Introduction to Robot Modeling (ENPM 662)

Project 2 Report

Mars rover

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Introduction

Robots are being rapidly deployed in space exploration missions. Utilizing robots in space missions eliminates the risk of loss of human life due to accidents. The deployment of robots also makes the process more cost-effective. Mars Rover is one among several such robots used by NASA in its space mission to Mars. Mars Rover is equipped with a high definition camera to click images of Mars' surface to find evidence of life-supporting elements like water, oxygen, carbon, etc. It also has a robotic arm attached to it to perform various tasks.

Studies have shown that Mars has the potential to harbour life. Although there is no visual evidence of the existence of life on Mars presently, it is possible that the Red Planet could have supported life sometime in the past. Soil and rock samples found on Mars' surface can be analyzed to identify the fossils of the life that now cease to exist. Since sending human beings to the Red Planet to collect the soil and rock samples involves a tremendous amount of risk, a robot can be sent on a space mission to collect the soil and rock samples from Mars' surface.

Application

Mars' surface is full of rocks, volcanoes, dry lake beds, and craters. Red dust covers most of its surface. The robot that we designed, named Mars Rover, is capable of traversing the uneven Martian terrain. Mars Rover has a mobile base so that it can traverse to any position on Mars' surface. 6 degrees of freedom robotic arm on top of the mobile base has an end effector that can hold a drill bit and drill holes in the rock and collect powdered rock samples. A gripper can also be placed at the end-effector to pick and place the rock and soil samples. Once collected, these samples can be brought to the Earth where they can be analysed and studied.

Robot Type

Mars Rover is a mobile robot that can traverse the uneven terrain of Mars. The mobile base of the robot has four wheels of which the front two are steerable and the rear two are the ones where the torque is provided through direct current motors. Motors are also placed on top of the two steerable wheels to control the steering action. Mars Rover also has an onboard solar panel that is used to trap solar energy from the sun and is converted into electrical energy to drive the motors at the wheels and the joints of the robotic arm.

6 degrees of freedom KUKA KR5 robotic manipulator is mounted on top of the mobile base. All the 6 joints of the arm are revolute and there is no prismatic joint. The joints are controlled by direct current motors. The maximum reach of the robotic manipulator is 1423 millimetres and its rated payload is 5 kilograms.

Degrees of Freedom and Dimensions

The mobile base enables the robot to reach any point on the Martian surface and also orient the robot at any desired angle. This gives 3 degrees of freedom to the Mars Rover. Since the KUKA KR5 robotic manipulator has 6 joints, 6 more degrees of freedom are added to the Mars Rover robot system. This makes the Mars Rover a robot with 9 degrees of freedom. However, for the purpose of this project, it is assumed that the robot has only 6 degrees of freedom by ignoring the 3 degrees of freedom due to the mobile base.

CAD Models

Figure.a. CAD model of Kuka KR5

Figure.b. CAD model of Kuka KR5

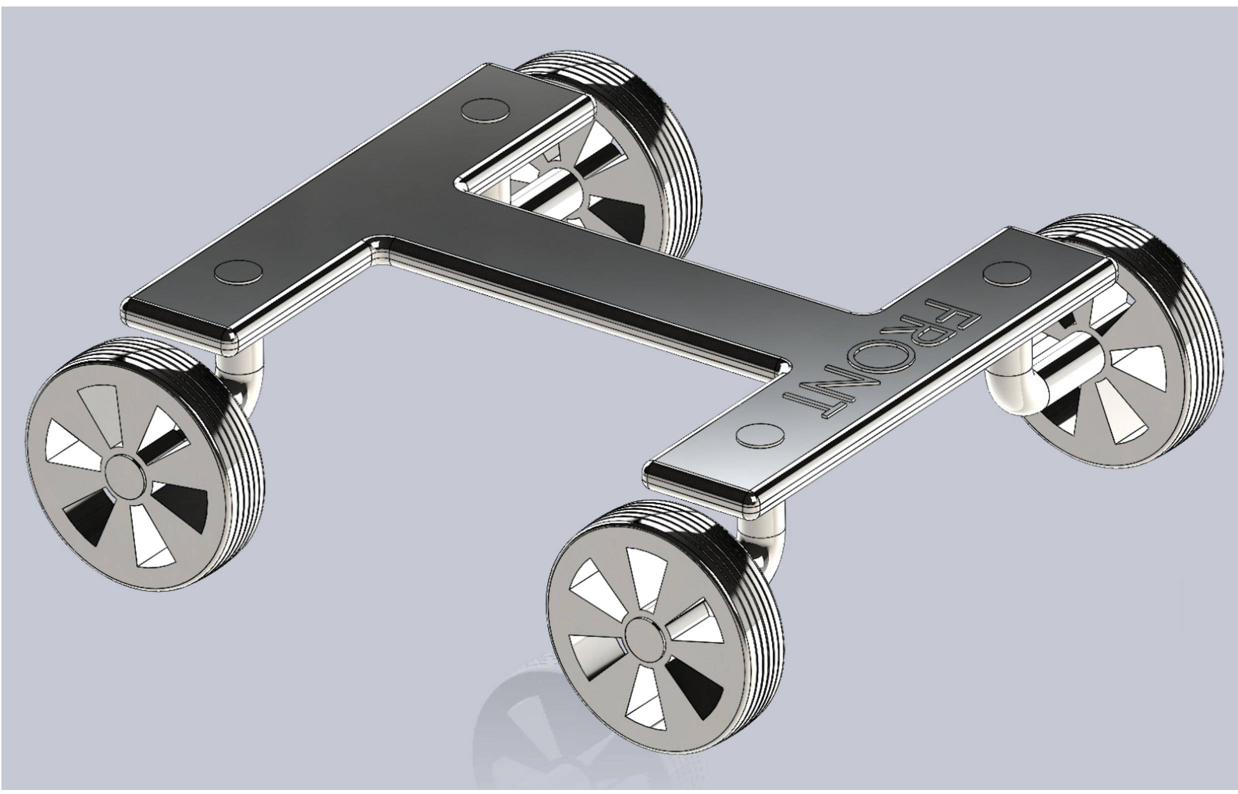


Figure.c. CAD model of Rover

Link: [**Robot Parts and Assembly**]

