University of Maryland, College Park

ENPM 662: Introduction to Robot Modeling

Final Project Report

6-DOF Mobile base manipulator

Group 23

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Contents

1 Introduction

Mobile manipulators, which merge the mobile platforms with the capabilities of robotic manipulators, are the focus of this project. The introduction presents an innovative mobile-based manipulator with a total of six Degrees of Freedom (6-DOF), strategically divided between a three-DOF mobile base and a three-DOF manipulator.

The incorporation of a three-DOF car-like mobile base endows the system with the ability to navigate through complex and dynamic environments with ease. This mobility not only extends the reach of the manipulator but also allows for strategic positioning and adaptation to diverse working conditions. The addition of wheels further enhances the platform's maneuverability, enabling it to traverse tight spaces and navigate with remarkable dexterity.

Complementing the mobile base is a three-DOF manipulator, providing the necessary spatial freedom for precise and intricate manipulation tasks. The manipulator's three rotational degrees of freedom ensure the versatility needed for tasks such as grasping, lifting, and orienting objects in three-dimensional space.

The fusion of a mobile base with a manipulator introduces a dynamic element to the traditional static robotic systems, making it well-suited for tasks in real-world environments. Applications span a wide range of industries, from logistics and manufacturing to healthcare and service robotics. The simultaneous control of the mobile base and manipulator, along with advanced sensor integration, opens avenues for intelligent and adaptive behavior in response to changing surroundings.

This project delves into the design, kinematics, and control strategies employed in creating this innovative robotic platform, shedding light on its potential to revolutionize various sectors by bridging the gap between mobility and manipulation in a seamless and efficient manner.

2 Application

Application of a mobile-based manipulator with a total of six Degrees of Freedom (6-DOF), consisting of a three-DOF car-like mobile base and a three-DOF manipulator, stems from the growing demand for versatile and adaptive robotic systems in various industries. Traditional robotic manipulators excel in precision tasks within controlled environments, while mobile platforms provide the agility to navigate dynamic surroundings. By integrating these capabilities into a unified system, our project seeks to address the limitations of static manipulators and extend the range of applications to scenarios that require both mobility and manipulation.

Industries such as logistics, manufacturing, and healthcare are increasingly demanding robotic solutions that can seamlessly transition between manipulation tasks and dynamic navigation in real-world environments. The amalgamation of a mobile base and manipulator offers a compelling solution to these evolving challenges. For instance, in warehouse automation, a mobile manipulator can efficiently navigate through cluttered spaces, pick and place items, and adapt to changing layouts without the need for fixed infrastructure modifications.

Furthermore, applications where human-robot collaboration is pivotal. The ability of a mobile manipulator to navigate through shared spaces, collaborate with human workers, and perform intricate manipulation tasks opens the door to safer and more efficient collaboration in environments where static robots might be impractical or cumbersome.

In summary, the motivation behind our project lies in the pursuit of a robotic system that seamlessly integrates mobility and manipulation, breaking down the barriers between traditionally specialized robotic functions. This innovation aims to empower robots with the flexibility to operate in diverse and dynamic settings, fostering advancements in automation and robotics that transcend the capabilities of existing systems.

3 Robot Description

The robot is a combination of a car-like mobile base with three DOFs (X, Y, Orientation) and a manipulator with three additional DOFs (θ_1, θ_2, θ_3). The table provides a concise overview of the Degrees of Freedom (DOFs) and associated angular ranges for a robotic system with a total of six DOFs.

Each angular range for the DOFs is specified as -180 to 180 degrees.

DOF's (Degree's of Freedom)	6
Range (θ_{axle})	$-\pi$ to π
Range (θ_1)	$-\pi$ to π
Range (θ_2)	$-\pi$ to π
Range (θ_3)	$-\pi$ to π
Mobile base length	1.5 m
Mobile base width	0.75 m
Manipulator link1 length	0.19 m
Manipulator link2 length	0.48 m
Manipulator link3 length	0.45 m

The angular range θ_{axle} corresponds to the rotation of the mobile base, while (θ_1, θ_2, θ_3) pertain to the joint rotations of the manipulator. The system's total length is indicated as 52 inches, providing a physical parameter that adds context to the dimensional aspects of the robotic configuration.

