Kinematics Simulation of Welding Manipulator Based on V-REP PRO EDU

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Abstract. As the primary tool in modern industrial welding, 6 DOF manipulator robots can weld in all positions. In this context, Danevit-Hartenberg parameters were developed to simplify kinematics equations for manipulator equations. Inverse kinematics is obtained based on the algebraic method. Simulation of kinematics manipulators based on V-REP PRO EDU is present. Kinematics simulations produce processing motion and relevant kinematics curves. The simulation results and kinematic equations of robotic manipulators are compared, showing that valid kinematic equations and weld trajectories can be passed by the end-effector successfully.

1. Introduction

Welding in manufacturing tasks has become an essential part, especially welding overhead positions, shape, material, and other variables. Welding using a robot manipulator is nothing new. However, so many variations V-REP (Virtual Robot Experimentation Platform) in the shape of the welded workpiece make it essential to be able to handle it quickly. Therefore, simulation is the necessary and primary step before using these robots in real duty [1].

The idea of welding in the welding industry is not only done on one workpiece but also more. Human welding operators devote themselves to more straightforward jobs and more natural positions, such as underhand welding [2]. While the welding robot will do some duties such as; uniform work, intricate welding patterns, high accuracy, and repetitive [3], in this way, the system can accommodate increased quality and welding production capacity.

In short, 6 DOF can be divided into two parts. The first three parts are used to specific positions, and the other three are the essential dexterity characteristics of robotic space manipulators [3]. Therefore, the focus of this paper is six degrees of freedom from specific permits and connections.

The manipulator is a critical part of robot welding. Vitally, kinematic analysis, and manipulator simulation is needed to analysis the welding results before being applied. This paper is organized as follows: the structure of the manipulator described in section 2 continues with kinematic analysis discussed in section 3. The procedure for developing the manipulator modelling in simulation is outlined in section 4, and the results are displayed in section 5. Definitely, conclusions are drawn in section 6.

2. Structure of Manipulator

The manipulator is an essential element of the whole system. The basis of manipulators is to imitate human hands designed with certain DOFs. The number of DOF is very influential on the system to be designed. The same number of DOF with different dimensions will have strange results even applied to the same system or vice versa [4] [5]. The application of manipulators to welding requires us to be able to work based on 3D fields. Whereas the 6 DOF constructively accomplish to work on 3D dimensions, as shown in Figure 1.
Figure 1. The structure of the manipulator

2.1. D-H Coordinate System
The idea of Denavit and Hartenberg (DH) proposed a matrix method for constructing a coordinate system attached to each link in a chain with a robot to describe the translation or rotation relationship between links [6] [7]. Fig. 2 depicts the rotation and translation relationships for each link.

Figure 2. Kinematic coordinate system of ABB IRB4600-60

In this paper, the ABB IRB4600-60 robot industry is taken as a simulation object [8] [9]. DH coordinates are composed of four parameters. This notation describes the parameters of the relationship between one joint $i$ and another joint $i+1$. The four parameters consisted of 1) link length is the distance between the common vertical line of joint axes $l_i$ and $i+1$, 2) the angle of torsion connected with rod $\alpha_i$.
is the angle between of the joint axes \( i \) and \( i+1 \), 3) the distance between the two connection rods; \( d_i \) is the distance between two vertical lines \( l_i \) and \( l_{i-1} \), and 4) angle \( \theta_i \) is the angles between \( l_i \) and \( l_{i+1} \). Based on the DH parameters above, the structure can be written for the ABB IRB4600-60 manipulator robot, as shown in Table 1.

**Table 1. A DH parameter for ABB IRB4600-series**

| joint | \( \theta_i \) | \( l_{i,i+1}(\text{mm}) \) | \( d_i(\text{mm}) \) | \( \alpha_{i,i-1}(\text{deg.}) \) | range |
|-------|----------------|-------------------------|-----------------|--------------------------|--------|
| 1     | \( \theta_1 \) | 0                       | 0               | 0                        | -180~180 |
| 2     | \( \theta_2 \) | \( l_1=175 \)            | 0               | -90                      | -90~150 |
| 3     | \( \theta_3 \) | \( l_2=900 \)            | 0               | 0                        | -180~75 |
| 4     | \( \theta_4 \) | \( l_3=175 \)            | \( d_3=960 \)   | -90                      | -400~400 |
| 5     | \( \theta_5 \) | 0                       | 0               | 90                       | -125~120 |
| 6     | \( \theta_6 \) | 0                       | 0               | -90                      | -400~400 |

Based on Table 1 of the DH parameter system, the homogeneous transformation of the link \( \mathbf{T}_{i-1}^{-1} \mathbf{T}_i \) can be obtained.

