PVP 23

Code: 23ME2601

III B.Tech – II Semester - Regular Examinations – APRIL 2026

INTRODUCTION TO INDUSTRIAL ROBOTICS
(Common for ALL BRANCHES)

Duration: 3 hours Max. Marks: 70

Note: 1. This question paper contains two Parts A and B.
2. Part-A contains 10 short answer questions. Each Question carries 2 Marks.
3. Part-B contains 5 essay questions with an internal choice from each unit. Each Question carries 10 marks.
4. All parts of Question paper must be answered in one place.

BL – Blooms Level CO – Course Outcome

PART – A

		BL	CO
1.a)	Describe the coordinate systems used in robotics.	L2	CO1
1.b)	Define degrees of freedom in the robot.	L2	CO1
1.c)	What is actuator and how they classified?	L2	CO2
1.d)	Describe the working principle of resolver.	L2	CO2
1.e)	Highlight the importance of homogeneous transformation.	L2	CO3
1.f)	Define Joint and world coordinate systems.	L2	CO3
1.g)	Define obstacle avoidance in path planning.	L2	CO4
1.h)	Describe joint integrated motion.	L2	CO4
1.i)	Describe the function of machine vision in robotics.	L2	CO5
1.j)	What are the robotic applications of machine vision?	L2	CO5

PART – B

			BL	CO	Max. Marks
UNIT-I					
2	a)	Differentiate automation and robotics.	L2	CO1	5 M
	b)	Illustrate anatomy of industrial robot with its functions.	L2	CO1	5 M
OR					
3	What is end-effector? Discuss requirements and challenges of end-effectors.		L2	CO1	10 M
UNIT-II					
4	a)	Explain the working principle of stepper motors.	L2	CO2	5 M
	b)	Illustrate the working of Hydraulic drive system.	L2	CO2	5 M
OR					
5	a)	Write about the working of velocity sensors.	L2	CO2	5 M
	b)	Explain the working principle of encoder.	L2	CO2	5 M
UNIT-III					
6	Obtain homogeneous transformation matrix(T) for the motions in the following sequence a) Rotation about X axis by 60^o b) Translation along Y axis by 10 units c) Rotation about Z axis by 30^o		L3	CO3	10 M

OR				
7	Explain in detail about DH representation of a robot.	L2	CO3	10 M
UNIT-IV				
8	Differentiate path and trajectory. Derive the cubic polynomial equation for trajectory planning of joint angle rotation.	L2	CO4	10 M
OR				
9	Explain in detail about various programming methods of robots.	L2	CO4	10 M
UNIT-V				
10	Demonstrate various functions of machine vision system.	L2	CO5	10 M
OR				
11	Explain the sensing and digitizing function in machine vision.	L2	CO5	10 M

Code: 23HE2601

PVP23

III B. Tech –II Semester – Regular Examinations – ~~October 2024~~ April - 2026

Introduction to Industrial Robotics

Common for All Brancehes

Scheme of Evaluation and solutions

Part – A

1.a) Coordinate Systems: 1 mark for mentioning Cartesian, joint, and tool; 1 mark for brief description of their use in link positioning.

1.b) Degrees of Freedom (DOF): 1 mark for the definition (independent variables/movements); 1 mark for mentioning its relationship to the number of joints (e.g., 6 DOF for a typical robot).

1.c) Actuator & Classification: 1 mark for definition (energy to motion conversion); 1 mark for classification into Electrical, Hydraulic, and Pneumatic.

1.d) Resolver: 1 mark for mentioning it is a rotary transformer; 1 mark for the principle of sine/cosine voltage induction to determine position.

1.e) Homogeneous Transformation: 1 mark for mentioning the 4×4 matrix format; 1 mark for its utility in combining rotation and translation in a single calculation.

1.f) Joint & World Systems: 1 mark for Joint (relative to the axis of motion); 1 mark for World (fixed reference frame/Cartesian coordinates).

1.g) Obstacle Avoidance: 1 mark for the concept of collision-free path planning; 1 mark for the role of sensors in real-time detection.

1.h) Joint Integrated Motion: 1 mark for defining coordinated joint movement; 1 mark for explaining that all joints reach the destination simultaneously.

1.i) Machine Vision Function: 1 mark for sensing/perception; 1 mark for the analysis and decision-making role (e.g., pass/fail).

1.j) Machine Vision Applications: 1 mark for pick-and-place/sorting; 1 mark for quality inspection or guidance.

Part – B

2.a) Automation vs. Robotics (5M): 2 marks for clear definitions; 3 marks for a comparative table (Flexibility, Intelligence, Physical Form).

2.b) Anatomy of Robot (5M): 2 marks for a diagram (Base, Arm, Wrist); 3 marks for describing functions of the Manipulator, Controller, and Actuators.

3. End-Effector (10M): 2 marks for definition; 4 marks for types and requirements; 4 marks for challenges

4.a) Stepper Motors (5M): 2 marks for the working principle (pulses to discrete steps); 3 marks for construction/application.

4.b) Hydraulic System (5M): 2 marks for the fluid pressure principle; 3 marks for components (Pump, Valves, Actuator) and their functions

5.a) Velocity Sensors (5M): 2 marks for defining the Tachometer principle; 3 marks for explaining EMF proportionality to speed.

5.b) Encoder (5M): 2 marks for construction (Optical disc, light source); 3 marks for working principle

6. Transformation Matrix (10M): 2 marks each for individual matrices (T_1, T_2 *and* T_3),2 mark for correct final multiplication order and 2 marks for combined transformation matrix.

7. DH Representation (10M): 4 marks for describing the 4 DH parameters ,6 marks for the step-by-step procedure of coordinate frame assignment.

8. Path vs. Trajectory (10M): 3 marks for differentiating (Geometric path vs. Time-based trajectory); 7 marks for the derivation of the cubic polynomial $\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$.

9. Programming Methods (10M): 3 marks for Lead-through programming; 3 marks for Teach-pendant method; 4 marks for Off-line/Simulation-based programming.

10. Machine Vision Functions (10M): 2 marks each for: Imaging, Preprocessing, Segmentation, Feature Extraction, and Recognition.