4 CAD model

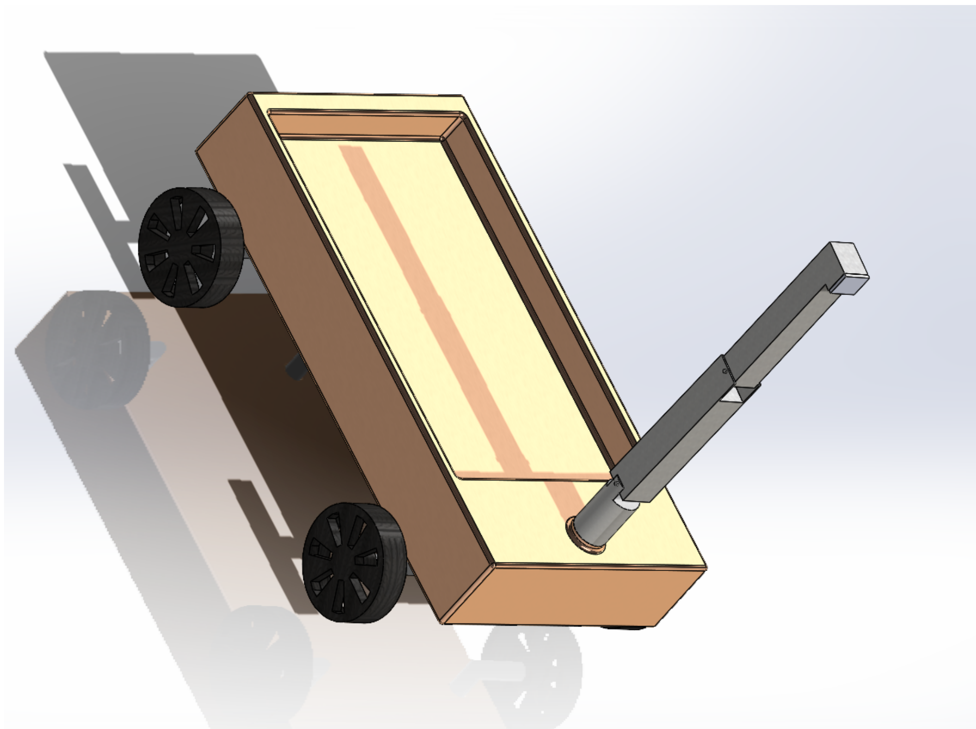


Figure 1: CAD model

5 Kinematics

5.1 DH frame assignment

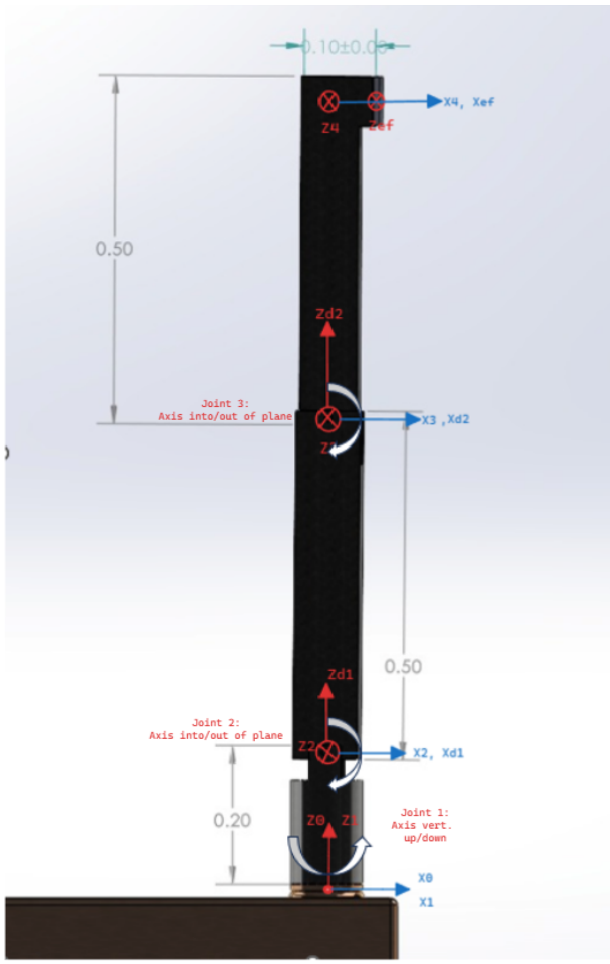


Figure 2: Frame Assignment

5.2 DH Table

Transform	α (rad)	$a(m)$	$d(m)$	θ (rad)
0 - 1	0	0	0	θ_1
1 - 2	$-\pi/2$	0	0.19	θ_2
2 - d_1	$\pi/2$	0	0	0
d_1 - 3	$-\pi/2$	0	0.48	θ_3
3 - d_2	$\pi/2$	0	0	0
d_2 - 4	$-\pi/2$	0	0.45	0
4 - ef	0	0.06	0	0

Table 1: DH parameter table

5.3 Forward Kinematics

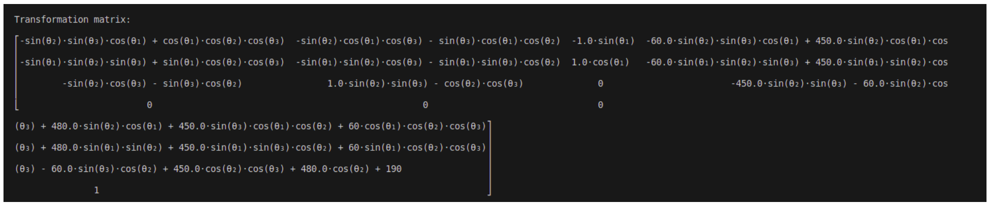
Substituting the values from the DH table into the matrix yields the transformation between the two frames, i-1 and i:

$$T_i^{i-1} = Rot_{z,\theta_i} * Trans_{z,d_i} * Trans_{x,a_i} * Rot_{x,\alpha_i}$$

$$T_i^{i-1} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i.\cos\alpha_i & \sin\theta_i.\sin\alpha_i & a_i.\cos\theta_i \\ \sin\theta_i & \cos\theta_i.\cos\alpha_i & -\cos\theta_i.\sin\alpha_i & a_i.\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The transformation from end effector to base frame is given by T_{ef}^0:

$$T_{ef}^0 = T_1^0 * T_2^1 * T_{d1}^2 * T_3^{d1} * T_{d2}^3 * T_4^{d2} * T_{ef}^4$$



