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Kuka KR5 arc Welding Industrial Manipulator Workspace Modelling Based on Kinematics Study

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Abstract In this study Kuka KR5 arc industrial manipulator was study using Denavit Hartenberg (DH) parameters representation and homogeneous matrix in order to obtain the transformation matrix for six degree of freedom articulated robot using MATLAB. The workspace of Kuka robot can be deduce by computing the transformation matrix with each motor workspace range. finally, the study in this paper allows us to control the manipulator in order to achieve any wanted orientation and position.

1. Introduction

In the University of the Debrecen, Department of mechatronics a Cyber Physical laboratory and intelligent robot systems has been established that is to follow up the latest developments in technical field specially in the industrial one. this laboratory contains many industrial and engineering tools and the one of the most important equipment in this laboratory is Kuka KR5 arc industrial welding manipulator controlling this industrial manipulator requires entry into relevant details of industry 4.0 concept also Many industries these days are shifting their focus to adding robots to their assembly line in order to speed up the production process.

It should also be noted that the most challenging issue in robotics systems is the Kinematics study which is considered to be the core of any study in order to start tasks such like control, follow trajectory, handling, painting etc.

Undoubtedly that the kinematics study allows us to create the kinematics equation which represent the robot, these nonlinear equations are used to form the links and joints parameters to the configuration of the industrial manipulator system [1], [2], [3].

2. Forward Kinematics

We can define forward kinematics as a problem which takes the initial position of each of the robot's joints and then gives us the final position of the end effect of the robot, so it's basically considered a relationship between robot's joints and position and orientation of the end effector or the two which located on the end effector.

2.1. Joints and Links

As known the forward kinematics problem is the uses of all given values for the manipulators joints in order to determine the orientation and position of the end effector. The angles between the links called as joint variables in two cases sliding or prismatic [4]. We can specify the joint parameters and computes the chains configuration using the forward kinematics. In case of serial manipulators, we can achieve



that by direct substitution of the joint parameters into direct kinematics equation for serial chain. There is a wide variety kinds of manipulators mechanisms that we can reach by categorizing their joint type and arrangement of joints if we ignore the shape and the size of the link and focus on categorization [5]. There are three types of joints revolute, prismatic, and spherical each one describing the allowed transformations between 2 links to the one it is attached to.

Prismatic: translation among a common axis.

Revolute: rotation about a common axis.

Spherical: rotation about a point.

An industrial manipulator with n joint has n+1 link the two links connected by 1 joint. so we basically have 1 to n joints and 0 to n links, and and we should start numbering from the base. based on this we connect link i-1 to link i by joint i. Therefore, when the joint is actuated the first link does not move.

2.2. Denavit Hartenberg

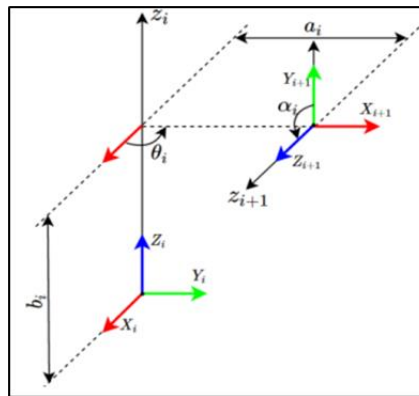


Figure 1. DH Frame Assignment [6].

We can get T_i depend on four primary transformation:

$$T_i = Rot(z, \theta_i) Trans(z, d_i) Trans(x, a_i) Rot(x, \alpha_i) \tag{1}$$

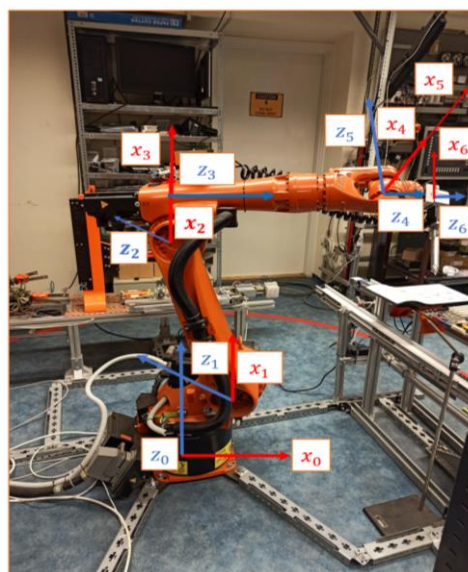


Figure 2. Robotic Arm Frame Assignment [photographed by authors].