11. Sensing & Digitizing (10M): 5 marks for Sensing (Lighting and Camera hardware); 5 marks for Digitizing (Sampling, Quantization, and A/D conversion).

Code: 23ME2601

PVP23

III B. Tech –II Semester – Regular Examinations – ~~October 2024~~ April-2026

Introduction to Industrial Robotics

Common for All Branches

Scheme of Evaluation and solutions

1.a) Describe the coordinate systems used in robotics.

Ans. In robotics, coordinate systems are used to define the position and orientation of a robot's links and its end-effector in space. The three primary systems include:

- **Cartesian (World) Coordinate System:** A fixed global reference frame (X, Y, Z) used to define the robot's position relative to its environment.
- **Joint Coordinate System:** Defined by the individual motion of each joint (angles for revolute joints or displacements for prismatic joints).
- **Tool Coordinate System:** A local frame attached to the robot's end-effector (hand), used to define the orientation and movement of the tool itself.

1.b) Define degrees of freedom in the robot.

Ans. DOF represents the number of independent variables (translations and rotations) required to specify the state of a robot's links and joints. Each joint in a robot typically provides one degree of freedom. For example, a revolute joint allows one rotational DOF, while a prismatic joint allows one translational DOF. A standard industrial robot often requires 6 DOF (3 for position and 3 for orientation) to reach any point in its workspace with any orientation.

1.c) What is actuator and how they classified?

Ans. An **actuator** is a component of a machine or robot that is responsible for moving and controlling a mechanism or system by converting energy (such as electrical, hydraulic, or pneumatic) into physical motion. It acts as the "muscle" of the robot, receiving a signal from the controller to perform a specific action.

Classification of Actuators

Actuators are generally classified based on the type of energy they use to generate motion:

- **Electrical Actuators:** Convert electrical energy into mechanical motion. Common examples include DC motors, stepper motors, and servomotors. They are widely used in robotics due to their precision and ease of control.

- **Hydraulic Actuators:** Use pressurized liquids (usually oil) to produce high-force linear or rotational movement. These are typically used for heavy-duty industrial robots that require significant strength.
- **Pneumatic Actuators:** Use compressed air to create motion. They are often used for simple "pick-and-place" tasks because they are fast and relatively inexpensive, though they offer less precision than electrical systems.

1.d) Describe the working principle of resolver.

Ans. A resolver is a type of rotary electrical transformer used to measure the precise angular position and velocity of a robot's joints.

- **Working Principle**
- Structure: It consists of a stationary part called the stator and a rotating part called the rotor, which is connected to the motor shaft.
- Stator Windings: The stator contains two primary windings placed at 90° to each other (Sine and Cosine windings).
- Electromagnetic Induction: An AC reference signal is applied to the rotor winding, which induces a voltage in the stator windings through electromagnetic induction.
- Signal Output: As the rotor turns, the magnitude of the induced voltage in the stator windings changes according to the sine and cosine of the shaft angle.
- Position Calculation: The robot's controller compares these two output signals to determine the exact absolute position of the joint.

1.e) Highlight the importance of homogeneous transformation.

Ans. In robotics, **homogeneous transformation** is a fundamental mathematical tool that combines rotation and translation into a single $4 \times 4\ matrix$. Its importance lies in the following areas:

Unified Representation: It allows both the position (translation) and orientation (rotation) of a robot's link or end-effector to be represented simultaneously within a single matrix.

Simplified Calculations: By using homogeneous coordinates, complex sequences of multiple movements can be calculated through simple matrix multiplication rather than separate, cumbersome operations.

Coordinate Mapping: It provides a systematic way to transform points or vectors between different reference frames, such as moving from a joint coordinate system to the world coordinate system.

Kinematic Modelling: It is essential for deriving the forward and inverse kinematics of a robot, enabling the controller to determine exactly where the hand is in space based on joint angles.

1.f) Define Joint and world coordinate systems.

Ans. In robotics, the joint and world coordinate systems are used to define movement and positioning from different perspectives:

Joint Coordinate System: This system defines the position of the robot based on the individual motions of its joints. For a revolute joint, the position is expressed as an angle, while for a prismatic joint, it is expressed as a linear displacement.

World Coordinate System: Also known as the Cartesian coordinate system, this is a fixed global reference frame (X, Y, Z). It defines the position and orientation of the robot's end-effector relative to a stationary point in the environment, such as the base of the robot or the workstation.

1.g) Define obstacle avoidance in path planning.

Ans. Obstacle avoidance is a critical component of robotic path planning that ensures a robot moves from a starting point to a goal destination without colliding with any objects in its environment.

- Definition: It is the process of detecting and bypassing physical obstructions in real-time or during the pre-planning phase to maintain a collision-free trajectory.
- Sensor Integration: The robot uses sensors (such as Ultrasonic, LiDAR, or Vision systems) to identify the distance and position of obstacles.
- Dynamic vs. Static: Path planning must account for static obstacles (fixed objects like walls) and dynamic obstacles (moving objects like people or other robots), requiring the algorithm to constantly recalculate the path to ensure safety.

1.h) Describe joint integrated motion.

Ans. **Joint integrated motion** refers to a method of robot control where multiple joints move simultaneously and reach their destination at the same time to produce a smooth, coordinated movement.

- **Coordinated Movement:** Instead of joints moving one after another, all participating joints start and stop their motion at the same instant.
- **Speed Regulation:** The controller calculates the time required for the "slowest" joint (the one with the largest displacement) and slows down the other joints proportionally so they finish together.

- **Efficiency:** This approach reduces mechanical stress on the robot and allows for more fluid, predictable paths compared to independent joint motion.

1.i) Describe the function of machine vision in robotics.

Ans. In robotics, **machine vision** functions as the "eyes" of the system, providing the necessary visual data to allow a robot to perceive, analyse, and interact with its environment. It transitions a robot from a blind, pre-programmed machine to an intelligent system capable of making decisions based on visual input.

