ME 547 Winter 2024

Lab 2 Instructions: Inverse Kinematics *(10 pts)*

This lab focuses on inverse kinematics in robot manipulators. The task to be completed with the QArm and Fanuc is to perform pick-and-place with joint commands. You will be given a series of poses that the robot needs to reach. By solving the inverse kinematics problem, you can find the corresponding joint angles for each pose. The joint angles and inverse kinematics algorithms will be used in the program to control the robot.

Objectives:

For both QArm and Fanuc,

- The goal is to command the robot to pick up objects from a given positions and orientations and place them at different positions with a specified orientation. After completing the pick-and-place task, the robot should return to the home position.

Pre-Lab (3 pts):

Please email the results of your pre-lab to the TAs at least two days before your in-person scheduled lab session.

- Complete the pre-lab using either the geometric or algebraic approach for solving the inverse kinematics problems
- Regardless of the method you choose above make sure to convert and report joint angle expressions in the modified DH convention
- In case there are multiple valid solutions for the pre-lab
  - Only use the "elbow-up" configuration
  - Use the joint angle resulting in less amount of motion (e.g., use θ instead of $\theta + 180°$)

QArm Pre-Lab:

- Given the location of an object (x_e, y_e, z_e) in millimeter with respect to the robot's base frame as shown in Figure 1, find the expressions of the corresponding joint angles in radians to reach this position. The fourth joint angle should always set to be zero.
  - Refer to Figure 2 for frame definitions and dimensions.
  - You can verify your inverse kinematics function with the following examples given in the format:

$$\text{Input: } \begin{bmatrix} x \\ y \\ z \end{bmatrix} \Longrightarrow \text{Output: } \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ 0 \end{bmatrix}$$

$$\text{Input 1: } \begin{bmatrix} 400 \\ 250 \\ 130 \end{bmatrix} \Longrightarrow \text{Output 1: } \begin{bmatrix} 0.5586 \\ -0.8375 \\ 0.1260 \\ 0 \end{bmatrix} \qquad \text{Input 2: } \begin{bmatrix} 420 \\ 80 \\ 110 \end{bmatrix} \Longrightarrow \text{Output 2: } \begin{bmatrix} 0.1882 \\ -0.8685 \\ 0.2823 \\ 0 \end{bmatrix}$$

$$\text{Input 3: } \begin{bmatrix} 540 \\ -50 \\ 175 \end{bmatrix} \Longrightarrow \text{Output 3: } \begin{bmatrix} -0.0923 \\ -0.7772 \\ -0.1607 \\ 0 \end{bmatrix} \qquad \text{Input 4: } \begin{bmatrix} 480 \\ -80 \\ 330 \end{bmatrix} \Longrightarrow \text{Output 4: } \begin{bmatrix} -0.1651 \\ -1.1301 \\ -0.0720 \\ 0 \end{bmatrix}$$

- Referring to the Lab 1 QArm in-lab experiment, write a MATLAB function. The input should be the number of pixels in the x and y directions from the camera image after both vertical and horizontal flip. The output should indicate the location of the object with respect to the robot's base frame. Check your function with the result of your Lab 1 experiment.

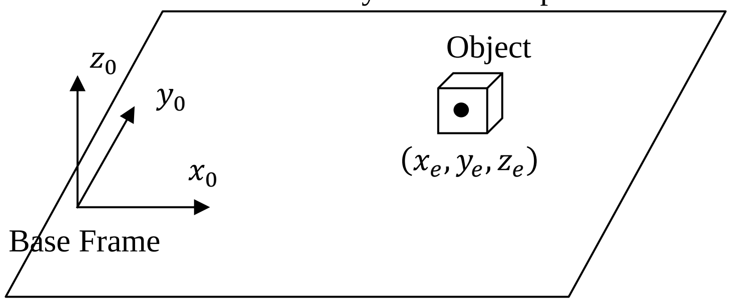

Figure 1: Setup of the QArm workspace.

