Here are the answers to the questions from the CAI3034N-September 2022 past year paper, based on general robotics knowledge and the concepts we have discussed using your notes.

**Question 1 (25 marks)**

**(a) There are a number of ways a robot can avoid running into obstacles. Describe two solutions that a robot can avoid running into obstacles. (8 marks)**

Here are two solutions a robot can use to avoid obstacles:

1. **Sense and Stop:** The simplest approach is for the robot to use proximity or distance sensors (like ultrasonic sensors, infrared sensors, or a laser rangefinder ) to detect if an obstacle is within a certain safety distance. If a sensor detects an obstacle too close, the robot immediately stops moving. This is a basic safety mechanism, effective for preventing collisions with detected obstacles, but it doesn't allow the robot to navigate *around* the obstacle.
2. **Sense and Navigate Around:** A more advanced solution involves detecting an obstacle and then using a local navigation or obstacle avoidance algorithm to plan a path around it. The robot uses sensor data (e.g., from LiDAR, cameras, or proximity sensors) to understand the shape and location of the obstacle and the available free space. It can then generate a temporary trajectory to steer away from the obstacle while ideally continuing towards its overall goal. (As discussed, algorithms might use simple rules like turning away from the obstacle direction or more complex methods).

**(b) Explain on the way that can a robot use path integration and landmarks to keep track of its position. (8 marks)**

A robot can use path integration and landmarks together to keep track of its position:

* **Path Integration (Odometry):** The robot starts from a known initial position. It then continuously estimates its change in position and orientation by integrating (adding up) its own movements. This is typically done by using sensors like wheel encoders to measure how far and fast its wheels have turned, and potentially an Inertial Measurement Unit (IMU) or compass to estimate heading changes. The robot updates its estimated position by adding the calculated displacement for each small movement step. (xt​=xt−1​+dcos(θ), yt​=yt−1​+dsin(θ)).
* **The Problem:** The main issue with path integration is that small errors in measuring distance or heading accumulate over time, causing the robot's estimated position to drift away from its actual position.
* **Using Landmarks for Correction:** To counteract this drift, the robot uses **landmarks**. These are distinctive, recognizable features in the environment (either natural like a tree or artificial like a road sign ). When the robot's sensors detect and recognize a known landmark, it can compare its *estimated* position relative to the landmark (based on path integration) with the landmark's *actual* known position in its map. This comparison allows the robot to calculate the error in its path integration estimate and **recalibrate** its position, correcting the accumulated drift. Good landmarks are detectable over a wide area, do not move, and are unique.

**(c) Describe with examples on the way that a mobile robot uses the following control methods to orient towards a landmark. (3 marks each)**

*(This question is identical to Question 4(c) from the January 2023 paper we discussed earlier).*

* **(i) Open-loop**
  + **Description:** The robot measures the direction to the landmark and calculates the required turn angle. It then executes a pre-calculated motor command (e.g., turn motors for a set duration or encoder count) without checking if it actually ended up facing the landmark.
  + **Example:** Robot sees landmark 90 degrees right. Commands a 90-degree turn and assumes success, not checking its final orientation.
* **(ii) Feed-forward**
  + **Description:** The robot calculates the target turn angle and adjusts the motor command based on a model of how its motors or the environment typically cause errors, aiming to compensate *before* executing the turn. It still doesn't measure the final orientation to correct.
  + **Example:** Robot needs to turn 90 degrees right. Model predicts an 88-degree actual turn from a 90-degree command. It commands a 92-degree turn instead, hoping to get closer to 90 degrees without checking the final result.
* **(iii) Feedback control**
  + **Description:** The robot continuously measures its orientation relative to the landmark (e.g., using a camera to track the landmark's position in the image). It calculates the error (difference between current and desired orientation) and uses this error to adjust its turning motion in a loop until the error is minimized and it is facing the landmark.
  + **Example:** Robot needs to face landmark. It sees landmark is 30 degrees left (error). Turns left. Checks camera: landmark is now 10 degrees left. Turns left less. Checks camera: landmark is 2 degrees right. Turns right slightly. Repeats until landmark is centered (error ~0).

