ENPM 662: Introduction to Robot Modeling

Project Report

Modeling, Simulation and analysis of a 6 DOF Industrial Robot for Sheet Metal Manufacturing Industry

By

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Abstract

The main objective of our project is to design a 6 DoF Industrial Robot with magnetic gripper as the end effector to hold and perform sheet metal bending process.

The Robotic Manipulator used is a 6 DOF Collaborative arm from Universal Robots namely UR5. The Robot has 3 spherical wrists. The considered manipulator has six revolute joints and no prismatic joint.

We Performed the Forward and Inverse Kinematics of the Manipulator along with the workspace and singularity of the industrial robot. We created an Industrial setup in V-REP platform to simulate the working environment.

We also worked on the path planning aspect of the robot with obstacle avoidance and simulated the same in MATLAB

Introduction

In Sheet Metal Industry, there is always a level of difficulty in handling thin metal sheets in production lines and machinery which involves bending, press to press transfer of ferrous sheets to fabricate a product.

The manufacturing production line setup employed in the industry is manual in nature. Thin sheets were placed at the respective regions of the workbench and corresponding process of the production line operation was performed with the help of manual labor.

To reduce manual operation and save time, I decided to model an industrial collaborative robot that will perform the sheet metal picking and bending process by adsorbing and holding the sheet. Using the robot, these metal sheets can be placed in workbench in extremely confined spaces. With respect to the project, I have considered an UR-5 robot for this task as it is the most suitable for the task. Also, to pick up thin metal sheets, I have employed a magnetic gripper instead of conventional suction and vacuum grippers due to factors that will be explained later.

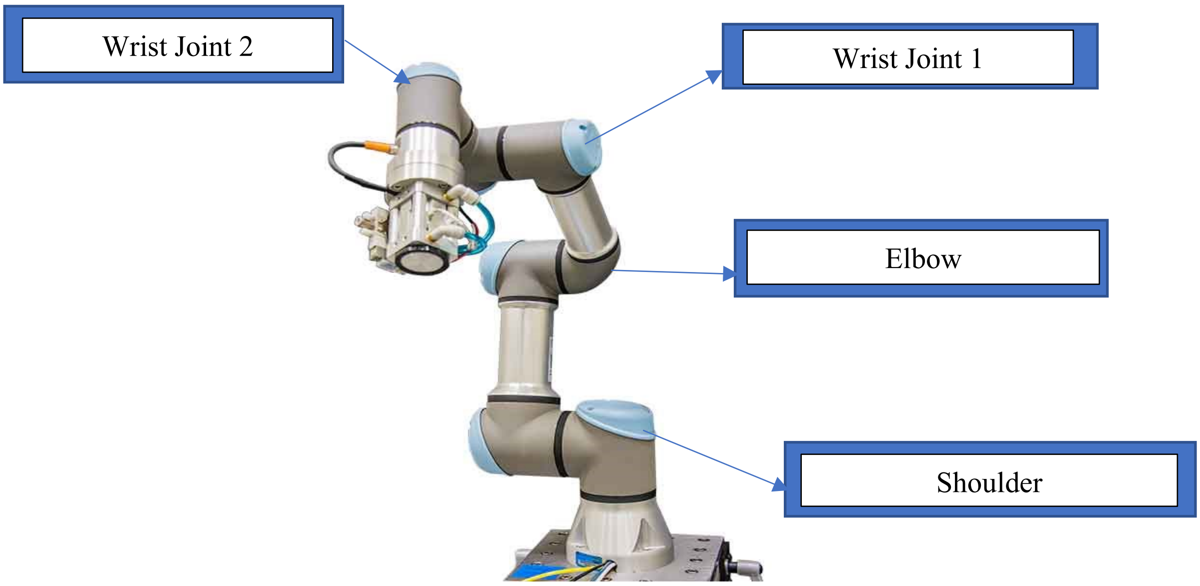


Figure of Universal Robot 5(UR5) with description

Robot Description

The manipulator that will be used to perform the sheet metal bending process is 6 DoF Universal Robot UR5E.

The technical specifications are from UR5 catalog found in Universal Robotics provided below:

- The weight of the robot is 20.6 kg
- The payload is 5 kg
- Footprint is Ø 149 mm
- Robot reach is 850 mm
- Degrees of freedom – six rotating joints
- Power consumption – Approx. 200 watts
- Power supply – 100 – 240 VAC, 50 – 60 Hz
- Cabling – cable between robot and control box is 6m

The joints are given by shoulder pan (θ_1), shoulder lift (θ_2), elbow (θ_3), wrist 1 (θ_4), wrist 2 (θ_5), and wrist 3 (θ_6). Here the tool is considered as the 7th joint (θ_7) and is assumed as the target center point.

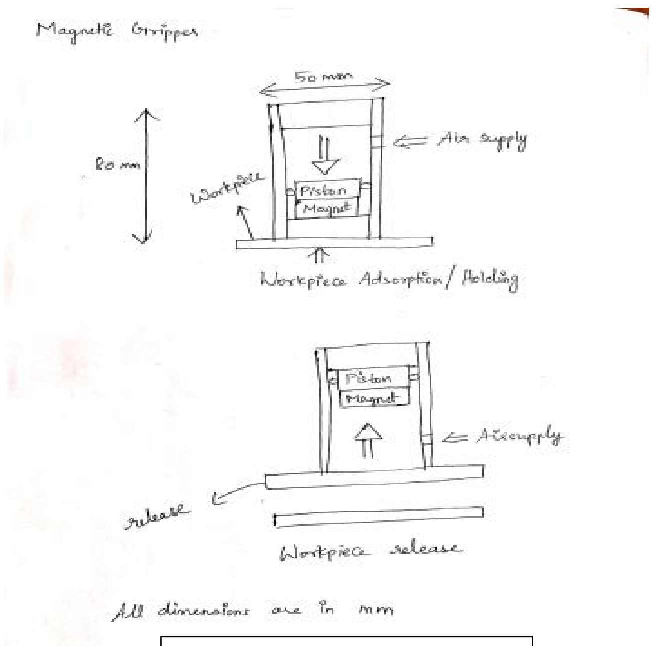
Selection of Magnetic Gripper

After performing a detailed study about sheet metal industry, the metal sheets used in the manufacturing industry were lubricated and placed on the workbench manually for press to press transfers or bending operations to take place. The problem with handling thin metal sheets is that distortion takes places due to the sheet's low thickness coefficient.

Hence to tackle this issue, we are implementing a magnetic gripper with a piston mechanism using permanent magnet enclosed in an aluminum case. A rubber bumper is present at the bottom to prevent sheet deformation or adsorption of the second sheet when the gripper remains in contact with one.

When I investigated about lubricated sheets, I realized that the sheet can shift position. This pushed me to research through a lot of gripping mechanisms available in the industry to satisfy our desired task. Thin metal sheets require maximum holding force in extremely confined spaces.

Existing technologies such as a vacuum pad won't suffice in holding uneven or irregular metal sheets. Therefore, a magnetic gripper was found to be the ideal solution.



