ROBOTICS

Modules 1 - 3 | Question Bank Answers

Reference: S. K. Saha, Introduction to Robotics, 2e (TMH) + Course PPTs

MODULE 1: INTRODUCTION TO ROBOTICS

Q1. Define robotics and explain its interdisciplinary nature.

Definition: Robotics is the science and technology of designing, constructing, operating, and applying robots. The ISO defines a robot as a *reprogrammable, multifunctional manipulator* designed to move material, parts, tools, or specialised devices through variable programmed motions for a variety of tasks.

Interdisciplinary Nature: Robotics draws from three core engineering fields:

- **Mechanical Engineering** - deals with the *motion subsystem*: links, joints, actuators, transmissions, and the structural design of the manipulator.
- **Electrical Engineering** - handles the *control subsystem*: servo drives, sensors, signal conditioning, power electronics, and control algorithms (PID, etc.).
- **Computer Science** - responsible for the *recognition subsystem*: robot programming, AI, vision processing, and decision-making software.

All three domains interact tightly: a mechanical arm is useless without sensors and a controller, and a controller is useless without a physical structure to move.

Q2. Discuss the role of Mechanical Engineering, Electrical Engineering, and Computer Science in robotics.

- **Mechanical Engineering:** Designs the physical structure - links, joints (revolute, prismatic), end-effectors, and transmissions (gears, belts, ball-screws). Also handles statics, dynamics, and kinematics of the manipulator.
- **Electrical Engineering:** Designs actuators (DC servo, stepper, AC servo, hydraulic), sensor interfaces, ADC/DAC circuits, amplifiers, and closed-loop control systems. Responsible for signal conditioning and power management.
- **Computer Science:** Develops robot programming languages (KRL, Karel, RAPID), embedded control software, machine vision algorithms, path planning, and AI/ML for autonomous decision-making.

It is common for specialists to cross boundaries - an EE may work on dynamic simulation (traditionally ME), while a CS engineer may handle sensor-data-driven control.

Q3. Briefly describe the historical evolution of robots, including key milestones such as the origin of the term 'robot' and the development of industrial robots.

- **Ancient origins:** The concept of mechanical automata goes back ~3000 years (mechanical elephants in Indian legend, Greek myths of Talos).
- **1921 - Origin of 'Robot':** Czech writer Karel Capek coined the word in his play *Rossum's Universal Robots (RUR)*. The word derives from the Czech *'robota'* meaning 'forced or compulsory labour.'
- **1940s - Asimov's Laws:** Isaac Asimov envisioned robots as helpers, formalising the Three Laws of Robotics in his science-fiction stories.
- **1958 - UNIMATION:** Joseph Engelberger and George Devol founded UNIMATION (UNIversal autoMATION) in the USA - the first robot company.
- **1961 - First Industrial Robot:** Unimate robot installed at General Motors, New Jersey - a 5-DOF hydraulic arm for handling hot die-cast parts.
- **1974 - First Electric Robot:** ABB (then ASEA) introduced the first commercially electrically driven industrial robot.
- **1980s onwards:** Proliferation into welding (~25%), assembly (~33%), painting, and machining. Rise of SCARA robots for electronics assembly.

• **2000s - Present:** Collaborative robots (cobots), mobile robots, medical/surgical robots (da Vinci), space robots (Curiosity, Mangalyaan), service robots.

Q4. List and explain the elements of a robotic system.

A robotic system has three major subsystems, each with specific elements:

1. Motion Subsystem

• **Manipulator:** Series of links and joints (revolute or prismatic) forming the arm and wrist.

• **End-Effector:** Gripper, welding gun, paint nozzle, etc., attached at the manipulator tip - equivalent to the human hand.

• **Actuators:** Electric (DC servo, stepper, AC servo), hydraulic, or pneumatic devices that drive each joint.

• **Transmission:** Gears, belt-pulley, ball-screw, or link mechanisms that transmit actuator motion to the links.

2. Recognition Subsystem

• **Sensors:** Encoders, potentiometers, LVDT (internal); proximity sensors, vision cameras, force sensors (external). They sense the robot's state and environment.

• **ADC (Analog-to-Digital Converter):** Converts analog sensor signals to digital values the controller can process.

3. Control Subsystem

• **Digital Controller:** CPU + memory. Processes user programs and sends motion commands to actuators.

• **DAC (Digital-to-Analog Converter):** Converts controller's digital commands back to analog signals (voltage) to drive electric motors.

• **Amplifier:** Boosts weak DAC output signals to the power levels needed to drive the actuators.

Q5. Explain Isaac Asimov's Three Laws of Robotics and their relevance in modern robotics.

Isaac Asimov introduced these laws in his 1940s science-fiction stories as guidelines for safe robot behaviour:

• **Law 1:** A robot must not harm a human being, nor through inaction allow one to come to harm.

• **Law 2:** A robot must always obey human beings, unless that conflicts with the First Law.

• **Law 3:** A robot must protect itself from harm, unless that conflicts with the First or Second Law.

Relevance Today: These laws form the philosophical basis for robot safety design. In practice they translate to: emergency stop systems on industrial robots, force-limiting in cobots (collaborative robots), ISO 10218 safety standards, and ethical guidelines in autonomous vehicles and medical robots. However, no automatic mechanism fully implements them - military robots, for example, may be designed to break Law 1.

Q6. What is the fourth law of robotics introduced by Fuller in 1999? How does it impact employment?

Fuller's Fourth Law (1999):

'A robot may take a human being's job but it may not leave that person jobless!'

Meaning: Automation and robotics must serve to improve human lives. When a robot displaces a worker, society and industry have a responsibility to ensure that the displaced worker is redeployed, retrained, or supported - not simply discarded.

Employment Impact: Statistics show that countries with the highest robot usage (Japan, Germany, South Korea) do *not* have the highest unemployment rates. This suggests that robots create new types of jobs (maintenance, programming, integration) even while eliminating repetitive manual tasks. The key is proactive workforce retraining. In India, the growing robotics market (estimated ~16,300 units by 2016) is opening roles in robot commissioning, PLM software, and systems integration.

Q7. Differentiate between industrial, non-industrial, and special-purpose robots with examples.

Category	Definition	Examples
Industrial Robots	Reprogrammable, general-purpose manipulators u[illegible]	KUKA KR-5 (welding), Fanuc M-series (palletizing), A[illegible]
Non-Industrial / Service Robots	Robots operating in unstructured environments, pe[illegible]	Domestic robots (LG HomBot vacuum cleaner), medical [illegible]
Special-Purpose Robots	Designed for a specific task in extreme or hazardo[illegible]	DRDO's Daksh (bomb disposal), NASA Curiosity (Mars [illegible]

Q8. What are the three main subsystems of a robotic system? Explain their functions.

- **Motion Subsystem:** The physical structure that carries out desired motion. It comprises the manipulator (links + joints), end-effector, actuators, and transmission elements. This is analogous to the human arm and hand - it physically moves and interacts with objects.
- **Recognition Subsystem:** Gathers information about the robot's own state and its environment using sensors. Converts physical signals (position, force, light) to digital data via ADCs. Equivalent to the human sensory system (eyes, skin, ears).
- **Control Subsystem:** The 'brain' of the robot. It processes sensor data (from the recognition subsystem), executes the user program, and sends commands to the actuators via DACs and amplifiers. Determines *what* motion to make and *when*.

These three subsystems interact in a closed loop: the controller commands motion, sensors measure the result, and the controller corrects as needed.

Q9. Describe the motion subsystem and its components, including manipulators, joints, and end-effectors.

The Motion Subsystem is the physical structure that executes robot movement.

