The Indonesian Journal of Computer Science
www.ijcs.net
Volume 14, Issue 1, February 2025
https://doi.org/10.33022/ijcs.v14i1.4668

Kinematics Analysis of Articulated Robot

Mon Mon Thae[1], Su Yadanar[2], Aung Myat San[3]
monmonoo12@gmail.com[1], suyadanarmtu@gmail.com[2], agmyatsanmc@gmail.com[3]
[1,2,3]Mandalay Technological University, Mandalay , Myanmar

Article Information

Received : 28 Jan 2025
Revised : 3 Feb 2025
Accepted : 10 Feb 2025

Keywords

Kinematics analysis, GUI, RoboAnalyzer, DH & geometric method, accuracy and repeatability

Abstract

Robot technology is applied to support the farmers in various stages, from seeding and farm maintenance to harvesting and packaging agricultural products. The purpose of this paper is to analyze the kinematic modeling of an articulated robot that can be used for sorting mangoes based on their weight. Two methods are used to analyze the robot arm: forward and inverse kinematics. The DH method is employed to analyze both forward and inverse kinematics in this paper. Transformation matrices for each joint were obtained using the DH method to derive the forward kinematics results. For inverse kinematics, a geometric approach is presented to determine the joint angles. A graphical user interface (GUI) is used to control the articulated robot. The results are validated by comparing the calculated outcomes with the Robo-Analyzer results. In this analysis, the articulated robot's accuracy was investigated by repeating the same predetermined movement and measuring the error. After implementing the articulated robot, an experimental results were obtained to measure the accuracy and repeatability of its performance. At the end of the experimental results, the highest positioning error of the articulated robot is 1.7205 mm, and the lowest positioning error is 0.2 mm, depending on the five predetermined positions.

A. Introduction

Myanmar is a developing country based on an agriculture. The agriculture is facing technological challenges such as planting, production and so on. Packaging system is very importance for production in every country. Weight based sorting system is essential for packaging in production process. Nowaday, most young people are interested in agriculture and trading the main business of Myanmar country. So, it is collaborating in agricultural production with the aid of advance technology. Encouraging the interest of youths in agriculture through technology holds the key to a prosperous future.

Robotic technology is developed the farmers from seeding, farm main-tenances, harvesting and to packing the agriculture product. For qualities exports, the products must be packed accurately based on weight. Sorting system is required a lot of labor, time and accurate. Therefore, many errors can occur in sorting system with repeatability process such as incorrect weight because by using more worker, by working for a long time. Robotic technologies should be used instead of human labors. If robotic technology is applied instead of labors in sorting system, it can solve reducing labor cost, processing time and protect incorrect weight. Today, Myanmar mangoes are the main export product in Myanmar country. In the mango export industry, the weight of the mangoes must be selected and packed correctly according to their weight. Therefore, a robot arm system was built for the sorting system to be able to accurately select the mango based on weight.

For a robot to perform a specific task, the position and orientation of the end-effector, i.e. its pose or configuration, relative to the base should be established first. This is essential for solving positioning problem. There are two types of problems exist, namely, forward and inverse kinematics analysis of articulated robot. In the forward kinematics, the joint positions are given, and the problem is to find the end-effector configuration. In inverse kinematics, the reverse problem is solved, i.e. the configuration of the end-effector is given, the problem is to find the joint angles [1]. The main contribution of this research is kinematics analysis for four links articulated robot that looks like a human arm and maximum payload is 1 kg for sorting system. The system block diagram of four links articulated robot is shown in Figure1.

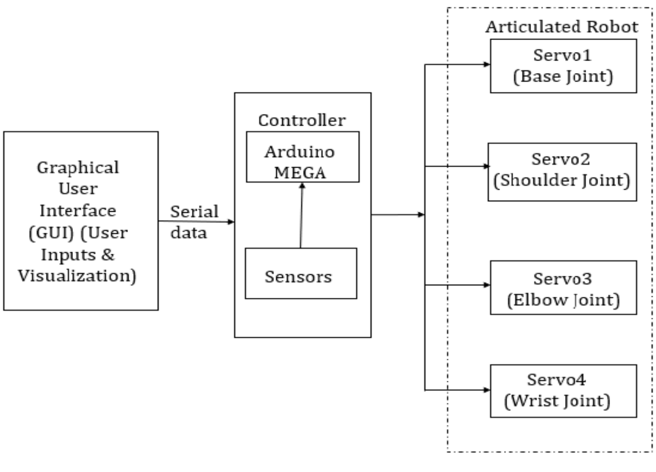


Figure 1. System Block Diagram of Four Links Articulated Robot

B. Kinematics Modeling

The kinematics method is the motion geometry of the robot manipulator from the reference position to the desire position with no regard to forces or other factors that influence robot motion. There is two main class in kinematics: forward and inverse kinematics. Forward kinematics is used for transferring the joint variable to get the end-effector position. On the other hand, inverse kinematics will be applied to find a joint variable from the end-effector position [1]. The four links articulated robot for sorting system is shown in Figure2.

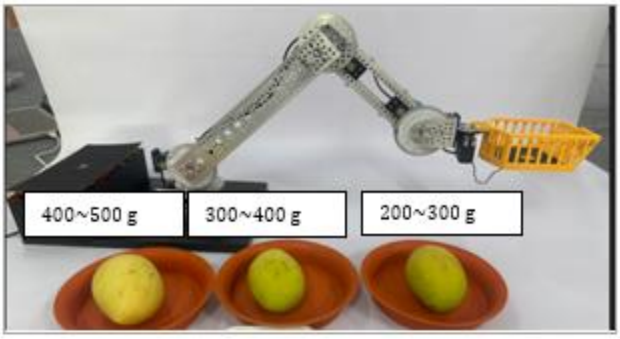


Figure2. Four Links Articulated Robot for Sorting System

Base frame is connected with second link with revolute joint. It has length of 0.105meter and a weight of 0.305kg respectively. Shoulder frame is connected with third link with revolute joint. It has length of 0.3meter and a weight of 0.68kg respectively. Elbow frame is connected with fourth link with revolute joint. It has length of 0.2meter and a weight of 0.35kg respectively. Wrist frame is connected with gripper. It has length of 0.14meter and a weight of 0.28kg respectively. All frame is made up of aluminum. Gripper design is a unique design of this articulated robot to hold the mangoes for sorting system. This gripper design can open 90 degrees (1.571meter) in open condition. This gripper weight is 0.175kg and this is about the 1 kg maximum payload. Four servo motors are used to control the articulated robot such as base, shoulder, elbow and wrist. One servo motor is used to open and close the gripper. And then finally, effective linkage lengths and mass for joints are shown in Table 1.

