Mobile and Autonomous Robotics - ESA Answers

## 1.a. Discuss the importance of technical, social, and ethical challenges in the development of autonomous Robots, with specific examples for each challenge.

The development and deployment of autonomous robots have revolutionized various industries. However, the implementation is not without its challenges. These challenges can be categorized into technical, social, and ethical domains.  
  
Technical Challenges:  
1. Perception and Sensing: Robots must accurately perceive their environment using sensors like LiDAR, cameras, IMUs.  
2. Localization and Mapping: Real-time SLAM requires computational resources and accuracy.  
3. Path Planning and Control: Generating optimal paths avoiding obstacles in real time is complex.  
4. Power and Hardware Limitations: Limited battery life and processing power can restrict robot operation.  
  
Social Challenges:  
1. Human-Robot Interaction (HRI): Ensuring that robots communicate effectively and safely with humans.  
2. Job Displacement: Fear of robots replacing human labor in manufacturing, logistics, etc.  
3. Public Trust and Acceptance: People may fear or resist robots due to lack of understanding.  
  
Ethical Challenges:  
1. Privacy and Surveillance: Robots equipped with cameras and microphones may violate individual privacy.  
2. Decision-Making and Bias: AI-driven robots might exhibit bias due to flawed training data.  
3. Accountability and Liability: In case of an accident, it's unclear who is responsible.  
  
Conclusion: Addressing these challenges is crucial for safe and effective deployment of autonomous robots. Multidisciplinary collaboration is required to build robots that are technically sound, socially acceptable, and ethically aligned.

## 1.b. What is forward and inverse kinematics in robotics? Why is inverse kinematics important, and how does it work in the context of robot arm manipulators?

Kinematics is the study of motion without considering the forces that cause it. In robotics, it deals with the motion of links and joints of a robot.  
  
Forward Kinematics (FK): Calculates the position and orientation of the end-effector given the joint parameters.  
Inverse Kinematics (IK): Determines the joint parameters required to reach a desired end-effector position and orientation.  
  
IK is crucial because robots operate in Cartesian space but actuators are controlled in joint space. Efficient IK enables precise movement for tasks like picking objects.  
  
In robot arms, IK algorithms compute the required joint angles for a given hand position using analytical, numerical, or optimization-based methods.  
  
Conclusion: Forward and inverse kinematics are core concepts in robotics. Inverse kinematics is crucial for real-world tasks requiring precise end-effector control.

## 1.c. Explain the role and functionality of encoders in robotics. What factors should be considered when selecting an encoder for a specific application in robotics?

Encoders convert mechanical motion into electrical signals, allowing robots to track position, speed, and direction.  
  
Types:  
- Rotary Encoders: For angular motion (incremental, absolute)  
- Linear Encoders: For linear displacement  
- Optical Encoders: Use light interruption for pulse generation  
  
Functions in Robotics:  
- Motion control and feedback  
- Closed-loop system integration  
- Localization and odometry  
  
Selection Factors:  
- Resolution (CPR)  
- Environment (dust, moisture, etc.)  
- Mounting and size  
- Output type (analog/digital)  
- Cost and durability  
  
Conclusion: Encoders are vital for precise motion control in robots. Their selection depends on the application environment and system requirements.

## 1.d. Distinguish between active and passive sensors, and give examples of each type.

Active Sensors:  
- Emit their own energy and detect reflections.  
- Examples: LiDAR, RADAR, Ultrasonic  
  
Passive Sensors:  
- Detect naturally occurring signals.  
- Examples: Cameras, IR sensors, Thermometers  
  
Difference Summary:  
- Active sensors work in darkness, but consume more power.  
- Passive sensors are low-power but rely on external energy sources.  
  
Conclusion: Both sensor types are critical in robotics and are used together for robust sensing and perception.

## 2.a. What is the difference between locomotion and manipulation? Discuss the key issues and limitations affecting locomotion in robotic systems.

