Foundations of Robotics

Session 1: Robotics + Sensors & Actuators

Part A: Introduction to Robotics

Part B: Sensors & Actuators

Dr. Niranjan Deshpande

Minor in AI, IIT Ropar

May 22, 2025

Table of Contents

Part A – Introduction to Robotics

What is a Robot?

Definition:

A **robot** is a programmable machine capable of carrying out a series of actions automatically or semi-autonomously in response to its environment.

Essential Components:

- **Sensors:** Perceive surroundings (e.g., cameras, touch, proximity)
- **Actuators:** Enable physical interaction (e.g., motors, servos)
- **Controller:** Computes decisions and commands

Key Idea: *"A robot senses, thinks, and acts."*

What is Robotics?

Definition:

Robotics is an interdisciplinary field focused on the design, construction, operation, and use of robots — machines that can perceive, decide, and act in the physical world.

Core Disciplines Involved:

- **Mechanical Engineering:** Structure, movement, kinematics
- **Electrical & Electronics:** Sensors, actuators, circuits
- **Computer Science:** Programming, AI, control algorithms
- **Control Systems:** Feedback loops, stability, automation

Goal: Create autonomous systems that can assist, augment, or replace human effort.

Characteristics of a Robot

Robots exhibit a combination of the following core capabilities:

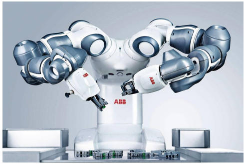
- **Perception:** Ability to sense and interpret the environment
  (e.g., cameras, proximity sensors, LIDAR)
- **Computation:** Ability to process information and make decisions
  (e.g., embedded systems, microcontrollers, AI models)
- **Actuation:** Ability to perform actions physically
  (e.g., motors, grippers, legs, wheels)
- **Autonomy:** Operate independently, fully or partially
  (e.g., automated navigation, obstacle avoidance)
- **Embodiment:** Physical presence in the environment
  (robots interact with the real world, unlike virtual agents)

Types of Robots

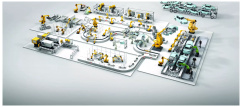
Robots come in many forms, depending on their application and environment:

- **Industrial Robots:**
  Fixed robotic arms used for welding, painting, assembly
  Example: ABB, KUKA robotic arms

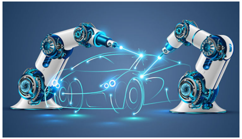
1



2



3



4

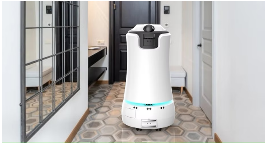
Image Sources:

1. `https://niryo.com/what-are-industrial-robots/`
2. `https://www.wsj.com/articles/meet-the-new-generation-of-robots-for-manufacturing-1433300884`
3. `https://davincisurgery.com`
4. `https://www.theautomonitor.com/the-role-of-automation-robotics-in-the-automotive-industry/`

- **Service Robots:**
  Perform tasks for humans in homes, hotels, warehouses
  Example: Boston Dynamics Spot, delivery bots

1

2



3

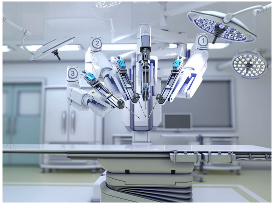
4

Image Sources:

1. `https://www.kedglobal.com/robotics/newsView/ked202208170019`
2. `https://qviro.com/blog/what-are-service-robots/`
3. `https://davincisurgery.com`
4. `https://www.mdpi.com/2218-6581/11/6/127`

- **Medical Robots:**
  Assist in surgery, rehabilitation, or diagnostics
  Example: da Vinci Surgical System

1



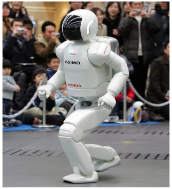
2

3

Image Sources:

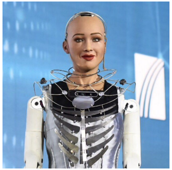
1. https://theenterpriseworld.com/types-of-robots-used-in-healthcare/
2. https://www.ul.com/insights/safety-standards-healthcare-robotics
3. https://www.expresshealthcare.in/news/leading-medical-robots-used-in-healthcare-globaldata/415951/

