Bangladesh University of Engineering & Technology

Course : EEE-318 (Control System Laboratory)

PROJECT REPORT

PROJECT Title: Robotic Arm Design & Simulation

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Introduction

The most widely used industrial robot is the robotics arm. Robotic arms have many applications in manufacturing because the end-effector of a robotic arm can be changed to fit particular industries. For instance, welding manipulators are used as spot-welding robots in manufacturing (automotive), spray nozzles for spray painting parts and assemblies (numerous industries), grippers for pick and place (electronics industry), with a pressing need for increased productivity and the delivery of end products of uniform quality, industry is turning more and more towards computer-based automation. Most automated manufacturing tasks, at the present time, are carried out by special purpose machines designed to perform a predetermined function in a manufacturing process. The inflexibility and generally high cost of these machines, often called hard automation systems, have led to a broad-based interest in the use of robots capable of performing a variety of manufacturing functions in a more flexible working environment. An industrial robot is computer-controlled manipulator consisting of several rigid links connected in series by revolute or prismatic joints. One end of the chain is attached to a supporting base, while the other end is free and equipped with a tool to manipulate objects or perform assembly tasks. The motion of the joints results in relative motion of the links. Mechanically, a robot is composed of an arm, wrist and tool. The work volume is the sphere of influence of a robot whose arm can deliver the wrist subassembly unit to any point within the sphere. The arm subassembly generally can move within 3 degrees of freedom (3DOF). Most of today’s industrial robots are controlled by mini- and micro-computers and are basically simple positional machines. They execute a given task by playing back prerecorded or preprogrammed sequences of motion that have been previously guided or taught by the user with a hand-held control-teach pendant. Moreover, these robots are equipped with little or no external sensors for obtaining the information vital to its working environment. As a result, robots are used mainly for relatively simple, repetitive tasks. More research effort is being directed towards improving the overall performance of the manipulator system.

Terminology and Definitions

Common robotics terms are defined as follows :

The Manipulator:A mechanism, generally composed of a series of links, jointed between them, which aims to grasp and move objects. It is multifunctional and it can be governed directly by a human operator or through a logic device.

The Wrist: It is a set of joints, usually rotational, between the arm and the endeffector , which allows the latter to be oriented relative to the workspace.

The End-Effector: A robot arm by itself can serve no purpose until a load or a tool is suspended from or attached to it. Devices which connect between the robot wrist and the load are known as end-effectors.

The Work Envelope (Work Volume): One of the most important characteristics in robotics is the shape of the arm reach envelope, or the arm work envelope. The shape of work volume depends on the coordinate system, where its size depends on the dimension of the robot arm.

The Tool Center Point (TCP) :A tool-related reference point that lies along the last wrist axis at a user specified distance from the wrist

Orientation: When the tool is at a point in space, it could be oriented in different ways. For example, it could be pointing downward, parallel to the negative Z axis, or pointing forward, parallel to the positive X axis. The orientation of a tool is identified by a rotation (positive or negative) around the X, Y, and Z axes (or around axes that are parallel to the X, Y, and Z axes). Rotation around the X axis is called yaw, around the Y axis, pitch, and around the Z axis, roll. By convention, these are written in the order: yaw, pitch and roll.

Robot Manipulator Modeling:

In order to understand mathematics behind motion planning, it is important to understand the geometry of serial robotic system. Serial robotic manipulators are made up of a series of controllable variable joints. These joints are usually either prismatic (P) or revolute (R) as shown in figure

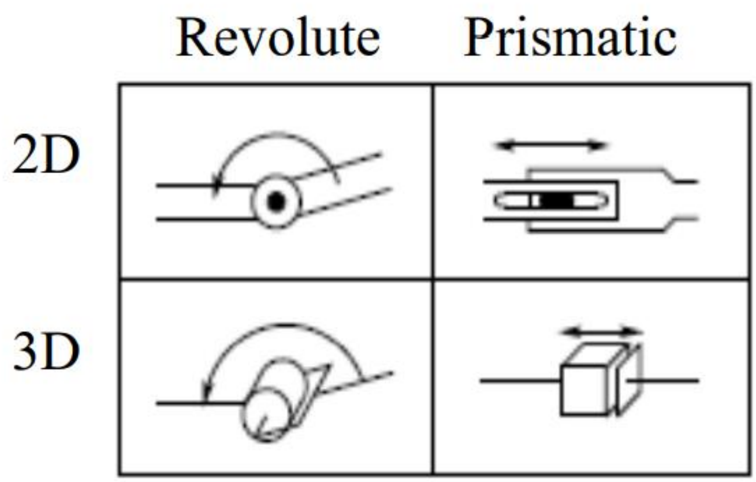


Figure (1.1): Symbolic representation of robot joints [3].

A prismatic joint provides linear motion along an axis, and a revolute joint provides rotation about an axis. The degrees of freedom of a serial robot is defined to be the number of active variable joints (i.e. each joint is driven). The current configuration of a serial system is a function of the current joint positions.

Kinematical Structure

First of all, let us see how a manipulator is mechanically design and how can be expressed by parameters and equations. The kinematical structure refers to how to calculate a position of the end-point and to get the manipulator to the desired configuration. Dynamic properties, such as weight, inertia etc., are not considered as part of the kinematics. A manipulator has one or more links. Links are connected by joints. links are assumed to be rigid bodies, and all joints described by one degree of freedom. If a joint has more than one DOF, it is straight forward to think of it as several links with a length of zero connected with joints of one D.O.F.There are two design directions for manipulators; an open kinematic chain as shown in figure (1.2.a), that is when all links are in a series; or a closed chain (parallel) as shown in figure (1.2.b), when both ends of two links are connected to a third link [3].

a b

Figure (1.2): Examples of (a) Serial and (b) parallel Robot Manipulators.