T_i Final matrix will be the result of multiple of those matrixes [7].

$$T_i = \begin{bmatrix} c_{\theta_i} & -s_{\theta_i} & 0 & 0 \\ s_{\theta_i} & c_{\theta_i} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{\alpha_i} & -s_{\alpha_i} & 0 \\ 0 & s_{\alpha_i} & c_{\alpha_i} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_i = \begin{bmatrix} c_{\theta_i} & -s_{\theta_i}c_{\alpha_i} & s_{\theta_i}s_{\alpha_i} & a_i c_{\theta_i} \\ s_{\theta_i} & c_{\theta_i}c_{\alpha_i} & -c_{\theta_i}s_{\alpha_i} & a_i s_{\theta_i} \\ 0 & s_{\alpha_i} & c_{\alpha_i} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

- $\alpha_i, \theta_i, d_i, a_i$
- a_i : The distance between z_i to z_{i+1} along the x_i axis.
- α_i : The angle between z_i to z_{i+1} about x_i axis.
- d_i : The distance between x_i to x_{i+1} along the z_i axis.
- θ_i : The angle between x_i to x_{i+1} about z_i axis.

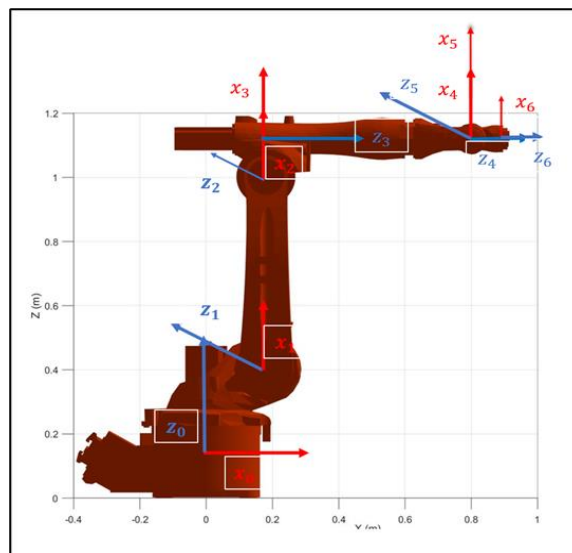


Figure 3. Robotic Arm Frame Assignment

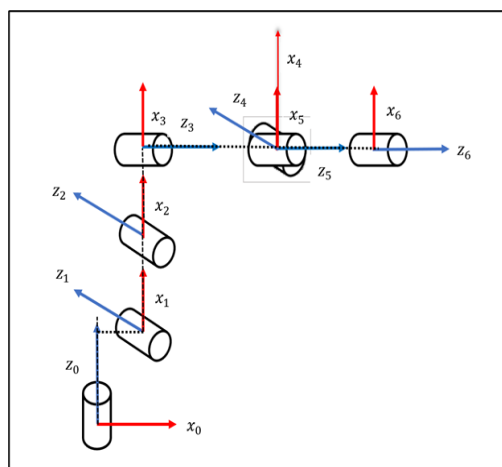


Figure 4. Robotic Arm Frame Assignment

2.3. Robotic Arm DH Parameters [8].

Table 1. Denavit Hartenberg Parameters.

i	θ_{i-1}	d_{i-1}	a_i	α_i
1	q_1	d_1	a_1	$-\frac{\pi}{2}$
2	$q_2 - \frac{\pi}{2}$	0	a_2	0
3	q_3	0	a_3	$\frac{\pi}{2}$
4	q_4	d_4	0	$-\frac{\pi}{2}$
5	q_5	0	0	$\frac{\pi}{2}$
6	q_6	d_6	0	π

$$T_1^0 = \begin{bmatrix} c_{q_1} & 0 & -s_{q_1} & c_{q_1} a_1 \\ s_{q_1} & 0 & -c_{q_1} & s_{q_1} a_1 \\ 0 & -1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$T_2^1 = \begin{bmatrix} c_{q_2 - \frac{\pi}{2}} & -s_{q_2 - \frac{\pi}{2}} & 0 & c_{q_2 - \frac{\pi}{2}} a_2 \\ s_{q_2 - \frac{\pi}{2}} & c_{q_2 - \frac{\pi}{2}} & 0 & s_{q_2 - \frac{\pi}{2}} a_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$T_3^2 = \begin{bmatrix} c_{q_3} & 0 & s_{q_3} & c_{q_3} a_3 \\ s_{q_3} & 0 & -c_{q_3} & s_{q_3} a_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

