

**COURSE OBJECTIVES**

The main learning objective of this course is to prepare the students for:

1. To learn and understand generalized co-ordinates, Jacobian matrix Mass Distribution and other fundamental equations.
2. To understand Lagrangian and Hamiltonian mechanics
3. To understand nonlinearities in control system
4. To Understand various force control strategies
5. To understand various concepts in linearizing a no linear signal.

**UNIT I ROBOT FORCE MODELS****9**

Generalized co-ordinates - Generalized Forces - Equation of Motions – Static Forces in Manipulators - Jacobian matrix - Jacobians in The Force Domain - Cartesian Transformation of Velocities and Static Forces - Acceleration of A Rigid Body – Non rigid Body.

**UNIT II ROBOT DYNAMICS****9**

General Expressions for Kinetic and Potential Energy - Kinetic Energy for an n-Link Robot - Potential Energy for an n-Link Robot - Equations of Motion -Lagrangian Multiplier - Langrage's Equation.

**UNIT III ROBOT CONTROL SYSTEM****9**

Functions of controller and power amplifier. Joint actuators- stepper motor, servo motor. Control Schemes: PID control scheme – Position and force control schemes. Robotic sensors and its classification, Internal sensors – Position, velocity, acceleration and force information, External Sensors – Contact sensors-Limit switches, piezoelectric, pressure pads, Non-contact sensors – Range sensors, Vision sensor- robotic vision system.

**UNIT IV CONTROL OF MANIPULATORS****9**

Linear Time Varying and Linearization – Input and Output Stability - Background: The Frobenius Theorem - Single-Input Systems. Introduction to nonlinear system – time varying systems - multi-input, multi-output control systems - practical considerations - current industrial - robot control systems

**UNITV FORCE CONTROL****9**

Constrained Dynamics - Static Force/Torque Relationships - Constraint Surfaces - Natural and Artificial Constraints - Network Models and Impedance - Impedance Operators - Classification of Impedance Operators.

**TOTAL: 45 PERIODS****COURSE OUTCOMES:**

At the end of the course the students would be able to

- CO1 :** Describe generalized co-ordinates, Jacobian matrix Mass Distribution and equation of motion.
- CO2 :** Develop the static force model and inverse dynamic model of multi-degree of freedom (DOF) manipulator. Evaluate dynamics of robot using Lagrangian and Hamiltonian mechanics.
- CO3:** Describe the control architecture of robot manipulator
- CO4:** Evaluate linear and nonlinearities in dynamics of robot.

**CO5:** Develop the control strategies for robot system.

**CO6:** Evaluate the dynamics of the robots Systems.

**TEXT BOOKS:**

1. Mark W. Spong, Seth Hutchinson, M. Vidyasagar, “Robot Modeling and Control” , John Wiley & Sons, Inc 2005.
2. John J. Craig, “Introduction to Robotics – Mechanics and control”, 3<sup>rd</sup> edition, Prentice hall, 2005.

**REFERENCE BOOKS:**

1. Groover, M.P., Weis, M., Nagel, R.N. and Odrey, N.G., “Industrial Robotics Technology, Programming and Applications”, McGraw-Hill, Int., 1986.
2. K.S. Fu, Gonzalez, R.C. and Lee, C.S.G., “Robotics Control, Sensing, Vision and Intelligence”, McGraw Hill, 1987.
3. Saeed B. Niku, “Introduction to Robotics: Analysis, Control, Applications”, 2<sup>nd</sup> edition, John Wiley & sons, Inc., 2011
4. Klafter, R.D., Chmielewski, T.A. and Negin, M., “Robotics Engineering – An Integrated Approach”, Prentice-Hall of India Pvt. Ltd., 1984.

## ROBOT DYNAMICS AND CONTROL (U23RAT61)

### UNIT I: ROBOT FORCE MODELS

#### Part A

1. Define generalized coordinates.

Answer: Generalized coordinates are a set of independent parameters that uniquely define the configuration of a mechanical system, reducing the number of variables needed to describe its motion.

2. What are generalized forces?

Answer: Generalized forces are forces associated with generalized coordinates, representing the work done per unit displacement in the direction of each generalized coordinate.

3. Write the equation of motion for a rigid body.

Answer:  $F = ma$  (translational) and  $\tau = I\alpha$  (rotational), where  $F$  is force,  $m$  is mass,  $a$  is acceleration,  $\tau$  is torque,  $I$  is moment of inertia, and  $\alpha$  is angular acceleration.