Robotic Manipulator System

Typically, a robot manipulator system consists of the following components:

• **The robot arm:** It consists of the whole electromechanical structure: the robot base, links, joints, motors or actuators and end-effector if one attached.

• **The robot controller:** A computer system with all the control circuits including microprocessors, motor drivers, interface connectors, and the power units. The controller is, in general, provided as separate unit, but in some recent models, it can be integrated with robot arm.

• **A teach pendant:** The teach pendent is a tethered handheld controller that allows an operator to program the robot by direct control of the joints and motions.

• **An interface computer:** the computer provides the interface between the operator and the robot controller. Programs can be written, accomplished, or interpreted and downloaded to the robot controller for execution.

• **Robot system software:** the software consists of a robot programming language, a program development environment, possibly some program simulation and testing facility, and more.

ROBOT ARM MECHANICS

General Characteristics of Robot Arm Mechanics

Kinematics in robotics is the science of motion investigation. Robot arm links can be rotated or offset according to the reference coordinate frame. A systematic and general approach developed by Denavit and Hartenberg establishes the relationship between the robot endpoint and the total displacement of robot arm links. Angular and linear displacements between limbs are called joint coordinates and are defined by limb variables. In order to determine the amount of rotation and displacement according to the reference coordinate system of the endpoint, the matrices A which represent the amounts of each limb rotation and displacement are multiplied in turn. If the coordinates of the end point are given, limb variables can be obtained by going backward. These operations are called forward and inverse kinematics. The next section will explain how to determine forward and reverse kinematics.

Coordinate Frames and Transformation Matrices for a General Robot Arm

An n-dimensional position vector is denoted by an n + 1-dimensional vector and is called a homogeneous coordinate representation. In the following, a matrix of 4 X

4 is shown which shows a position vector in the homogeneous coordinates between the coordinate frames.

$$
{}^{R}\mathrm{T}_{H} = \left[\begin{array}{c|c} (3*3) & (3*1) \\ \hline 0 & 1 \\ (1*3) & (1*1) \end{array}\right] = \begin{bmatrix} x_x & y_x & z_x & p_x \\ x_y & y_y & z_y & p_y \\ x_z & y_z & z_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

p = p i + p j + p k x y z The vector of the origin of the new frame,
x = x i + x j + x k x y z The contour vector of the x-axis of the new frame,
y = y i + y j + y k x y z The contour vector of the y-axis of the new frame,
z = z i + z j + z k x y z Represents the contouring vector of the z-axis of the new frame.
Column 4 of the transformation matrix has 3 elements corresponding to displacement in the x, y, and z directions.

$$
\mathbf{Trans}(p_x, p_y, p_z) = \begin{bmatrix} 1 & 0 & 0 & p_x \\ 0 & 1 & 0 & p_y \\ 0 & 0 & 1 & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

If any of the 3 coordinate axes is possible to rotate, there are 3 rotational transforms corresponding to the rotations in the x, y, and z-axes up to the q angle. The following matrix can be written for x-axis;

$$\mathbf{Rot}\,(x,\theta)=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & \cos(\theta) & -\sin(\theta) & 0\\ 0 & \sin(\theta) & \cos(\theta) & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

The matrices representing only the revolutions around the y and z-axes can be written in a similar manner.

$$\mathbf{Rot}\,(y,\theta)=\begin{bmatrix} \cos(\theta) & 0 & \sin(\theta) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{Rot}\,(z,\theta)=\begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 & 0 \\ \sin(\theta) & \cos(\theta) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The elements of the transformation matrix can be found by the arithmetic multiplication of pure rotation and displacement matrices. This can be obtained by a sequence of rotations about the axes of the stationary reference frame if the orientation is desired according to the reference frame of the Cartesian space endpoint. Although there are many ways to do this, one of the best known is the "roll-pitch-yaw" transformation. 3 turns. First turn around the x-axis, then y and then around the z-axis.

$$\mathbf{RPY}(\phi,\theta,\Psi) = \mathbf{Rot}(z,\phi)\mathbf{Rot}(y,\theta)\mathbf{Rot}(x,\Psi)$$

$$= \begin{bmatrix} C(\phi)C(\theta) & C(\phi)S(\theta)S(\Psi) - S(\phi)C(\Psi) & C(\phi)S(\theta)C(\Psi) + S(\phi)S(\Psi) & 0 \\ S(\phi)C(\theta) & S(\phi)S(\theta)S(\Psi) + C(\phi)C(\Psi) & S(\phi)S(\theta)C(\Psi) - C(\phi)S(\Psi) & 0 \\ -S(\theta) & C(\theta)S(\Psi) & C(\theta)C(\Psi) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Kinematics in robotics is the science of motion investigation. The robot examines the positions of the limb limbs, the relationships between velocities and accelerations, ignoring forces and other factors that affect movement.

