonic sensors operate based on the time-of-flight principle using sound waves beyond the range of human hearing.

1. **Emission:** The sensor emits a burst of high-frequency sound waves (typically at 40 kHz) through a transmitter.
2. **Reflection:** These waves travel through the air until they strike an object and reflect back toward the sensor.
3. **Reception:** The sensor's receiver detects the returning echo wave.

4. **Time Measurement:** The sensor measures the time taken for the sound wave to make the round trip from the sensor to the object and back.
5. **Distance Calculation:** The distance is computed using the formula:

$$d = \frac{v \times t}{2}$$

   where:

   - d = distance to the object,
   - v = speed of sound in air (approximately 343 m/s at 20°C),
   - t = total time taken by the pulse for the round trip.

   The division by 2 accounts for the round trip (to the object and back).

Features and Characteristics

- **Range:**
  - Typical operational range is between **2 cm to 4 meters**.
  - Useful for both short-range obstacle detection and medium-range distance measurement.
- **Lighting Independence:**
  - Performance is **unaffected by ambient light conditions**.
  - Suitable for use in both dark and brightly lit environments.
- **Material Limitations:**
  - Accuracy can be reduced when detecting:
    * *Soft materials* (e.g., cloth or foam) that absorb sound.
    * *Angled surfaces* that deflect the sound away from the receiver.
  - Best results with flat, hard surfaces directly facing the sensor.
- **Resolution and Precision:**
  - Offers relatively precise distance readings.
  - Resolution is typically in the millimeter range, depending on the sensor model and processing.

Applications in Robotics

- **Obstacle Avoidance:**
  - Used in autonomous robots to detect and avoid collisions with obstacles.
  - Often mounted on the front and sides of mobile robots for all-around awareness.
- **Distance Measurement:**
  - Allows robots to measure the distance to walls or objects, which is helpful for path planning and environment sensing.
- **Mapping and Localization:**
  - Integrated into SLAM (Simultaneous Localization and Mapping) systems.
  - Used in conjunction with encoders or IMUs for spatial awareness.
- **Industrial Automation:**
  - Used in factory robots for detecting product presence on conveyors or shelves.

Note: Ultrasonic sensors are often combined with other sensors (e.g., IR, LIDAR, vision) to provide redundant and complementary environmental data.

Proximity Sensor: Laser Range Sensor and LIDAR

Working Principle

Laser range sensors and LIDAR (Light Detection and Ranging) operate by using light to measure the distance to objects. They offer precise measurements over long ranges.

- **Laser Emission:** A coherent beam of laser light is emitted toward a target object. The laser is usually infrared or visible, and extremely narrow for precise targeting.
- **Time-of-Flight Measurement:** The sensor measures the time it takes for the emitted laser beam to reflect back after hitting an object. The distance is then calculated using:

  $$d = \frac{c \cdot t}{2}$$

  where d is the distance, c is the speed of light (approximately 3×10^8 m/s), and t is the round-trip time.
- **Phase Shift Method (alternative):** Some systems use a continuous wave and compute the phase difference between emitted and received signals to infer distance.
- **LIDAR Systems:** These use spinning mirrors or rotating units to sweep the laser beam across a scene. By collecting many distance measurements over an angular sweep, the sensor constructs a 2D or 3D map of the environment.

Features

- **High Precision and Long Range:** Can measure distances up to 100 meters or more with centimeter-level precision.
- **Generates 2D/3D Point Clouds:** By scanning the environment, LIDAR provides a dense set of spatial points called a *point cloud*, which can be used for mapping and object detection.
- **Environmental Sensitivity:** The performance may degrade in adverse weather conditions (e.g., rain, fog, dust), and measurements can be affected by highly reflective or absorptive surfaces.

Applications

- **Autonomous Navigation:** Used in self-driving cars, drones, and robots for terrain mapping, localization, and path planning.
- **SLAM:** A core component in Simultaneous Localization and Mapping (SLAM) to help robots map unknown environments while tracking their location.
- **Industrial Safety:** Used in automated factories for collision detection and worker proximity monitoring.

External Sensor: Vision Systems

Working Principle

Vision systems allow robots to interpret their surroundings using image and video data.

- **Image Capture:** Cameras (monocular or stereo) capture visual data in the form of 2D images or video frames.
- **Feature Extraction:** Computer vision algorithms analyze the captured data to detect:
  - Edges, corners, and contours
  - Motion and object boundaries
  - Colors and textures

- **Depth Estimation:** Done through:
  - *Stereo Vision:* Two cameras placed at known separation infer depth from disparity.
  - *Structured Light/IR Patterns:* Emit known patterns and infer shape from distortions.