**Question 2 (25 marks)**

**(a) Navigation and positioning of mobile robots with machine vision systems are usually carried out with natural or artificial landmarks. (i) Outline the process that would allow a robot to recognise landmarks of different shapes while wandering around its world. (4 marks)**

Based on the computer vision process we discussed:

1. **Data Acquisition/Pre-processing:** The robot uses a camera to capture images. These images are then pre-processed (e.g., sampled, color space transformed, normalized, background removed) to prepare them for analysis.
2. **Image Segmentation:** The processed image is segmented to identify distinct regions or potential objects. This involves classifying pixels (e.g., using thresholding) and grouping them into regions, from which features like color, area, and bounding box are computed.
3. **Feature Extraction (Shape):** For recognizing landmarks of different shapes, specific shape-based features would be extracted from the segmented regions. These could include properties of the region's boundary, moments, or fitting shapes like circles, squares, or polygons.
4. **Classification/Recognition:** The extracted shape features (along with potentially color or size features) are compared against a database or set of rules for known landmark shapes. The segmented region is classified as a specific landmark type if its features match those of a known landmark in the database/rules.

**(ii) Identify two potential problems and consider possible solution for the process described in Question 2 a(i) (8 marks)**

Based on general computer vision challenges and the notes:

1. **Problem:** **Variations in Lighting Conditions.** Changes in illumination (e.g., shadows, glare, different times of day) can drastically alter the appearance of landmark colors and shapes in the image, making recognition difficult.
   * **Possible Solution:** Use **color normalization** during pre-processing to make colors less sensitive to brightness changes. Use computer vision techniques like **local feature descriptors** (e.g., SIFT, SURF) that are designed to be more robust to illumination changes than simple color or shape outlines. Using **active vision** could also provide controlled illumination.
2. **Problem:** **Partial Obstruction or Changes in Viewpoint.** Landmarks may be partially blocked by other objects, or the robot might see them from unusual angles, making their shape or features appear different from the stored representation.
   * **Possible Solution:** Use **more robust feature extraction techniques** that can recognize objects from partial views or different perspectives. Employ **multiple viewpoints** or **stereo vision** to get 3D information, which is less sensitive to viewpoint changes than 2D shape. Implement **matching algorithms** that can tolerate partial matches or变形 shapes.

**(iii) Describe how you might use active vision to improve the performance. (4 marks)**

*(This part was not directly covered in your notes, but relates to the concept of active vision we discussed generally).*

You could use active vision to improve landmark recognition performance by:

1. **Controlled Illumination:** Instead of relying on ambient light, the robot could use a controlled light source (like an LED or structured light projector). This eliminates the problems caused by shadows, glare, and poor lighting conditions, ensuring consistent illumination of the landmark's surface for better feature extraction.
2. **Structured Light or Laser Scanning:** An active vision system could project a known pattern of light (structured light) or use a laser scanner to directly measure the 3D shape of the landmark. This provides accurate 3D data, which is much more reliable for recognizing shapes than analyzing 2D images, especially from different viewpoints or with partial occlusions.

**(b) Proprioception is an active field of research in robotic systems. (i) Define proprioception in the context of mobile robotics. (2 marks)**

* **Definition:** In the context of mobile robotics, **proprioception** refers to the robot's sense of its own body's state – its position, orientation, joint angles, motor speeds, and internal forces – without relying on external sensory information about the environment. It's the robot's internal awareness of its own configuration and movement.

**(ii) Explain the approach to use vision as proprioception. (3 marks)**

* **Vision as Proprioception:** Vision can be used as proprioception by placing cameras on the robot to **observe parts of the robot itself**. For example, a camera on a robot arm could look at the arm's joints or markers on its links to determine their angles. A mobile robot could use a camera looking at its wheels or chassis to estimate its own movement or vibration. The visual data provides feedback about the robot's internal state or motion.