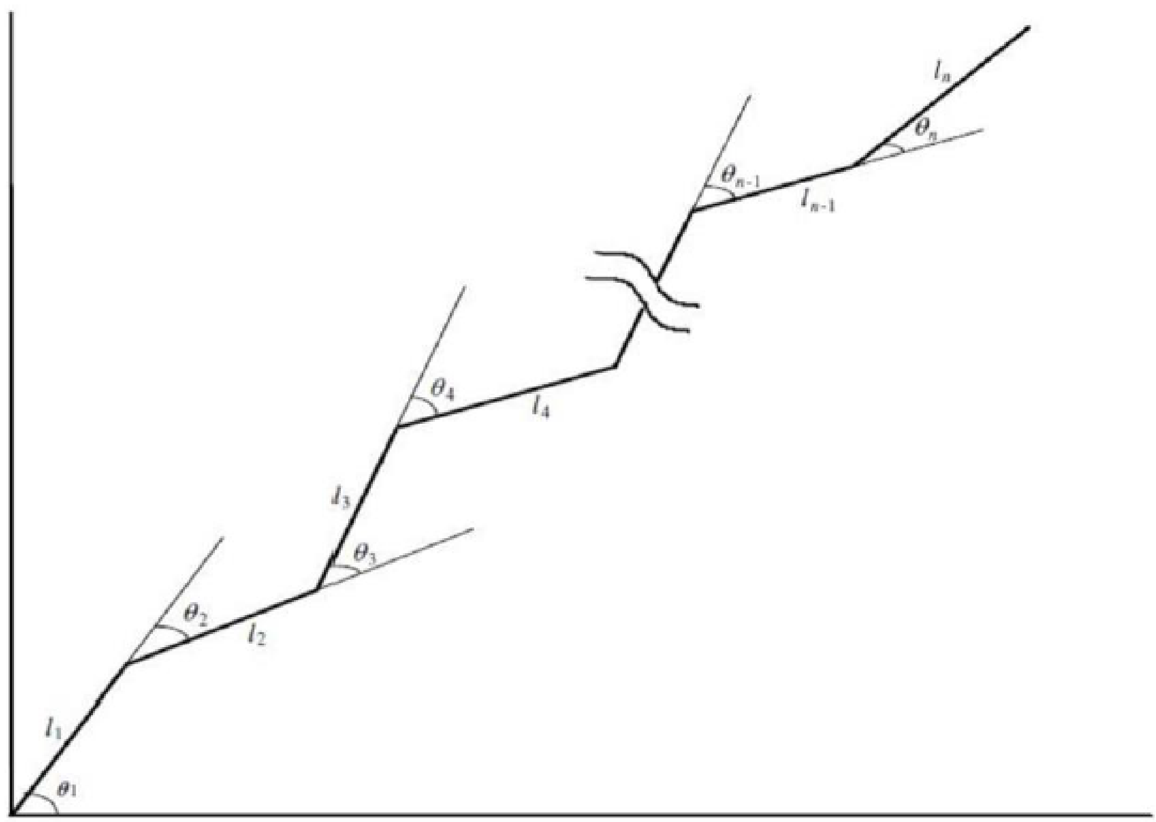


Figure 5Serial robot arm with n lines showing relative angles

The position and orientation of one of the limbs, or the orientation of the limbs between this limb and the end point, will change when the serial limb robot arm is shown in Fig. When the positions and orientations of the limbs change, it is generally desirable to determine the position and orientation of the end point according to the basic reference frame.
When each mobile station is connected to a coordinate frame, the transformation between both limbs can be defined by a homogeneous transformation matrix, called the matrix A. For example, the first limb is connected to the base frame by 0A1, which is the matrix 1.A. The transformation matrix RTH of the end point can be expressed according to the reference frame by the arithmetic product of matrices A from the matrices 1.A of the matrices A to the matrix A of the endpoints.

$$^{R}\mathbf{T}_{H} = {}^{R}\mathbf{T}_{1} . {}^{1}\mathbf{T}_{2} .. {}^{n-2}\mathbf{T}_{n-1} . {}^{n-1}\mathbf{T}_{H} = {}^{0}\mathbf{A}_{1} . {}^{1}\mathbf{A}_{2} .. {}^{n-2}\mathbf{A}_{n-1} . {}^{n-1}\mathbf{A}_{n}$$

When this equation is in closed form, any term can be expressed by another and is very important in the kinematic analysis of the robot arm. Because the robot is used to analyze the forward and inverse kinematics of the arm.

3.2. D & H (Denavit and Hartenberg) Coordinate Frames

The distances between the limbs and the displacements are called the joint coordinates defined by limb variables. A series of n articulated limb robots with one DOF for each limb has n + 1 joints. Using the D & H parameters, any nonlinear limb, as shown below, can be characterized by structural kinematic limb parameters

