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Research Article

Kinematics Analysis and Modeling of 6 Degree of Freedom Robotic Arm from DFROBOT on Labview

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Abstract: The aim of this study is to analyze the robot arm kinematics which is very important for the movement of all robotic joints. Also they are very important to obtain the indication for controlling or moving of the robot arm in the workspace. In this study the kinematics of ROB0036 DFROBOT Arm will be accomplished by using LabVIEW. Finding the parameters of Denavit-Hartenberg representation, the kinematic equations of motion can be derived which solve the problems of automatic control of the 6 revolute joints DFROBOT manipulator. The kinematics solution of the LabVIEW program was found to be nearest to the robot arms actual measurements.

Keywords: DFROBOT 6DOF robot arm, forward kinematics, inverse kinematics, LabVIEW, robot manipulator

INTRODUCTION

The kinematics problem is related to finding the transformation from the Cartesian space to thejoint space and vice versa. The solutions of the kinematics problem of any robot manipulatorhave two types; the forward kinematic and inverse kinematics. When all joints are known the forward kinematic will determine the Cartesian space, or where the manipulator arm will be. In the inverse kinematic the calculations of all joints is done if the desired position and orientation of the end- effectors is determined, that means by the inverse kinematic the robotic arm joint space angles will be calculated as referred to Craig (2005).

A six degree of freedom DFROBOT has five rotational joints with a gripper and operate with their servo motors connected as an intersecting or parallel joint axis, it is a low cost educational robot manipulator, flexible and similar to industrial robot arms. In this study the parameters of the standard Denavit Hardenberg listed in Table 1 for the 6DOF Robot Arm shown in Fig. 1 has been used for modeling and simplifying its associated kinematics.

The kinematic analysis of industrial robots was discussed in many literatures (Craig, 2005; Spong *et al*., 2005). Koyuncu and Guzel (2007) suggested a method for solving the kinematics of the Lynx 6d of Robot and propose a software package named MSG that used to test the behavior of robot motion. Qassem *et al*. (2010) proposed a software package to solve the kinematics of the AL5B Robot arm. More analysis have been achieved for modeling a 6dof robotic manipulators using the MATLAB software for their simulation by Iqbal *et al*. (2012), Kumar *et al*. (2013) and Singh *et al*. (2015).

Forward kinematic is much easier than inverse kinematic and so called direct kinematic, Mohammed and Sunar (2015) began their kinematic analysis by using the product of Exponential Formula (PE) to simplify the analysis.

In this study a simple and direct solution to the mathematical model and kinematical analysis of the DFROBOT equations which relate all joints together as refer to the base is achieved. Applying the robot arm kinematics on LabVIEW, the manipulator motion can be introduced with respect to its mathematical analysis.

In this study the target will be on the Kinematics and how to obtain the joint angles from the inverse kinematics modeling that can be used for the control of a variety of industrial processes. The work takes the benefit of using the numeric values for the position and orientation of the end- effector which is the results of the forward kinematics and find all the joint angles of the robot arm from the inverse kinematic solutions applied in the new developed closed form package of the 6 DOF robot which is the case study of this study.

DFROBOT MODELING

The DFROBOT is a 6DOF robotic arm delivers fast, accurate and repeatable movement and called articulated because it has a series manipulator having

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Table 1: The DH parameters of the DFROBOT

Joint	Link	a_{i-1} min	α_{i-1} degree	d_i mm	θi degree
0-1	1	0	0	45	θ_1
1-2	2	0	90	0	θ_2
2-3	3	90	0	0	θ_3
3-4	4	90	0-90	0	θ_4
4-5	5	0	-90	30	θ_5
5-6	6	0	0	0	gripper

