Recommended Assessment
Forward Kinematics

Workspace Identification

1. How does the range of motion of each joint contribute to the overall workspace shape?

   The range of motion (ROM) of each joint defines the size, shape and dexterous characteristics of the manipulator's workspace:

   Joint Limits Set Boundaries:
   - Rotational joints expand the workspace in circular or spherical regions.
   - Linear joints extend reach along straight paths.

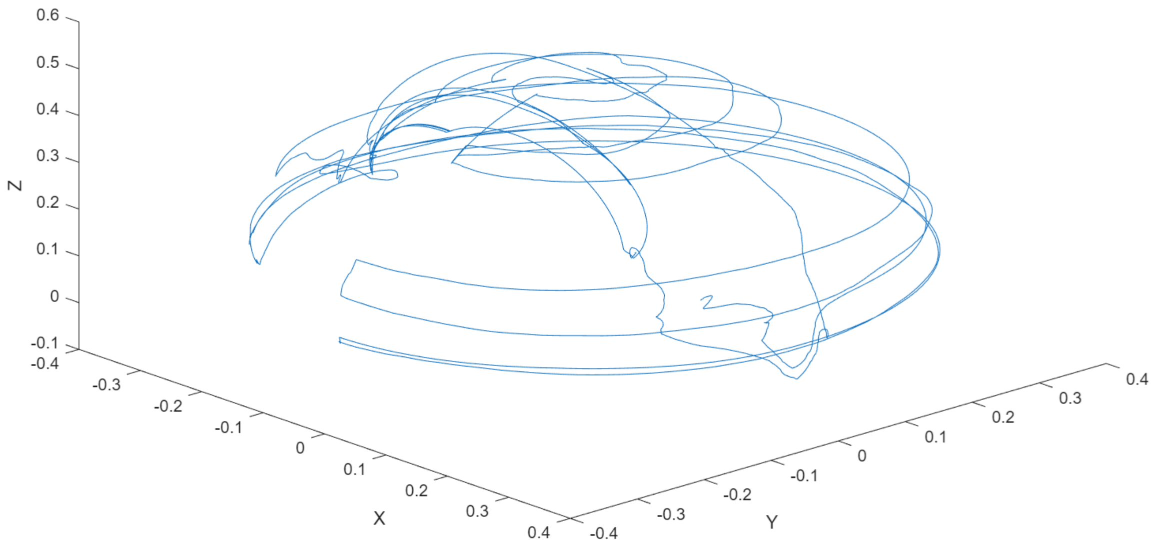
   Impact of Joint Position:
   - Base joints affect the overall reach, while end joints fine-tune positioning.

   Workspace Shape:
   - Full rotation creates a spherical workspace.
   - Limited angles produce truncated workspaces.

   Singularities:
   - Certain joint positions cause control loss, reducing the effective workspace.

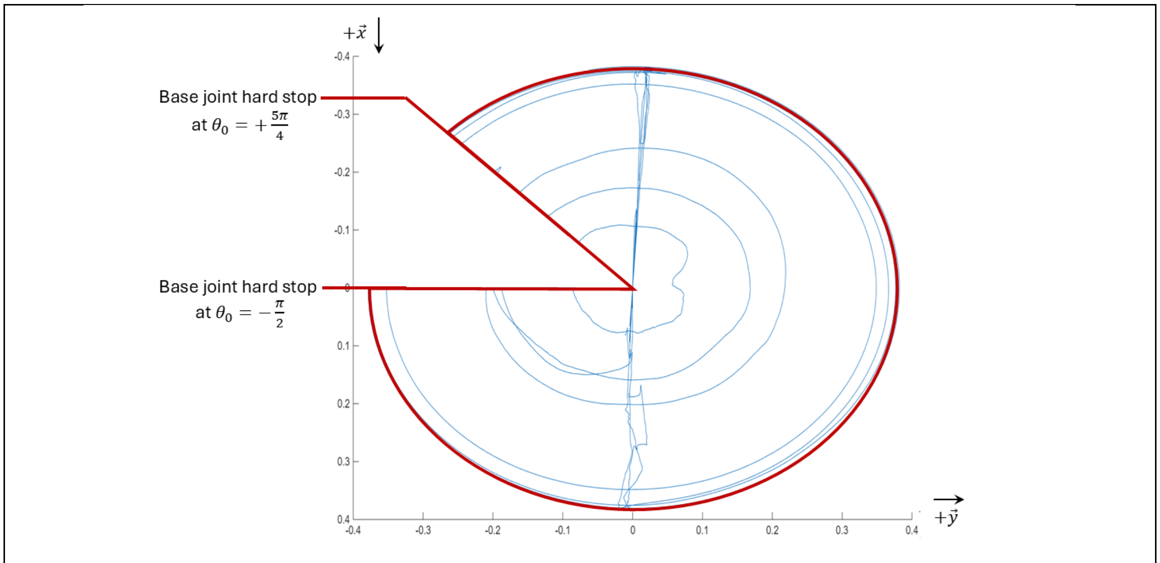
2. Looking at the generated graph, does the workspace match your expectations based on how you moved the arm? Add your generated graph.