DH parameters

Figure. Actual image of KUKA KR5

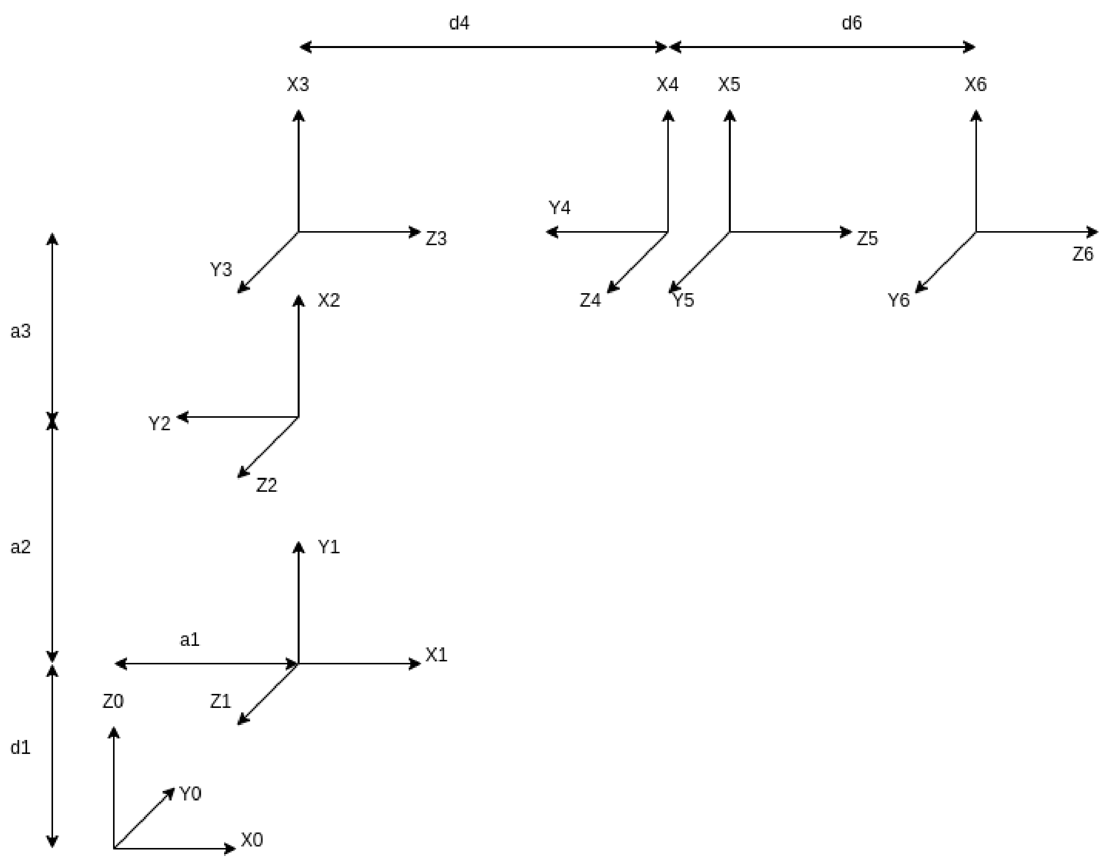


Figure. KUKA KR5 Frame Assignment

While assigning frames to formulate DH parameters, the following two conditions should be satisfied:

$X_i \perp Z_{i-1}$ i.e. X_i should be perpendicular to Z_{i-1}
$X_i \cap Z_{i-1}$ i.e. X_i should intersect to Z_{i-1}

Frames have been assigned to each joint in figure XXXXX. Frames can be shifted from the joint positions to satisfy the aforementioned conditions. Note that in the figure, frame 3 is shifted on top of frame 2 and frame 5 is shifted to frame 4.

a_i ➔ link length, the distance between Z_{i-1} and Z_i along with X_i
α_i ➔ link twist, the angle between Z_{i-1} and Z_i measured along with X_i
d_i ➔ link offset, the distance between O_{i-1} and intersection of Z_{i-1} and X_i along Z_{i-1}
Θ_i ➔joint angle, the angle between X_{i-1} and X_i measured along Z_{i-1}

n	**a**	$\boldsymbol{\alpha}$	**d**	Θ
1	$a_1 = 180$	90°	$d_1 = 400$	Θ_1
2	$a_2 = 600$	0	$d_2 = 0$	$90° + \Theta_2$
3	$a_3 = 170$	90°	$d_3 = 0$	Θ_3
4	$a_4 = 0$	-90°	$d_4 = 620$	Θ_4
5	$a_5 = 0$	90°	$d_5 = 0$	Θ_5
6	$a_6 = 0$	0°	$d_6 = 200$	Θ_6

All dimensions are in millimetres.

Forward Kinematics

Forward Kinematics involves formulating a relationship between the joint angles and end-effector position. The transformation matrix between two frames in terms of DH parameters is as below:

$$A_j^i = \begin{bmatrix} \cos\theta & -\sin\theta\cos\alpha & \sin\theta\sin\alpha & a_i\cos\theta \\ \sin\theta & \cos\theta\cos\alpha & -\cos\theta\sin\alpha & a_i\sin\theta \\ 0 & \sin\alpha & \cos\alpha & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The final transformation matrix between the base frame and the end effector is computed by multiplying all the transformation matrices between the individual frame i.e.

$$T_n^0 = \prod_{i=0}^{n-1} A_{i+1}^i$$

The transformation matrices between two consecutive frames are given below. Note that the values of the DH parameters are used from the above table.

$$A_1^0 = \begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 & 180\cos\theta_1 \\ \sin\theta_1 & 0 & -\cos\theta_1 & 180\sin\theta_1 \\ 0 & 1 & 0 & 400 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_2^1 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_3 & 0 & 600\cos\theta_3 \\ \sin\theta_2 & \cos\theta_3 & 0 & 600\sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_3^2 = \begin{bmatrix} \cos\theta_3 & 0 & \sin\theta_3 & 170\cos\theta_3 \\ \sin\theta_3 & 0 & -\cos\theta_3 & 170\sin\theta_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_4^3 = \begin{bmatrix} \cos\theta_4 & 0 & -\sin\theta_4 & 0 \\ \sin\theta_4 & 0 & \cos\theta_4 & 0 \\ 0 & -1 & 0 & 620 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_5^4 = \begin{bmatrix} \cos\theta_5 & 0 & \sin\theta_5 & 0 \\ \sin\theta_5 & 0 & -\cos\theta_5 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_6^5 = \begin{bmatrix} \cos\theta_6 & -\sin\theta_6 & 0 & 0 \\ \sin\theta_6 & \cos\theta_6 & 0 & 0 \\ 0 & 0 & 1 & 200 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Multiplication of all the above transformation matrices yields the final transformation matrix between the base frame and the end effector.

$$T_6^0 = A_1^0\, A_2^1\, A_3^2\, A_4^3\, A_5^4\, A_6^5$$

The final transformation matrix is given below.

$$T_6^0 = \begin{bmatrix} e_{1,1} & e_{1,2} & e_{1,3} & e_{1,4} \\ e_{2,1} & e_{2,2} & e_{2,3} & e_{2,4} \\ e_{3,1} & e_{3,2} & e_{3,3} & e_{3,4} \\ e_{4,1} & e_{4,2} & e_{4,3} & e_{4,4} \end{bmatrix}$$

$e_{1,1}$

$$(((-\sin(\theta_2)\cdot\sin(\theta_3)\cdot\cos(\theta_1) + \cos(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_4) + \sin(\theta_1)\cdot\sin(\theta_4))\cdot\cos(\theta_5) + (-\sin(\theta_2)\cdot\cos(\theta_1)\cdot\cos(\theta_3) - \sin(\theta_3)\cdot\cos(\theta_1)\cdot\cos(\theta_2))\cdot\sin(\theta_5))\cdot\cos(\theta_6) + (-(-\sin(\theta_2)\cdot\sin(\theta_3)\cdot\cos(\theta_1) + \cos(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\sin(\theta_4) + \sin(\theta_1)\cdot\cos(\theta_4))\cdot\sin(\theta_6)$$

$e_{1,2}$

$$-(((-\sin(\theta_2)\cdot\sin(\theta_3)\cdot\cos(\theta_1) + \cos(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_4) + \sin(\theta_1)\cdot\sin(\theta_4))\cdot\cos(\theta_5) + (-\sin(\theta_2)\cdot\cos(\theta_1)\cdot\cos(\theta_3) - \sin(\theta_3)\cdot\cos(\theta_1)\cdot\cos(\theta_2))\cdot\sin(\theta_5))\cdot\sin(\theta_6) + (-(-\sin(\theta_2)\cdot\sin(\theta_3)\cdot\cos(\theta_1) + \cos(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\sin(\theta_4) + \sin(\theta_1)\cdot\cos(\theta_4))\cdot\cos(\theta_6)$$

