Mechanical Engineering – Scientific Journal, Vol. **42,** No. 1, pp. 43–51 (2024)
Number of article: 678
Received: May 22, 2024
Accepted: May 28, 2024
In print: ISSN 1857–5293
On line: ISSN 1857–9191
UDC: 621.791:004.896]:531.1-3
https://doi.org/10.55302/MESJ24421043dj

Original scientific paper

KINEMATICS ANALYSIS OF 6 DOF INDUSTRIAL MANIPULATOR AND TRAJECTORY PLANNING FOR ROBOTIC WELDING OPERATION

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A b s t r a c t: Robotic manipulators are commonly used in the manufacturing industry for tasks such as assembly, welding, painting, and palletizing. In these applications, precise control over the position and orientation of the robot's end-effector is crucial for efficient and accurate operation. Both inverse and forward kinematics play crucial roles in the design, programming, and operation of industrial robotic manipulators, helping to ensure their effectiveness, efficiency, and safety in various manufacturing environments. In this paper the forward and inverse kinematic model of 6 degrees of freedom (DOF) industrial manipulator are presented. Additionally, the study focuses on analyzing single pass welding across a range of different scenarios. These cases involve welding paths that have different geometric shapes, with a goal to join the materials together and form a closed shape. Maintaining a vertical orientation of the welding torch was achieved, because it is important for realizing uniform heat distribution, consistent weld bead geometry, and better control over the welding process, ultimately contributing to the effectiveness of the robotic welding operation.

Key words: robotic manipulator; forward kinematics; inverse kinematics; welding robot; manufacturing

КИНЕМАТСКА АНАЛИЗА НА ИНДУСТРИСКИ МАНИПУЛАТОР СО 6 СТЕПЕНИ СЛОБОДА НА ДВИЖЕЊЕ И ПЛАНИРАЊЕ НА ТРАЕКТОРИЈА ПРИ ПРОЦЕСОТ НА РОБОТСКО ЗАВАРУВАЊЕ

А п с т р а к т: Индустриските роботски манипулатори обично се користат во производствените процеси со задача да се реализира склопување, заварување, бојадисување и складирање. За ваква примена, прецизната контрола на положбата и ориентацијата на крајниот член на роботот е клучна за ефикасно и прецизно работење. Инверзната и директната кинематика играат клучна улога во дизајнот, програмирањето и работата на индустриските роботи, помагајќи да се обезбеди нивна ефективност, ефикасност и безбедност во различни производствени капацитети. Во овој труд се претставени директна и инверзна кинематика на индустриски манипулатор со 6 степени слобода на движење (DOF). Дополнително, истражувањето се фокусира на заварување со поединечно поминување за различни сценарија. Овие случаи вклучуваат завари, односно траектории со различна геометриска форма, со цел спојување на материјалите и формирање затворени патеки. Одржувањето на вертикалната ориентација на пламенот за заварување беше постигнато, бидејќи тоа е важно за остварување рамномерна дистрибуција на топлината, конзистентна геометрија на заварот и подобра контрола врз процесот на заварување, што на крајот придонесува за ефективноста на процесот на роботско заварување.

Клучни зборови: роботски манипулатор; директна кинематика; инверзна кинематика; роботско заварување; производство

1. INTRODUCTION

The demand for precise positioning and tracking accuracy in industrial robots continues to increase as industries strive for higher efficiency, quality, and safety standards in their manufacturing processes [1]. Correct positioning allows robots to perform tasks more efficiently by minimizing the need for additional adjustments or rework, which improves overall productivity and reduces production time and costs. In industries where robots work alongside human operators, precise positioning helps prevent accidents and injuries [2]. Robots can avoid collisions with other equipment or workers by precisely tracking their movements [3]. Industrial robots are often employed for repetitive tasks where consistency is crucial [4]. Precise robot controlling ensures that each cycle of the operation is performed identically, leading to uniformity in output [5, 6]. As automation technologies advance, the integration of robots with other automated systems becomes more common [7], therefore seamless coordination between different robotic and machinery components within an automated workflow is necessity. In manufacturing processes such as welding and assembly, even minor deviations in positioning can lead to defects in the final product [8]. Robotic welding needs to ensure that components are joined correctly and that tolerances are met, resulting in higher quality products. Moreover, in fields such as robotics-assisted surgery [9] or high-precision manufacturing [10], where even slight errors can have significant consequences, ultra-precise positioning is imperative. This ensures that delicate operations are performed accurately and safely.