Features

- **Rich Scene Understanding:** Provides high-dimensional data (images) enabling complex perception tasks.
- **Multi-feature Detection:** Can recognize shape, color, texture, and track multiple moving objects.
- **Lighting Sensitivity:** Performance may degrade under low light, glare, or occlusion (e.g., a blocked field of view).

Applications

- **Object Recognition:** Identifying and classifying items in the environment (e.g., sorting, face detection).
- **Path Planning:** Detecting paths, free space, and obstacles based on visual cues.
- **Human-Robot Interaction:** Tracking gestures or facial expressions to enable intuitive interaction.
- **Visual SLAM:** Used for localization and mapping in GPS-denied environments.

External Sensor: Tactile Sensors

Working Principle

Tactile sensors detect physical interactions, such as touch, force, and pressure, enabling robots to sense contact with objects.

- **Contact Detection:** When the robot touches an object, the sensor surface deforms.
- **Signal Generation:** The deformation is converted into electrical signals through various mechanisms:
  - *Piezoresistive:* Resistance changes when pressure is applied.
  - *Capacitive:* Capacitance varies with distance between conductive plates.
  - *Optical:* Light path distortion or interruption signals contact.

Features

- **Contact Sensitivity:** Detects when and where a robot makes contact with objects or surfaces.
- **Varied Configurations:**
  - *Point-based:* Simple sensors like buttons for binary contact.
  - *Array-based:* Distributed sensors over a surface (robot skin) for spatial resolution of touch.
- **Embedded Use:** Commonly placed on robotic fingers, grippers, or arms to measure grasp strength or detect slippage.

Applications

- **Object Manipulation:** Feedback allows robots to hold objects with appropriate force, avoiding damage or drops.
- **Collision Detection:** Detects unexpected contacts for safety in human-robot interaction.
- **Interactive Robots:** Used in social and service robots to respond to human touch (e.g., hugs, taps).

Internal Sensor: IMU (Inertial Measurement Unit)

Working Principle

An Inertial Measurement Unit (IMU) is a sensor module that measures a robot's motion characteristics — such as linear acceleration, angular velocity, and orientation — using a combination of sub-sensors. It provides critical information for estimating the robot's pose and dynamics.

- **Accelerometer:**
  - Measures linear acceleration (in m/s^2) along one or more axes — typically x, y, and z.
  - Based on the deflection of a proof mass inside a MEMS (Micro-Electro-Mechanical System) structure.
  - Sensitive to both motion-induced acceleration and gravity, making it useful for tilt sensing.
- **Gyroscope:**
  - Measures angular velocity (in degrees/s or rad/s) around the roll, pitch, and yaw axes.
  - MEMS gyroscopes commonly use the Coriolis effect, where vibrating masses shift under rotation.
  - Provides rotational motion data necessary for tracking turns, spins, and orientation changes.
- **Magnetometer (optional):**
  - Measures magnetic field vectors, particularly Earth's magnetic field.
  - Functions like a digital compass to help correct heading/orientation drift.
  - Useful in outdoor navigation, where magnetic north is a consistent reference.
- **Sensor Fusion:**
  - The raw data from these sub-sensors is fused algorithmically (e.g., using Kalman Filters or Complementary Filters) to estimate the robot's pose and trajectory.
  - IMUs alone accumulate error over time due to noise and drift, hence fusion with external sensors (like GPS, visual odometry, or encoders) improves reliability.

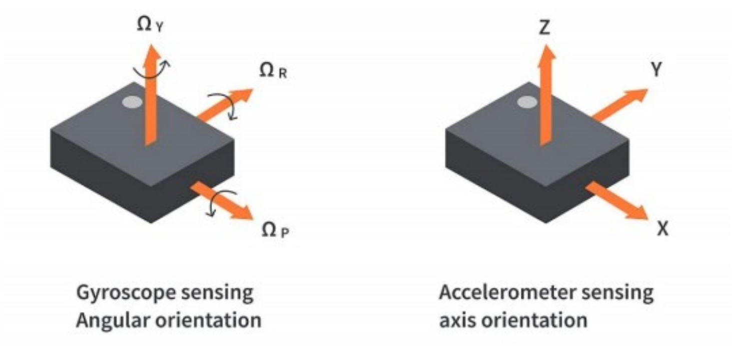


Figure: Accelerometer and Gyroscope [1]

Features

- **High-Frequency Tracking:**
  - IMUs provide data at high update rates (typically 50–1000 Hz), making them suitable for real-time dynamic response.
  - Essential for fast-moving robots such as drones, legged robots, or autonomous vehicles.
- **Compact and Self-Contained:**
  - IMUs are small and lightweight with no reliance on external infrastructure.
  - Can be embedded in mobile robots, wearables, or handheld devices.
- **Drift Accumulation:**
  - Integration of noisy acceleration and rotation data over time causes error accumulation — especially in position estimates.
  - To combat drift, IMUs are typically fused with absolute reference sensors like GPS, cameras, or wheel encoders.