- **Manipulator:** A series of rigid links connected by joints. Links are typically made of steel or aluminium. The first 3 links+joints form the *arm* (position), the last 3 joints form the *wrist* (orientation). Equivalent to the human arm.
- **Joints (Kinematic Pairs):** (a) **Revolute (R):** Allows rotation about one axis - like a door hinge. 1 DOF. (b) **Prismatic (P):** Allows linear sliding along one axis - like a piston. 1 DOF. Other joints: helical (1 DOF), cylindrical (2 DOF), spherical (3 DOF), planar (3 DOF).
- **End-Effector:** Attached at the distal end of the manipulator. It is the 'working tool' of the robot. Can be: (a) Gripper/hand - for material handling, (b) Welding gun - for arc/spot welding, (c) Paint spray nozzle, (d) Drilling tool, (e) Surgical instrument. It directly interacts with the workpiece.

• **Actuators:** Electric (DC servo, stepper, AC brushless), hydraulic cylinders, or pneumatic cylinders. Provide the force/torque to move each joint.

• **Transmission:** Gears, belt-drives, ball-screws, or link mechanisms that convert actuator output (usually high-speed, low-torque) to the required joint motion (low-speed, high-torque).

Q10. Define Degree of Freedom (DOF) in robotics. Why is it important in designing robotic systems?

Definition: The Degree of Freedom (DOF) of a mechanical system is the number of independent coordinates (or minimum parameters) required to completely describe its configuration (pose). A free rigid body in 3D space has 6 DOF - 3 translational (x, y, z) and 3 rotational (roll, pitch, yaw).

Grubler-Kutzbach Criterion for computing DOF:

$$n = s(r - p - 1) + sum(n_i)$$

where: s = dimension of working space (3 for planar, 6 for spatial), r = number of links, p = number of joints, n_i = DOF of each joint.

Importance in Design:

• Determines the robot's flexibility - how many independent motions it can perform.

• 6 DOF is the minimum needed to place the end-effector at any arbitrary position AND orientation in 3D space.

• Fewer DOF = cheaper, simpler, but limited tasks (e.g., 3-DOF Cartesian robot can only position, not orient).

• More DOF = redundancy, enabling obstacle avoidance and optimised postures.

• DOF directly influences the robot's work envelope, task suitability, control complexity, and cost.

Q11. Differentiate between planar DOF, spatial DOF, and redundant DOF. Provide examples.

Type	Description	Formula	Example
Planar DOF	Robot moves in a 2D plane. Max 3 DOF: 2 translations (x, y) + 1 rotation (about z)	n = 3(n-1) - 2p	SCARA robot (for assembly), 2D pic
Spatial DOF	Robot moves in full 3D space. Max 6 DOF: 3 translations + 3 rotations (roll, pitch, yaw)	n = 6(n-1) - 5p	KUKA KR-5 (6-DOF arc welding), P
Redundant DOF	Robot has MORE than 6 DOF. The extra DOF(s) provide extra flexibility for obstacle avoidance, singularity avo	n > 6	Human arm (~7 DOF; shoulder 3 +

A Stanford robot with 6 revolute/prismatic joints: r=7 (incl. base), p=6, n = 6(7-6-1) + 6x1 = 6 DOF.

Q12. How does the number of DOF affect the flexibility and task complexity of a robot?

• **Position Only (3 DOF):** Can reach any point within its workspace but cannot control orientation. Suitable only for simple pick-and-place in structured setups. Example: Cartesian gantry robots.

• **Position + Partial Orientation (4-5 DOF):** Can handle limited assembly tasks requiring specific approach directions. Example: 4-DOF SCARA robot is ideal for vertical-insertion assembly of PCBs.

• **Full 6 DOF:** Can position the end-effector at any arbitrary point with any arbitrary orientation within the workspace. Essential for arc welding, spray painting, complex assembly, and machine tending.

• **Redundant (7+ DOF):** Offers multiple solutions to reach the same end-effector pose. Allows: (a) avoiding obstacles in cluttered environments, (b) avoiding singularities (configurations where the robot loses DOF), (c) optimising joint torques for minimum energy.

Increasing DOF increases workspace versatility but also increases cost, weight, control complexity, and the risk of calibration errors.

Q13. Discuss the significance of having a 6-DOF robotic arm in industrial applications.

A **6-DOF arm** can place its end-effector at *any reachable position* (3 DOF) with *any desired orientation* (3 DOF) within its workspace. This is the minimum required for fully general spatial tasks.

Industrial Significance:

- **Arc Welding:** The torch must approach the weld seam at a specific angle for penetration quality. 6 DOF enables continuous-path welding along complex 3D seams with correct torch angle throughout.
- **Spray Painting:** Requires the spray gun to maintain a specific stand-off distance AND normal orientation to the curved body panel surface throughout the stroke. Impossible with fewer DOF.
- **Assembly:** Inserting a component from an arbitrary direction with controlled force requires full 6-DOF control.
- **Machine Tending:** Loading/unloading complex fixtures where the part must be approached from specific directions.
- **Surgical Robotics:** da Vinci surgical robot requires precise 6-DOF control at the instrument tip inside the patient body through small ports.

Example: KUKA KR-5 Arc has 6 axes with repeatability of +/-0.04 mm, making it suitable for precision arc welding in automotive plants.

Q14. Discuss the impact of degrees of freedom (DOF) on the functionality and flexibility of a robotic system.

DOF is the single most important parameter determining a robot's functional capability:

DOF	Capability	Limitation	Typical Application
1-2	Linear or rotary positioning along/about an axis	Cannot reach arbitrary poses	Conveyor indexers, dispensers
3	Any position in 3D workspace (no orientation control)	Cannot orient end-effector	Cartesian pick-and-place
4	Position + limited orientation (wrist roll only)	Cannot achieve full 6-DOF task	SCARA for vertical assembly
6	Full position AND orientation control	Singularities may exist	Welding, painting, general-purpose
7+	Full 6-DOF + redundancy for obstacle avoidance	Complexity, singularities, higher cost	Cobots, surgical robots

Flexibility also depends on: workspace volume, payload, speed, and repeatability. DOF alone does not define a robot's usefulness - a high DOF robot with a small workspace may be less useful than a 6-DOF robot with large reach in many industrial scenarios.

MODULE 2: CLASSIFICATION OF ROBOTIC SYSTEMS

Q1. Explain the classification of robotic systems based on: a) Work volume b) Type of drive c) Type of control methods.

a) Classification by Work Volume (Arm Configuration)

- **Cartesian / Rectangular:** Three prismatic joints (PPP). Workspace = rectangular box. High rigidity, easy programming, large floor space needed.
- **Cylindrical:** One revolute + two prismatic joints (RPP). Workspace = cylindrical shell. Can reach all around; good for pipe welding.
- **Spherical / Polar:** Two revolute + one prismatic (RRP). Workspace = spherical sector. Large work volume; first Unimate was spherical.
- **Articulated / Revolute:** Three revolute joints (RRR). Workspace = near sphere. Most compact footprint for largest volume; used in most modern robots.

