

Kinematic Analysis of 8-DOF Robot ARM

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Abstract:

The present work has been done with Kinematic analysis of 8-DOF, robot arm. The robot arm manipulator is Bio-inspired model, which mimics human arm for the design of the robot. Generally 3-DOF arm is enough to locate a specific point and another 3-DOF for orientation, but increasing the DOF increases the flexibility of the arm to reach a specific point in different directions or orientations. The Kinematic analysis includes the Forward Kinematics analysis and Inverse Kinematics analysis. In forward Kinematic analysis the position of the end effector is found using the joint angles as input. In the inverse kinematic analysis the joint angles are found out using the required end effector position. The Visual simulation is also shown. This work has been done using MATLAB, SIMULINK for Analysis, and Modeling has been done using CATIA. Two points, one intermediate and one final position have been defined, such that the end effector has to reach the intermediate point before reaching final point (goal). This type of intermediate points helps in avoiding obstacles in practical scenario.

Key words: Kinematic analysis, Robot arm, DOF, Matlab, Simulink, CATIA

I. INTRODUCTION

The utilization of robots for various applications like industries, Medical field, and research laboratories is increasing day by day. Robots are generally designed based on the specific application, the robot need to perform. And there is need for the robots to perform multiple functions is also increasing, which cannot be designed based on specific application. These robots can be designed mimicking Human arm such that they can perform all the tasks done by human arm. These robots come under the category of Bio-Inspired robotic models. Robot is rooted from a Czech word 'robot', which mean slave labor. Robot Institute of America (RIA), defined it as, "A robot is a reprogrammable multifunctional manipulator designed to move materials, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks".

1.2 Degree of Freedom (DOF)

A rigid body in 3-D space has 6 degrees of freedom (dof) and is described by its position and orientation. The position of a point on the rigid body is best described by a vector drawn from a chosen reference point. The position vector has three scalar components since considering 3-D space. The components have different meaning depending on the co-ordinate system. The Cartesian co-ordinate system consists of three axes X, Y & Z. In Cartesian co-ordinate system, the components of the position vector of a point P is denoted by $(P_x, P_y, P_z)^T$, are distances along the three axes measured from the origin.

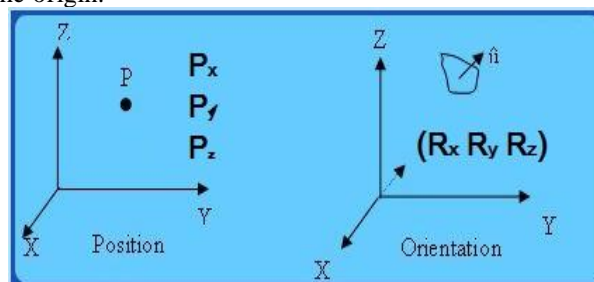


Fig 1. Position and orientation of spatial vector

Obtaining the position of any one point is clearly not enough to completely describe the rigid body in space. We need to know the orientation of the rigid body. It is the rotation of the co-ordinate. This is denoted using rotation angles with respect to three axes (R_x , R_y , & R_z) shown in fig.1

1.3 Rigid Motions and Homogeneous Transformation

A large part of robot kinematics is concerned with the establishment of various co-ordinate systems to represent the positions and orientations of rigid objects and transformations among these co-ordinate systems. The geometry of 3-D space and of rigid motions plays a central role in all aspects of robot manipulation. This includes rotation and transformation of rigid bodies. The homogeneous transformations combine the operations of rotation and translation into single matrix multiplication.

1.3.1 Rotation

The figure shows a rigid body to which a co-ordinate frame $Ox_1Y_1Z_1$ is attached. This is to be related to the reference frame $Ox_0Y_0Z_0$. $\{i_0, j_0, k_0\}$ are the unit vectors along the reference frame axes. $\{i_1, j_1, k_1\}$ be the standard orthogonal axes of body.

$$P_0 = P_{0x}i_0 + P_{0y}j_0 + P_{0z}k_0$$

Or with respect to $Ox_1Y_1Z_1$ as

$$P_1 = P_{1x}i_1 + P_{1y}j_1 + P_{1z}k_1$$

Since P_0 and P_1 are representations of the same vector P , the relationship between the components of P in three two coordinate of P in the two coordinate frames can be obtained follows.

$$P_{0x} = P_0 \cdot i_0 = p_1 \cdot i_0 = P_{1x}i_1 \cdot i_0 + P_{1y}j_1 \cdot i_0 + P_{1z}k_1 \cdot i_0$$