- **Humanoid Robots:**
  Resemble human shape or behavior for social or research roles
  Example: Honda ASIMO, SoftBank Pepper, Hanson Sophia, BostonDynamics ATLAS



1

2



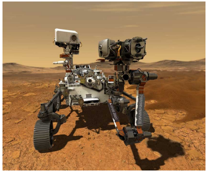
3

4

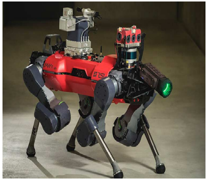
Image Sources:

1. https://global.honda/en/robotics/asimo/
2. https://us.softbankrobotics.com/pepper
3. https://www.hansonrobotics.com/sophia/
4. https://bostondynamics.com/blog/electric-new-era-for-atlas/

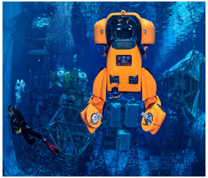
- **Exploration Robots:**
  Operate in harsh, inaccessible environments
  Example: Mars rovers, deep-sea robots



1



2



3

4

Image Sources:

1. https://www.jpl.nasa.gov/edu/resources/teachable-moment/meet-perseverance-nasas-newest-mars-rover/
2. https://www.news.uzh.ch/en/articles/2022/lunar-rover.html
3. https://nauticusrobotics.com/aquanaut/
4. https://www.saildrone.com/

- **Defense Robots:**
  Robots used in military, security, and defense applications
  Examples: MAARS (Modular Advanced Armed Robotic System), DOGO robot, UAVs like MQ-9 Reaper, PackBot

1

2

3

4

Image Sources:

1. `https://www.qinetiq.com/en-au/capabilities/ai-analytics-and-advanced-computing/maars-weaponized-robot`
2. `https://www.armadainternational.com/2017/10/dogo-ultra-light-hand-held-anti-terror-robot/`
3. `https://www.ga-asi.com/remotely-piloted-aircraft/mq-9a`
4. `https://www.flir.com/products/packbot/?vertical=ugs&segment=uis/`

Part B – Sensors & Actuators

What are Sensors and Actuators?

Sensors and **Actuators** form the core of a robot's ability to interact with the environment.

Sensor

A device that detects or measures a physical property (e.g., distance, light, temperature) and converts it into a signal that can be interpreted by a controller.

Actuator

A device that converts control signals into physical motion or action (e.g., motors, grippers).

Interaction Flow:

$$\text{Environment} \rightarrow \text{Sensor} \rightarrow \text{Controller} \rightarrow \text{Actuator} \rightarrow \text{Environment}$$

Types of Sensors in Robotics

In robotics, sensors are broadly classified into two categories based on what they measure:

1. **External Sensors**
   - Measure the external environment surrounding the robot
   - Enable the robot to perceive obstacles, surfaces, light, sound, etc.
   - Examples:
     - Proximity sensors: IR, Ultrasonic, LIDAR
     - Vision sensors: Cameras, depth sensors
     - Tactile sensors: Touch, pressure pads
     - Environmental sensors: Light, gas, temperature

2. **Internal Sensors**
   - Measure the robot's internal state or movement
   - Help track motion, orientation, and system health
   - Examples:
     - Wheel encoders and joint potentiometers
     - IMU (gyroscope + accelerometer)
     - Battery level and motor current sensors

Proximity Sensors

Proximity sensors detect the presence or distance of nearby objects without physical contact. They're essential for obstacle avoidance, mapping, and navigation.

Proximity Sensor: Infrared (IR)

Working Principle:

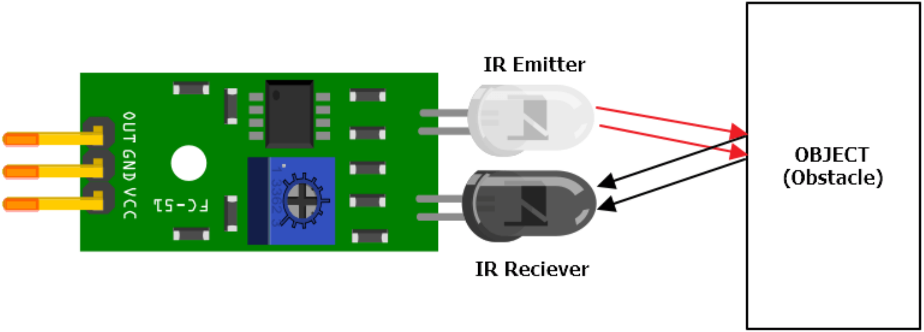
- Emits an infrared light beam toward an object
- Measures the intensity of reflected light to estimate distance