\[
\mathbf{T}_{i-1}^{i} = \begin{bmatrix}
\cos \theta_i & -\sin \theta_i & 0 & \alpha_{i-1} \\
\sin \theta_i \cos \theta_{i-1} & \cos \theta_i \cos \alpha_i & -\sin \theta_{i-1} & -\sin \alpha_{i-1} d_i \\
\sin \theta_i \cos \theta_{i-1} & \cos \theta_i \cos \alpha_i & \cos \theta_{i-1} & \cos \alpha_{i-1} d_i \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  

(1)

Transformation of a robot manipulator matrix is given based on the DH parameters method, so for each transformation at each joint as follows.

\[
\begin{align*}
\mathbf{T}_1^0 &= \begin{bmatrix}
\cos \theta_1 & -\sin \theta_1 & 0 & 0 \\
\sin \theta_1 \cos \theta_{i-1} & \cos \theta_1 \cos \alpha_i & 0 & 0 \\
\sin \theta_1 \cos \theta_{i-1} & \cos \theta_1 \cos \alpha_i & 0 & 1 \\
0 & 0 & 0 & 1
\end{bmatrix} \quad (2) \\
\mathbf{T}_2^1 &= \begin{bmatrix}
\cos \theta_2 & -\sin \theta_2 & 0 & l_1 \\
0 & 0 & 1 & 0 \\
-\sin \theta_2 & -\cos \theta_2 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \quad (3) \\
\mathbf{T}_3^2 &= \begin{bmatrix}
\cos \theta_3 & -\sin \theta_3 & 0 & l_2 \\
\sin \theta_3 & \cos \theta_3 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \quad (4) \\
\mathbf{T}_4^3 &= \begin{bmatrix}
\cos \theta_4 & -\sin \theta_4 & 0 & l_3 \\
0 & 0 & 1 & d_4 \\
-\sin \theta_4 & -\cos \theta_4 & 0 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \quad (5) \\
\mathbf{T}_5^4 &= \begin{bmatrix}
\cos \theta_5 & -\sin \theta_5 & 0 & 0 \\
0 & 0 & -1 & 0 \\
\sin \theta_5 & \cos \theta_5 & 0 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \quad (6)
\end{align*}
\]
In this paper, this software can run scripts from C/C++, Lua, Python, Java, MATLAB, Octave, and ROS nodes, Remote API clients, Plugins, Embedded Scripts, add-ons, and BlueZero nodes. V-REP PRO EDU is a free professional education version. Because it has the capability of Remote API, this software can run scripts from C/C++, Lua, Python, Java, MATLAB, Octave, and Urbi.

2.2. Forward Kinematics Analysis

The forward kinematic analysis means that the position of the end-effector is unknown. In this case, it will set angle $\theta_i$ to reach the intended end position. In case forward kinematic is a translation from joint space to Cartesian space [4]. It could be expressed by the following equation.

$$
0_6^T = 0_1^T \cdot 1_2^T \cdot 2_3^T \cdot 3_4^T \cdot 4_5^T \cdot 5_6^T
$$

where $(n_x, n_y, n_z)$, $(a_x, a_y, a_z)$, and $(p_x, p_y, p_z)$ are the normal vector, orientation vector, approach vector, and position of the end-effector, respectively.

2.3. Inverse Kinematics Analysis

Inverse kinematics is the opposite of the forward kinematic process. In this method, the position of the end-effector is known, and the joint angle will calculate how much it must rotate or translate. The solution for kinematic inverses can be done by algebraic, geometric, and iterative methods. In this paper, we use the algebraic method for inverse kinematics [3].

Based on formula (8) will be obtained $\frac{2}{3} T^{-1}(\theta) \frac{0}{6} T = \frac{1}{1} T \cdot \frac{2}{3} T \cdot \frac{3}{4} T \cdot \frac{4}{5} T \cdot \frac{5}{6} T$ through the correspondence of the matrices element, the equation of the two segments can determine values from $\theta_1$ to $\theta_6$. In this simulation, we use the Algebraic method; thus, we can separate all joint angles as follows.

$$
\frac{0}{1} T^{-1} \cdot \frac{0}{6} T = \frac{1}{6} T
$$

$$
\frac{1}{2} T^{-1} \cdot \frac{0}{1} T^{-1} \cdot \frac{0}{6} T = \frac{2}{6} T
$$

$$
\frac{2}{3} T^{-1} \cdot \frac{1}{2} T^{-1} \cdot \frac{0}{1} T^{-1} \cdot \frac{0}{6} T = \frac{3}{6} T
$$

$$
\frac{3}{4} T^{-1} \cdot \frac{2}{3} T^{-1} \cdot \frac{1}{2} T^{-1} \cdot \frac{0}{1} T^{-1} \cdot \frac{0}{6} T = \frac{4}{6} T
$$

$$
\frac{4}{5} T^{-1} \cdot \frac{3}{4} T^{-1} \cdot \frac{2}{3} T^{-1} \cdot \frac{1}{2} T^{-1} \cdot \frac{0}{1} T^{-1} \cdot \frac{0}{6} T = \frac{5}{6} T
$$

Although DH parameters have become standard in robotic manipulators, there is no standard for optimal solutions in inverse kinematic applications. Practically, we can choose the solution closest to the position of the manipulator according to the range of motion, collision, and robotic joint axis requirements.

