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A DEMONSTRATIVE-KINESTHETIC TEACHING APPROACH FOR INVERSE KINEMATICS OF A 4-DOF ROBOT MANIPULATOR

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Kinesthetic guidance as a paradigm of programming by demonstration of robot manipulators has eased the process of robot programming, especially for non-skilled and semi-skilled shop-floor operators in manufacturing industries. Today, the inverse problem remains an area of interest in robotics, leading up to the deployment of robots for collaborative technology with humans. The paper proposes using a demonstrative-kinesthetic teaching technique to program a robot manipulator, determine the inverse kinematics using the approach, and compare with structured texts to program the manipulator. The approach was carried out on a Dobot magician, a 4-DOF robot manipulator. A control platform was created using MS Visual Studio IDE, using Python to control the arm, and it was programmed demonstratively using the lock arm button and structured texts to carry out a palletizing task. The joint parameters were collected and compared using the demonstrative-kinesthetic technique and structured texts as programming methods. The structured texts were used as a control for the experiment. The results showed that joint values obtained using the demonstrative-kinesthetic technique did not vary significantly from structured texts' joint values. The approach provided an avenue for quickly programming a robot manipulator, especially concerning the non-skilled workforce, and finding analytical solutions to the inverse problem of the robot manipulator.

Keywords: Dobot Magician, inverse kinematics, demonstrative-kinesthetic teaching, robot manipulator, palletizing

1 INTRODUCTION

Humans have always been fascinated by the concept of creating entities that can perform repetitive, tedious, and laborious tasks. Through the works of Czech writer Karel Capek, the term "robot" was first used in his novel 1920, "RUR: Rossum's Universal Robots" [1, 2]. The term "robot" comes from the Czech word "robota," which means "forced labour" [3].

Kinesthetic teaching (KT) or kinesthetic guidance [4] is a programming methodology in which the programmer teaches new behaviours by manipulating the body of a learning robot [5-7]. Tele-kinesthetic teaching (TKT) has been applied to trajectory learning, task learning, grasping, and high-level tasks [8]. Graphical user interfaces, haptic devices, virtual reality (VR) interfaces, and a joystick are required to provide external input to the robot. While providing an avenue for remote programming, the technique faces setbacks, especially as additional lengthy user training on the interfaces, availability of the chosen input hardware, and additional effort required to develop the selected interfaces.

Demonstrative-kinesthetic teaching (DKT) takes advantage of the onboard sensors to record the state of the robot during interaction [8], providing an intuitive approach with minimal training requirements [9, 10] as it does not burden the programmer with the requirement of knowledge of programming languages such as Python [4]. The correspondence problem, induced by the mapping of human actions, is eliminated as the programmer directly guides the robot [11, 12], and there is no need for extra instruments beyond the robot's sensors and actuators. The demonstrations are restricted to the known kinematic limits of the robot.

The inverse kinematics problem has been a significant area of scientific research interest, and various approaches have been taken to find solutions to it. The use of genetic algorithms was discussed by Momani, Abo-Hammour and Alsmadi [13] especially for redundant robots due to the complex kinematic equations, which are non-linear, coupled, and with multiple solutions in these robot manipulations. The use of artificial intelligence, such as neural networks such as in [14-16] and analytical approaches [17] are also attempts by scientists to solve the problem. While the said approaches provide innovative steps in tackling the inverse problem, they require very sophisticated devices that are expensive, tenuous, and cumbersome with an expectation of a skilled end-user of robot programming. The methods may prove difficult to implement especially in semi-skilled to non-skilled workforces in developing countries. This would require dependence on the manufacturer having to carry out the reprogramming if need be and it may become expensive to apply robotized systems in these industrial setups. The study proposed using the demonstrative-kinesthetic teaching (DKT) technique as a means of robot programming to determine the inverse kinematics of a four-degree-of-freedom (4-DOF) robotic manipulator and to compare it with the structured texts approach.

2 MATERIALS AND METHODS

2.1 Kinematics of Robot Manipulators

Kinematics is the branch of mechanics that deals with the motion of bodies and systems without considering the forces that cause the motion. Robot kinematics applies geometry to the sturdy movement of multi-DOF kinematic chains that form the structure of the robot manipulator; robot kinematics involves rotation and translation displacement to bring about movement [18]. A translation is a displacement in which no part in the rigid body remains in its initial position, and all straight lines in the rigid body remain parallel to their initial orientations. A rotation is a displacement in which at least one point of the rigid body remains in its initial position. Not all lines in the body remain parallel to their initial orientations [18, 19]. The kinematics refer to pose, velocity, acceleration, and all higher derivatives of the pose of the bodies that comprise a mechanism.