```
Transformation matrix:
⎡-sin(θ₂)·sin(θ₃)·cos(θ₁) + cos(θ₁)·cos(θ₂)·cos(θ₃)  -sin(θ₂)·cos(θ₁)·cos(θ₃) - sin(θ₃)·cos(θ₁)·cos(θ₂)  -1.0·sin(θ₁)  -60.0·sin(θ₂)·sin(θ₃)·cos(θ₁) + 450.0·sin(θ₂)·cos(θ₁)·cos
⎢-sin(θ₁)·sin(θ₂)·sin(θ₃) + sin(θ₁)·cos(θ₂)·cos(θ₃)  -sin(θ₁)·sin(θ₂)·cos(θ₃) - sin(θ₁)·sin(θ₃)·cos(θ₂)  1.0·cos(θ₁)   -60.0·sin(θ₁)·sin(θ₂)·sin(θ₃) + 450.0·sin(θ₁)·sin(θ₂)·cos
⎢        -sin(θ₂)·cos(θ₃) - sin(θ₃)·cos(θ₂)                1.0·sin(θ₂)·sin(θ₃) - cos(θ₂)·cos(θ₃)              0                       -450.0·sin(θ₂)·sin(θ₃) - 60.0·sin(θ₂)·cos
⎣                        0                                                0                                     0
(θ₃) + 480.0·sin(θ₂)·cos(θ₁) + 450.0·sin(θ₃)·cos(θ₁)·cos(θ₂) + 60·cos(θ₁)·cos(θ₂)·cos(θ₃)⎤
(θ₃) + 480.0·sin(θ₁)·sin(θ₂) + 450.0·sin(θ₁)·sin(θ₃)·cos(θ₂) + 60·sin(θ₁)·cos(θ₂)·cos(θ₃)⎥
(θ₃) - 60.0·sin(θ₃)·cos(θ₂) + 450.0·cos(θ₂)·cos(θ₃) + 480.0·cos(θ₂) + 190               ⎥
             1                                                                           ⎦
```