$$T_4^3 = \begin{bmatrix} c_{q_4} & 0 & -s_{q_4} & 0 \\ s_{q_4} & 0 & c_{q_4} & 0 \\ 0 & -1 & 0 & d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

$$T_5^4 = \begin{bmatrix} c_{q_5} & 0 & -s_{q_5} & 0 \\ s_{q_5} & 0 & c_{q_5} & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

$$T_6^5 = \begin{bmatrix} c_{q_6} & s_{q_6} & 0 & 0 \\ s_{q_6} & -c_{q_6} & 0 & 0 \\ 0 & 0 & -1 & d_6 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

$$T_7^0 = T_1^0 \cdot T_2^1 \cdot T_3^2 \cdot T_4^3 \cdot T_5^4 \cdot T_6^5 \cdot T_7^6 = \begin{bmatrix} \mu_x & O_x & \alpha_x & p_x \\ \mu_y & O_y & \alpha_y & p_y \\ \mu_z & O_z & \alpha_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9)$$

3. Workspace analysing and modelling.

The industrial manipulators workspace can be determined by set all positions that we can reach using the manipulator depending on dimension of the robot arm taking into consideration the type of movement which based on type of joint. In any robot design the most important consideration is determined any possible points that can be reach. That is also important for workers to set the safety working area.

3.1. Kuka KR5 arc characteristics.

Kuka KR5 arc industrial manipulator is designed based on 6 axes its components are base frame, electrical installations, link arm, arm, in-line wrist and rotation column. The base of Kuka KR5arc bolted to the mounting base also there is a tube contain the electrical installations with a cable junction box. on the rotating base there are the motors for axis 1 and axis 2.

The rotational motion of the manipulator around axis 1 cause the column rotation. And with a gear unit screwed to the base the link arm mounted on the column. And between the rotating column and the arm there is the link arm. And the arm located between the link arm and the inline wrist. on the arm we can find the motor of the main axis (A3). and you Motors of the wrist axes (A4, A5, A6). On the inline wrist there are Motors for axis 4 axis 5 and axis 6. The end effector is attached on the In-line Wrist's mounting flange. Axes 4, 5, and 6 are located at the in-line wrist [10].

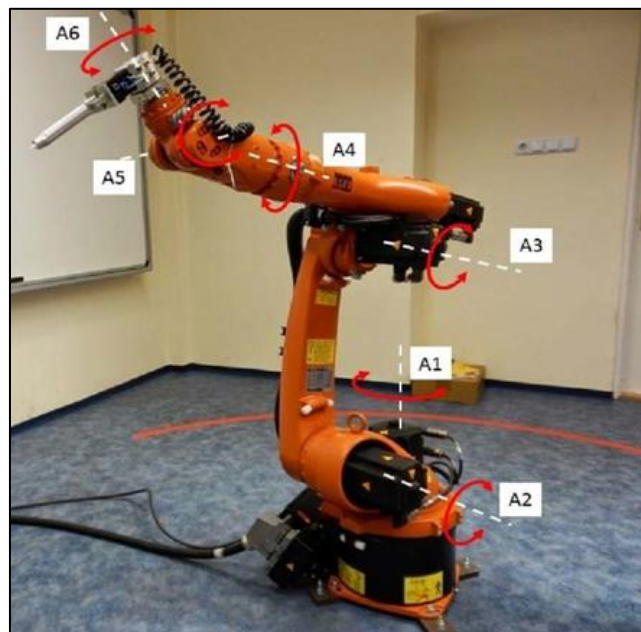


Figure 5. The KUKA KR5 robot mechanism [10].

The following table clarifies the range of each axis depending on manufacturing configurations.