$e_{1,3}$

$$((-\sin(\theta_2)\cdot\sin(\theta_3)\cdot\cos(\theta_1) + \cos(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_4) + \sin(\theta_1)\cdot\sin(\theta_4))\cdot\sin(\theta_5) - (-\sin(\theta_2)\cdot\cos(\theta_1)\cdot\cos(\theta_3) - \sin(\theta_3)\cdot\cos(\theta_1)\cdot\cos(\theta_2))\cdot\cos(\theta_5)$$

$e_{1,4}$

$$200\cdot((-\sin(\theta_2)\cdot\sin(\theta_3)\cdot\cos(\theta_1) + \cos(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_4) + \sin(\theta_1)\cdot\sin(\theta_4))\cdot\sin(\theta_5) - 200\cdot(-\sin(\theta_2)\cdot\cos(\theta_1)\cdot\cos(\theta_3) - \sin(\theta_3)\cdot\cos(\theta_1)\cdot\cos(\theta_2))\cdot\cos(\theta_5) - 170\cdot\sin(\theta_2)\cdot\sin(\theta_3)\cdot\cos(\theta_1) + 620\cdot\sin(\theta_2)\cdot\cos(\theta_1)\cdot\cos(\theta_3) + 620\cdot\sin(\theta_3)\cdot\cos(\theta_1)\cdot\cos(\theta_2) + 170\cdot\cos(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3) + 600\cdot\cos(\theta_1)\cdot\cos(\theta_2) + 180\cdot\cos(\theta_1)$$

$e_{2,1}$

$$(((-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) + \sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_4) - \sin(\theta_4)\cdot\cos(\theta_1))\cdot\cos(\theta_5) + (-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\cos(\theta_3) - \sin(\theta_1)\cdot\sin(\theta_3)\cdot\cos(\theta_2))\cdot\sin(\theta_5))\cdot\cos(\theta_6) + (-(-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) + \sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\sin(\theta_4) - \cos(\theta_1)\cdot\cos(\theta_4))\cdot\sin(\theta_6)$$

$e_{2,2}$

$$-(((-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) + \sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_4) - \sin(\theta_4)\cdot\cos(\theta_1))\cdot\cos(\theta_5) + (-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\cos(\theta_3) -$$

$\sin(\theta_1)\cdot\sin(\theta_3)\cdot\cos(\theta_2))\cdot\sin(\theta_5))\cdot\sin(\theta_6) + (-(-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) + \sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\sin(\theta_4) - \cos(\theta_1)\cdot\cos(\theta_4))\cdot\cos(\theta_6)$

$e_{2,3}$

$((-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) + \sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_4) - \sin(\theta_4)\cdot\cos(\theta_1))\cdot\sin(\theta_5) - (-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\cos(\theta_3) - \sin(\theta_1)\cdot\sin(\theta_3)\cdot\cos(\theta_2))\cdot\cos(\theta_5)$

$e_{2,4}$

$200\cdot((-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) + \sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_4) - \sin(\theta_4)\cdot\cos(\theta_1))\cdot\sin(\theta_5) - 200\cdot(-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\cos(\theta_3) - \sin(\theta_1)\cdot\sin(\theta_3)\cdot\cos(\theta_2))\cdot\cos(\theta_5) - 170\cdot\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) + 620\cdot\sin(\theta_1)\cdot\sin(\theta_2)\cdot\cos(\theta_3) + 620\cdot\sin(\theta_1)\cdot\sin(\theta_3)\cdot\cos(\theta_2) + 170\cdot\sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3) + 600\cdot\sin(\theta_1)\cdot\cos(\theta_2) + 180\cdot\sin(\theta_1)$

$e_{3,1}$

$((-\sin(\theta_2)\cdot\sin(\theta_3) + \cos(\theta_2)\cdot\cos(\theta_3))\cdot\sin(\theta_5) + (\sin(\theta_2)\cdot\cos(\theta_3) + \sin(\theta_3)\cdot\cos(\theta_2))\cdot\cos(\theta_4)\cdot\cos(\theta_5))\cdot\cos(\theta_6) -(\sin(\theta_2)\cdot\cos(\theta_3) + \sin(\theta_3)\cdot\cos(\theta_2))\cdot\sin(\theta_4)\cdot\sin(\theta_6)$

$e_{3,2}$

$-((-\sin(\theta_2)\cdot\sin(\theta_3) + \cos(\theta_2)\cdot\cos(\theta_3))\cdot\sin(\theta_5) + (\sin(\theta_2)\cdot\cos(\theta_3) + \sin(\theta_3)\cdot\cos(\theta_2))\cdot\cos(\theta_4)\cdot\cos(\theta_5))\cdot\sin(\theta_6) - (\sin(\theta_2)\cdot\cos(\theta_3) + \sin(\theta_3)\cdot\cos(\theta_2))\cdot\sin(\theta_4)\cdot\cos(\theta_6)$

$e_{3,3}$

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

$e_{3,4}$

$-200\cdot(-\sin(\theta_2)\cdot\sin(\theta_3) + \cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_5) + 200\cdot(\sin(\theta_2)\cdot\cos(\theta_3) + \sin(\theta_3)\cdot\cos(\theta_2))\cdot\sin(\theta_5)\cdot\cos(\theta_4) + 620\cdot\sin(\theta_2)\cdot\sin(\theta_3) + 170\cdot\sin(\theta_2)\cdot\cos(\theta_3) + 600\cdot\sin(\theta_2) + 170\cdot\sin(\theta_3)\cdot\cos(\theta_2) - 620\cdot\cos(\theta_2)\cdot\cos(\theta_3) + 400$

$e_{4,1}$

0

$e_{4,2}$

0

$e_{4,3}$

0

$e_{4,4}$

1

Inverse Kinematics

The two methods to compute the Inverse Kinematics of a robotic manipulator are:

1. Geometrical Method
2. Numerical Method

The complexity involved in computing the Inverse Kinematics of a robotic manipulator using the Geometric Method increases with the number of links. Therefore, this method is not feasible to compute the Inverse Kinematics of a 6 DOF KUKA KR5 robot. Hence, the Numerical Method is being used to compute the Inverse Kinematics of the robot. The Numerical Method involves the formulation of the 6xn Jacobian matrix, where n is the number of joints. The Jacobian matrix gives a relationship between end-effector velocity and joint velocity and the relationship is given by:

$$\vec{v} = J\vec{\dot{q}}$$

$\vec{v}$ ➔ 6x1 end-effector velocity vector

$\vec{\dot{q}}$ ➔ nx1 joint velocity vector

Note that the Jacobian Matrix formulated in the Numerical method doesn't give a direct relationship between the joint angles and the end-effector position, but instead gives a relationship between joint velocities and the end-effector velocity.

The Jacobian Matrix is computed using the first method where each column of Jacobian Matrix (J) is:

$$J_i = \begin{bmatrix} J_v \\ J_w \end{bmatrix}$$

$$J_i = \begin{bmatrix} Z_{i-1} \times (O_n - O_{i-1}) \\ Z_{i-1} \end{bmatrix}$$

Where,

Z_{i-1} ➔ first three elements in the 3rd column of the T_i^0 matrix

O_{i-1} ➔ first three elements in the 4th column of the T_{i-1}^0 matrix

The Jacobian Matrix is given by:

$$J = [J_1 \quad J_2 \quad J_3 \quad J_4 \quad J_5 \quad J_6]$$

$$J = \begin{bmatrix} e_{1,1} & e_{1,2} & e_{1,3} & e_{1,4} & e_{1,5} & e_{1,6} \\ e_{2,1} & e_{2,2} & e_{2,3} & e_{2,4} & e_{2,5} & e_{2,6} \\ e_{3,1} & e_{3,2} & e_{3,3} & e_{3,4} & e_{3,5} & e_{3,6} \\ e_{4,1} & e_{4,2} & e_{4,3} & e_{4,4} & e_{4,5} & e_{4,6} \\ e_{5,1} & e_{5,2} & e_{5,3} & e_{5,4} & e_{5,5} & e_{5,6} \\ e_{6,1} & e_{6,2} & e_{6,3} & e_{6,4} & e_{6,5} & e_{6,6} \end{bmatrix}$$