3. Kinematics Simulation Based on V-REPPRO EDU

V-REP is software that is used for robotic simulations. This software is quite powerful because it can facilitate ROS nodes, Remote API clients, Plugins, Embedded Scripts, add-ons, and BlueZero nodes. V-REP PRO EDU is a free professional education version. Because it has the capability of Remote API, this software can run scripts from C/C++, Lua, Python, Java, MATLAB, Octave, and Urbi.

3.1. Simulation Setting

In this paper, the simulation is done using V-REP PRO EDU version 3.5.0 software (rev.4) 64 bits. Manipulator robots using ABB IRB4600-40 will work with inverse and forward kinematics for the same
welding task. The DH parameter values for robotic manipulators are as shown in Table 1. The inverse and forward kinematic calculations were done in MATLAB 2017. Computers used Intel Core i5 CPU @ 3.0 GHz (6 CPUs), 16 GB RAM, with Windows 10 Pro 64 bit operating system.

3.2. 3D Modeling for the 6 DOF Manipulator
The 3D robot manipulator modeling consists of four parts: base, shoulder \((l_1)\) 175 mm, elbow \((l_2)\) 175 mm, and wrist \((l_3)\) 175 mm. The 3D simulation model was built using the V-REP PRO EDU software as shown in Figure 3. The welding torch is placed at the end of the end-effector with a length of 300 mm, while the yellow circle shows the welding path 1010 mm in diameters.

![Virtual ABB IRB4600 with welding torch and yellow welding path in V-REP PRO EDU](image)

**Figure 3.** Virtual ABB IRB4600 with welding torch and yellow welding path in V-REP PRO EDU

3.3. Trajectory Planning Expected
The weld trajectory planning in this simulation is set for flat-circular objects (Figure 3). The basis for planning a point to point (PTP) manipulator has three points. Point A \((\theta_1...6= 0 90 0 0 0 0)\) as the prefix then moves down to point B \((\theta_1...6= 0 120 60 0 0 0)\) as well as the starting point of the circle. Finally, at point C \((\theta_1...6= 0 52 -13 0 0 0)\), which is 180 degrees from point A, in other words, it will be at the point after forming a half-circle. A series of data variations of all joints together with time has been obtained. Data is stored in the script and given to V-REP PRO EDU; data can be used for torch welding to move along the specified circle line.

4. Simulation Result
Simulation results are compared using the RoboAnalyzer formula. The aim is to verify the correctness of kinematic equations and simulation time is 50 seconds with 100 steps. From V-REP PRO EDU we can see the displacement of the end-effector in XYZ as described in Table 2 and all units in millimeters. Now based on the Eq. 8 above we can find out the values of \(n\) for each endpoint A, B, and C. Including for orientation \((o)\) and approach vector \((a)\) are obtained from the forward kinematics of formula too.
The end-effector position in this paper compares the simulation results and the DH parameter from RoboAnalyzer software. There is a difference, especially in the column of position (p), where this column represents the end-effector position of the first three lines (X, Y, and Z). Initially, this simulation was given in flat 1G (groove) welding with a circular shape. Because it is flat, the position of Z should not change, but we can see the results of the highest DH analysis with a deviation of 0.094 mm. This condition is still acceptable in welding for objects with a diameter of 1010 mm [10].

The Δp value, which reaches up to 0.094 mm, is suspected to be influenced by the number of steps in RoboAnalyzer. The number of steps around 100 is considered still too rough to compare with this simulation. As an illustration, see Figure 4, the motion position of each step is always shorter than the 1/100 arc or 10.1 mm apart; the aforementioned is where the deviation occurs. Whereas to overcome this deviation could be done by increasing the number of steps in crossing the circle or welding path.

![Image of deviation](image_url)

**Figure 4.** The deviation in the simulation and RoboAnalyzer
5. Conclusion
This paper takes ABB IRB4600-60 robot manipulator as a welding simulation object. Kinematic simulation is made in V-REP PRO EDU. DH parameters and trajectory welding solve modeling is obtained for a workpiece. The robot model was made, and RoboAnalyzer verified the truth of the robot kinematics model. Simulation results show that kinematic analysis is correct with acceptable errors.

6. References
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