**(iii) Besides vision, describe two other kinds of proprioceptive sensors which are commonly used in robotics. (4 marks)**

Besides vision, two other common proprioceptive sensors are:

1. **Encoders:** These are sensors attached to motors or joints that measure rotation (rotary encoders) or linear movement (linear encoders). They are used to determine joint angles, wheel rotations, speed, and distance traveled (used in odometry).
2. **Inertial Measurement Units (IMUs):** An IMU contains accelerometers and gyroscopes to measure linear acceleration and angular velocity. This data can be integrated over time to estimate the robot's orientation (pitch, roll, yaw) and changes in position.

**Question 3 (25 marks)**

**(a) Describe one main type of sensors used in wheel odometry. (2 marks)**

One main type of sensor used in wheel odometry is an **encoder**. Encoders are typically attached to the robot's wheels or motors to measure the amount of rotation.

**(b) Sketch an odometry-based navigation flowchart, and explain the way that a robot navigates in outdoor environment using wheel odometry. Note that the odometry-based navigation implements odometry and compass sensor for navigation. In the case that robot encounters an obstacle along its path, the robot avoids the detected obstacle according to the range data from the attached laser rangefinder. (10 marks)**

*(Note: As I cannot sketch a flowchart, I will describe the steps of the process as outlined in the question.)*

An odometry-based navigation process for an outdoor robot with odometry, a compass, and a laser rangefinder would typically follow these steps:

1. **Initialization:** The robot starts at a known initial position and orientation.
2. **Read Sensors:** The robot continuously reads data from its wheel encoders (for odometry) and its compass (for orientation). It also reads range data from its laser rangefinder.
3. **Estimate Position & Orientation (Odometry + Compass):**
   * Using the encoder data, the robot calculates its incremental movement (distance and rotation) based on wheel rotations. This is the core odometry calculation.
   * The compass data provides an estimate of the robot's absolute heading relative to magnetic North.
   * The robot combines the odometry (for relative movement) and the compass (to correct or refine the heading estimate) to update its estimated global position and orientation.
4. **Obstacle Detection:** The robot processes the range data from the laser rangefinder to detect if there are any obstacles within its path or immediate vicinity.
5. **Obstacle Avoidance (if needed):** If a laser rangefinder detects an obstacle, the robot temporarily suspends its direct path following. It uses the range data to determine the obstacle's position and the available free space. It then executes a local obstacle avoidance maneuver (e.g., turning away and moving around the obstacle).
6. **Path Following/Goal Seeking:** While not avoiding obstacles, the robot uses its estimated position and orientation (derived from odometry and compass) to follow a planned path towards its goal location.
7. **Loop:** The robot continuously repeats steps 2 through 6, sensing, updating its pose estimate, checking for obstacles, and navigating accordingly.

**(c) State two advantages and two disadvantages of odometry-based navigation technique stated in Question 3 (b). (8 marks)**

Based on the notes on Path Integration/Odometry:

* **Advantages:**
  1. **Provides continuous localization:** Odometry provides a constant update of the robot's position and orientation as it moves.
  2. **Relatively inexpensive and simple to implement:** Wheel encoders are common and calculating position based on wheel rotations is computationally straightforward.
  3. *(Additional based on general knowledge):* Works well indoors or in environments without external reference systems like GPS.
* **Disadvantages:**
  1. **Accumulation of errors (Drift):** Small errors in measuring wheel rotations or slippage accumulate over time, causing the estimated position to drift away from the true position. This is the primary disadvantage.
  2. **Sensitive to wheel slippage:** Errors are significantly increased on slippery or uneven surfaces where wheels may rotate without the corresponding linear motion.
  3. *(Relating to Q3b setup):* The compass can be affected by magnetic interference, adding error to the orientation estimate.