Applications

- **Orientation Estimation:**
  - Estimating roll, pitch, and yaw for stabilizing platforms or navigating 3D space.
  - Used in smartphones, VR headsets, and AR glasses to determine user orientation.
- **Inertial Navigation:**
  - Enables navigation in GPS-denied environments (e.g., tunnels, underwater) by integrating acceleration and rotation data to estimate position.
  - Often used in submarines, aircraft, and autonomous ground vehicles.
- **Balance Control:**
  - Essential for bipedal robots and drones to maintain balance and respond to disturbances.
  - Feedback from the IMU allows control algorithms to adjust motor outputs to stabilize the system.
- **Motion Stabilization:**

- In drones, IMUs allow flight controllers to maintain level flight, perform acrobatic maneuvers, and reject wind disturbances.
- In camera gimbals, IMUs are used to counteract unwanted shakes or motion.

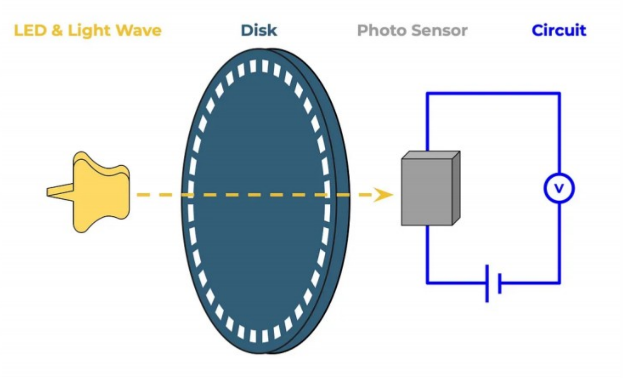


Figure: Optical Wheel Encoder [1]

What Are Actuators in Robotics?

Definition

- Actuators are mechanical or electro-mechanical devices that convert control signals (electrical, hydraulic, or pneumatic) into physical motion.
- In robotics, actuators are the components that **enable movement or mechanical interaction with the environment**, such as moving joints, driving wheels, or operating grippers.
- They form the *"action"* part of the sense-think-act cycle in robotics.

Types of Actions Performed

- **Linear Movement:**
  - Movement in a straight line, commonly executed using *linear actuators*.
  - Examples include telescoping prismatic joints or hydraulic pistons.
- **Rotational Movement:**
  - Rotation around a fixed axis, used in robot joints, wheels, or turrets.
  - Achieved using motors (DC, servo, or stepper) coupled to rotary shafts.
- **Gripping/Manipulation:**
  - Actuation of robotic hands or grippers to grasp and manipulate objects.
  - Can involve complex linkages, fingers, or force feedback systems.

Control of Actuators

- Actuators respond to electrical control inputs such as:
  - **PWM (Pulse Width Modulation):** Common for controlling motor speed or angle.
  - **Voltage Level:** Varying voltage changes speed or force.
  - **Current Drive:** Especially in high-torque or industrial actuators.
- Closed-loop control systems often use feedback from *sensors* (e.g., encoders or potentiometers) to:
  - Monitor actual position or speed.
  - Adjust control signals to minimize error.
  - Ensure precise and stable actuation.

Electric Actuators in Robotics

Electric actuators are the most commonly used in robotics due to their versatility, simplicity, and integration with digital controllers.

1. DC Motors

- **Principle:** Operate on the Lorentz force principle — current through a conductor in a magnetic field causes motion.
- **Continuous Rotation:** Provides smooth and continuous rotational motion.
- **Control:** Speed is controlled by varying input voltage or PWM duty cycle.
- **Advantages:**
  - Simple and cost-effective.
  - Easy to integrate into wheeled mobile robots.
- **Disadvantages:**
  - No built-in position feedback — requires external encoders for precise control.
- **Applications:** Mobile robot drive systems, conveyor belts, fans.