   The students generated graph should reflect the arm's physical movements. If they moved the arm in specific patterns (e.g., square or circular), the graph should display similar shapes. Ensure the graph's limits align with the arm's joint constraints, accurately representing maximum extension and retraction. This can be seen in the isometric view below.

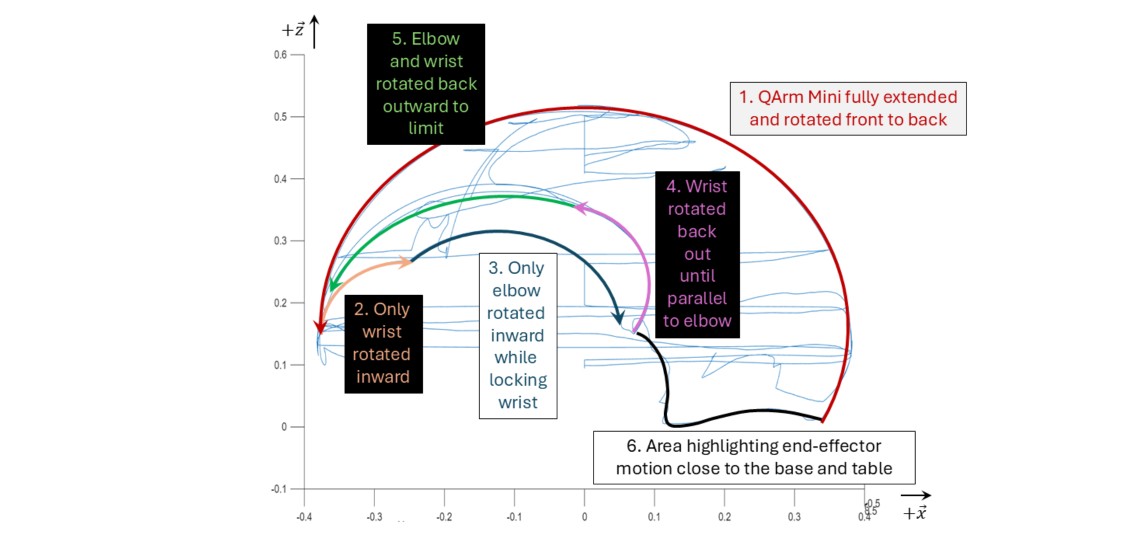


3. Can you identify areas where the manipulator could not reach? Why do you think these areas are inaccessible? Add pictures of your generated plots.

   Areas where the manipulator cannot reach typically fall outside its physical workspace, which is defined by the range of motion of each joint. Inaccessible regions mainly result from mechanical limits, such as joint angle restrictions due to hard stops. In addition, they may also result from software limits preventing the manipulator from entering regions with singularities, where small joint movements cause unpredictable end-effector motion. The XY and XZ planes from the isometric view in this case show the circular arcs followed by the end-effector, highlighting joint limitations and arm reach.