We have similar formula for P_{0y} and P_{0z} , namely

$$P_{0y} = P_{1x}i_1 \cdot j_0 + P_{1y}j_1 \cdot j_0 + P_{1z}k_1 \cdot j_0$$

$$P_{0z} = P_{1x}i_1 \cdot k_0 + P_{1y}j_1 \cdot k_0 + P_{1z}k_1 \cdot k_0$$

We may write the above equations together as

$$P_0 = R_0^{-1}P_1$$

Where,

$$R_0^{-1} = \begin{bmatrix} i_1 \cdot i_0 & j_1 \cdot i_0 & k_1 \cdot i_0 \\ i_1 \cdot j_0 & j_1 \cdot j_0 & k_1 \cdot j_0 \\ i_1 \cdot k_0 & j_1 \cdot k_0 & k_1 \cdot k_0 \end{bmatrix}$$

Case 1: if the frame $Ox_1Y_1Z_1$ is rotated through an angle of θ about the Z_0 axis (ref.fig.2)

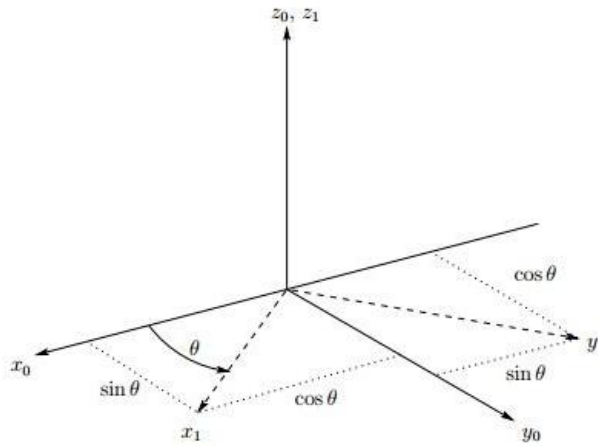


Fig. .2 Rotation about Z_0

From the above shown figure we can know that,

$$i_1 \cdot i_0 = \cos\theta, \quad j_1 \cdot i_0 = -\sin\theta, \quad j_0 \cdot j_1 = \cos\theta, \quad i_1 \cdot j_0 = \sin\theta.$$

And all other dot products are zeros

$$\text{Therefore, } R_0^{-1} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

This is called basic rotation matrix about Z-axis, denoted by $R_{z,\theta}$.

$$R_{x,\theta} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$$

$$R_{z,\theta} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$$

1.3.2 Homogeneous Transformation

Consider a system $O_1X_1Y_1Z_1$ obtained from $O_0X_0Y_0Z_0$ by a parallel translation of distance d , thus i_0, j_0, k_0 are parallel to i_1, j_1, k_1 , respectively. Then any point P is represented by P_0 & P_1 in both frames respectively. And they are related as,

$$P_0 = P_1 + d^1_0.$$

Hence the basic homogeneous for translation is given by

$$\text{Trans}_{x,a} = \begin{bmatrix} 1 & 0 & 0 & a \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\text{Trans}_{y,b} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\text{Trans}_{z,c} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & c \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

And for rotation

$$R_{x,\alpha} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_{y,\phi} = \begin{bmatrix} \cos\phi & 0 & \sin\phi & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\phi & 0 & \cos\phi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_{z,\theta} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

1.4 Robot Manipulators

Robot manipulators are composed of links connected by joints into a kinematic chain. Joints are typically rotary (revolute) or linear (prismatic). A revolute joint rotates about a motion axis and a prismatic joint slide along a motion axis. It can also be defined as a joint, where the pair of links makes a translational displacement along a fixed axis. In other words, one link slides on the other along a straight line. Therefore, it is also called a sliding joint. A revolute joint is a joint, where a pair of links rotates about a fixed axis. This type of joint is often referred to as a hinge, articulated, rotational joint.

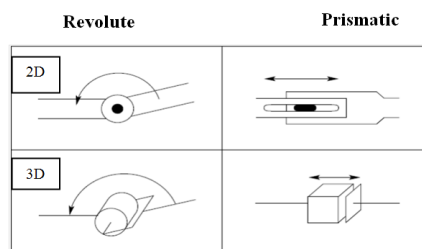


Fig.3 Symbolic representation of robot joints.

The **end – effector** which is a gripper tool, a special device, or fixture attached to the robot's arm, actually performs the work. Power supply provides and regulates the energy that is converted to motion by the robot actuator, and it may be electric, pneumatic, or hydraulic. The controller initiates, terminates, and coordinates the motion of sequences of a robot. Also it accepts the necessary inputs to the robot and provides the outputs to interface with the outside world. In other words the controller processes the sensory information and computes the control commands for the actuator to carry out specified tasks.

1.5 Redundant Manipulator

A manipulator is required to have a minimum of six degree of freedom if it needs to acquire any random position and orientation in its operational space or workspace. Assuming one joint is required for each degree of freedom, such a manipulator needs to be composed of minimum of six joints. Usually in standard practice three degree of freedom is implemented in the robotic arm so it can acquire the desired position in its workspace. The arm is then fitted with a wrist composed of three joints to acquire the desired orientation. Such manipulators are kinematically simple to design and solve, but they lead to two fundamental problems, singularity and inability to avoid obstacles.