Fig. 1: 6DOF robot manipulator

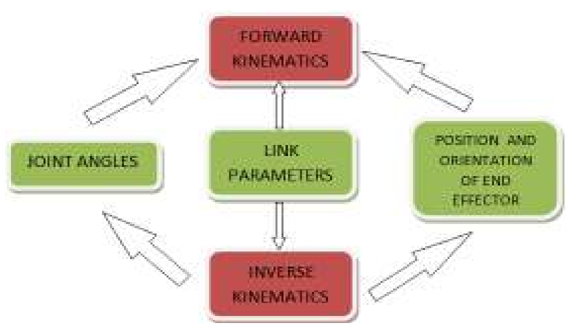

Fig. 2: Kinematic modeling block diagram

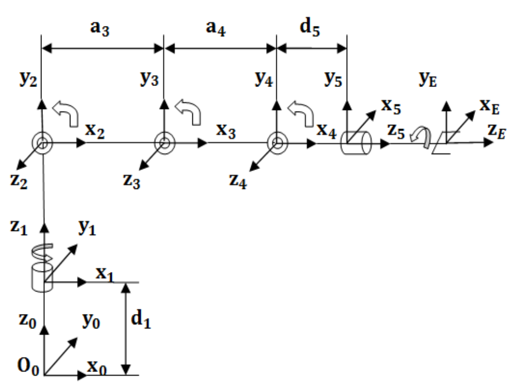

Fig. 3: The robot coordinate frame

all joints as revolute. The main features of this kind: base rotation, single plane shoulder, elbow, wrist motion, functional gripper and optional wrist rotate. The kinematic modeling requires the solutions of the forward and inverse kinematics of the manipulator and the link parameters are needed for the two solutions as shown in the block diagram of Fig. 2.

FORWARD KINEMATICS

The joint variables of the robot are given to determine the position and orientation of the end-effector. Each joint for each frame has a single degree of freedom and can be represented by a single number, which is the angle of rotation in the case of a revolute joint i.e., $(\theta_0, \theta_1, \ldots\ldots, \theta_n, \theta_{n-1})$. Starting from the base which is denoted as link 0 to the n links the cumulative effect of the joint variables can be calculated. z_i is a unit vector along the axis in space between links i-1 and i. Next, each link is attached with coordinate frames from 1 to n, the frame i is rigidly attached to link i. Figure 3 illustrates the DFROBOT frames and links connections.

Assignments of joints and all parameters used to define the robot frames can be defined by using the DH parameters table explained by Tahseen (2013).

Table 1 shows the related six joints parameters of the robotic arm ROB0036 manipulator in order to find the position and orientation of the rigid body which is useful for obtaining the composition of coordinate transformations between the consecutive frames:

where,

a_i : The length distance from z_i to z_{i+1} measured along z_i

α_i: The twist angle between z_i and z_{i+1} measured about x_i

d_i: The offset distance from x_i to x_{i+1} measured along z_i

θ_i: The angle between x_i and x_{i+1}measured about z_i

Forward kinematics analysis is the process of calculating the position and orientation of the end-effector with given joints angles so by substituting these parameters in the homogenous transformation matrix from joint i to joint i+1 (Craig, 2005):

$$Ai = \begin{bmatrix} C\theta i & -S\theta iC\alpha i & S\theta iS\alpha i & aiC\theta i \\ S\theta i & C\theta iC\alpha i & -C\theta iS\alpha i & aiS\theta i \\ 0 & S\alpha i & C\alpha i & di \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The transformation matrices $A_1$and A_6 for the DFROBOT joints can be obtained as shown:

$$A_1^0 = A_1 = \begin{bmatrix} C_1 & -S_1 & 0 & 0 \\ S_1 & C_1 & 0 & 0 \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where, the matrix A_1 for example shows the transformation between frames 0 and 1, $C_i = \cos\theta_i$ and $S_i = \sin\theta_i$:

$$A_2^1 = A_2 = \begin{bmatrix} C_2 & 0 & S_2 & 0 \\ S_2 & 0 & -C_2 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$A_3^2 = A_3 = \begin{bmatrix} C_3 & -S_3 & 0 & a_3C_3 \\ S_3 & C_3 & 0 & a_3S_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$A_4^3 = A_4 = \begin{bmatrix} C_4 & -S_4 & 0 & a_4C_4 \\ S_4 & C_4 & 0 & a_4S_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$A_5^4 = A_5 = \begin{bmatrix} C_5 & 0 & -S_5 & 0 \\ S_5 & 0 & C_5 & 0 \\ 0 & -1 & 0 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

$$A_6^5 = A_6 = \begin{bmatrix} C_6 & -S_6 & 0 & 0 \\ S_6 & C_6 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