- **SCARA:** Cylindrical variant with revolute reach. Excellent for vertical assembly operations.
- **Gantry:** Cartesian robot mounted overhead (inverted). Large, versatile, expensive.

b) Classification by Type of Drive

- **Electric Drive:** DC servo, stepper, or brushless AC servo motors. Most common today. Clean, precise, easy to control. First commercial electric robot: ABB (1974).
- **Hydraulic Drive:** High power-to-weight ratio. Used for heavy payloads (spot welding guns 10-80 kg). Risk of leaks, noisy (~70 dBA), complex servo control.
- **Pneumatic Drive:** Compressed air. Cheapest, fast, intrinsically safe. Limited to on/off (non-servo) control. Mainly used for gripper actuation.

c) Classification by Control Method

- **Servo vs Non-servo:** Servo (closed-loop) continuously monitors actual position and corrects error. Non-servo (open-loop) assumes the command is executed. Most industrial robots are servo-controlled.
- **Point-to-Point (PTP):** Robot moves from one waypoint to the next; path between points is not controlled. Used in spot welding, palletising, machine tending.
- **Continuous Path (CP):** Exact path is specified and followed continuously with controlled speed. Essential for arc welding, spray painting, deburring.

Q2. Compare and contrast Cartesian, Cylindrical, Spherical, and Articulated robotic configurations with suitable diagrams.

Configuration	Joint Types	Workspace Shape	Advantages	Disadvantages	Application
Cartesian (PPP)	3 prismatic (x,y,z)	Rectangular box	High rigidity; easy offline programming; simple ... [illegible]	Large floor space; [illegible]	[illegible]
Cylindrical (RPP)	1 revolute (theta) + 2 prismatic (y,z)	Hollow cylindrical shell	Can reach all around; rigid y, z axes	Cannot reach above itself; theta axis [illegible]	Machine loading, [illegible]
Spherical (RRP)	2 revolute (theta,phi) + 1 prismatic (r)	Spherical sector	Can reach above/below obstacles; large work volume	Short vertical reach; complex kinematics	Spot welding, material handl[illegible]
Articulated (RRR)	3 revolute (theta, phi, psi)	Near-spherical	Largest volume per floor area; can reach above/below [illegible]	Complex offline programming; [illegible]	Arc welding, painting, [illegible]

Note: A SCARA robot is a cylindrical variant where the 3rd prismatic joint is replaced by a revolute. A Gantry robot is a Cartesian type mounted overhead.

Q3. Describe the various types of drive systems used in robots. Which type is most suitable for high-precision applications and why?

Drive Type	Principle	Advantages	Disadvantages	Power Range
Electric - Stepper	Incremental rotation per pulse	No feedback needed; open-loop capable; precise incremental motion	Low torque/efficiency; risk of stall if overloaded	< 1 kW (small robots)
Electric - DC Servo	PM or wound-field DC motor with encoder feedback	High torque density; good speed control	Brushes need maintenance; EMI from commutation	[illegible] kW
Electric - AC Servo (Brushless)	3-phase PMSM with encoder, inverter drive	Maintenance-free; highest precision; highest efficiency	Requires complex vector control drive; higher cost	[illegible] kW
Hydraulic	Pressurised oil drives pistons/vane motors	Highest power-to-weight; handles heavy shock loads; stiff	Leaks, noisy, fire risk; complex servo valves; messy	[illegible] kW
Pneumatic	Compressed air drives cylinders	Cheap; fast; intrinsically safe; simple	Compressible: poor position control; on/off only	Light duty

Best for High Precision: AC Servo (Brushless) drive. Reasons: (1) Encoder feedback gives position resolution down to 0.01 mm or better. (2) No brushes = no torque ripple from commutation. (3) Vector (field-oriented) control provides smooth, precise torque even at low speeds. (4) Modern industrial robots like KUKA, ABB, and Fanuc use AC servo drives exclusively achieving repeatability of +/-0.02 to +/-0.05 mm.

Q4. Define the following robotic performance parameters and explain their significance: a) Accuracy b) Repeatability c) Precision

Parameter	Definition	Significance
Accuracy	Difference between the commanded (desire [illegible]	[illegible]
Repeatability	Closeness between the actual positions atta [illegible]	[illegible]
Precision / Resolutio [illegible]	The smallest increment of motion the robot ca [illegible]	[illegible]

Note: A robot can be **repeatable but inaccurate** (all shots land together but away from target) or **accurate but not repeatable** (shots average to target but scatter widely). For production use, repeatability is paramount.

Q5. Explain the concept of dexterity in robotics. How does it influence the performance of a robotic manipulator?

Dexterity is a measure of a robot's ability to achieve arbitrary end-effector poses (position + orientation) throughout its workspace. A robot with high dexterity can reach a given point from multiple directions and with multiple configurations (i.e., it is far from singularities).

Mathematical Measure: Dexterity is often quantified using the **condition number** or **manipulability measure** of the Jacobian matrix J:

*w = sqrt(det(J * J^T)) [Yoshikawa's manipulability]*

• w = 0 at a singularity (robot loses DOF - cannot move in some direction).

• High w = high dexterity = the robot can apply force or velocity in any direction with similar ease.

Influence on Performance:

• **Assembly:** A high-dexterity wrist allows the robot to insert a pin from awkward angles, adapting to fixture variations.

• **Surgical Robotics:** Dexterous instruments can reach deep inside the body through small ports, manipulating tissue at angles a surgeon's hand cannot achieve (e.g., da Vinci endowrist has 7 DOF).

• **Painting:** Dexterous arm can maintain constant gun-to-surface normal even on complex curved surfaces.

• **Singularity Avoidance:** More dexterous robots have smaller singular regions, improving path quality throughout the workspace.

Q6. What is compliance in robotic systems? Explain with examples where compliant motion is necessary.

Compliance is the inverse of stiffness. A compliant robot (or compliant joint) can yield slightly under an applied force rather than rigidly resisting it. Compliance can be passive (mechanical spring-like behaviour) or active (force-controlled by the controller).

Why Compliance is Needed: In most assembly tasks, perfect alignment is impossible due to position errors, part tolerance, or fixture inaccuracy. A rigid robot attempting to force-fit a misaligned peg into a hole would jam or damage the part. A compliant robot can *accommodate* small misalignments.

Examples:

• **Peg-in-Hole (Pin Insertion):** Assembling a shaft into a bearing requires lateral and angular compliance to guide the shaft into the hole despite small positional errors. Without compliance, the shaft jams.

• **Deburring:** The robot must apply a constant force along a surface whose exact geometry is not perfectly known. A compliant end-effector maintains contact and consistent force while accommodating surface variations.

• **Grinding and Polishing:** Same as deburring - constant-force contact required on an unknown surface profile.

- **Haptic/Surgical Robots:** Surgical instruments must be compliant enough to prevent tearing of delicate tissue during unexpected patient movement.

Types of Compliance: Active compliance (force-controlled), passive compliance (spring/elastomer element), and remote-centre compliance (RCC device).

Q7. What is a Remote Center Compliance (RCC) device? Discuss its role in assembly applications.

A **Remote Center Compliance (RCC) device** is a passive mechanical end-effector attachment that provides compliance (lateral + angular) centred at a point remote from the device itself - typically at the tip of the peg being inserted.

Working Principle: The RCC device contains elastic elements (springs or rubber shear pads) arranged so that:

- A **lateral offset** at the peg tip causes a **pure lateral translation** of the gripper (no rotation).
- An **angular misalignment** of the peg causes a **pure rotation** about the peg tip (no translation).

These two decoupled compliance modes allow the peg to self-align into the chamfered hole opening without jamming.

Role in Assembly:

- Eliminates the need for active force sensing/control for simple insertions, reducing cost and complexity.
- Dramatically reduces assembly forces during peg-in-hole, circuit board component insertion, bearing press-fit, and connector mating.
- Tolerates positional errors of ~1-2 mm and angular errors of ~1-2 degrees passively, without any sensor or feedback.
- Used extensively in electronics assembly (chip insertion), automotive (bolt insertion), and precision machining setups.

Q8. List and explain at least five industrial applications of robots. Highlight how automation improves productivity in these sectors.