The singularities of the robot manipulator are present both in the arm and the wrist and can occur anywhere inside the workspace of the manipulator. While passing through these singularities, the manipulator can effectively lose certain degree of freedom, resulting in uncontrollability along those directions. The obstacle avoidance is another desirable characteristic to effectively plan the motion trajectories, especially for manipulators designed to perform demanding tasks in constricted environment.

The above two problems can be solved by adding additional degree of freedom to the manipulator. This additional degree of freedom can be added to the joints, which effectively become regular in certain positions like shoulder, elbow, or wrist and hence help to overcome the singularities or obstacles avoidance. So a redundant manipulator should possess at least one degree-of-freedom (DOF) more than the number required for the general free positioning. When a manipulator can reach a specified position with more than one configuration of the linkages, the manipulator is said to be redundant. From a general point of view, any robotic system in which the way of achieving a given task is not unique may be called redundant. A redundant manipulator offers several potential advantages over a non-redundant manipulator. The extra DOF that require for the free positioning of manipulator can be used to move around or between obstacles and thereby to manipulate in situations that otherwise would be inaccessible. Due to the redundancy the manipulators become flexible, compliant, extremely dexterous and capable of dynamically adaptive, in unstructured environment.

1.6 Robot Configuration

Robotics is a special engineering science which deals with designing, modeling, controlling and robots' utilization. Nowadays robots accompany people in everyday life and take over their daily routine procedures. The range of robots' utilization is very wide, from toys through office and industrial robots finally to very sophisticated ones needed for space exploration. A large family of manufacturing equipment among the variety, which exists, is the one which supplies the motion required by a manufacturing process, such as: arc-welding, spray painting, assembly, cutting, polishing, milling, drilling, de-burring etc. Of this class of equipment, an increasingly popular type is the industrial robot. Different manipulator configurations are available as Rectangular Cylindrical, Spherical, SCARA, Revolute and Horizontal Jointed. The robot Arm determines the position of the wrist in 3D space. The mechanics of the robot Arm with 3 DOF depends on type of three joints & their arrangements.

According to Joint movements & arrangements of links, structural possible configurations are possible. They are,

1. Cartesian Configuration (Rectangular)
2. Cylindrical Configuration
3. Polar Configuration (Spherical)
4. Articulated / Jointed Configuration
5. SCARA

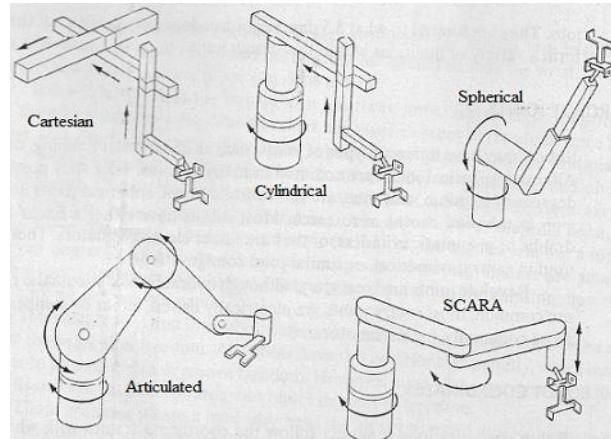


Fig. 4 Configurations of Robots

II. METHODOLOGY

2.1 Forward Kinematic Analysis

The forward kinematics, the position and orientation of the end effector is found out based on the given joint angles. This is done using two methods:

- a) Using SIMULINK MODEL,
- b) Using a MATLAB FUNCTION PROGRAM.

2.1.1 Using Simulink Model

The simulink model is designed using rigid transforms and joint actuators provide the required transformations for each link and the rotation required is given through joint actuators such the following link rotates with respect to the previous link. The robot simulink model consists parts categorized, as shoulder, elbow and wrist. All the details of the robot link dimensions and other details are obtained from the imported solid model. The dialog box of the rigid link shows the detailed information of the model, like Geometry, units, inertia, graphic and visual properties shown in fig.5. The origin of the base is connected to the origin of the world frame; the axes of base are coincident with the world frame axes.