Performing the composition from the n- th frame to the base frame we multiply the six matrices from 1 to 6:

$$A_n^0 = A_1^0 \,.\, A_2^1 \ldots\ldots A_n^{n-1} = \prod_{i=1}^{n} A_i^{i-1} = \begin{bmatrix} R_n^0 & P_n^0 \\ 0 & 1 \end{bmatrix}$$

where, R is a 3×3 matrix for rotation and P is the position, so the total matrix of transformation:

$$A_6^0 = A_1^0 * A_2^1 * A_3^2 * A_4^3 * A_5^4 * A_6^5 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

where, p_x, p_y, p_z represent the position and $\{(n_x, n_y, n_z), (o_x, o_y, o_z), (a_x, a_y, a_z)\}$, represent the orientation of the end- effector, they can be calculated in terms of joint angles:

$$n_x = C_6C_{12}C_{345} - S_6S_{12}$$
$$n_y = C_6S_{12}C_{345} + C_{12}S_6$$
$$n_z = C_6S_{345}$$
$$o_x = -C_{12}S_6C_{345} - S_{12}C_6$$
$$o_y = -S_6\,S_{12}C_{345} + C_{12}C_6$$
$$o_z = -S_6S_{345}$$
$$a_x = -C_{12}S_{345}$$
$$a_y = -S_{12}S_{345}$$
$$a_z = C_{345}$$
$$p_x = a_4C_{12}C_3C_4 - a_4C_{12}S_3S_4 + S_{12}d_5 + a_3C_{12}C_3$$
$$p_y = a_4S_{12}C_3C_4 - a_4S_{12}S_3S_4 - C_{12}d_5 + a_3S_{12}C_3$$
$$p_z = a_4S_3C_4 + a_4C_3S_4 + a_3S_3 + d_1 \quad (8)$$

where,

$C_{23} = \cos(\theta_2 + \theta_3), S_{23} = \sin(\theta_2 + \theta_3)$, $C_{234} = \cos(\theta_2 + \theta_3 + \theta_4)$ and $S_{234} = \sin(\theta_2 + \theta_3 + \theta_4)$

Making use of some trigonometric equations helps for easy solutions:

$$C_{12} = C_1C_2 - S_1S_2$$
$$S_{12} = C_1S_2 + S_1C_2$$
$$C_{234} = C_2(C_3C_4 - S_3S_4) - S_2(C_4S_3 + C_3S_4)$$
$$S_{234} = S_2(C_3C_4 - S_3S_4) + C_2(S_3C_4 + C_3S_4).$$

INVERSE KINEMATICS

The solution of Inverse kinematics is more complex than forward kinematics and there is many solutions approach such as geometric and algebraic analysisused for finding the inverse kinematics considering the system structure of the robotic arm. In case of inverse kinematics the joint angles can be determined for any desired position and orientation in Cartesian space. For simplicity of solutions to find the joint angles of 6d of articulated robot arm of the DFROBOT the transformation matrix in Eq. (7) can be multiplied by A_n^{-1} for n = 1,…,6 on both sides of the equation sequentially, then solving the produced equations obtained by equating terms of the both sides of matrices:

$$A_1^{-1} = \begin{bmatrix} C_1 & S_1 & 0 & 0 \\ -S_1 & C_1 & 0 & 0 \\ 0 & 0 & 1 & -d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9)$$

$$A_2^{-1} = \begin{bmatrix} C_1 & S_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ S_2 & -C_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (10)$$

$$A_3^{-1} = \begin{bmatrix} C_3 & S_3 & 0 & -a_3 \\ -S_3 & C_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (11)$$

$$A_4^{-1} = \begin{bmatrix} C_4 & S_4 & 0 & -a_4 \\ -S_4 & C_4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (12)$$

$$A_5^{-1} = \begin{bmatrix} C_5 & S_5 & 0 & 0 \\ 0 & 0 & -1 & d_5 \\ -S_5 & C_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (13)$$

$$A_6^{-1} = \begin{bmatrix} C_6 & S_6 & 0 & 0 \\ -S_6 & C_6 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (14)$$

INVERSE KINEMATIC SOLUTIONS

To solve the matrix in Eq. (7) it is easy to use the algebraic solution technique for:

$$A_6^0 = A_1^0 A_2^1 A_3^2 A_4^3 A_5^4 A_6^5 \tag{15}$$

To solve for θi when A_6^0 is given as numeric values, multiply each side byA_1^{-1}:

$$A_1^{-1} * \left[\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}\right] = A_1^{-1} * A_1^0 * A_2^1 * A_3^2 * A_4^3 * A_5^4 * A_6^5 \tag{16}$$

The matrix manipulations has resulted the following matrix solutions:

$$\begin{bmatrix} . & . & C_1 a_x + S_1 a_y & C_1 p_x + S_1 p_y \\ . & . & -S_1 ax + C_1 a_y & -S_1 p_x + C_1 p_y \\ . & . & a_z & p_z - d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} . & . & -C_2 S_{345} & a_4 C_2 C_{34} + a_3 C_2 C_3 + S_2 d_5 \\ . & . & -S_2 S_{345} & a_4 S_2 C_{34+} a_3 S_2 C_3 - C_2 d_5 \\ . & . & C_{345} & a_4 S_{34} + a_3 S_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{17}$$

