Seminar R&D 2010, 12-15 Oktober 2010,
Dewan Tun Dr Ismail, Agensi Nuklear Malaysia

THE PRELIMINARY SOFTWARE DEVELOPMENT FOR THE KINEMATICS ANALYSIS OF 5 DOF NUCLEAR MALAYSIA ROBOT ARM V2

Mohd Zaid Hassan @ Abdul Rahman, Anwar Abdul Rahman, Rosli Darmawan, Mohd Arif Hamzah

Malaysian Nuclear Agency
Bangi, 43000 Kajang, Selangor Darul Ehsan, Malaysia
Email: mohdzaid@nuclearmalaysia.gov.my

ABSTRACT

This paper presents the preliminary software development for the kinematics analysis of 5 DOF robotic arms. The kinematics analysis is the study of relationship between the individual joints of robot manipulator, the position and orientation of the end-effector. The Denavit-Hartenberg (DH) model is used to model the robot links and joints. Both forward and inverse kinematic are presented. The simulation software has been developed by using MATLAB to solve the robot arms kinematic behavior.

Keywords: Robotic arm, forward kinematics, inverse kinematics, software, DH parameters, simulation, 5 DOF

1. INTRODUCTION

The kinematic analysis of robotics arm is an important area in the robotics control system. The kinematic analysis consists of forward kinematic and inverse kinematic behavior of robotic manipulator. The kinematic is the transformation between joint space and the Cartesian space. The forward analysis is defined as transformation from joint space to Cartesian space whereas Inverse kinematics is defined as transformation from Cartesian space to joint space. In this study, the standard Denavit-Harbenterg approach was used for modeling the 5 DOF Robot Arm V2. The Denavit and Hartenberg parameters of the robot and can be created by the user for any serial link manipulator.

The basic robot configurations generally follow the coordinate frame with which defined as Cartesian (3P), Cylindrical (R2P), Spherical (2RP), Articulate (3R) and Selective Compliance Assembly Robot Arm (SCARA).The Robot Arm V2 is a 5 degree of freedom articulate robotic arm that consist 6 links, 5 joint variables and grip movement. It is similar to human arm in term of the number of joint point of view. A graphical view of all joints is shown in Fig 1.

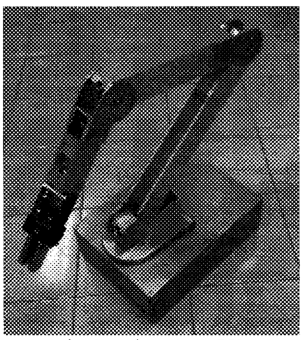

Fig.1 Robot Arm V2

Denavit and Hartenberg published a way to represent and a model to derive equation of motion. Later, these techniques become the standard way to represent robot and motion modeling. The Denavit-Hartenberg (DH) model of representation is simple for any robot configuration regardless of its sequence or complexity. The final result of the Denavit-Hartenberg equation is as follows;

$$^{n}T_{n+1}=A_{n+1} = Rot(z,\theta_{n+1}) \times Trans(0,0,d_{n=1}) \times Trans(a_{n+1},0,0) \times Rot(x,\alpha_{n+1}) \quad (1.1)$$

$$A_{n+1} = \begin{bmatrix} C\theta_{n+1} & -S\theta_{n+1}S\alpha_{n+1} & S\theta_{n+1}S\alpha_{n+1} & a_{n+1}C\theta_{n+1} \\ S\theta_{n+1} & C\theta_{n+1}C\alpha_{n+1} & -C\theta_{n+1}S\alpha_{n+1} & a_{n+1}S\theta_{n+1} \\ 0 & S\alpha_{n+1} & C\alpha_{n+1} & d_{n+1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1.2)$$

Where:
α_i: Rotation angle from Z_{i-1} to Z_i about X_i
a_i: distance from intersection of Z_{i-1} & X_i to origin of i coordinate along X_i
d_i : distance from origin of (i-1) coordinate to intersection of Z_{i-1} & X_i along Z_{i-1}
θ_i: rotation angle from X_{i-1} to X_i about Z_{i-1}