x-y plane

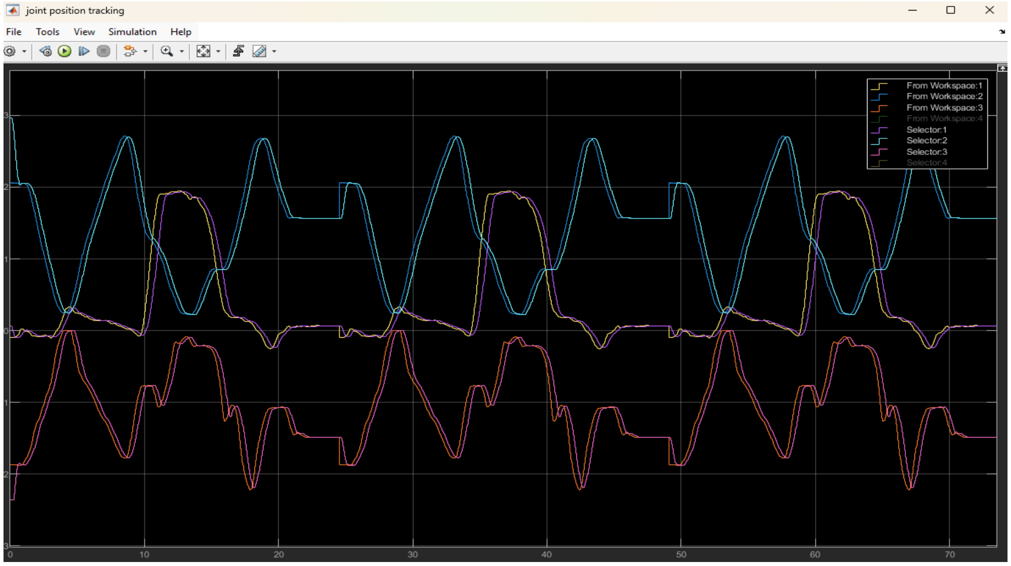


x-z plane

Lead Through

1. Attach screenshots from the “joint position tracking” scope. Are the recorded trajectory and measured position Identical? If not, why?

   The recorded and measured position trajectories are identical for the most part with minor delays between them. PID controllers at each joint will demonstrate improved tracking performance under square wave commands, as each joint's controller has time to react and get the joint to the desired position. In this case however, command trajectories are continuously changing. As such, a minor delay between the measured and commanded trajectories is expected, and as such, observed.



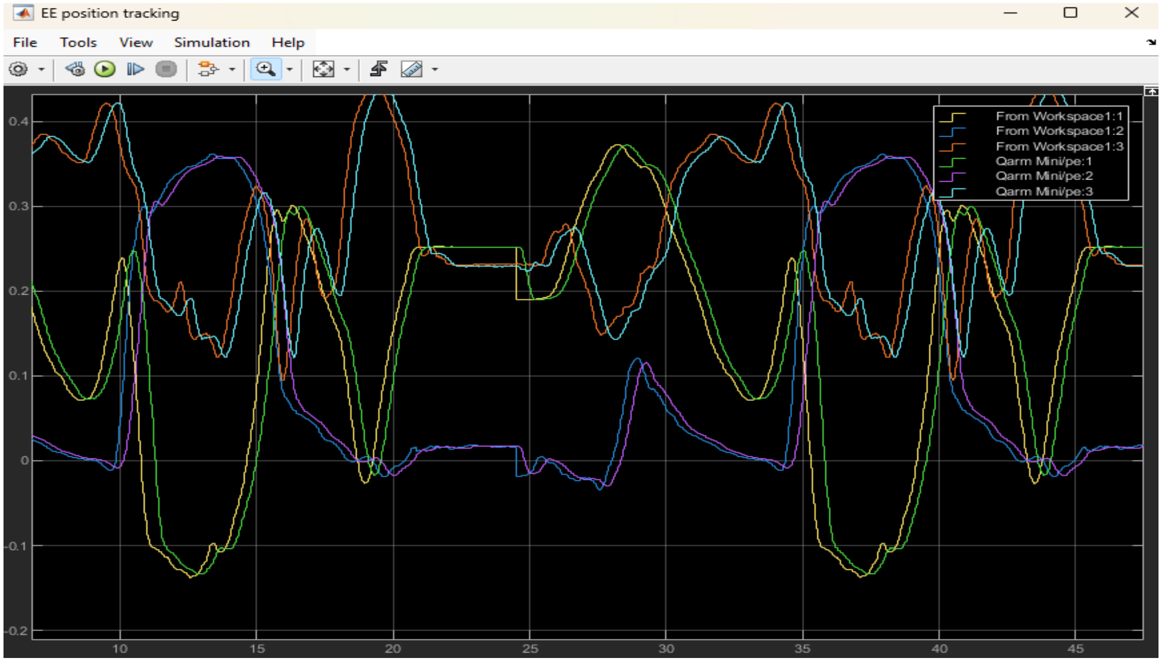
2. Attach screenshots from the “EE position tracking scope”. When comparing the screenshots from the above question, what differences do you notice? Why?

   The delay from the joint level scope is also observed here and is as expected, although with a much larger magnitude. This is from three sources,

   i. natural response delay from the joint level controllers themselves (see previous answer)

   ii. an accumulated tracking error from each joint, growing larger as you move down the manipulator chain. In later labs, students will analyze a matrix that will hold information about how sensitive the end-effector is to changes in individual joint positions.

   iii. A low-pass filter was introduced to reduce noise in the command trajectories recorded in the previous sections, which can introduce slight delays in the response.