The primary functions of machine vision include:

- **Object Identification and Recognition:** The system identifies specific parts or objects based on their shape, colour, or texture, allowing the robot to distinguish between different items on a production line.
- **Position and Orientation Detection:** It determines the exact coordinates (X, Y, Z) and the rotation of an object, which is essential for accurate "pick-and-place" operations.
- **Quality Inspection:** Machine vision performs high-speed automated inspections to detect defects, missing components, or irregularities that are invisible or too fast for the human eye.
- **Navigation and Guidance:** In mobile robots, vision systems help in mapping the environment, detecting obstacles, and providing guidance for the robot to move safely from one point to another.
- **Measurement and Gauging:** It can precisely measure the dimensions of a part to ensure it meets strict engineering tolerances without physical contact.

1.j) What are the robotic applications of machine vision?

Ans. Machine vision is a cornerstone of modern industrial robotics, enabling machines to perform complex tasks that require visual feedback.

Here are the primary robotic applications of machine vision:

- **Pick and Place:** Vision systems allow robots to identify, locate, and orient parts on a moving conveyor belt or in a bin, ensuring they are grasped and placed correctly even if their position is randomized.
- **Automated Inspection and Quality Control:** Robots use vision to scan products for defects, cracks, or missing components, ensuring that every item on a production line meets strict quality standards.

- **Robot Guidance and Positioning:** Machine vision provides the "coordinates" for a robot to perform precise actions, such as inserting a tiny electronic component into a circuit board or guiding a welding torch along a seam.
- **Object Sorting:** Vision-enabled robots can classify and sort items based on various visual characteristics like shape, colour, size, or barcodes.
- **Mobile Robot Navigation:** For Autonomous Mobile Robots (AMRs), machine vision is used for mapping environments, detecting obstacles, and recognizing landmarks to navigate safely through a facility.
- **Assembly Tasks:** It assists in the high-precision assembly of mechanical parts by ensuring that components are perfectly aligned before they are joined together.

UNIT-I

2.a) Differentiate automation and robotics. 5 M

Ans. In the context of modern engineering and manufacturing, "automation" and "robotics" are often used interchangeably, but they represent distinct concepts with significant differences in their scope, flexibility, and application.

- **Automation:** This is the process of using technology, programs, or machinery to perform a repetitive task with minimal human intervention. The primary goal is to increase efficiency and consistency by replacing human labour in a specific, predefined process.
- **Robotics:** This is a branch of engineering that involves the design, construction, and operation of robots. A robot is a programmable machine capable of carrying out a complex series of actions automatically, often involving interaction with its physical environment through sensors and actuators.

Types of Automation

Automation can be categorized based on its application and rigidity:

- **Fixed (Hard) Automation:** Used for high-volume production with very low variability, such as a specialized assembly line where the sequence of operations is fixed by the equipment.
- **Programmable Automation:** Used for batch production where the equipment can be reconfigured or reprogrammed to produce different products.
- **flexible Automation:** Includes tools like Robotic Process Automation (RPA), which handles digital tasks like data entry or invoice processing without any physical machinery.

While they are different, they overlap in the field of Industrial Automation. For example, an industrial robot on an automotive assembly line is a form of automation because it performs a repetitive task (like welding), but it is also robotics because it is a programmable, multi-axis mechanical system.

Feature	Automation	Robotics
Primary Goal	To perform a specific task more efficiently and consistently.	To perform a variety of complex tasks, often mimicking human actions.
Flexibility	Generally low; designed for one specific, rigid task (e.g., a software script or a conveyor belt).	High; robots can be reprogrammed to perform entirely different tasks.
Physical Form	May or may not have a physical form (can be purely software-based).	Always possesses a physical structure or mechanical body.
Intelligence	Usually follows a fixed set of "If-Then" rules or pre-programmed logic.	Often utilizes sensors and AI to adapt to changes in the environment.
Interaction	Minimal interaction with the environment; usually operates in a controlled loop.	Constantly interacts with and responds to physical surroundings.

2.b) Illustrate anatomy of industrial robot with its functions. 5 M

Ans. Robot anatomy refers to the study of the physical structure and components of a robot, much like studying the skeleton and muscles of a living organism. Understanding robot anatomy is essential for designing, building, and operating robots effectively.

The main components that make up a robot's anatomy are

1. **Manipulator/Robot Arm (Structural Framework):**
   - This is the physical "body" or "skeleton" of the robot, often resembling a human arm in industrial robots.
   - It consists of rigid segments called links connected by movable joints.
   - Links: These are the rigid segments between joints, providing structural support and protecting internal components. They can be made of various materials like metal, plastic, or composites, depending on the robot's application and required strength.

- Joints: These are the articulation points that allow relative motion between two links. They provide degrees of freedom (DOF) to the robot, enabling it to bend, rotate, or slide. Common types include:
- Revolute (Rotary) Joints (R-type): Allow rotation around a single axis, similar to an elbow or shoulder.
- Prismatic (Linear) Joints (P-type): Allow linear motion along a single axis, like a sliding door.
- Spherical Joints: Allow rotation around multiple axes, similar to a ball-and-socket joint.
- The arrangement and number of links and joints determine the robot's kinematics (possible motions) and its reachability and workspace.

2. **End Effector:**
   - Often called the "hand" of the robot, the end effector is a tool or device attached to the end of the robot's arm (the last link).
   - It's designed to interact with the environment and perform specific tasks.
   - Examples include:
   - Grippers: For grasping and holding objects (e.g., two-fingered claws, vacuum grippers, multi-fingered humanoid hands).
   - Process Tools: Tools for specific applications like welding torches, drills, grinding wheels, spray painting tools, laser cutters, or screwdrivers.
   - Sensors: Sometimes sensors are integrated into the end effector to gather information during manipulation
3. **Actuators (Muscles):**
   - These are the "muscles" of the robot, responsible for converting energy into mechanical motion at the joints.
   - They drive the movement of the links and end effectors.
   - Common types of actuators include:
   - Electric Motors: Most common, offering precise control (e.g., servo motors, stepper motors).
   - Hydraulic Actuators: Use fluid pressure for high force and power, often found in heavy-duty applications.
   - Pneumatic Actuators: Use air pressure for high-speed cyclical movements, typically for smaller robots.