Table 1. Measurement of Linkage Lengths and Mass for Joints

Description	Measurement Value
Base Length	0.105m
Base Mass	0.305kg
Shoulder Length	0.3m
Shoulder Mass	0.68kg
Elbow Length	0.2m
Elbow Mass	0.35kg
Wrist Length	0.14m
Wrist Mass	0.28kg
Gripper Mass	0.175kg
Maximum Payload (Fruit Weight)	1kg

Mass of shoulder, elbow and wrist drive	3*0.226kg=0.678kg
Total weight	3.408kg

Forward kinematic model determines the position and orientation of the tip of the gripper, with respect to the base of the robotic arm, as a function of joint angles. Denavit and Hartenberg (DH) parameters are used to establish the transformation matrices between joint coordinate frames [9]. DH table for four links articulated robot is expressed in Table 2.

Table 2. DH Parameters of Four Links Articulated Robot

Frame	Joint Offset	Joint Angle	Link Length	Twist Angle	Angle Range
Base	L_1	θ_1	0	90°	$-90^\circ$to $+90^\circ$
Shoulder	0	θ_2	L_2	0	-10° to $+170^\circ$
Elbow	0	θ_3	L_3	0	-80° to $+80^\circ$
Wrist	0	θ_4	L_4	0	-90° to $+80^\circ$

The robotic arm that has been designed for this paper is the revolute type that closely resembles the human arm. There are altogether four degrees of freedom. The base of the robotic arm can move 90 degrees left and 90 degrees right. Shoulder that mounted on the base can move the arm through 0 degree to 170 degrees. Attached to the shoulder piece is an elbow that can also move through -80 degrees to +80 degree. The wrist is attached to the elbow that can move 90 degrees upward and 90 degrees downward. The gripper is attached to the wrist to capture the mango and place the respective box base on the mango weight. The orientation angle of four links articulated robot is shown in Figure3.

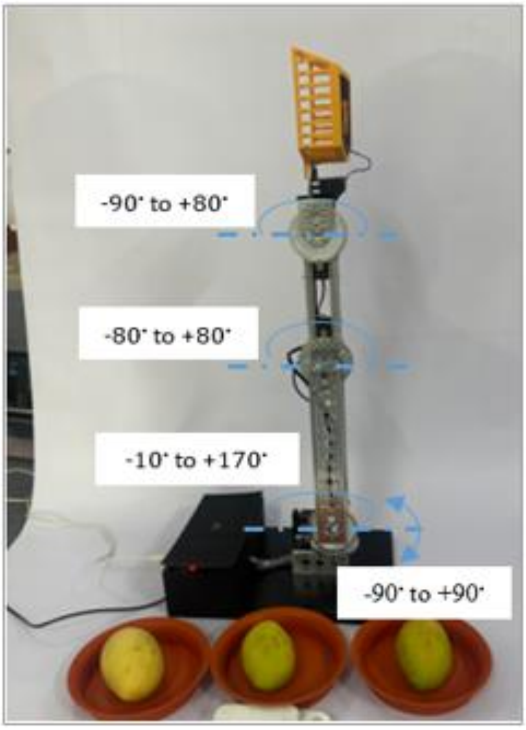


Figure3. Orientation Angle of Four Links Articulated Robot

Once the DH table is ready, the transformation matrices of two successive coordinate frames can be found. Generally, the transformation matrix from frame {i} to frame {i-1} for standard DH method is given by the following equation:

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

The individual transformation matrices for i=1,2,3 and 4 can be determined by using the DH table. For simplicity, the short notations 'c_i' and 's_i' will be used for $\cos\theta_i$ and $\sin\theta_i$ respectively. The overall transformation arm matrix from gripper frame to base frame can be found by multiplying the individual transformation matrices as follows:

$$T_4^0 = \begin{bmatrix} c_1c_{234} & -c_1s_{234} & s_1 & c_1(L_2c_2 + L_3c_{23} + L_4c_{234}) \\ s_1c_{234} & -s_1s_{234} & -c_1 & s_1(L_2c_2 + L_3c_{23} + L_4c_{234}) \\ s_{234} & c_{234} & 0 & L_1 + L_2s_2 + L_3s_{23} + L_4s_{234} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

where:

$c_{23} = \cos(\theta_2 + \theta_3), s_{23} = \sin(\theta_2 + \theta_3)$

$c_{234} = \cos(\theta_2 + \theta_3 + \theta_4), s_{234} = \sin(\theta_2 + \theta_3 + \theta_4)$

But the final arm matrix of equation (2) can be expressed as:

$$T_{gripper}^{base} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} R(\theta) & P(\theta) \\ 0 & 1 \end{bmatrix}$$

where, R (θ) is the rotation matrix which describes the orientation of the gripper and P (θ) is the position vector which determines the Cartesian coordinates of the tip of the gripper. Finally, forward kinematic model of the four degrees of freedom articulated robot can be summarized as follows:
The position vector which determines the Cartesian coordinates of gripper with respect to the base frame is:

$$P(\theta) = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} \cos\theta_1 \left[L_2.\cos\theta_2 + L_3.\cos(\theta_2 + \theta_3) + L_4.\cos(\theta_2 + \theta_3 + \theta_4) \right] \\ \sin\theta_1 \left[L_2.\cos\theta_2 + L_3.\cos(\theta_2 + \theta_3) + L_4.\cos(\theta_2 + \theta_3 + \theta_4) \right] \\ L_1 + L_2.\sin\theta_2 + L_3.\cos(\theta_2 + \theta_3) + L_4.\sin(\theta_2 + \theta_3 + \theta_4) \end{bmatrix}$$

The rotation matrix which describes the orientation of gripper is:

$$R(\theta) = \begin{bmatrix} \cos\theta_1.\cos(\theta_2 + \theta_3 + \theta_4) & -\cos\theta_1.\sin(\theta_2 + \theta_3 + \theta_4) & \sin\theta_1 \\ \sin\theta_1.\cos(\theta_2 + \theta_3 + \theta_4) & -\sin\theta_1.\sin(\theta_2 + \theta_3 + \theta_4) & -\cos\theta_1 \\ \sin(\theta_2 + \theta_3 + \theta_4) & \cos(\theta_2 + \theta_3 + \theta_4) & 0 \end{bmatrix}$$

The inverse kinematics problem consists of the determination of the joint variables corresponding to a given end-effector's orientation and position. One approach to the inverse kinematics problem is to find a closed-form solution using algebra or geometry. Another approach is to find a numerical solution by some successive-approximation algorithm. Although the former approach is generally more desirable in applying the solution to real-time control of robots, it is not always possible to obtain the closed-form solutions for the manipulators with arbitrary architectures. The geometry method is used to obtain the inverse kinematics of four links articulated robot in this paper.

