ARROWBOT MANIPULATOR FOR WAREHOUSE AUTOMATION

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1 Introduction

INTRODUCTION AND ORGANIZATION: Arrowbot is the name of the wheeled robotic manipulator designed for warehouse automation. This document contains the Final implementation report for project 2 of course 'Introduction to Robot Modeling (ENPM662)'. The document describes the structure and implementation of the project through 10 different sub sections. The first section **Introduction and Organization** describes the overall structure of this report. The section Motivation and Application which introduces to the topic of the project and reason behind this particular application in robotics. The next section **Robot Description, Dimensions and DOFs** provides the specifications of the wheeled manipulator, it's dimensions and its reach such as physical dimensions, sensors planning to use, material of the robot. .

The section **Forward Kinematics** describes the relationship between the position and orientation of the manipulator with the joint variables like position, velocity. Also, it details the Geometrical validation performed using the above details. This is primarily done for the UR5 manipulator. The next section **Inverse Kinematics** is the section where the approach for calculating Joint angles for a particular task or trajectory. Ambitious and fallback goals are also discussed in this section. After this we proceed to included the **Forward Kinematics Kinematics and Inverse Kinematics Validation** results. The previous section is followed by a detailed **Workspace study** considering the dimensions of the mobile robot and manipulator's maximum reach. The next section **Assumptions** mentions all the assumptions considered while designing the project i.e., structure and limitation of the robot, analysis etc. The next section **Control Method** describes the types of controllers used for this project and the reasons of finalizing those controllers for the respective robot joints. The **Gazebo and Rviz Simulation** section contains video links to our work of Simulation to this project. The next sections discuss the **Problems faced, Lessons Learned and Future work** regarding this project. Finally the **Results** are described and a **Conclusion** for this project is given

2 Motivation and Application of the Robot:

There are many solutions available for material storage and retrieval in a warehouse. In this scenario we have considered a warehouse which has been newly setup and requires start of operations as soon as possible. Since installation of legacy automated storage and retrieval systems requires a lot of capital investment and has longer construction times, a robotics company is tasked to deploy mobile manipulators which can be deployed rapidly out of the box for package retrieval and dispatch. This kind of system will help in ramping up operations of a logistics hub rapidly. Our purpose is to design a mobile robot capable of handling pick and place as well as locomotion tasks simultaneously.

3 Robot Type Description, DOFs and Dimensions:

3.1 Robot Type Description:

Our goal was to design a mobile vehicle which has two degrees of freedom but can use two degrees of freedom only since it is non-holonomic. The mobile vehicle is attached with a 6 Degree of Freedom Serial manipulator consisting of all Revolute joints. The serial manipulator is used (UR5 Robot) for pick and place operations of different goods and placing inside the boxes located on the mobile vehicle itself. A lidar sensor was used to detect the obstacles. Also, a Vision sensor/Camera is mounted on the end effector of the UR5 manipulator to identify and place the good it picked on the assigned box. Although the perception and navigation tasks were not attempted in this project.

3.2 Dimensions and Degrees of Freedom:

The arrowbot geometrical specifications and sensors used are mentioned in below table:

ARROWBOT SPECIFICATIONS		
Specification	Proposal	Actual Implementation
Weight	Upto 200 kgs	140 KGS (Kerb weight of mobile robot from Solidworks) +14 KGS (Weight of UR5 from URDF) = 154 KGS
Dimensions of the robot	1040 * 650 * 731 mm	1040 * 650 * 650 mm (Mobile Robot Dimensions) + UR5 Robot Dimensions as per URDF
Material	Aluminum, Plastic, Steel	Steel density considered for Mobile Robot, UR5 default material as per URDF
Degrees of Freedom of the mobile vehicle	2	2 (As per Proposed)
Degrees of Freedom of the manipulator	6	6 (UR5 manipulator)
Maximum reach	1200mm	850 mm (UR5 max reach)
Payload	Upto 120 Kgs	UR5 max lifting load 5 KGS as per manufacturer; Mobile robot can carry upto 50 kgs
Applications	Material or goods handling, automatic placement of order in respective box assigned to a particular city.	Application is the same but sensors have changed
Motors	2 Traction motor, 2 Servo motors for steering	2 Velocity Joint Controllers for Traction motors 2 Position controller for Steering purposes simulating servos 6 Trajectory Controller Simulating Motors of manipulator
Sensor	Lidar, RFID	Lidar integrated for Mobile Robot Camera integrated on Manipulator for package identification (Perception and navigation tasks using this sensors were not attempted)
Gripper	Hand gripper	Vacuum Gripper simulating pick and place operation.