Figure 3: Final Transformation matrix

5.4 Forward Kinematics Validation

Validation 1:

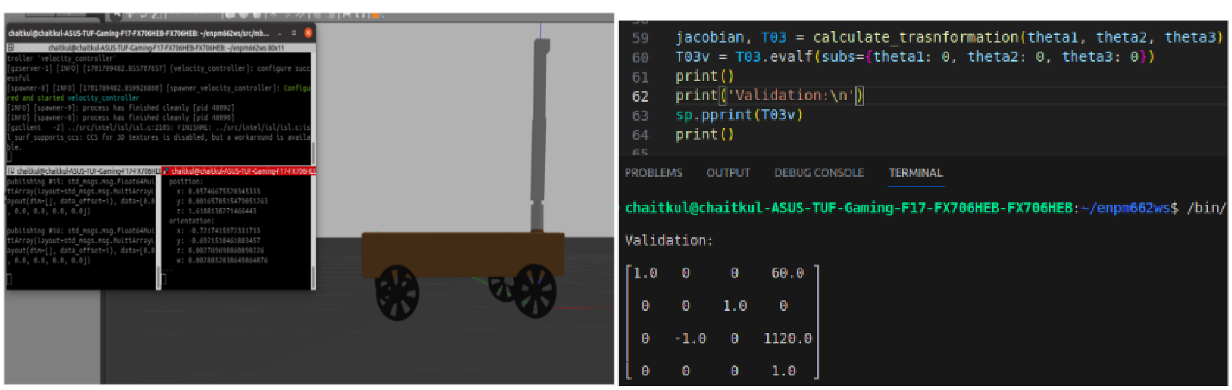
When $\theta_1 = \theta_2 = \theta_3 = 0$

The position of the end effector when the robot is in the home position

$$x = 60mm,$$

$$y = 0mm,$$

$$z = 190 + 480 + 450 = 1120mm$$



(a) $\theta_1 = \pi/2$ (b) $\theta_1 = \pi/2$

Figure 4: Validation 1

Validation 2:

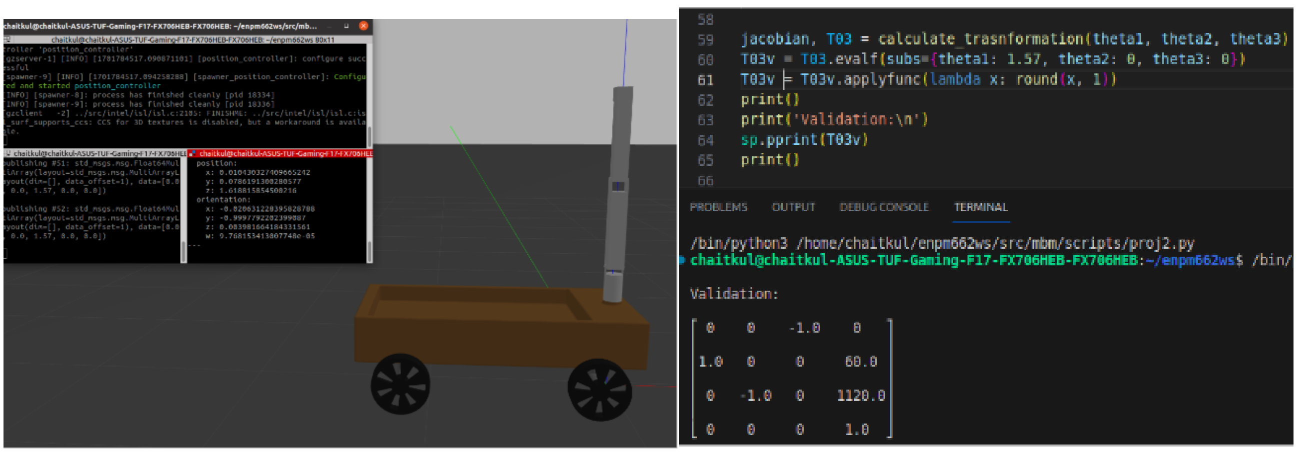
When $\theta_2 = \theta_3 = 0, \theta_1 = \pi/2$