4. Define static forces in manipulators.

Answer: Static forces in manipulators refer to the forces and torques required at the joints to maintain equilibrium when the manipulator is holding a load without motion.

5. What is a Jacobian matrix in robotics?

Answer: The Jacobian matrix relates joint velocities to end-effector velocities in Cartesian space, representing the differential kinematics of a manipulator.

6. State the significance of Jacobians in the force domain.

Answer: Jacobians in the force domain relate forces/torques at the end-effector to equivalent joint torques using the transpose of the Jacobian:  $\tau = J^T F$ .

7. What is Cartesian transformation of velocities?

Answer: It is the process of converting joint space velocities to end-effector velocities in Cartesian coordinates using the Jacobian matrix:  $v = J(q)\dot{q}$ .

8. Define acceleration of a rigid body.

Answer: Acceleration of a rigid body includes both linear acceleration of its center of mass and angular acceleration about its center of mass.

9. What distinguishes a non-rigid body from a rigid body?

Answer: A non-rigid body can deform under applied forces, changing its shape, whereas a rigid body maintains fixed distances between all its points.

10. Write the relationship between joint torques and end-effector forces.

Answer:  $\tau = J^T(q)F$ , where  $\tau$  is joint torque vector,  $J^T$  is transpose of Jacobian, and  $F$  is end-effector force vector.

11. What is the degree of freedom (DOF) of a manipulator?

Answer: DOF is the number of independent joint variables required to specify the complete configuration of a manipulator.

12. Define virtual work principle.

Answer: The principle states that for a system in equilibrium, the total virtual work done by all forces during any virtual displacement is zero.

13. What is the role of the Jacobian in singularity analysis?

Answer: The Jacobian helps identify singular configurations where the manipulator loses one or more degrees of freedom in Cartesian space ( $\det(J) = 0$ ).

14. Define homogeneous transformation matrix.

Answer: A 4x4 matrix that represents both rotation and translation between two coordinate frames in 3D space.

15. What is the difference between forward and inverse statics?

Answer: Forward statics computes end-effector forces from joint torques; inverse statics computes required joint torques for desired end-effector forces.

16. State D'Alembert's principle.

Answer: It states that the sum of applied forces and inertial forces for a dynamic system is zero, allowing dynamic problems to be treated as static equilibrium problems.

17. What is a wrench in robotics?

Answer: A wrench is a 6-dimensional vector combining force and torque components acting on a rigid body in 3D space.

18. Define twist in robot kinematics.

Answer: A twist is a 6-dimensional vector representing the linear and angular velocity of a rigid body in spatial motion.

19. What is the physical meaning of Jacobian transpose?

Answer: The Jacobian transpose maps Cartesian forces at the end-effector to equivalent joint torques, enabling force control and static analysis.

20. Why is acceleration analysis important in robot dynamics?

Answer: Acceleration analysis is essential for computing inertial forces, designing controllers, and ensuring accurate trajectory tracking in dynamic operations.

**Part B:**

1. Derive the relationship between joint space velocities and Cartesian space velocities using the Jacobian matrix. Explain its significance in robot control.
2. Explain the concept of generalized coordinates and generalized forces with suitable examples from robotic manipulators. Derive the equation of motion using these concepts.
3. Discuss static force analysis in manipulators. Derive the expression for joint torques required to balance an external force at the end-effector using the Jacobian transpose.
4. Explain Cartesian transformation of velocities and static forces. How are these transformations used in robot motion planning and force control?
5. Derive the acceleration equations for a rigid body in spatial motion. Discuss the importance of acceleration analysis in robot dynamics and control.
6. Compare and contrast rigid body and non-rigid body dynamics. What additional considerations are needed when modeling flexible manipulators?
7. Explain the role of Jacobian matrix in singularity analysis. How do singular configurations affect robot performance and how can they be avoided?
8. Discuss the complete force model of a robotic manipulator including gravitational, inertial, Coriolis, and external forces. Derive the general dynamic equation.

## UNIT II: ROBOT DYNAMICS

### Part A:

1. Write the general expression for kinetic energy of a rigid body.

Answer:  $T = \frac{1}{2}mv^T v + \frac{1}{2}\omega^T I \omega$ , where  $m$  is mass,  $v$  is linear velocity,  $\omega$  is angular velocity, and  $I$  is inertia tensor.