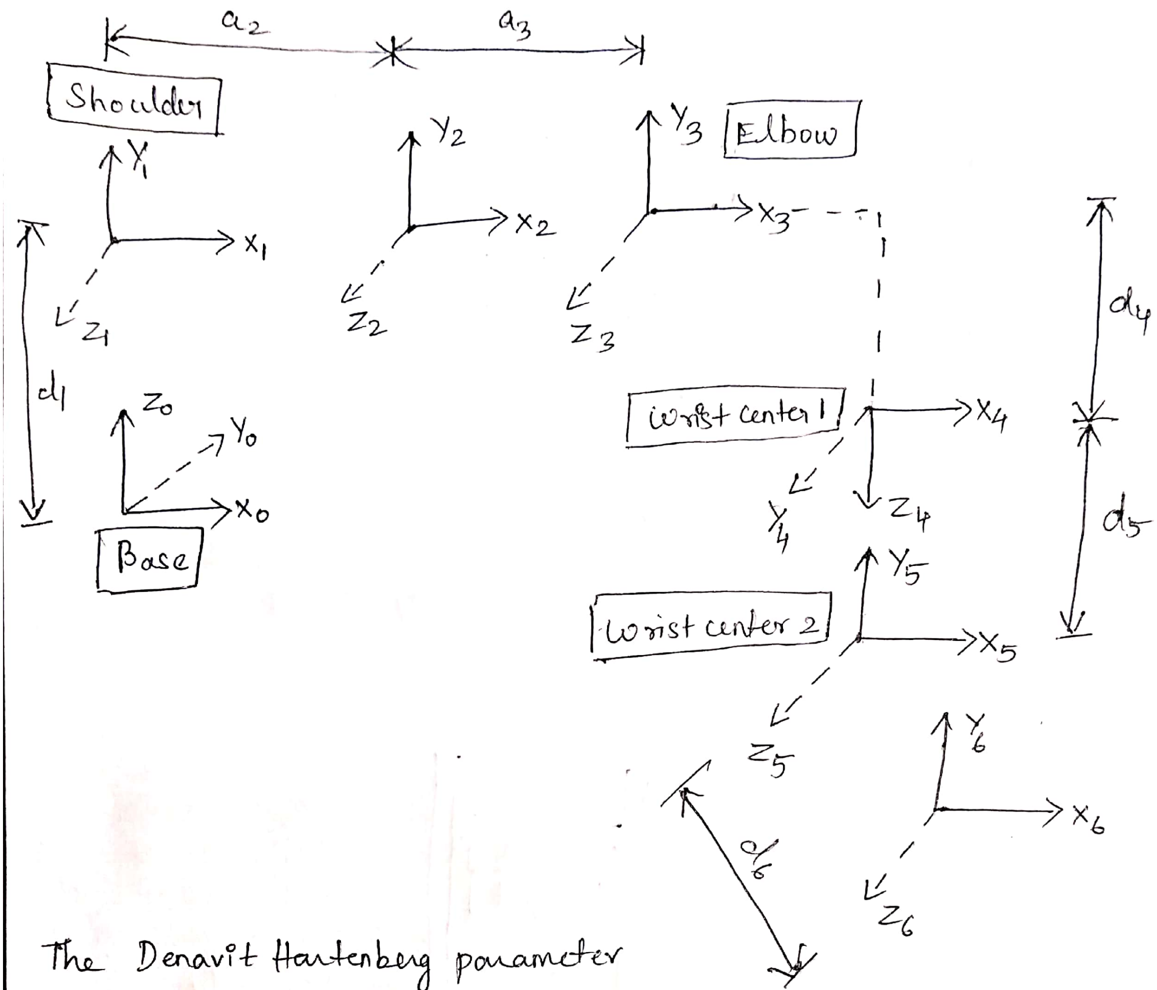
Gripper mechanism design

Assumptions

- Right-handed coordinate system convention is implemented throughout the project.
- No friction between the joints.
- No collision due to manipulator movements
- The end effector doesn't surpass the payload of the robot.
- All links of the robot are rigid and fixed to the ground/table.
- Positive rotation of the joints is assumed counterclockwise about the z axis and negative rotation of the joints is clockwise.
- Neglecting the masses. Hence, not deriving the dynamics of the robot
- The trajectories given to robot are assumed to be smooth and continuous. No consideration of jerk (i.e it is assumed to be jerk free trajectories).

Forward Kinematics

Forward kinematics of Universal Robot UR5



The Denavit Hartenberg parameter table is given by -

i	(z) θ	(z) d	(x) a	(x) α
0-1	θ_1^*	d_1	0	$\pi/2$
1-2	θ_2^*	0	$+a_2$	0
2-3	θ_3^*	0	$+a_3$	0
3-4	θ_4^*	d_4	0	$\pi/2$
4-5	θ_5^*	d_5	0	$-\pi/2$
5-6	θ_6^*	d_6	0	0

Here,

(x0,y0,z0) represents the robot base frame and (x6,y6,z6) represents the robot end effector frame.

DH table:

DH convention is followed in writing the frames of robot. The following two conditions must be met.

1) The x axis of the next joint x must be perpendicular to the previous z axis

2) The x axis must also intersect with the previous z axis.

General Transformation matrix for DH parameters is found by

$$T_0^1 = \mathrm{Rot}_{z,\,\theta} * \mathrm{Trans}_{z,\,d} * \mathrm{Trans}_{x,\,a} * \mathrm{Rot}_{x,\,\alpha}$$

This gives frame 1 represented in zero frame.

Now we find that,

```
R1 =

[ cos(th1), 0,  sin(th1),  0]
[ sin(th1), 0, -cos(th1),  0]
[        0, 1,         0, d1]
[        0, 0,         0,  1]

R2 =

[ cos(th2), -sin(th2), 0, -a2*cos(th2)]
[ sin(th2),  cos(th2), 0, -a2*sin(th2)]
[        0,         0, 1,            0]
[        0,         0, 0,            1]


R3 =

[ cos(th3), -sin(th3), 0, -a3*cos(th3)]
[ sin(th3),  cos(th3), 0, -a3*sin(th3)]
[        0,         0, 1,            0]
[        0,         0, 0,            1]


R4 =

[ cos(th4), 0,  sin(th4),  0]
[ sin(th4), 0, -cos(th4),  0]
[        0, 1,         0, d4]
[        0, 0,         0,  1]
```

```
R5 =

 [ cos(th5),   0, -sin(th5),   0]
 [ sin(th5),   0,  cos(th5),   0]
 [        0,  -1,         0,  d5]
 [        0,   0,         0,   1]


R6 =

[ cos(th6), -sin(th6), 0,  0]


[ sin(th6),  cos(th6), 0,  0]
[        0,         0, 1, d6]
[        0,         0, 0,  1]
```

The final transformation matrix is given by:

$$T_0^6 = R_1 * R_2 * R_3 * R_4 * R_5 * R_6$$

The final transformation matrix can be found as:

The Final Transformation Matrix T^0_6 is computed using MATLAB and is given by –

[cos(th6)*(sin(th1)*sin(th5) + cos(th2 + th3 + th4)*cos(th1)*cos(th5)) - sin(th2 + th3 + th4)*cos(th1)*sin(th6), - sin(th6)*(sin(th1)*sin(th5) + cos(th2 + th3 + th4)*cos(th1)*cos(th5)) - sin(th2 + th3 + th4)*cos(th1)*cos(th6), cos(th5)*sin(th1) - cos(th2 + th3 + th4)*cos(th1)*sin(th5), d6*(cos(th5)*sin(th1) - cos(th2 + th3 + th4)*cos(th1)*sin(th5)) + d4*sin(th1) + a2*cos(th1)*cos(th2) + d5*sin(th2 + th3 + th4)*cos(th1) + a3*cos(th1)*cos(th2)*cos(th3) - a3*cos(th1)*sin(th2)*sin(th3)]

[- cos(th6)*(cos(th1)*sin(th5) - cos(th2 + th3 + th4)*cos(th5)*sin(th1)) - sin(th2 + th3 + th4)*sin(th1)*sin(th6), sin(th6)*(cos(th1)*sin(th5) - cos(th2 + th3 + th4)*cos(th5)*sin(th1)) - sin(th2 + th3 + th4)*cos(th6)*sin(th1), - cos(th1)*cos(th5) - cos(th2 + th3 + th4)*sin(th1)*sin(th5), a2*cos(th2)*sin(th1) - d4*cos(th1) - d6*(cos(th1)*cos(th5) + cos(th2 + th3 + th4)*sin(th1)*sin(th5)) + d5*sin(th2 + th3 + th4)*sin(th1) + a3*cos(th2)*cos(th3)*sin(th1) - a3*sin(th1)*sin(th2)*sin(th3)]