Features:

- Short-range: 10–80 cm
- Cost-effective and compact
- Performance affected by ambient light and object color/texture

Applications:

- Line-following robots
- Cliff or edge detection
- Basic object avoidance



IR Reflection [1]

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

Proximity Sensor: Ultrasonic

Working Principle:

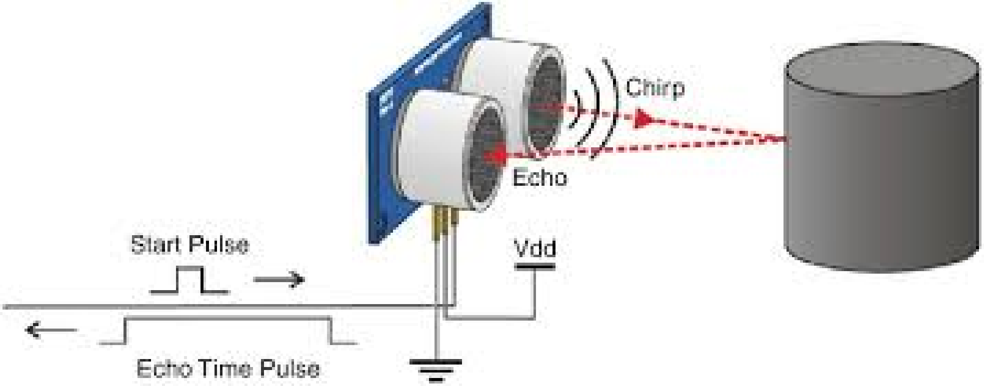
- Emits high-frequency sound waves (40 kHz)
- Measures time taken for the echo to return after reflecting from an object
- Calculates distance using: $d = \frac{vt}{2}$ (where v is sound speed, t is time)

Features:

- Range: 2 cm to 4 m
- Reliable in various lighting conditions
- Can be affected by soft or angled surfaces

Applications:

- Obstacle avoidance in mobile robots
- Distance measurement and mapping



Working principle of ultrasonic sensor [1]

Source: 1. Deepak, B., Bahubalendruni, M.V.A. Raju, Biswal, B., Budiyono, A., & Srigrarom, S. (2016). *Development of in-pipe robots for inspection and cleaning tasks: Survey, classification and comparison*. International Journal of Intelligent Unmanned Systems, 4. https://doi.org/10.1108/IJIUS-07-2016-0004

Proximity Sensor: Laser Range Sensor and LIDAR

Working Principle:

- Emit laser beams and measure time-of-flight or phase shift of reflected light
- LIDAR systems use spinning or scanning mechanisms to collect range data over a wide field

Features:

- High precision and long range (up to 100+ meters)
- Generates 2D or 3D point clouds for mapping and obstacle detection
- Sensitive to weather and reflective surfaces

Applications:

- Autonomous navigation (self-driving cars, drones)
- SLAM (Simultaneous Localization and Mapping)
- Industrial safety systems

External Sensor: Vision Systems

Working Principle:

- Capture images or video from the robot's surroundings
- Use computer vision algorithms to detect features, objects, or depth
- Depth sensors project infrared patterns or use stereo vision to estimate distances.

Features:

- High-dimensional data (images) for rich scene understanding
- Can detect shape, color, motion, and track multiple objects
- Sensitive to lighting and occlusions

Applications:

- Object recognition, path planning, gesture detection
- Navigation (visual SLAM), human-robot interaction

External Sensor: Tactile Sensors

Working Principle:

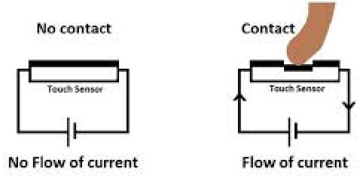
- Detect physical contact or pressure on the robot's surface
- Measure force, pressure, texture, or vibration through deformation-sensitive materials (e.g., piezoresistive, capacitive, or optical)

Features:

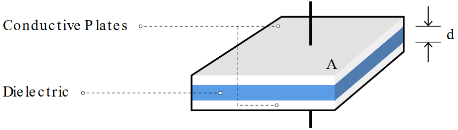
- Detect contact events or grasp strength
- Can be point-based (buttons) or distributed over a surface (sensor arrays)
- Often integrated into fingers, grippers, or skins

Applications:

- Object manipulation and gripping
- Collision detection and response
- Human-robot interaction (e.g., touch-based feedback)



Touch Sensor [1]



Capacitive Tactile Sensor [2]

Image Sources:
1. `https://www.seeedstudio.com/blog/2019/12/31/what-is-touch-sensor-and-how-to-use-it-with-arduino/`
2. `https://www.tacterion.com/wiki/tactile-sensing`

Internal Sensor: Wheel Encoders and Odometry

Working Principle:

- Wheel encoders measure rotational motion using magnetic or optical sensing
- Count ticks or pulses as the wheel rotates
- Combine tick data with wheel radius to estimate distance traveled

Features:

- Provides local motion estimation (odometry)
- Can be incremental (quadrature) or absolute encoders
- Accuracy affected by wheel slip, uneven terrain

Applications:

- Dead reckoning for mobile robots
- Measuring speed, position, and heading
- Feedback in closed-loop motion control

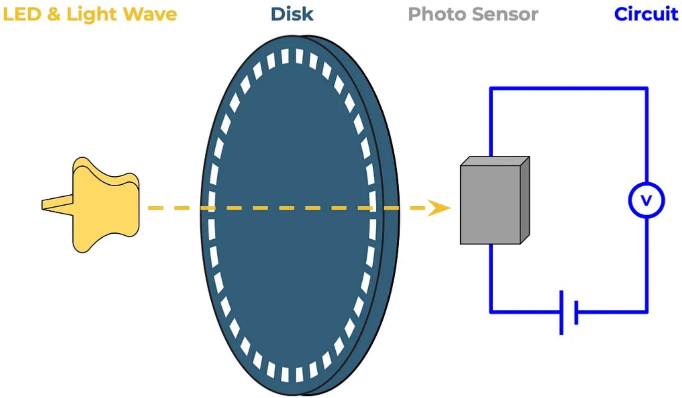


Figure: Optical Wheel Encoder [1]

Image Sources:
1. https://medium.com/@nahmed3536/wheel-odometry-model-for-differential-drive-robotics-91b85a012299https

Internal Sensor: IMU (Inertial Measurement Unit)

Working Principle:

- Combines one or more of the following:
  - **Accelerometer**: measures linear acceleration along x, y, z axes
  - **Gyroscope**: measures angular velocity (rotational speed)
  - **Magnetometer (optional)**: measures orientation with respect to Earth's magnetic field
- Integrates motion data to estimate robot pose/orientation

Features:

- High-frequency, continuous motion tracking
- Drift accumulates over time $\rightarrow$ requires sensor fusion (e.g., with GPS or encoders)
- Widely used in drones, mobile robots, and wearables

Applications:

- Orientation estimation
- Balance control and inertial navigation
- Motion stabilization in drones and bipedal robots

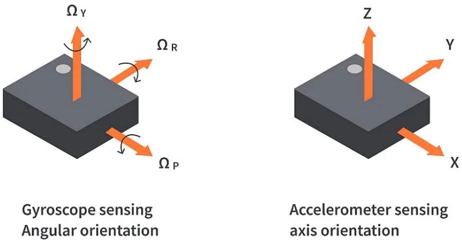


Figure: Accelerometer and Gyroscope [1]

Image Sources:
1. `https://www.circuitbread.com/ee-faq/how-do-accelerometers-and-gyroscopes-work`

What Are Actuators in Robotics?

