Forward Kinematics Modeling of 5DOF Stationary Articulated Robots

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ABSTRACT

This paper presents a direct kinematics modeling of 5 DOF stationary articulated robot arm which is used for educational tasks, and presents an adopted modeling method to represent and simulate the simultaneous positional coordinates for each joint of the robot while it moves from one target to another, where a Lab Volt R5150 robot arm has been taken as a case study. The Denavit – Hartenberg (D-H) model of representation is used to model robot links and joints in this paper. It utilizes Matlab 2010a software as the tool for manipulation and testing. The adopted modeling solution was found to be identical with the physical behaviors.

Keywords: LabVolt R5150 robot arm, forward kinematics, D-H parameters, modeling and simulation

INTRODUCTION

Robot manipulator field is one of the interested fields in industrial, educational and medical applications. It works in unpredictable, hazardous and inhospitable circumstances which human cannot reach. For example, working in chemical or nuclear reactors is very dangerous, while when a robot instead human it involves no risk to human life [1]. The robot has become important equipment in manufacturing of a country’s
manufacture level and technological level. Robot kinematics analysis is the basis of robot motion control [7], therefore, modeling and analysis of the robot manipulators are very important before using them in these circumstances to work with high accuracy. Robots are operated with their motors in the joint space, whereas tasks are defined and objects are manipulated in the Cartesian space. The transformation between joint space and the Cartesian space of the robot is very important.

There is a large amount of literature which discusses the kinematics of industrial robots. Yang et al [3], have described that the placement of an open loop robotic manipulator in a working environment is characterized by defining the position and orientation of the manipulator's base with respect to a fixed reference frame. Bi and Lang [4], have proposed a forward kinematics model for determining workspace by using joint motion. Forward and Inverse equation analysis, were generated and implemented using a simulation program [5] and [6]. Annand [7] derived the kinematics analysis of PUMA 560, and calculated the equation of motion of the robot by deriving the so-called Euler-Lagrange equations.

ROBOT DESCRIPTION

LabVolt Robot 5150 is a small tabletop robotic arm manufactured by LabVolt Inc Fig(1). It is a five articulated coordinate robotic manipulator that uses stepper motors for joint actuators, and its motion are controlled by RoboCIM software.

Lab-Volt R5150 robot arm has base, shoulder, elbow, tool pitch and tool roll which are all consisting rotary joints and provide 5 directions of motion (DOF) plus a grip movement. These joints provide shoulder rotation, shoulder motion, elbow rotation, wrist up and down motion, wrist rotation and gripper motion.

Lab-Volt R5150 has five rotational joints, five axis (three major axes: base – shoulder - elbow to position the wrist, and two minor axes: pitch and roll to orient the gripper) and a moving grip.

![Figure (1) LabVolt R5150 robot arm.](image-url)
Kinematics

Robot arm kinematics explain the analytical description of the motion geometry of the manipulator with the reference to a robot coordinate system fixed to a frame without the consideration of the forces or the moments causing the movements.[8]

For the direct kinematics the inputs are the joint angle vectors and the link length parameters, while the output of the problem is the orientation and the position of the tool or gripper. The block diagram representation of the direct kinematics shown by Fig.2

![Direct Kinematic Block Diagram](image)

Figure (2). Direct Kinematic Block Diagram.

Many methods can be used in the direct kinematics calculation. The Denavit-Hartenberg (D-H) analyses is one of the most used, in this method the direct kinematics is determinate from some parameters that have to be defined, depending on each mechanism. However, it was chosen to use the homogeneous transformation matrix [9]. This transformation specifies the location (position and orientation) of the hand in space with respect to the base of the robot, but it does not tell us which configuration of the arm is required to achieve this location.