[cos(th2 + th3 + th4)*sin(th6) + sin(th2 + th3 + th4)*cos(th5)*cos(th6), cos(th2 + th3 + th4)*cos(th6) - sin(th2 + th3 + th4)*cos(th5)*sin(th6), -sin(th2 + th3 + th4)*sin(th5), d1 + d5*(sin(th2 + th3)*sin(th4) - cos(th2 + th3)*cos(th4)) + a3*sin(th2 + th3) + a2*sin(th2) - d6*sin(th5)*(cos(th2 + th3)*sin(th4) + sin(th2 + th3)*cos(th4))]

[0, 0, 0, 1]

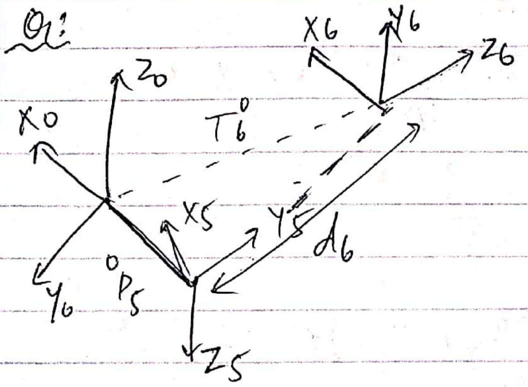
Inverse Kinematics

Inverse Kinematics calculation for all the joint angles θ_1 to θ_6:

Inverse kinematics of UR-5:

Calculating the joint angles $\theta_1 - \theta_6$

θ_1:



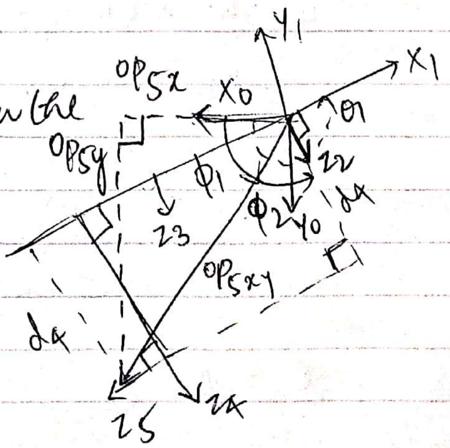
${}^0P_5 = {}^0P_6 - d_6$ where ${}^0P_5$ is the wrist frame

$${}^0P_5 = T_6^0 \begin{bmatrix} 0 \\ 0 \\ -d_6 \\ 1 \end{bmatrix}$$

$\theta_1 = \phi_1 + (\phi_2 + \frac{\pi}{2})$

where ϕ_1 is the angle b/w the sides ${}^0P_{5x}$ and ${}^0P_{5y}$.

$\phi_1 = atan2({}^0P_{5y}, {}^0P_{5x})$



ϕ_2 is found by examining the rightmost triangle with sides ${}^0p_{5xy}$ and d_4.

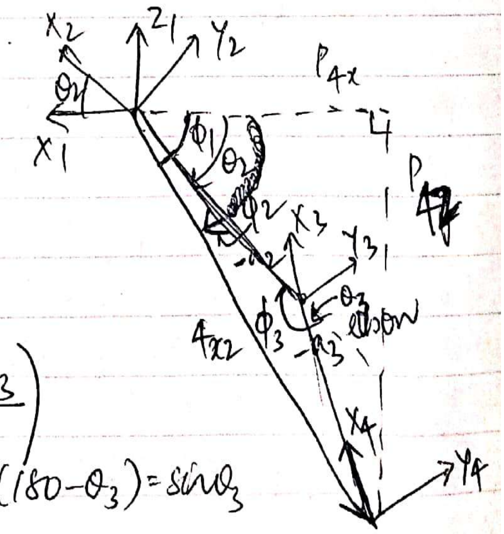
$$\cos\phi_2 = \frac{d_4}{{}^0p_{5xy}}$$

$$\phi_2 = \pm a\cos\left(\frac{d_4}{{}^0p_{5xy}}\right) = \pm a\cos\left(\frac{d_4}{\sqrt{{}^0p_{5x}^2 + {}^0p_{5y}^2}}\right)$$

$$\therefore \theta_1 = \phi_1 + \phi_2 + \frac{\pi}{2}.$$

$$\theta_1 = atan2({}^0p_{5y}, {}^0p_{5x}) \pm a\cos\left(\frac{d_4}{\sqrt{{}^0p_{5x}^2 + {}^0p_{5y}^2}}\right) + \frac{\pi}{2}$$

<u>θ_2:</u>



$$\theta_2 = \phi_2 - \phi_1$$

Here,

$$\phi_1 = atan2({}^1P_{4z}, {}^1P_{4x}).$$

$$\frac{\sin\phi_2}{-a_3} = \frac{\sin\phi_3}{P_{4xz}}$$

$$\phi_2 = a\sin\left(\frac{-a_3\sin\phi_3}{P_{4xz}}\right)$$

Also, w.k that $\sin\phi_3 = \sin(180 - \theta_3) = \sin\theta_3$

$$\therefore \theta_2 = \phi_1 - \phi_2$$
$$= atan2({}^1P_{4z}, {}^1P_{4x}) - a\sin\left(\frac{a_3\sin\theta_3}{P_{4xz}}\right)$$

θ_3:

From the above diagram, $\cos\phi_3$ is given by

$$\cos\phi_3 = \frac{(-a_2)^2 + (-a_3)^2 - |P_{4xz}|^2}{2(-a_2)(-a_3)} \quad \text{[By law of cosines]}.$$

$$= \frac{a_2^2 + a_3^2 - |P_{4xz}|^2}{2a_2 a_3}.$$

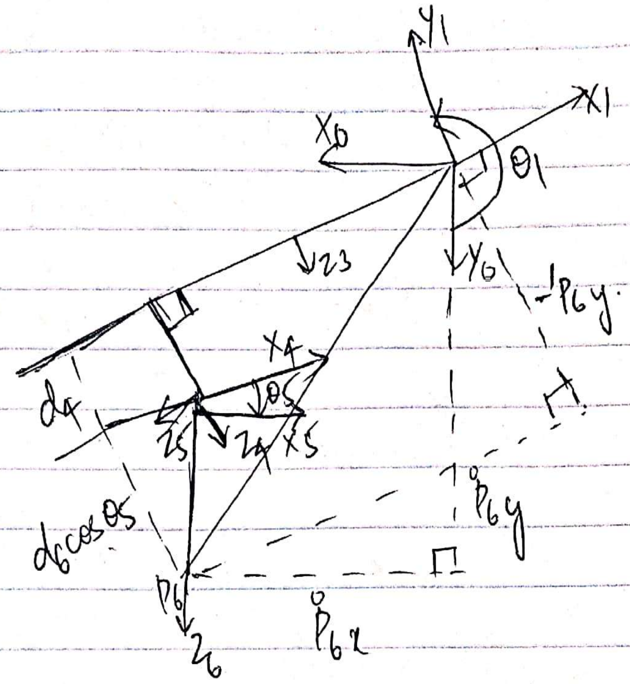
We know that; $\cos\theta_3 = \cos(\pi - \phi_3) = -\cos(\phi_3)$

$$\therefore \cos\theta_3 = -\left[\frac{a_2^2 + a_3^2 - |P_{4xz}|^2}{2a_2 a_3}\right]$$

$$\theta_3 = \pm \operatorname{acos}\left[\frac{|P_{4xz}|^2 - a_2^2 - a_3^2}{2a_2 a_3}\right]$$

θ_3 exists if acos is within $[-1,1]$. There are two different solutions with respect to the configuration employed (elbow up and elbow down) where $|a_2 - a_3|$; $|a_2 + a_3|$ is possible

θ_5:



${}^1P_{6y}$ depends on θ_5.

$$-{}^1P_{6y} = d_4 + d_6\cos\theta_5$$

${}^1P_{6y}$ can be given by rotation of ${}^0P_6$ across Z_1.