The homogenous transformations combine position vectors and rotation matrices in a compact rotation. Usually adopted when the ease of programming is the most critical consideration. The links that compose the robotic mechanism are assumed to be perfectly rigid bodies with geometrically perfect surfaces in both position and shape. The Denavit-Hartenberg (DH) convention was adopted here because it only requires four rather than six parameters to locate one reference frame relative to another. These are:

- Joint angle (qi)
- Link distance/Link Offset (di)
- Link length (ai-1)
- Link twist at the link (αi-1) [18, 20, 21]

The convention applies to manipulators consisting of revolute and prismatic joints. The kinematics comprise forward kinematics (FK) and inverse kinematics (IK). FK transforms from joint space to cartesian space, providing the manipulator position information, while IK transforms from cartesian space to joint space [22].

The FK problem for a serial-chain manipulator is to find the position and orientation of the end-effector relative to the base, given the positions of all the joints and values of all the geometric links. The DH parameters help to determine the spatial relationship between the coordinate frames of successive links.

The solution to FK for a robot manipulator is provided by calculating the homogeneous transformation matrix, which contains the position and orientation information of the end-effector. The homogeneous transformation matrix of the frame (i-1) to frame (i) consists of rotation about the Z_{i-1} axis by angle i, translation along the Zi-1 axis by distance di, translation by distance i along the xi-axis and rotation about the xi-axis by angle i as shown by equation (1).

$$ {}^{i-1}_{\ \ i}T = Rot_z(\theta_i).Trans_z(d_i).Trans_x(\theta_i)Rot_x(\alpha_i) \tag{1}$$

Where; T- overall transformation,

Rot- rotation,

Trans-translation

According to Craig [23], the general form of a link transformation that relates to frame (i) relative to the frame (i-1) is:

$$ {}^{i-1}_{\ \ i}T = \begin{bmatrix} {}^{i-1}_{\ \ i}R^{3\times3} & {}^{i-1}_{\ \ i}P^{3\times1} \\ 0^{1\times3} & 1 \end{bmatrix} \tag{2}$$

Where;

${}^{i-1}_{\ \ i}R^{3\times3}$ is a rotation matrix describing the frame (i) relative to the frame (i-1), which is expressed as:

$$ {}^{i-1}_{\ \ i}R^{3\times3} = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 \\ \sin\theta_i\cos\alpha_{i-1} & \cos\theta_i\cos\alpha_{i-1} & -\sin\alpha_{i-1} \\ \sin\theta_i\sin\alpha_{i-1} & \cos\theta_i\sin\alpha_{i-1} & \cos\alpha_{i-1} \end{bmatrix} \tag{3}$$

Moreover, ${}^{i-1}_{\ \ i}P^{3\times1}$ is a vector that locates the origin of the frame (i) relative to the frame (i-1) and can be expressed as:

$$ {}^{i-1}_{\ \ i}P^{3\times1} = [a_{i-1} \quad -\sin\alpha_{i-1}d_i \quad \cos\alpha_{i-1}d_i]^T \tag{4}$$

Thus, equation (2) is represented as follows;

$$ {}^{i-1}_{\ \ i}T = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_{i-1} \\ \sin\theta_i\cos\alpha_{i-1} & \cos\theta_i\cos\alpha_{i-1} & -\sin\alpha_{i-1} & -\sin\alpha_{i-1}d_i \\ \sin\theta_i\sin\alpha_{i-1} & \cos\theta_i\sin\alpha_{i-1} & \cos\alpha_{i-1} & \cos\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

[18, 21, 24-29]

Equation (2) represents a 4 x 4 homogenous transformation matrix relating successive frames.

A serial-chain manipulator's inverse kinematics (IK) involves determining the joint positions based on the end-effector's position and orientation relative to the base values of all the geometric link parameters. However, the non-linear equations derived from the transformation matrices pose a challenge in finding a closed-form solution. It is possible that no solution exists or multiple solutions exist. For a solution to be viable, the desired placement and alignment of the end effector must fall within the manipulator's workspace [18]. In non-existent solution cases, numerical methods are required. The closed-form solutions are faster than the numerical ones and readily identify all possible solutions. They are preferable because, in many applications where the manipulator supports or is to be supported by a sensor system, the kinematic computations must be supplied rapidly to have control actions [30]. The solutions are not general but rather robot-dependent. The solutions can be determined algebraically or geometrically.