Applying the D-H algorithm, the link coordinate diagram can be represented as shown in fig, (3), the dotted diagonal line between the origin of link3 and the origin of link4 indicates that the origin of these two coordinate frames coincide.
Since LabVolt R5150 robot is a five-axis articulated coordinate robot as shown in figures (1) and (3) then:

The vector of joint variables is given by: \( \theta = [\theta_1, \theta_2, \theta_3, \theta_4, \theta_5]^T \)

The vector of joint distances is given by: \( d = [d_1, d_2, d_3, d_4, d_5]^T \)

The vector of link lengths is given by: \( a = [a_1, a_2, a_3, a_4, a_5]^T \)

The vector of the link twist angle is given by: \( \alpha = [\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5]^T \)

These four parameters are called Denavit-Hartenberg (D-H) parameters. The D-H representation provides a systematic method for describing the relationship between adjacent links and gives a mathematical description for all serial manipulators depending on the robot geometry [5],[8],[9]. It defines the position and orientation of the current link with respect to previous one. Using fig. (3), the set of kinematics D-H parameters for LabVolt R5150 robot are shown in Table (1).
Table (1) Link parameters for LabVolt R5150 robot arm.

<table>
<thead>
<tr>
<th>Axis</th>
<th>θ</th>
<th>d</th>
<th>a</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>θ₁</td>
<td>255.5mm</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>θ₂</td>
<td>0</td>
<td>190mm</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>θ₃</td>
<td>0</td>
<td>190mm</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>θ₄</td>
<td>0</td>
<td>0</td>
<td>90</td>
</tr>
<tr>
<td>5</td>
<td>θ₅</td>
<td>115mm</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

As shown in fig. (3) the origins of the coordinate frames associated with the tool orientation coincide at the wrist because the robot has a spherical wrist with no tool yaw motion

THE ARM EQUATION

In physical applications, it is important to describe the position of the end effector of the robot manipulator in one global coordinates. In transforming, the coordinates of the end effector from the local position to the global position, the robot movements are represented by a series of movements of rigid links. Each link defines a proper transformation matrix relating the position of the current link to the previous one [10]. Once a set of link coordinates is assigned using D-H algorithm, then the transform from coordinate frame i to coordinate frame i-1 can be achieved using homogeneous coordinate transformation matrix. To determine the transformation matrix rotation and translation of the frame i-1 have to be done successively to render it coincident with coordinate frame i, this involves four fundamental operations as illustrated in Table (2) [11].

Table (2) Transferring from frame i to frame i-1

<table>
<thead>
<tr>
<th>Operation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rotation  ( z_{i-1} ) by ( \theta_i )</td>
</tr>
<tr>
<td>2</td>
<td>Translate along ( z_{i-1} ) by a disance ( d_i )</td>
</tr>
<tr>
<td>3</td>
<td>Translate along ( x_{i-1} ) through a length ( a_i )</td>
</tr>
<tr>
<td>4</td>
<td>Rotation  ( x_{i-1} ) by twist ( \alpha_i )</td>
</tr>
</tbody>
</table>

This can be expressed as a product of four homogeneous transformation relating coordinate frame of i-1 link to that of link i this relation is known as Arm Matrix
\[ A_{i-1}^i = R_{(Z,0)} \cdot T_{(0,0,d)} \cdot T_{(a,0,0)} \cdot R_{(x,a)} \]

\[ A_{i-1}^i = R_{(Z,0)} \cdot T_{(a,0,d)} \cdot R_{(x,a)} \]

Hence
\[
A_{i-1}^i =
\begin{bmatrix}
\cos\theta & -\sin\theta & 0 & 0 \\
\sin\theta & \cos\theta & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & a \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & d \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos\alpha & -\sin\alpha & 0 \\
0 & \sin\alpha & \cos\alpha & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

...1

\[
A_{i-1}^i =
\begin{bmatrix}
\cos\theta & -\sin\theta & \cos\alpha & \sin\theta & \cos\alpha & a.\cos\theta \\
\sin\theta & \cos\theta & \cos\alpha & \sin\theta & \sin\alpha & a.\sin\theta \\
0 & \sin\alpha & \cos\alpha & d \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

...2

After obtaining the table of DH convention, a series of homogeneous matrices can be derived depending on the number of the DOF. The transformation matrix for each joint from joint 1 to the joint \(i\) can be calculated as:

\[ A_{i} = R_{(Z,0)} \cdot T_{(0,0,d_i)} \cdot T_{(a_i,0,0)} \cdot R_{(x,a_i)} \]