$$^0P_6 = {}^0_1R \cdot {}^1P_6$$

$$\Rightarrow {}^1P_6 = {}^0_1R^T \cdot {}^0P_6$$

$$\begin{bmatrix} {}^1P_{6x} \\ {}^1P_{6y} \\ {}^1P_{6z} \end{bmatrix} = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & 1 \end{bmatrix}^T \begin{bmatrix} {}^0P_{6x} \\ {}^0P_{6y} \\ {}^0P_{6z} \end{bmatrix}$$

$$\Rightarrow {}^1P_{6y} = {}^0P_{6x}(-\sin\theta_1) + {}^0P_{6y}\cos\theta_1.$$

∴ The above eqn becomes

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

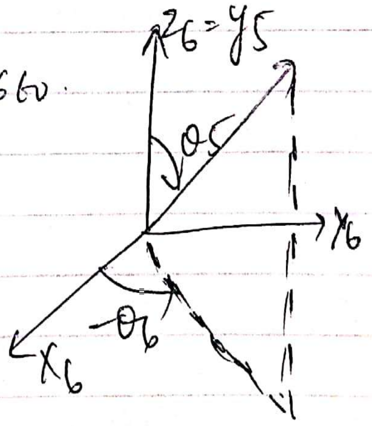
$$\cos\theta_5 = \frac{{}^0P_{6x}\sin\theta_1 - {}^0P_{6y}\cos\theta_1 - d_4}{d_6}.$$

$$\therefore \theta_5 = \pm a\cos\left(\frac{{}^0P_{6x}\sin\theta_1 - {}^0P_{6y}\cos\theta_1 - d_4}{d_6}\right)$$

Two solutions with respect to configuration of wrist being up ~~or~~ down.

θ_6:

Transformation from frame 6 to frame 1.



$$T_1^6 = ((T_1^0)^{-1} T_6^0)^{-1}$$

$$-\sin(\theta_6)\sin(\theta_5) = z_y$$

$$\therefore \theta_6 = \operatorname{atan2}\left(\frac{-z_y}{\sin(\theta_5)}, \frac{z_x}{\sin\theta_5}\right)$$

$\underline{\theta_4}$: Looking into the previous geometric frame diag

w.k. that Angle from X_3 to X_4 measured at Z_4 is θ_4

From the T_4^3 transformation matrix, using the first column vector

$$\theta_4 = \operatorname{atan2}(X_{4y}^3, X_{4x}^3)$$

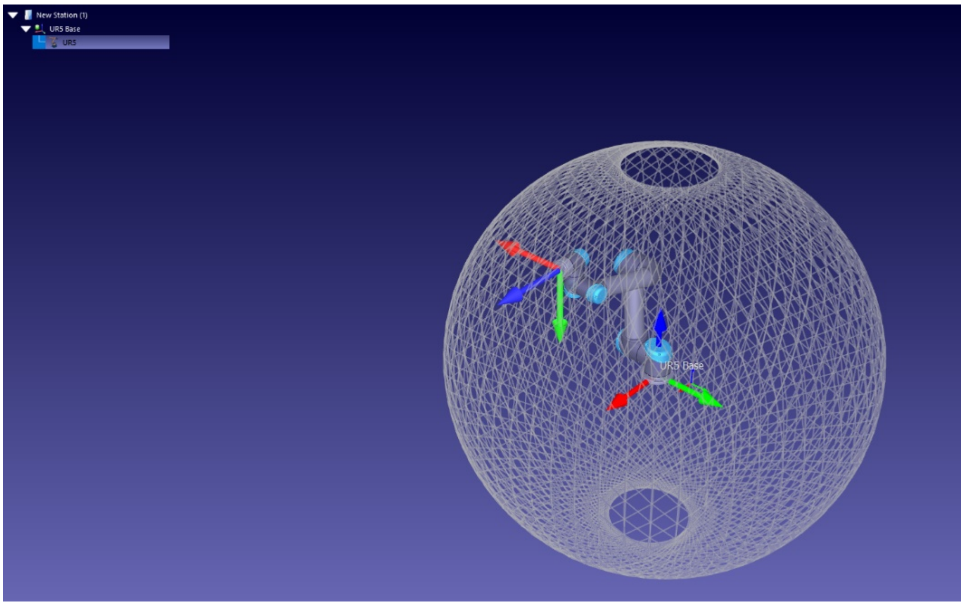
where X_{4y}^3 - Y component

X_{4x}^3 - X-component

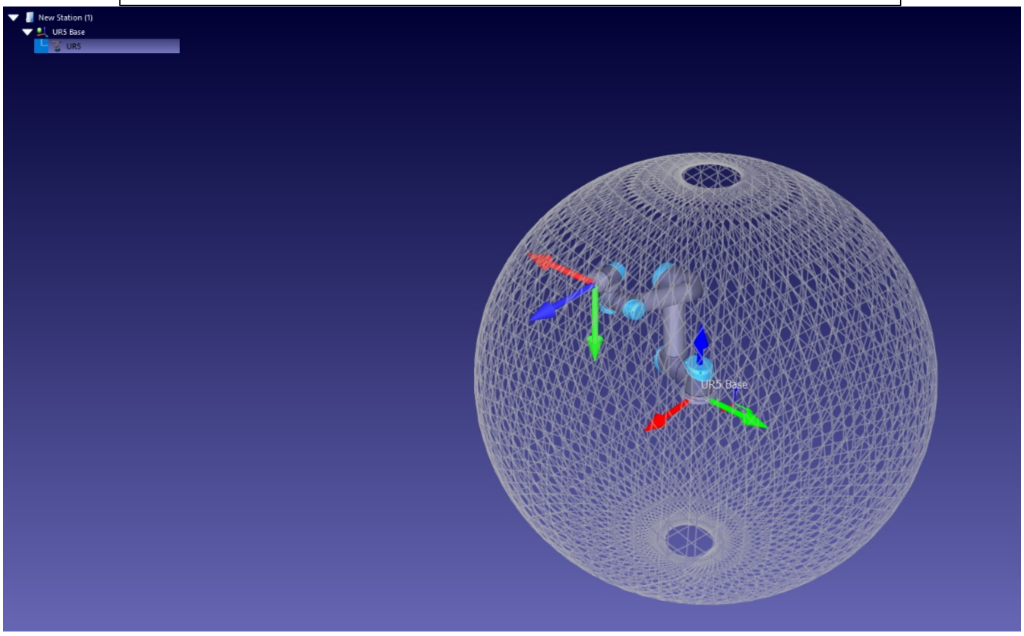
Workspace and Singularity

There are three instances of singularity observed in our UR5 Manipulator and these occur at:

- Shoulder
- Elbow
- Wrist of UR5



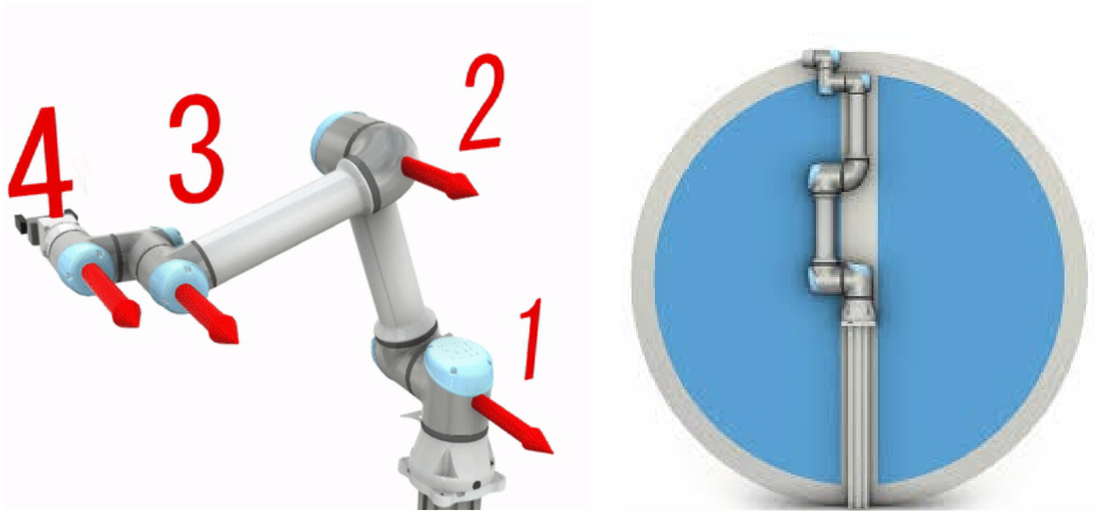
Workspace with respect to the current tool



Workspace with respect to the wrist center of the manipulator

Wrist alignment Singularity:

The shoulder, elbow and wrist 1 joints all rotate in the same plane on UR robots, as shown by the arrows numbered 1, 2 and 3 in the picture below. However, when we also align the movement of wrist joint 2 (labelled 4) with this same plane by moving it to an angle of 0 or 180 degrees, we limit the range of movements of the robot, regardless of the area of the workspace.