$e_{1,1}$

$(200\cdot(\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) - \sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_4) + 200\cdot\sin(\theta_4)\cdot\cos(\theta_1))\cdot\sin(\theta_5) + (-200\cdot\sin(\theta_1)\cdot\sin(\theta_2)\cdot\cos(\theta_3) - 200\cdot\sin(\theta_1)\cdot\sin(\theta_3)\cdot\cos(\theta_2))\cdot\cos(\theta_5) + 170\cdot\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) - 620\cdot\sin(\theta_1)\cdot\sin(\theta_2)\cdot\cos(\theta_3) - 620\cdot\sin(\theta_1)\cdot\sin(\theta_3)\cdot\cos(\theta_2) - 170\cdot\sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3) - 600\cdot\sin(\theta_1)\cdot\cos(\theta_2) - 180\cdot\sin(\theta_1)$

$e_{1,2}$

$(-200\cdot\sin(\theta_2)\cdot\sin(\theta_3)\cdot\cos(\theta_1) + 200\cdot\cos(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_5) + 200\cdot(-\sin(\theta_2)\cdot\cos(\theta_1)\cdot\cos(\theta_3) - \sin(\theta_3)\cdot\cos(\theta_1)\cdot\cos(\theta_2))\cdot\sin(\theta_5)\cdot\cos(\theta_4) - 620\cdot\sin(\theta_2)\cdot\sin(\theta_3)\cdot\cos(\theta_1) - 170\cdot\sin(\theta_2)\cdot\cos(\theta_1)\cdot\cos(\theta_3) - 600\cdot\sin(\theta_2)\cdot\cos(\theta_1) - 170\cdot\sin(\theta_3)\cdot\cos(\theta_1)\cdot\cos(\theta_2) + 620\cdot\cos(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3)$

$e_{1,3}$

$(-200\cdot\sin(\theta_2)\cdot\sin(\theta_3)\cdot\cos(\theta_1) + 200\cdot\cos(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_5) + 200\cdot(-\sin(\theta_2)\cdot\cos(\theta_1)\cdot\cos(\theta_3) - \sin(\theta_3)\cdot\cos(\theta_1)\cdot\cos(\theta_2))\cdot\sin(\theta_5)\cdot\cos(\theta_4) - 620\cdot\sin(\theta_2)\cdot\sin(\theta_3)\cdot\cos(\theta_1) - 170\cdot\sin(\theta_2)\cdot\cos(\theta_1)\cdot\cos(\theta_3) - 170\cdot\sin(\theta_3)\cdot\cos(\theta_1)\cdot\cos(\theta_2) + 620\cdot\cos(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3)$

$e_{1,4}$

$(-200\cdot(-\sin(\theta_2)\cdot\sin(\theta_3)\cdot\cos(\theta_1) + \cos(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\sin(\theta_4) + 200\cdot\sin(\theta_1)\cdot\cos(\theta_4))\cdot\sin(\theta_5)$

$e_{1,5}$

$(200\cdot(-\sin(\theta_2)\cdot\sin(\theta_3)\cdot\cos(\theta_1) + \cos(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_4) + 200\cdot\sin(\theta_1)\cdot\sin(\theta_4))\cdot\cos(\theta_5) - (200\cdot\sin(\theta_2)\cdot\cos(\theta_1)\cdot\cos(\theta_3) + 200\cdot\sin(\theta_3)\cdot\cos(\theta_1)\cdot\cos(\theta_2))\cdot\sin(\theta_5)$

$e_{1,6}$

0

$e_{2,1}$

$$(200\cdot(-\sin(\theta_2)\cdot\sin(\theta_3)\cdot\cos(\theta_1) + \cos(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_4) + 200\cdot\sin(\theta_1)\cdot\sin(\theta_4))\cdot\sin(\theta_5) + (200\cdot\sin(\theta_2)\cdot\cos(\theta_1)\cdot\cos(\theta_3) + 200\cdot\sin(\theta_3)\cdot\cos(\theta_1)\cdot\cos(\theta_2))\cdot\cos(\theta_5) - 170\cdot\sin(\theta_2)\cdot\sin(\theta_3)\cdot\cos(\theta_1) + 620\cdot\sin(\theta_2)\cdot\cos(\theta_1)\cdot\cos(\theta_3) + 620\cdot\sin(\theta_3)\cdot\cos(\theta_1)\cdot\cos(\theta_2) + 170\cdot\cos(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3) + 600\cdot\cos(\theta_1)\cdot\cos(\theta_2) + 180\cdot\cos(\theta_1)$$

$e_{2,2}$

$$(-200\cdot\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) + 200\cdot\sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_5) + 200\cdot(-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\cos(\theta_3) - \sin(\theta_1)\cdot\sin(\theta_3)\cdot\cos(\theta_2))\cdot\sin(\theta_5)\cdot\cos(\theta_4) - 620\cdot\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) - 170\cdot\sin(\theta_1)\cdot\sin(\theta_2)\cdot\cos(\theta_3) - 600\cdot\sin(\theta_1)\cdot\sin(\theta_2) - 170\cdot\sin(\theta_1)\cdot\sin(\theta_3)\cdot\cos(\theta_2) + 620\cdot\sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3)$$

$e_{2,3}$

$$(-200\cdot\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) + 200\cdot\sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_5) + 200\cdot(-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\cos(\theta_3) - \sin(\theta_1)\cdot\sin(\theta_3)\cdot\cos(\theta_2))\cdot\sin(\theta_5)\cdot\cos(\theta_4) - 620\cdot\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) - 170\cdot\sin(\theta_1)\cdot\sin(\theta_2)\cdot\cos(\theta_3) - 170\cdot\sin(\theta_1)\cdot\sin(\theta_3)\cdot\cos(\theta_2) + 620\cdot\sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3)$$

$e_{2,4}$

$$(-200\cdot(-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) + \sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\sin(\theta_4) - 200\cdot\cos(\theta_1)\cdot\cos(\theta_4))\cdot\sin(\theta_5)$$

$e_{2,5}$

$$(200\cdot(-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) + \sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_4) - 200\cdot\sin(\theta_4)\cdot\cos(\theta_1))\cdot\cos(\theta_5) - (200\cdot\sin(\theta_1)\cdot\sin(\theta_2)\cdot\cos(\theta_3) + 200\cdot\sin(\theta_1)\cdot\sin(\theta_3)\cdot\cos(\theta_2))\cdot\sin(\theta_5)$$

$e_{2,6}$

0

$e_{3,1}$

0

$e_{3,2}$

$$(-200\cdot\sin(\theta_2)\cdot\sin(\theta_3) + 200\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\sin(\theta_5)\cdot\cos(\theta_4) + (200\cdot\sin(\theta_2)\cdot\cos(\theta_3) + 200\cdot\sin(\theta_3)\cdot\cos(\theta_2))\cdot\cos(\theta_5) - 170\cdot\sin(\theta_2)\cdot\sin(\theta_3) + 620\cdot\sin(\theta_2)\cdot\cos(\theta_3) + 620\cdot\sin(\theta_3)\cdot\cos(\theta_2) + 170\cdot\cos(\theta_2)\cdot\cos(\theta_3) + 600\cdot\cos(\theta_2)$$