Table 1: Arrowbot Proposed and Actual Make Specifications

4 CAD Model

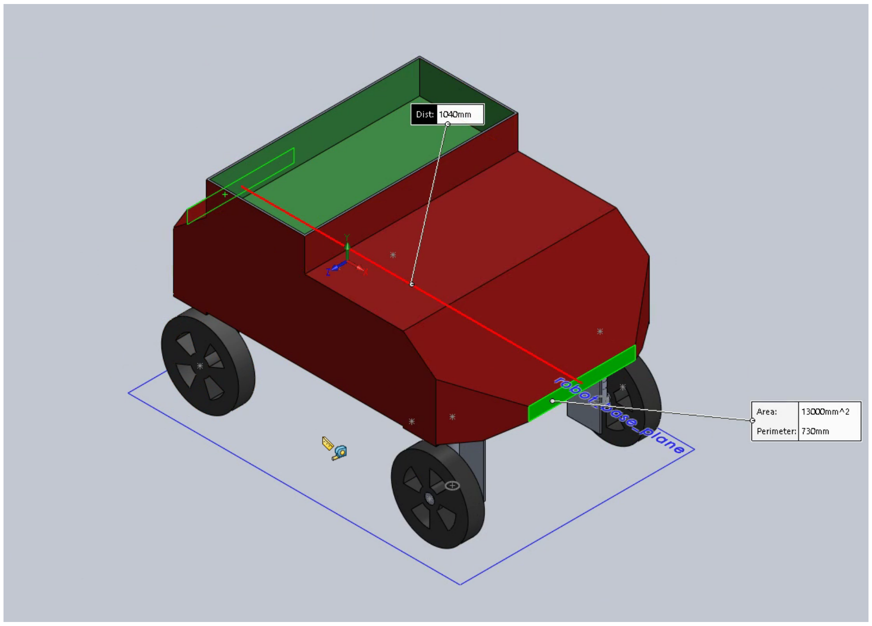


Figure 1: Isometric view of the Mobile Robot

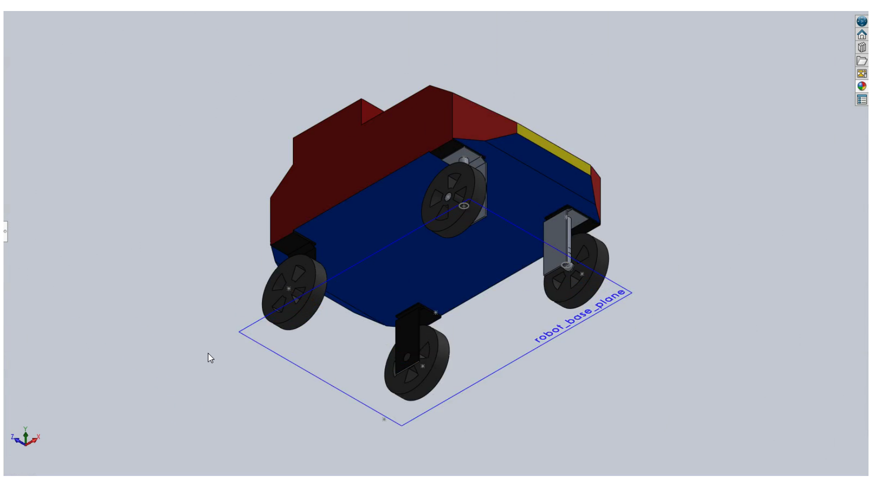


Figure 2: Bottom side view of the Mobile Robot

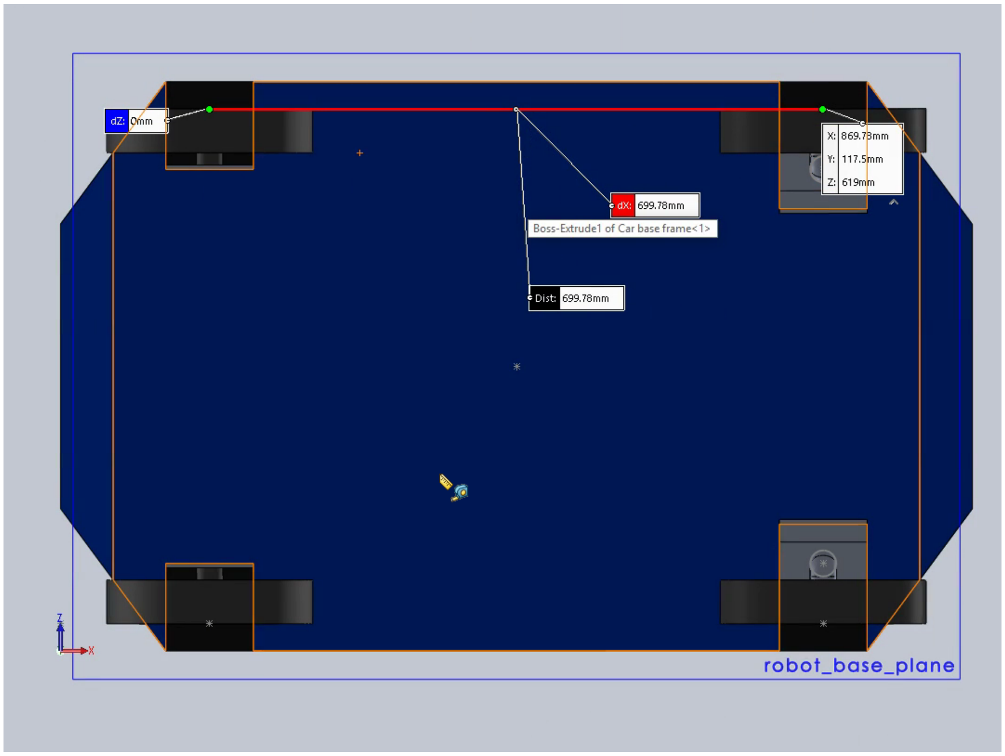


Figure 3: Wheel to Wheel Longitudinal Dimensions

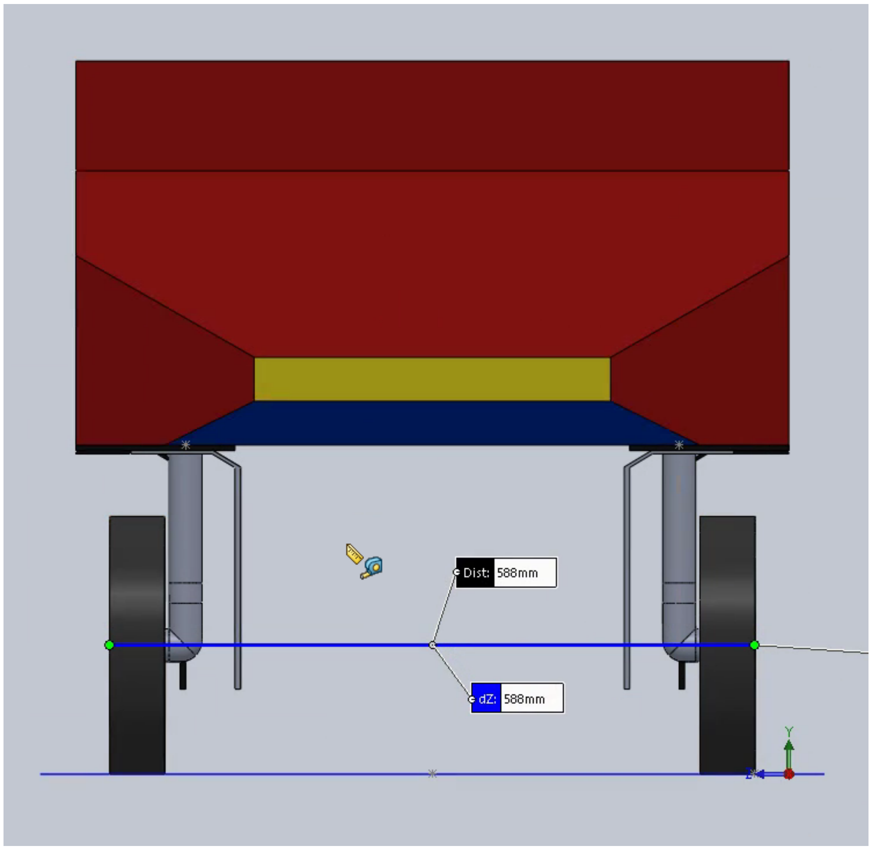


Figure 4: Wheel to Wheel Lateral Dimensions

5 Forward Kinematics

Forward Kinematics is to determine the position and orientation of the end-effector given the values for the joint variables of the robot. The forward kinematics problem is concerned with the relationship between the individual joints of the robot manipulator and the position and orientation of the tool or end effector.

In this project, the mobile robot has 3-DOF(Degree of Freedom) robot which can move in two directions and rotate about one direction but is constrained to 2-DOF by moving in one direction and rotation. Thus, it is known as non-holonomic robot. The forward kinematics of the mobile robot is such that given the effort or speed to motors attached to wheels , the robot travels particular distance in a certain time.