Singularity and Workspace constraints

This can be avoided by laying out the robot task in such a way that it need not necessarily align the robot wrist joints in this configuration. Also, offset the direction of the tool, so that the tool can point horizontally without the problematic wrist alignment.

Inner and Outer Workspaces:

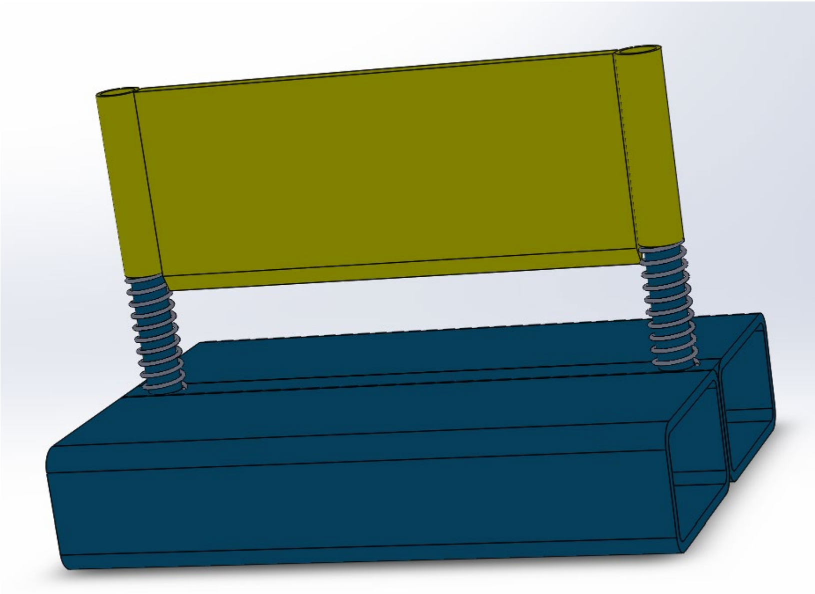
The robot should not move in the columns above and below the base as many orientations would be unreachable because of the way the joints are connected.

The robot should work in the recommended sphere because the robot cannot reach far enough in some situations. We can arrange the equipment around the robot in such a way that we do not have to work outside the recommended workspace.

Solidworks Model

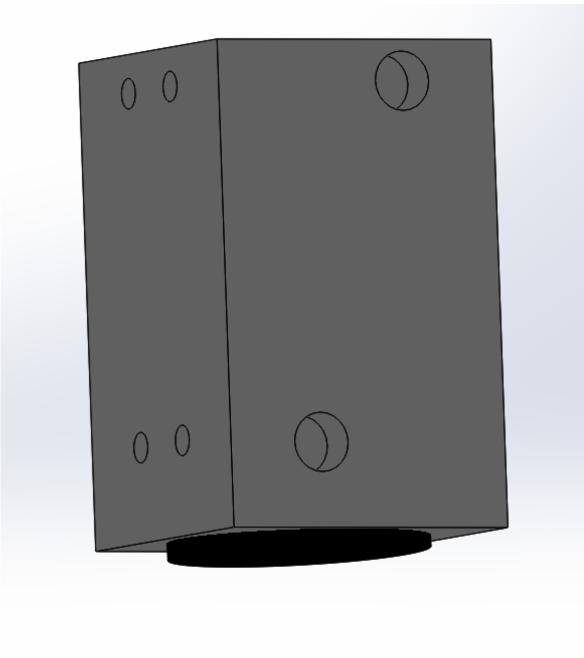
Sheet metal working machine:

This is the Solidworks model of the press brake operation machine. The dimensions have been reduced for simulation purposes.

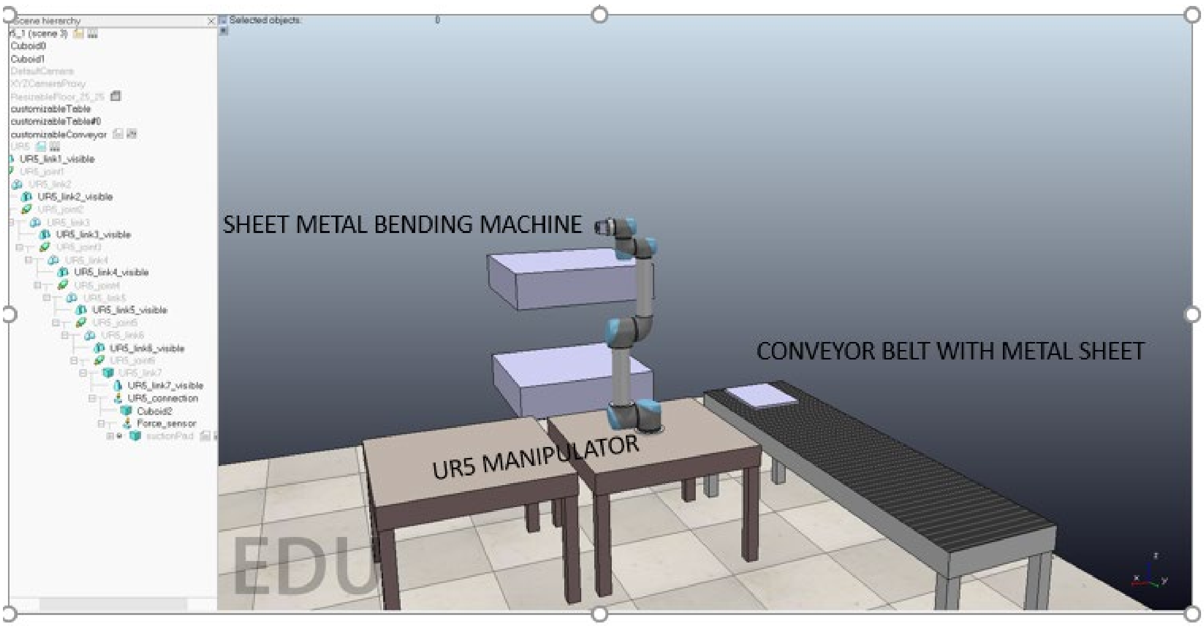


Magnetic gripper:

This is the Solidworks model of the magnetic gripper. The dimensions are (50 mm * 50 mm * 80 mm). This model has been designed to use it for simulation purposes.