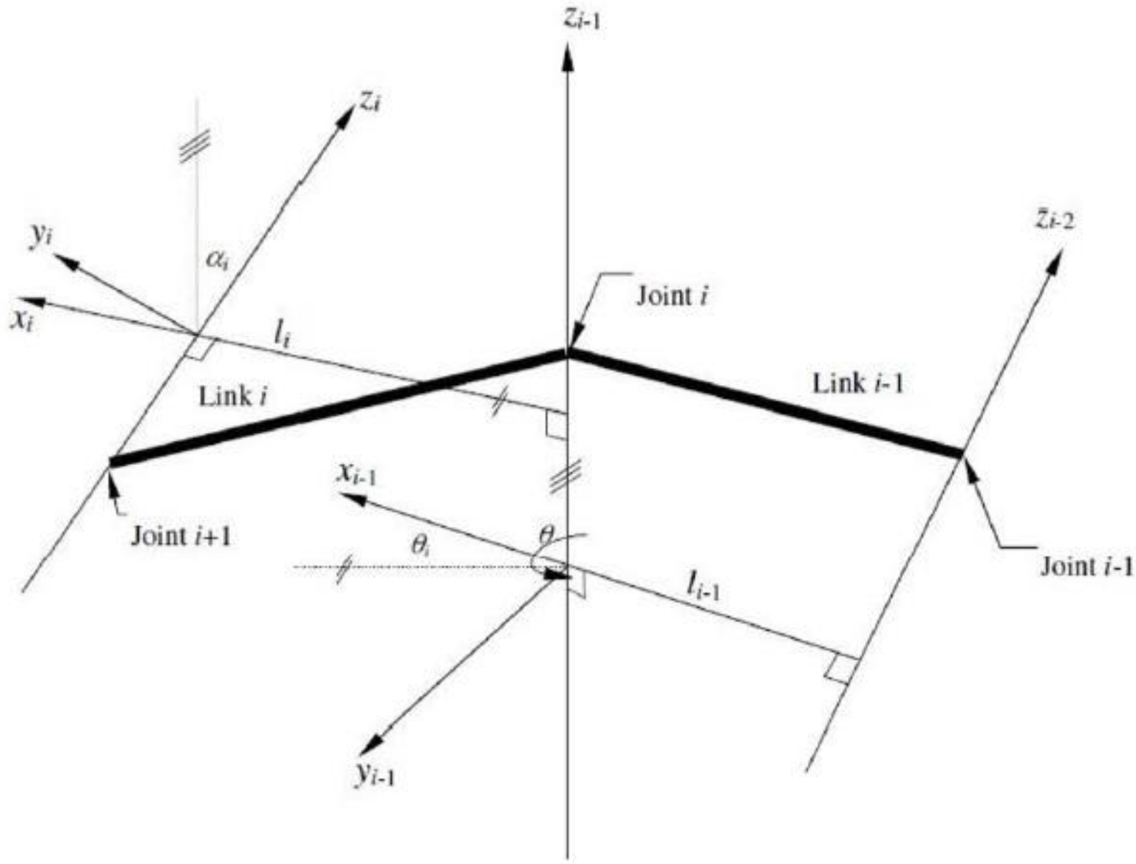


Figure 6D & H parameters

Ln: the length of the limb is the distance along the common normal between the axes of the joints. Z and Zi-1.

αi: is the positive angle of rotation about the positive X-axis from the positive Zi-1 axis to the positive Zi axis.

Θi: The positive angle of rotation about the positive Zi-1 axis from the positive Xi-1 axis to the positive Xi axis.

di : is the distance to the intersection of the Zi-1 and xi axes along the Xi-1 axis from the origin of the first coordinate frame.

3.4. Inverse Mechanics

For an endpoint position and orientation given in Cartesian coordinates, the process of finding the values that the joint variables must take is called inverse kinematics. Reverse kinematics can be difficult to solve according to the advanced kinematics. In many cases, it is necessary to use techniques that do not guarantee a solution and include trial and error.

Project design and Kinematic Modeling:

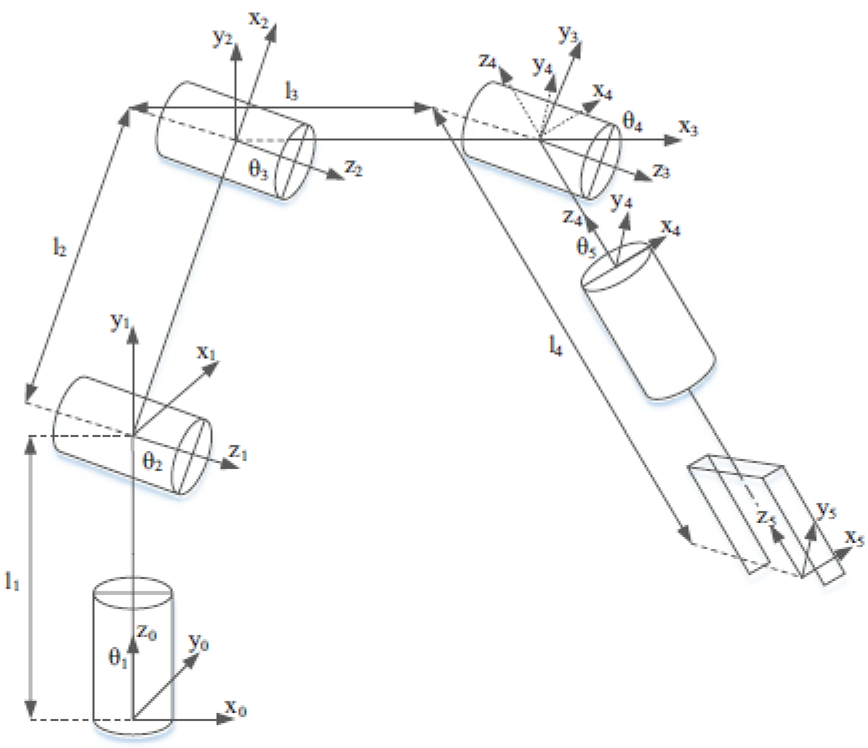


Fig. 2 Kinematic chain of 5 DoF manipulator

Link	Theta	alpha	r	d
1	Q1	90	0	20
2	Q2	0	20	0
3	Q3	0	20	0
4	Q4	-90	0	0
5	Q5	0	0	40

Table-1: Input Denavit-Hartenberg parameter table.

The kinematic modeling and the coordinate establishment is the key point to achieve the harmonization between the robotic manipulator and the control device.Thereafter, the Denavit Hartenberg (DH) conception is performed where some homogeneous matrices of individual kinematic pairs are used to define the transformation of the coordinate. The DH coordinate frames are exhibited in Fig. 2 which comprises the layout of the manipulator's joints, links and the orientations. From the figure, the four links of the manipulator are labeled as l1, l2, l3, and l4 and their lengths are 20 cm, 20 cm,20 cm and 40 cm respectively. The arm comprises five rotational joints which are labeled as Q1 , Q2 , Q3 , Q4 , and Q5 . These five joints work concurrently for gripping an object in a three-dimensional workspace and thereby acquire a high performance gripping.For analyzing the inverse kinematics, the DH parameters are listed in Table 1.