The 6-DOF UR5 manipulator studied in this project has 6 Revolute joints and is placed on the top of the mobile manipulator to perform pick and place. The forward kinematics of this manipulator deals with given joint angles, the manipulator orients resulting in different positions and orientations of the end effector. The Final transformation for the end-effector is given by individual transformation matrices of each link of the manipulator which is given by formula below:

$$^{0}T_6 =^{0} T_1 *^{1} T_2 *^{2} T_3 *^{3} T_4 *^{4} T_5 *^{5} T_6 \tag{1}$$

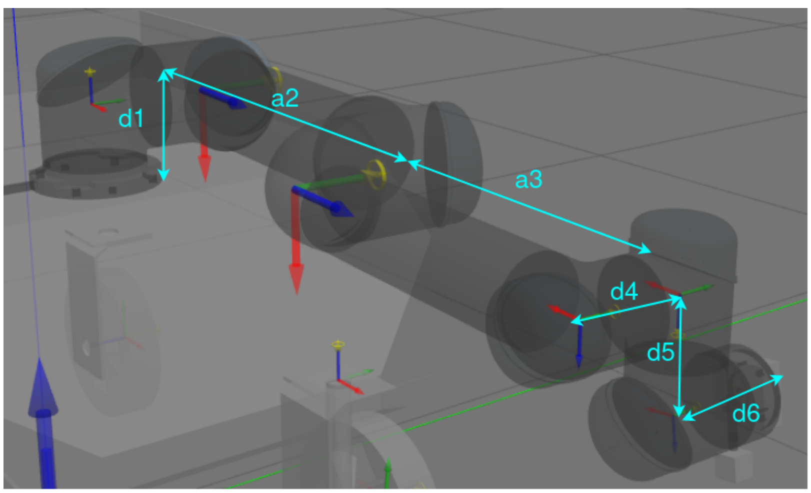


Figure 5: DH diagram of UR5 robot in scene of Gazebo frames

The DH Parameter Table of the manipulator is :

Link	θ	d	a	α
$1->0$	θ_1	$d_1 = 0.08159$	0	$\pi/2$
$2->1$	θ_2	0	$a_2 = -0.425$	0
$3->2$	θ_3	0	$a_3 = -0.39225$	0
$4->3$	θ_4	$d_4 = 0.1095$	0	$\pi/2$
$5->4$	θ_5	$d_5 = 0.09465$	0	$\pi/2$
$6->5$	θ_6	$d_6 = 0.0823$	0	0

Table 2: DH Table of the UR5 Robot

The final individual transformation matrices for each link from 1 to 6 are given below:

$$^0T_1 = \begin{bmatrix} \cos(\theta_1) & 0 & \sin(\theta_1) & 0 \\ \sin(\theta_1) & 0 & -\cos(\theta_1) & 0 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad ^1T_2 = \begin{bmatrix} \cos(\theta_2) & -\sin(\theta_2) & 0 & a_2\cos(\theta_2) \\ \sin(\theta_2) & \cos(\theta_2) & 0 & a_2\sin(\theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^2T_3 = \begin{bmatrix} \cos(\theta_3) & -\sin(\theta_3) & 0 & a_3\cos(\theta_3) \\ \sin(\theta_3) & \cos(\theta_3) & 0 & a_3\sin(\theta_3) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad ^3T_4 = \begin{bmatrix} \cos(\theta_4) & 0 & \sin(\theta_4) & 0 \\ \sin(\theta_4) & 0 & -\cos(\theta_4) & 0 \\ 0 & 1 & 0 & d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^4T_5 = \begin{bmatrix} \cos(\theta_5) & 0 & -\sin(\theta_5) & 0 \\ \sin(\theta_5) & 0 & \cos(\theta_5) & 0 \\ 0 & -1 & 0 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad ^5T_6 = \begin{bmatrix} \cos(\theta_6) & -\sin(\theta_6) & 0 & 0 \\ \sin(\theta_6) & \cos(\theta_6) & 0 & 0 \\ 0 & 0 & 1 & d_6 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The Final Transformation matrix is obtained by multiplying above individual transformation matrices in reference to equation (1) given below:

$$
\left[\begin{matrix}
(\sin(\theta_1)\sin(\theta_5) + \cos(\theta_1)\cos(\theta_5)\cos(\theta_2+\theta_3+\theta_4))\cos(\theta_6) - \sin(\theta_6)\sin(\theta_2+\theta_3+\theta_4)\cos(\theta_1) \\
(\sin(\theta_1)\cos(\theta_5)\cos(\theta_2+\theta_3+\theta_4) - \sin(\theta_5)\cos(\theta_1))\cos(\theta_6) - \sin(\theta_1)\sin(\theta_6)\sin(\theta_2+\theta_3+\theta_4) \\
\sin(\theta_6)\cos(\theta_2+\theta_3+\theta_4) + \sin(\theta_2+\theta_3+\theta_4)\cos(\theta_5)\cos(\theta_6) \\
0
\end{matrix}\right.
$$

$$
\begin{matrix}
-(\sin(\theta_1)\sin(\theta_5) + \cos(\theta_1)\cos(\theta_5)\cos(\theta_2+\theta_3+\theta_4))\sin(\theta_6) - \sin(\theta_2+\theta_3+\theta_4)\cos(\theta_1)\cos(\theta_6) \\
(-\sin(\theta_1)\cos(\theta_5)\cos(\theta_2+\theta_3+\theta_4) + \sin(\theta_5)\cos(\theta_1))\sin(\theta_6) - \sin(\theta_1)\sin(\theta_2+\theta_3+\theta_4)\cos(\theta_6) \\
-\sin(\theta_6)\sin(\theta_2+\theta_3+\theta_4)\cos(\theta_5) + \cos(\theta_6)\cos(\theta_2+\theta_3+\theta_4) \\
0
\end{matrix}
$$

$$
\begin{matrix}
\sin(\theta_1)\cos(\theta_5) - \sin(\theta_5)\cos(\theta_1)\cos(\theta_2+\theta_3+\theta_4) \\
-\sin(\theta_1)\sin(\theta_5)\cos(\theta_2+\theta_3+\theta_4) - \cos(\theta_1)\cos(\theta_5) \\
-\sin(\theta_5)\sin(\theta_2+\theta_3+\theta_4) \\
0
\end{matrix}
$$

$$
\left.\begin{matrix}
a_2\cos(\theta_1)\cos(\theta_2) + a_3\cos(\theta_1)\cos(\theta_2+\theta_3) + d_4\sin(\theta_1) + d_5\sin(\theta_2+\theta_3+\theta_4)\cos(\theta_1) + d_6\sin(\theta_1)\cos(\theta_5) - d_6\sin(\theta_5)\cos(\theta_1)\cos(\theta_2+\theta_3+\theta_4) \\
a_2\sin(\theta_1)\cos(\theta_2) + a_3\sin(\theta_1)\cos(\theta_2+\theta_3) - d_4\cos(\theta_1) + d_5\sin(\theta_1)\sin(\theta_2+\theta_3+\theta_4) - d_6\sin(\theta_1)\sin(\theta_5)\cos(\theta_2+\theta_3+\theta_4) - d_6\cos(\theta_1)\cos(\theta_5) \\
a_2\sin(\theta_2) + a_3\sin(\theta_2+\theta_3) + d_1 - d_5\cos(\theta_2+\theta_3+\theta_4) - d_6\sin(\theta_5)\sin(\theta_2+\theta_3+\theta_4) \\
1
\end{matrix}\right]
$$

Figure 6: Final Transformation Matrix

6 Inverse Kinematics

Inverse Kinematics is defined as the determination of all possible and feasible sets of joint variables, which would achieve the specified position and orientation of the manipulator's end-effector with respect to the base frame. Inverse Kinematics is complex because the solution is to be found for non linear simultaneous equations, involving transcendental functions. The number of simultaneous equations is also generally more than the number of unknowns, making some of the equations mutually dependent.