Simulations



Simulation Setup in V-REP

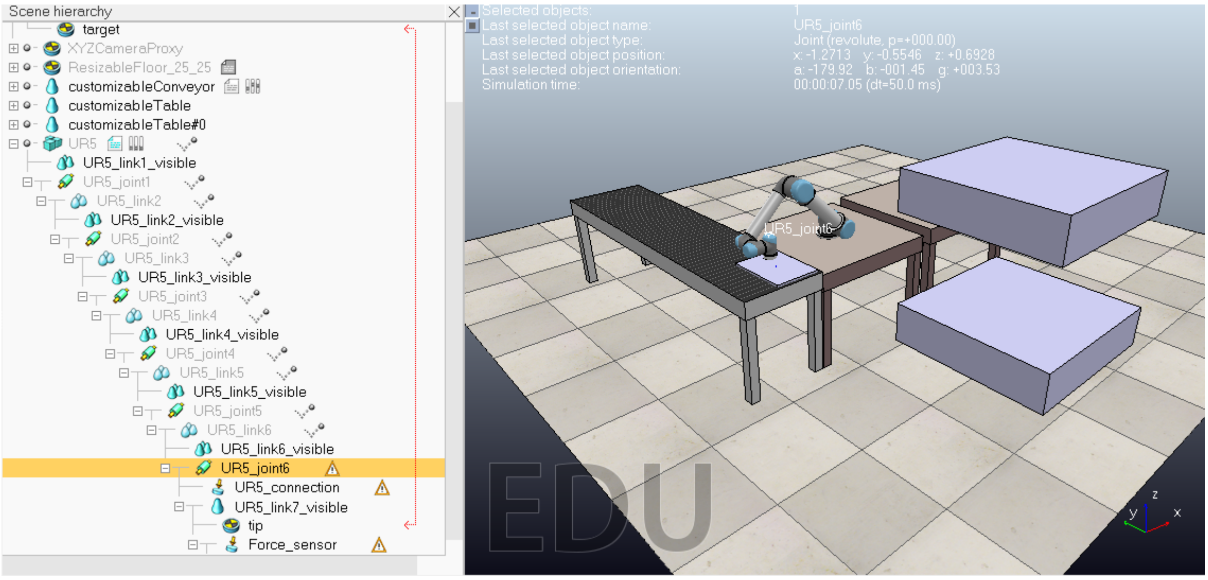
Due to some problems importing the Solidworks model, we consider the two solid blocks to be the sheet bending machine. The task of our robot is as follows:

The robot picks the metal sheet from the conveyer belt and rotates across two sides to perform the bending process in the press brake machine (two solid blocks). Then it places the sheet on the table. It picks the sheet again and performs the bending operation across the remaining two sides. Finally, it places the sheet back on the table.

The path planning aspect here is to avoid collision with an object that we created and simulated in MATLAB.

V-REP Simulation:

With respect to our V-REP Scene created,we were able to direct our UR5 manipulator to reach our metal sheet centre frame running on the conveyor .The gripper attached wasn't able to pickup the sheet .



V-REP Simulation Scene where our gripper reached the sheet moving in a Conveyor belt

We added a tip and a target in our simulation platform using a dummy. The tip was attached at the end effector of the manipulator and target at the center of the sheet and using calculation modules, we added and edited the IK elements. The manipulator started showing dynamic behaviour.

For reference, do visit the drive link to see the codes and the simulation videos for the same:

https://drive.google.com/open?id=1oXqrpRG7HyxhEqgSmFT2Wox6dz90_XWG

Path Planning Approach

We have employed Rapidly exploring random trees (RRT) algorithm for obstacle avoidance with an obstacle placed in front of the UR5 manipulator.

RRT Algorithm:

The premise of RRT is quite straight forward.

- Points are randomly generated and connected to the closest available node.
- Each time a vertex is created, a check must be made that the vertex lies outside of an obstacle.
- Furthermore, chaining the vertex to its closest neighbor must also avoid obstacles.
- The algorithm ends when a node is generated within the goal region, or a limit is hit.

The benefit of the algorithm is its speed and implementation. Compared to other path planning algorithms, RRT is quick. The costliest part of the algorithm is finding its closest neighbor as this process grows depending on the number of vertices that have been generated.

Execution of Path Planning algorithm:

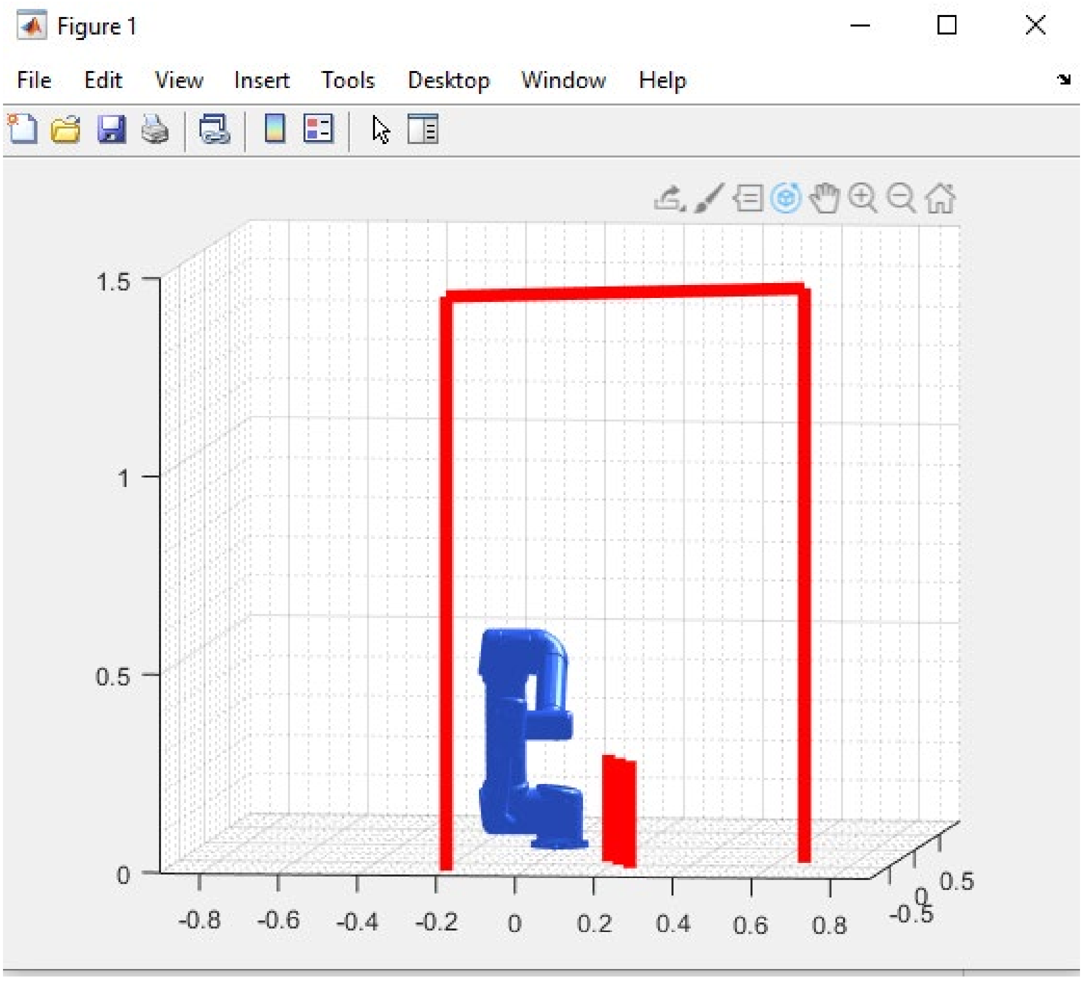
At first, we are using *UR5Robot-MEX-Matlab* from Mathworks which includes UR5 kinematics and inverse kinematics which have been "mexified" for performance and an efficient, lag-free visualization of the UR5 robot model.

In order to mex the files which are compiled in C++,in MATLAB command window, we install the appropriate wsx64C++compiler.mex file.