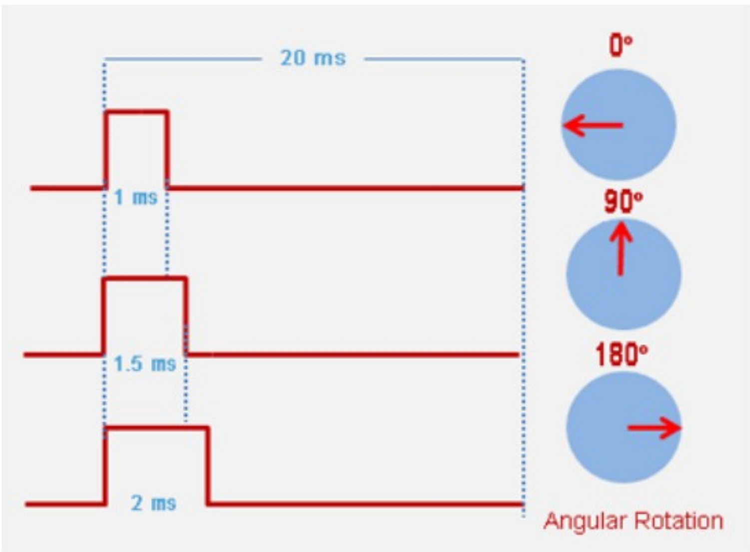


Figure: Servo Motor [1]

2. Servo Motors

- **Construction:** Typically a DC motor combined with a position feedback sensor and control circuitry.
- **Working:**
  - Controlled by PWM signals where pulse width determines target angle.
  - Internal feedback loop adjusts motor to reach and hold desired position.
- **Range:** Typically 0° to 180°, though some allow continuous rotation.
- **Advantages:**

- Built-in position control and ease of use.
- Compact and widely supported in robotic kits.

- **Limitations:**
  - Limited torque and motion range.
- **Applications:** Robotic arms, pan-tilt mechanisms, grippers, humanoid limbs.

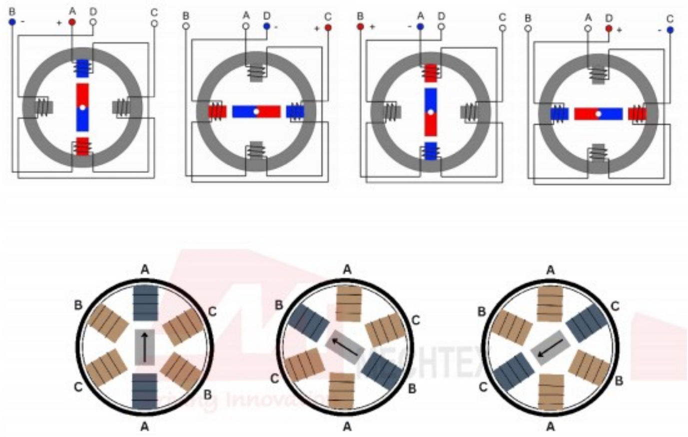


Figure: Stepper Motor [1] [2]

3. Stepper Motors

- **Working:** Rotate in fixed discrete steps (e.g., 1.8° per step for 200 steps/rev motors).
- **Open-Loop Control:**
  - Controlled by sending step pulses — no feedback is needed for basic positioning.
- **Microstepping:** Enables finer resolution by dividing steps into smaller increments.
- **Advantages:**
  - Excellent accuracy and repeatability.
  - Hold position without drift.
- **Limitations:**
  - Loses torque at high speeds.
  - Can skip steps under heavy loads if not properly managed.
- **Applications:** 3D printers, CNC machines, precision robotic stages.

Control Loops in Robotics

What is a Control Loop?

- A **control loop** is a fundamental concept in robotics and control systems where the robot continuously monitors its environment and adjusts its actions accordingly.
- It creates a continuous cycle of:
  - **Sensing:** Gathering data about the environment or the robot's own state through sensors.
  - **Decision Making:** Processing the sensed data to determine the appropriate response or action.

   - **Action:** Executing movements or operations through actuators.

- This cycle allows robots to behave autonomously, adaptively, and intelligently.

Two Main Types of Control Loops

[label=**0.**]**Open-Loop Control**

1. - The robot executes actions based on preset commands or instructions without using any feedback from sensors.
   - It assumes the environment behaves as expected and does not adjust if something goes wrong.
   - This type of control is generally *faster* and simpler but lacks adaptability.