The total transformation between the base robot and the end effectors:

$$^{R}TH={}^{R}T_1{}^{1}T_2{}^{2}T_3\ldots{}^{n-1}Tn = A_1A_2A_3\ldots A_n \quad (1.3)$$

Where n is joint number

2. KINEMATIC

2.1. FORWARD KINEMATICS

Given a set of joint angle, the forward kinematics problem is simply to compute the position and orientation of the end-effector. It is solved by using homogeneous transformation. The homogeneous transformation is a 4×4 matrix, which can describe both rotations and translations. First, the matrix for each link is represented as below according to DH parameters.

$$A_1 = \begin{bmatrix} C_1 & 0 & S_1 & 0 \\ S_1 & 0 & -C_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A_2 = \begin{bmatrix} C_2 & -S_2 & 0 & C_2a_2 \\ S_2 & C_2 & 0 & S_2a_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_3 = \begin{bmatrix} C_3 & -S_3 & 0 & C_3a_3 \\ S_3 & C_3 & 0 & S_3a_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A_4 = \begin{bmatrix} C_4 & 0 & -S_4 & C_4a_4 \\ S_4 & 0 & C_4 & S_4a_4 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_5 = \begin{bmatrix} C_5 & -S_5 & 0 & 0 \\ S_5 & C_5 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The final equation of motion for this robot arm can be found by multiplying all the individual link matrices.

$$^{R}T_{H} = A_1\, A_2\, A_3\, A_4\, A_5 \tag{2.1.1}$$

$$^{R}T_{H} = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.1.2}$$

$n_x = C_5C_1C_{234} - S_2S_1$
$n_y = C_5S_1C_{234} - S_5C_1$
$n_z = -C_5S_{234}$
$o_x = -S_5C_1C_{234} + C_5S_1$
$o_y = -S_5S_1C_{234} + C_5C_1$
$o_z = S_5S_{234}$
$a_x = -C_1S_{234}$
$a_y = S_1S_{234}$
$a_z = C_{234}$
$p_x = C_1(C_{234}a_4 + C_{23}a_3 + C_2a_2)$
$p_y = S_1(C_{234}a_4 + C_{23}a_3 + C_2a_2)$
$p_z = -S_{234}a_4 + S_2a_2$

Where,
$C_i = \cos\theta_i$
$C_i = \sin\theta_i$
$S_{12} = S_1C_2 + C_1S_2$
$C_{12} = C_1C_2 - S_1S_2$
$C_{234} = C_2(C_3C_4 - S_3S_4) - S_2(S_3C_4 + C_3S_4)$
$S_{234} = Cs_2(C_3C_4 - S_3S_4) + C_2(S_3C_4 + C_3S_4)$

2.2. INVERSE KINEMATICS

Given the position of end-effector, the inverse kinematic (IK) is used to compute the angle of each joint. The IK problem is solved by using numerical approach due to its degree of complexity. First, the inverse matrices for each link were carried out.

$$A_1^{-1} = \begin{bmatrix} C_1 & S_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ S_1 & -C_1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A_2^{-1} = \begin{bmatrix} C_2 & S_2 & 0 & -a_2 \\ -S_2 & C_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_3^{-1} = \begin{bmatrix} C_3 & S_3 & 0 & a_3 \\ -S_3 & C_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad A_4^{-1} = \begin{bmatrix} C_4 & S_4 & 0 & -a_4 \\ 0 & 0 & 0 & 0 \\ -S_4 & C_4 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_5^{-1} = \begin{bmatrix} C_5 & S_5 & 0 & 0 \\ -S_5 & C_5 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Premultiplying $^{R}T_{H}$ with A_1^{-1} in order to solve problem for each individual angles.