Robot kinematics determines how accurately the robot can move its joints to reach a desired position and orientation in its workspace. By understanding the kinematics of the robot, engineers can calculate the required joint angles or end-effector positions to achieve the given desired task [11]. Kinematics plays a role in optimizing the robot's motion to accomplish tasks efficiently. Through kinematic analysis and optimization, engineers can minimize the time and energy required [12] for the robot to move between different positions, leading to improved productivity. Kinematics is essential for ensuring that the robot's movements are within safe limits. By understanding the kinematic constraints of the robot, the motion trajectories that avoid collisions with obstacles or other machinery in the workspace can be designed and programed, contributing to enhance safety for human operators and equipment. Furthermore, by precisely controlling the robot's joint motions for consistent performance of repetitive tasks, the variations in task execution can be minimized that leads towards greater consistency in product quality. Kinematics is fundamental for coordinating the motions of multiple robots or robotic systems within an automated manufacturing environment [13]. By understanding the kinematic relationships between different robotic components, engineers can synchronize their motions to achieve seamless operation. Robot kinematics is central to achieving precise positioning, efficient motion, and safe operation of industrial robots across a wide range of applications. It provides the foundation to design and control robotic systems that meet the demanding requirements of modern manufacturing environments.

In robotics, the inverse kinematics problem involves finding the joint configurations or angles of a robotic manipulator to achieve a desired position and orientation of its end-effector. Conversely, the forward kinematics problem involves determining the end-effector pose based on the joint variables. Solving the inverse kinematics problem is essential in robotics, particularly in fields such as robot kinematics, motion planning, and control theory. Different approaches can be used to solve this problem, and each has its own strengths and weaknesses. Numerical methods use iterative techniques to approximate solutions. They are more versatile and can handle a wider range of manipulators and end-effector poses. However, they tend to have higher computational costs, longer execution times, and may encounter issues such as local minima and numerical errors. The most common approach is Jacobian-based methods [14], which use the Jacobian matrix to iteratively update joint configurations until a desired end-effector pose is reached. Closed-form methods provide solutions in explicit mathematical forms, often based on the geometry of the robotic manipulator. They have advantages such as lower computational cost and faster execution time compared to numerical methods. However, they may not be applicable to all types of manipulators and end-effector poses. These methods include strategies based on matrix manipulations, arm angle parameter definitions, and geometric methods [15] or soft computing approaches [16].

In the manufacturing industry, robotic arc welding has grown in popularity because it provides a fast return on investment, increases productivity and weld quality, reduces production costs, and saves time. Numerous industries have found success with robotic welding due to its advanced features, which include welding process control, workpiece handling, sensors, and programming. Welding processes are the most popular joining techniques in today's industry. It is used for joining metal materials permanently, with or without the additional material by using heat and, or pressure. It is also thought to be the most economical technique in terms of material use and fabrication, producing a welded joint that is homogenous and stronger than the parent metal. These benefits make this process perfect for the production and restoration of structures across various industries, including but not limited to automotive, construction, agriculture, food processing, marine and offshore, power generation, and aerospace [17, 18].

In the following, Section 2 is dedicated to robot kinematics, including both forward and inverse kinematics. Effective trajectory planning for industrial robot welding operations plays a crucial role in optimizing productivity, ensuring quality welds, and maintaining a safe working environment. Hence, in Section 3 modeling and simulation are included, considering manipulator characteristics and defining different welding cases. In these instances, welding is utilized to connect materials along various geometric paths, with the objective of creating a unified closed shape. Section 4 presents the results and analysis, followed by Section 5 that refers to the conclusions.

2. ROBOT KINEMATICS

For modeling robotic manipulators, the Denavit-Hartenberg (DH) method provides a systematic way to describe the geometry and kinematics of a manipulator. Frames are assigned to each joint of the manipulator, starting from the base frame and progressing towards the end-effector frame. The DH parameters used in this method include: θ_i as joint angle about the Z_{i-1} axis; α_i as angle of rotation about the X_{i-1} axis; d_i as the length of the link along the Z_{i-1} axis; and a_i as distance between the Z_{i-1} and Z_i axes, measured along the X_{i-1} axis [19]. Figure 1 shows intermediate links in the chain.