4. **Sensors (Eyes and Ears):**
   - Sensors are the robot's "sense organs," gathering information about the robot itself (internal sensors) and its surrounding environment (external sensors).
   - They provide feedback to the controller, allowing the robot to perceive, adapt, and make decisions.
   - Examples include:
   - Vision Sensors (Cameras): For object recognition, navigation, and inspection.
   - Proximity Sensors: Detect nearby objects to avoid collisions.
   - Force/Torque Sensors: Measure forces applied by or to the robot, crucial for delicate tasks.
   - Tactile Sensors: Detect contact and pressure.
   - Temperature and Pressure Sensors: Monitor environmental conditions.
   - Positioning Sensors (Encoders, Potentiometers, GPS, LiDAR): Determine the robot's location, orientation, and joint positions.
5. **Controller (Brain):**
   - This is the "brain" of the robot, typically a computer system (hardware and Software).
   - It receives inputs from sensors, processes information, makes decisions based on its programming, and sends commands to the actuators.
   - The controller coordinates all robot movements, manages data storage, and can communicate with other systems. It's responsible for trajectory planning, speed control, and position accuracy.

3. What is end-effector? Discuss requirements and challenges of end-effectors 10 M

Ans. In robotics, an "end effector" is a device or tool connected to the end of a robot arm to enable the robot to accomplish a specific task. Basically, it is a tool to grip, hold, and transport object and position them in a desired location. End effectors are the devices through which a robot interacts with the world around it, grasping and manipulating parts, inspecting surfaces, and working on them. As such, end effectors are among the most important elements of a robotic system. Robot end effectors are also known as robot's hand, robotic peripherals, robotic accessories, robot tools or robotic tools, end-of-arm tooling (EOA), or end-of-arm devices. The two categories of end effectors are grippers and tools.

Requirements of End Effectors

- **Compatibility with Task and Workpiece**: The end effector must be suited to the size, shape, material and fragility of the item it handles. For example, delicate components may require soft-grip or vacuum-based end effectors.
- **Adequate Payload Capacity**: The end effector must handle the maximum payload including additional forces during processing without deformation or accuracy loss.
- **Positional Accuracy and Repeatability**: Precise positioning relative to the workpiece is essential for consistent execution of operations such as insertion, welding, or assembly.
- **Reliability and Durability:** End effectors must withstand mechanical stresses and environmental conditions (heat, dust, liquids, vibration) throughout their working life.
- **Flexibility and Ease of Changeover:** End effectors should offer adaptability or quick changeover features to handle multiple product types with minimal downtime.
- **Safety:** The design must prevent accidental dropping of components and avoid harming human operators. Features such as force limiting and fail-safe mechanisms are essential.
- **Integration and Control:** The end effector should integrate easily with the robot controller, sensors and auxiliary equipment, responding accurately to control commands.

Challenges in End Effector Design and Use

- Diversity of Workpieces: The wide variation of workpiece geometries and materials makes it difficult to design a single gripper to handle all parts without compromise.
- Balancing Grip Force and Damage Risk: Providing enough force to hold a part firmly while ensuring it is not damaged is a major challenge, especially for fragile products.
- Environmental Influence: Extreme temperatures, dust, corrosive fluids, or electromagnetic noise can affect end effector performance and degrade sensors and actuators.
- Space Constraints: Robots often operate in restricted or cluttered spaces. Designing an end effector that fits within available workspace while providing required functionality is challenging.
- Cost vs Flexibility Trade-off: Highly adaptive or multi-purpose end effectors are expensive, while low-cost ones are usually application-specific.
- Wear and Maintenance: Contact surfaces, actuators, seals, and suction cups are subject to wear and require regular inspection and maintenance.

- Sensing and Feedback Integration: Integrating built-in sensors (force, tactile, proximity) and effectively using the data to adapt remains technically difficult.

UNIT-II

4.a) Explain the working principle of stepper motors. 5 M

Ans. A stepper motor is a special type of electric motor that converts electrical pulses into precise mechanical angular movements (steps). It is mainly made of the following parts:

- **Stator**

  The stationary part of the motor.

  Made of laminated steel and has several salient poles.

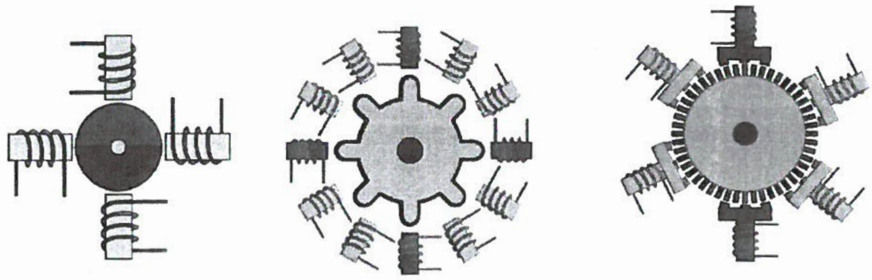
  Each pole is wound with a coil (stator winding) that produces a magnetic field when energized.

- **Rotor**

  The rotating part, placed inside the stator.

  It can be of three types:

  - Permanent Magnet Rotor – uses a permanent magnet, simple construction.
  - Variable Reluctance Rotor – made of soft iron with teeth to provide a low reluctance path for magnetic flux.
  - Hybrid Rotor – combines both permanent magnet and reluctance features for high precision.



- **Shaft**
  - Connected to the rotor, transmits motion to the external load.
- **Bearings**
  - Support the shaft and allow smooth rotation.
- **Driver Circuit**

- An electronic driver is used to energize stator windings sequentially according to input pulses from a controller (like a microcontroller or computer).

Working Principle of Stepper Motor:

- When an electrical pulse is applied to a stator winding, it creates a magnetic field in that pole.
- The rotor aligns itself with the energized stator pole due to magnetic attraction.
- When the next winding is energized (as per sequence), the magnetic field shifts, and the rotor moves a fixed angular distance (step angle) to align with the new pole.
- By applying pulses in a specific sequence, the rotor continues to rotate step by step.
- The step angle depends on the number of stator and rotor teeth and defines the resolution of movement (e.g., 1.8° per step means 200 steps per revolution).
- The speed of the motor is controlled by the frequency of input pulses, and the position is controlled by the number of pulses applied.