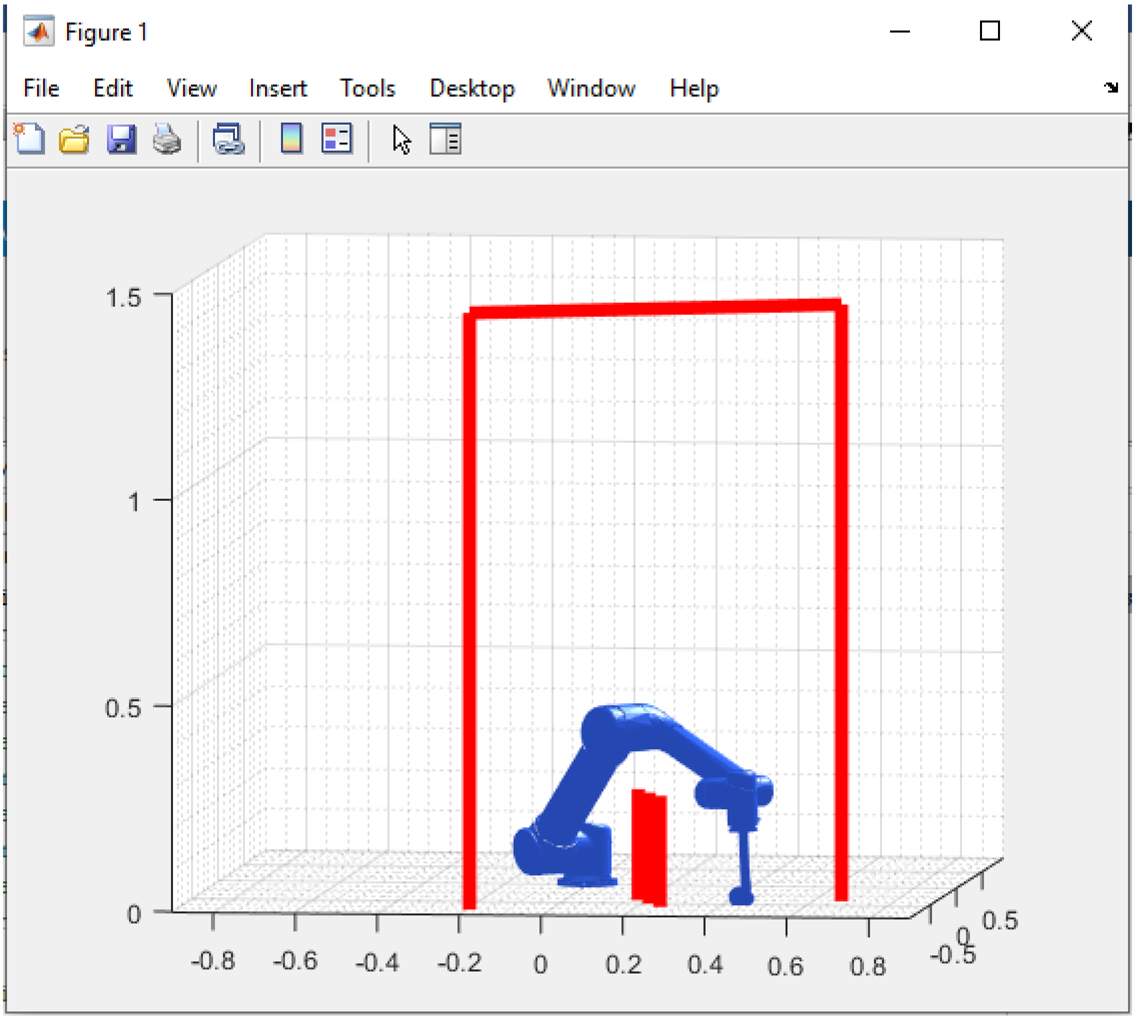
To obtain the robot model, we run the *run_me.m* file to initialize the toolbox package parameters which are the kinematics, joint angles, jacobians of the UR5 and via Simulink 3D,we obtain the model for UR5 as a figure.

Now, with respect to creating an environment for path planning, we load a variable file *load demo_vars.mat* created which has the positions of the starting and the goal position of the manipulator in the command window.

Now, we run the path planning algorithm file to get the desired output. *MPExtendRRT(C_ini, C_goal, Obs)* in the command window.



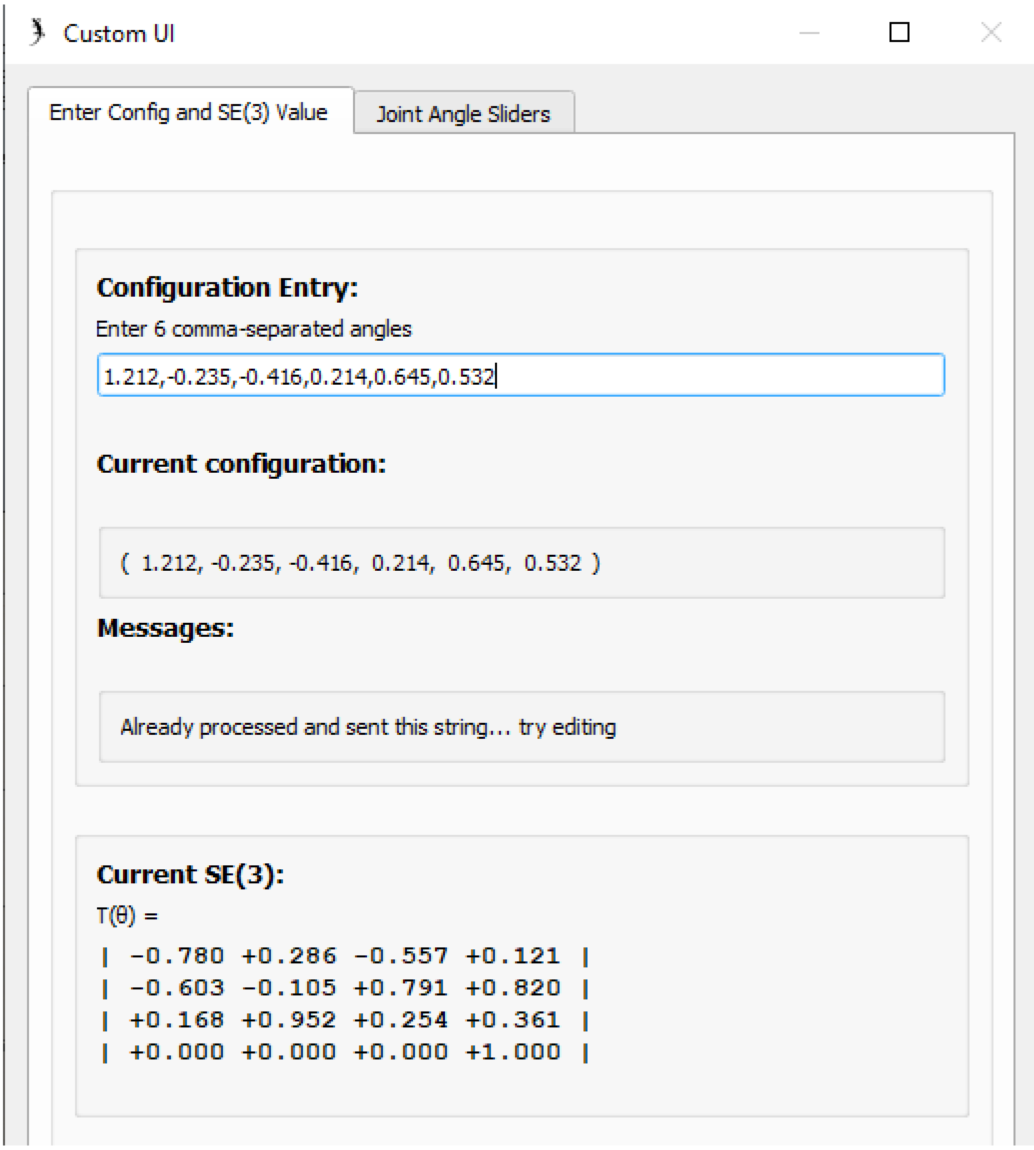
Initial Starting position of the UR5 manipulator