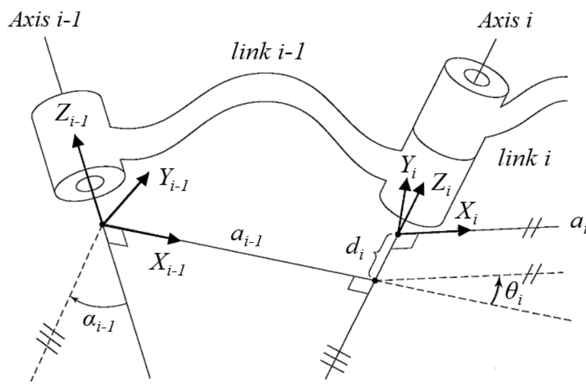

Fig. 1. Link frames

The Z-axis of frame {i}, called Z_i, is coincident with the joint axis i. The origin of frame $\{i\}$ is located where the a_i perpendicular intersects the joint axis i. X_i points along a_i in the direction from joint i to joint i+1. In the case of $a_i = 0$, X_i is normal to the plane of Z_i and Z_{i+1}. As being measured in the right-hand sense about X_i, the α_i is defined and the freedom of choosing the sign of α_i in this case corresponds to two choices for the direction of X_i. Also, Y_i is formed by the right-hand rule to complete the i-th frame [20]. These DH parameters are essential for defining the transformation between adjacent frames in the manipulator. By appropriately choosing and assigning these parameters, the kinematics of the manipulator can be accurately represented, allowing for control and trajectory planning. In DH parameterization, each joint of the robotic manipulator is assigned a sequential number starting from 1 to n, where 1 represents the first joint nearest to the base and n represents the last joint of the manipulator, which is typically located at the end-effector. The robotic manipulator with 6 rotational axes is presented in Figure 2.

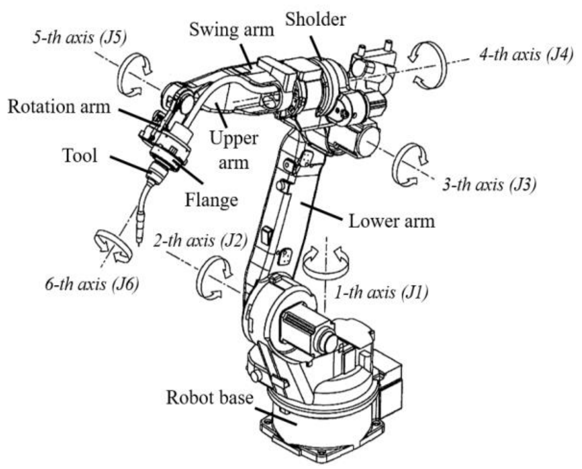

Fig. 2. Industrial robot with 6 rotational axes

2.1. *Forward kinematics*

Forward kinematics as one of the fundamental concepts in robotics deals with the determination of the position and the orientation of the end-effector, the tool or end point of a robotic arm given the joint variables, such as angles of its individual joints and the link length. To achieve forward kinematics, one typically defines a series of homogeneous transformation matrices for each joint of the robot. These matrices describe the transformation from one coordinate system to another as the robot moves through its various joint configurations. By combining these transformations, the position and orientation of the end-effector relative to a fixed reference frame can be calculated.

The position and orientation of the tool frame in relation to the base frame are determined by combining the transformations (both translation and rotation) between each intermediate frame and the base frame using homogeneous transformation matrices. Each intermediate frame provides information about how much the robot has translated and rotated from the base frame. By combining these transformations using homogeneous transformation matrices, we can accurately determine the position and alignment of the tool frame relative to the base frame.

These matrices are typically 4×4 matrices T_i^{i-1} $(i = 1,..6)$:

$$T_i^{i-1} = \\ = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i)\cos(\alpha_i) & \sin(\theta_i)\sin(\alpha_i) & a_i\cos(\theta_i) \\ \sin(\theta_i) & \cos(\theta_i)\cos(\alpha_i) & -\cos(\theta_i)\sin(\alpha_i) & a_i\sin(\theta_i) \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

The process of calculating the position and orientation of the tool frame in relation to the base frame involves multiplying the homogeneous transformation matrices of each intermediate frame with respect to the base frame. This multiplication effectively combines the translation and rotation information from each frame to determine the overall position and orientation of the tool frame.

$$T_6^0 = T_1^0\, T_2^1\, T_3^2\, T_4^3\, T_5^4\, T_6^5 \tag{2}$$

$$T_6^0 = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

The rotation matrix *R* (3 × 3) is formed by the first three columns with notation *r*, and the translation vector *T* (3 × 1) is represented by the elements in the last column, with notation *t*. The submatrix *R* represents the rotation, while *T* is the translation part of the homogeneous transformation matrices.