$e_{3,3}$

$$(-200\cdot\sin(\theta_2)\cdot\sin(\theta_3) + 200\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\sin(\theta_5)\cdot\cos(\theta_4) + (200\cdot\sin(\theta_2)\cdot\cos(\theta_3) + 200\cdot\sin(\theta_3)\cdot\cos(\theta_2))\cdot\cos(\theta_5) - 170\cdot\sin(\theta_2)\cdot\sin(\theta_3) + 620\cdot\sin(\theta_2)\cdot\cos(\theta$$

$_3) + 620 \cdot \sin(\theta_3) \cdot \cos(\theta_2) + 170 \cdot \cos(\theta_2) \cdot \cos(\theta_3)$

$e_{3,4}$

$-(200 \cdot \sin(\theta_2) \cdot \cos(\theta_3) + 200 \cdot \sin(\theta_3) \cdot \cos(\theta_2)) \cdot \sin(\theta_4) \cdot \sin(\theta_5)$

$e_{3,5}$

$-(200 \cdot \sin(\theta_2) \cdot \sin(\theta_3) - 200 \cdot \cos(\theta_2) \cdot \cos(\theta_3)) \cdot \sin(\theta_5) + (200 \cdot \sin(\theta_2) \cdot \cos(\theta_3) + 200 \cdot \sin(\theta_3) \cdot \cos(\theta_2)) \cdot \cos(\theta_4) \cdot \cos(\theta_5)$

$e_{3,6}$

0

$e_{4,1}$

$\sin(\theta_1)$

$e_{4,2}$

$\sin(\theta_1)$

$e_{4,3}$

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

$e_{4,4}$

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

$e_{4,5}$

$((-\sin(\theta_2) \cdot \sin(\theta_3) \cdot \cos(\theta_1) + \cos(\theta_1) \cdot \cos(\theta_2) \cdot \cos(\theta_3)) \cdot \cos(\theta_4) + \sin(\theta_1) \cdot \sin(\theta_4)) \cdot \sin(\theta_5) - (-\sin(\theta_2) \cdot \cos(\theta_1) \cdot \cos(\theta_3) - \sin(\theta_3) \cdot \cos(\theta_1) \cdot \cos(\theta_2)) \cdot \cos(\theta_5)$

$e_{4,6}$

$((-\sin(\theta_2) \cdot \sin(\theta_3) \cdot \cos(\theta_1) + \cos(\theta_1) \cdot \cos(\theta_2) \cdot \cos(\theta_3)) \cdot \cos(\theta_4) + \sin(\theta_1) \cdot \sin(\theta_4)) \cdot \sin(\theta_5) - (-\sin(\theta_2) \cdot \cos(\theta_1) \cdot \cos(\theta_3) - \sin(\theta_3) \cdot \cos(\theta_1) \cdot \cos(\theta_2)) \cdot \cos(\theta_5)$

$e_{5,1}$

$-\cos(\theta_1)$

$e_{5,2}$

$-\cos(\theta_1)$

$e_{5,3}$

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

$e_{5,4}$

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

$e_{5,5}$

$((-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) + \sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_4) - \sin(\theta_4)\cdot\cos(\theta_1))\cdot\sin(\theta_5) - (-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\cos(\theta_3) - \sin(\theta_1)\cdot\sin(\theta_3)\cdot\cos(\theta_2))\cdot\cos(\theta_5)$

$e_{5,6}$

$((-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\sin(\theta_3) + \sin(\theta_1)\cdot\cos(\theta_2)\cdot\cos(\theta_3))\cdot\cos(\theta_4) - \sin(\theta_4)\cdot\cos(\theta_1))\cdot\sin(\theta_5) - (-\sin(\theta_1)\cdot\sin(\theta_2)\cdot\cos(\theta_3) - \sin(\theta_1)\cdot\sin(\theta_3)\cdot\cos(\theta_2))\cdot\cos(\theta_5)$

$e_{6,1}$

0

$e_{6,2}$

0

$e_{6,3}$

$\sin(\theta_2)\cdot\sin(\theta_3) - \cos(\theta_2)\cdot\cos(\theta_3)$

$e_{6,4}$

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

$e_{6,5}$

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

$e_{6,6}$

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

Forward Kinematics & Inverse Kinematics Validation

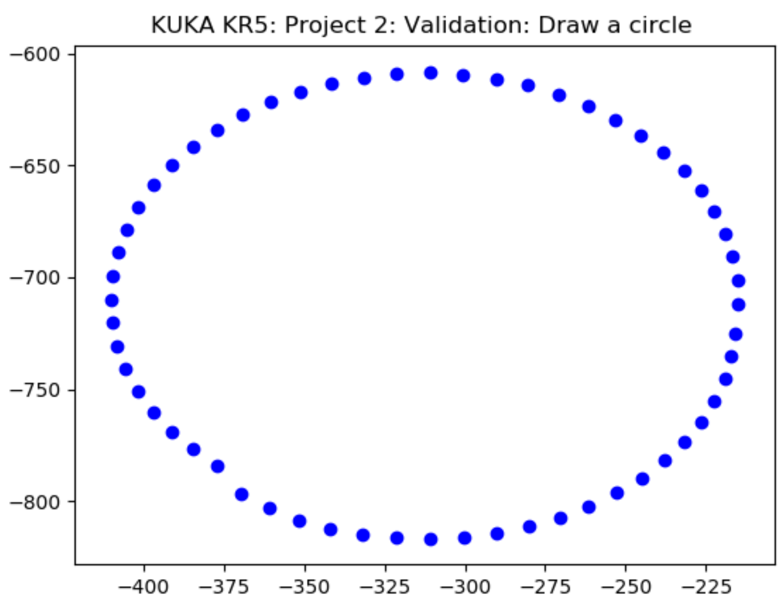
Frame assignment, DH parameters, DH table, and transformation matrices are determined to analyse the forward kinematics of the robot. This gives us the end-effector position by knowing the joint angles.

Further, using numerical method to compute the Inverse Kinematics of a robotic manipulator and determine the Jacobian matrix, which gives a relationship between end-effector velocity and joint velocity.

The python script is written to compute transformation matrices using the DH table. Script also computes the Jacobian matrix and its inverse. Forward and Inverse Kinematics are validated using the Jacobian matrix and its inverse to draw a circle of radius 100 mm on the wall.

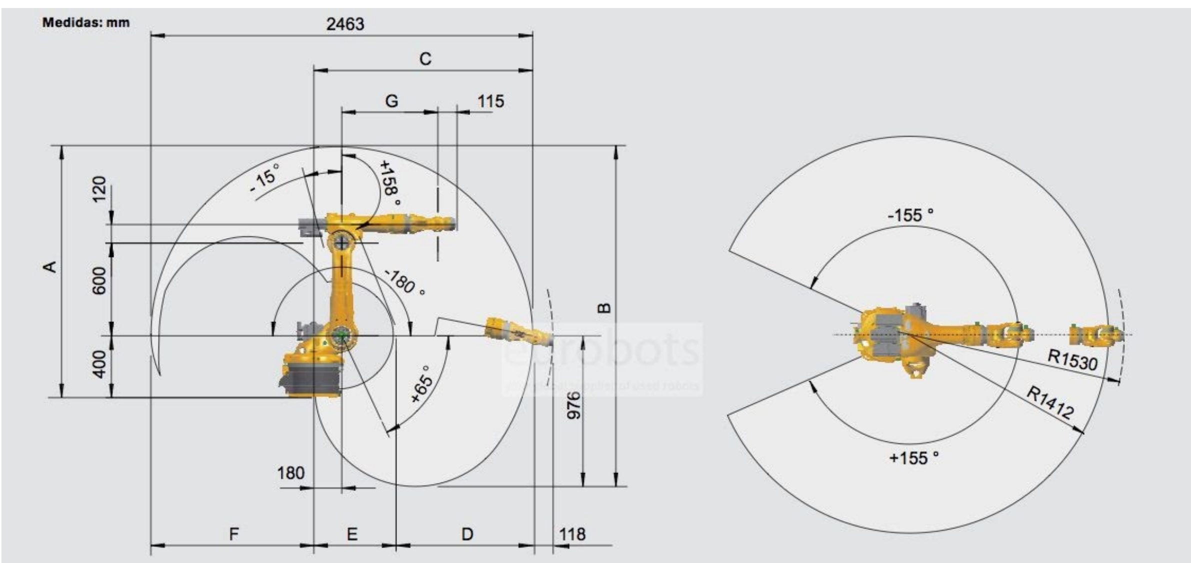
File Link: Python Script

Results:



Workspace study

The workspace also called work volume or work envelope of a manipulator is the volume of space, which the end-effector of the manipulator can reach. The size and shape of the workspace depends on the coordinate geometry of the robot arm, and also on the number of degrees of freedom. The workspace of a robot is an important criterion in comparing manipulator geometries. The reachable workspace and the dexterous workspace are two important characteristics used in specifying the workspace of a robot manipulator. The reachable workspace, in which the robot manipulator is able to arbitrarily move its end-effector, does not include any singular points at which the manipulator loses one or more degrees of freedom. The dexterous workspace is the volume of space in which the end-effector can be arbitrarily oriented. The reachable workspace is the volume of space, which the robot can reach in at least one orientation. In the dexterous workspace, the robot has the complete manipulative capability. The dexterous workspace is a subset of the reachable workspace and is a very important performance index of the robot manipulator. A good robotic design has the volume of the reachable workspace as large as possible and additionally provides a maximum dexterous workspace in this volume. The below image describes the space and values in which the robotic arm can move.



Campo de trabajo	Medidas[1]							Volumen
	A	B	C	D	E	F	G	
KR 5 arc	1.632 mm	2.207 mm	1.412 mm	881 mm	531 mm	1.052 mm	620 mm	8,4 m^3

[1] Referido al punto de intersección del eje 4/5.

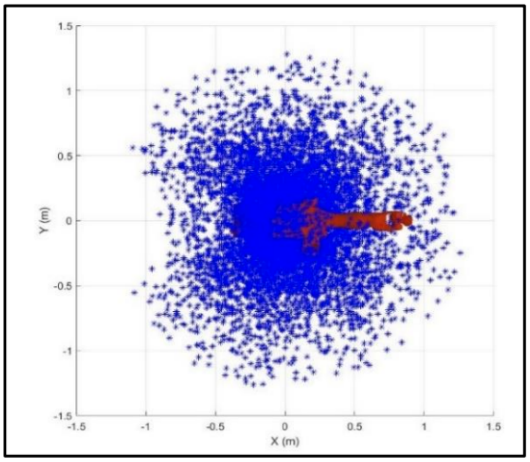


Figure. The simulation result of the workspace’s top view

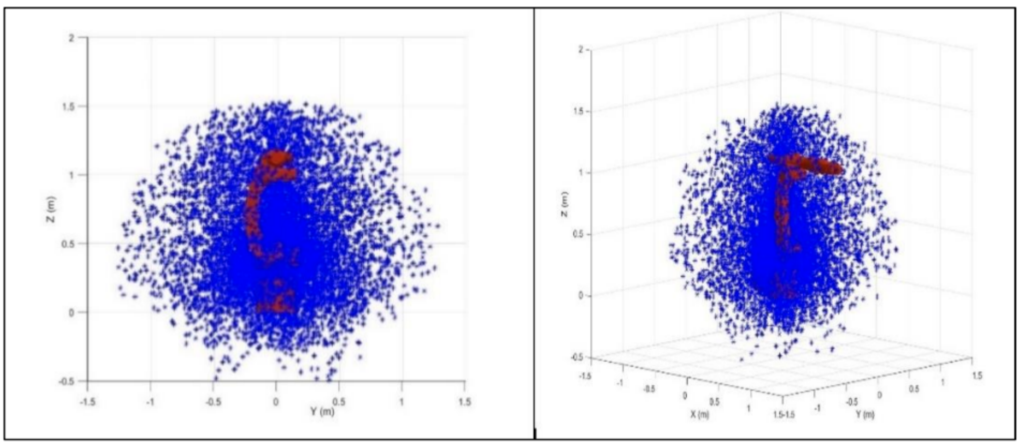


Figure. The simulation results of workspaces’ side views (x,y) and (x,y,z).

Assumptions

Following assumptions are being made while executing the project:

1. The body, wheels, and all the links of the robot are considered to be rigid.
2. Friction between links that are connected by means of joints is assumed to be zero.
3. The effect of ambient conditions due to the harsh dusty weather on the surface of Mars is ignored.
4. No collision between different parts of the robot.
5. Friction is large enough for no slippage at the contact point of wheels with the surface.
6. Work done by friction is zero.
7. Dynamics involved in the motion of the robot is ignored.

8. Electrical components like motors, wires, etc. and instruments like sensors, cameras, etc. don't act as a hindrance to the motion of the robotic manipulator.

Control Method

Rover:

For the wheels and steering joints, EffortJointInterface type transmission is used. Front steering joints use JointPositionController and rear-wheel joints use JointVelocityController type of controllers with PID gains as parameters. The above controllers are selected because the position controller works well for steering as it tracks the position in the rotation and velocity controllers for rear wheels as they have one functionality of longitudinal motion.

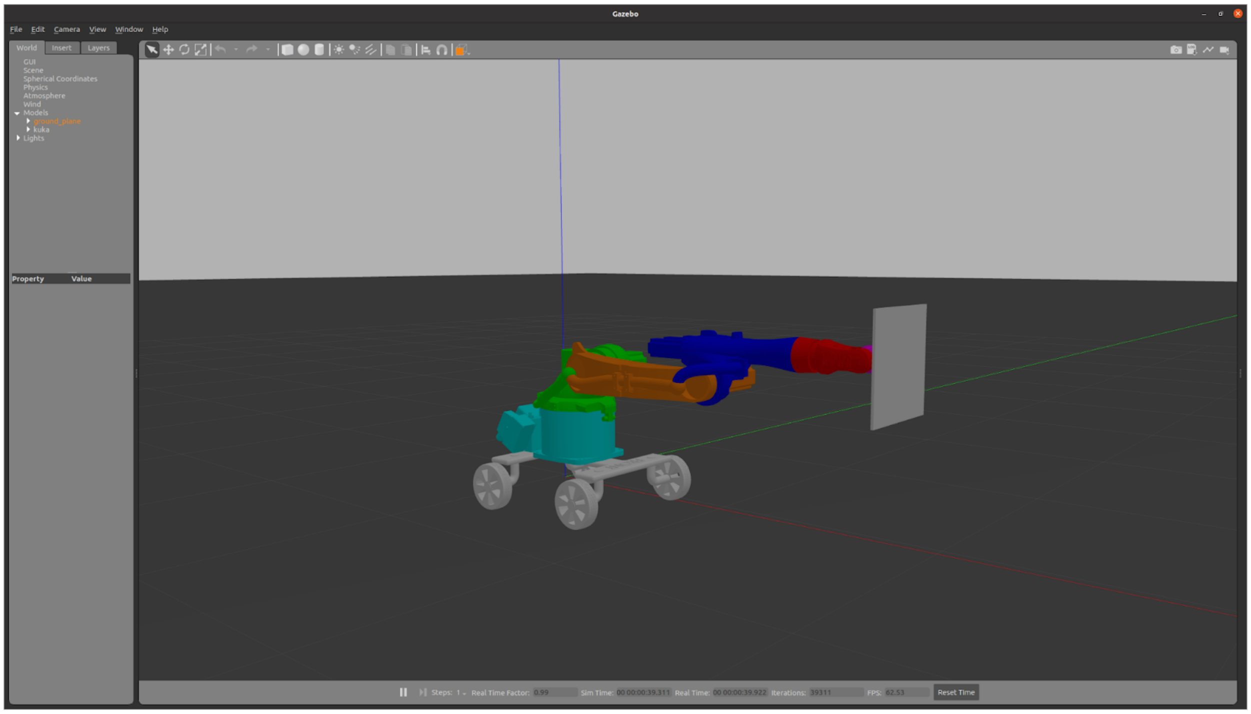
Robotic arm:

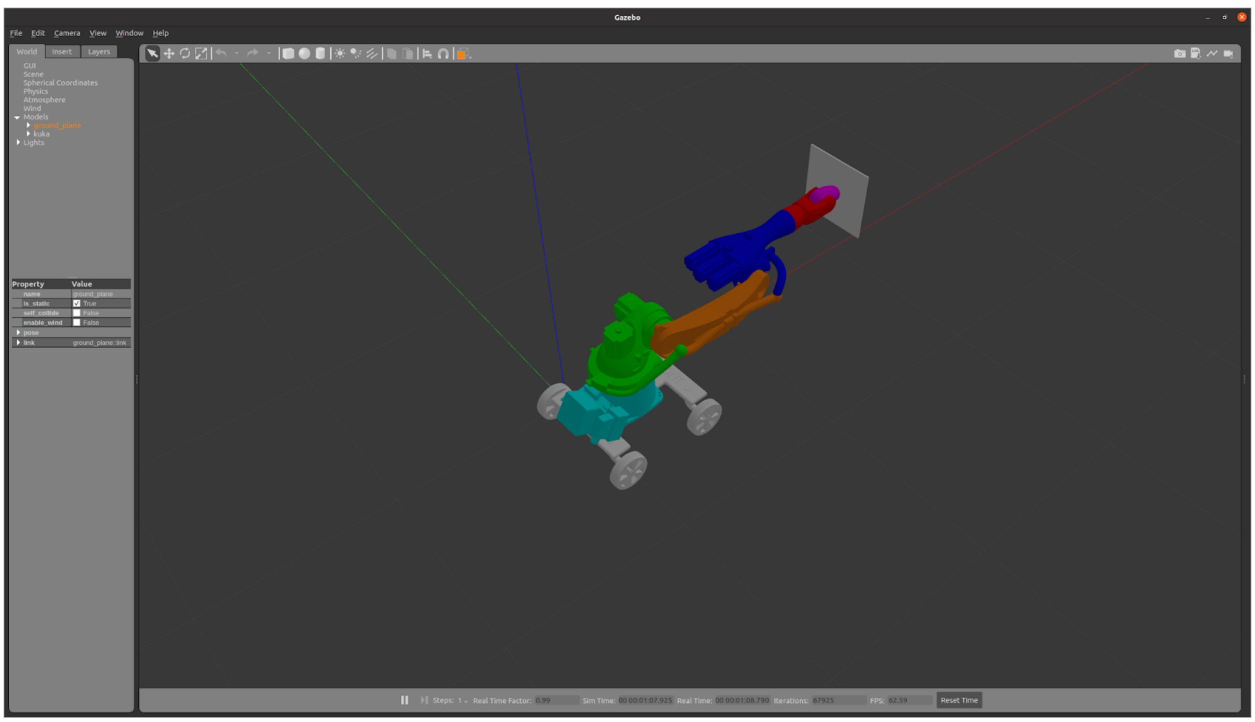
For joints, PositionJointInterface type transmission is used. All joints in the robotic arm use the JointTrajectoryController type of controller with PID gains as parameters. The above controller was selected because it is templated to work with multiple hardware interface types. For position-controlled joints, desired positions are simply forwarded to the joints; while for velocity (effort) joints, the position+velocity trajectory following error is mapped to velocity (effort) commands through a PID loop.

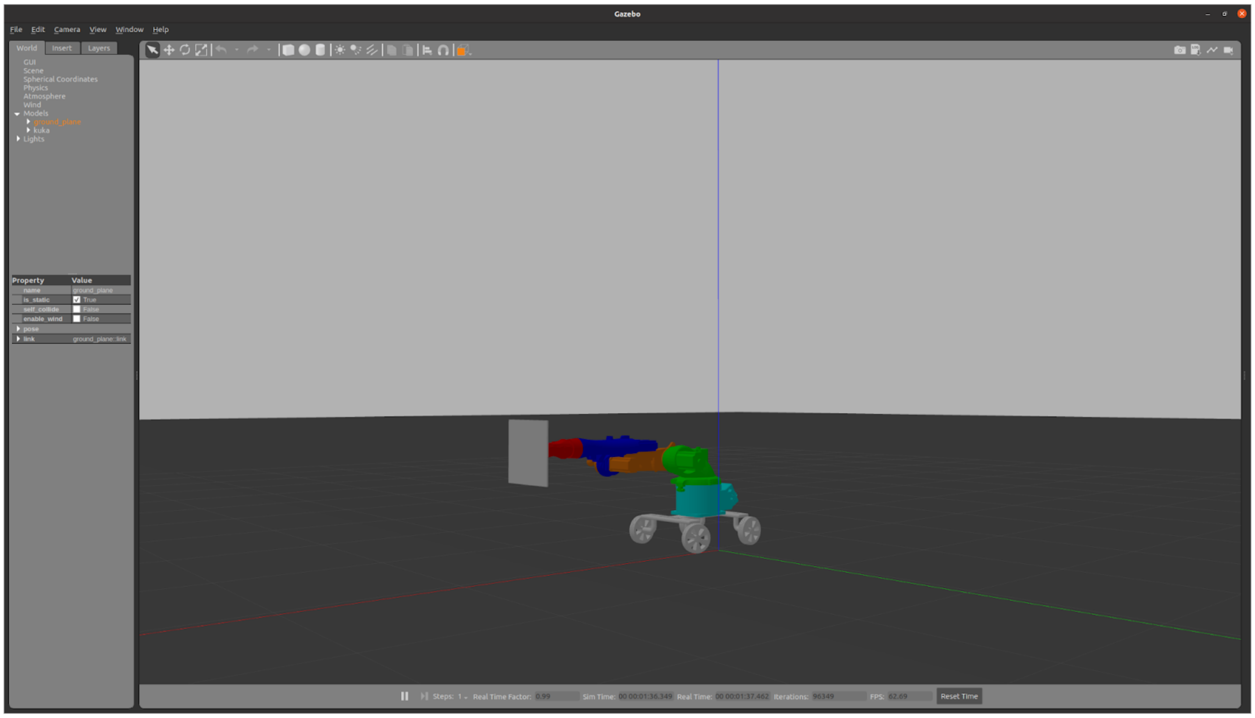
Gazebo Visualization

After the development of the Mars rover, it was simulated in Gazebo and RViz to move the rover around and function the robotic arm well. Here are a few screenshots of the simulation and **also find the video link below**:

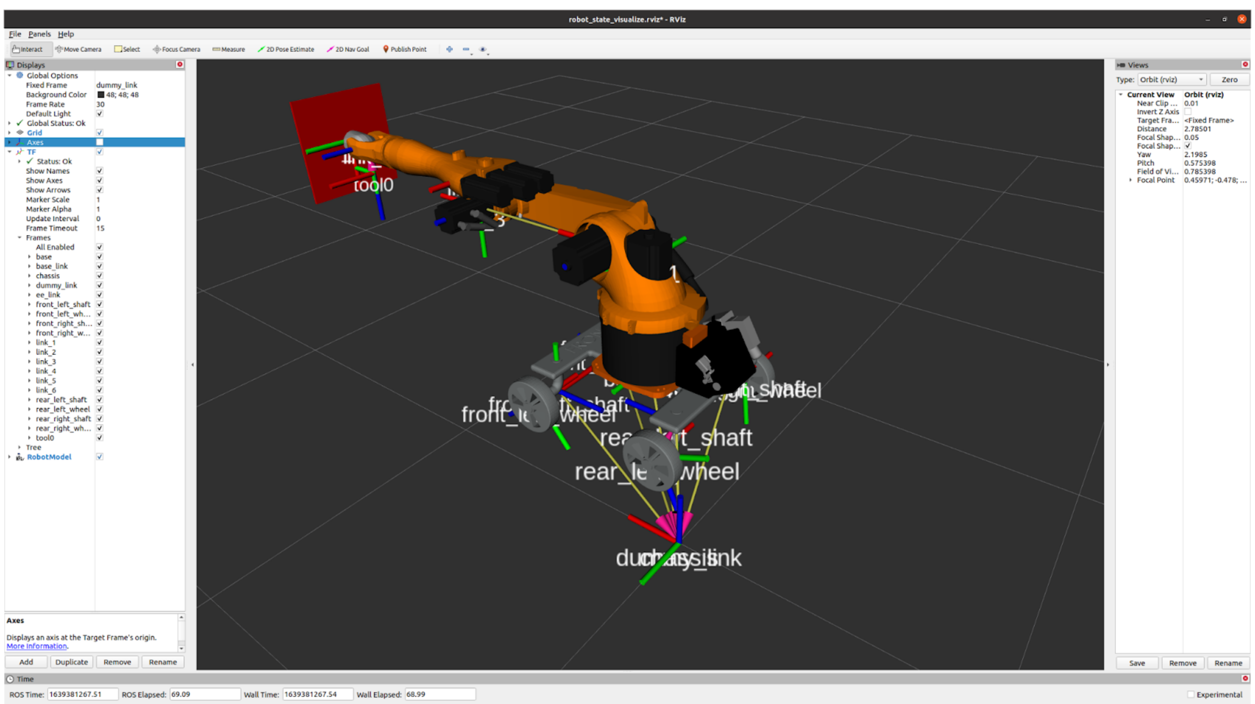
Gazebo:

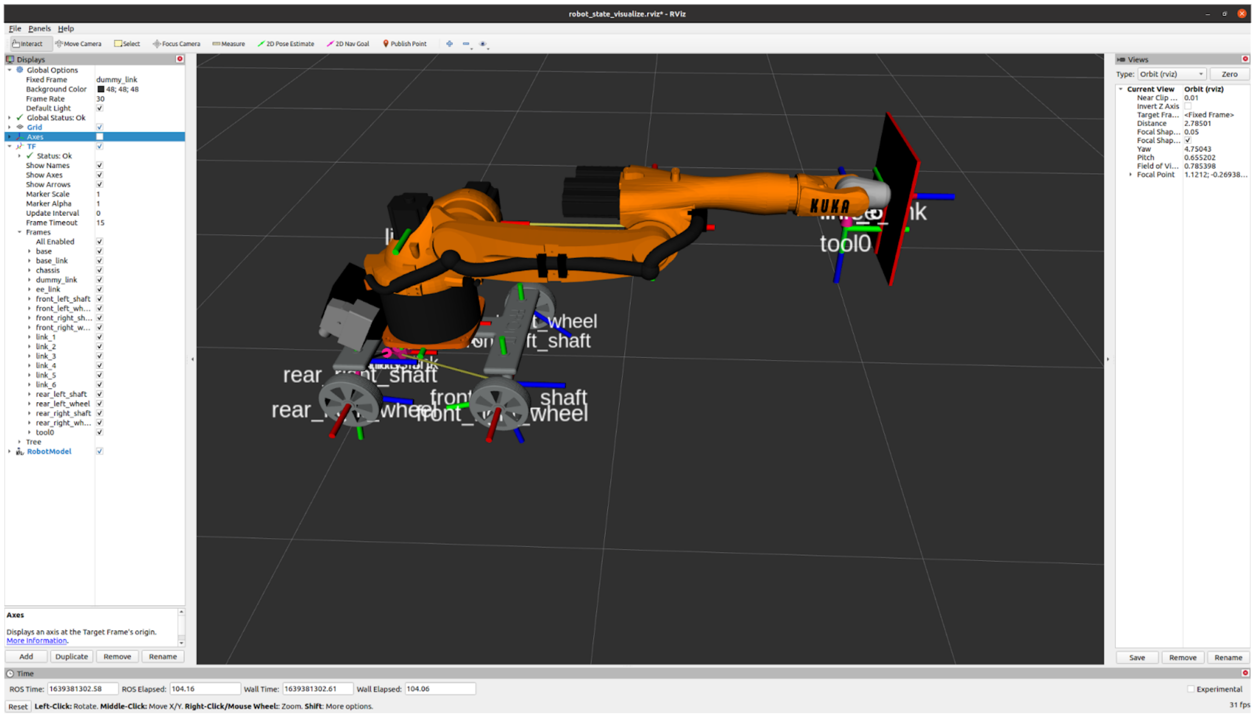

Gazebo
File Edit Camera View Window Help
World Insert Layers
GUI
Scene
Spherical Coordinates
Physics
Atmosphere
Wind
Models
ground_plane
kuka
Lights
Property Value
Reset Time


Gazebo
File Edit Camera View Window Help
World Insert Layers
GUI
Scene
Spherical Coordinates
Physics
Atmosphere
Wind
Models
ground_plane
kuka
Lights
Property Value
Reset Time



RViz:





Video Link 1: [Mars rover video 1]

Video Link 2: [Mars rover video 2]

Problems faced

Even though the mars world was successfully spawned, we faced improper spawning of the robot on the rough mars generated terrain. Here is the link of terrain video

Faced difficulty in developing and implementing controllers through URDF. Encountered issues in designing and implementing Rocker-Bogie Mechanism and also to control the robot so we utilized a simple 4 wheel rover.

Lessons learned

More prior technical read-up and hands-on implementation are required to implement more complex robots in special environments or designed task space.

Conclusion

Space exploration has always been at the forefront of human curiosity. More and more space exploration robots will be designed and optimized in near future. The purpose of this project was to develop a robot that can collect soil and rock samples from the surface of Mars using a 6 DOF robotic arm that will be useful to achieve this goal. The design of 4 -wheel RWD with two steerable wheels enhanced the stability and manoeuvrability of the robot. This project taught us and helped us apply the knowledge of robot modelling as a whole. Overall, the developed robot is able to perform the specified functions and goals but with few minor changes along the way during development. The project helped us lay a good foundation in topics like CAD designing, DH parameters, transformations matrix, Forward Kinematics, Inverse Kinematics and Simulation in Gazebo using ROS.

Future Work

Designing a robotic manipulator that can pick objects of uneven shape, traversing on undulated terrain and actual implementation of rocker-bogie mechanism could be considered as scope of future work or development.

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A. Rankin, M. Maimone, J. Biesiadecki, N. Patel, D. Levine and O. Toupet, "Driving Curiosity: Mars Rover Mobility Trends During the First Seven Years," 2020 IEEE Aerospace Conference, 2020, pp. 1-19, DOI: 10.1109/AERO47225.2020.9172469.

The Design and Engineering of Curiosity: How the Mars Rover Performs Its Job ~ Emilly Lakdawalla

Package and Results

Link: [Files and Results]