4.b) Illustrate the working of Hydraulic drive system. 5 M

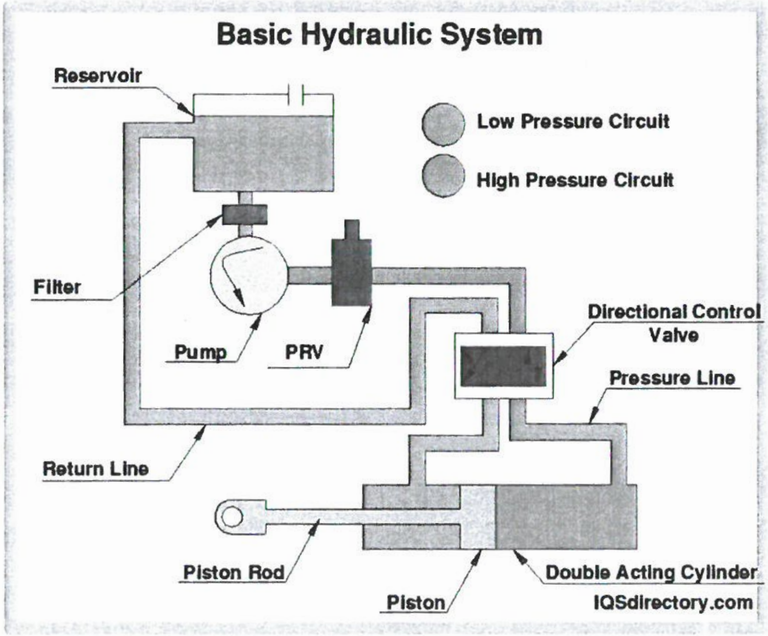
Ans. A hydraulic drive system is a power transmission system that uses pressurized fluid (usually oil) to generate, control, and transmit motion in robotic and industrial applications. It is widely used where high force and smooth motion are required, such as robotic arms, heavy manipulators, and industrial automation systems.

Basic Principle

The system operates on Pascal's Law, which states that pressure applied to a confined fluid is transmitted equally in all directions. $P = \frac{F}{A}$ .This means a small input force can generate a large output force by using different piston areas.

Main Components of Hydraulic Drive System

- Reservoir (Tank): Stores hydraulic fluid
- Pump: Converts mechanical energy into hydraulic energy (flow of fluid)
- Control Valves: Regulate flow, pressure, and direction
- Actuator (Cylinder/Motor): Converts hydraulic energy into mechanical motion
- Pipes and Hoses: Carry fluid between components
- Filters: Remove contaminants



Working of Hydraulic Drive System

1. **Fluid Supply:** Hydraulic oil is stored in the reservoir.
2. **Pressurization:** The pump draws fluid from the reservoir and pressurizes it.
3. **Flow Control:** Pressurized fluid passes through control valves, which regulate:
   - Direction (forward/reverse)
   - Speed (flow rate)
   - Force (pressure)
4. **Actuation:** The fluid enters the actuator:
   - In a **hydraulic cylinder**, pressure pushes the piston → linear motion
   - In a **hydraulic motor**, fluid causes rotation → rotary motion
5. **Return Flow:** After doing work, the fluid returns to the reservoir for reuse.

5.a) **Write about the working of velocity sensors.** 5 M

Ans. Velocity sensors are essential components in robotic systems, used to measure the rate of change of position (i.e., speed) of a robot's joints, wheels, or end-effectors. These sensors provide real-time feedback to control systems, enabling accurate motion control, stability, and trajectory tracking.

<u>Principle of Operation:</u>Velocity sensors operate based on detecting changes in position or motion over time. The general relation is: $v = \frac{dx}{dt}$ This means velocity is obtained either by:

Direct measurement using specialized sensors, or Indirect computation by differentiating position signals.

<u>Types of Velocity Sensors and Their Working</u>

a) **Tachometers (DC/AC Tachogenerators):** A tachometer is directly coupled to the rotating shaft. When the shaft rotates, it generates a voltage proportional to angular velocity.

Working: Based on electromagnetic induction. Faster rotation → higher induced voltage.

Output: Analog voltage signal proportional to speed.

b) **Optical Encoders (Incremental Encoders)**

These sensors measure velocity indirectly. A rotating disk with slots interrupts a light beam.

Working: As the disk rotates, pulses are generated. Velocity is calculated by counting pulses per unit time.

Formula: Velocity ∝ Number of pulses / times

Widely used in robotic joints and mobile robots.

c) Hall Effect Sensors

Operate based on the Hall Effect.

A magnetic field is applied to a rotating element.

Working: As the rotor moves, the magnetic field changes, producing voltage pulses proportional to speed. Common in brushless DC motors.

5.b) Explain the working principle of encoder. 5 M

Ans. An encoder is a simple device with a digital output signal for each small portion of a movement. The encoder disk or strip is divided into small sections. Each section is either opaque or transparent (it can also be either reflective or nonreflective). A light source, such as an LED on one side, projects a beam of light onto the other side of the encoder disk or strip, where it is seen by a light-sensitive sensor, such as a phototransistor. If the disk's angular position is such that the light is revealed, the sensor on the opposite side is turned on and has a high signal. If the angular position of the disk is such that the light is occluded, the pick-up sensor is off and its output is low (therefore, a digital output). As the disk rotates, it continuously sends signals. If the signals are counted, the approximate total displacement of the disk can be measured at any time.

Incremental Encoders

There are two basic types of encoders: incremental and absolute.

In incremental encoders the areas (arcs) of opaque and transparent sections are all equal and repeating. Since all arcs are the same size, each represents an equal angle of rotation. If the disk is divided into only two portions, each portion is 180° and its resolution is also 180°. Within this arc, the system is incapable of reporting any more accurate information about the displacement or position. If the number of divisions increases, the accuracy increases as well. Therefore, the resolution of an optical encoder is related to the number of arcs of transparent/opaque areas.