2.2. *Inverse kinematics*

Finding the position and orientation of the end-effector given the joint angles of the robot, i.e., calculating how the robot's joints move the end-effector in space is a task for forward kinematics. On the other hand, finding the joint angles required to place the end-effector at a specific position and orientation in space is a task related to inverse kinematics. Robots typically operate in joint space, where movements are defined by the angles of the robot's joints. However, tasks are often specified in Cartesian space, where positions and orientations are described in terms of coordinates and orientation matrices. Converting from Cartesian space to joint space involves solving the inverse kinematics problem. This requires finding the joint angles that achieve the desired end-effector position and orientation [21].

The general problem of inverse kinematics can be stated via the desired position and orientation of the end-effector T_d and 4 × 4 homogeneous transformations [22], namely, to find (one or all) solutions of the equation:

$$T_n^0(q_1, \dots q_n) = T_d \tag{4}$$

Among the most challenging issues in robotics is inverse kinematics. The task is to find the values for the joint variables $q_1, \dots q_n$ that satisfied the equation. Because each link in the robotic manipulator has a transformation matrix that describes how it moves relative to the previous link or the robot's base, by taking the inverses of these transformation matrices and premultiplying them [23, 24], it can be combine the effects of each link's movement to find the joint angles required to achieve the desired end-effector pose. Consequently, for:

$$[T_1^0(\theta_1)]^{-1} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = [T_1^0]^{-1}\, T_1^0\, T_2^1\, T_3^2\, T_4^3\, T_5^4\, T_6^5 \tag{5}$$

$$\begin{bmatrix} c_1 & s_1 & 0 & 0 \\ -s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = T_2^1\, T_3^2\, T_4^3\, T_5^4\, T_6^5 \tag{6}$$

it follows:

$$\theta_1 = \text{atan2}\left(t_y, t_x\right) - \text{atan2}(-s_1 t_x + c_1 t_y, \pm\sqrt{t_x^2 + t_y^2 + \left(-s_1 t_x + c_1 t_y\right)^2}) \tag{7}$$

$$(\theta_3 = \text{atan2}(a_3, d_4) - \text{atan2}(K, \pm\sqrt{a_3^2 + d_4^2 - K^2}) \tag{8}$$

where simplify notations are c_i for $\cos(\theta_i)$, and s_i for $\sin(\theta_i)$, and

$$K = \; [t_x^2 + t_y^2 + t_x^2 - a_2^2 \; - a_3^2 \left(-s_1 t_x + c_1 t_y\right)^2 - d_4^2] \,/\, 2a_2 \tag{9}$$

Taking into consideration that:

$$[T_3^0(\theta_2)]^{-1} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = [T_1^0\, T_2^1\, T_3^2]^{-1}\, T_1^0\, T_2^1\, T_3^2\, T_4^3\, T_5^4\, T_6^5 \tag{10}$$

$$\begin{bmatrix} c_1 c_{23} & s_1 c_{23} & -s_{23} & -a_2 c_3 \\ -c_1 s_{23} & -s_1 s_{23} & -c_{23} & a_2 s_3 \\ -s_1 & c_1 & 0 & -d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = T_4^3(\theta_4)\, T_5^4(\theta_5)\, T_6^5(\theta_6) \tag{11}$$

it follows:

$$\theta_2 = \text{atan2}[(-a_3 - a_2 c_3)t_z - \left(c_1 t_x + s_1 t_y\right)(d_4 - a_2 s_3), (a_2 s_3 - d_4)t_z - (a_3 + a_2 c_3)(c_1 t_x + s_1 t_y)] - \theta_3 \tag{12}$$

$$\theta_4 = \text{atan2}(-r_{13} s_1 + r_{23} c_1, -r_{13} c_1 c_{23} - r_{23} s_1 c_{23} + r_{33} s_{23}), \tag{13}$$

where simplify notations are c_{ij} for $\cos(\theta_i + \theta_j)$, and s_{ij} for $\sin(\theta_i + \theta_j)$. If $\theta_5 = 0$, the joint axes 4 and 6 line up and cause the same motion of the last link of the robot, it means that the manipulator is in a singular configuration. Furthermore, considering that:

$$[T_4^0(\theta_4)]^{-1} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = [T_1^0\, T_2^1\, T_3^2\, T_4^3]^{-1}\, T_1^0\, T_2^1\, T_3^2\, T_4^3\, T_5^4\, T_6^5 \tag{14}$$

$$\begin{bmatrix} c_1 c_{23} c_4 + s_1 s_4 & s_1 c_{23} c_4 - c_1 s_4 & -s_{23} c_4 & -a_2 c_3 c_4 + d_3 s_4 - a_3 c_4 \\ -c_1 c_{23} s_4 + s_1 c_4 & -s_1 c_{23} s_4 - c_1 c_4 & s_{23} s_4 & a_2 c_3 s_4 + d_3 c_4 + a_3 s_4 \\ -c_1 s_{23} & -s_1 s_{23} & -c_{23} & a_2 s_3 - d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \; T_5^4(\theta_5)\, T_6^5(\theta_6) \tag{15}$$

it follows:

$$\begin{aligned} \theta_5 = \text{atan2}[- r_{13}(c_1 c_{23} c_4 + s_1 s_4) - r_{23}(s_1 c_{23} c_4 - c_1 s_4) + r_{33}(s_{23} c_4), \\ r_{13}(- c_1 s_{23}) + r_{23}(- s_1 s_{23}) + r_{33}(- c_{23})] \end{aligned} \tag{16}$$

At last, since:

$$[T_5^0]^{-1} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{22} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = [T_1^0\, T_2^1\, T_3^2\, T_4^3]^{-1}\, T_1^0\, T_2^1\, T_3^2\, T_4^3\, T_5^4\, T_6^5 = T_6^5(\theta_6) \tag{17}$$

The following angle is obtained:

$$\begin{aligned} \theta_6 = \text{atan2}[\, -r_{11}(c_1 c_{23} s_4 + s_1 c_4) - r_{21}(s_1 c_{23} s_4 + c_1 c_4) = \\ = +r_{31}(s_{23} s_4), r_{11}[(c_1 c_{23} c_4 + s_1 s_4) c_5 - c_1 s_{23} s_5] + \\ +r_{21}[(s_1 c_{23} c_4 - c_1 s_4) c_5 - s_1 s_{23} s_5] - r_{31}(s_{23} c_4 c_5 + c_{23} s_5)] \end{aligned} \tag{18}$$

In this manner, solving the inverse kinematics of the 6 DOF manipulator needs addressing twelve sets of nonlinear equations. The primary unknown is θ_1 that appears on the left side of the equation (5). Furthermore, the twelve nonlinear matrix elements on the right side of the equation can be either zero, constant, or functions of θ_2 through θ_6. Therefore, by equating the elements on both sides of the equation, the joint variable θ_1 is solved as functions of $r_{11}, r_{12}, \ldots, r_{33}, t_x, t_y, t_z$, and fixed link parameters. Once θ_1 is determined, subsequently the remaining joint variables can be solved using this procedure.

3. TRAJECTORY PLANNING

3.1. *Modeling and simulation*

Modeling and simulation play crucial roles in industrial robot path planning by providing a structured approach to designing and optimizing motion trajectories in complex environments. Through describing the physical structure of the robot and developing mathematical equations that describe the relationship between the joint angles and the position and orientation of the end-effector in space, these models provide a simplified yet accurate description of the robot's capabilities, allowing to understand how it will move and interact with its environment. The process begins with importing a CAD model of the robot into the software environment. This model includes the geometrical and mechanical information about the robot, such as its links, joints, and end-effector. It is followed by configuring the virtual environment within the software by setting up the workspace, defining any obstacles or constraints, and specifying the task requirements. Establishing the kinematic model of the robot in this kind of environment includes defining the joint types, ranges of motion, and kinematic constraints based on the physical characteristics of a real robot. When these steps are complete, programing the desired tasks with motions that the robot needs to perform can be done. This could involve defining trajectories, and sequences of movements in the direction of accomplishing specific objectives. The key features of the simulation approach are its ability to demonstrate the robot's movements within the virtual environment and to visualize how the robot will execute the programmed tasks, identify potential issues, and refine the robot's movements as needed. Analyzing the simulation can result in verification of the programmed tasks, meeting the desired criteria and performance objectives, optimizing the efficiency, accuracy, and safety.