Definition:

- Actuators are components that convert control signals into physical motion or action
- They allow robots to move, lift, rotate, grasp, or interact with the environment

Types of Actions Performed:

- Linear movement (e.g., prismatic joint)
- Rotational movement (e.g., wheels, arms)
- Gripping or manipulating objects

Control:

- Actuators are driven by control signals (usually PWM, voltage, or current)
- Often used in feedback loops with sensors to achieve precise motion

Electric Actuators in Robotics

1. **DC Motors**
   - Provide continuous rotation with variable speed
   - Simple control using voltage or PWM
   - Commonly used for wheels and drive systems
2. **Servo Motors**
   - Controlled by PWM to rotate to a specific angle (typically $0°$–$180°$)
   - Include internal feedback for position control
   - Used in robotic arms, pan-tilt units, grippers
3. **Stepper Motors**
   - Rotate in precise steps (e.g., $1.8°$ per step)
   - Excellent for accurate positioning and speed control
   - Used in 3D printers, CNC machines, precision actuators

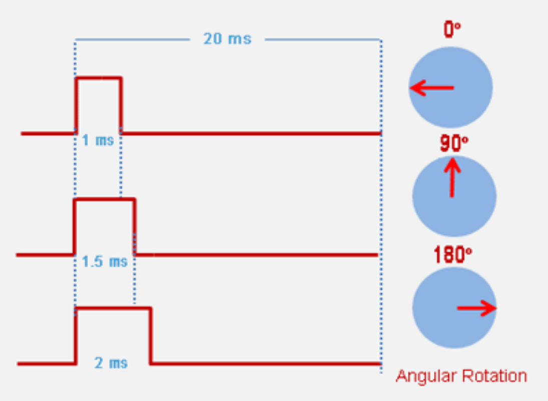


Figure: Servo Motor [1]

Image Sources:
1. https://circuitdigest.com/article/servo-motor-working-and-basics

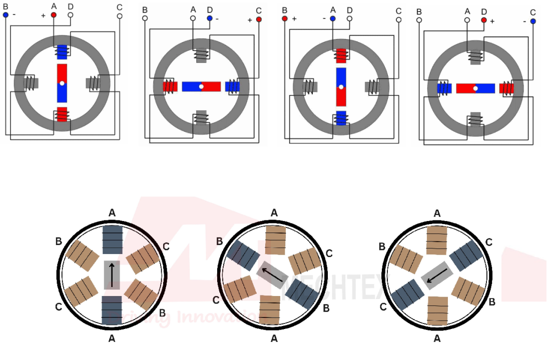


Figure: Stepper Motor [1] [2]

Image Sources:

1. `https://mypractic.com/stepper-motors-principle-of-operation-types-characteristics/`
2. `https://mechtex.com/blog/types-of-stepper-motor`

Control Loops in Robotics

What is a Control Loop?

- A control loop allows a robot to make decisions and act on them based on inputs from sensors.
- It connects **Sensing** $\rightarrow$ **Decision Making** $\rightarrow$ **Action**.

Two Main Types of Control Loops:

- **1. Open-Loop Control**
  - No feedback from sensors
  - Action is based only on preset commands
  - Fast but not adaptive
- **2. Closed-Loop Control**
  - Uses sensor feedback to update decisions
  - Enables error correction and adaptation
  - Foundation of intelligent robotic behavior

Open-Loop Control System

Definition:

- Executes actions based on preset commands without sensing the result
- No feedback from the environment or system state

Characteristics:

- Simple and cost-effective
- Fast response, minimal hardware
- Cannot correct errors or adapt to disturbances

Example:

- A robot moves forward for 5 seconds assuming it reaches the target — even if it encounters an obstacle or slips

Figure: Open Loop System [1]

Image Source:
1. https://www.ntchip.com/electronics-news/difference-between-open-loop-and-closed-loop

Closed-Loop Control System

Definition:

- Continuously adjusts actuator commands based on feedback from sensors
- Compares actual performance with desired behavior and corrects errors

Characteristics:

- More accurate and robust
- Adaptive to disturbances, uncertainty, and noise
- Requires sensors, real-time control, and feedback processing

Example:

- A balancing robot uses IMU data to detect tilt and adjust motors to stay upright

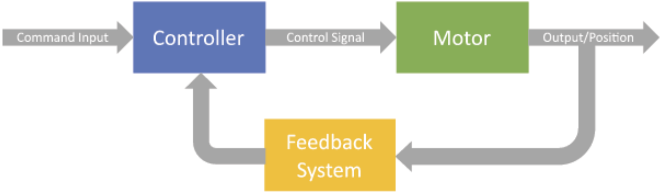


Figure: Close Loop System [1]

Image Source:
1. `https://www.ntchip.com/electronics-news/difference-between-open-loop-and-closed-loop`