$$A_1^{-1} * {}^{R}T_{H} = A_1^{-1} * A_1\, A_2\, A_3\, A_4\, A_5 \tag{2.2.1}$$

$$A_1^{-1} * {}^{R}T_{H} = \begin{bmatrix} C_1n_x + S_1n_y & C_1o_x + S_1o_y & C_1a_x + S_1a_y & C_1p_x + S_1p_y \\ n_y & o_y & a_y & p_y \\ S_1n_x - C_1n_y & S_1o_x - C_1a_y & S_1a_x - C_1a_y & S_1p_x - C_1p_y \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_2A_3A_4A_5 = \begin{bmatrix} C_5C_{234} & -S_5C_{234} & -S_{234} & a_4C_{234} + a_3C_{23} + a_2C_2 \\ C_5S_{234} & -S_5S_{234} & C_{234} & a_4S_{234} + a_3S_{23} + a_2S_2 \\ -S_5 & -C_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} C_1n_x + S_1n_y & C_1o_x + S_1o_y & C_1a_x + S_1a_y & C_1p_x + S_1p_y \\ n_y & o_y & a_y & p_y \\ S_1n_x - C_1n_y & S_1o_x - C_1a_y & S_1a_x - C_1a_y & S_1p_x - C_1p_y \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} C_5C_{234} & -S_5C_{234} & -S_{234} & a_4C_{234} + a_3C_{23} + a_2C_2 \\ C_5S_{234} & -S_5S_{234} & C_{234} & a_4S_{234} + a_3S_{23} + a_2S_2 \\ -S_5 & -C_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.2.2}$$

From these matrices equation, calculations for the angle can be done. Equating [3, 4] element of both matrices gives,

$$S_1p_x - C_1p_y = 0 \tag{2.2.3}$$

$$\theta_1 = \tan^{-1}\left(\frac{p_y}{p_x}\right) \tag{2.2.4}$$

And

$$\theta_1 = \theta_1 + 180°$$

Rearranging and squaring [1, 4], [2, 4] element matrices and adding it gives

$$C_1p_x + S_1p_y = a_4C_{234} + a_3C_{23} + a_2C_2 \tag{2.2.5}$$

$$C_1p_x + S_1p_y - a_4C_{234} = a_3C_{23} + a_2C_2$$

$$\left(C_1p_x + S_1p_y - a_4C_{234}\right)^2 = (a_3C_{23} + a_2C_2)^2 \tag{2.2.6}$$

$$p_z = a_4S_{234} + a_3S_{23} + a_2S_2 \tag{2.2.7}$$

$$p_z - a_4S_{234} = a_3S_{23} + a_2S_2$$

$$(p_z - a_4S_{234})^2 = (a_3S_{23} + a_2S_2)^2 \tag{2.2.8}$$

Add equation (2.2.6) and (2.2.8),

$$\left(C_1p_x + S_1p_y - a_4C_{234}\right)^2 + (p_z - a_4S_{234})^2 = (a_3C_{23} + a_2C_2)^2 + (a_3S_{23} + a_2S_2)^2$$

$$\left(C_1p_x + S_1p_y - a_4C_{234}\right)^2 + (p_z - a_4S_{234})^2 = a_2^2 + a_3^2 + 2a_2a_3(S_2S_{23} + C_2C_{23}) \quad (2.2.9)$$

$$S_2S_{23} + C_2C_{23} = \cos[(\theta_2 + \theta_3) - \theta_2] = \cos\theta_3 \quad (2.2.10)$$

Thus,

$$C_3 = \frac{\left(C_1p_x + S_1p_y - C_{234}a_4\right)^2 + (p_z - S_{234}a_4)^2 - a_2^2 - a_3^2}{2a_2a_3}$$

$$S_3 = \pm\sqrt{1 - C_3^2}$$

It can be said that:

$$\theta_3 = \tan^{-1}\left(\frac{S_3}{C_3}\right) \quad (2.2.11)$$

$$A_4^{-1}A_3^{-1}A_2^{-1}A_1^{-1} \times \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = A_5 \quad (2.2.12)$$

$$\begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} C_5 & -S_5 & 0 & 0 \\ S_5 & C_5 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where,