3.2. *Robotic manipulator characteristics*

Robotic systems possess diverse characteristics, encompassing factors such as robot size, its load capacity and range of motion, which are governed by joint limits that define the allowable range of motion for each articulated joint. As discussed previously, their kinematics are further described by DH parameters, crucial for precise trajectory planning and control. Table 1 represents the characteristics of the 6 DOF manipulator used for this study, related to parameters α, a, d, and the corresponding six joint limits.

T a b l e 1

6 DOF manipulator characteristics

i	α_i d (degree)	a_i (mm)	d_i (mm)	Joint limits (degree)
1	–90	160	430	–60 / 60
2	180	580	0	0 / 90
3	90	125	0	–80 / 80
4	–90	0	239	–180 / 180
5	90	0	0	–80 / 80
6	0	0	411	–270 / 270

3.3. *Weld seam trajectories*

Single-pass welding involves making a single weld pass to fill the joint, while multi-pass welding involves making multiple passes to fill larger or deeper joints. The choice between single and multi-pass welding depends on factors such as the thickness of the material and the desired strength of the weld. In this study we consider the single pass welding in 3 different cases, as shown in Figure 3. These cases involve welding paths that have different geometric shapes, with a goal to join the materials together and form a closed shape. The welding torch moves along the edges of a triangle, rectangle and curved edge of a semicircle, i.e., creating welding seams along straight and curved paths. Case 1 has one path length of 243 mm and two of 172 mm. Case 2 has four straight lines, each with a length of 120 mm, and Case 3 has one straight line with a length of 243 mm and a curved path of 382 mm. The starting and ending positions of the welding torch are 10 mm above the *xy*-plane, and each case has its own starting and ending position. The positions of the robot base and the work bench do not change during the execution of these three cases.

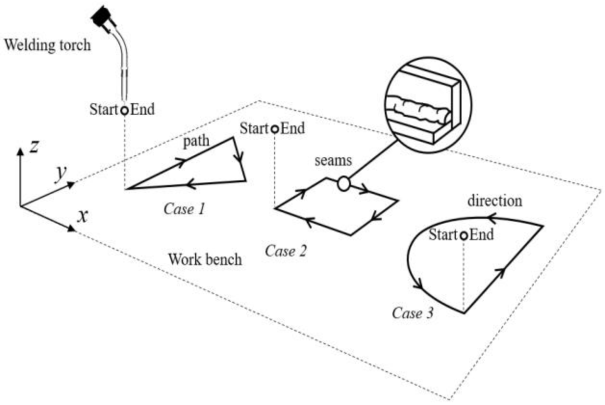

Fig. 3. Welding seams trajectories

4. RESULTS AND ANALYSIS

The results obtained from these three setups, i.e. for the different welding paths and robot movements, are presented in Figures 4, 5 and 6. It is notable the changes in the angles of each of the 6 joints during the realization of the sated goals, which is to pass the entire path to form a closed trajectory, i.e., welding seams. The change in angles is obvious for each of the 6 joints, but it is smooth and without sudden variations, and it is within the set joint limit values. The biggest change in the angles is observed for case 3, where in addition to moving in a straight line, moving along a path in the form of a semicircle is also needed. When movement along a curve is performed, it is observed that there are greater changes in the angles of joints 4 and 6 compared to other joints. This is due to the fact that these are robot joints associated with rotating the welding torch attached to the robot, while keeping it constantly in a vertical direction for the purpose of effective welding. The vertical dashed lines separate the time when the robot performs welding and moving along the given trajectory. The time intervals on the left and far right refer to the robot approaching and retracting, moving towards and away from the workpiece, respectively. Therefore, the change of the angles when the robot begins to move from the marked start point to the point where the welding is, also when it has reached the last point of the path and retracting from the work piece to the point marked as the end, is presented. The angles of the robot's joints evolve during the entire process, from initial movement to welding, welding itself and to retraction, reflecting the dynamic nature of robotic motion in industrial applications.