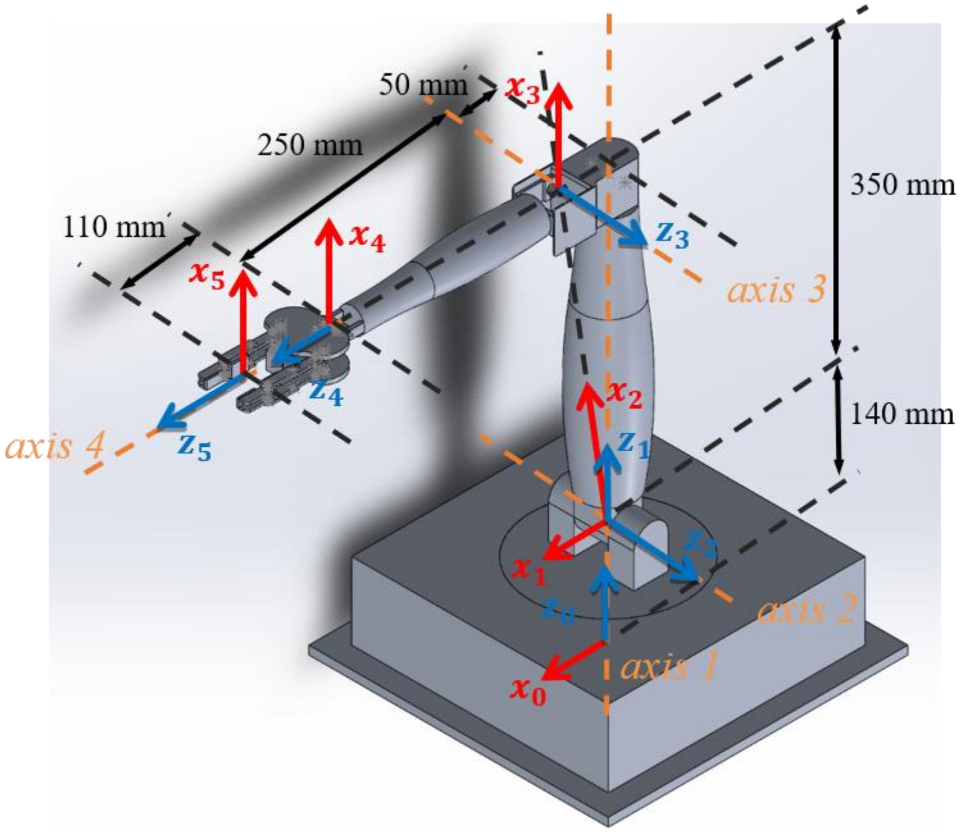

Figure 2: QArm dimension and joint coordinates.

Fanuc Pre-Lab:

- Given the location of an object (x_e, y_e, z_e) and its orientation α with respect to the robot's base frame as shown in Figure 3, find **expressions** of the corresponding joint angles to reach this position.
    - Note that since the Fanuc robot has 1 more DOF than the QArm, it is more flexible. Therefore, the object orientation can be taken into account.
    - The end effector should be looking downwards while reaching the object and the x_6 axis should be aligned with the orientation of the object (See Figure 3).
    - Refer to Figure 4 for frame definitions and dimensions. Note that the joint variables for the configuration shown in Figure 4 is $\begin{bmatrix}\theta_1\\\theta_2\\\theta_3\\\theta_4\\\theta_5\end{bmatrix} = \begin{bmatrix}0\\-90\\-86.1\\86.1\\0\end{bmatrix}$
- Use the inverse kinematics expressions you found above to write a function named `*invKin*`. The inputs for this function should be the location of an object (x_e, y_e, z_e) in millimeters and its orientation α in degrees with respect to the robot's base frame (as shown in Figure 3). Since you are required to write the final function code in Visual Basic for running the robot, it is advisable to implement the function in Visual Basic. You may need to perform a small search to adapt your MATLAB or Python code syntax to Visual Basic.
- You can verify your inverse kinematics function with the following examples given in the format:

$$\text{Input: } \begin{bmatrix}x\\y\\z\\\alpha\end{bmatrix} \Longrightarrow \text{Output: } \begin{bmatrix}\theta_1\\\theta_2\\\theta_3\\\theta_4\\\theta_5\end{bmatrix}$$

$$\text{Input 1: } \begin{bmatrix}435\\-105\\-80\\45^\circ\end{bmatrix} \Longrightarrow \text{Output 1: } \begin{bmatrix}-13.57\\-37.75\\-71.43\\33.67\\121.43\end{bmatrix} \qquad \text{Input 2: } \begin{bmatrix}435\\-105\\-120\\45^\circ\end{bmatrix} \Longrightarrow \text{Output 2: } \begin{bmatrix}-13.57\\-32.26\\-70.72\\38.46\\121.43\end{bmatrix}$$

$$\text{Input 3: } \begin{bmatrix}430\\100\\-80\\90^\circ\end{bmatrix} \Longrightarrow \text{Output 3: } \begin{bmatrix}13.09\\-38.9\\-73.55\\34.65\\103.09\end{bmatrix} \qquad \text{Input 4: } \begin{bmatrix}430\\100\\-120\\90^\circ\end{bmatrix} \Longrightarrow \text{Output 4: } \begin{bmatrix}13.09\\-33.35\\-72.86\\39.5\\103.09\end{bmatrix}$$