$$M_{11} = C_{234}\left(C_1n_x + S_1n_y\right) + S_{234}n_z$$
$$M_{12} = C_{234}\left(C_1o_x + S_1no_y\right) + S_{234}o_z$$
$$M_{13} = C_{234}\left(C_1a_x + S_1a_y\right) + S_{234}a_z$$
$$M_{14} = C_{234}\left(C_1p_x + S_1p_y\right) + S_{234}p_z - C_{34}a_2 + C_4a_3 - a_4$$
$$M_{21} = S_1n_x - C_1n_y$$
$$M_{22} = S_1o_x - C_1o_y$$
$$M_{23} = S_1a_x - C_1a_y$$
$$M_{24} = S_1p_x - C_1p_y$$
$$M_{31} = -S_{234}\left(C_1n_x + S_1n_y\right) + C_{234}n_z$$
$$M_{32} = -S_{234}\left(C_1o_x + S_1o_y\right) + C_{234}o_z$$
$$M_{33} = -S_{234}\left(C_1a_x + S_1a_y\right) + C_{234}a_z$$
$$M_{34} = -S_{234}\left(C_1p_x + S_1p_y\right) + C_{234}p_z$$

According to [3, 4] element of the matrices

$$-S_{234}\left(C_1p_x + S_1p_y\right) + C_{234}p_z = 0 \quad (2.2.13)$$

$$\theta_{234} = \tan^{-1}\left(\frac{p_z}{C_1p_x + S_1p_y}\right) \quad (2.2.14)$$

$$\theta_{234} = \theta_{234} + 180°$$

Referring to equation (2.2.5) and (2.2.7)

$$C_1p_x + S_1p_y = a_4C_{234} + a_3C_{23} + a_2C_2$$
$$p_z = a_4S_{234} + a_3S_{23} + a_2S_2$$

By using trigonometry theorem

$$S_{23} = S_2C_3 + C_2S_3$$
$$C_{23} = C_2C_3 - S_2S_3$$

The equation above becomes:

$$C_1p_x + S_1p_y - a_4C_{234} = (C_2C_3 - S_2S_3)a_3 + a_2C_2$$
$$p_z - a_4S_{234} = (S_2C_3 + C_2S_3)a_3 + a_2S_2$$

Treating this as a set of unknown for two set of equations and solving for C_2 and S_2, the equation becomes:

$$S_2 = \frac{(C_3a_3 + a_2)(p_z - S_{234}a_4) - S_3a_3\left(C_1p_x + S_1p_y - C_{234}a_4\right)}{(C_3a_3 + a_2)^2 + S_3^2a_3^2} \quad (2.2.15)$$

$$C_2 = \frac{(C_3a_3 + a_2)\left(C_1p_x + S_1p_y - C_{234}a_4\right) + S_3a_3(p_z + S_{234}a_4)}{(C_3a_3 + a_2)^2 + S_3^2a_3^2} \quad (2.2.15)$$

$$\theta_2 = \tan^{-1}\frac{S_2}{C_2} \quad (2.2.17)$$

The θ_2 and θ_3 are known, calculation can be made by:

$$\theta_4 = \theta_{234} - \theta_2 - \theta_3 \quad (2.2.18)$$
$$\theta_4 = \theta_4 + 180°$$

For $\theta 5$, calculation can be done by referring to element [2, 1] and [2, 2] on the matrices equation

$$C_{234}\left(C_1n_x + S_1n_y\right) + S_{234}n_z = C_5 \quad (2.2.19)$$

$$S_1n_x - C_1n_y = S_5$$

$$\theta_5 = \tan^{-1}\frac{S_1n_x - C_1n_y}{C_{234}\left(C_1n_x + S_1n_y\right) + S_{234}n_z} \quad (2.2.20)$$

$$\theta_5 = \theta_5 + 180°$$

3. SOFTWARE

The Matlab Kinematics analysis graphical user interface (GUI) was developed to compute the forward and inverse kinematics of Robot Arm V2. A graphical view of Matlab Kinematic analysis GUI is shown in Fig 2. This GUI can calculate both forward and inverse kinematics solutions of the Robot Arm V2.The equation (2.1.1) and (2.1.2) were used to calculate the forward kinematic analysis, while equations (2.2.1) until (2.2.20) were used in algorithm to generate inverse kinematic of the analysis. A flow chart of the software is described in Fig.3.