Both matrix elements in Eq. (17) are equated to each other and the resultant θ values are extracted. By taking (1, 4) (2, 4):

$$C_1 p_x + S_1 p_y = a_4 C_2 C_{34} + a_3 C_2 C_3 + S_2 d_5 \tag{18}$$

$$-S_1 p_x + C_1 p_y = a_4 S_2 C_{34} + a_3 S_2 C_3 - C_2 d_5 \tag{19}$$

Squaring and adding the two Eq. (18) and (19):

$$C_3 = \text{Cos } \theta_3 = \frac{\sqrt{p_x^2 + p_y^2 - d_5^2} - a_4 C_{34}}{a_3} = n$$

$$\theta_3 = \text{Cos}^{-1} n = \text{Atan2}\left(\mp\sqrt{1 - n^2}, n\right) \tag{20}$$

Eq. (3, 4):

$$p_z - d_1 = a_4 S_{34} + a_3 S_3$$

$$S_{34} = \frac{a_3 S_3 - p_z + d_1}{a_4}$$

$$\theta_{34} = \text{Atan2}\left[\frac{a_3 S_3 - p_z + d_1}{a_4}, \mp\sqrt{1 - \left(\frac{a_3 S_3 - p_z + d_1}{a_4}\right)^2}\right] \tag{21}$$

$$\theta_4 = \theta_{34} - \theta_3 \tag{22}$$

Multiplying each side of Eq. (15) with$A_1^{-1} A_2^{-1}$:

$$A_1^{-1} * A_2^{-1} * \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = A_3^2 * A_4^3 * A_5^4 * A_6^5 \tag{23}$$

$$\begin{bmatrix} . & . & . & C_1 C_2 p_x + C_1 S_2 p_y + S_1 p_z \\ . & . & . & -S_1 C_2 p_x - S_1 S_2 p_y + C_1 p_z \\ S_2 n_x - C_2 n_y & S_2 o_x - C_2 o_y & . & S_2 p_x - C_2 p_y - d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} C_6 C_{345} & -S_6 C_{345} & -S_{345} & a_4 C_{34} + a_3 C_3 \\ C_6 S_{345} & -S_6 S_{345} & C_{345} & a_4 S_{34} + a_3 S_3 \\ -S_6 & -C_6 & 0 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{24}$$

Equating elements (3, 4) of the right hand side matrix and the left hand side matrix of Eq. (24):

$$S_2p_x - C_2p_y - d_1 = d_5$$
$$S_2p_x - C_2p_y = d_1 + d_5$$
$$\theta_2 = \operatorname{atan2}(p_x, -p_y) \mp \operatorname{atan2}\left[\sqrt{p_x^2 + p_y^2 - (d_1 + d_5)^2}, (d_1 + d_5)\right] \tag{25}$$

From Eq. (8) we can obtain:

$$a_x = -C_{12}S_{345}$$

$$a_y = -S_{12}S_{345}$$

Dividing the two equations:

$$\frac{S_{12}}{C_{12}} = \frac{a_y}{a_x}\theta_{12} = \operatorname{atan2}(a_y, a_x) \tag{26}$$

And then we find:

$$\theta_1 = \theta_{12} - \theta_2 \tag{27}$$

Then also equating elements (3, 1) and (3, 2) of the two sides of the matrices in Eq. (24):

$$-S_6 = S_2n_x - C_2n_y \text{ Or} S_6 = C_2n_y - S_2n_x$$
$$-C_6 = S_2o_x - C_2o_y \text{Or } C_6 = C_2o_y - S_2o_x\theta_6 = \operatorname{Atan2}[(C_2n_y - S_2n_x), (C_2o_y - S_2o_x)] \tag{28}$$

Or alternatively:

$$\theta_6 = \operatorname{Atan2}\left[\mp\sqrt{1 - (C_{12}o_y - S_{12}o_x)^2}, (C_{12}o_y - S_{12}o_x)\right] \tag{29}$$