According to the DH parameters, the transformation matrices of the links are represented in (1), (2), (3), (4) and (5).

$$H_1^0 = \begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 & 0 \\ \sin\theta_1 & 0 & -\cos\theta_1 & 0 \\ 0 & 1 & 0 & l_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$H_2^1 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & l_2\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & l_2\sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$H_3^2 = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & l_3\cos\theta_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & l_3\sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$H_4^3 = \begin{bmatrix} \cos\theta_4 & 0 & \sin\theta_4 & 0 \\ \sin\theta_4 & 0 & -\cos\theta_4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$H_5^4 = \begin{bmatrix} \cos\theta_5 & -\sin\theta_5 & 0 & 0 \\ \sin\theta_5 & \cos\theta_5 & 0 & 0 \\ 0 & 0 & 1 & l_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

By multiplying these transformation matrices, the equations of the forward kinematics are obtained from (6).

$$H_{end-effector}^{base} = H_5^0 = H_1^0 H_2^1 H_3^2 H_4^3 H_5^4 \quad (6)$$

$$H_5^0 = \begin{bmatrix} i_x & j_x & k_x & p_x \\ i_y & j_y & k_y & p_y \\ i_z & j_z & k_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

In where, for the proposed robotic manipulator:

$$
\begin{array}{ll}
i_x = -s_1 s_5 + c_5 c_1 c_{234} & j_x = -s_5 c_1 c_{234} - c_5 s_1 \\
i_y = c_1 s_5 + c_5 s_1 c_{234} & j_y = c_5 s_1 - s_5 s_1 c_{234} \\
i_z = c_5 s_{234} & j_z = -s_5 s_{234} \\
k_x = -c_1 s_{234} & p_x = c_1 \left(l_2 c_2 - l_4 s_{234} + l_3 c_{23} \right) \\
k_y = -s1 s_{234} & p_y = s_1 \left(l_2 c_2 - l_4 s_{234} + l_3 c_{23} \right) \\
k_z = c_{234} & p_z = l_1 + l_2 s_2 + l_3 s_{23} + l_4 c_{234}
\end{array}
$$

The human operator inputs the expected position of the manipulator through a joystick. In order to move the robotic arm to that expected position, the actuators set the arms joint values. The values of joint angle $\theta 1$, $\theta 2$, $\theta 3$, $\theta 4$, and $\theta 5$ are calculated by using (8), (9), (10), (11), and (13).

$$\theta_1 = \tan^{-1} \frac{p_y}{p_x} \tag{8}$$

$$\theta_2 = \tan^{-1} \frac{n \left(l_2 + l_3 c_3 \right) - m l_3 s_3}{n l_3 s_3 + m \left(l_2 + l_3 c_3 \right)} \tag{9}$$

$$\theta_3 = \cos^{-1} \frac{m^2 + n^2 - l_2^2 - l_3^2}{2 l_2 l_3} \tag{10}$$

$$\theta_{234} = \tan^{-1} \frac{l_2 c_2 + l_3 c_{23} - p_x c_1 - p_y s_1}{p_z - l_1 - l_2 s_2 - l_3 s_{23}} \tag{11}$$

$$\theta_4 = \theta_{234} - \theta_2 - \theta_3 \tag{12}$$

$$\theta_5 = \tan^{-1} \frac{\left(i_y c_1 - i_x s_1 \right) s_{234}}{i_y s_1 + i_x c_1} \tag{13}$$

where, in (9) and (10):

$$m = p_x c_1 + p_y s_1 + l_4 s_{234}$$

$$n = p_z - l_1 - l_4 c_{234}$$

Simulation of Robotic Arm:

Modeling Forward Kinematics

Solution to the forward kinematics was modeled by means of MATLAB for the Denavit-Hanterberg parameters given in Table 2.

Link	Theta	alpha	r	d
1	0	90	0	20
2	-30	0	20	0
3	30	0	20	0
4	-45	-90	0	0
5	30	0	0	40