- **Spot Welding (Automotive):** Robots carry heavy welding guns (10-80 kg) to join sheet metal parts. First used at GM in 1969. Multiple robots work simultaneously on one car body, producing 50-90 cars/hour. Repeatability ~+/-1 mm ensures consistent weld placement, eliminating the extra 'safety welds' needed with human operators.
- **Arc Welding:** Continuous-path robots maintain a constant welding speed (10-120 in/min) and torch angle for uniform weld penetration. 6-DOF enables complex 3D seam paths. Productivity: uninterrupted operation, no fatigue, consistent quality.
- **Spray Painting:** The painting booth is toxic (solvents, noise) and temperature-controlled. Robots apply paint uniformly at consistent speed, reducing paint wastage (better atomisation control) and improving finish quality. Repeatability of ~+/-1 mm, though painting robots need lower accuracy than welding.
- **Material Handling / Pick-and-Place:** Robots load/unload CNC machines, transfer parts between stations, and palletise products. Up to 95% of manufacturing time is transfer/waiting; robots running 24/7 in 3 shifts dramatically increase throughput. Example: ABB FlexPicker (delta robot) does 150 picks/minute in food packaging.
- **Deburring / Machining:** Robots hold a deburring tool (or the part) and follow complex 3D contours with consistent force. CP control with ~0.2 mm repeatability required. Eliminates costly, tedious manual deburring work.
- **Assembly:** SCARA robots assemble PCBs, insert connectors, and mate sub-assemblies. Programmability allows quick product changeover - the same robot re-programmed for a new product rather than buying a new machine. Tactile/vision sensors enable complex adaptive assembly.

Q9. Explain the role of robots in welding applications. What factors should be considered while selecting a robot for welding?

Types of Robotic Welding:

- **Spot Welding:** Joins thin sheet metal at discrete points by passing high current (electric resistance heating). Welding gun is heavy (10-80 kg). Hydraulic or heavy-duty electric drive robots used. PTP control sufficient. Dominant in automotive body assembly.
- **Arc Welding:** Filler metal is melted along a continuous seam by an electric arc. Welding current: 100-1200 A, speed: 0.25-3 m/min. Lightweight gun (~2-3 kg). DC servo robots with CP control required. Shielding gas must flow through the nozzle during welding.

Factors for Robot Selection in Welding:

- **Payload:** Spot welding guns: 10-80 kg -> heavy-duty hydraulic or high-payload electric robot. Arc welding gun: ~2-5 kg -> medium electric robot.
- **Reach / Work Envelope:** Must cover the full extent of the weld seam on the largest workpiece.
- **DOF:** 6 DOF essential for complex 3D seam paths with correct torch angle.
- **Control Type:** CP for arc welding; PTP acceptable for spot welding.
- **Repeatability:** Spot welding: +/-1 mm; Arc welding: +/-0.1 mm for good weld quality.
- **Drive Type:** Spot welding: hydraulic for heavy guns; Arc welding: DC/AC servo electric for precision and speed.
- **Safety:** IP rating for welding fumes/spatter; thermal protection.
- **Integration:** Compatibility with welding power source, positioner (turntable), and safety fencing.

Q11. Compare and contrast electric and hydraulic drive technologies in robotic systems. Provide examples of their applications.

Parameter	Electric Drive	Hydraulic Drive
Power Source	Electrical mains (230V / 415V AC in India)	Hydraulic pump + pressurised oil reservoir
Payload Capacity	Low to medium (0.5-500 kg typical)	High (100-1000+ kg)
Power-to-Weight Ratio	Medium	Very high (compact actuators, huge force)
Precision/Repeatability	High (+/-0.02 to +/-0.1 mm with encoder)	Lower due to oil compressibility and valve hysteresis
Speed Control	Excellent (smooth, wide range)	Good but complex (servo valves)
Maintenance	Low (brushless motors are maintenance-fre[illegible]	High (seals, filters, fluid changes, leak detection)
Safety/Cleanliness	Clean, no fire risk (brushless)	Fire risk from hydraulic fluid; leaks contaminate floor
Noise	Quiet	High (~70 dBA from hydraulic pump)
Cost	Moderate to high (drive electronics)	High (hydraulic unit + servo valves)
Application	KUKA KR-5 arc welding, ABB assembly, F[illegible]	Heavy-duty spot welding robots (GM lines), forge-press robo[illegible]

Q12. Discuss the types of electric drives used in robots and their respective advantages and disadvantages.

Type	Working Principle	Advantages	Disadvantages	Robot Use
Stepper Motor	Rotates by fixed steps per pul[illegible]	[illegible]	[illegible]	[illegible]
DC Servo Motor	PM or separately excited DC m[illegible]	[illegible]	[illegible]	[illegible]
AC Servo Motor	[illegible]	[illegible]	[illegible]	[illegible]

Q13. Describe the Cartesian, cylindrical, and spherical robot configurations. Provide an industrial application for each.

- **Cartesian (PPP):** Three mutually perpendicular prismatic joints for x, y, z motion. Workspace is a rectangular box. Rigid structure, easy linear path programming. Requires large floor space and sealed screws. *Application:* CNC machine loading/unloading, gantry welding of large structures (e.g., ship hull welding), waterjet cutting machines.
- **Cylindrical (RPP):** Base revolute joint + two prismatic joints (height + reach). Workspace is a hollow cylindrical shell. Can reach around its base; theta axis easy to seal from dust. *Application:* Pipe welding, loading/unloading of cylindrical machining fixtures, die-casting machines where the robot must reach inside a circular mould.
- **Spherical / Polar (RRP):** Two revolute joints (base rotation + elevation) + one prismatic (reach). Workspace is a spherical sector. Large work volume for a compact robot base. *Application:* Original Unimate robot (die-casting and spot welding). Die-casting parts retrieval where the robot must reach into mould cavities from different angles.

Q14. How does a SCARA robot differ from an articulated robot in terms of motion and applications?

Aspect	SCARA Robot	Articulated (RRR) Robot
Full Form	Selective Compliance Assembly Robot Arm	Revolute-jointed arm / anthropomorphic
Joint Types	2 revolute (horizontal plane) + 1 prismatic (vertical) + 1 (wrist roll) = 4 DOF	3 revolute (arm) + 3 revolute (wrist) = 6 DOF
Compliance	Selective: compliant in horizontal XY (for lateral peg insertion), rigid in Z (vertical insertion force)	No inherent selective compliance; must be programmed
Workspace	Horizontal disc / donut shape - excellent for planar tasks	Near-spherical; can reach above and below itself
Speed	Very fast for planar pick-and-place (cycle times < 0.4 s)	Moderate; optimised for 3D path following
Precision	Excellent for vertical insertions due to Z-axis rigidity	Good; 6-DOF enables complex approach directions
Primary Application	PCB assembly, vertical peg-in-hole, small part assembly, electronics manufacturing	Arc welding, spray painting, material handling, general-purpose
Example	Epson T-series, Yamaha YK-series (used in Indian electronics factories)	KUKA KR, ABB IRB, Fanuc M-series

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Q15. Why is an articulated robot often considered similar to a human arm? Describe its joint configuration.