The solution is divided into two processes. The first process is the calculation to get the angle for joint1. The movement of the robot arm on the x-y surface depends only on the angle of joint1. Regarding the x-y surface projection of the robot arm movement, the angle for joint1, θ_1 can be calculated as follows:

$$\theta_1 = \tan^{-1}\left(\frac{p_y}{p_x}\right) \tag{3}$$

Since θ_1 is the rotation angle for the robot arm base, the angle range is between -90 degree and +90 degree. The quadrant for θ_1 is identified to determine the sign for each trigonometric ratio in a given quadrant. In this manipulator, base servo moves only 1^{st} and 4^{th} quadrants. +X axis set as 90 degree and convert the calculated values to deal with (0 to 180 degree) range. Table 3 shows the signs for the trigonometric ratio in each quadrant.

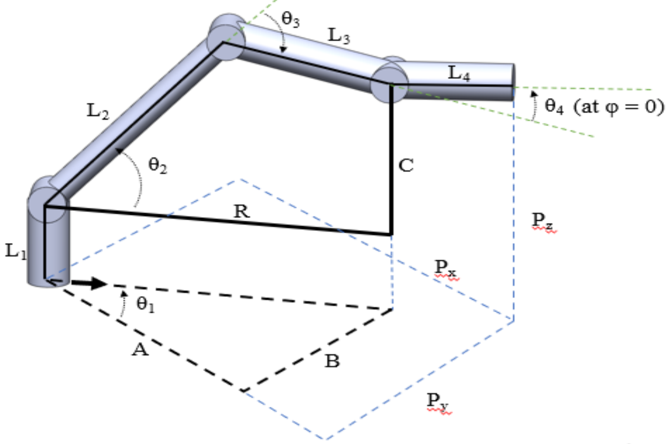
Table 3. Signs For The Trigonometric Ratio In Each Quadrant

P_x	P_y	**Quadrant**	θ_1
+	+	1	θ_1
-	+	2	$\theta_1 + 180$
-	-	3	$\theta_1 - 180$
+	-	4	θ_1

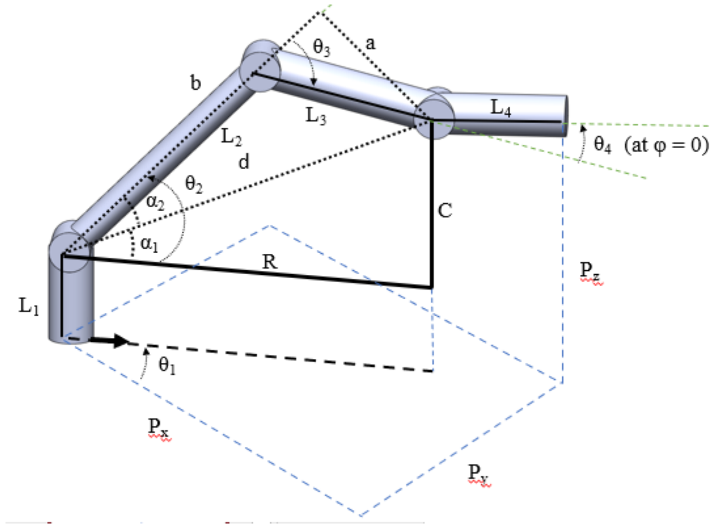
The second process involves calculating the angle for joints 2, 3 and 4 (θ_2, θ_3 and θ_4). For obtaining the solution for θ_2, θ_3 and θ_4, the 3-dimensional (3D) space which is consisting of the x, y and z coordinate axes. In a four links articulated robot, the orientation of the end-effector is the summation of θ_2, θ_3 and θ_4 because these joint angles collectively determine the rotation of the subsequent links. Each joint contributes to the overall orientation by rotating the links that follow it in the kinematic chain. The final orientation of the end-effector is the result of these combined rotations, as each angle influences the cumulative rotation around the relevant axes. Therefore, the orientation (φ) of the end-effector is calculated as follows:

$$\varphi = \theta_2 + \theta_3 + \theta_4 \tag{4}$$

Where, end-effector condition is always set horizontally along x axis. Thus, θ_4 calculate based on θ_2 and θ_3 while φ is zero. Elbow joint θ_3 is calculated by two condition such as elbow up and down. And then, shoulder joint θ_2 is calculated. Elbow up and down condition are shown in Figure4 and 5.



(a)



(b)

Figure 4. (a,b) Elbow Up Condition for Four Links Articulated Robot

According to the Figure4 (a) and (b):

$$A = P_x - (L_4 c\theta_1 c\varphi)$$

$$B = P_y - (L_4 s\theta_1 c\varphi)$$

$$C = P_z - L_1$$

$$R^2 = A^2 + B^2$$

$$K^2 = R^2 + C^2$$

By using law of cosine;

$$K^2 = L_2^2 + L_3^2 - 2L_2L_3\cos(180 - \theta_3)$$

$$\theta_3 = +\cos^{-1}\left(\frac{A^2 + B^2 + C^2 - L_2^2 - L_3^2}{2L_2L_3}\right) \tag{5}$$

$$a = L_3 s\theta_3$$

$$b = L_2 + L_3 c\theta_3$$

$$d^2 = a^2 + b^2 = R^2 + C^2$$

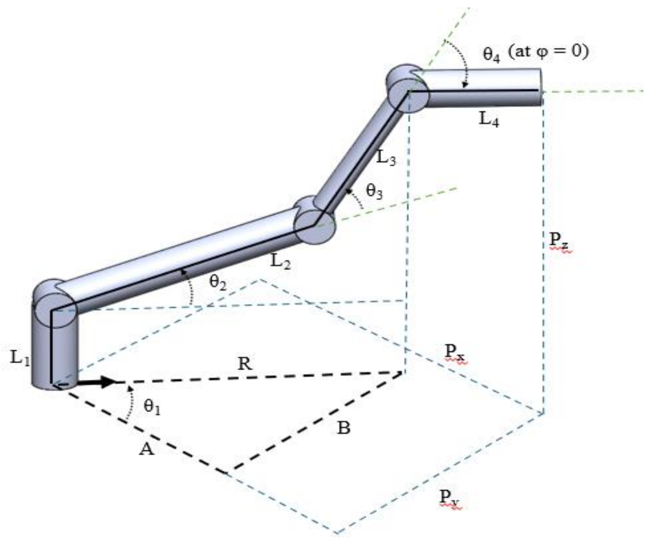
$$R = \sqrt{a^2 + b^2 - C^2}$$

$$\alpha_1 = \tan^{-1}\left(\frac{C}{R}\right)$$

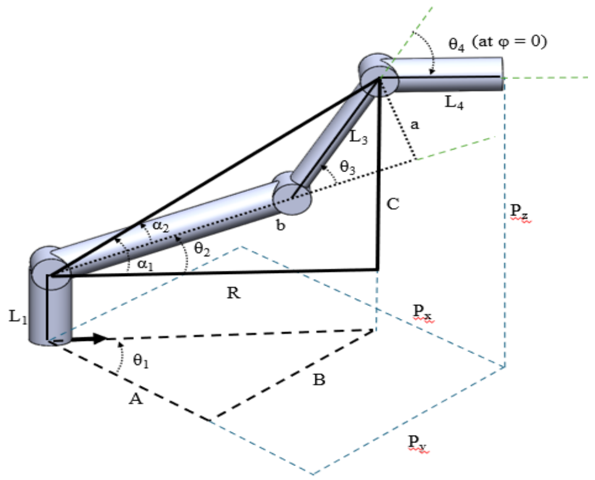
$$\alpha_2 = \tan^{-1}\left(\frac{a}{b}\right)$$