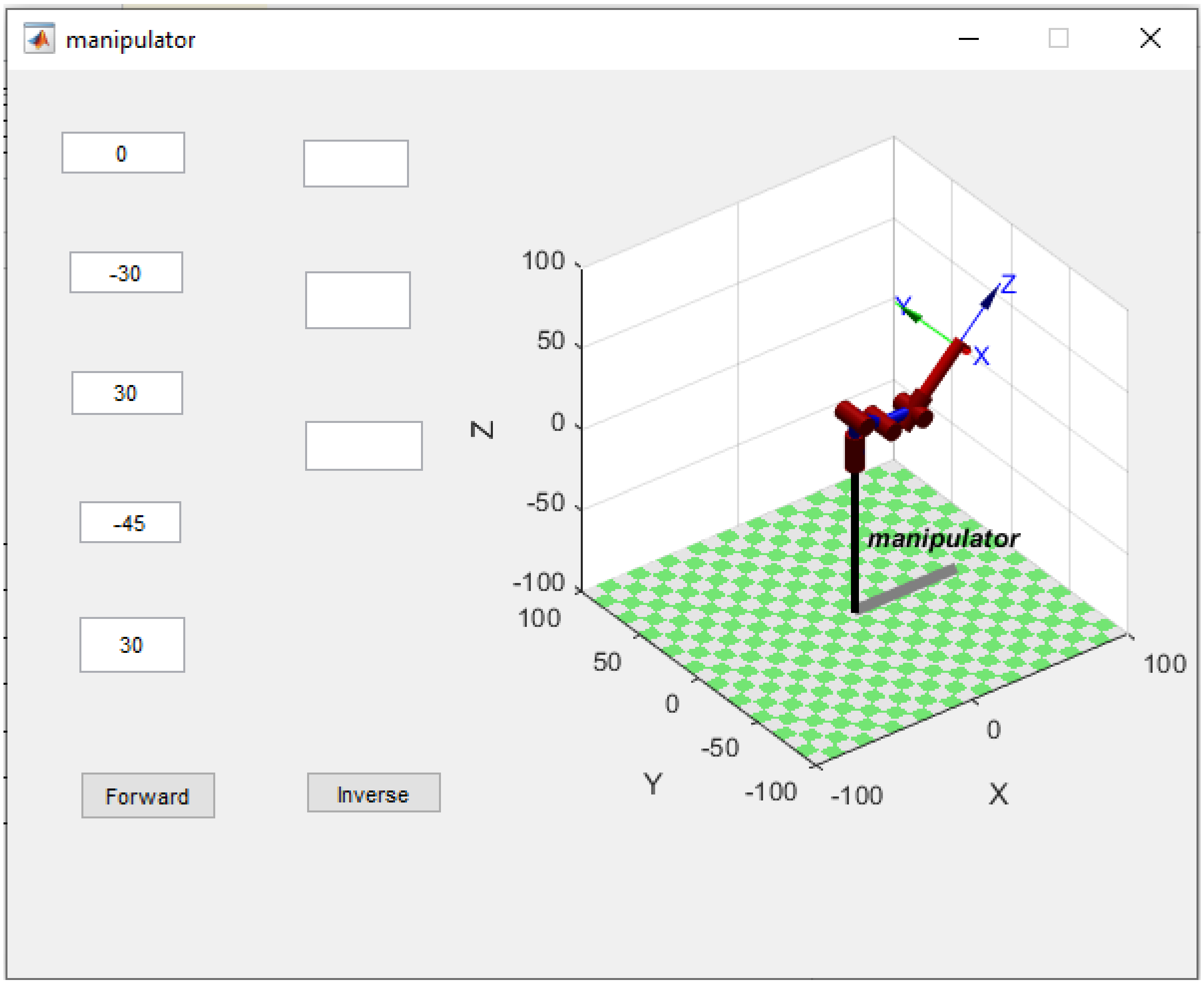
Table-2: Input Denavit-Hartenberg parameters.

The homogeneous transformation matrix T5 connecting the system of axes O5X5Y5Z5 with the absolute system of axes O0X0Y0Z0 can be expressed as:

```
T =

    0.6124   -0.3536   -0.7071    9.0362
   -0.5000   -0.8660         0         0
   -0.6124    0.3536   -0.7071  -18.2843
         0         0         0    1.0000
```

The results of computation are depicted below:


manipulator
0
-30
30
-45
30
Forward
Inverse
100
50
0
-50
-100
Z
Y
X
Z
X
manipulator
100
50
0
-50
-100
Y
-100
0
100
X

Code for Running the manipulator with arduino

```
clear all;
close all;
clc;

Theta_1=0/180;
Theta_2=0/180;
Theta_3=0/180;
Theta_4=0/180;
Theta_5=0/180;


a = arduino('com6','uno');

s1= servo(a,6);
s2= servo(a,3);
s3= servo(a,11);
s4= servo(a,5);
s5= servo(a,9);


writePosition(s1,Theta_1);
writePosition(s2,Theta_2);
writePosition(s3,Theta_3);
writePosition(s4,Theta_4);
writePosition(s5,Theta_5);
```

Additional Task:

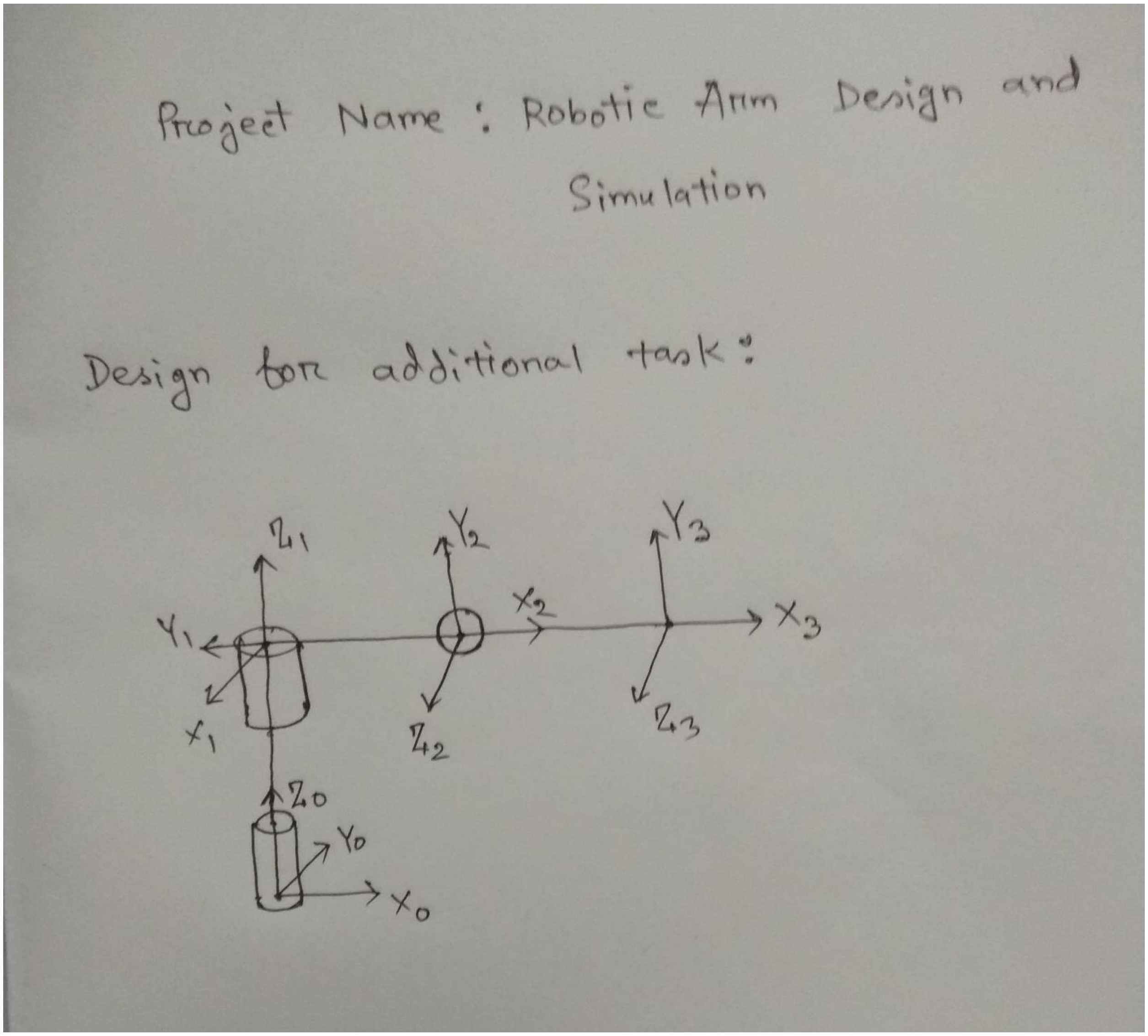
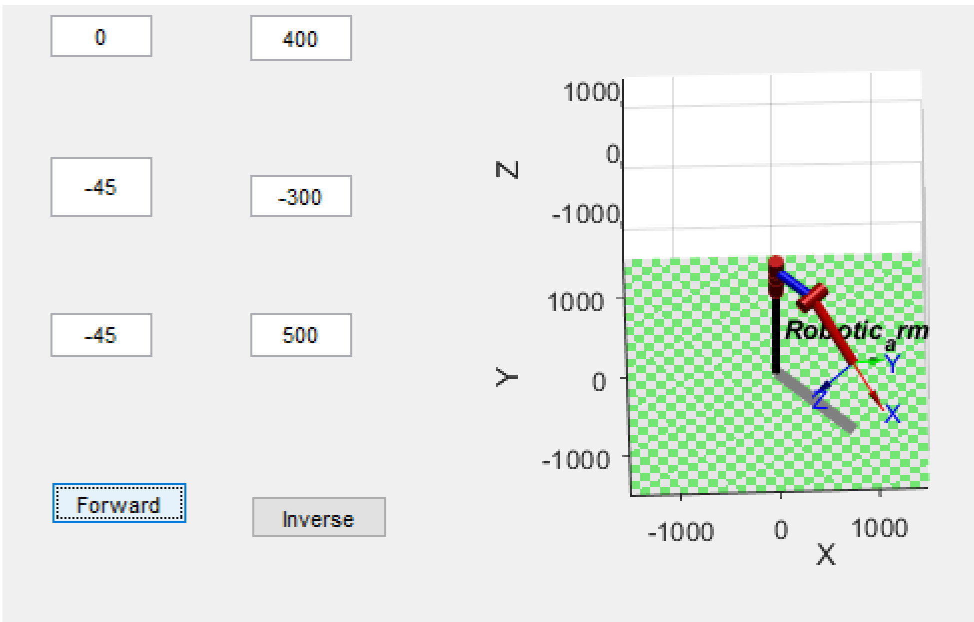


Fig:Manipulator Design

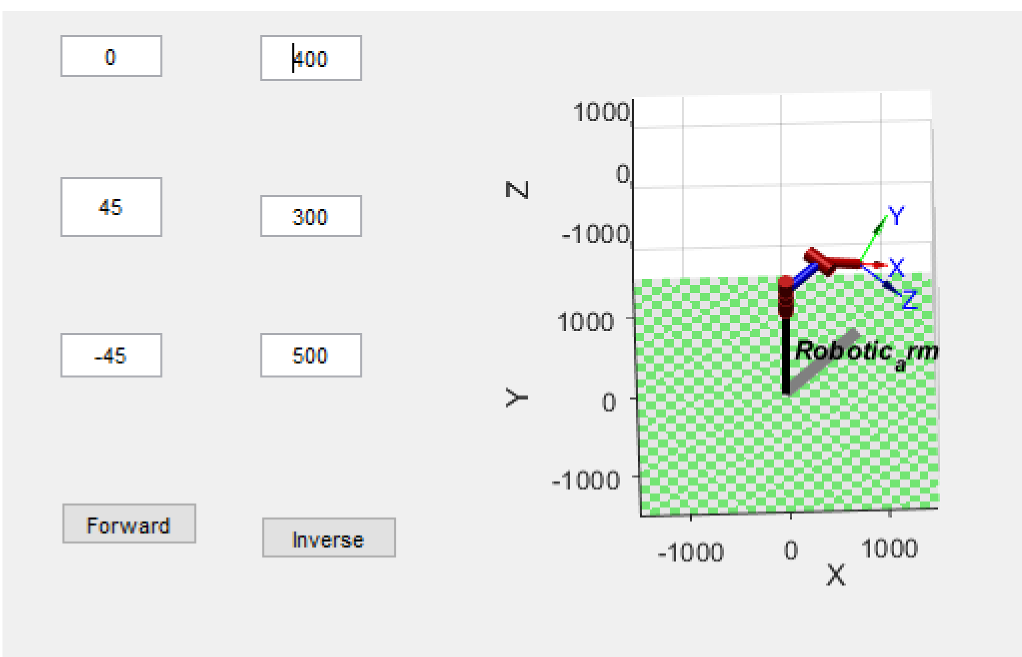
DH parameter table:

Link	Theta	alpha	r	d
1	-90	0	0	200
2	90	90	500	0
3	0	0	800	0

Output:



0
400
-45
-300
-45
500
Forward
Inverse
1000
0
-1000
Z
1000
0
-1000
Y
-1000
0
1000
X
Robotic_arm



0
400
45
300
-45
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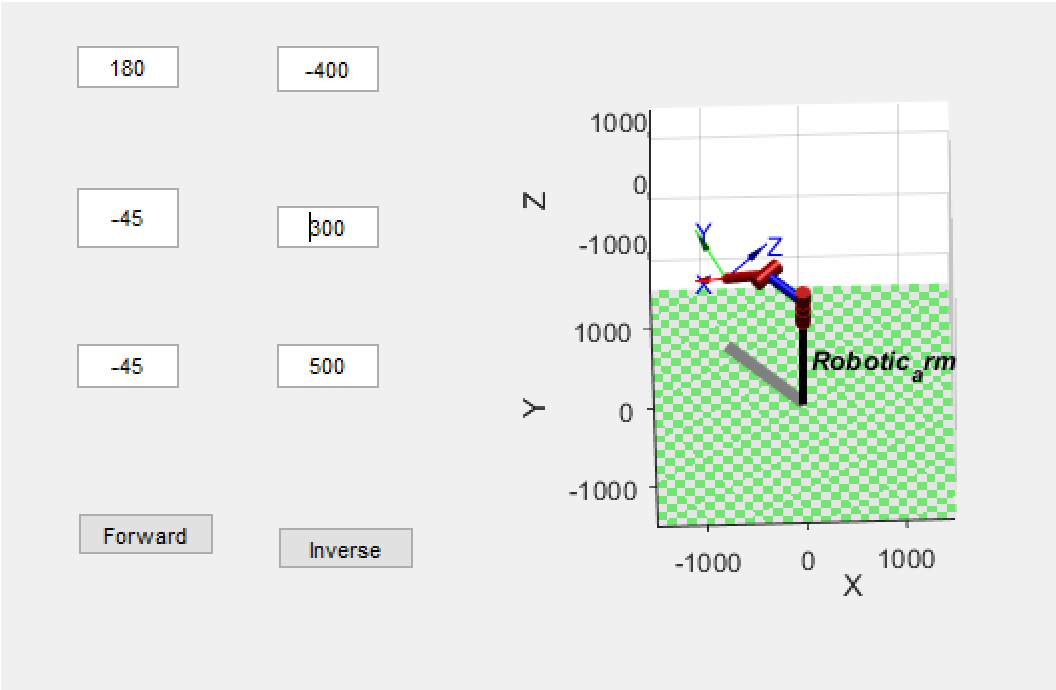
Forward
Inverse
1000
0
-1000
Z
1000
0
-1000
Y
-1000
0
1000
X
Robotic_arm


180
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Forward
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Z
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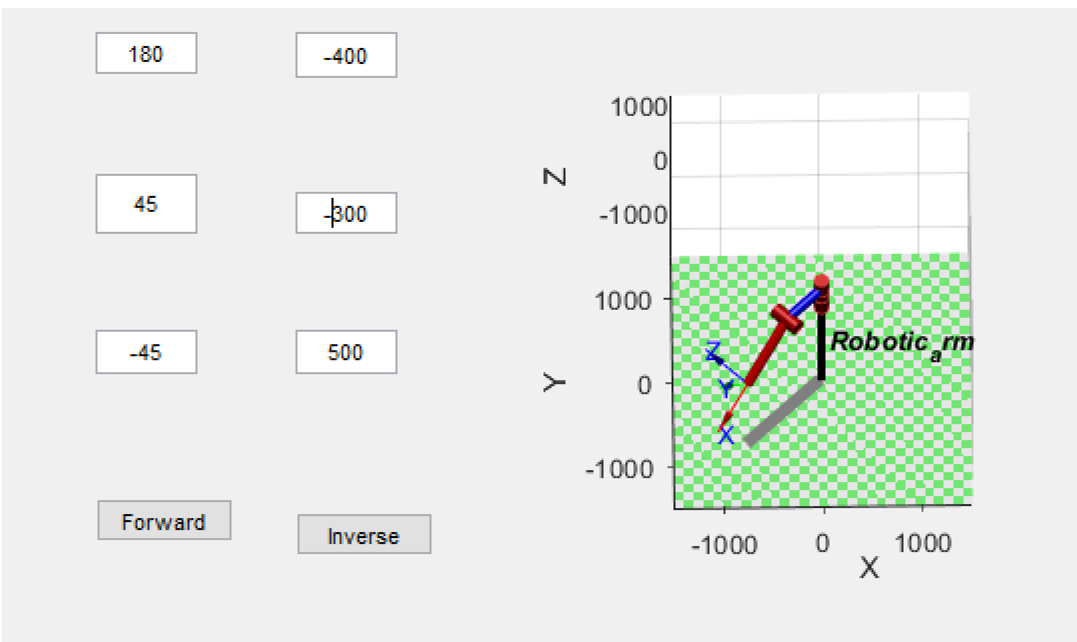
-1000
Y
Robotic_arm
-1000
0
1000
X


180
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Forward
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Z
1000
0
-1000
Y
Robotic_arm
-1000
0
1000
X

Conclusion

In this project we have designed a 5 DOF manipulator.We have derived it's forward and inverse kinematics.We have simulated forward kinematics by MATLAB GUI.But,unfortunately,we couldn't simulate inverse kinematics as it is hard to implement in MATLAB GUI for 5 DOF manipulator.But,we have shown a geometric approach to find inverse kinematics.However,The application of this robotic arms are many.If we attach a camera and a grip in the end effector and do image processing and motion control then the manipulator can be used in a wide range of applications from the medical sector to the automation systems.