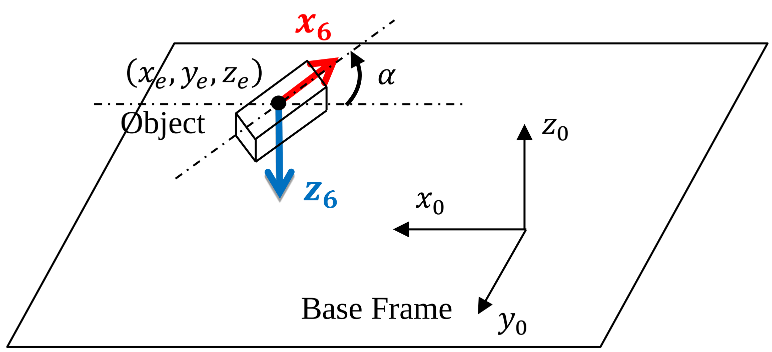

Figure 3: Setup of the Fanuc workspace.

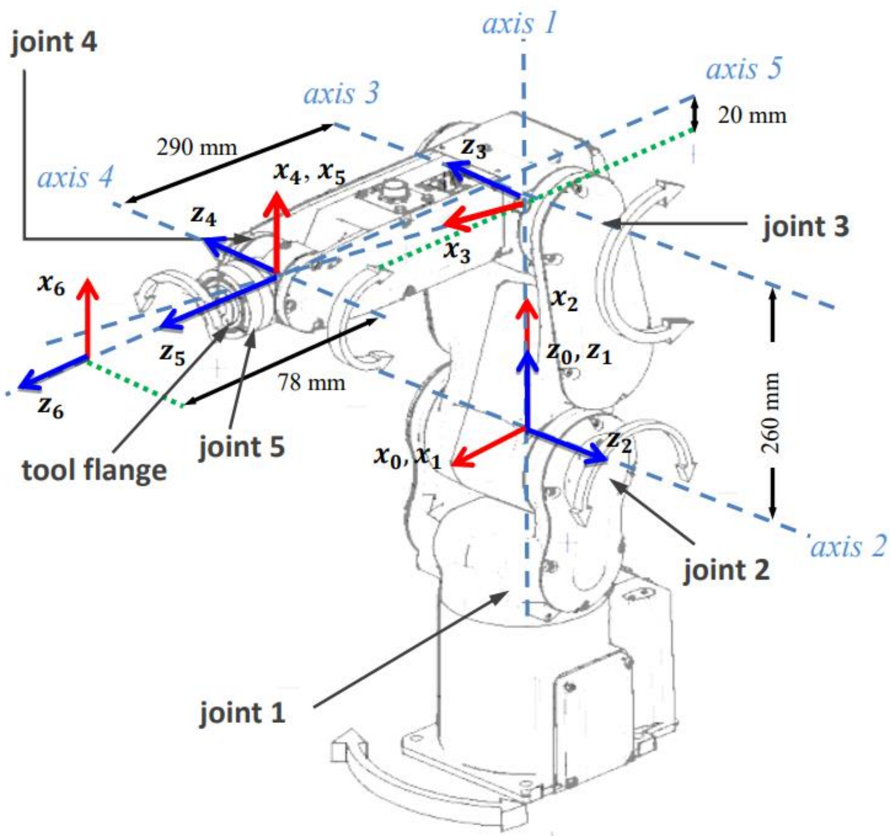

Figure 4: Fanuc dimensions and joint coordinates.

In-Lab Experiments

The following parts will be performed during your scheduled lab session.

QArm Experiment (3 pts)

Tasks:

- In this experiment, your task is to send joint commands to the robot to transfer an object from point B to a box located at point F. After the pick-and-place operation completes, the robot should return to its initial position.