2. Define potential energy in robotic systems.

Answer: Potential energy is the energy stored due to position in a gravitational field:  $V = mgh$ , where  $h$  is height of center of mass.

3. What is the Lagrangian function?

Answer: The Lagrangian  $L$  is defined as the difference between kinetic and potential energy:  $L = T - V$ .

4. State Lagrange's equation of motion.

Answer:  $d/dt(\partial L/\partial \dot{q}_i) - \partial L/\partial q_i = \tau_i$ , where  $q_i$  are generalized coordinates, and  $\tau_i$  are generalized forces/torques.

5. What is the significance of kinetic energy expression for an n-link robot?

Answer: It accounts for coupled motion between links, including translational and rotational energy of each link, essential for accurate dynamic modeling.

6. Define potential energy for an n-link robot.

Answer: Total potential energy is the sum of gravitational potential energies of all links:  $V = \sum m_i g h_i$ , where  $h_i$  is height of each link's center of mass.

7. What are Lagrangian multipliers used for?

Answer: Lagrangian multipliers are used to incorporate constraint equations into the Lagrangian formulation for systems with holonomic constraints.

8. Write the dynamic equation of an n-link manipulator.

Answer:  $M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau$ , where  $M$  is inertia matrix,  $C$  represents Coriolis/centrifugal terms,  $G$  is gravity vector, and  $\tau$  is joint torque.

9. What does the inertia matrix  $M(q)$  represent?

Answer:  $M(q)$  is a symmetric, positive-definite matrix that relates joint accelerations to inertial forces, dependent on manipulator configuration.

10. Define Coriolis and centrifugal forces in robot dynamics.

Answer: Coriolis forces arise from interaction between joint velocities; centrifugal forces result from rotational motion, both appearing in the  $C(q, \dot{q})\dot{q}$  term.

11. What is the gravity vector  $G(q)$ ?

Answer:  $G(q)$  represents joint torques required to counteract gravitational forces on each link, dependent on manipulator configuration.

12. State the properties of the robot dynamic equation.

Answer: (i)  $M(q)$  is symmetric and positive definite, (ii)  $\dot{M} - 2C$  is skew-symmetric, (iii) dynamics are linear in inertial parameters.

13. What is recursive Newton-Euler formulation?

Answer: An efficient  $O(n)$  algorithm for computing inverse dynamics by recursively propagating velocities/accelerations forward and forces/torques backward.

14. Differentiate between forward and inverse dynamics.

Answer: Forward dynamics computes accelerations from torques; inverse dynamics computes required torques for desired motion.

15. Why is the Lagrangian method preferred for robot dynamics?

Answer: It systematically handles complex multi-body systems using energy methods, avoiding explicit constraint forces and providing compact equations.

16. What is the role of the Christoffel symbols in robot dynamics?

Answer: Christoffel symbols help compute the Coriolis and centrifugal matrix  $C(q, \dot{q})$  from the inertia matrix  $M(q)$ .

17. Define configuration space in robotics.

Answer: Configuration space is the space of all possible joint positions ( $q$ ) that define the robot's posture.

18. What is the significance of the skew-symmetric property  $(\dot{M} - 2C)$ ?

Answer: This property is crucial for proving stability in adaptive and robust control laws, enabling energy-based controller design.

19. How is potential energy affected by manipulator configuration?

Answer: As joint angles change, the height of each link's center of mass changes, altering gravitational potential energy and required joint torques.

20. What computational advantages does the Lagrangian formulation offer?

Answer: It provides systematic derivation, handles constraints elegantly, and yields equations suitable for control design and parameter identification.

### Part B:

1. Derive the general expressions for kinetic and potential energy of an n-link robotic manipulator. Explain how these energies are used in Lagrangian formulation.
2. Using Lagrange's equation, derive the dynamic model of a 2-link planar manipulator. Identify the inertia, Coriolis, and gravity terms.
3. Explain the recursive Newton-Euler algorithm for inverse dynamics. Compare its computational efficiency with the Lagrangian method.
4. Discuss the properties of the robot dynamic equation  $M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau$ . Prove the skew-symmetric property of  $(\dot{M} - 2C)$ .
5. Derive the equations of motion for a single-link robot arm using both Newton-Euler and Lagrangian methods. Compare the approaches.
6. Explain the concept of Lagrangian multipliers in constrained robotic systems. Derive the modified Lagrange's equation with holonomic constraints.
7. Discuss parameter identification in robot dynamics. How can the linear-in-parameters property of dynamic equations be exploited for adaptive control?
8. Analyze the computational complexity of different dynamic formulation methods (Lagrangian, Newton-Euler, Kane's method). Which is most suitable for real-time control?