2. **Closed-Loop Control (Feedback Control)**
   - The robot continuously receives feedback from sensors about the outcome of its actions.
   - This feedback is used to adjust commands dynamically to correct errors or adapt to changes.
   - Closed-loop control forms the basis of *intelligent robotic behavior* because it allows self-correction and precision.

Open-Loop Control System

Definition

- An open-loop control system executes commands strictly based on preprogrammed instructions without sensing or reacting to the actual outcome.
- There is **no feedback** about whether the desired action was successful or if external factors have interfered.

Characteristics

- **Simplicity:** Since it does not require sensors or feedback hardware, it is easier and cheaper to implement.
- **Fast Response:** The system can quickly execute actions without waiting for sensor data or feedback processing.
- **No Adaptation or Error Correction:** Because there is no feedback, it cannot detect or fix errors, such as unexpected obstacles or slippage.

Example

- Consider a robot programmed to move forward for 5 seconds assuming it will reach a target location.
- If an obstacle blocks its path or it slips on the floor, it will not detect this and will continue moving blindly.
- This can lead to failure in unpredictable environments.

Figure: Open Loop System [1]

Closed-Loop Control System

Definition

- A **closed-loop control system** is one that continuously monitors the robot's performance by collecting real-time feedback from sensors.
- The system **compares the actual state or output** of the robot with the **desired goal or reference state**.
- Any **difference (error)** detected between actual and desired values is used to **adjust actuator commands** dynamically.
- This feedback-driven process allows the robot to **self-correct** and maintain proper functioning even in changing or uncertain environments.

Characteristics

- **Accuracy and Robustness:**
  - The system can reduce errors by constantly tuning its behavior, making it *more precise* than open-loop systems.
  - It is robust against external disturbances like obstacles, changes in terrain, or unexpected forces.
- **Adaptivity:**
  - Can adapt to *uncertainty* and *noise* in sensor measurements or environment changes.
  - Automatically adjusts the control commands to maintain stability and desired performance.
- **Requirements:**
  - Needs appropriate sensors to provide real-time data on the robot's state (e.g., position, speed, orientation).
  - Requires computational resources to process feedback signals quickly.
  - Implementation of control algorithms that calculate corrective actions.

Example

- **Balancing Robot:**
  - Uses an *Inertial Measurement Unit (IMU)* to continuously sense its tilt angle.
  - The control system compares the current tilt with the desired upright position.
  - If the robot tilts forward or backward, the control algorithm computes corrective motor commands to drive wheels and restore balance.
  - This continuous loop of sensing, comparing, and acting keeps the robot upright despite disturbances.

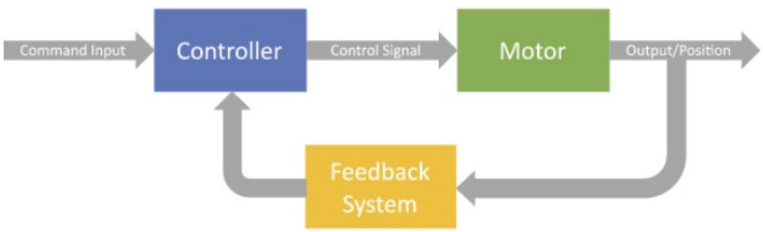


Figure: Close Loop System [1]

Key Points on Robotics

1. **Definition of a Robot:** A programmable machine that can sense, think, and act autonomously or semi-autonomously in response to its environment.

2. **Essential Components of Robots:** Sensors (perceive environment), Actuators (perform physical actions), and Controllers (make decisions).

3. **What is Robotics:** An interdisciplinary field involving mechanical engineering, electronics, computer science, and control systems focused on creating intelligent, autonomous machines.

4. **Characteristics of Robots:** Perception, computation, actuation, autonomy, and embodiment.

5. **Types of Robots:** Industrial, service, medical, humanoid, exploration, and defense robots with distinct applications.

6. **Sensors in Robotics:** External sensors (e.g., proximity, vision, tactile) measure the environment; internal sensors (e.g., IMU, encoders) track robot state and movement.

7. **Proximity Sensors:** Detect objects without contact; IR sensors use reflected infrared light, ultrasonic sensors use sound echoes, LIDAR uses laser beams.

8. **Actuators:** Devices that convert control signals into physical motion such as DC motors, servo motors, and stepper motors.

9. **Control Loops:** Open-loop control acts on preset commands without feedback; closed-loop control uses sensor feedback for error correction and adaptive behavior.

10. **Inertial Measurement Unit (IMU):** Combines accelerometer, gyroscope, and sometimes magnetometer to estimate orientation and motion, widely used in robotics for stabilization and navigation.