...3

In order to compute the arm matrix, it is often helpful to partition the problem at the wrist, this effectively decomposes the problem into two smaller sub problems, one sub problem associated with the major axes used to position the tool and the other sub problem associated with the minor axes used to orient the tool that can be formulated as follows:

\[ A^5 = A^4 \cdot A^2 \cdot A^1 \cdot A_0 \]

\[ A^4 = A^3 \cdot A^2 \cdot A_1 \cdot A_0 \]

\[ A^3 = A^2 \cdot A_1 \cdot A_0 \]

\[ A^2 = A_1 \cdot A_0 \]

\[ A_0 = \begin{bmatrix} 1 \end{bmatrix} \]

...4
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Where

\[ C_1 = \cos \theta_1, \quad S_1 = \sin \theta_1, \quad C_{23} = \cos(\theta_2 + \theta_3) \quad \text{and} \quad S_{23} = \sin(\theta_2 + \theta_3) \]

The final expression for \( A_{\text{Wrist}} \) depends only on the first three joint variables.

Computing the tool coordinates relative to the wrist:

\[
A_{\text{Wrist}} = \begin{bmatrix}
C_1 & 0 & S_1 & 0 \\
S_1 & 0 & -C_1 & 0 \\
0 & 1 & 0 & d_1 \\
0 & 0 & 0 & 1 \\
\end{bmatrix} \begin{bmatrix}
C_2 & -S_2 & 0 & a_2C_2 \\
S_2 & C_2 & 0 & a_2S_2 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix} \begin{bmatrix}
C_3 & -S_3 & 0 & a_3C_3 \\
S_3 & C_3 & 0 & a_3S_3 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\]

The final expression for \( A_{\text{Tool}} \) depends only on the last two joint variables.

The matrix of the Lab Volt R5150 robot arm can be achieved by multiplying the two partitioned factors together:

\[
A_{\text{Base}}^{\text{Wrist}} = \begin{bmatrix}
C_1C_{23} & -C_1S_{23} & S_1 & C_1(a_2C_2 + a_3C_{23}) \\
S_1C_{23} & -S_1S_{23} & -C_1 & S_1(a_2S_2 + a_3S_{23}) \\
S_{23} & C_{23} & 0 & d_1 + a_2S_2 + a_3S_{23} \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\]

\[
A_{\text{Base}}^{\text{Wrist}} = \begin{bmatrix}
C_4 & 0 & S_4 & 0 \\
S_4 & 0 & -C_4 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix} \begin{bmatrix}
C_5 & -S_5 & 0 & 0 \\
S_5 & C_5 & 0 & 0 \\
0 & 0 & 1 & d_5 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\]

\[
A_{\text{Base}}^{\text{Wrist}} = \begin{bmatrix}
C_4C_5 & -C_4S_5 & S_4 & S_4d_5 \\
S_4C_5 & -S_4S_5 & -C_4 & -C_4d_5 \\
S_5 & C_5 & 0 & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\]

The matrix of the Lab Volt R5150 robot arm can be achieved by multiplying the two partitioned factors together:

\[
A_{\text{Base}}^{\text{Tool}} = \begin{bmatrix}
C_1C_{234} & S_1C_{234} & C_1S_{234} & C_1(a_2C_2 + a_3C_{23} + d_3S_{234}) \\
S_1C_{234} & -C_1C_{234} & S_1S_{234} & S_1(a_2S_2 + a_3S_{23} + d_3S_{234}) \\
S_{234} & -S_{234} & -C_{234} & 0 \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\]

\[...5\]

\[...6\]

\[...7\]
Hence the coordinate of the tool-tip position can be found according to the following expression:

\[
\begin{align*}
P_x &= C_1(a_3C_2 + a_2C_2 + d_3S_{234}) \\
P_y &= S_1(a_2C_2 + a_2C_2 + d_3S_{234}) \\
P_z &= d_1 + a_2S_2 + a_3S_{23} - d_3C_{234}
\end{align*}
\]

...8

Where \( S_{234} = \sin(\theta_1 + \theta_2 + \theta_3) \), \( C_{234} = \cos(\theta_1 + \theta_2 + \theta_3) \)

The previous forward kinematics solution can be used for modeling the position of each joint of the manipulator as it moves.