Since existence of multiple solutions for a inverse kinematics problem, the project aims to implement and study two different methods to solve a inverse kinematics problem. The two different methods are : Geometric Approach and Geometric Jacobian.

6.1 Geometric Approach

A Geometric Approach is a closed form solution which gives a solution when three coordinate joint axes intersect or its three consecutive joint axes are parallel. A composite approach based on direct inspection of individual transformation matrices, algebra and inverse transforms are used in solving the inverse kinematics problem in reference [1]. The process of the inverse kinematics is solved below by using using a known end-effector position and orientation with help of python to code all the transforms and calculations as shown below:
Note: For a final position of the end effector which is on positve x and y, we consider negative x and y since the final transformation matrices and frames place the robot in negative direction. The visbility of manipulator on positive x and y in gazebo is due to rotation of manipulator by 180 degrees to be aligned to gazebo world.

$$^0T_6 = \begin{bmatrix} 1 & 0 & 0 & -0.1 \\ 0 & 1 & 0 & -0.5 \\ 0 & 0 & 1 & 0.5 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} ^0X_{6x} & ^0Y_{6x} & ^0Z_{6x} & ^0P_{6x} \\ ^0X_{6y} & ^0Y_{6y} & ^0Z_{6y} & ^0P_{6y} \\ ^0X_{6z} & ^0Y_{6z} & ^0Z_{6z} & ^0P_{6z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

1. **Calculation of θ_1 :**

$$^0P_5 =^0 T_6 * \begin{bmatrix} 0 \\ 0 \\ -d_6 \\ 0 \end{bmatrix} = \begin{bmatrix} -0.1 \\ -0.5 \\ 0.4177 \\ 1 \end{bmatrix}$$

$$\theta_1 = \arctan 2(^0P_{5y}, ^0P_{5x}) + \arccos \frac{d4}{\sqrt{^0P_{5x}{}^2 +^0 P_{5y}{}^2}} + \frac{\pi}{2}$$

After substitutions, $\theta_1 = 1.157$(in rads).

2. **Calculation of θ_5 :**

$$\theta_5 = -\arccos(\frac{^0P_{6x}\sin\theta_1 +^0 P_{6y}\cos\theta_1 - d_4}{d_6})$$

Assumption to give an arbitrary value for the angle if magnitude of value inside arccos is greater than 1. After calculations and substitutions, $\theta_5 = 0.001$(in rads).

3. **Calculation of θ_6 :**

$$^6T_0 = [^0T_6]^{-1}$$

$$\theta_6 = \arctan 2\left(-\frac{^6X_{0y}\sin\theta_1 +^6 Y_{0y}\cos\theta_1}{\sin\theta_5}, \frac{^6X_{0x}\sin\theta_1 -^6 Y_{0x}\cos\theta_1}{\sin\theta_5}\right)$$

   Before Calculations, if $\sin\theta_5$ is 0 , we assume an arbitrary value for θ_6. After calculations, $\theta_6 = 0.0$ (in rads).

4. **Calculation of θ_3 :**

$$^1T_4 =^5 T_6{}^{-1} *^4 T_5{}^{-1} *^0 T_1{}^{-1} *^0 T_6$$

$$\theta_3 = \arccos\left(\frac{(\sqrt{^1P_{4x}{}^2 +^1 P_{4z}{}^2})^2 - a_2^2 - a_3^2}{2a_2a_3}\right)$$

   After Calculations, $\theta_3 = 1.570$ (in rads).

5. **Calculation of θ_2 :**

$$\theta_2 = \arctan 2(-^1P_{4z}, -^1P_{4x}) - \arcsin\left(\frac{-a_3\sin\theta_3}{\sqrt{^1P_{4x}{}^2 +^1 P_{4z}{}^2}}\right)$$

   After Calculations , $\theta_2 = -1.301$ (in rads).

6. **Calculation of θ_4 :**

$$^3T_4 =^5 T_6{}^{-1} *^4 T_5{}^{-1} *^2 T_3{}^{-1} *^1 T_2{}^{-1} *^0 T_1{}^{-1} *^0 T_6$$

$$\theta_4 = \arctan(^3P_{4y}, ^3 P_{4x})$$

   After calculations, $\theta_4 = -0.0069$ (in rads).

6.2 Geometric Jacobian

The manipulator Jacobian relates the vector of joint velocities to the end-effector velocities. A Jacobian matrix is 6X6 square matrix consist of partial differentiation's. The Geometric Jacobian derives the joint velocities by product of inverse of jacobian with end-effector velocities which comes under Velocity Kinematics. These joint velocities are converted into joint angles by numerical integration. In this project, a circle is considered as a trajectory to be traced by the end-effector and joint angles at each instant is calculated using velocity kinematics.

The process of calculating Jacobian for velocity kinematics is as follows:

1. The relation between Jacobian, Cartesian and joint velocities of the manipulator is given as:

$$\zeta = J\dot{q}$$

   where ζ is the end-effetor velocity vector, J is the Jacobian Matrix, $\dot{q}$ is the joint velocities vector. To calculate the joint velocities for given end-effector velocities, we use Jacobian inverse given as:

$$\dot{q} = [J]^+ * \zeta \tag{3}$$

   where $[J]^+$ is the right pseudoinverse of J given as $[J]^+ = J^T(JJ^T)^{-1}$

2. Calculation of Jacobian Matrix starts by taking the position vector ${}^0P_6$ from ${}^0T_6$ of (1). Then, the partial differentiation of position vector ${}^0P_6$ with respect to joint angles are calculated and form a 3X6 matrix of 6X6 Jacobian Matrix. Calculation of ${}^0Z_i$ for the second 3X6 matrix is calculated by taking the third column from transformation matrices ${}^0T_i$ for $i = 1, 2, ...6$. The Jacobian 6X6 matrix with two 3X6 matrix as mentioned above is given as

$$J = \begin{bmatrix} \frac{\partial^0 P_6}{\partial\theta_1} & \frac{\partial^0 P_6}{\partial\theta_2} & \frac{\partial^0 P_6}{\partial\theta_3} & \frac{\partial^0 P_6}{\partial\theta_4} & \frac{\partial^0 P_6}{\partial\theta_5} & \frac{\partial^0 P_6}{\partial\theta_6} \\ {}^0Z_1 & {}^0Z_2 & {}^0Z_3 & {}^0Z_4 & {}^0Z_5 & {}^0Z_6 \end{bmatrix}_{6X6}$$