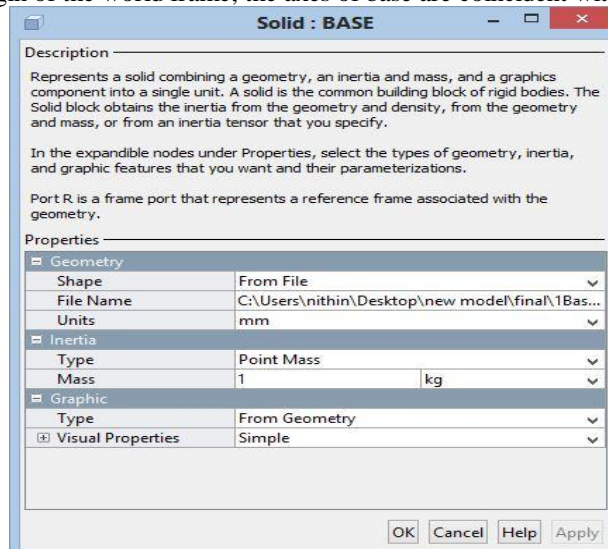


Fig. 5 Model Parameters of Simulink Base Block

The rigid transform is used to transform or create a new co-ordinate frame a required point in the space with respect to the previous co-ordinate system. The fig.6 shows the rigid transform created after the base such that the next rigid link origin coincides with the created rigid transform.

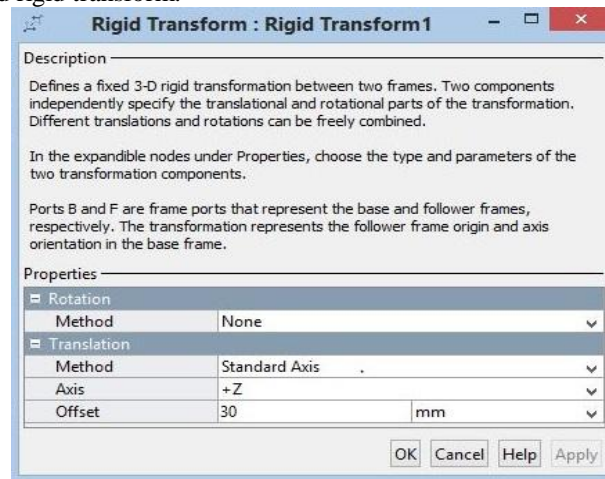


Fig. 6 Rigid Transform parameters

The above picture shows the dialog box of the joint actuator, which is used to actuate joints between two links, the joint is actuated by input signal, the angle through which the following link is rotated with respect to the base.

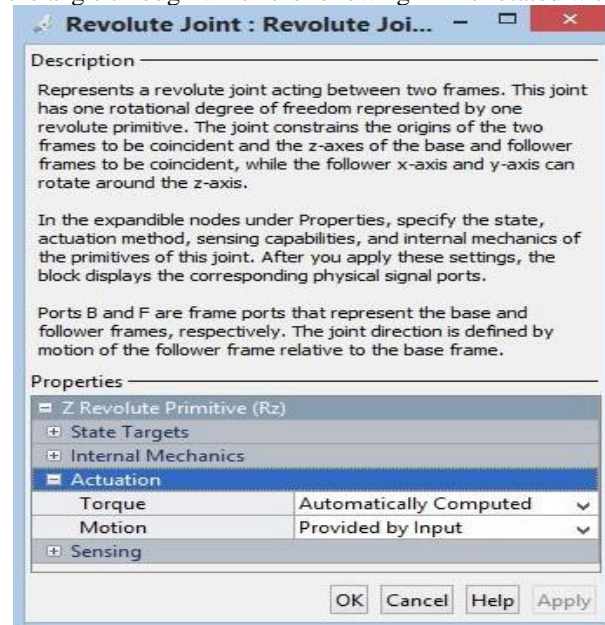


Fig.7 Model Parameters of Revolute Joint

A signal builder is used to give the input to the joint actuator; the value of the angle of rotation must be given in radians shown in fi.8

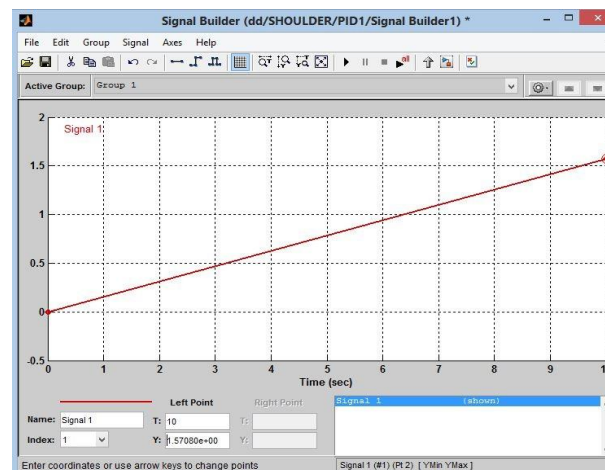


Fig.8 Signal Builder

A transform sensor is used to find the position of rigid transform with respect to world frame which gives the results required in the forward kinematics analysis as shown in fig.9.