An **articulated robot** (also called a revolute-jointed or anthropomorphic robot) closely mimics the human arm's structure and range of motion:

Human Arm Joint	Robot Equivalent	Motion
Shoulder (3 DOF: flexion, abduction, rotation)	Joint 1 (base rotation) + Joint 2 (shoulder pitch)	Rotates the arm around the body and raises it
Elbow (1 DOF: flexion)	Joint 3 (elbow pitch)	Bends the forearm relative to the upper arm
Wrist (3 DOF: roll, pitch, yaw)	Joints 4, 5, 6 (wrist roll, wrist pitch, tool rotation)	Orients the tool in space

Configuration: In a 6-DOF articulated robot like KUKA KR-5: Axis 1 (waist rotation, +-155 deg), Axis 2 (shoulder, +65/-180 deg), Axis 3 (elbow, +158/-15 deg) form the *positioning arm*. Axes 4, 5, 6 (wrist) form the *orientation wrist*, with A4/A6 having +-350 deg range.

Similarities to human arm: All-revolute joints, same approximate DOF (6 robot vs. ~7 human arm), compact base with large reach, can place tool at any position/orientation within the workspace.

Q17. Explain the importance of precision, repeatability, and accuracy in robotic manipulators.

- **Accuracy:** Essential when the robot must go to absolute positions programmed offline (in CAD) without hand-teaching. Factors affecting accuracy: joint calibration, link length errors, gear backlash, thermal deflection. Improving accuracy requires kinematic calibration. Example: a poorly calibrated robot may have commanded pose at x=500 mm but actually reach x=503 mm.
- **Repeatability:** The most critical parameter for production. In a production line, the robot is taught the positions once, then must hit them identically on every cycle for thousands of cycles. High repeatability ensures consistent product quality. Modern AC servo robots: +/-0.02 to +/-0.05 mm repeatability. A robot can be repeatable but inaccurate (systematic offset), which is acceptable if positions are always taught (not computed offline).
- **Precision/Resolution:** Determines the finest motion increment possible. Depends on encoder resolution (pulses/rev) and gear ratio. High resolution enables smooth, fine paths necessary for polishing or laser cutting. Low resolution causes step-like motion on curved paths.

Practical Trade-off: High accuracy requires expensive calibration. High repeatability requires good mechanical design (zero backlash gears, stiff structure, low thermal expansion). For most production tasks, high repeatability is prioritised over absolute accuracy.

Q18. Describe the significance of yaw, pitch, and roll in tool orientation for robotic manipulators.

The end-effector's **orientation** in 3D space is described by three rotation angles. Using the tool frame (TCP - Tool Center Point):

Rotation	Axis	Description	Robotics Significance
Roll	About tool Z-axis (approach axis)	Spinning the tool about the direction it's pointing	Determines weld torch rotation angle; spray gun swirl angle;
Pitch	About tool Y-axis	Tilting the tool up/down (elevating the nose)	Sets welding torch lean angle for penetration; drilling angle;
Yaw	About tool X-axis	Swinging the tool left/right (turning the nose sideways)	Welding torch travel angle; lateral approach for confined spa

Why all three matter: A 3-DOF robot (positioning arm only) can place the TCP at any point but cannot control orientation. For welding, the torch must maintain a specific combination of roll/pitch/yaw throughout the seam for consistent penetration and bead shape. This requires the wrist's 3 DOF (Joints 4, 5, 6 in a 6-DOF arm) to control these angles independently.

Q19. What is dexterity in robotics, and why is it important for applications such as surgical robotics and assembly tasks?

Dexterity is the robot's ability to reach a desired end-effector pose (position + orientation) from multiple configurations and to apply forces/velocities in any direction with similar ease. It is the opposite of being near a singularity (where the robot loses effective DOF).

Mathematical Definition: Yoshikawa's manipulability index:

$$w = \sqrt{\det(J \cdot J^T)}$$

w = 0 at singularities (robot is immobilised in some directions); higher w = more dexterous.

Importance in Surgical Robotics:

- Surgeons operate through small ports (laparoscopy). Instruments must bend and rotate inside the body at angles a human wrist cannot achieve.
- da Vinci's EndoWrist instruments have 7 DOF, providing +/-90 deg bend + 540 deg rotation inside a 8 mm port - far beyond human dexterity.
- High dexterity enables fine manipulation near critical vessels without accidentally colliding with the port or adjacent anatomy.

Importance in Assembly:

- Allows the robot to approach a connector or peg from the required direction even if the fixture is in a tight space.
- Enables graceful degradation near obstacles - rather than stopping, the robot finds an alternative path using its extra DOF.
- Critical for multi-robot assembly cells where arms must avoid each other while working simultaneously.

Q20. List and describe three main categories of robotic applications: material handling, processing, and assembling.

- **Material Handling:** Robot grasps objects with a gripper and transfers them. Subtypes: (a) *Pick-and-Place* - picking parts from a conveyor and placing them in fixtures/pallets. (b) *Machine Loading/Unloading* - serving a CNC lathe with raw stock and removing finished parts. (c) *Palletising* - stacking cartons on pallets in a pattern. PTP control is standard. Key metrics: speed (cycle time), payload, and reach.
- **Processing:** Robot manipulates a *tool* (not a gripper) to perform a process on the workpiece. Subtypes: (a) *Welding* (spot/arc - discussed above). (b) *Spray Painting* - CP robot with high dexterity follows complex body surface contours. (c) *Deburring/Grinding* - CP robot applies constant force along surface. (d) *Drilling* - PTP robot positions a portable drill at each hole location. Requires high repeatability and in some cases active force control.
- **Assembling:** Most complex category. Robot must interact with fixtures, feeders, and other robots to join sub-assemblies. Requires: tactile/vision sensors for part detection, compliant motion for peg-in-hole tasks, RCC devices or active impedance control. SCARA robots dominate small-part assembly (electronics); 6-DOF arms used for larger assemblies (automotive sub-assemblies). Key metric: assembly cycle time and reject rate.

Q21. What are the different types of welding robots? How do they enhance industrial productivity?

Types of Welding Robots:

- **Spot Welding Robots:** Carry a welding gun (resistance spot welding). Typically 6-DOF, high-payload (20-150 kg rated) electric or hydraulic drives. PTP control. Used in automotive body shops. Multiple robots on one cell can weld 50-90 cars/hour. First used at GM in 1969.
- **Arc Welding Robots:** Use continuous arc (MIG/MAG/TIG/plasma) along a seam. Lightweight 6-DOF arm (5-10 kg payload for the torch). CP control, path accuracy +/-0.1 mm. Servo electric drives. Welding speed 0.25-3 m/min. Used for structural steel, pressure vessels, automotive frames.
- **Laser Welding / Cutting Robots:** Robot carries a laser head for high-speed, narrow-bead welding or precision cutting. Very high speed, no consumable electrode.

Productivity Enhancement:

- **Speed and Uptime:** A robot can operate 3 shifts/day, 7 days/week without fatigue or breaks. Human welders need frequent breaks due to heat and fumes.
- **Consistency:** Robotic spot welds are placed identically every cycle - fewer extra safety welds needed, reducing material usage.
- **Quality:** Arc welding robots maintain constant speed and torch angle for uniform bead width and penetration, reducing rework and scrap.
- **Safety:** Removes human workers from toxic fumes, UV radiation, and hot spatter environments.
- **Multi-robot Collaboration:** Multiple arms welding simultaneously on one car body (synchronised by a cell controller) reduce cycle time from minutes to seconds per car.

Q22. Explain how robotic systems are used in machining processes like drilling and deburring.

Drilling:

- Robot holds a portable drill and moves it from hole to hole using PTP control. At each hole location (detected by a template or vision), a fixed drill cycle is executed (drill-in, dwell, retract).
- A chamfered guide in the template ensures the drill self-centers. Programming is straightforward - teach-and-playback for each hole location.
- Applications: aircraft skin drilling (thousands of rivet holes in an aluminium panel), automotive flange drilling. Robot is faster and more consistent than manual operators, especially for large batch sizes.