**Base** = \[
\begin{bmatrix}
0 \\
0 \\
0 \\
1
\end{bmatrix}
\]

, as a reference point (origin) : \( P_x = 0, \ P_y = 0, \ P_z = 0 \)

**Shoulder** = \[
\begin{bmatrix}
0 \\
0 \\
d_1 \\
1
\end{bmatrix}
\]

, as shown in Figure.(3) there is no change in axes direction (no rotation) at the shoulder joint but just translation along Z-axis so :

\( P_x = 0, \ P_y = 0, \ P_z = d_1 \)

**Elbow** = \[
\begin{bmatrix}
a_2C_1C_2 \\
a_2C_2S_1 \\
d_1 + a_2S_2 \\
1
\end{bmatrix}
\]

, the position of elbow joint can be deduced by multiplying the two matrices (fourth column):

\[
A_{\text{elbow}} = A^0_1A^j_2 = \begin{bmatrix}
C_1 & 0 & S_1 & 0 \\
S_1 & 0 & -C_1 & 0 \\
0 & 1 & 0 & d_1 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
C_2 & -S_2 & 0 & a_2C_2 \\
S_2 & C_2 & 0 & a_2S_2 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} =
\begin{bmatrix}
C_1C_2 & -C_1S_2 & S_1 & a_2C_1C_2 \\
S_1C_2 & -S_1S_2 & -C_1 & a_2S_1C_2 \\
S_2 & C_2 & 0 & d_1 + a_2S_2 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]
Wrist = \[ \begin{bmatrix}
  a_2 C_1 C_2 + a_3 C_1 C_{23} \\
  a_2 S_1 C_2 + a_3 S_1 C_{23} \\
  d_1 + a_2 S_2 + a_3 S_{23} \\
  1
\end{bmatrix} \]

the position of wrist joint can be deduced by multiplying the three matrices (fourth column represent the joint position):

\[
A_{\text{Wrist}}^0 = \begin{bmatrix}
  C_i & 0 & S_j & 0 \\
  S_i & 0 & -C_j & 0 \\
  0 & 1 & 0 & d_j \\
  0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  C_2 & -S_2 & 0 & a_2 C_2 \\
  S_2 & C_2 & 0 & a_2 S_2 \\
  0 & 0 & 1 & 0 \\
  0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  C_j & -S_j & 0 & a_j C_j \\
  S_j & C_j & 0 & a_j S_j \\
  0 & 0 & 1 & 0 \\
  0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
A_i^0 A_j^1 A_j^2 = \begin{bmatrix}
  C_{C_{23}} & -C_{S_{23}} & S_i & C_i (a_i C_2 + a_i C_{23}) \\
  S_{C_{23}} & -S_{S_{23}} & -C_j & S_j (a_j C_2 + a_j C_{23}) \\
  S_{C_{23}} & C_{S_{23}} & 0 & d_i + a_i S_2 + a_i S_{23} \\
  0 & 0 & 0 & 1
\end{bmatrix}
\]

While tool-tip position has been deduced by multiplying the five matrices \( A_i^0 A_j^1 A_j^2 A_j^3 A_j^4 \) as illustrated in equation (7) (fourth column in the final matrix):

\[
\text{Tool-tip} = \begin{bmatrix}
  C_i (a_i C_2 + a_i C_{23} + d_i S_{234}) \\
  S_i (a_i C_2 + a_i C_{23} + d_i S_{234}) \\
  d_i + a_i S_2 + a_i S_{23} - d_i C_{234} \\
  1
\end{bmatrix}
\]

The above models have been invested to simulate the positional coordinates of each joint of the robot arm while it moves to a desired target.

RESULTS AND DISCUSSION

The adopted model has been tested in real environment at university of technology /Dep. of production engineering and metallurgy for five different cases using a Lab-Volt R5150 robot arm, also the method has been tested by linking the output of the mathematical formulation with Matlab Software for simulation using robot toolbox.

The simulation algorithm includes the following three steps:

**Input:**

1- identify each link parameters (D-H) of the robot as in Table (1)
2- identify the value of each angle \( \theta_1, \theta_2, \theta_3, \theta_4, \theta_5 \)

**Processing:**

mathematical processing according to the equation (7)

**Output:**

1- graphical representation of the robot as in Figure.(4) ( b, d, f, h and j)
2- tool-tip position as in Table (3)

In both tests the adopted model gives good results for all the tested cases as shown in the Figure (4) and Table (3).