The Final Jacobian Matrix is given as below:

$$\begin{bmatrix} 0.0823 \sin(\theta_1) \sin(\theta_5) \cos(\theta_2 + \theta_3 + \theta_4) - 0.09465 \sin(\theta_1) \sin(\theta_2 + \theta_3 + \theta_4) + 0.425 \sin(\theta_1) \cos(\theta_2) + 0.39225 \sin(\theta_1) \cos(\theta_2 + \theta_3) + 0.0823 \cos(\theta_1) \cos(\theta_5) + 0.10915 \cos(\theta_1) \\ 0.0823 \sin(\theta_1) \cos(\theta_5) + 0.10915 \sin(\theta_1) - 0.0823 \sin(\theta_5) \cos(\theta_1) \cos(\theta_2 + \theta_3 + \theta_4) + 0.09465 \sin(\theta_2 + \theta_3 + \theta_4) \cos(\theta_1) - 0.425 \cos(\theta_1) \cos(\theta_2) - 0.39225 \cos(\theta_1) \cos(\theta_2 + \theta_3) \\ 0 \\ \sin(\theta_1) \\ -\cos(\theta_1) \\ 0 \end{bmatrix}$$

$$\begin{matrix} (0.425 \sin(\theta_2) + 0.0823 \sin(\theta_5) \sin(\theta_2 + \theta_3 + \theta_4) + 0.39225 \sin(\theta_2 + \theta_3) + 0.09465 \cos(\theta_2 + \theta_3 + \theta_4)) \cos(\theta_1) \\ (0.425 \sin(\theta_2) + 0.0823 \sin(\theta_5) \sin(\theta_2 + \theta_3 + \theta_4) + 0.39225 \sin(\theta_2 + \theta_3) + 0.09465 \cos(\theta_2 + \theta_3 + \theta_4)) \sin(\theta_1) \\ -0.0823 \sin(\theta_5) \cos(\theta_2 + \theta_3 + \theta_4) + 0.09465 \sin(\theta_2 + \theta_3 + \theta_4) - 0.425 \cos(\theta_2) - 0.39225 \cos(\theta_2 + \theta_3) \\ \sin(\theta_1) \\ -\cos(\theta_1) \\ 0 \end{matrix}$$

$$\theta_1) \quad (0.0823 \sin(\theta_5) \sin(\theta_2 + \theta_3 + \theta_4) + 0.39225 \sin(\theta_2 + \theta_3) + 0.09465 \cos(\theta_2 + \theta_3 + \theta_4)) \cos(\theta_1)$$

$$\theta_1) \quad (0.0823 \sin(\theta_5) \sin(\theta_2 + \theta_3 + \theta_4) + 0.39225 \sin(\theta_2 + \theta_3) + 0.09465 \cos(\theta_2 + \theta_3 + \theta_4)) \sin(\theta_1)$$

$$-0.0823 \sin(\theta_5) \cos(\theta_2 + \theta_3 + \theta_4) + 0.09465 \sin(\theta_2 + \theta_3 + \theta_4) - 0.39225 \cos(\theta_2 + \theta_3)$$

$$\sin(\theta_1)$$

$$-\cos(\theta_1)$$

$$0$$

$$(0.0823 \sin(\theta_5) \sin(\theta_2 + \theta_3 + \theta_4) + 0.09465 \cos(\theta_2 + \theta_3 + \theta_4)) \cos(\theta_1)$$

$$(0.0823 \sin(\theta_5) \sin(\theta_2 + \theta_3 + \theta_4) + 0.09465 \cos(\theta_2 + \theta_3 + \theta_4)) \sin(\theta_1)$$

$$-0.0823 \sin(\theta_5) \cos(\theta_2 + \theta_3 + \theta_4) + 0.09465 \sin(\theta_2 + \theta_3 + \theta_4)$$

$$\sin(\theta_2 + \theta_3 + \theta_4) \cos(\theta_1)$$

$$\sin(\theta_1) \sin(\theta_2 + \theta_3 + \theta_4)$$

$$-\cos(\theta_2 + \theta_3 + \theta_4)$$

$$\left.\begin{matrix}
-0.0823 \sin(\theta_1) \sin(\theta_5) - 0.0823 \cos(\theta_1) \cos(\theta_5) \cos(\theta_2 + \theta_3 + \theta_4) & 0 \\
-0.0823 \sin(\theta_1) \cos(\theta_5) \cos(\theta_2 + \theta_3 + \theta_4) + 0.0823 \sin(\theta_5) \cos(\theta_1) & 0 \\
-0.0823 \sin(\theta_2 + \theta_3 + \theta_4) \cos(\theta_5) & 0 \\
\sin(\theta_1) \cos(\theta_5) - \sin(\theta_5) \cos(\theta_1) \cos(\theta_2 + \theta_3 + \theta_4) & \sin(\theta_1) \cos(\theta_5) - \sin(\theta_5) \cos(\theta_1) \cos(\theta_2 + \theta_3 + \theta_4) \\
-\sin(\theta_1) \sin(\theta_5) \cos(\theta_2 + \theta_3 + \theta_4) - \cos(\theta_1) \cos(\theta_5) & -\sin(\theta_1) \sin(\theta_5) \cos(\theta_2 + \theta_3 + \theta_4) - \cos(\theta_1) \cos(\theta_5) \\
-\sin(\theta_5) \sin(\theta_2 + \theta_3 + \theta_4) & -\sin(\theta_5) \sin(\theta_2 + \theta_3 + \theta_4)
\end{matrix}\right]$$

Figure 8: Final Jacobian Matrix

3. In this project the final Jacobian Matrix and Jacobian Inverse Matrix after substitution of intial joint angles as zero along with link lengths and link offsets is given as :

$$J = \begin{bmatrix} 0.191 & 0.095 & 0.095 & 0.095 & -0.082 & 0 \\ -0.817 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.817 & -0.392 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & -1 & -1 & 0 & -1 & -1 \\ 0 & 0 & 0 & -1 & 0 & 0 \end{bmatrix}$$

$$J^{-1} = \begin{bmatrix} -3.05 \cdot 10^{-5} & -1.22 & 0.00146 & 0 & 0.000366 & 1.19 \cdot 10^{-5} \\ -3.6 & -1.05 & -1.75 & 0 & 0.18 & -0.341 \\ 7.49 & 2.2 & 1.11 & 0 & -0.371 & 0.711 \\ -0.00166 & 4.6 \cdot 10^{-5} & 0.000305 & 0 & -0.000366 & -0.999 \\ -7.89 & -1.52 & -0.711 & 0 & -0.261 & -0.748 \\ 3.98 & 1.59 & 1.35 & 0 & -0.548 & 0.378 \end{bmatrix}$$