The position of the end effector when the second joint $\theta_1$is rotated by $\pi/2$.

$$x = 0mm,$$

$$y = 60mm,$$

$$z = 190 + 480 + 450 = 1120mm$$



(a) $\theta_1 = \pi/2$ (b) $\theta_1 = \pi/2$

Figure 5: Validation3

Validation 3:

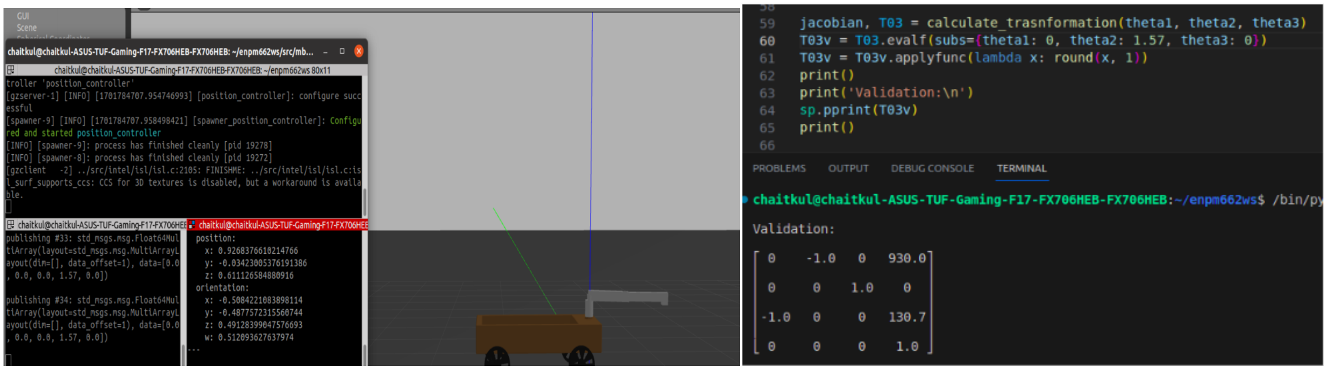
When $\theta_1 = \theta_3 = 0, \theta_2 = \pi/2$

The position of the end effector when the third jointθ_2 is rotated by $\pi/2$.

$$x = 450 + 480 = 930mm,$$

$$y = 0mm,$$

$$z = 190 - 60 = 130mm$$



(a) $\theta_2 = \pi/2$ (b) $\theta_2 = \pi/2$

Figure 6: Validation 3

5.5 Inverse Kinematics

1. **Step 1**: Setting up of the Jacobian

   The Jacobian matrix has been computed using the second method.

   First we have to calculate the transformation matrices for all jonts with the base frame.

   This is done as follows:

   T01 = T[1]

   T02 = T[1] * T[2] * T[3]

   T03 = T[1] * T[2] * T[3] * T[4] * T[5] * T[6]

   T[2] contains frame 2 and dummy frame d1.

   T[3] contains frame 3, dummy frame d2 and end effector frame.