2.2 Description of Robot Manipulator

The robot manipulator used in this study is the Dobot Magician. It has three stepper motors and one servo motor. The robotic manipulator is shown in Fig. 1. The manipulator has four axes, with an end-effector having a payload of 500g. The robot manipulator's joint range of motion is in Table 1.

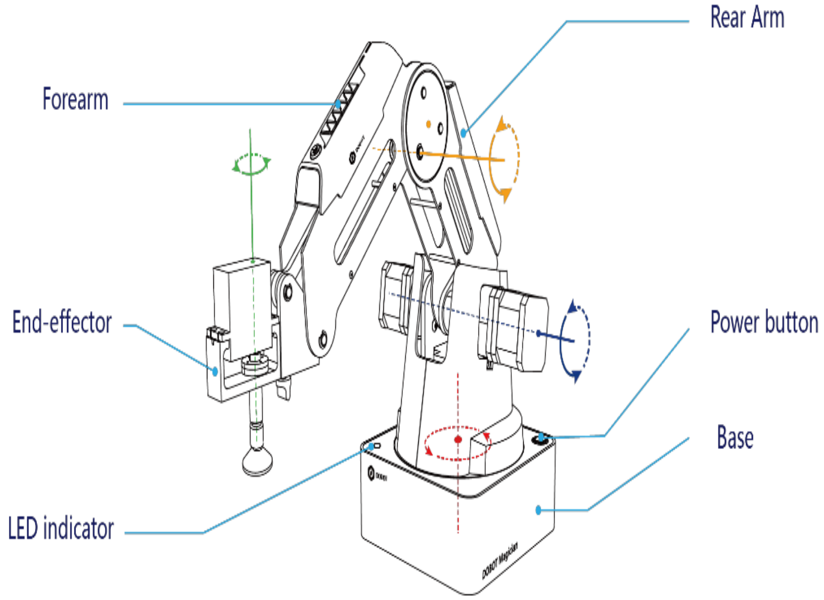

Fig. 1. Dobot Magician (Adapted from Shenzhen Yuejiang Technology Co. [31])

Table 1: Joint Range of Motion [31]

Axis Movement	
Axis	Range
Joint 1	-135º to +135º
Joint 2	0º to +85º
Joint 3	-10º to +95º
Joint 4	+90º to –90º

The joint and cartesian configurations of the Dobot magician are shown in Fig. 2.

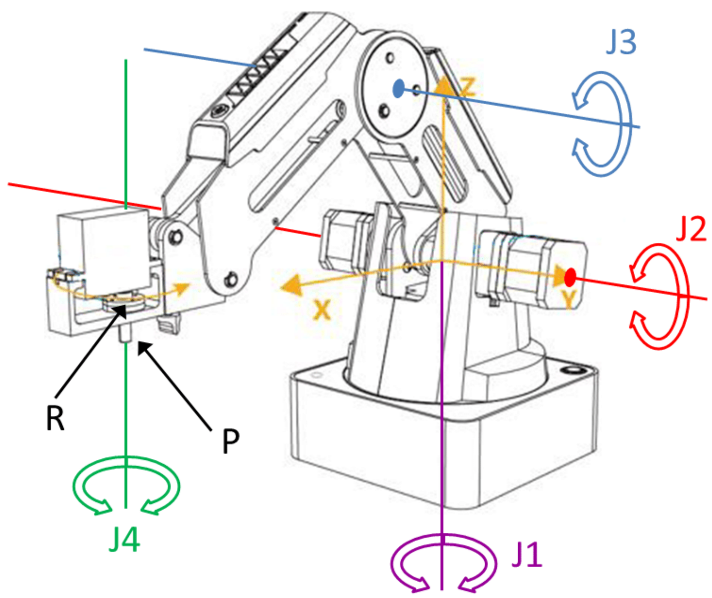

Fig. 2. Joint and Cartesian Configurations of Dobot Magician (Adapted from Shenzhen Yuejiang Technology Co. [31])

2.3 Experimental Set-up and Procedures

The materials for the experiment were a laptop, robotic manipulator (Dobot Magician), wooden block, USB connection cable, power source, pneumatic pump, and pneumatic gripper (end-effector). The experiment was set up as shown in Fig. 3.