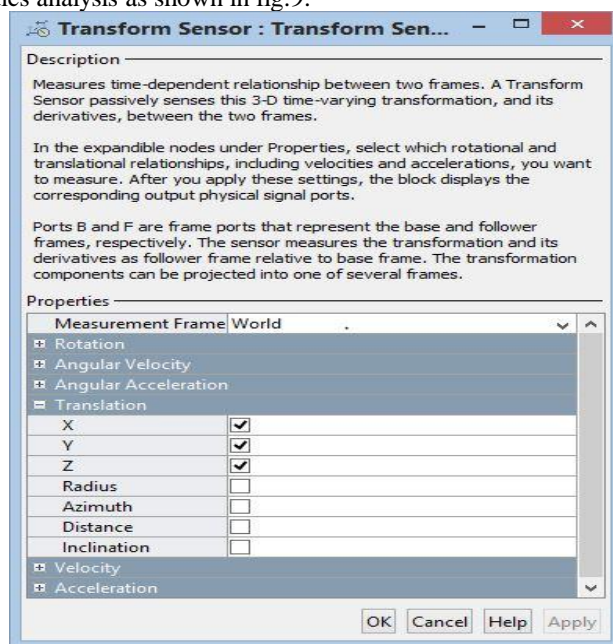


Fig. Transform Sensor

The display box or scope is used to show the results of the transform sensor (refer fig.10). The display box shows the final numerical values, while the scope shows the variation of the parameter.

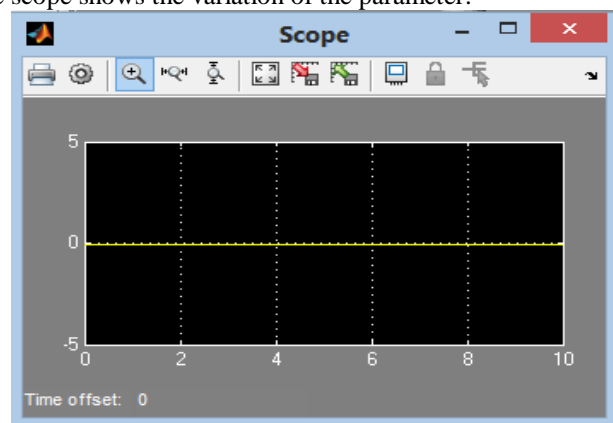


Fig.10 Scope

2.1.2 Using Matlab Function Program

The forward kinematic analysis can also be done using the regular techniques of calculation the overall transformation matrix but using the aid of MATLAB program function for computation. This program also needs the same inputs required for the calculation of the forward kinematic analysis, the Devait H table of the robot manipulator with the entire joint and link parameters and the joint angles through each angle is rotated.

The Matlab script is used to write the program function for calculating the overall transformation matrix which gives us the details about the rotation and translation of the end effector with respect to the world co-ordinate system. For the Matlab function we need the DH parameter table and which is used as input argument to the function. The D-H parameters table and line diagram (Fig.11) for the 8-DOF arm is given in the table 1 below.

Table 1. Denavit-Hartenberg Table

Link	Joint distance (d)	Joint angle (θ)	Link length (a)	Link twist (α)
1	50	$\pi/2 + \theta_1$	0	$\pi/2$
2	0	$\pi/2 + \theta_2$	35	$\pi/2$
3	0	θ_3	240	0
4	0	$\pi/2 + \theta_4$	0	$\pi/2$
5	230	θ_5	0	0
6	0	$\pi + \theta_6$	0	$\pi/2$
7	0	θ_7	0	$-\pi/2$
8	40	θ_8	0	0

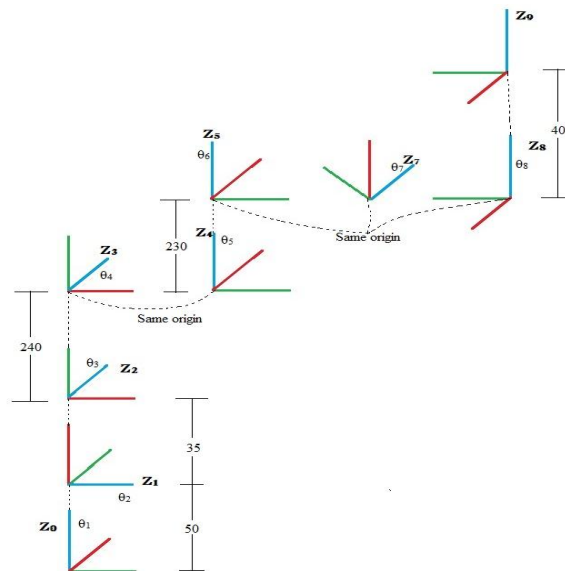


Fig. 11 Line diagram of the 8-DOF robot arm

2.2 Inverse Kinematic analysis

The inverse kinematic solution gives the joint variables for a given position of end effector. The robot being 8-DOF is redundant manipulator is difficult to get the inverse kinematic solution analytically. It is possible to de couple the inverse kinematics problem into two simpler problems, known respectively, as inverse position kinematics, and inverse orientation kinematics. To put it another way, for a 8-DOF manipulator with a spherical wrist, the inverse kinematics problem may be separated into two simpler problems, namely first finding the position of the intersection of the wrist axes, hereafter called the wrist center, and then finding the orientation of the wrist. The position of end effector is represented in terms transformation matrix with respect to the world frame.