$$\theta_2 = \alpha_1 + \alpha_2 \tag{6}$$

$$\theta_4 = 0 - \theta_2 - \theta_3 \tag{7}$$



(a)



(b)

Figure 5. (a,b) Elbow Down Condition for Four Links Articulated Robot

According to the Figure.5. (a) and (b);

$$\theta_2 = \alpha_1 - \alpha_2 \tag{8}$$

$$\theta_3 = -\cos^{-1}\left(\frac{A^2 + B^2 + C^2 - L_2^2 - L_3^2}{2L_2L_3}\right) \tag{9}$$

$$\theta_4 = 0 - \theta_2 - \theta_3 \tag{10}$$

C. Kinematics Analysis

The flowchart of forward kinematics model is shown in Figure6. D-H parameters are included in the developed algorithm to obtain the end-effector coordinate of the robot arm, and the transformation matrix is calculated to obtain the equations for the end-effector's coordinates. Next, random values of the four joint angles are used to analyze the forward kinematics model. Finally, the end-effector's coordinates are calculated by intersecting the random values for the four joint angles into the transformation matrix equations. Table 4 shows the results of the forward kinematics modeling developed.

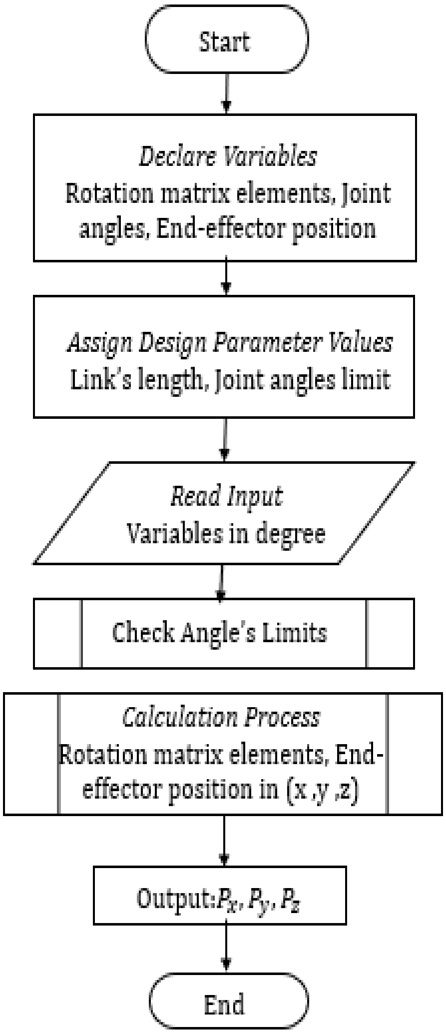


Figure 6. Flowchart of Forward Kinematics Modeling Algorithm

Table 4. Results of Forward Kinematics Modeling

Positions	Joint Angles(degree)				End-Effector's Coordinates		
	θ_1	θ_2	θ_3	θ_4	P_x	P_y	P_z
1	0	45	-45	0	0.557	0	0.317
2	45	60	-45	-15	0.345	0.345	0.417
3	45	45	-45	0	0.394	0.394	0.317
4	20	30	10	-40	0.524	0.191	0.384
5	0	0	0	0	0.645	0	0.105

The flowchart of inverse kinematics model is shown in Figure7. The coordinates of the end-effector are entered into the algorithm to obtain the joint angles that achieve a particular end-effector position. And then, the angle value θ_1 for joint 1 is calculated and the angle values θ_2, θ_3 and θ_4 for joints 2, 3 and 4 are calculated. Finally, all solution sets for the joint angles are obtained. Table 5 shows the results of the inverse kinematics modeling for five positions of end-effector coordinate.

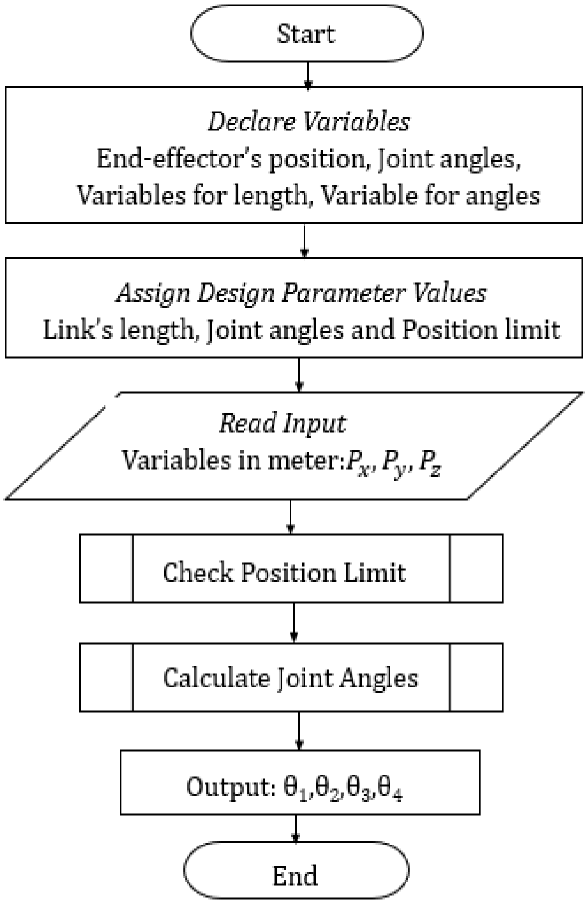


Figure.7. Flowchart of Inverse Kinematics Modeling Algorithm

Table 5. Results of Inverse Kinematics Modeling

Positions	**End-Effector's Coordinates**			**Joint Angles (degree)**			
	P_x	P_y	P_z	θ_1	θ_2	θ_3	θ_4
1	0.557	0	0.317	0	45	-45	0
2	0.345	0.345	0.417	45	60	-45	-15
3	0.394	0.394	0.317	45	45	-45	0
4	0.524	0.191	0.384	20	30	10	-40
5	0.645	0	0.105	0	0	0	0