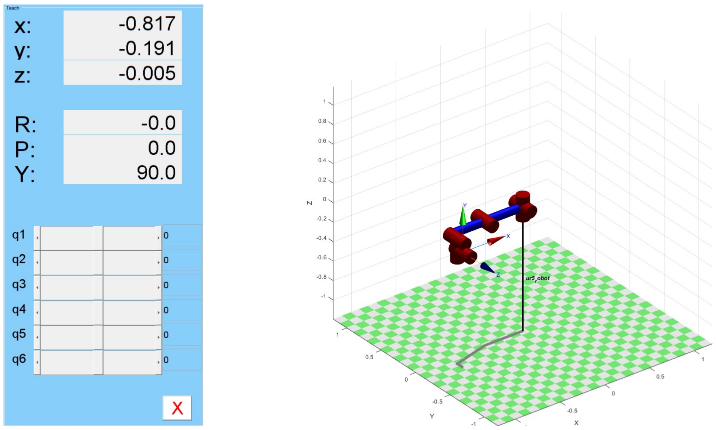
4. Once the variable Jacobian Matrix is derived, we use (3) to calculate the joint velocity vector from the Jacobian Matrix and Cartesian Velocity Vector. This is done by considering a circle trajectory equation in polar coordinate form for the Cartesian Velocity vector and substituting joint angles (starting from predefined initial angles) in Jacobian inverse matrix to get the joint velocity vector for the next iteration. Numerical integration is performed on the joint velocity vector to obtain joint angles for the first iteration and position and considered.

5. The above process is repeated for n times to complete a circle. The joint angles at each iteration are stored and fed to the the manipulator to trace the circle trajectory by the end-effector.

7 Forward Kinematics Validation

Forward Kinematics Validations are performed using MATLAB Peter Corke Toolbox for certain joint angles and the final end-effector position and orientation are displayed which is validated against final transformation matrix calculated by substitution of joint angles.

1. Considering (1), the final transformation matrix obtained by substituting all joint angles as zero which is the home position of the robot and the geometrical orientation of the robot are below

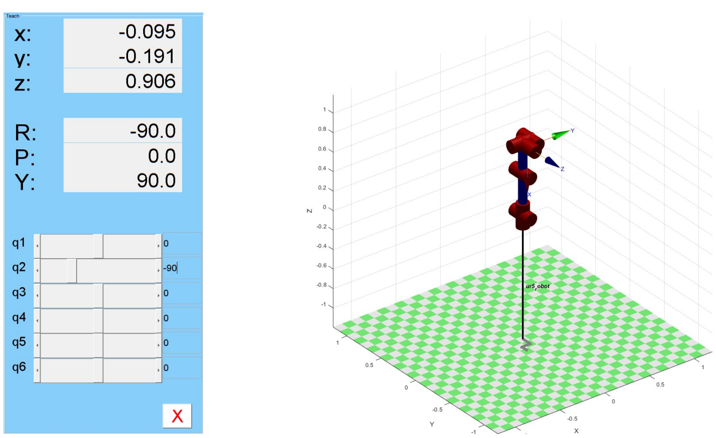


The Final Transformation matrix is:

$$\begin{bmatrix} 1 & 0 & 0 & -0.817 \\ 0 & 0 & -1 & -0.191 \\ 0 & 1 & 0 & -0.005 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 9: Geometric Figure when all joint angles are zero

2. Considering (1), the final transformation matrix obtained by substituting θ_2 rotated by $-\pi/2$ and all other joint angles as zero along with the geometrical orientation of the robot are below

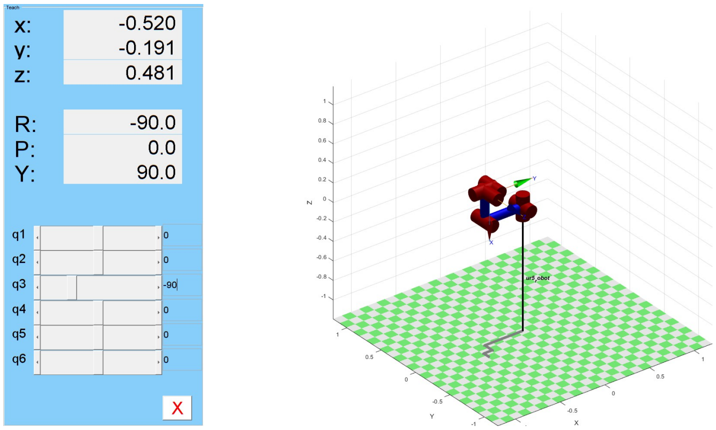


The Final Transformation matrix is:

$$\begin{bmatrix} 0 & 1.0 & 0 & -0.095 \\ 0 & 0 & -1 & -0.191 \\ -1.0 & 0 & 0 & 0.906 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 10: Geometric Figure when θ_2 by $-\pi/2$ all other joint angles are zero

3. Considering (1), the final transformation matrix obtained by substituting θ_3 by $-\pi/2$ and all other joint angles as zero along with the geometrical orientation of the robot are below

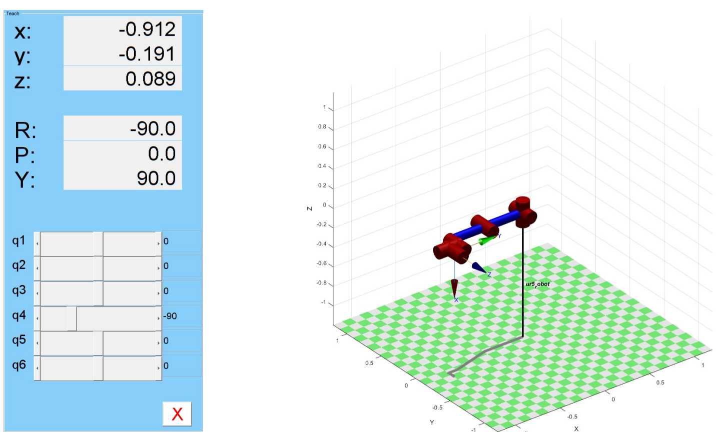


The Final Transformation matrix is:

$$\begin{bmatrix} 0 & 1.0 & 0 & -0.52 \\ 0 & 0 & -1 & -0.191 \\ -1.0 & 0 & 0 & 0.481 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 11: Geometric Figure when θ_3 rotated by $-\pi/2$ all other joint angles are zero

4. Considering (1), the final transformation matrix obtained by substituting θ_2 by $-\pi/2$ and all joint angles as zero which is the home position of the robot and the geometrical orientation of the robot are below



The Final Transformation matrix is:

$$\begin{bmatrix} 0 & 1.0 & 0 & -0.912 \\ 0 & 0 & -1 & -0.191 \\ -1.0 & 0 & 0 & 0.089 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 12: Geometric Figure when θ_4 rotated by $-\pi/2$ and all other joint angles are zero

8 Inverse Kinematics Validation

1. For the given below final position and orientation, the joint angles derived using inverse kinematics approach are:

$$\begin{bmatrix} 1 & 0 & 0 & -0.1 \\ 0 & 1 & 0 & -0.5 \\ 0 & 0 & 1 & 0.5 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \\ \theta_5 \\ \theta_6 \end{bmatrix} (\text{in rads}) = \begin{bmatrix} 1.157 \\ -1.30 \\ 1.570 \\ -0.0069 \\ 0.001 \\ 0 \end{bmatrix}$$

   The above is validated through below image in Gazebo World.