Final position of the UR5 Manipulator avoiding the obstacle

Validation Plan

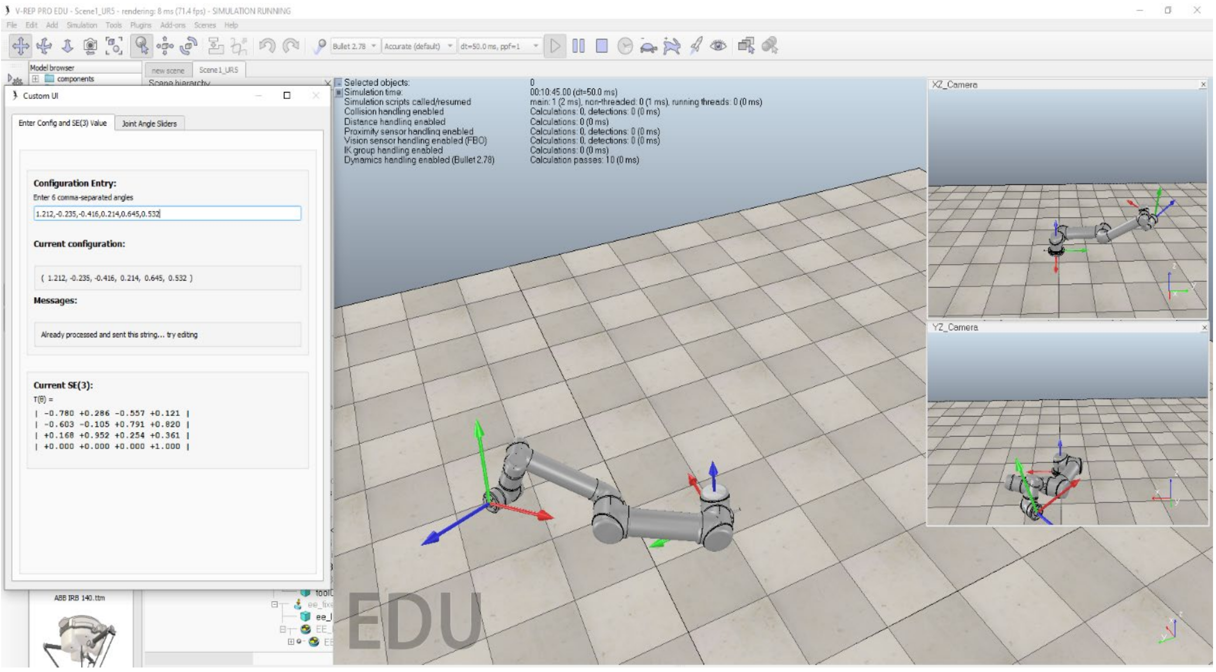
To validate our manipulator joint angles, we made a VREP scene which has a custom UI wherein one can enter the joint angles in order to visualize how the manipulator moves in the workspace.



Custom UI to enter joint angles

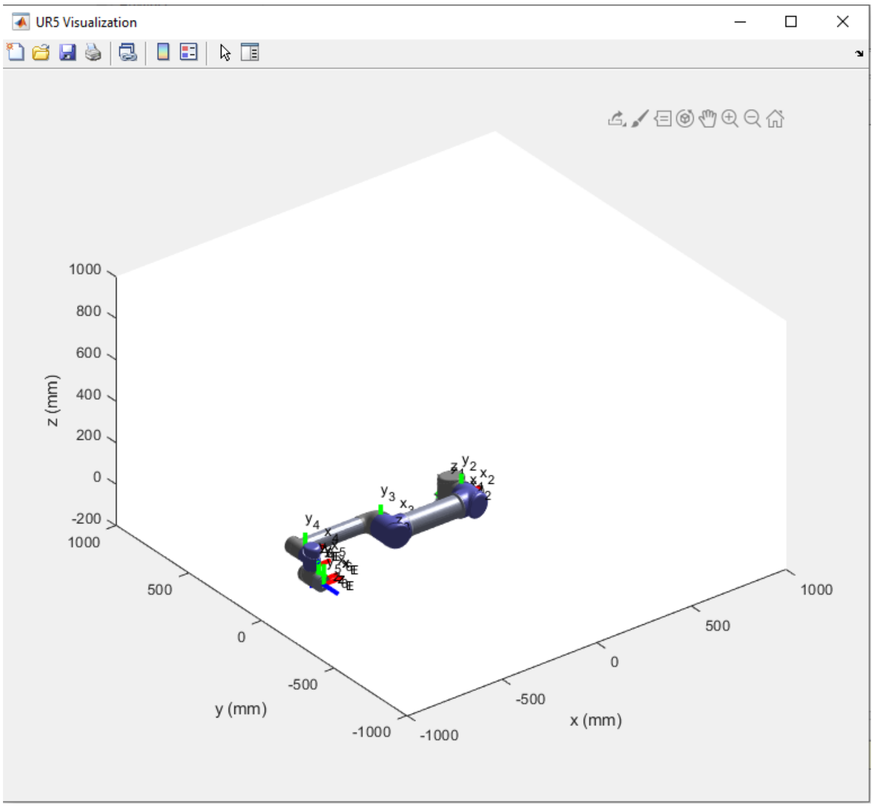
The joint angles entered must be in radians and not degress.

With respect to the joint angles entered,the UR5 manipulator from its home position rotates with respect to the joint angles entered above which are (1.212,-0.235,-0.416,0.214,0.645,0.532)

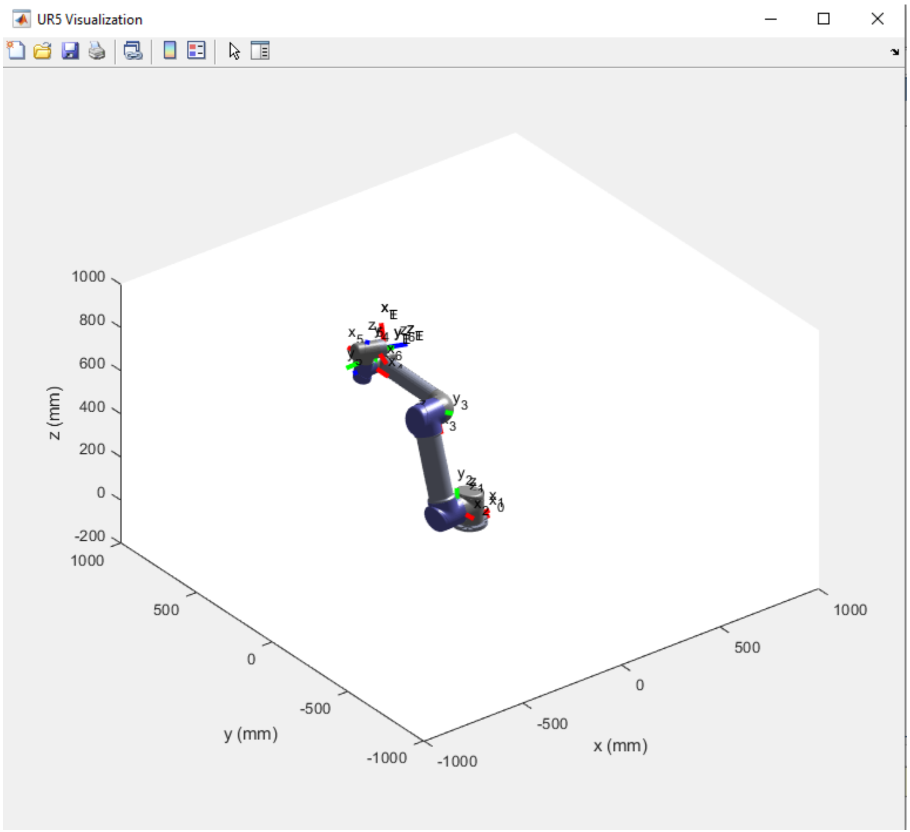


VREP Scene for the given joint angle configuration

Following the joint angle verification of UR5,we have also verified our Inverse Kinematics for our manipulator. This is done with the help of *kutzer/URToolbox* available from Mathworks. After installing the toolbox, we run *UR-IK.m* file. The manipulator model gets created and IK model for the same is created. *URsim* function can be used with the help of the above toolbox to visualize the IK Model.



UR-5 Model in Zero configuration



UR-5 Model in Target configuration

Conclusion

The manipulator was able to reach the metal sheet moving on the conveyor belt but was not able to grip and pick it up. Also, the manipulator exhibited dynamic behavior in the VREP environment. Despite that we were able to derive the forward and inverse kinematics of the same and we were able to validate it with MATLAB. Further, we have done Path planning for our manipulator by employing RRT algorithm which helped in obstacle avoidance.

References

- Robot Modelling and Control: Mark W Spong, Seth Hutchinson, and M. Vidyasagar
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