## UNIT III: ROBOT CONTROL SYSTEM

### Part A

1. What are the functions of a controller in robotics?

Answer: Controllers compute actuator commands to minimize error between desired and actual robot behavior, ensuring stability, accuracy, and performance.

2. Define power amplifier in robot control.

Answer: A power amplifier converts low-power control signals into high-power electrical signals to drive motors and actuators.

3. What is a stepper motor? State one advantage.

Answer: A stepper motor moves in discrete angular steps; advantage: precise open-loop position control without feedback sensors.

4. What is a servo motor? How does it differ from a stepper motor?

Answer: Servo motors use closed-loop feedback for precise control of position/speed; unlike steppers, they provide higher torque at speed and better dynamic response.

5. Write the PID control law.

Answer:  $u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}$ , where  $e(t)$  is error, and  $K_p$ ,  $K_i$ ,  $K_d$  are proportional, integral, derivative gains.

6. What is position control in robotics?

Answer: Position control regulates joint or end-effector positions to follow desired trajectories using feedback from position sensors.

7. Define force control scheme.

Answer: Force control regulates contact forces between robot and environment, essential for tasks like assembly, polishing, or human-robot interaction.

8. Classify robotic sensors.

Answer: Sensors are classified as internal (proprioceptive: position, velocity, force) and external (exteroceptive: vision, range, tactile).

9. What information do internal sensors provide?

Answer: Internal sensors measure joint position, velocity, acceleration, and motor current/force for feedback control and state estimation.

10. Give two examples of contact sensors.

Answer: Limit switches and piezoelectric sensors detect physical contact for collision avoidance or tactile feedback.

11. What is a pressure pad sensor?

Answer: A pressure pad measures distributed contact forces over a surface, used in grippers for object detection and grasp force control.

12. Define range sensors in robotics.

Answer: Range sensors (e.g., ultrasonic, LiDAR) measure distance to objects for navigation, obstacle avoidance, and environment mapping.

13. What are the components of a robotic vision system?

Answer: Camera, lighting, image acquisition hardware, processing algorithms, and software for object recognition, positioning, and inspection.

14. What is the role of encoders in robot control?

Answer: Encoders provide precise measurement of joint position and velocity for feedback control, enabling accurate trajectory tracking.

15. Differentiate between absolute and incremental encoders.

Answer: Absolute encoders provide unique position code at any angle; incremental encoders output pulses relative to a reference point.

16. What is impedance control?

Answer: Impedance control regulates the dynamic relationship between robot motion and contact forces, defining desired mass-spring-damper behavior.

17. Why is PID control widely used in robotics?

Answer: PID is simple, robust, and effective for linear systems; it provides good tracking performance with proper gain tuning.

18. What are the limitations of PID control in robotics?

Answer: PID struggles with nonlinear dynamics, coupling between joints, and varying payloads; may require gain scheduling or advanced control.

19. Define hybrid position/force control.

Answer: Hybrid control simultaneously regulates position in unconstrained directions and force in constrained directions using task-space decomposition.

20. What is the significance of sensor fusion in robotics?

Answer: Sensor fusion combines data from multiple sensors to improve accuracy, reliability, and robustness of state estimation and control.

### **Part B:**

1. Explain the architecture of a robot control system including controller, power amplifier, and actuators. Discuss the signal flow from command to motion.
2. Compare stepper motors and servo motors for robotic applications. Discuss their working principles, advantages, limitations, and suitable applications.
3. Derive the PID control law and explain the role of each term (P, I, D). Discuss tuning methods and practical implementation issues in robot control.
4. Explain position and force control schemes with block diagrams. When is each scheme preferred? Discuss challenges in switching between them.
5. Classify robotic sensors with examples. Explain the working principles and applications of internal sensors (encoders, resolvers) and external sensors (vision, LiDAR).
6. Discuss the design and implementation of a robotic vision system. What are the key processing steps for object recognition and pose estimation?
7. Explain hybrid position/force control strategy. How are natural and artificial constraints handled? Derive the control law for a simple task.