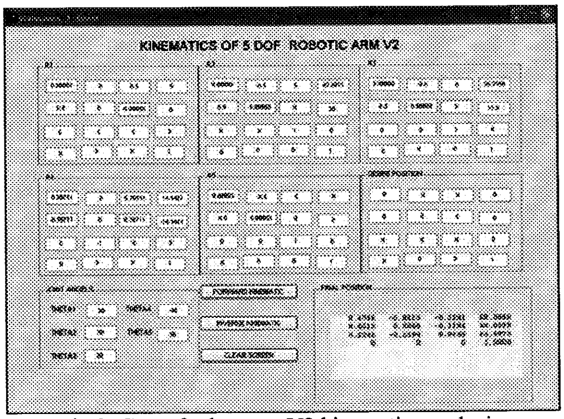

Fig 2. GUI of robot arm V2 kinematics analysis

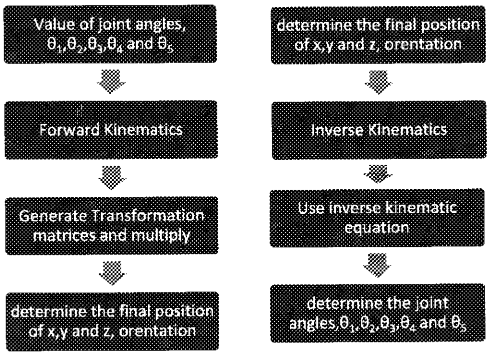

Fig 3. A kinematic analysis flow chart

4. RESULT AND DISCUSSION

In order to perform the modeling using D-H representation a local reference for each joint need to be assigned to Robot Arm V2. Each joint have to be assigned with a z –axis and an x-axis. A graphical view of the frame assignment of Robot Arm V2 is displayed in Fig. 4.

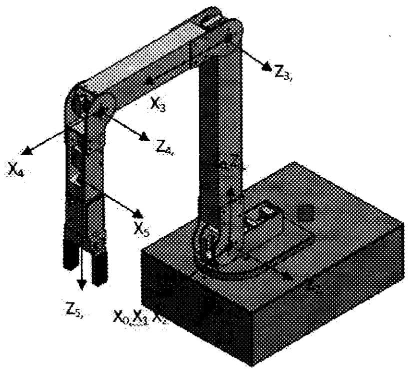

Fig 4. D-H parameters layout for Robot Arm V2

The Robot Arm V2 manipulator structure is defined by assigning each link with four standard parameters which are α_i, a_i, d_i and θ_i. Where, the rotation angle from Z_{i-1} to Z_i about X_i is α_i. The distance from intersection of Z_{i-1} & X_i to origin of i coordinate along X_i is a_i. The distance from origin of (i-1) coordinate to intersection of Z_{i-1} & X_i along Z_{i-1} is d_i. Finally, the rotation angle from X_{i-1} to X_i about Z_{i-1} is θ_i. The four given parameters are shown in Table 1.

Table 1: The robot arm V2 parameters

Joint	θ_i	α_i	a_i	d_i
1	θ_1	90	0	0
2	θ_2	0	50	0
3	θ_3	0	35	0
4	θ_4	-90	20	0
5	θ_5	0	0	0

Mathematical modeling of Robot Arm V2 was carried out. The robot was modeled by using DH representation. The Matlab GUI was developed to generate and implement both forward and inverse kinematics. The example showed below was calculated with the software generation.

Table 2: The example of robot arm V2 parameters

Joint	θ_i	α_i	a_i	d_i
1	45	90	0	0
2	30	0	50	0
3	30	0	35	0
4	-45	-90	20	0
5	30	0	0	0

Based on the given parameters, the transformation matrices are generated by using equations (1.2), (2.1.1) and (2.1.2).

$$A_1=\begin{bmatrix}0.7071 & 0 & 0.7071 & 0\\ 0.7071 & 0 & -0.7071 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$A_2=\begin{bmatrix}0.8660 & -0.5 & 0 & 43.3013\\ 0.5 & 0.8660 & 0 & 25\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$A_3=\begin{bmatrix}0.8660 & -0.5 & 0 & 30.3109\\ 0.5 & 0.8660 & 0 & 17.5\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$A_4=\begin{bmatrix}0.7071 & 0 & 0.7071 & 14.1421\\ -0.7071 & 0 & 0.7071 & -14.1421\\ 0 & -1 & 0 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$A_5=\begin{bmatrix}0.8660 & -0.5 & 0 & 0\\ 0.5 & 0.8660 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$${}^{R}T_{H}=\begin{bmatrix}0.2380 & -0.9539 & -0.1830 & 56.6532\\ 0.9451 & 0.2709 & -0.1830 & 56.6532\\ 0.2241 & -0.1294 & 0.9659 & 60.4873\\ 0 & 0 & 0 & 1\end{bmatrix} \quad (4.1)$$