Absolute Encoders

An alternative to incremental optical encoders is an absolute encoder. Each portion of the encoder disk's angular displacement has a unique combination of clear/opaque sections that give it a unique signature. Through this, it is possible to determine the exact position of the disk at any time without the need for a starting position. In other words, even at start time, the controller can determine the position of the disk by the unique signature of the disk at that location

UNIT-III

6. Obtain homogeneous transformation matrix (T) for the motions in the following sequence: 10 M

a) Rotation about X axis by 60°

b) Translation along Y axis by 10 units

Ans **Individual Transformation Matrices**

(a) Rotation about X-axis (60°)

$$T_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 60^o & -\sin 60^o & 0 \\ 0 & \sin 60^o & \cos 60^o & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0.5 & -0.866 & 0 \\ 0 & 0.866 & 0.5 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(b) Translation along Y-axis (10 units)

$$T_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \mathbf{1} & \mathbf{0} & \mathbf{10} \\ 0 & \mathbf{0} & \mathbf{1} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(c) Rotation about Z axis by 30°

$$T_3 = \begin{bmatrix} \cos 30^o & -\sin 30^o & 0 & 0 \\ -\sin 30^o & \cos 30^o & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0.866 & -0.5 & 0 & 0 \\ 0.5 & 0.866 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Combined Transformation

Since transformations are applied in sequence:

$$T = T_3 \times T_2 \times T_1$$

$$= \begin{bmatrix} 0.866 & -0.5 & 0 & 0 \\ 0.5 & 0.866 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 10 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0.5 & -0.866 & 0 \\ 0 & 0.866 & 0.5 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 0.866 & -0.25 & 0.433 & -5 \\ 0.5 & 0.433 & -0.75 & 8.66 \\ 0 & 0.866 & 0.5 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

7. Explain in detail about DH representation of a robot. 10 M

Ans. The Denavit–Hardenberg (DH) representation is a systematic and widely used method in robotics to describe the kinematic structure of a serial manipulator. It provides a standardized way to assign coordinate frames to robot links and express the relative motion between successive links using a minimal set of parameters. Instead of dealing with complex spatial relationships, the DH method simplifies robot modeling by defining only four parameters for each link, which are sufficient to completely describe the geometry and motion of the robot.

In DH representation, each link of the robot is associated with a coordinate frame, and the transformation between two consecutive frames is defined using four parameters: link length (a_i), link twist (α_i), link offset (d_i), and joint angle (θ_i).

The link length, a_i, is the distance between two joint axes measured along the common normal (X-axis), while the link twist α_i, is the angle between the Z-axes of consecutive frames measured about the X-axis. The link offset d_i, represents the distance along the Z-axis between two coordinate frames, and the joint angle θ_i, is the angle between the X-axes measured about the Z-axis. For revolute joints, θ_i is the variable parameter, whereas for prismatic joints, d_i becomes the variable.

The relationship between two consecutive links is expressed using a homogeneous transformation matrix, which incorporates both rotation and translation. This transformation is obtained by performing a sequence of operations:

i. rotation about the Z-axis by , θ_i
ii. translation along the Z-axis by d_i,
iii. translation along the X-axis by a_i, and
iv. finally, rotation about the X-axis by α_i.

By multiplying these individual transformation matrices for all links, the overall transformation from the base frame to the end-effector can be obtained, which is essential for forward kinematics analysis.

To apply the DH method, certain rules are followed for assigning coordinate frames.

- The Z-axis of each frame is aligned with the axis of motion of the corresponding joint.
- The X-axis is chosen along the common normal between two consecutive Z-axes, and the origin is placed at the intersection of these axes.
- The Y-axis is then determined to complete a right-handed coordinate system. These rules ensure consistency and reduce ambiguity in defining transformations.

The DH representation is extensively used in robotic analysis, simulation, and control because it simplifies mathematical modelling and reduces computational complexity. It is particularly useful in deriving forward kinematics, trajectory planning, and robot programming. However, the method requires careful frame assignment, and multiple valid DH parameter sets may exist for the same robot, which can sometimes lead to confusion.

UNIT-IV

8. Differentiate path and trajectory. Derive the cubic polynomial equation for trajectory planning of joint angle rotation. 10 M

Ans. **Difference between Path and Trajectory**

In robotics, *path* and *trajectory* are related but not identical concepts. A **path** is the geometric route followed by the robot in space, defined purely in terms of positions (or configurations) without considering time. It specifies *where* the robot should move but not *how fast* it should move along that route. For example, a straight line or a curved arc between two points is a path.

A **trajectory**, on the other hand, is a time-parameterized version of a path. It specifies not only the positions but also the velocity and acceleration of the robot at each instant of time. In other words, a trajectory defines *where the robot should be at a specific time*. Thus, while a path is independent of time, a trajectory explicitly depends on time and is essential for motion planning and control in robotic systems.

Cubic polynomial trajectory planning

In this application, the initial location and orientation of the robot are known and, using the inverse kinematic equations, the final joint angles for the desired position and orientation are found. However, the motions of each joint of the robot must be planned individually. Therefore, consider one of the joints, which at the beginning of the motion segment at time t_i, is at θ_i, and which we want to move to a new value of θ_f at time t_f. One way to do this is to use a polynomial to plan the trajectory such that the initial and final boundary conditions match what We already know, namely that θ_i and θ_f are known and the velocities at the beginning and the end of the motion segment are zero (or other known values). These four pieces of information is allowed to solve for the four unknowns in the form of:

$$\theta(t) = c_0 + c_1 t + c_2 t^2 + c_3 t^3 \qquad (1)$$

with the initial and final conditions are:

$$\theta(t_i) = \theta_i, \theta(t_f) = \theta_f$$

$$\dot{\theta}(t_i) = 0, \dot{\theta}(t_f) = 0 \qquad (2)$$

Taking the first derivative of the polynomial equation (1), we get

$$\dot{\theta}(t) = c_1 + 2c_2 t + 3c_3 t^2 \qquad (3)$$

Substituting the initial and final conditions in to equations (1) and (3) Yields:

$$\theta(t_i) = c_0 = \theta_i \,; \theta\,(t_f) = c_0 + c_1 t_f + c_2 t_f^2 + c_3 t_f^3$$

$$\dot{\theta}(t_i) = c_1 = 0 \Rightarrow \dot{\theta}(t_f) = c_1 + 2c_2 t_f + 3c_3 t_f^2 = 0$$

By solving these four equations simultaneously, we get the necessary values for the constants.