Here also solution is done using Matlab script for finding the joint angles, as the robot contain a spherical wrist it can be split into two parts 5-DOF(arm) + 3-DOF(spherical wrist). Thus all joint angles are found out this can be tested out using the forward kinematics.

Table.2 Denavit-Hartenberg Table

Link	Joint distance (d)	Joint angle (θ)	Link length (a)	Link twist (α)
1	50	$\pi/2 + \theta_1$	0	$\pi/2$
2	0	$\pi/2 + \theta_2$	35	$\pi/2$
3	0	θ_3	240	0
4	0	$\pi/2 + \theta_4$	0	$\pi/2$
5	230	θ_5	0	0
6	0	$\pi + \theta_6$	0	$\pi/2$
7	0	θ_7	0	$-\pi/2$
8	40	θ_8	0	0

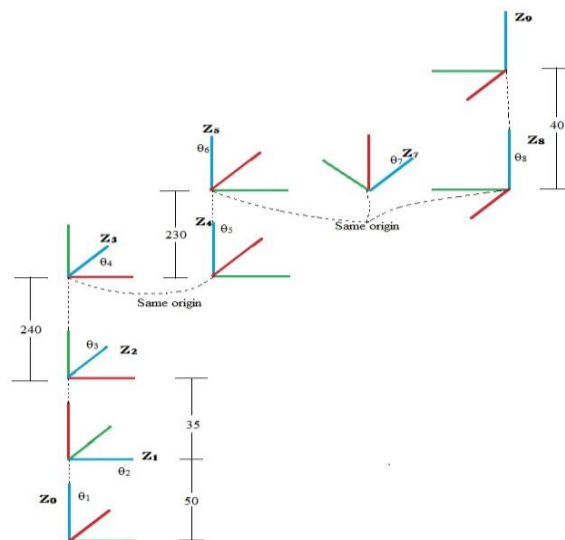


Fig.12 Line diagram of the 8-DOF robot arm

III. RESULTS AND DISCUSSION

3.1 Forward kinematics

3.1.1 Forward analysis using Simulink

For forward kinematics analysis the joint angles are the input and the position of end effector is the output. Let the joint angles be 0° , 45°

Table 3: Angle for Forward Kinematics

Joint angle (θ)	Initial joint angle	Final joint angle
θ_1	0	$\pi/4$
θ_2	0	$\pi/4$
θ_3	0	$\pi/4$
θ_4	0	$\pi/4$
θ_5	0	$\pi/4$
θ_6	0	$\pi/4$
θ_7	0	$\pi/4$
θ_8	0	$\pi/4$

The Angle is given in the signal such that the rotation is linear with respect to time,

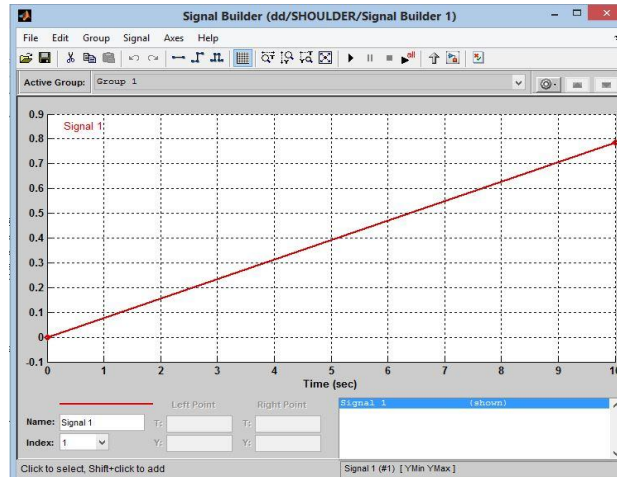


Fig. 13: Angle input for each joint

The position of end effector (Fig. 14) after the 45° rotation of each angle from the simulink model is,