Table 2. Kuka Kr5 arc Axes range

Axis	Range (software)
Axis 1	$\pm 155^\circ$
Axis 2	-180° to 65°
Axis 3	-15° to 158°
Axis 4	$\pm 350^\circ$
Axis 5	$\pm 130^\circ$
Axis 5	$\pm 350^\circ$

We can find the diagram in the following figure (fig 6) also this diagram comes with any industrial manipulator’s data sheet and from this figure side view of the industrial manipulator we can see the area marked in grey is the reachable area of the industrial manipulator and also we can see the area around the industrial manipulator which is contains unreachable points. and this due mechanical limits on the range of motion of particular joints or because of industrial manipulator control software (to avoid collision between prevent parts of the manipulator with other parts of the manipulator or it's space).

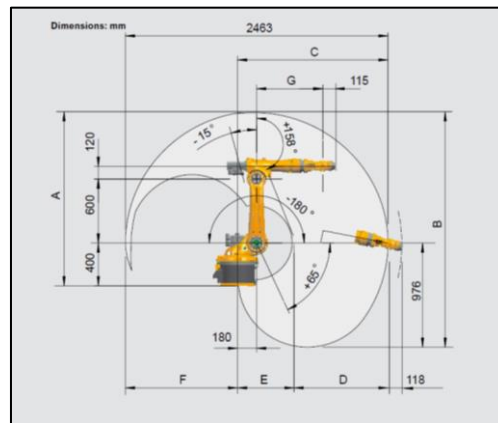


Figure 6. side elevation view of the robot.

3. 2 *Workspace analysing and modelling.*

We use the following values for modelling the workspace depends on the dimensions previous figure.

Table 3. Kuka Kr5 arc dimensions

	<i>d</i>		<i>a</i>
<i>d</i> ₁	0.4	<i>a</i> ₁	0.186
<i>d</i> ₂	0	<i>a</i> ₂	0.6
<i>d</i> ₃	0	<i>a</i> ₃	0.120
<i>d</i> ₄	0.620	<i>a</i> ₄	0
<i>d</i> ₅	0	<i>a</i> ₅	0
<i>d</i> ₆	0.115	<i>a</i> ₆	0

Finally, depending on previous values axes range, homogeneous transformation matrix and dimensions of Kuka Kr5 arc robot a modelling for manipulator had done using MatLab as seen in the following figure 7, and 8 which clarify the volume coordinate of all points that the end effector can reach.

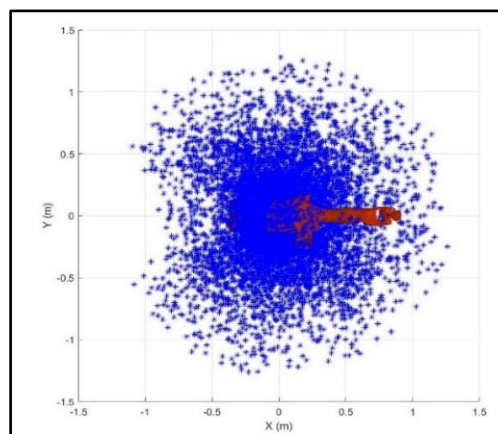


Figure 7. The simulation result of workspace’s top view

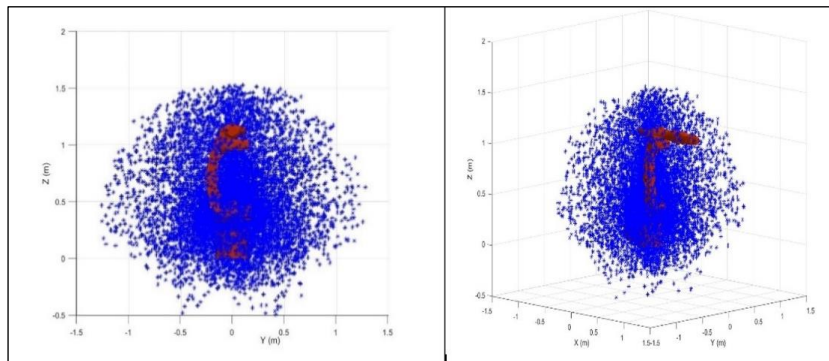


Figure 8. The simulation results of workspaces' side views (x,y) and (x,y,z).

Conclusion

The forward Kinematics model has been validated using MATLAB. The result from the forward kinematics model match with the result from the homogenous transformation matrix script result. The positions obtained from the model have been compared with a practical test of the industrial manipulator to detect the end-effector position and orientation.

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