Final Cubic Trajectory Equation

$$\theta(t) = \theta_i + \frac{3(\theta_f - \theta_i)}{(t_f)^2} t^2 - \frac{2(\theta_f - \theta_i)}{(t_f)^3} t^3$$

This allows us to calculate the joint position at any interval of time, which can be used by the controller to drive the joint to position, the same process must be used for each joint individually, but they all driven together from start to finish. Obviously, if the initial and final velocities are not zero. The given values can be used in these equations. Therefore, applying this third-order polynomial to each joint motion creates a motion profile that can be used to drive each joint.

9. Explain in detail about various programming methods of robots. 10 M

Ans. **Robot Programming** is the defining of desired motions so that the robot may perform them without human intervention. According to the consistent performance by the robots in industries, the robot programming can be divided in two common types such as:

- Lead through Programming Method (online Programming)
- Off-line Programming

Lead through Programming Method:

During this programming method, the traveling of robots is based on the desired movements, and it is stored in the external controller memory. There are two modes of a control system in this method such as a run mode and teach mode. The program is taught in the teach mode, and it is executed in the run mode.

- The lead through programming method can be done by two methods.

Powered Lead through Method:

- The powered lead through is the common programming method in the industries. A teach pendant is incorporated in this method for controlling the motors available in the joints. It is also used to operate the robot wrist and arm through a sequence of points.
- The playback of an operation is done by recording these points.
- The control of complex geometric moves is difficult to perform in the teach pendant.
- As a result, this method is good for point to point movements. Some of the key applications are spot welding, machine loading & unloading, and part transfer process.

Manual Lead through Method

- In this method, the robot's end effector is moved physically by the programmer at the desired movements.
- Sometimes, it may be difficult to move large robot arm manually.
- To get rid of it a teach button is implemented in the wrist for special programming.
- The manual lead through method is also known as Walk Through method.
- It is mainly used to perform continuous path movements. This method is best for spray painting and arc welding operations.
- Lead through programming is not readily compatible with modern computer-based technology.

Advantages:

- Easy
- No special programming skills or training

Disadvantages:

- Robot cannot be used in production, while it is being programmed.
- not practical for large or heavy robots
- High accuracy and straight-line movements are difficult to achieve, as are any other kind of geometrically defined trajectory, such as circular arcs, etc.
- difficult to edit out unwanted operator moves
- difficult to incorporate external sensor data
- Synchronization with other machines or equipment in the work cell is difficult
  - A large amount of memory is required

Robot Offline Programming Methods

- **Definition:** Offline programming is a method of programming industrial robots on a **computer workstation** without stopping production or physically teaching the robot with a pendant. The program is created, tested, and simulated offline, and then transferred to the robot controller for execution.
- This is widely used in industries such as **automobile, aerospace, painting, welding, assembly, and machining** where downtime is very costly.

Methods of Offline Programming

- Manual Coding (Text-based Programming)
  - The programmer writes the robot's movements and logic using a robot programming language (such as VAL, RAPID, KRL, or TRL).
  - Motion commands (MOVE, APPROACH), I/O control (ON/OFF signals), and logic statements are written as text.
  - Requires deep knowledge of robot kinematics and coordinate systems.
  - Advantage: Very flexible, precise control.

Limitation: Time-consuming and prone to errors if not verified with simulation

- CAD-based Programming
  - The robot program is generated directly from a CAD (Computer-Aided Design) model of the workpiece and workspace.
  - The software automatically extracts tool paths from the CAD geometry (e.g., surface paths for painting, cutting, or welding).
  - The robot trajectory is then simulated in 3D.
  - Advantage: Fast generation of complex paths.

- Limitation: Requires accurate CAD models and calibration.

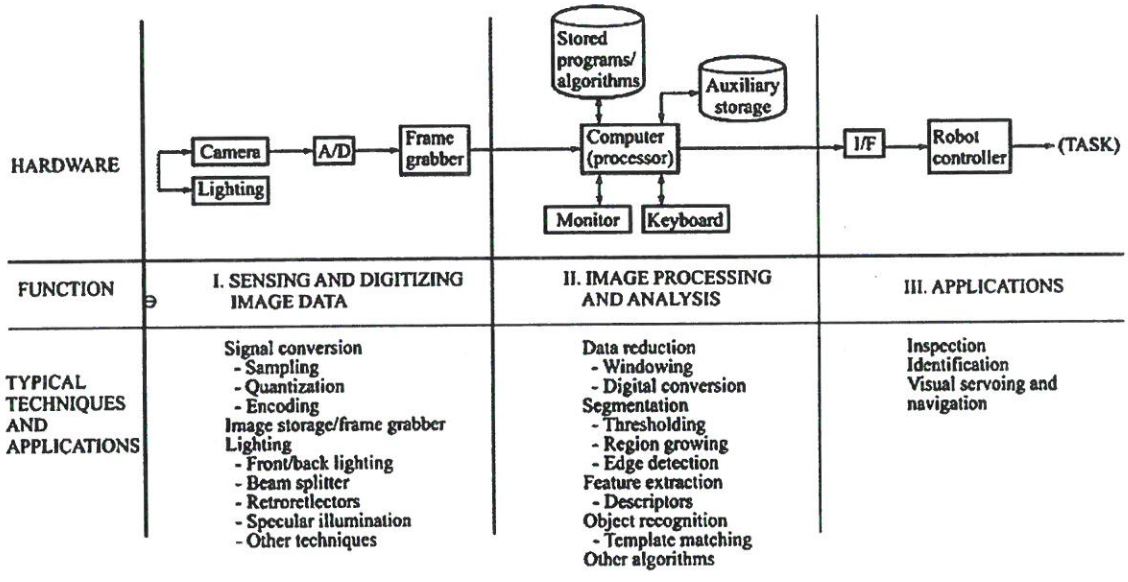
➢ Simulation-based Programming

- Uses dedicated robot simulation software (e.g., RoboDK, ABB RobotStudio, FANUC ROBOGUIDE, Siemens Process Simulate).
- The entire robot cell (robot, tools, fixtures, conveyors) is modelled in a virtual environment.
- The programmer defines the path, speed, and process in the simulator, checks for collisions, reachability, and cycle time, and then downloads the program to the real robot.
- Advantage: No production stoppage, safe testing.
- Limitation: Requires powerful software and calibration to match real-world accuracy