**(d) Visual odometry has been used as a complement to wheel odometry. Define the term visual odometry and explain the advantages of visual odometry over wheel odometry. (5 marks)**

* **Definition of Visual Odometry:** Visual odometry is the process of **estimating the robot's motion (change in position and orientation) using only the input from cameras**. It does this by tracking features or patterns in successive images and calculating the camera's (and thus the robot's) movement between frames.
* **Advantages of Visual Odometry over Wheel Odometry:**
  1. **Less susceptible to wheel slippage:** Visual odometry estimates motion based on what the robot *sees* in the environment, not just how its wheels are turning. Therefore, it is generally much more accurate than wheel odometry in environments where wheels might slip (e.g., on slippery floors, sand, rough terrain).
  2. **Provides richer information:** Camera data contains rich information about the environment, which can be used not only for odometry but also for tasks like mapping, object detection, and landmark recognition.

**Question 4 (25 marks)**

Consider the three-link gantry manipulator of Figure 1.

**(a) Redraw the kinematic diagram and assign the frames according to the Denavit-Hartenberg rules. Also, include the prismatic parameters on your diagram. (7 marks)**

*(Note: I cannot redraw the diagram or perform the visual assignment of frames according to Denavit-Hartenberg rules. This requires manual interpretation and drawing on the figure. However, I can describe the general approach for a gantry robot and explain what would be involved.)*

To answer this question, you would redraw the robot structure, representing each link as a line segment and each joint as an axis. Then, applying the Denavit-Hartenberg (DH) convention, you would:

1. Define a base frame (Frame 0) at the robot's base.
2. Define a coordinate frame (Fi​) for each link (i), typically located at or after Joint i.
3. Align the zi​ axis with the axis of motion of Joint i+1.
4. Align the xi​ axis along the common normal between the zi−1​ and zi​ axes.
5. Determine the four DH parameters (αi​, ai​, di​, θi​) that describe the geometric relationship between frame Fi−1​ and frame Fi​.
6. For this three-link gantry robot, which is a Cartesian robot, it has three prismatic joints (moving linearly). You would typically align the axes with the sliding directions. The prismatic parameters (di​ in standard DH if movement is along z, or ai​ or others depending on frame assignment) would be the variable distances along the prismatic joints.

Your diagram should clearly show the assigned coordinate frames (xi​,yi​,zi​) at each joint or link and indicate the variable prismatic parameters.

(b) For each frame of the manipulator, determine: (7 marks)

(i) the rotation matrix. (9 marks)

(ii) the translation vector. (9 marks)

*(Note: I cannot perform the specific mathematical derivation of the rotation matrices and translation vectors for each frame without the explicit DH parameters derived from the frame assignments in part (a). This is a calculation based on the geometric properties determined in the previous step.)*

However, I can explain the general process based on the Denavit-Hartenberg convention:

1. **Rotation Matrix (Ri−1i​):** For each link i, the rotation matrix Ri−1i​ describes the orientation of frame Fi​ relative to frame Fi−1​. Using the DH parameters (αi​, ai​, di​, θi​) derived in part (a), you construct this 3x3 matrix using standard formulas that involve rotations and translations based on the DH convention.
2. **Translation Vector (pi−1i​):** For each link i, the translation vector pi−1i​ describes the position of the origin of frame Fi​ relative to the origin of frame Fi−1​, expressed in the coordinates of frame Fi−1​. This 3x1 vector is also constructed using the DH parameters from part (a).

For a prismatic joint, one of the DH parameters (di​ or ai​, depending on the axis of the prismatic joint relative to the frame assignment) will be a variable representing the joint position, and this variable will appear in the translation vector and potentially the rotation matrix formula.

To fully answer this part, you would need to perform the DH frame assignment on the diagram and then plug the resulting DH parameters for each of the three links into the standard DH transformation matrix formula (which combines rotation and translation into a 4x4 homogeneous matrix). The 3x3 upper-left block of this matrix is the rotation matrix, and the 3x1 upper-right part is the translation vector.

I hope this detailed breakdown of the second past year paper is helpful for your studies! Let me know if you have more questions.