$$x = 390.8$$

$$y = 214.4$$

$$z = 214.7$$

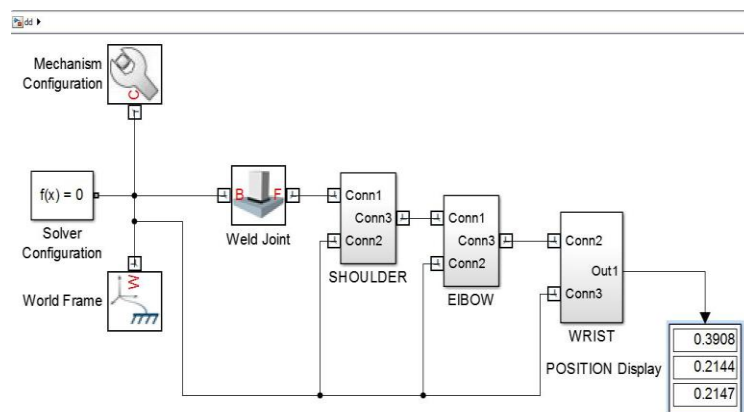


Fig. 14 Position of End effector

The variation of X, Y, Z with respect time after simulation shown in fig.15,16 and 17

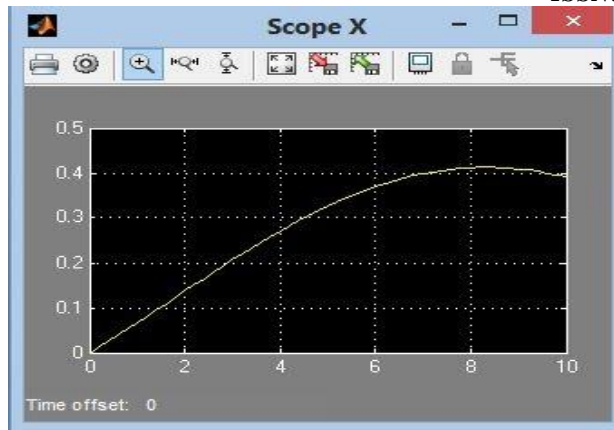


Fig.15 Variation of X with Respect to Time

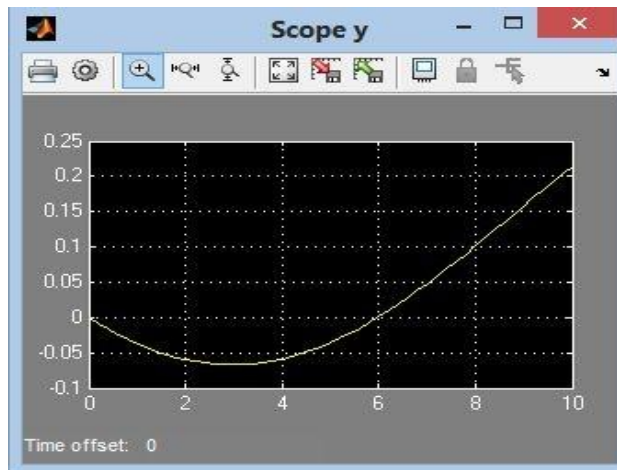


Fig. 16 Variation of Y with respect to time

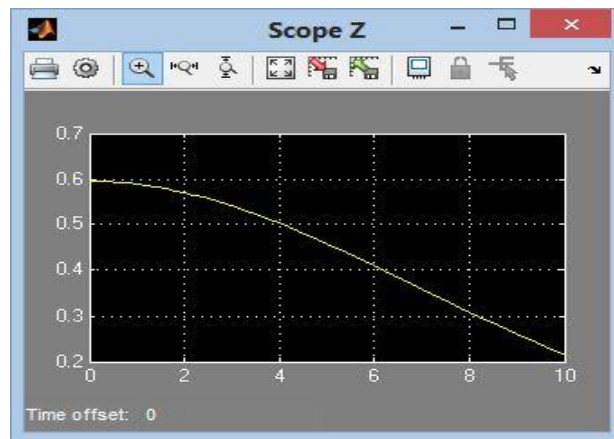


Fig.17 Variation of Z with respect to time

3.1.2 Forward Analysis using Matlab Function program

For the Matlab program function the input parameters/ arguments is the Denavit-Hartenberg table given in matrix format.

Table 4: Denavit-Hartenberg table For Rotation of 45° Angle

Link	Joint distance (d)	Joint angle (θ)	Link length (a)	Link twist (α)
1	50	$3*\pi/4$	0	$\pi/2$
2	0	$3*\pi/4$	35	$\pi/2$
3	0	$\pi/4$	240	0
4	0	$3*\pi/4$	0	$\pi/2$
5	230	$\pi/4$	0	0
6	0	$5*\pi/4$	0	$\pi/2$
7	0	$\pi/4$	0	$-\pi/2$
8	40	$\pi/4$	0	0

3.2 Inverse Kinematic Analysis

In the inverse kinematic Analysis the position is given as input along with orientation in the form as transformation matrix.