8. Discuss practical considerations in implementing robot control systems: sampling rate, computational delay, sensor noise, actuator saturation, and safety.

## UNIT IV: CONTROL OF MANIPULATORS

### Part A

1. Define linear time-varying (LTV) systems.

Answer: LTV systems have state-space matrices that vary with time:  $\dot{x} = A(t)x + B(t)u$ , requiring time-dependent analysis and control design.

2. What is linearization in control systems?

Answer: Linearization approximates a nonlinear system by a linear model around an operating point using Taylor series expansion for simplified analysis.

3. Define input stability.

Answer: Input stability (BIBO) means bounded inputs produce bounded outputs; essential for predictable system behavior under external commands.

4. Define output stability.

Answer: Output stability ensures system outputs converge to desired values or remain bounded despite disturbances and modeling errors.

5. State the Frobenius theorem in control context.

Answer: Frobenius theorem provides conditions for integrability of differential forms, used in feedback linearization and nonlinear control design.

6. What characterizes a single-input system?

Answer: A single-input system has one control input variable; analysis and design are simpler, often serving as foundation for multi-input extensions.

7. Define nonlinear systems in robotics.

Answer: Nonlinear systems have dynamics where outputs are not proportional to inputs, exhibiting phenomena like saturation, hysteresis, or coupling.

8. What are time-varying systems?

Answer: Time-varying systems have parameters or structure that change with time, requiring adaptive or gain-scheduled control strategies.

9. Define MIMO control systems.

Answer: Multi-Input Multi-Output systems have multiple control inputs and measured outputs, requiring multivariable control techniques for decoupling.

10. What are practical considerations in robot control implementation?

Answer: Sampling rate, computational load, sensor noise, actuator limits, communication delays, and safety constraints must be addressed.

11. Describe current industrial robot control systems.

Answer: Industrial robots typically use hierarchical control: trajectory planner → joint-space controller → motor drives, with PID or computed torque control.

12. What is feedback linearization?

Answer: Feedback linearization uses nonlinear state feedback to transform a nonlinear system into an equivalent linear system for easier control design.

13. Define Lyapunov stability.

Answer: A system is Lyapunov stable if, for any small initial deviation, the state remains close to equilibrium; asymptotic stability requires convergence.

14. What is computed torque control?

Answer: Computed torque control uses dynamic model inversion to linearize and decouple robot dynamics, enabling independent joint control via PD loops.

15. Why is robustness important in robot control?

Answer: Robustness ensures performance despite model uncertainties, parameter variations, and external disturbances, critical for reliable operation.

16. What is adaptive control in robotics?

Answer: Adaptive control adjusts controller parameters online to compensate for unknown or changing system dynamics, improving performance under uncertainty.

17. Define sliding mode control.

Answer: Sliding mode control uses discontinuous control to force system states onto a predefined sliding surface, providing robustness to matched uncertainties.

18. What is gain scheduling?

Answer: Gain scheduling varies controller gains based on operating conditions (e.g., configuration, speed) to maintain performance across the workspace.

19. Explain the concept of passivity in robot control.

Answer: Passivity ensures energy dissipation, enabling stable interaction with environments and humans without complex modeling.

20. What role does the Jacobian play in operational space control?

Answer: The Jacobian maps joint-space dynamics to task-space, enabling direct control of end-effector motion and forces in Cartesian coordinates.

### **Part B**

1. Explain linearization techniques for nonlinear robotic systems. Derive the linearized model of a manipulator around a nominal trajectory and discuss its limitations.
2. Discuss input-output stability analysis for robotic systems. Explain BIBO stability, Lyapunov stability, and their relevance to robot controller design.
3. Explain the Frobenius theorem and its application in feedback linearization of robotic manipulators. Derive conditions for exact linearization.
4. Compare single-input and multi-input control strategies for robots. Discuss challenges in MIMO control and techniques for decoupling joint dynamics.
5. Analyze practical considerations in implementing industrial robot control systems: real-time constraints, sensor integration, safety protocols, and fault tolerance.
6. Explain computed torque control with block diagram. Derive the control law and discuss its advantages over independent joint PID control.
7. Discuss robust and adaptive control methods for manipulators with uncertain dynamics. Compare sliding mode, adaptive, and robust PID approaches.
8. Explain operational space control framework. How does it enable intuitive task-level control? Derive the operational space dynamic equation.