- All the points needs to be reached by the robot are shown in Figure 5. The complete sequence of tasks are as follows:
    - The robot moves from its initial position to point A, which is a point vertically above point B. Note that, in pick-and-place operations, it is common for the robot to first move to an intermediate point close to the object and then approach the target location.
    - The robot lowers its gripper from point A to point B where the object is located.
    - Close the gripper to pick up the object.
    - Return to A from B.
    - Move the gripper to waypoints (intermediate points) C and D. Sometimes, there may be other obstacles in the workspace. Moving to waypoints is necessary to avoid collision with obstacles.
    - Move the gripper center from D to E, a point above point F (vertical shift of point F).
    - Lower the gripper to point F.
    - Open the gripper to release the object.
    - Return to E from F.
    - Return to the initial position.

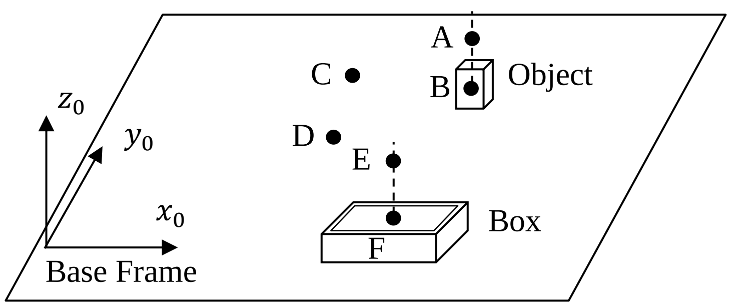

Figure 5: Waypoints for the QArm experiment.

Procedure:

- Let the TA place the object in an arbitrary place for you.
- Take pictures of the initial location for your lab report
- Use the MATLAB function you have written during the Pre-Lab section to calculate location of the object (i.e., (x_B, y_B, z_B)) and location of the box (i.e., (x_F, y_F, z_F)) with respect to the robot's base frame.
- Use the QArm inverse kinematics algorithm you have found during the Pre-Lab section to calculate the joint angles corresponding to points A to F. Their locations with respect to the robot's base frame are given below.
    - A: $(x_B, y_B, 200)$ mm
    - B: $(x_B, y_B, 110)$ mm
    - C: (450, 200, 300) mm
    - D: (500, 0, 350) mm
    - E: $(x_F, y_F, 200)$ mm
    - F: $(x_F, y_F, 135)$ mm

- In the provided Simulink template, modify variables A to F according to your calculated joint angles.
  - The joint angles should follow the modified DH convention.
  - Keep the angle of the last joint to 0 for all points.
  - Ask the TA to check your code before running it.
- Build and run the code.
- Do not forget to take pictures/videos during the lab to complete your report

Fanuc Experiment (4 pts)

Tasks:

- In this experiment, you are going to play dominoes using the Fanuc robot. The robot is required to pick up four dominoes from a series of initial points with specific orientations and place them at the final points using joint angle commands coming out from the inverse kinematics function. One major difference compared with QArm is that the object's orientation needs to be considered.
- All the points the robot needs to reach are shown in Figure 6. The figure indicates that four black boxes should be placed in the positions of the red boxes, as shown by the black arrow. The complete sequence of tasks are as follows:
  - The robot moves from its initial position to point 1_Up, which is above point 1_Down (vertically shifted). When the end effector reaches point 1_Up, it should be vertically looking downwards. The gripper should also line up with the orientation of the object, α_1.
  - The robot lowers its gripper from point 1_Up to point 1_Down while maintaining its orientation.
  - Close the gripper to pick up the object.
  - Return to 1_Up from 1_Down while maintaining the end effector orientation.
  - Move the gripper center from 1_Up to 1f_Up, a point vertically above point 1f_Down. The gripper should still point vertically downwards and it should line up with the object's target orientation, 0°.
  - Lower the gripper to point 1f_Down while maintaining its orientation.
  - Open the gripper to release the object.
  - Return to 1f_Up from 1f_Down while maintaining its orientation.
  - The robot moves from 1f_Up to 2_Up, which is above point 2_Down (vertically shifted). When the end effector reaches point 2_Up, it should be oriented vertically downwards. The gripper should also align with the orientation of the object, α_2. Repeat the seven previous steps for the other three objects.
  - After placing the fourth object, the end effector travels from 4f_Up to hit_Up. After that, the robot lowers its end effector from hit_Up to hit_Down. By moving from hit_Down to 1f_Down, the first domino starts falling and causes all others to fall in a chain shape.
  - The robot then returns to the initial position.