Locomotion: Movement of the entire robot (wheels, legs).  
Manipulation: Controlled motion of arms or effectors to interact with objects.  
  
Key Issues in Locomotion:  
- Terrain variability  
- Energy consumption  
- Stability (static/dynamic)  
- Kinematic constraints  
- Obstacle avoidance and path planning  
- Slip/skid  
  
Limitations:  
- Mechanical complexity  
- Sensor dependency  
- Power requirements  
  
Conclusion: Locomotion and manipulation are fundamental robotic capabilities. Locomotion in particular faces many real-world challenges in dynamic environments.

## 2.b. What is static and dynamic stability in a robot? Explain support polygon with example.

Static Stability: Robot remains balanced without moving (CoG within support polygon).  
Dynamic Stability: Balance maintained during motion, considering forces like inertia.  
  
Support Polygon: Area on ground enclosed by robot's contact points (e.g., legs or wheels). Stability is ensured if the projected CoG lies within this polygon.  
  
Example: A 4-legged robot has a rectangular support polygon. If it lifts one leg, it must shift weight to maintain balance.  
  
Conclusion: Stability is vital for safe robot operation. Support polygon is a foundational concept in robotic balance and motion planning.

## 2.c. Explain the concept of degrees of freedom (DOF) in robotics and describe the capabilities of robots with different DOF levels, specifically 2-DOF, 3-DOF, 5-DOF, and 6-DOF.

Degrees of Freedom (DOF): Number of independent movements a robot can perform.  
  
- 2-DOF: Planar movement (e.g., SCARA robot for 2D tasks)  
- 3-DOF: Adds vertical movement (e.g., Cartesian robot)  
- 5-DOF: Limited rotation capabilities (e.g., light-duty arms)  
- 6-DOF: Full spatial positioning and orientation (e.g., industrial robot arms)  
  
Applications range from basic positioning to precise tasks like surgery and welding.  
  
Conclusion: DOF defines a robot's flexibility. Higher DOFs offer greater control but increase mechanical and computational complexity.

## 2.d. Write four differences between legged and wheeled robots.

1. Terrain: Legged robots handle uneven terrain; wheeled robots need flat surfaces.  
2. Complexity: Legged robots are complex and harder to control; wheeled robots are simpler.  
3. Speed: Wheeled robots are faster; legged robots are slower but more adaptable.  
4. Energy: Legged robots consume more power; wheeled robots are more efficient.  
  
Conclusion: The choice between legged and wheeled platforms depends on terrain and application requirements.

## 3.a. What do optical encoders measure? How do they work? How does the sensor on the opposite side of the light source react when the encoder disk blocks the light beam?

Optical encoders measure rotational or linear motion, specifically position, speed, and direction.  
  
Working Principle:  
- A disk with transparent and opaque segments rotates between a light source and a photodetector.  
- Transparent areas let light through (HIGH signal), opaque areas block light (LOW signal).  
- As the disk spins, the sensor generates pulses representing movement.  
  
This pulse data helps compute motion characteristics. Optical encoders are key in robotics for motor feedback and accurate movement control.

## 3.b. What is corner detection in feature extraction? Explain Moravec’s corner detection algorithm with the help of a diagram. What is the improvement introduced by the Harris corner detector?

Corner detection identifies points in an image with sharp intensity changes in multiple directions.  
  
Moravec Algorithm:  
- Shifts a window around each pixel in 8 directions.  
- Computes SSD (sum of squared differences).  
- A pixel is a corner if SSD is high in all directions.  
  
Limitations: Only checks discrete shifts, not smooth or accurate.  
  
Harris Improvement:  
- Uses image gradients and an autocorrelation matrix for continuous, more robust corner detection.  
- Corner response function: R = det(M) - k(trace(M))^2  
- Rotation-invariant, more accurate, and less sensitive to noise.  
  
Conclusion: Harris corner detector improves accuracy and robustness for robotic vision systems.