Now multiply each side of Eq. (15) by:

$$A_1^{-1} * A_2^{-1} * A_3^{-1} * \left[\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}\right] = A_4^3 * A_5^4 * A_6^5 \tag{30}$$

$$\begin{bmatrix} C_1C_{23} & C_1S_{23} & S_1 & -a_3C_1C_2 \\ -S_1C_{23} & -S_1S_{23} & C_1 & a_3S_1C_2 \\ S_{23} & -C_{23} & 0 & -a_3S_2 - d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \text{RHS} \begin{bmatrix} C_6C_{45} & -S_6C_{45} & -S_{45} & a_4C_4 \\ C_6S_{45} & -S_6S_{45} & C_{45} & a_4S_4 \\ -S_6 & -C_6 & 0 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \text{LHS} \tag{31}$$

Equating elements (3, 4) from the two sides of Eq. (31):

$$S_{23}p_x - C_{23}p_y - a_3S_2 - d_1 = d_5$$
$$S_{23}p_x - C_{23}p_y = a_3S_2 + d_1 + d_5$$
$$\theta_{23} = \operatorname{atan2}\left(p_x, -p_y\right) \mp \operatorname{atan2}\left[\sqrt{p_x^2 + p_y^2 - \left(a_3S_2 + d_1 + d_5\right)^2}, (a_3S_2 + d_1 + d_5)\right] \tag{32}$$

$$\theta_3 = \theta_{23} - \theta_2 \tag{33}$$

From the Eq. in (8) we can also obtain:

$$C_{345} = a_z\theta_{345} = \operatorname{atan2}\left(\mp\sqrt{1 - a_z^2}, a_z\right) \ldots \tag{34}$$

$$\theta_5 = \theta_{345} - \theta_3 - \theta_4 \tag{35}$$

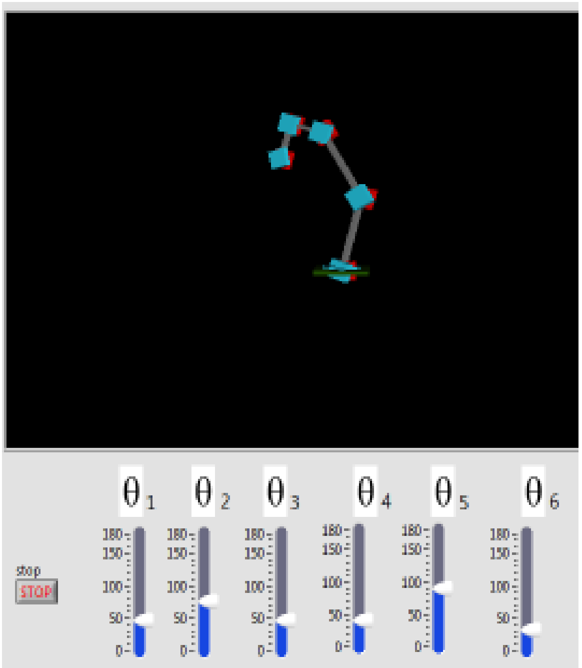

Fig. 4: The robot angles

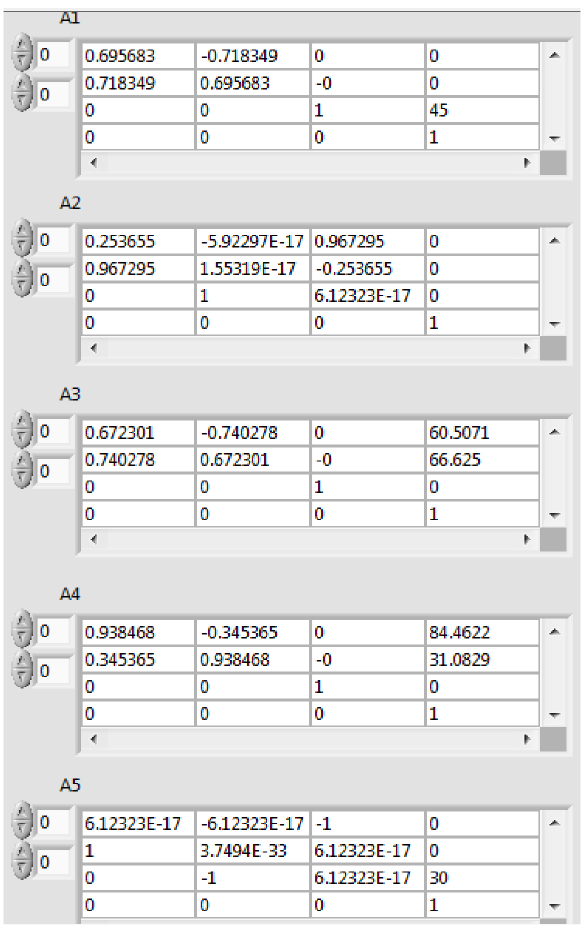

Fig. 5: Forward kinematics simulation with the matrices A_6 and A_n not shown in diagram