## **UNIT V: FORCE CONTROL**

### **Part A**

1. Define constrained dynamics in robotics.

Answer: Constrained dynamics describes robot motion subject to environmental constraints (e.g., surface contact), requiring modified equations of motion.

2. Write the static force/torque relationship at contact.

Answer:  $\tau = J^T(q)F$ , where joint torques  $\tau$  balance end-effector contact forces  $F$  through the Jacobian transpose.

3. What are constraint surfaces?

Answer: Constraint surfaces define geometric boundaries (e.g., plane, curve) that restrict robot motion, modeled as holonomic or nonholonomic constraints.

4. Define natural constraints.

Answer: Natural constraints are physically imposed by the environment (e.g., no penetration, friction limits), limiting feasible motions and forces.

5. Define artificial constraints.

Answer: Artificial constraints are control-imposed specifications (e.g., desired force, trajectory) that guide robot behavior within natural constraints.

6. What is impedance in robotic control?

Answer: Impedance defines the dynamic relationship between motion and force:  $F = M_e \ddot{q} + B_e \dot{q} + K_e q$ , specifying desired mechanical behavior.

7. Define impedance operators.

Answer: Impedance operators are mathematical representations (mass, damping, stiffness matrices) that shape robot's dynamic response to contact.

8. Classify impedance operators.

Answer: Classified as: (i) admittance (motion output for force input), (ii) impedance (force output for motion input), (iii) hybrid combinations.

9. What is admittance control?

Answer: Admittance control computes desired motion from measured contact forces using a reference model, suitable for compliant interaction tasks.

10. Differentiate impedance and admittance control.

Answer: Impedance: force output for motion input (robot behaves like spring-damper);  
Admittance: motion output for force input (robot yields to forces).

11. What is hybrid force/position control?

Answer: Hybrid control independently regulates position in unconstrained directions and force in constrained directions using selection matrices.

12. Define selection matrix in force control.

Answer: A diagonal matrix  $S$  that selects which task-space directions are force-controlled ( $S=1$ ) vs. position-controlled ( $S=0$ ).

13. What is explicit force control?

Answer: Explicit force control directly uses force sensor feedback in the control loop to regulate contact forces to desired values.

14. What is implicit force control?

Answer: Implicit force control achieves force regulation through position control with compliant reference trajectories or impedance shaping.

15. Why is force control challenging in robotics?

Answer: Challenges include sensor noise, contact instability, model uncertainty, and the need for high-bandwidth force loops with safety guarantees.

16. Define contact stability.

Answer: Contact stability ensures that interaction forces remain bounded and converge during contact tasks, avoiding oscillations or loss of contact.

17. What role does the environment model play in force control?

Answer: Environment models (stiffness, geometry) enable predictive force control, feedforward compensation, and stable interaction planning.

18. Explain the concept of virtual fixtures.

Answer: Virtual fixtures are software-imposed constraints that guide or restrict motion/force in teleoperation or collaborative tasks for safety and precision.

19. What is force reflection in haptic interfaces?

Answer: Force reflection renders contact forces to the human operator through a haptic device, enabling intuitive teleoperation and training.

20. How is impedance control implemented in joint space?

Answer: Joint-space impedance control computes desired joint torques:  $\tau = M(q)[\ddot{q}_d + K_d(\dot{q}_d - \dot{q}) + K_p(q_d - q)] + C\dot{q} + G$ , shaping dynamic response.

## Part B

1. Explain constrained dynamics of robotic manipulators. Derive the equations of motion for a robot in contact with a rigid surface using Lagrange multipliers.

2. Discuss static force/torque relationships in manipulators. How does the Jacobian transpose enable force mapping? Analyze force transmission in singular configurations.

3. Explain natural and artificial constraints with examples. How are they used in task specification for assembly or machining operations?

4. Develop network models for robot-environment interaction. Explain how impedance operators represent mechanical behavior and facilitate stable contact.
5. Classify impedance operators and discuss their design considerations. How do mass, damping, and stiffness parameters affect interaction performance?
6. Compare impedance control, admittance control, and hybrid force/position control. Discuss suitability for different applications (grinding, assembly, rehabilitation).
7. Design a force control strategy for a robot performing surface polishing. Address trajectory generation, force regulation, and stability considerations.
8. Discuss practical implementation issues in force control: force sensor selection, filtering, contact detection, transition between free and constrained motion, and safety.