Now, the Jacobian matrix is given by

$$\begin{bmatrix} \frac{\partial P^0}{\partial q_1} & \frac{\partial P^0}{\partial q_2} & \frac{\partial P^0}{\partial q_3} \\ \\ \\ Z_1^0 & Z_2^0 & Z_3^0 \end{bmatrix}$$

The Jacobian is a 6xn matrix, in this specific case, the Jacobian is of the shape 6x3 since the manipulator has 3 joints.

The bottom half of the Jacobian is given by Z_1^0 to Z_3^0 which are the axis of rotations, which is the z column of the transformation matrices from T01 to T03.

The top half of the Jacobian matrix can be computed by differentiating the x, y and z end effector coordinates with respect to θ_1 to θ_3.

The end effector coordinates can be found using the last column of the T03 matrix which would give us p_x, p_y and p_z respectively.

2. **Step 2**: Equation of the circular trajectory

The circle is to be drawn on the XY plane with a radius of 930 mm

The centre of the circle is x=0 and y=0

The equation of the circular trajectory is given by

$$x = r\cos(\omega t)$$

$$y = r\sin(\omega t)$$

$$z = c$$

Differentiating with respect to time, we get

$$\dot{x} = -\omega r \sin(\omega t)$$
$$\dot{y} = \omega r \cos(\omega t)$$
$$\dot{z} = 0$$

The radius of the circle is given as 930, and ω can be calculated by the formula $2\pi/T$ where T is 20 seconds, hence $\omega = 2\pi/20$

3. **Step 3**: Obtaining the joint angular velocities

   Substitute the value of the joint angles in the Jacobian matrix. The velocity matrix is given by

$$v = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$$

   In our specific case, the values of ω_x, ω_y, ω_z are zero, even the value of $\dot{z}$ is also zero as z is constant. We can obtain the values of $\dot{x}$ and $\dot{y}$ from the above equations.

   After setting up the velocity matrix find the joint angle velocities using,

$$\dot{\theta} = J^{-1} v$$

   This will give us the joint angular velocities

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix}$$

4. **Step 4**: Obtaining the joint angles

   The inverse Jacobian matrix is a 3x6 matrix and the velocity matrix is a 6x1 matrix. After multiplying them we get the angular velocities matrix which is also a 3x1 matrix representing the angular velocities of all the 3 joints.

   Integrating these joints will give us the joint angles,

$$\theta = \dot{\theta} * dt$$

$$\begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix}$$

5. **Step 5**: Plotting the trajectory

   After obtaining the joint angles, the final step is to plot the trajectory. Substitute these joint angles into the final transformation matrix T03. This will give us the rotation and translation of the end effector with respect to the base frame.

   The last column of the transformation matrix gives us the coordinates of the end effector. Plot the coordinates

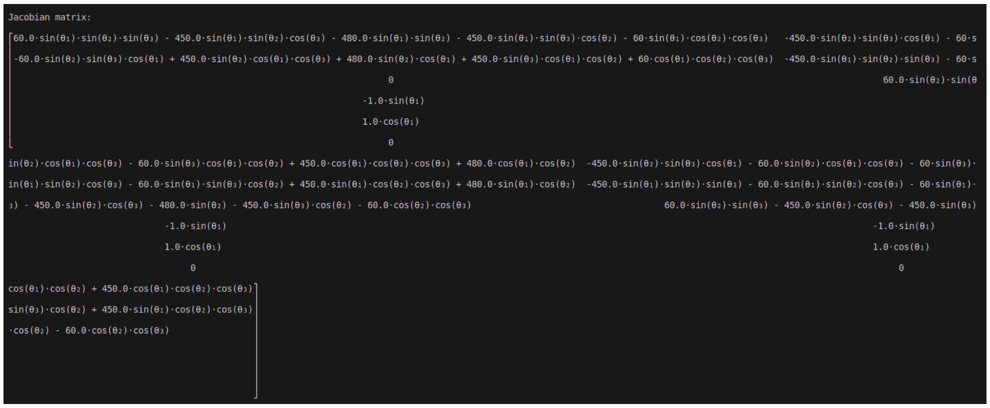


Figure 7: Jacobian matrix

5.6 Inverse Kinematics Validation

Equations for inverse kinematics: (where $r = 930mm, T = 20seconds, \omega = 2\pi/T$)

$$
\begin{aligned}
x &= r\cos(\omega t) & \dot{x} &= -\omega r\sin(\omega t) \\
y &= r\sin(\omega t) & \dot{y} &= \omega r\cos(\omega t) \\
z &= c & \dot{z} &= 0
\end{aligned}
$$