3.2.1 Inverse Kinematic solution

Let us consider the transformation matrix of three points: Initial point (S_0), one Intermediate Point (S_i) and final point (S_f). The angles obtained through inverse kinematics for the intermediate and final points are

Table 5 Joint Angles at 3 positions

Joint	Initial Point	Intermediate Point	Final Point
θ_1	-1.3879	-0.3922	-0.1499
θ_2	1.2411	0.7445	0.5321
θ_3	-0.4372	-0.0167	0.0280
θ_4	1.0953	0.9322	0.8444
θ_5	0	0	0
θ_6	1.4277	0.2121	-0.1830
θ_7	0.6285	0.3862	0.3496
θ_8	0.4866	0.8338	1.0580

3.2.2 Validation of the Inverse Kinematic Solution

The Denavit-Hartenberg table at the Initial point,

Table 6 D-H table at initial point %INITIAL point D-H table%

Link	Joint Distance (d)	Joint angle (θ)	Link length (a)	Link twist (α)
1	50	-0.3922	0	$\pi/2$
2	0	0.7445	35	$\pi/2$
3	0	-0.0167	240	0
4	0	0.9322	0	$\pi/2$
5	230	0	0	0
6	0	0.2121	0	$\pi/2$
7	0	0.3862	0	$-\pi/2$
8	40	0.8338	0	0

Table 7 D-H Table at Intermediate position DH table at Final position

Link	Joint Distance (d)	Joint angle (θ)	Link length (a)	Link twist (α)
1	50	-1.499	0	$\pi/2$
2	0	0.5321	35	$\pi/2$
3	0	0.0280	240	0
4	0	0.8444	0	$\pi/2$
5	230	0	0	0
6	0	-0.1830	0	$\pi/2$
7	0	0.3496	0	$-\pi/2$
8	40	1.0580	0	0

The Simulink model at Initial position as shown in fig.18

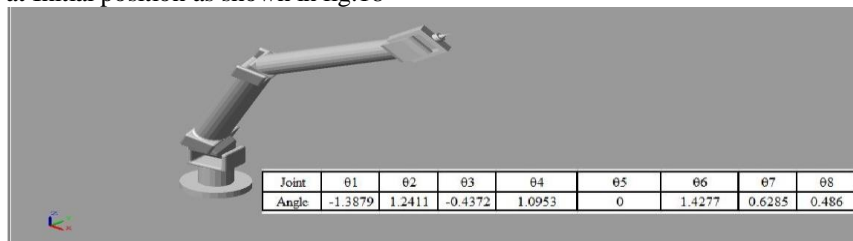


Fig 18 Simulink Model at initial Position

The Simulink Model at Intermediate position as shown in fig.19

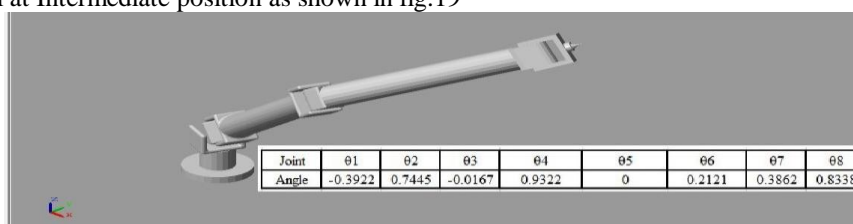


Fig.19 Simulink Model at Intermediate Position

The Simulink Model at Final position as shown in fig.20.

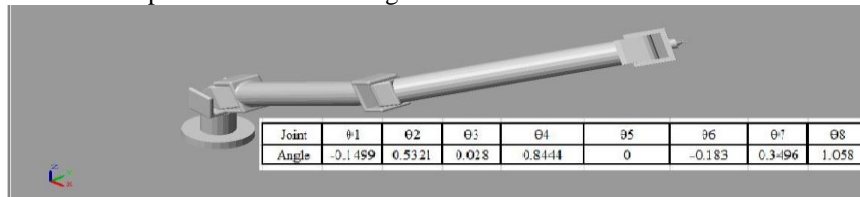


Fig.20 Simulink Model at Final Position

IV. CONCLUSIONS

The kinematic analysis of 8-DOF Robot arm, designed mimicking the human arm (Bio-inspired model) is performed. This 5-DOF robotic arm is attached to a 3-DOF spherical wrist.

The Modelling is done using the CATIA, and the Forward analysis is done using SIMULINK, and MATLAB function program. The Inverse Kinematic analysis is done using MATLAB function program. The analysis is validated by finding the solution by rotating the joints by an arbitrary angle, and finding the transformation matrix, and verifying the solution in two different techniques. And the same transformation matrix is used for validating the Inverse Kinematic solution. The accuracy difference at initial position in X, Y, Z directions is 0.2603mm, 0.3501mm, 0.0044mm respectively. The accuracy difference at intermediate position in X, Y, Z directions is 0.0103mm 0.0034mm 0.0204mm respectively. The accuracy difference at final position in X, Y, Z directions is 0.0102mm 0.0224mm 0.0070mm respectively.

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