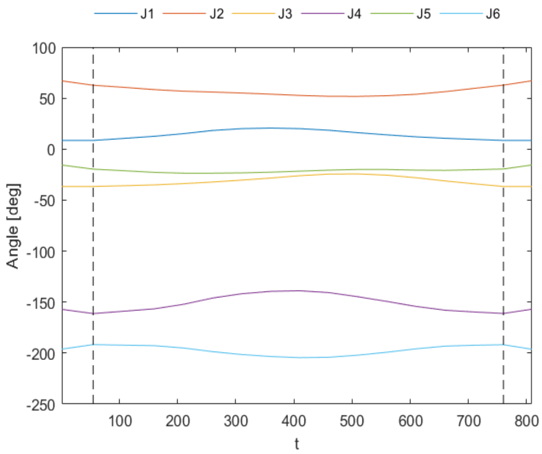

Fig. 4. Joint angles case 1

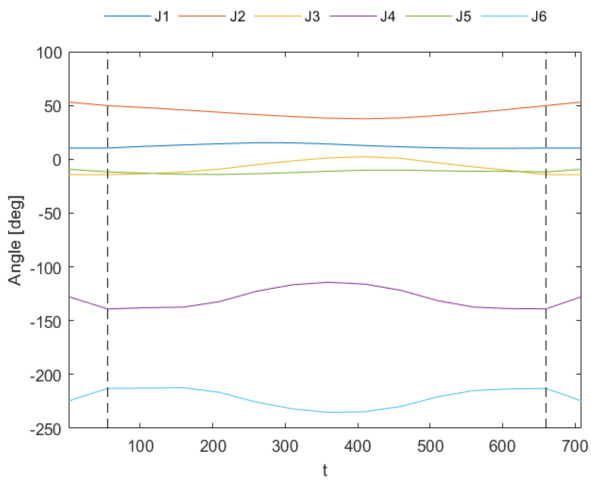

Fig. 5. Joint angles case 2

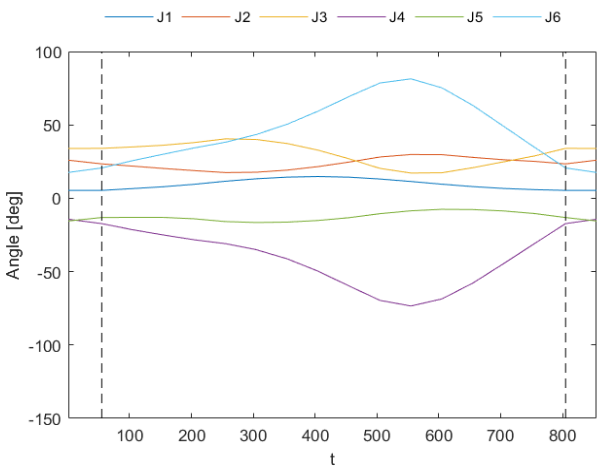

Fig. 6. Joint angles case 3

5. CONCLUSIONS

Comprehensive understanding of the kinematics of an industrial manipulator is important for accurate controlling its movements, programing it to perform various tasks, to optimize its performance, and for ensuring safe operation in industrial environments. Each joint of the manipulator can be rotated to different angles, allowing the end-effector to reach various positions and orientations in the workspace. Forward kinematics involves determining the position and orientation of the end-effector given the joint angles, using mathematical models, often based on transformation matrices or DH parameters. On the other hand, inverse kinematics deals with determining the joint angles required to achieve a desired position and orientation of the end-effector. Solving inverse kinematics problems can be more complex and time-consuming considering manipulators with more degrees of freedom. As the number of degrees of freedom increases, the number of equations needed to solve the inverse kinematics problem also increases. This leads to more complex mathematical relationships between the joint angles or positions and the desired end-effector pose.

In our study we considered 3 cases related to 3 different welding operations where materials are joined together along different specific paths to create a unified, closed shape. This could be a necessary step in various manufacturing processes, such as fabricating metal components for machinery, or building structural frameworks. When the 6 DOF manipulator is used to move the welding torch along a curve path, is observed that there are greater changes in the value of the angles of joints 4 and 6. More significant changes in their angles compared to other joints during the movement along the curve occur because they are joints associated with the rotation of the welding torch attached to the robot. For the purpose of effective welding, the aim of keeping the tool oriented vertically as much as possible during the welding process was achieved. This vertical orientation is crucial for ensuring proper weld penetration and quality. The adoption of robotic arc welding in the manufacturing industry offers numerous benefits, including cost savings, improved productivity, enhanced weld quality, and shorter lead times, making it an attractive investment for many companies. Besides increasing the efficiency, repeatability, and precision, the manufacturers can consistently produce high-quality welds across a wide range of products and materials.

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