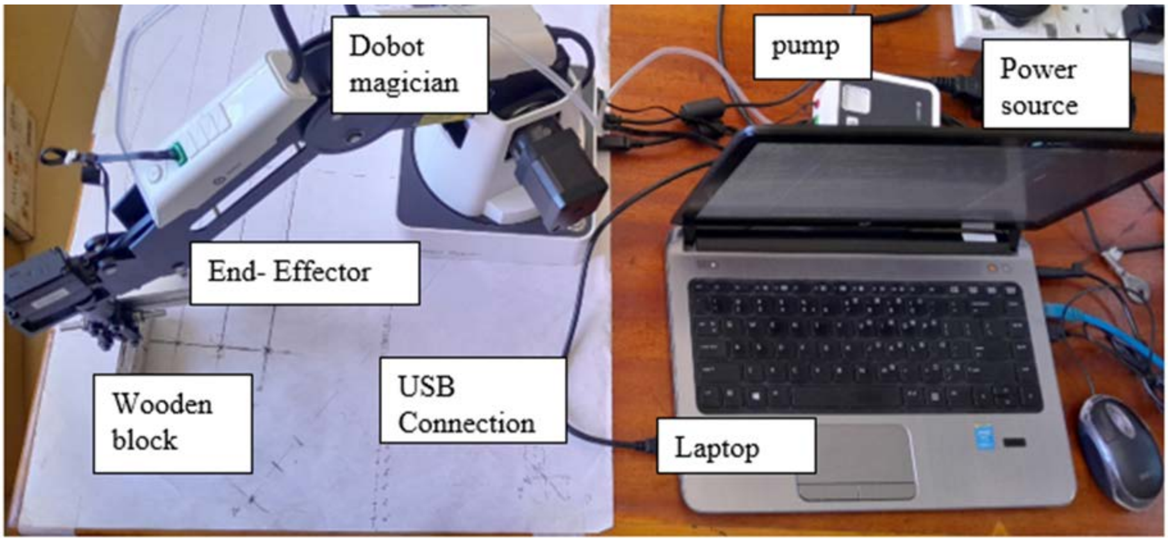

Fig. 3. Experimental Set-up

To determine the inverse kinematics, a control platform (Fig. 4) based on Python language was created using Visual Studio IDE to control the robot demonstratively (DKT) by using the lock button on the forearm to capture the positions of the end-effector (Hand-held Trigger (HHT)) and tabulate the joint values in a pose.csv file. For the control experiment, the same effector positions were captured using a Python program, and the joint positions were saved on the pose1.csv file using the getpose () command in the code. A palletizing experiment was carried out to validate using the DKT approach.

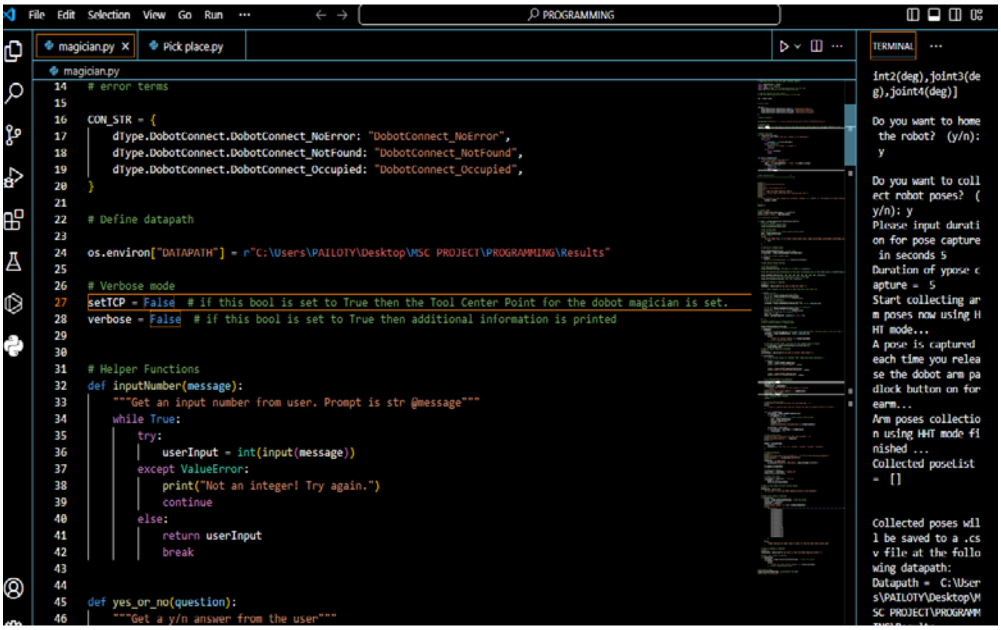

Fig. 4. Control Platform in MS Visual Studio

The experiment involved picking the wooden block from the start to the stop position over four levels. The position of points A and B were determined for distances 25mm, 40mm, and 55mm apart from the initial position of A_1 (Start) and B_1 (Stop) on a straight line as the stop points of the experiment in Fig. 5 and Fig. 6 respectively.