10. Demonstrate various functions of machine vision system. 10 M

Ans. A machine vision system acts as the "eyes" and "brain" of a robot, allowing it to interpret visual data to make autonomous decisions. In an industrial environment, these functions are typically performed in a high-speed, non-contact manner to ensure efficiency and accuracy.

The various functions of a machine vision system can be categorized as follows:



1. Sensing and Imaging

This is the foundational step where the system captures the physical image of the object.

- **Image Acquisition:** The system uses a specialized camera and lighting to capture a high-quality image of the workpiece.
- **Digitization:** The analog light signals are converted into digital pixels (values) that the computer can process.

2. Image Processing and Analysis

Once the image is captured, the software analyses the pixels to extract meaningful information.

- **Pre-processing:** The system enhances the image by removing "noise" or increasing contrast to make features stand out.
- **Feature Extraction:** The software identifies specific edges, holes, colors, or textures that define the object.

3. Applications

In a production environment, machine vision performs these specific tasks:

- **Object Identification and Recognition:** The system distinguishes between different parts on a conveyor belt by comparing their features to a stored database.
    - *Example:* Identifying whether a part is a Bolt-A or Bolt-B based on its shape.
- **Position and Orientation Detection:** It calculates the exact X, Y, Z coordinates and the angular rotation of a part.
    - *Function:* This tells the robot exactly how to orient its gripper to pick up the object.
- **Automated Inspection (Quality Control):** This is one of the most common functions, where the system checks for defects.
    - *Examples:* Detecting cracks, checking if a cap is properly sealed on a bottle, or ensuring all components are present in an assembly.
- **Measurement and Gauging:** The system acts as a high-precision digital caliper.
    - *Function:* It calculates the distance between two points on an object to ensure it meets engineering tolerances.
- **Navigation and Guidance:** For mobile robots or high-precision tasks like welding, the system provides real-time "steering" data.
    - *Function:* It guides the robot tool along a specific path or seam.

4. Decision Making and Execution

The final step is the output where the system communicates with the robot controller.

- **Logic Evaluation:** Based on the analysis (e.g., "Part is defective"), the system makes a pass/fail decision.
- **Output Signal:** The system sends a signal to the robot or a pneumatic ejector to take action, such as removing the defective part from the line.

11. Explain the sensing and digitizing function in machine vision. 10 M

Ans. Image sensing requires some type of image formation device such as a camera and a digitizer which stores a video frame in the computer memory. The sensing and digitizing functions can be divided into several steps. The initial step involves capturing the image of the scene with the vision camera. The image consists of relative light intensities corresponding to the various portions of the scene. These light intensities are continuous analogue values which must be sampled and converted into a digital form.

The second step, digitizing, is achieved by an analog-to-digital (A/D) converter. The A/D converter is either a part of a digital video camera or the front end of a frame grabber. The choice is dependent on the type of hardware in the system. The frame grabber, representing the third step, is an image storage and computation device which stores a given pixel array. The frame grabber can vary in capability from one which simply stores an image to significant computational capability. In the more powerful frame grabbers, thresholding, windowing, and histogram modification calculations can be carried out under computer control. The stored image is then subsequently processed and analysed by the combination of the frame grabber and the vision controller.

Imaging Devices

There are a variety of commercial imaging devices available. Camera technologies available include the older black-and-white vidicon camera, and the newer, second-generation, solid state cameras. Solid state cameras used for robot vision include charge-coupled devices (CCD), charge injection devices (CID), and silicon bipolar sensor cameras.

Lighting Techniques

An essential ingredient in the application of machine vision is proper lighting. Good illumination of the scene is important because of its effect on the level of complexity of image processing algorithms required. Poor lighting makes the task of interpreting the scene more difficult. Proper lighting techniques should provide high contrast and minimize specular reflections and shadows unless specifically designed into the system. The basic types of lighting devices used in machine vision may be grouped into the following categories:

- Diffuse surface devices Examples of diffuse surface illuminators are the typical fluorescent lamps and light tables.
- Condenser projectors A condenser projector transforms an expanding light source into a condensing light source. This is useful in imaging optics.
- Flood or spot projectors Flood lights and spot lights are used to illuminate surface areas.
- Collimators are used to provide a parallel beam of light on the subject.
- Imagers such as slide projectors and optical enlargers form an image of the target at the object plane.

Analog-to-Digital Signal Conversion

For a camera utilizing the vidicon tube technology it is necessary to convert the analog signal for each pixel into a digital form. The analog-to-digital (A/D) conversion process involves taking an analog input voltage signal and producing an output that represents the voltage, signal in the digital memory of a computer. A/D conversion consists of three phases: sampling, quantization, and encoding.

Sampling: A given analog signal is sampled periodically to obtain a series of discrete time analog signals. By setting a specified sampling rate, the analog signal can be approximated by the sampled digital outputs. How well we approximate the analog signal is determined by the sampling rate of the A/D converter. The sampling rate should be at least twice the highest frequency in the video signal if we wish to reconstruct that signal exactly.

Quantization: Each sampled discrete time voltage level is assigned to a finite number of defined amplitude levels. These amplitude levels correspond to the gray scale used in the system. The predefined amplitude levels are characteristic to a particular A/D converter and consist of a set of discrete values of voltage levels.

Encoding: The amplitude levels that are quantized must be changed into digital code. This process, termed encoding, involves representing an amplitude level by a binary digit sequence. The ability of the encoding process to distinguish between various amplitude levels is a function of the spacing of each quantization level.