D. Experimental Results

Experiments are done at twenty different arm positions which can coverage the whole reachable work region of the four links articulated robot. Five predetermined positions are shown for the experimental setup. These experimental setup for kinematics models is shown in Figure8. Firstly, Cartesian coordinates and orientation angles of each arm positions are given as input parameters. Then, kinematic model gives the required joint angles to achieve the desired arm position. After that, microcontroller generates the pulse width modulation (PWM) signals for each servo according to the joint angles given from kinematic model. Servo motors are then operated with PWM signals to achieve the desired position of robotic arm. Finally, Cartesian coordinates achieved by operation of servo motors are measured. They are compared with Cartesian coordinates of input parameters and errors for horizontal direction, longitudinal direction and vertical direction are determined. Graphical User Interface (GUI) are used to show the experimental result of five position: position 1 (0, 45, -45, 0), position 2 (45, 60, -45, -15), position 3 (45, 45, -45, 0), position 4 (20,30, 10, -40) and position 5 (0,0,0,0) conditions. Compared with Robo Analyzer and experimental result as shown in Figure.9,10, 11, 12 and 13.

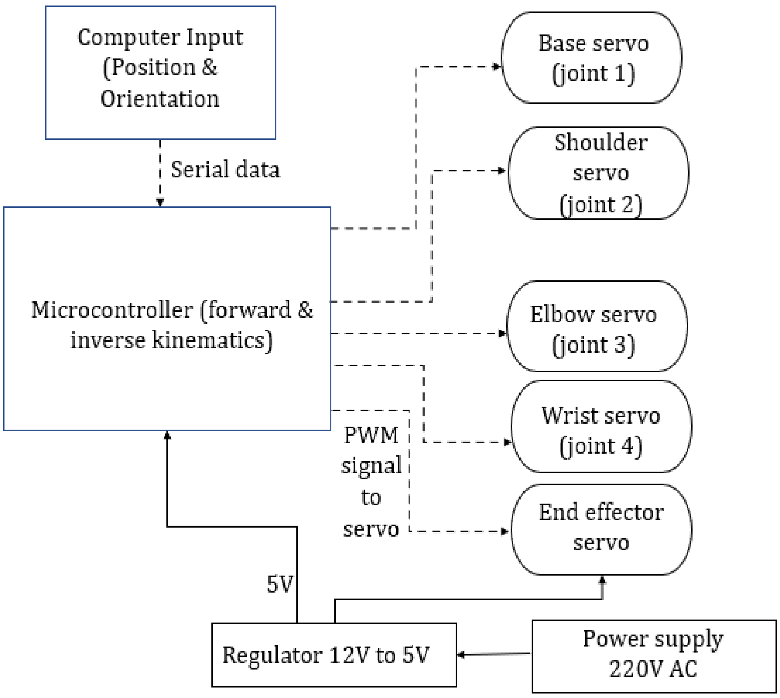


Figure 8. Experimental Setup for Kinematic Models Validation

A laser pointer is used to indicate the Cartesian coordinates of the articulated robot. The observed position of the articulated robot is measured with inspection tools. The position and orientation of the experimental results are identical to the position and orientation of the Robo-Analyzer results. The experimental results for position 1 are shown in Figure9.

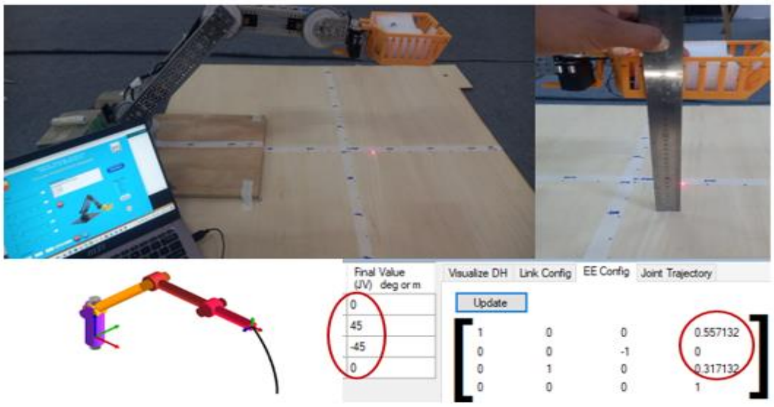


Figure 9. Experimental Result for Point1 (0, 45, -45, 0)

Angle values for the base, shoulder, elbow, and wrist are sent to the articulated robot as serial data. Based on the angle values, this is the elbow-down position of the articulated robot. The articulated robot then moves to the given desired position. These observed positions are the same as the Robo-Analyzer angles and positions. The experimental results for position 2 are shown in Figure10.

Figure10. Experimental Result for Position 2 (45,60, -45, -15)

A laser pointer is also used to check the position 3 of the articulated robot for greater accuracy. The angle values for the base, shoulder, elbow, and wrist are 45°, 45°, -45°, and 0°, respectively. The position corresponding to these angle values is (0.394, 0.394, 0.317). The experimental result for position 3 is shown in Figure 11.

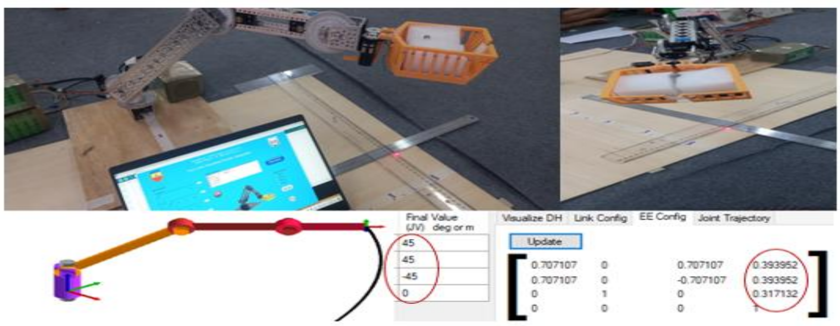


Figure11. Experimental Result for Position 3 (45,45, -45, 0)

The condition of position 4 is ideal for weighing the fruit. The angle values for the base, shoulder, elbow, and wrist are 20°, 30°, 10°, and -40°, respectively. Based on the input angle values, this is the elbow-up position of the articulated robot. These experimental results are the same as the Robo-Analyzer results. The experimental result for position 4 is shown in Figure 12.