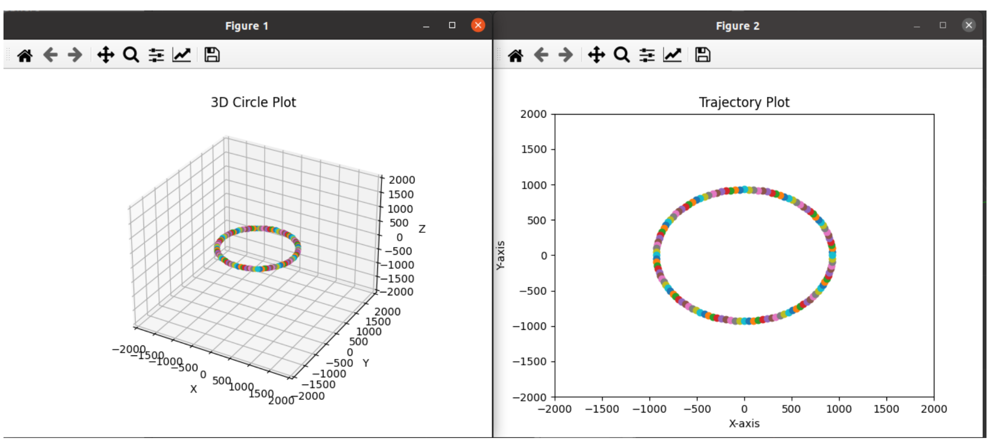


Figure 8: Inverse Kinematics Validation

6 Assumption

1. Neglecting real-world factors like surface friction that might affect the robot's motion.
2. All links are rigid.

7 Control method

For our project controllers that are used:

1. Position Controller: `position_controllers/JointGroupPositionController`
2. Velocity Controller: `velocity_controllers/JointGroupVelocityController`

For the first phase where the robot has to perform pick operation we have used a Closed-loop controller as a control mechanism. The odometry data, which is regularly published to update the robot's position, is an input for these controllers. The robot travels in a straight line until it reaches the pickup location. Then it picks up the object and places it in the cavity of the mobile base.

While for the later part, we have implemented an Open loop Controller, to go to the drop location and perform the place operation. A predefined linear velocity and steer angle are given to the robot and these values are published for a specific time until the robot reaches the drop location and delivers the object.

The position controllers were responsible for controlling the motions of the following important joints: `fr_axle_joint`, `fl_axle_joint`, `link1_joint`, `link2_joint`, and `link3_joint`. These `fr_axle_joint`, `fl_axle_joint` joints are responsible for steering of mobile base, where `fr_axle_joint`, `fl_axle_joint` are the mobile base front right axle joint and front left axle joint, while the other joints namely `link1_joint`, `link2_joint`, and `link3_joint` are the manipulators link joints, that are used in our pick and place operation.

The velocity controllers controlled the `fr_wheel_joint`, `fl_wheel_joint`, `rr_wheel_joint`, and `rl_wheel_joint`, that are front wheel joint, front left joint, rear right wheel joint, and rear left wheel joints respectively, which controls the wheels rotational speed.

8 Problems encountered

1. The main issue was an error in the inverse kinematics that prevented the robot from precisely following the desired trajectory. We started all over again by reassigning the DH frames to fix ithis ssue. This modification worked well and the robot was able to follow the desired trajectory.

2. The gripper was attracting the object but not picking it up after activation. Solved this issue by reducing the mass of the object which was used for the pick and place operation.