Deburring:

- Burrs form at edges after machining (milling, turning, casting). Manual deburring is tedious and inconsistent. Robots use CP control with ~0.2 mm repeatability to follow 3D edges precisely.
- **Two modes:** (a) Robot holds the tool (deburring spindle) and brings it to the part - for heavy, fixture-mounted parts. (b) Robot holds the part and brings it to a fixed deburring tool - for lighter parts.
- Active force control or compliance ensures constant contact force on the edge even if the exact burr geometry is unknown. End-effector: rotary file, abrasive wheel, or brush.
- Applications: engine block deburring, casting edge cleaning, turbine blade leading-edge deburring in aerospace.

Q23. Discuss the environmental factors that influence robot design and operation in industries such as space exploration, underwater environments, and hazardous areas.

- **Space Exploration:** Vacuum (no air cooling -> radiative thermal management only), radiation (damages electronics -> radiation-hardened components), extreme temperature swings (-150 to +150 degC), microgravity (no gravity loading on joints). Actuators must work without lubrication (vacuum). Communication delays (14 min Earth-Mars) require high autonomy. Example: Curiosity rover uses RTG power, radiation-hardened computers, and autonomous hazard avoidance.
- **Underwater:** High pressure (1 bar per 10 m depth - deep ROVs face 600+ bar), corrosive saltwater (stainless steel, titanium, polymer seals required), zero visibility (sonar + lights needed), buoyancy (affects weight on joints). Hydraulic actuation preferred (oil-filled pressure-balanced systems). Communication: fibre-optic tether for real-time video. Example: CMERI ROV for pipeline inspection, oil rig maintenance.
- **Hazardous / Nuclear:** Radiation damages sensors and electronics; remote operation required; high temperature near furnaces; explosive atmospheres (paint booths with solvent vapour). Solutions: radiation-hardened cameras, brushless motors (no sparks), hermetically sealed enclosures (IP65+), intrinsically safe pneumatics in explosive environments. Example: DRDO Daksh bomb disposal robot with manipulator arm.
- **Mining / Foundry:** Dust, high vibration, extreme heat, abrasive particles. IP54/IP65 rated enclosures (KUKA KR-5 is IP54), sealed bellows on linear axes, thermal management for electronics. Robust mechanical design to handle shock loads.

MODULE 3: SENSORS FOR ROBOTS

Q1. Define sensors in robotics and explain their significance in robot control and operation.

Definition: A sensor (or transducer) is a device that converts a physical quantity (position, force, temperature, light) into an electrical signal that the robot controller can process. In robotics, sensors are the equivalent of human sensory organs - providing the robot with awareness of its own state and its environment.

Significance in Robot Control:

- **Closed-Loop Control:** Joint encoders feed back actual position to the controller, enabling servo control. Without position feedback, the robot cannot correct trajectory errors.
- **Safety:** Proximity sensors detect humans in the workspace, stopping the robot before collision. Pressure-sensitive floor mats cut power when stepped on.
- **Interlocking:** Limit switches and I/O sensors coordinate multi-step operations (e.g., confirm that a part is clamped before the welding torch fires).
- **Inspection / Quality:** Vision sensors measure part dimensions, check for defects, or verify correct part orientation before pick-up.
- **Force Control:** Force/torque sensors at the wrist enable compliant assembly, constant-force grinding, and delicate handling.
- **Autonomy:** Without sensors, robots can only execute pre-programmed paths in perfectly structured environments. Sensors enable robots to adapt to variations, detect errors, and operate autonomously.

Q2. Classify different types of sensors used in robotics. Provide examples for each category.

Classification	Sub-Types	Examples
By Location: INTERNAL	Sense the robot's own joint states (position, velocity, acceleration, torque)	Encoders (incremental/absolute), potentiometers, LVDT, RVDT, re
By Location: EXTERNAL	Sense the environment and objects being manipulated. Divided into contact and non-contact	Contact: Limit switches, tactile arrays, force/torque sensors. Non-c
By Signal Type: ANALOG	Output varies continuously with input	Potentiometer (resistance varies with position), tacho-generator (v
By Signal Type: DIGITAL	Output is discrete (binary or encoded counts)	Incremental encoder (pulse count), absolute encoder (digital word)
By Sensing Capability	Simple Touch, Complex Touch (Tactile), Force, Proximity, Vision	Limit switch (simple touch), tactile array (complex touch), strain ga

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Q3. Discuss the working principle and applications of proximity sensors, force sensors, and vision sensors in robotics.

1. Proximity Sensors

- **Inductive Proximity Sensor:** An oscillator circuit generates an RF electromagnetic field at the sensor face. When a metallic target enters this field, eddy currents are induced, loading and damping the oscillator. A detector circuit senses the amplitude drop and triggers a digital output. Range: 2-100 mm. *Application:* Detecting metal workpieces on a conveyor; end-of-travel detection replacing mechanical limit switches; detecting ferrous parts in bins.
- **Capacitive Proximity Sensor:** One capacitor plate is in the sensor face. When a target (metallic or non-metallic) approaches, it changes the capacitance of the oscillator circuit, triggering a switch. Can detect plastic, wood, liquid, and powder. *Application:* Detecting plastic containers, liquid levels in tanks, paper/cardboard packages.

2. Force/Torque Sensors

- **Strain Gauge Based:** Metal foil strain gauges bonded to a structural element (beam or diaphragm). Applied force causes strain (change in length), which changes the gauge resistance (DR = G*e*R). Wheatstone bridge converts resistance change to voltage. Typical gauge factor G = 2. *Application:* 6-axis wrist force/torque sensor for assembly, grinding force control, collaborative robot (cobot) contact detection.
- **Piezoelectric Based:** Crystalline material (quartz) generates a charge proportional to applied force. Very high frequency response (kHz). Range: 1-20 kN. *Application:* Dynamic force measurement in machining, crash/impact detection.

3. Vision Sensors

- **CCD/CMOS Camera + Image Processor:** Camera captures image; image processor performs thresholding, edge detection, feature extraction, and object recognition. *Applications:* (a) Inspection - checking surface defects, measuring dimensions. (b) Bin picking - identifying part location and orientation for random-bin pick-up. (c) Seam tracking for arc welding - camera detects the weld groove and guides the torch in real time. (d) Barcode/QR reading - identifying part numbers on assembly lines.

Q4. Explain the importance of vision systems in robotics. How do they enhance robotic perception and control?

Vision systems provide robots with the ability to understand the visual world - detecting objects, measuring positions, verifying quality, and navigating space. They transform an 'open-loop' robot (that can only work with perfectly positioned parts) into an adaptive system.

Components of a Vision System:

- Light source (controlled LED ring, backlighting, dark-field, or diffuse)
- Lens (focuses reflected/transmitted light onto the image sensor)
- Image sensor (CCD or CMOS - converts light to charge/voltage pixel by pixel)
- Frame grabber / ADC (digitises the analog video signal)
- Processing computer (runs image analysis algorithms)

How Vision Enhances Perception and Control:

- **Part Localisation:** Vision finds the 2D/3D position and orientation of a part, allowing the robot to pick it up from a random position (bin picking). Eliminates need for expensive precision fixtures.
- **Inspection / Quality Control:** Vision checks dimensions (using calibrated pixel-to-mm mapping), detects surface scratches, verifies correct assembly (e.g., all bolts present). In-line 100% inspection impossible with human vision.
- **Seam/Edge Tracking:** In arc welding, a laser-vision sensor detects the actual weld groove geometry in real time and sends corrections to the robot controller - compensating for part variation and thermal distortion.
- **Navigation:** Mobile robots use stereo vision or depth cameras (like Intel RealSense) for simultaneous localisation and mapping (SLAM) and obstacle avoidance.
- **Identification:** Colour/shape recognition identifies which product variant is on the line, allowing the robot to switch its programme automatically.