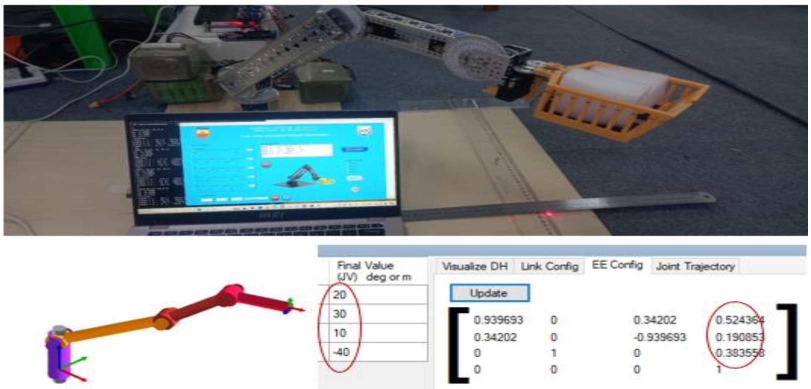


Figure12. Experimental Result for Position 4 (20,30, 10, -40)

Position 5 represents the extended condition of the articulated robot. In this condition, all joint angle values are 0°, the horizontal arm length is a maximum of 0.64 meter along the x-axis, and the maximum longitudinal length along the z-axis is 0.105 meter. The experimental result for position 5 is shown in Figure 13.

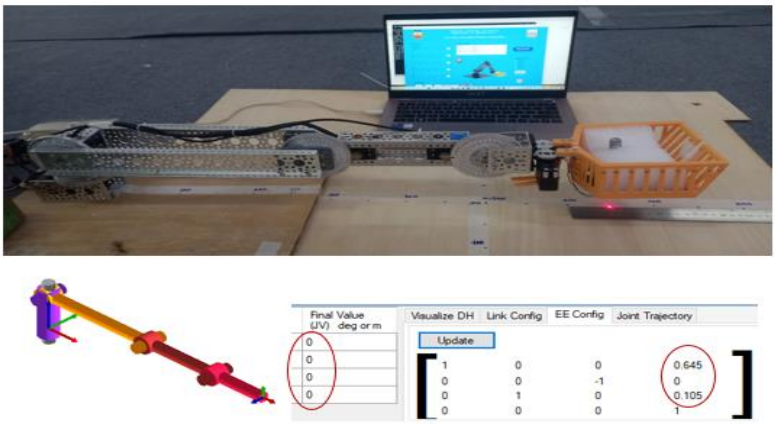


Figure13. Experimental Result for Position 5 (0,0, 0, 0)

E. Accuracy Test

Two important parameters in robotics are accuracy and repeatability. The difference between the desired position and the obtained position is called the accuracy, i.e, the error. Repeatability on the other hand, is the robot ability to repeat the same task, i.e., move back to a desired position repeatedly. Both accuracy and repeatability depend on many factors, e.g., friction, loading, motors, construction procedure, etc. The accuracy is calculated by [8];

$$AP_p = \sqrt{\left(\left(\bar{x} - x_c\right)^2 + \left(\bar{y} - y_c\right)^2\right)} \tag{11}$$

where;

$$\bar{x} = \frac{1}{n}\sum_{j=1}^{n} x_j, \bar{y} = \frac{1}{n}\sum_{j=1}^{n} y_j \tag{12}$$

Where $\bar{x} - x_c$ and $\bar{y} - y_c$ is the error along the x-axis and y-axis respectively. Xc and y_c is the commanded position. Expressions for $\bar{x}$ and $\bar{y}$ given by Equation.12 are the coordinates of the barycenter or center of mass of the cluster of points obtained. x_j and y_j is the measured position and n is number of measurements.
The repeatability is calculated by;

$$RP_L = \bar{L} + 3S_L \tag{13}$$

The distance from each point to the barycenter of the set is given by;

$$L_j = \sqrt{\left(x_j - \bar{x}\right)^2 + \left(y_j - \bar{y}\right)^2} \tag{14}$$

and the mean of these distances are given by;

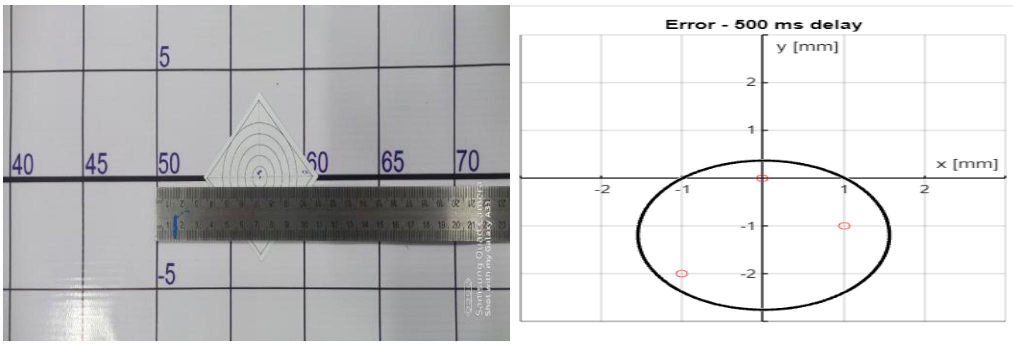
$$\bar{L} = \frac{1}{n}\sum_{j=1}^{n} L_j \tag{15}$$

and the standard deviation S_L;

$$S_L = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(L_j - \bar{L}\right)^2} \tag{16}$$

The displacement of the end effector moved by the robotic arm are listed in Tables 6, 7, 8, 9 and 10 respectively. And then, experimental results of five position are shown in Figure14, 15, 16, 17 and 18 respectively. These tables contain displacement in x-direction, measured in meters and displacement in y-direction, also measured in meters.

The observed position of the articulated robot during real-time movement at five time instances is shown in Figure14(a). In Figure14(b) below, the accuracy and repeatability of the tests can be seen. The red dots are where the object was placed by the articulated robotic arm. The black circle indicates the repeatability, and the radius this circle is the value of repeatability RP_L. According to the experimental results for position 1, the accuracy and repeatability of the tests are shown in Figure14.



(a) (b)

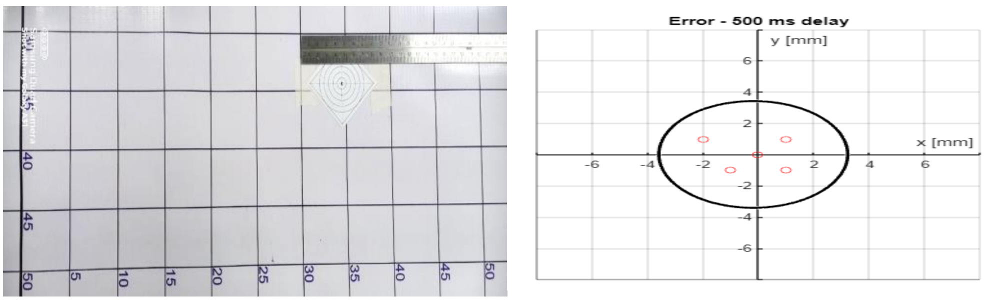
Figure14. (a,b) Experimental Result for Position 1 (0, 45, -45, 0)

The observed position data of an articulated robot at five different time instances are shown in Table 6. These data are used to calculate the error between the X and Y axes.