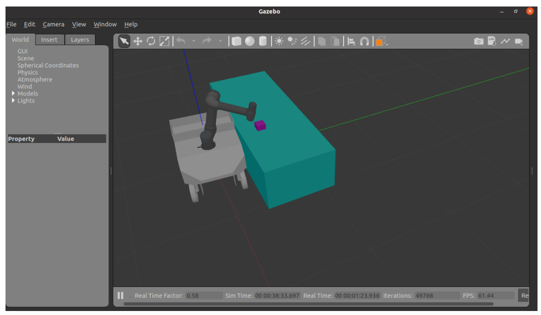


Figure 13: Robot Position and Orientation for given joint angles above.

   Note: The end-effector matrix has negative x and y but the gazebo world figure shows positive x and y as the manipulator is rotated by 180 degrees to align with gazebo world keeping the coordinate axes and lengths of the manipulator same. Also, there is an offset for manipulator in $x = 0.2$ and $z = 0.55$ as it is placed on mobile manipulator

2. Similary to above, the below shows validation for certain position and orientation given. The manipulator position looks like θ_2 rotated by $-\pi/2$ but done with inverse position kinematics.

$$\begin{bmatrix} 0 & 1 & 0 & -0.095 \\ 0 & 0 & -1 & -0.191 \\ -1 & 0 & 0 & 0.906 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \\ \theta_5 \\ \theta_6 \end{bmatrix} (\text{in rads}) = \begin{bmatrix} -0.004 \\ -1.36 \\ 0 \\ 3.14 \\ 0.001 \\ 1.57 \end{bmatrix}$$

3. The Jacobian Method is performed for inverse velocity kinematics and later obtained joint angles and position vectors which are used to plot a circle trajectory with the end effector. The Circle Trajectory traced by the end-effector and the process is shown below:

   (a) The circle is generated in x-y plane starting from intial position by changing θ_2 and θ_3 by $-\pi/2$

   $\begin{bmatrix} \theta_1 & \theta_2 & \theta_3 & \theta_4 & \theta_5 & \theta_6 \end{bmatrix}$ (in rads) $= \begin{bmatrix} 0, & -\pi/2, & -\pi/2, 0, 0, 0 \end{bmatrix}$

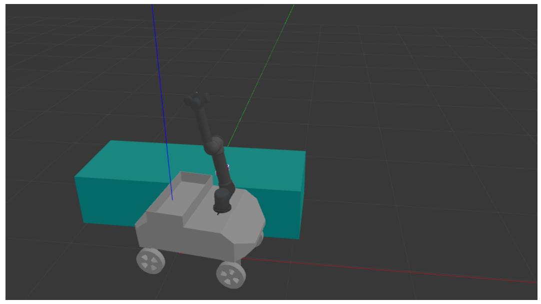


Figure 14: Robot Position and Orientation for given joint angles above.

(b) The end-effector position and orientation for the initial position at the start point of the circle for above joint angles is: $\begin{bmatrix} 0 & -1.0 & 0 & 0.487 \\ 0 & 0 & -1 & -0.191 \\ 1.0 & 0 & 0 & 0.514 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

(c) The circle is drawn in x-y plane with a radius of $0.439m$

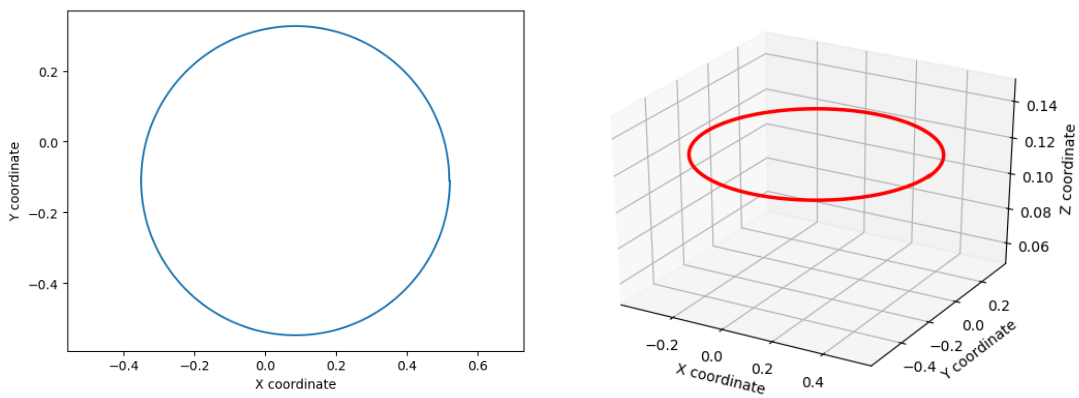


Figure 15: Circle Trajectory Using Inverse Jacobian

(d) From the above 2D and 3D figure you can see the end-effector of the manipulator making a circle.

9 Workspace Study

Workspace is the volume of the manipulator that the end-effector can reach. Reachable workspace is that volume of space that the robot can reach in at least one orientation. We checked in gazebo the maximum angles UR5 manipulator can reach without colliding with the car.