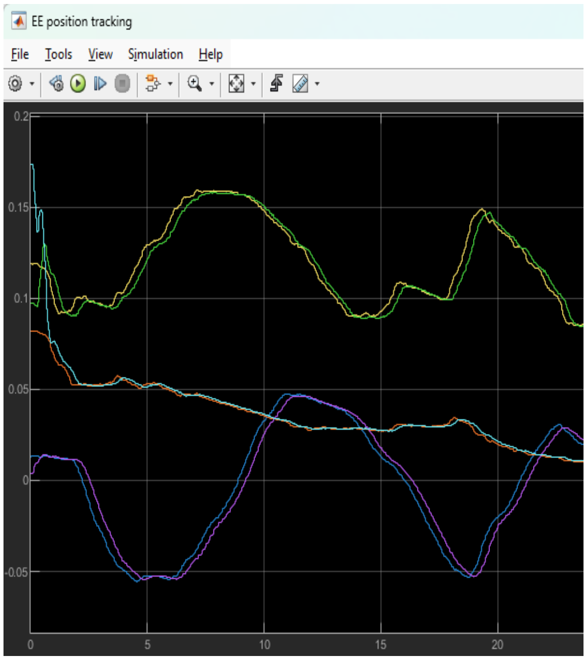


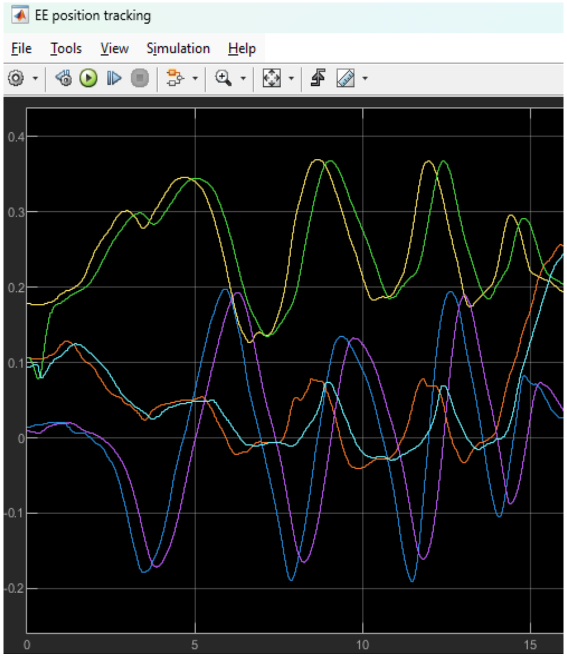
3. Examine the data from the "EE Position Tracking Scope" when guiding the arm along a closed-loop trajectory both near the base and further away. What differences do you notice between the two scenarios? Support your observations with screenshots from the "EE Position Tracking Scope.

When the arm follows a closed-loop trajectory close to the base, the end-effector tracks the desired path more accurately. This is because the joints operate within a more stable range, where mechanical leverage is greater, and the torque requirements are lower. As a result, deviations from the expected trajectory are smaller, and motion appears smoother.

However, when the trajectory is executed near the joint limits, tracking errors tend to increase. The end-effector lags behind the desired path due to reduced torque efficiency and greater mechanical constraints. At these extended positions, the arm experiences increased sensitivity to non-linear effects, such as backlash, joint flexibility, and dynamic instabilities. The control system struggles to compensate for these factors, leading to larger deviations in movement.

Overall, the further the arm extends from the base, the larger the tracking deviations become due to the reduced ability of the controller to make precise corrections at extreme positions.





4. By manually guiding the manipulator, how easy was it to trace a desired path? How accurately did the end-effector follow the intended trajectory?

   Manually guiding the manipulator by hand felt intuitive and straightforward, allowing easy control of the end-effector to trace a closed-loop path. However, maintaining precise control and smoothly following the trajectory proved challenging.

   In terms of accuracy, the end-effector did not always follow the exact intended path. Small deviations occurred due to variations in hand pressure, inconsistent speed, and minor resistance from the arm's structure.

   Despite these challenges, the system captured waypoints reasonably well. However, slight variations were noticeable when comparing multiple attempts at tracing the same trajectory.

5. If you were to program the manipulator to follow the same path instead of guiding it by hand, what challenges would you encounter in ensuring accuracy and repeatability?

   Programming the trajectory can be time-consuming, as defining precise waypoints and motion requires significant effort. Furthermore, achieving high accuracy demands advanced mathematical and programming skills, such as understanding kinematics and control algorithms. Even small errors in programming or calibration can lead to deviations from the intended path, requiring fine-tuning.

   But once programmed, the manipulator can follow the same path consistently without human-induced variations, ensuring accuracy in repeated tasks.