Table 6. The Displacement of the End-effector Along the X-axis And Y-axis of Position 1

Predicted Position	**Observed Position**				
	1st Time	**2nd Time**	**3rd Time**	**4th Time**	**5th Time**
P_x=0.557	0.557	0.556	0.558	0.556	0.558
P_y=0	0	0.001	0.002	0.001	0.002

Position 2 has the minimum error accuracy compared to the other four positions of the articulated robot. The experimental result for position 2 is shown in Figure15(a), and the corresponding results are shown in Figure15(b) using MATLAB.



(a) (b)

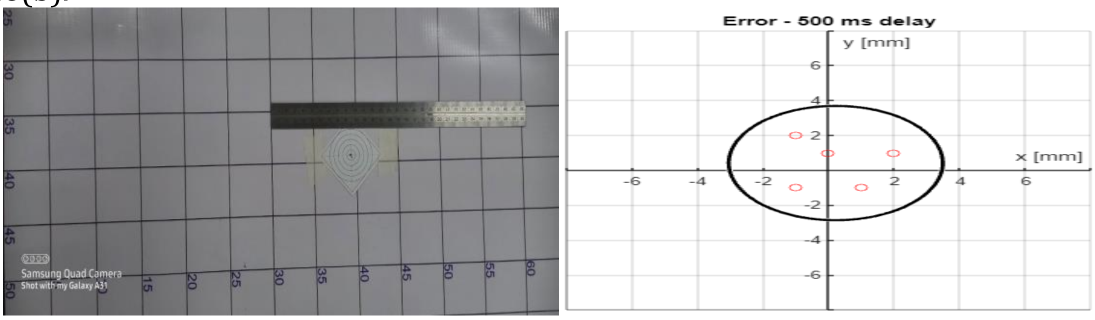
Figure15.(a,b) Experimental Result for Position 2 (45, 60, -45, -15)

The data presented are obtained from the articulated robot moving to the first quadrant. This position shows that the good accuracy and repeatability based on the experimental results. The experimental results for Position 2 are shown in Table 7.

Table 7. The Displacement of the End-effector Along the X-axis And Y-axis of Position 2

Predicted Position	Observed Position				
	1st Time	2nd Time	3rd Time	4th Time	5th Time
P_x=0.345	0.345	0.346	0.347	0.344	0.344
P_y=0.345	0.345	0.346	0.344	0.346	0.344

According to the experimental results for Position 3, the error accuracy is higher than that of Position 2 because this position is farther from the position 5 compared to Position 2. The repeatability tests for Position 3 are shown in Figure16(a). To better understand repeatability and accuracy, a blog post is used, as shown in Figure 16(b).



(a) (b)

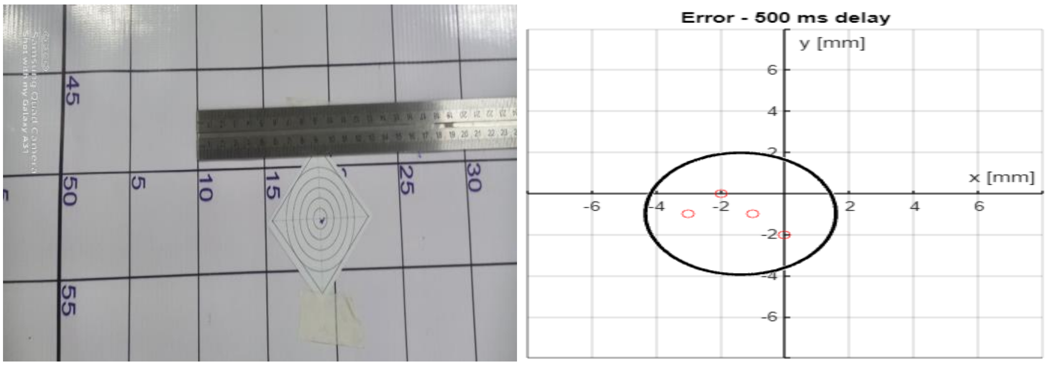
Figure 16.(a,b) Experimental Result for Position 3 (45, 45, -45, 0)

The articulated robot moves to Position 3 according to the input angles (θ1, θ2, θ3, and θ4). The experimental results for this position are shown in Table 8.

Table 8. The Displacement of the End-effector Along the X-axis And Y-axis of Position 3

Predicted Position	Observed Position				
	1st Time	2nd Time	3rd Time	4th Time	5th Time
P_x=0.394	0.395	0.394	0.395	0.393	0.392
P_y=0.394	0.395	0.393	0.392	0.395	0.393

The articulated robot moves to Position 4 with a delay time of 500 milliseconds for five repetitions, as shown in Figure 17(a). Additionally, the accuracy and repeatability of the tests are more clearly shown in Figure 17(b) using MATLAB.



(a) (b)

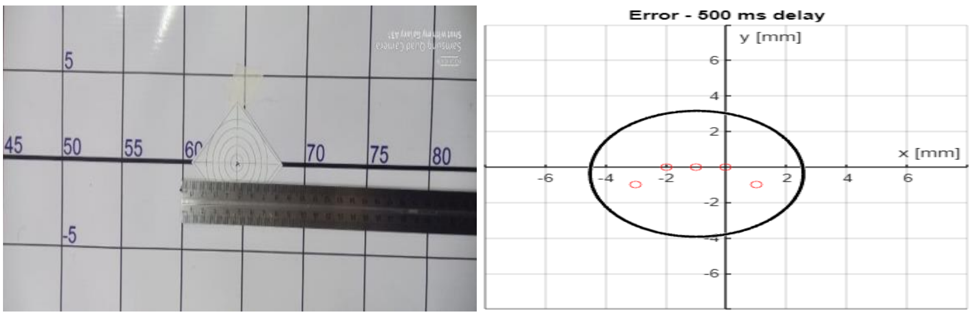
Figure17.(a,b) Experimental Result for Position 4 (20, 30, 10, -40)

The error accuracy is higher than in the other positions, but the repeatability is good. The experimental results for Position 4 are shown in Table 9.