We considered the following values for the six joint angles and varied it iterative process to plot the workspace: $\begin{bmatrix}\theta_1\\ \theta_2\\ \theta_3\\ \theta_4\\ \theta_5\\ \theta_6\end{bmatrix}$ (in rads) $= \begin{bmatrix}[-2\pi/3, 2\pi/3]\\ [-\pi/6, \pi]\\ [-\pi/2, \pi]\\ [-\pi, \pi]\\ [-\pi, \pi]\\ [-\pi, \pi]\end{bmatrix}$

We have written the code accordingly to plot it which is shown below:

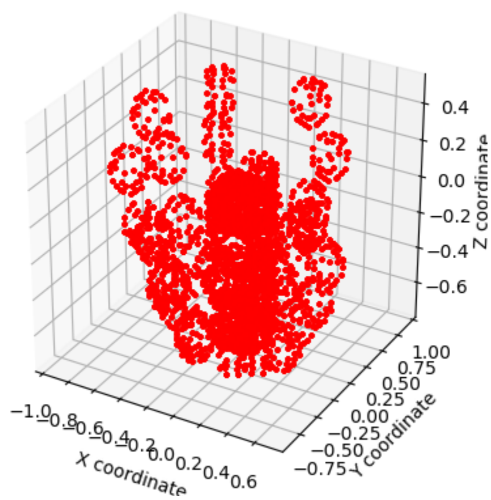


Figure 16: Workspace of UR5 robot plotted considering mobile robot

10 Assumptions

1. The manipulator's mass is assumed to be less than the mobile robot's mass so that the whole robot does not roll over due to higher weight of the manipulator.
2. The physical properties in gazebo world are modified to cater for the gripping of the object.
3. All the joints and objects are considered to be rigid.
4. The friction and the other external disturbances are not taken into account.
5. The path of the arm or the robot is just one solution among all the other solutions it can have, this may or may not be the optimal solution.
6. The vacuum gripper is assumed to be holding the object with zero leakage in vacuum chamber.

11 Control Method

1. The speed of the vehicle is controlled by Joint Velocity Controller under velocity controllers.
2. The front wheels turning is controlled by Joint Position Controller under effort controllers. PID values are tuned by trial and error method to accurately apply effort to the wheels while turning.
3. Effort Controllers are initially used for the control of the manipulator. Controllers for manipulator are changed finally to have a smooth trajectory of the manipulator joints.
4. Position Controller under Joint Trajectory Controller is used to control the movement of the joints. Joint Trajectory Controller in ROS generally uses spline trajectory, so, with the input of the joint angles as positions the controller generates a trajectory and moves the joints to desired positions.
5. Action-Client Interface of ROS is used while performing circle trajectory using jacobian method as continuous feedback is needed along with publishing joint angles continuously.

12 Gazebo and Rviz Visualization

1. The mobile manipulator is simulated in Gazebo Environment for all different tasks performed. The video links for respective task are as below:
   - The Pick and Place Operation performed by the robot using inverse kinematics solved by Geometric method.

     `https://drive.google.com/file/d/1F4TqWvGZ0BlKcac5Sqijzh1z0_vbMpse/view?usp=share_link`
   - The Circle Trajectory Generated by the manipulator using Jacobian Method.

     `https://drive.google.com/file/d/1bGCNyhyKmm9xP6yTCfAZfQAsFweyl16L/view?usp=share_link`

- The Rviz Visualization video is shown with the integration of Lidar Sensor on the manipulator.

  https://drive.google.com/file/d/1uzL0Z0UH1fzygQ-NhrnuENQcsqpPLcPa/view?usp=share_link

- The Pick and Place operation showing the function of gripper by giving accurate angles for given position and orientation(Used IK Solver) along with a Camera integrated with its movement in Pictures recorded in Rviz.

  https://drive.google.com/file/d/1sc5lYk7lH073bfp22U8k3cjHIqYwj_GH/view?usp=share_link

13 Problems Faced

1. Vacuum gripper rosservice activation: Although the gripper is near the object to be picked and the service is called, the object doesn't get attached to the gripper since the power is not appropriate. Modified the ur5 robot position to go near to the object.

2. As the ur5 model in URDF has been rotated by 180 degrees, we were not able to figure it out in the start and it caused problems while testing the manipulator in gazebo world.

3. Faced problems generating the circle trajectory in Gazebo world due to singularities and finding out the maximum reachable workspace by the manipulator. Also, the workspace of the manipulator is reduced with the mobile robot as the manipulator should not collide with the mobile robot.

4. Faced problems to get accurate joint angles for given position and orientation by using inverse kinematics via geometric approach due to existence of many solutions or some joint angles resulting zero.

14 Lessons Learned

1. Assignment of frames in CAD model to joints so that it matches with gazebo world coordinate axes and the base link coincides with origin of Gazebo without any offset.

2. Learned about all different ROS controllers present and differences between each controller thus deciding the type of controller to be used according to the application.

3. Studied the Workspace of the manipulator so that it does the goal placement can be happened according to maximum reachability of the manipulator.

4. Understanding the singularities of the manipulator.

5. Solving inverse kinematics using geometrical method and deciding upon one solution which approximately fits the manipulator.

15 Future Work

Most of the tasks mentioned in the goals are been achieved in this project. Some of the future works planned to be performed are:

1. The optimisation of inverse kinematics algorithms is planned to be performed in the future to present an optimal solution so that manipulator can move to any desired position efficiently within its workspace.

2. With the integration of camera, we are planning to include image processing so that without giving the desired position manually the robot can detect the object as it move along the path and feed the position to inverse kinematics method to evaluate the joint angles.

3. The gripper mechanism used is a simple one but for warehouse application multiple types of gripper assemblies may be required and the design of a mechanism to dynamically exchange grippers in the simulation environment still needs to be done.

16 Results and Conclusion

Through this project, we have a modeled a mobile manipulator using Solidworks and spawned the mobile robot integrated with the manipulator URDF in Gazebo. We have used variety of controllers and transmission in this project to make the robot move and perform tasks. Forward Kinematics and its validation are performed with some of the results enclosed in the report. A detailed study is made on inverse kinematics and different solutions and methods for solving of Inverse Kinematics is discussed and results are presented. The inverse kinematic solution derived through geometric and Jacobian method make the robot move to a desired position given.

17 References

1. A Inverse Geometric Approach: `http://rasmusan.blog.aau.dk/files/ur5_kinematics.pdf`

2. Robot Modeling and Control, Mark W. Spong, Seth Hutchinson, and M. Vidyasagar.

3. Robotics and Control, R K Mittal, I J Nagrath.

4. Lecture Notes-Introduction to Robot Modeling, Prof Reza Monafredi.

5. URDF UR5 - `https://github.com/ros-industrial/universal_robot/tree/melodic-devel/ur_description`

6. `https://www.universal-robots.com/`

7. Action Client Interface - `http://wiki.ros.org/pr2_controllers/Tutorials/Moving%20the%20arm%20using%20the%20Joint%20Trajectory%20Action`

8. Action Client Interface - `https://github.com/noshluk2`

Appendix

Individual Contributions:

1. **Darshit**

   - Design and CAD modeling.
   - Gazebo World Development and integration of Camera, Lidar and Gripper plugins.
   - Forward Kinematics Validation using Peter Coorke Toolbox.
   - Invere Kinematics Jacobian method and code to generate circle trajectory.
   - Preparation of report and ppt.
   - Identifying the errors and optimising the code and operations performed.

2. **Vinay**

   - Integration of URDF of mobile robot and ur5 URDF along with launch file, configuration files creation.
   - Spawning the model in gazebo and testing with different controllers, transmission interfaces.
   - Inverse Kinematics Geometric Approach derivation and code.
   - Preparation of report and ppt.
   - Identifying the errors and optimising the code and operations performed.