Resolution of vision system: a rule of thumb is that the sensor must have at least 2x more pixels than the ratio of the largest to smallest feature of interest.

Q6. How are sensors classified based on their mode of operation? Explain with examples.

Mode of Operation	Description	Examples
Active Sensors	Generate their own energy (e.g., emit light, [illegible]	Inductive proximity sensor (generates RF field), ultrasonic/[illegible]
Passive Sensors	Do not generate their own signal. Only detect [illegible]	CCD camera (detects ambient/controlled light), [illegible]
Contact (Touch) Sensors	Require physical contact with the target to sense.	Limit switches, tactile arrays, piezoelectric contact senso[illegible]
Non-Contact Sensors	Sense without touching the target. Preferred [illegible]	Vision cameras, laser scanners, ultrasonic sensors, [illegible]
Digital Sensors	Output is a discrete signal (0/1 or encoded word). [illegible]	Incremental encoder, absolute encoder, limit switch, [illegible]
Analog Sensors	Output is a continuous electrical signal (voltage, current, resistance) [illegible]	Potentiometer, LVDT, tachogenerator, strain gauge (Wh[illegible]

Q7. Discuss the role of position, velocity, and acceleration sensors in robotic motion control.

- **Position Sensors (Encoders, Pots, LVDT, Resolvers):** Measure joint angle or linear displacement. Primary feedback for position control loops. The controller compares measured position with desired position (setpoint) and computes a correction torque command. Incremental encoders count pulses; absolute encoders give position directly after power-on. Used on every servo-controlled robot joint.
- **Velocity Sensors (Tachogenerators, Computed from encoders):** Provide velocity feedback for the inner velocity control loop (which is inside the outer position loop). Damping: velocity feedback provides the 'derivative' term in a PD controller, preventing overshoot and oscillation. Tachogenerators generate voltage proportional to shaft speed (V proportional to omega). Modern systems compute velocity by differentiating encoder counts over time.
- **Acceleration Sensors (Accelerometers, Strain-gauge based):** Less commonly used in standard robot joint control. Used for: (a) detecting collisions (sudden acceleration spike = impact), (b) vibration monitoring/suppression, (c) computing inertial forces for feed-forward dynamic compensation in high-speed robots. Acceleration is more often computed from position data (double differentiation) but this amplifies noise, so direct accelerometers are preferred for high-frequency vibration.

Control Loop Architecture: Typical robot joint uses a 3-loop cascade control: outer position loop (encoder feedback), middle velocity loop (tach/encoder diff), inner current/torque loop (motor current sensor). This architecture provides fast, accurate, and stable joint control.

Q8. Why are sensors essential in collaborative robots (Cobots)? Discuss their impact on human-robot interaction.

Traditional industrial robots operate in caged cells, completely separated from humans. **Collaborative robots (cobots)** are designed to share workspace with human workers. This fundamentally changes safety requirements - sensors are not optional but mandatory.

Key Sensors in Cobots and Their Roles:

- **Joint Torque Sensors:** Each joint has a torque sensor (strain gauge or motor current monitoring). If the robot contacts a human unexpectedly, the torque spikes and the robot immediately stops or reduces force. KUKA LBR iiwa has torque sensors in all 7 joints, detecting forces as low as 1 N.
- **Force/Torque Sensor at Wrist:** 6-axis F/T sensor detects contact forces in all directions. Enables the cobot to limit contact force to safe levels (ISO/TS 15066 specifies max contact forces for different body parts).
- **Vision / Depth Cameras:** 3D cameras (e.g., Intel RealSense, structured light) create a 3D map of the workspace in real time. Robot slows down as humans approach (safety zone monitoring) and stops if a human enters the minimum safety zone.
- **Capacitive Skin Sensors:** Distributed capacitive sensors on the robot's surface detect the proximity of a human hand before physical contact, allowing the robot to stop before the collision.

Impact on Human-Robot Interaction:

- Enables intuitive hand-guided teaching - human physically moves the robot arm while torque sensors record the path.
- Allows safe handover tasks - robot holds a part, human takes it. Force sensors detect the human grip and release the part safely.
- Reduces retraining cost - workers can interact naturally without robotics expertise.
- Enables small-batch, flexible manufacturing where human adaptability combines with robot precision and endurance.

Q9. Define and explain the key characteristics of sensing devices: sensitivity, resolution, accuracy, and repeatability.

Characteristic	Definition	Formula / Example	Significance
Sensitivity	Ratio of change in output signal to [illegible]	S = Delta(Output) / Delta(Input) [illegible]	[illegible]
Resolution	Smallest change in input that pr[illegible]	[illegible]	[illegible]
Accuracy	Closeness of the sensor's reading to the true (actual) value [illegible]	[illegible]	[illegible]
Repeatability	Consistency of the sensor output for the same input [illegible]	[illegible]	[illegible]

Q10. How do response time and range affect sensor performance in robotic applications?

- **Response Time:** The time taken for the sensor output to respond to a step change in input (typically the time to reach 63% or 90% of the final value). Also called time constant or rise time.

Impact in Robotics:

- A slow sensor cannot keep up with fast joint motion. At 1000 rpm, an encoder must output pulses faster than the controller's sampling period (typically 1-4 ms for servo drives).
- Force sensors with slow response miss transient impact forces during high-speed assembly, causing parts to jam before the controller can react.
- Vision systems: frame rate (typically 30-120 fps) determines how fast moving parts can be tracked. A 60 fps camera at 250 mm/s motion allows 4 mm motion per frame - acceptable for slow conveyors, but not for high-speed pick-and-place.
- **Photoelectric sensor** response time: up to 3000x faster than mechanical limit switches - critical for high-speed counting applications.
- **Range:** The span of the measurand over which the sensor operates within its specified accuracy.

Impact in Robotics:

- Joint encoder must cover the full joint travel range. A rotary encoder on a joint with +-355 deg range must have at least that full range covered by its absolute word.
- Proximity sensor range (2-100 mm) determines the triggering distance. Too short a range misses objects; too long causes false triggers from background objects.
- Force sensor range must exceed the maximum expected contact force with adequate safety margin (e.g., 200% overload rating), while also being sensitive enough to detect small contact forces.
- Vision: depth-of-field determines the distance range over which objects are in focus - important for bin picking where parts are at different heights.

Q11. Discuss the factors influencing the selection of sensors for a robotic application.

- **Measurand Type:** What physical quantity needs to be measured: position/angle, velocity, force, distance, colour, temperature? Different measurands require fundamentally different sensor types.
- **Required Range:** The sensor's range must cover the full expected range of the measurand with some margin. E.g., joint range +-175 deg -> encoder must cover at least 350 deg.
- **Required Resolution and Accuracy:** High-precision welding may need 0.01 mm resolution; simple pick-and-place may need only 0.5 mm. Higher resolution = higher cost.
- **Response Time:** High-speed robot control (1 kHz servo loop) needs sensors that respond within 0.1-1 ms.
- **Environmental Conditions:** Temperature range, humidity, dust, chemicals, electromagnetic interference (EMI), vibration. Foundry/welding environments require IP65+ rated sensors; explosive areas need intrinsically safe sensors.
- **Contact vs Non-Contact:** Parts that must not be touched (hot, fragile, wet) require non-contact sensors (vision, laser, ultrasonic).