Table 9. The Displacement of the End-effector Along the X-axis And Y-axis of Position 4

Predicted Position	**Observed Position**				
	1st Time	**2nd Time**	**3rd Time**	**4th Time**	**5th Time**
P_x=0.524	0.526	0.525	0.527	0.524	0.525
P_y=0.191	0.191	0.192	0.192	0.193	0.192

Position 5 is the farthest from the home position (90,0,0,0) resulting in poor repeatability.The experimental results for Position 5 are shown in Figure 18(a). The maximum repeatability range of 3.5408 mm is shown in Figure 18(b).



(a) (b)

Figure18. (a,b) Experimental Result for Position 5 (0, 0, 0, 0)

The displacement of the end effector for Position 5 along the X-Y axis is shown in Table 10.

Table 10. The Displacement of the End-effector Along the X-axis And Y-axis of Position 5

Predicted Position	Observed Position				
	1st Time	2nd Time	3rd Time	4th Time	5th Time
P_x=0.645	0.645	0.644	0.646	0.648	0.647
P_y=0	0	-0.001	0	-0.001	0

The displacement of the end-effector moved by the articulated robot are listed in these tables. Table 11 contains displacement in x-direction, measured in milimeters. Table 12 contains displacement in y-direction, also measured in milimeters.

Table 11. Error in Accuracy along the X-axis

Repetition, X-direction	1st Time	2nd Time	3rd Time	4th Time	5th Time
Error[mm],delay:500ms (Position 1)	0	1	-1	1	-1
Error[mm],delay:500ms (Position 2)	0	-1	-2	1	1
Error[mm],delay:500ms (Position 3)	-1	0	-1	1	2
Error[mm],delay:500ms (Position 4)	-2	-1	-3	0	-1
Error[mm],delay:500ms (Position 5)	0	1	-1	-3	-2

Table 12. Error in Accuracy along the Y-axis

Repetition, Y-direction	1st Time	2nd Time	3rd Time	4th Time	5th Time
Error[mm],delay:500ms (Position 1)	0	-1	-2	-1	-2
Error[mm],delay:500ms (Position 2)	0	-1	1	-1	1
Error[mm],delay:500ms (Position 3)	-1	1	2	-1	1
Error[mm],delay:500ms (Position 4)	0	-1	-1	-2	-1
Error[mm],delay:500ms (Position 5)	0	-1	0	-1	0

The results of accuracy and repeatability results of position 1,2,3,4 and 5 are shown in Table 13. In the above figures, the accuracy and repeatability of the tests are shown. The red dots represent the positions where the object was placed by the robotic arm. The black circle indicates the repeatability, and the radius of this circle corresponds to the repeatability value (RP_L). Table 13 shows the results of accuracy and repeatability for five positions, calculated using equations 11 to 16. According to the experimental results, the robot achieved an error accuracy range of 0.4472 mm to 1.7205 mm and a repeatability range of 1.55703 mm to 3.6886 mm, respectively. The results from these calculations can be found below in the Table 13.

Table 13. Result of Accuracy and Repeatability

	AP_p[mm]	**RP_L[mm]**
Position 1	1.2	1.5571
Position 2	0.2	3.4105
Position 3	0.4472	3.2704
Position 4	1.7205	2.9608
Position 5	1.077	3.5408

F. Conclusion

In this paper, a four-link articulated robot is proposed for use in industrial applications, specifically for sorting fruit according to their weight. This manipulator is specially designed for mango sorting based on their weight. Forward kinematic modeling using the Denavit-Haternberg method and inverse kinematic modeling using a geometrical approach have been successfully developed for the articulated robot and implemented into the MATLAB program. A MATLAB program was developed based on the forward and inverse kinematics solutions. In the experimental results, the positions and orientations of the links and joints were compared with the Robo-Analyzer results. Accuracy and repeatability are crucial for robot manipulators because they directly influence the robot's ability to perform precise, reliable, and consistent tasks in various industries and applications. While the position accuracy was measured with five test positions, the results showed that the highest positioning error 1.7205mm appeared in horizontal axis. These errors occur because of variation in pitch between the gear teeth of base joint. However, the results of experiments achieved the repeatability in 1.5571 mm within the acceptable range of purposed application.

G. Acknowledgement

First and foremost, the author would like to acknowledge the support and the encouragement of Dr. San Yu Khaing, Rector(Acting), Mandalay Technological University. The author would like to express deeply indebted to all teachers from the department of Mechatronic Engineering, Mandalay Technological University, for their suggestions and help till this paper is completed. Finally, the author likes to express grateful thanks to her parents who played a great role in my career and their love and support has been a major stabilizing force till this moment.

H. References

[1] S. K. Saha, "Introduction to Robotics". New Delhi, India: Mechanical Engineering Department, IIT Delhi, 2008.

[2] Kerlm Gokhan Aktas,Fatih Pehivan and Ismail Esen,"Kinematics Analysis of 4 DoF Robotic Arm and Simutaneous Trajectory Tracking Using ADAMS-MATLAB Software",Conference Paper,November 2017.

[3] Guangbing Bao,Shizhao Liu,Hong Zhao,"Kinematics Simulation of 4-DoF Manipulator", Second International Conference on Materials Science,Machinery and Energy Engineering,2017.

[4] Tahseen Fadhil Alani,Ali Abbar and Mohanad Qusay Abbood,"Kinematics Analysis of 5 DoF Robotic Arm",Engineering and Technology Journal,March 2020.

[5] Myat Noe Wai,Thwe Thwe Htoo and Lu Maw,"4-DoF Robot Arm for Pick and Place Process",International Journal of Advances in Scientific Research and Engineering(ijasre),Volume 6,Issue 11,November-2020.

[6] Muhanned Ashraff Mohd Adzeman,Mohd Hairi Mohd Zaman,Muhammad Fikri Nasir,Mohd Faisal Ibrahim and SeriMastura Mustaza,"Kinematics Modeling of a Lo Cost a DoF Robot Arm System",International Journal of Emerging Trends in Engineering Research,October 2020.

[7] Zhong Ting Han,Mohd Hairi Zaman,Mohd Faisal Ibrahim and Asraf M Moubark,"Kinematics Analysis for Trajectory Planning of Open-Source 4-DoF Robot Arm"International Journal of Advanced Computer Science and Applications ,January 2021.

[8] Carl-Victor Lidholm, Victor Runnquist, "Accuracy and Repeatability of a Robotic Arm", Sweden 2021.

[9] Ayu Widyacandra, Adnan Rafi AI Tahtawi, Martin, "Forward and Inverse Kinematics Modeling of 3-DOF AX-12A Robot Manipulator",JITEL, Vol.2, No.2, September 2022, pp.139-150.

[10] Mon Mon Thae, "Design, Kinematics and Workspace Analysis of Four Links Articulated Robotic Manipulator", ICEAIR, 6-7 Oct 2024.