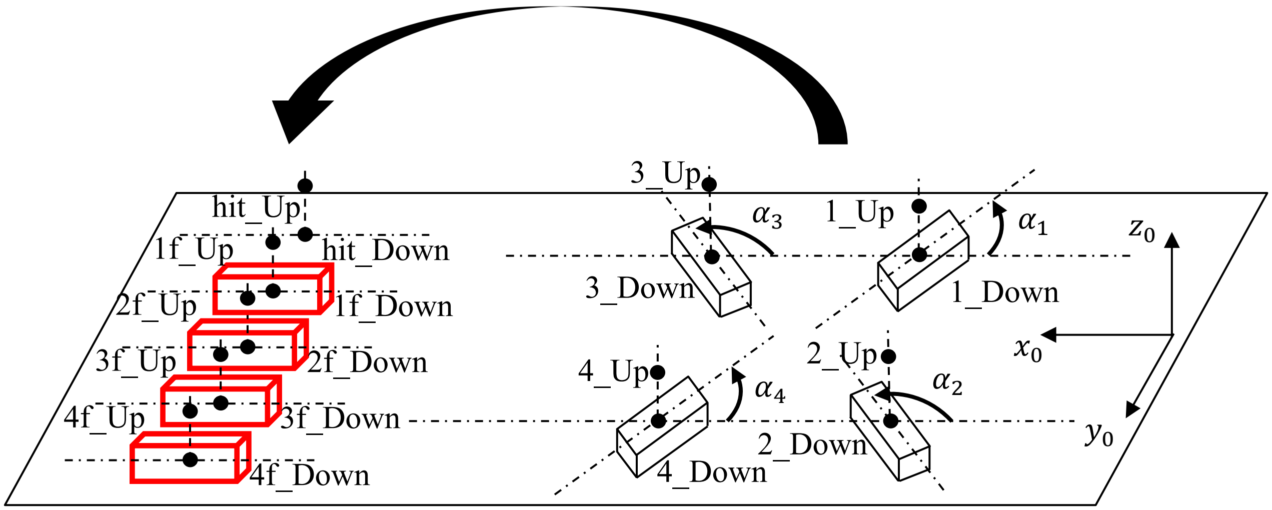

Figure 6: Waypoints for the Fanuc experiment.

Procedure:

- Take photo of the initial location of objects for your report.
- In the provided Visual Basic template, modify *invKin* function as you have written during the pre-lab section.
    - The joint angles should follow the modified DH convention.
    - Ask the TA to check your code before running it.
- The location of all the points that the robot end effector should travel and the corresponding end effector orientation α (as shown in Figure 3 and Figure 6) with respect to the robot's base frame are given below.
    - 1_Up: (385, -105, -80) mm, 45°
    - 1_Down: (385, -105, -210) mm, 45°
    - 1f_Up: (500, -100, -80) mm, 0°
    - 1f_Down: (500, -100, -210) mm, 0°
    - 3_Up: (435, -105, -80) mm, 135°
    - 3_Down: (435, -105, -210) mm, 135°
    - 3f_Up: (500, -20, -80) mm, 0°
    - 3f_Down: (500, -20, -210) mm, 0°
    - 2_Up: (385, -5, -80) mm, 135°
    - 2_Down: (385, -5, -210) mm, 135°
    - 2f_Up: (500, -60, -80) mm, 0°
    - 2f_Down: (500, -60, -210) mm, 0°
    - 4_Up: (435, -5, -80) mm, 45°
    - 4_Down: (435, -5, -210) mm, 45°
    - 4f_Up: (500, 20, -80) mm, 0°
    - 4f_Down: (500, 20, -210) mm, 0°
    - hit_Up: (500, -140, -80) mm, 0°
    - hit_Down: (500, -140, -210) mm, 0°
- Build and run the code.
- Do not forget to take pictures/videos during the lab to complete your report

Lab Report

- After the lab, each group is required to complete a short lab report.
- In your report, include the followings:
  - Analysis and results from the pre-lab
  - Any calculations performed during the lab
  - Pictures showing that both robots completed all of the required tasks
  - A short discussion on your observations on the accuracy of the performed tasks