## 3.c. Define the IMU and specify the number of degrees of freedom it typically estimates. Provide a schematic representation of its block diagram.

IMU (Inertial Measurement Unit) is a sensor module used to measure acceleration, orientation, and angular velocity.  
  
Typical DOF Estimated:  
- 3 from accelerometers (X, Y, Z)  
- 3 from gyroscopes (Roll, Pitch, Yaw)  
- Optional magnetometer adds 3 more (heading) → total 9-DOF  
  
Block Diagram:  
- Sensors: Accelerometer + Gyroscope (+ Magnetometer)  
- Sensor Fusion (e.g., Kalman Filter)  
- Outputs: Orientation (Euler angles or Quaternion), Acceleration  
  
IMUs are essential for navigation, control, and stabilization in mobile robots and drones.

## 3.d. What is dead reckoning? Which sensor is used for dead reckoning?

Dead reckoning estimates current position based on previous location using internal measurements.  
  
How it Works:  
- Tracks direction and distance traveled from a known starting point.  
- Integrates velocity and orientation over time.  
  
Sensors Used:  
- Wheel Encoders (measure rotation and distance)  
- IMUs (measure acceleration and orientation)  
  
Limitations:  
- Accumulated errors over time due to drift, wheel slip, or sensor noise.  
  
Conclusion: Dead reckoning provides basic position tracking, often used alongside SLAM or GPS for better accuracy.

## 4.a. Explain two types of Bug algorithm and discuss how it enables a robot to navigate around obstacles to reach its target with the help of a diagram.

Bug 1 Algorithm:  
- Move toward goal.  
- On hitting an obstacle, follow its full boundary.  
- Resume movement from the point closest to the goal.  
  
Bug 2 Algorithm:  
- Define a straight M-line (start to goal).  
- On obstacle contact, follow boundary until a closer M-line point is found.  
- Resume path along M-line.  
  
Comparison:  
- Bug 2 is more efficient as it avoids full boundary traversal.  
  
Conclusion: Bug algorithms provide simple yet effective strategies for obstacle avoidance and path planning.

## 4.b. Define temporal decomposition in the context of robotic navigation and illustrate it with a generic navigation architecture diagram. Briefly explain the four interrelated trends that correlate with temporal decomposition.

Temporal decomposition splits navigation into layers based on decision frequency.  
  
Layers:  
1. Deliberative: Long-term planning (map, goal setting)  
2. Sequencing: Task coordination (action order)  
3. Reactive: Real-time responses (obstacle avoidance)  
  
Four Trends:  
1. Reactive behavior integration (fast, sensor-driven)  
2. Hierarchical architectures (layered control)  
3. Hybrid systems (planning + reactivity)  
4. Learning and adaptation (real-time improvement)  
  
Conclusion: This structure balances long-term objectives with immediate reaction, essential for modern autonomous robots.

## 4.c. Discuss any five key points of implementing Particle Filter SLAM for localization and mapping in robotics.

1. Particle Representation: Each particle encodes a hypothesis of robot pose and map.  
2. Motion Update: Control inputs predict new particle positions (with noise).  
3. Measurement Update: Particles are weighted based on sensor match quality.  
4. Resampling: Select particles with high weights to focus on likely positions.  
5. Map Update: Each particle updates its own map using sensor data.  
  
Conclusion: Particle Filter SLAM is powerful for navigating and mapping unknown environments under uncertainty.

## 4.d. What are the advantages of using reinforcement learning in legged robots and autonomous vehicles?

Advantages in Legged Robots:  
- Adaptive gaits for different terrains  
- Real-time balance and motion recovery  
- Eliminates need for hand-tuned controllers  
  
Advantages in Autonomous Vehicles:  
- Learns optimal driving strategies  
- Adapts to dynamic environments (e.g., traffic)  
- Learns from experience to improve over time  
  
Conclusion: Reinforcement learning provides adaptive, intelligent decision-making for complex robotic behaviors.