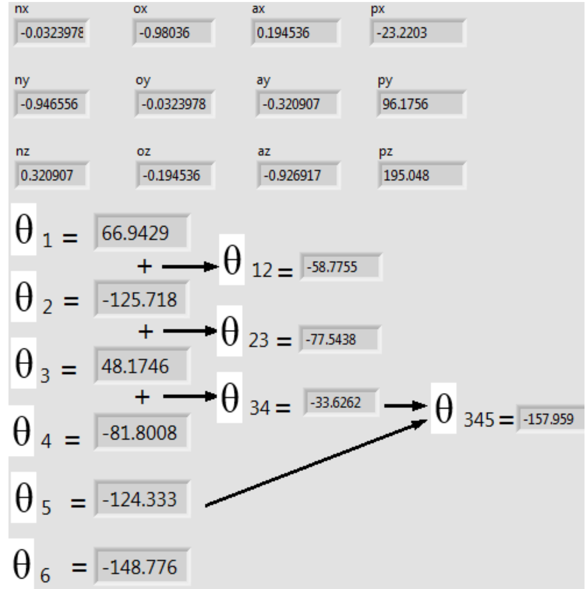

Fig. 6: Inverse kinematic simulation

The developed software will calculate the required angles for target orientation and target positioning, the angle values are calculated by using the equations as follows:

$$\theta_2 = \operatorname{atan2}\left(p_x, -p_y\right) \mp \operatorname{atan2}\left[\sqrt{p_x^2 + p_y^2 - (d_1 + d_5)^2}, (d_1 + d_5)\right]$$

$$\theta_{12} = \operatorname{atan2}(a_y, a_x)$$

$$\theta_1 = \theta_{12} - \theta_2$$

$$\theta_{23} = \operatorname{atan2}\left(p_x, -p_y\right) \mp \operatorname{atan2}\left[\sqrt{p_x^2 + p_y^2 - \left(a_3 S_2 + d_1 + d_5\right)^2}, (a_3 S_2 + d_1 + d_5)\right]$$

$$\theta_3 = \theta_{23} - \theta_2$$

$$\theta_3 = \operatorname{Cos}^{-1} n = \operatorname{Atan2}\left(\mp\sqrt{1 - n^2}, n\right),$$

where,

$$n = \operatorname{Cos}\theta_3 = \frac{\sqrt{p_x^2 + p_y^2 - d_5^2} - a_4 C_{34}}{a_3}$$

$$\theta_{34} = \operatorname{Atan2}\left[\frac{a_3 S_3 - p_z + d_1}{a_4}, \mp\sqrt{1 - \left(\frac{a_3 S_3 - p_z + d_1}{a_4}\right)^2}\right]$$

$$\theta_4 = \theta_{34} - \theta_3$$

$$\theta_{345} = \operatorname{atan2}\left(\mp\sqrt{1 - a_z^2}, a_z\right)$$

$$\theta_5 = \theta_{345} - \theta_3 - \theta_4$$

$$\theta_6 = \operatorname{Atan2}\left[(C_2 n_y - S_2 n_x), (C_2 o_y - S_2 o_x)\right]$$

RESULTS AND DISCUSSION

Kinematic analysis with mathematical solutions of the 6dof DFROBOT was done in this study. With the Denavit-Hartenberg method and for a given joint angles to be applied as the desired angles for an example (45.92, 75.3, 45.92, 20.20, 90, 31.23) in degrees shown in Fig. 4, forward and inverse kinematic solutions are generated by the developed software with LabVIEW. Figure 5 shows the implementations of these angles to find the total homogenous transformation matrix which contains position and orientation parameters related to the motion kinematic of the robot arm. The other simulator isthe inverse kinematic part with anew analysis technique for the user that use the result parameters of equations (8) being solved to obtain the new joint angles $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5$ and θ_6 for a given task of the Robot Arm.

For any desired joint frame with the position and orientation shown in total matrix the inverse kinematic nonlinear system solver will be run as shown in Fig. 6.

CONCLUSION

An analytical solution with a newly developed system solver for the Kinematics of a 6dof Robot Arm from DFROBOT is derived and developed in this study. This model gives correct joint angles so that the robot arm with its end- effector can easily moved to any reachable positions and orientations for performing a pick and place task. Less difference is found between measured and calculated valued which give an exactdesired points in the kinematics simulation process. Also this method can be used to solve kinematics for other robotics arm.

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