- **Output Type:** Digital output connects directly to PLC/microcontroller; analog output needs ADC. Some systems require Fieldbus (EtherCAT, Profibus) compatible sensors.
- **Size and Weight:** End-of-arm sensors must be lightweight to not reduce robot payload. Miniature force/torque sensors are preferred.
- **Cost:** 6-axis F/T sensor (INR 3-10 lakhs); simple inductive proximity sensor (INR 500-2000). Cost must be justified by the application value.
- **Reliability / MTBF:** Production sensors must operate 24/7 for years. Solid-state non-contact sensors preferred over mechanical contact sensors (higher MTBF).

Q12. Compare the advantages and limitations of wired vs. wireless sensors in robotics.

Aspect	Wired Sensors	Wireless Sensors
Signal Reliability	Very high - no interference from EMI, welding arcs, or other RF sources (in factory	Can be affected by EMI (welding robots generate strong R
Latency	Deterministic, very low latency (<1 ms possible with EtherCAT)	Variable latency; not suitable for real-time servo control (ty
Bandwidth	Very high (Ethernet: 100 Mbps - 10 Gbps; sufficient for full HD video)	Limited by protocol (Bluetooth: 3 Mbps, ZigBee: 250 kbps;
Installation	Complex cable routing; cables subject to wear at joints (drag chains needed for moving arms)	Simpler installation; no cable management; ideal for senso
Power	Powered over cable (no battery management)	Battery-powered: requires battery replacement/recharging;
Security	Physically secure; no wireless eavesdropping risk	Vulnerable to hacking, jamming, spoofing - concern in indu
Best Use Case	All servo-feedback sensors (encoders, F/T sensors), end-effector sensors, fixed joints	Mobile robots, AGVs, rotating/moving components where c

Q13. Why is sensor integration necessary for autonomous robots?

An autonomous robot must sense, interpret, decide, and act without human intervention. This is impossible without comprehensive sensor integration:

- **Environment Perception:** Without sensors, the robot cannot know where objects are, whether paths are clear, or what has changed. Sensor fusion combines data from multiple sensors (LiDAR + camera + IMU) for a complete environmental model.
- **Self-Awareness (Proprioception):** Internal sensors (encoders, IMU) tell the robot its own pose and velocity - essential for executing planned motions accurately.
- **Closed-Loop Control:** Every servo joint requires encoder feedback for position control. Without this, accumulated errors make the robot useless for any precision task.
- **Error Detection and Recovery:** Sensors detect when something goes wrong (part slipped from gripper, collision occurred, path is blocked) and allow the robot to take corrective action or request human help.
- **Task Verification:** After executing a task, sensors confirm success (vision checks that the weld is present; F/T sensor confirms assembly mated correctly).
- **Human Safety:** In collaborative or shared workspaces, sensor integration (vision + F/T + proximity) is the only way to ensure the robot stops before harming a human.
- **Navigation and Mapping (SLAM):** Mobile autonomous robots integrate LiDAR, cameras, wheel odometry, and IMU data to build a map, localise themselves, and plan collision-free paths in real time.

The integration challenge is sensor fusion - combining noisy, asynchronous data from different sensor types into a consistent, reliable world model. Kalman filters, Bayesian estimation, and deep learning are commonly used.

Q14. Discuss the importance of machine vision in robotic navigation and object detection.

Machine Vision gives robots the ability to perceive the visual world - enabling tasks that require spatial understanding of the environment.

In Object Detection:

- **Bin Picking:** A 3D vision system (structured light or stereo camera) identifies the position and orientation of randomly piled parts in a bin. The robot uses this data to compute an optimal grasp pose. Without vision, every part must be precisely positioned on a fixture - a major flexibility limitation.
- **Defect Inspection:** High-resolution camera + image processing detects surface scratches, dimensional errors, missing components, and labelling mistakes at line speeds up to 10 m/s (e.g., in beverage or pharmaceutical lines).
- **Barcode / QR Recognition:** Identifies which part or product is present, allowing the robot to select the correct programme from a library.
- **Seam Tracking (Arc Welding):** Laser-vision sensor profiles the weld groove in real time, guiding the torch to track deviations due to part tolerances or thermal distortion.

In Navigation (Mobile Robots / AGVs):

- **Obstacle Detection and Avoidance:** Depth cameras (structured light, time-of-flight) or stereo vision detect people, pallets, and machinery in the robot's path and trigger safe stops or path re-planning.
- **SLAM (Simultaneous Localisation and Mapping):** Robot uses LiDAR or vision to build a map while simultaneously determining its own position within that map. Enables navigation in GPS-denied environments (indoor warehouses).
- **Lane/Feature Following:** AGVs follow floor markers detected by downward-looking cameras; autonomous forklifts use pallet-face recognition to align forks precisely.

Limitation: Machine vision is computationally intensive and sensitive to lighting conditions. Robust industrial vision systems require controlled, consistent lighting (LED ring, backlighting) and GPU-accelerated image processing.

Q15. Define actuators and explain their role in robotic motion.

Definition: An actuator is a device that converts an energy source (electrical, hydraulic, or pneumatic) into mechanical motion (force or torque). In the context of a robot, the actuator system includes the motor, power amplifier, and transmission elements. Actuators are the 'muscles' of the robot.

Types of Actuators in Robotics:

- **Electric Actuators (DC/AC Servo, Stepper):** Most common. Convert electrical energy to rotary or linear motion. AC servo with encoder provides precise, programmable torque and position control.
- **Hydraulic Actuators (Cylinders, Rotary Hydraulic Motors):** Convert hydraulic pressure to force/torque. Highest power-to-weight ratio. Used for heavy payload robots (spot welding guns, forge-press handling).
- **Pneumatic Actuators (Cylinders, Rotary Actuators):** Convert compressed air to linear/rotary motion. Fast, cheap, and intrinsically safe. Limited to on/off control. Primarily used for grippers.

Role in Robot Motion:

- Each joint of a robot manipulator has one actuator (electric motor + gearbox). The motor shaft rotation is converted to joint rotation/translation by the transmission.
- The motor's torque/force is commanded by the robot controller (via current commands to the servo drive). The encoder on the motor shaft closes the position feedback loop.
- The transmission (gears, belt, harmonic drive) steps down the motor's high speed to the joint's required low speed, multiplying torque. A 100:1 harmonic drive converts 3000 rpm/0.5 Nm motor output to 30 rpm/50 Nm at the joint.
- Actuator choice determines the robot's payload capacity, speed, precision, and safety characteristics. Most modern industrial robots use brushless AC servo motors with harmonic drives or planetary gearboxes.

Q16. If the maximum count possible for an incremental rotary encoder is 5000 pulses and the encoder has a full-scale range of +/-180 deg, calculate the angular position corresponding to a count of n = 1250 pulses.

Given:

- Maximum count: p = 5000 pulses
- Full-scale range: q_m = +/-180 deg (total range = 360 deg, but measuring from 0 to +180 for the positive half)
- Count: n = 1250 pulses

Formula (from Saha, Eq. 4.1):

*theta = (n / p) * theta_m*

where theta is the angular position, n is the count, p is the maximum count, and theta_m is the maximum range angle.

Interpretation of the problem: The encoder measures from 0 to +180 deg (i.e., theta_m = 180 deg) with full-scale count p = 5000.

Calculation:

*theta = (1250 / 5000) * 180 deg*

*theta = 0.25 * 180 deg*

theta = 45 deg

Result: The angular position corresponding to n = 1250 pulses is 45 degrees.

Verification: At n = 5000 (max count), theta = (5000/5000) * 180 = 180 deg (full-scale). At n = 1250 (one-quarter of max count), theta = 0.25 * 180 = 45 deg. This is consistent.