Hence, the position of end-effector are x=56.6532, y=56.6532 and z=60.4873 forming the reference coordinate. On the other hand, the developed software can solve the inverse kinematic by calculating the required angles for targeted position. It executes the angles by using equation (2.2.4) to (2.2.20).

From equation (2.2.4),

$$\theta_1 = \tan^{-1}\left(\frac{56.6532}{56.6532}\right)$$

$$\theta_1 = 45°$$

From equation (2.2.14)

$$\theta_{234} = 15°$$

From equation (2.2.15) and (2.2.16)

$$C_3 = \frac{\left(C_1 p_x + S_1 p_y - C_{234} a_4\right)^2 + (p_z - S_{234} a_4)^2 - a_2^2 - a_3^2}{2 a_2 a_3}$$

$$C_3 = 0.8754$$

$$S_3 = 0.4833$$

$$\theta_3 = \tan^{-1}\left(\frac{S_3}{C_3}\right).$$

$$\theta_3 = 28.9°$$

From equation (2.2.17)

$$\theta_2 = \tan^{-1}\frac{(C_3 a_3 + a_2)(p_z - S_{234} a_4) - S_3 a_3 (C_1 p_x + S_1 p_y - C_{234} a_4)}{(C_3 a_3 + a_2)(C_1 p_x + S_1 p_y - C_{234} a_4) + S_3 a_3 (p_z - S_{234} a_4)}$$

$$\theta_2 = 30°$$

From equation (2.2.18)

$$\theta_4 = \theta_{234} - \theta_2 - \theta_3$$
$$\theta_4 = 15 - 30 - 28.9$$
$$\theta_4 = 43.9$$

From equation (2.2.20)

$$\theta_5 = \tan^{-1}\frac{S_1 n_x - C_1 n_y}{C_{234}(C_1 n_x + S_1 n_y) + S_{234} n_z}$$

$$\theta_5 = 29.97$$

5. CONCLUSION

In this paper, a kinematics analysis of 5 DOF Robot Arm V2 has been discussed. A Matlab GUI was developed to simulate the manipulator kinematic behavior. The developed simulation model can be used to create robotic arm path planning in any assigned workspace.

REFERENCES

Baki Koyuncu, and Mehmet Güzel,(2007), *Software Development for the Kinematic Analysis of a Lynx 6 Robot Arm*, World Academy of Science, Engineering and Technology 30,

Denavit J.R.S. Hartenberg,(1955), *A kinematic Notation for Lower- Pair Mechanism Based on Matrices*, ASME Journal of Applied Mechanics, 215 – 22

R. P. Paul, (1981), *Robot Manipulators: Mathematics, Programming, and Control*. Cambridge, Massachusetts: MIT Press.

Frank L. Lewis,(2004) *Robot Manipulator Control Theory and Practice, Second Edition*, University of Texas, U.S.A. pp 555-558

Saeed B. Niku, (2001), *Introduction to Robotic Analysis Systems*, Prentice Hall, ISBN 0-13-061309-6, pp 53-83

Arya Wirabhuana, Habibollah Haron, Jasril,(2005), *Industrial Robot Simulation Software development using virtual reality modelling approach (VRML) and Matlab Simulink Toolbox*, Prosiding RAPI, Simposium Nasional IV, ISSN 1412-9612

Peter I. Corke, (2007), *A computer tool for simulation and analysis, the Robotics Toolbox for MATLAB*, CSIRO Division of Manufacturing Technology

Arthur J. Critchlow, (1985), *Introduction to Robotics*, Macmillan, ISBN 0-02-325590-0

Fikri Akmal ,(2010), Stress And Kinematic Analysis of 5 DOF Robotic Arm In Malaysian Nuclear Agency, Bsc Thesis, College of Engineering Universiti Tenaga Nasional.