The results of comparison in five different cases as illustrated in table (3) shows that the derived solution is very accurate, it was found that the maximum error in the tool pose position do not exceed (0.001) mm. The derived analytical forward kinematics solution provides the correct joint position of the end-effector to any given reachable position.
Figure (4) The real and the simulation of the five selected tests.
Table (3) the real and simulated positional coordinates of the robot joints.

<table>
<thead>
<tr>
<th>Case</th>
<th>Target coord. Actual</th>
<th>Base</th>
<th>Shoulder Position</th>
<th>Elbow Position</th>
<th>Wrist Position</th>
<th>Tool-tip coord. Simulated</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \theta_1 = 0 ) ( \theta_2 = 40 ) ( \theta_3 = -85 ) ( \theta_4 = 90 ) ( \theta_5 = 90 )</td>
<td>( P_x : 361.45 ) ( P_y : 0 ) ( P_z : 161.98 )</td>
<td>0 0 0 0 255.5 141.548 0 377.12 242.779</td>
<td>( P_x : 361.216 ) ( P_y : 0 ) ( P_z : 162.012 )</td>
<td>0.06%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>( \theta_1 = 21 ) ( \theta_2 = 40 ) ( \theta_3 = -85 ) ( \theta_4 = 90 ) ( \theta_5 = 90 )</td>
<td>( P_x : 337.45 ) ( P_y : 129.53 ) ( P_z : 161.98 )</td>
<td>0 0 0 0 255.5 114.017 51.16 377.12 242.779</td>
<td>( P_x : 337.224 ) ( P_y : 129.448 ) ( P_z : 162.012 )</td>
<td>0.062%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>( \theta_1 = 33 ) ( \theta_2 = 40 ) ( \theta_3 = -67 ) ( \theta_4 = 90 ) ( \theta_5 = 90 )</td>
<td>( P_x : 350.26 ) ( P_y : 227.46 ) ( P_z : 239.31 )</td>
<td>0 0 0 0 255.5 122.067 52.16 377.12 242.779</td>
<td>( P_x : 350.98 ) ( P_y : 227.281 ) ( P_z : 239.212 )</td>
<td>0.08%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>( \theta_1 = 45 ) ( \theta_2 = 35 ) ( \theta_3 = -90 ) ( \theta_4 = 90 ) ( \theta_5 = 90 )</td>
<td>( P_x : 233.89 ) ( P_y : 233.89 ) ( P_z : 114.57 )</td>
<td>0 0 0 0 255.5 110.05 110.05 389.35 233.711</td>
<td>( P_x : 233.755 ) ( P_y : 233.755 ) ( P_z : 114.688 )</td>
<td>0.06%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>( \theta_1 = 72 ) ( \theta_2 = 77 ) ( \theta_3 = -147 ) ( \theta_4 = 90 ) ( \theta_5 = 90 )</td>
<td>( P_x : 45.38 ) ( P_y : 139.65 ) ( P_z : 154.05 )</td>
<td>0 0 0 0 255.5 13.207 40.648 440.13 353.289 107.452 157.159</td>
<td>( P_x : 45.445 ) ( P_y : 139.859 ) ( P_z : 154.074 )</td>
<td>0.13%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CONCLUSIONS

A complete analytical solution to the forward kinematics of the 5 DOF LabVolt robots is derived in this paper by partitioning the kinematics problem into two sub-problems at the wrist joint which greatly simplified the solution of the robot arm. An analytical formulation for determining the position of each joint of a 5 DOF articulated robot was presented, the results have been linked with the Matlab 2010a software to simulate the robot joint coordinates as the robot moves from one position to another, as it can be clearly seen from the formulation and the results that the roll angle ($\theta_5$) has no effect on the final position of the tool pose, but it effects the orientation of the end effector.

The results of comparison in five different cases as illustrated in table (3) shows that the adopted model is very effective, efficient and accurate, it was found that the maximum error in the tool pose position do not exceed (0.001) mm. We believe that the solution developed in this paper will make the 5 DOF LabVolt robot more useful in applications.

REFERENCES