9 Lessons Learned

1. Explored the forward and inverse kinematics of a robot with six degrees of freedom (6-DOF).

2. Learned how to build a model in SolidWorks, export it as urdf and use that model in gazebo

3. Creating a custom world in gazebo and spawning the robot into the custom world.

4. Learned how to add integrate sensors and controllers to the model for our simulations.

5. Learned how to use ROS2 to make the robot do certain things, like pick up and place objects. This involves subscribing to topics and publishing information to the robot, so that the robot can perform important tasks.

10 Conclusion

1. We have proposed and modelled a 6 Dof system, that has two components a mobile base with (x, y, orientation) as the degrees of freedom, and a manipulator installed over it with joint angles as the other 3 dof's.

2. Using this robotic system we have performed a pick and place operation, where the robot moves to the pick up location, picks up the object, places it in the cavity made in the model, moves towards the drop off location, and delivers the object.

3. Performed forward and inverse kinematics for the robot, also provided validations for both forward and inverse kinematics.

4. Successfully, carried out pick and place operation in gazebo custom world.

11 Future Work

1. **Object Detection**:

   The integration of advanced object detection and recognition systems would greatly improve the system's autonomy. Implementing computer vision algorithms, can help the system identify and interact with objects in its environment. This feature would be critical for tasks requiring precise object recognition, for our automated pick and place operations.

2. **Path Planning and Optimization:** The movement of the system during pick and place operations could be further optimized by creating intelligent path planning algorithms. To effectively navigate the mobile base manipulator, this includes developing algorithms that consider the surrounding environment, potential obstacles, and the intended trajectory.

12 Gazebo Visualization

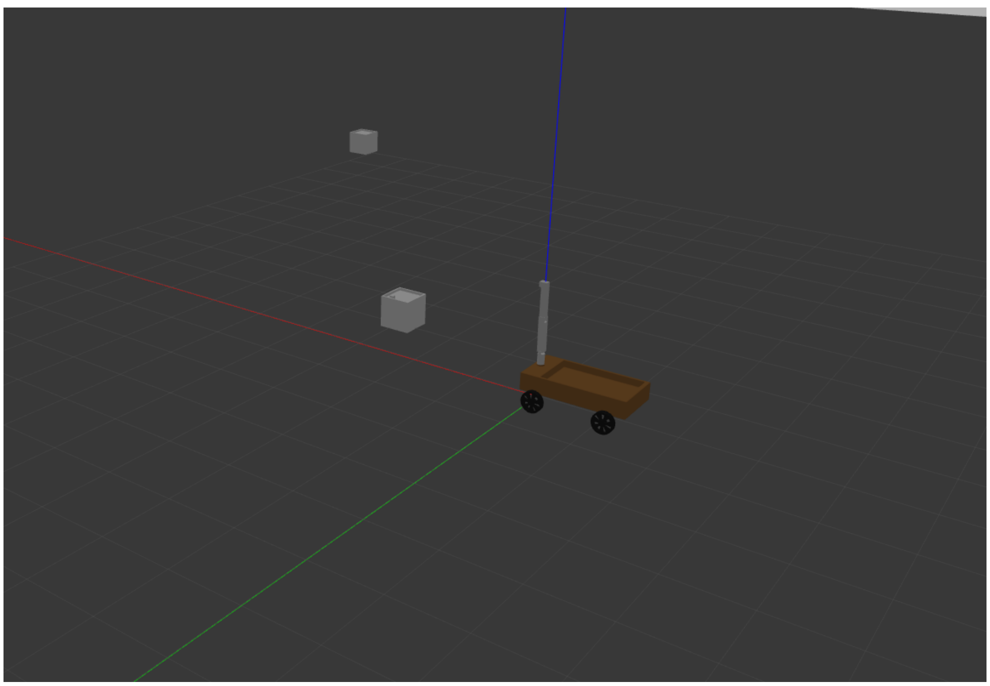


Figure 9: Gazebo visualization

Pick and place operation video link:

Click here

Inverse kinematics Validation link:

Click here

13 References

https://umd.instructure.com/courses/1350246/files