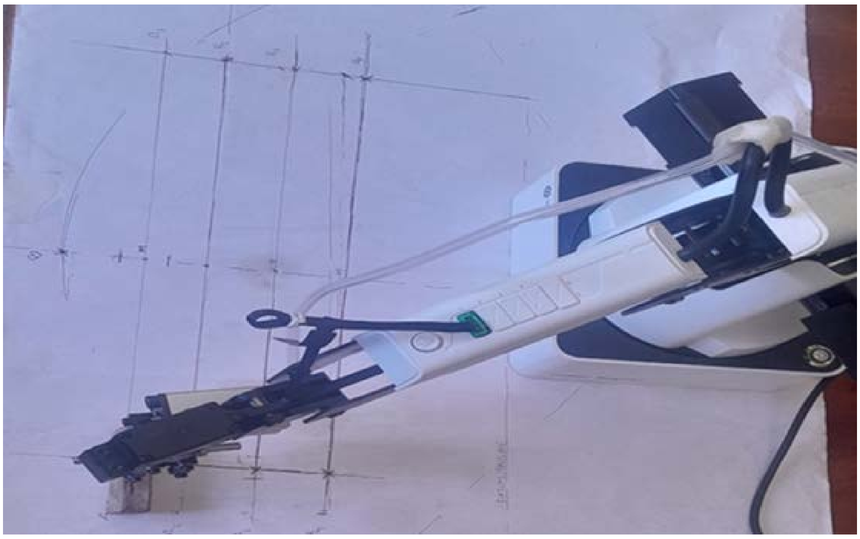

Fig. 5. The Start Position A_1

Fig. 6. The Stop Position B_1

The experiment was replicated five times for each level (A_2, B_2, A_3, B3, A_4, B_4). The joint values were recorded and stored in the CSV file for each replication and level. The collected data was analysed using Mini-tab, and the results discussed.

3 RESULTS AND DISCUSSION

Determining the joint angles is crucial in placing the end-effector at the expected cartesian points (x, y, z). The joint values can be algebraically obtained using equations outlined in the kinematics section from the literature's point of view. The joint values can be determined algebraically if the cartesian points and the respective DH- Parameters are known. Using the DKT approach, the joint angles were determined and compared to the joint values obtained using the structured texts, which acted as the control experiment. The results from the experiments were as shown in Fig. 7 to Fig. 9.

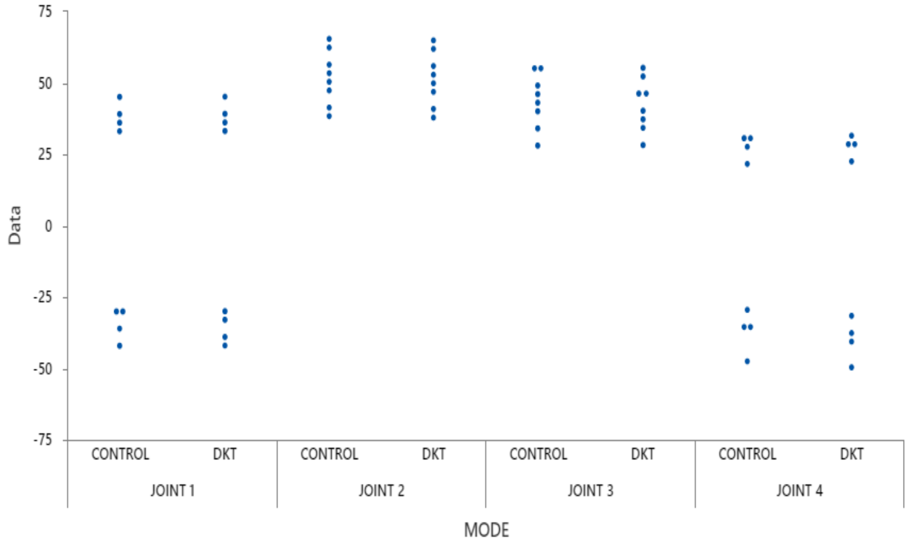

Fig. 7. Individual Joint Angle Value Plot

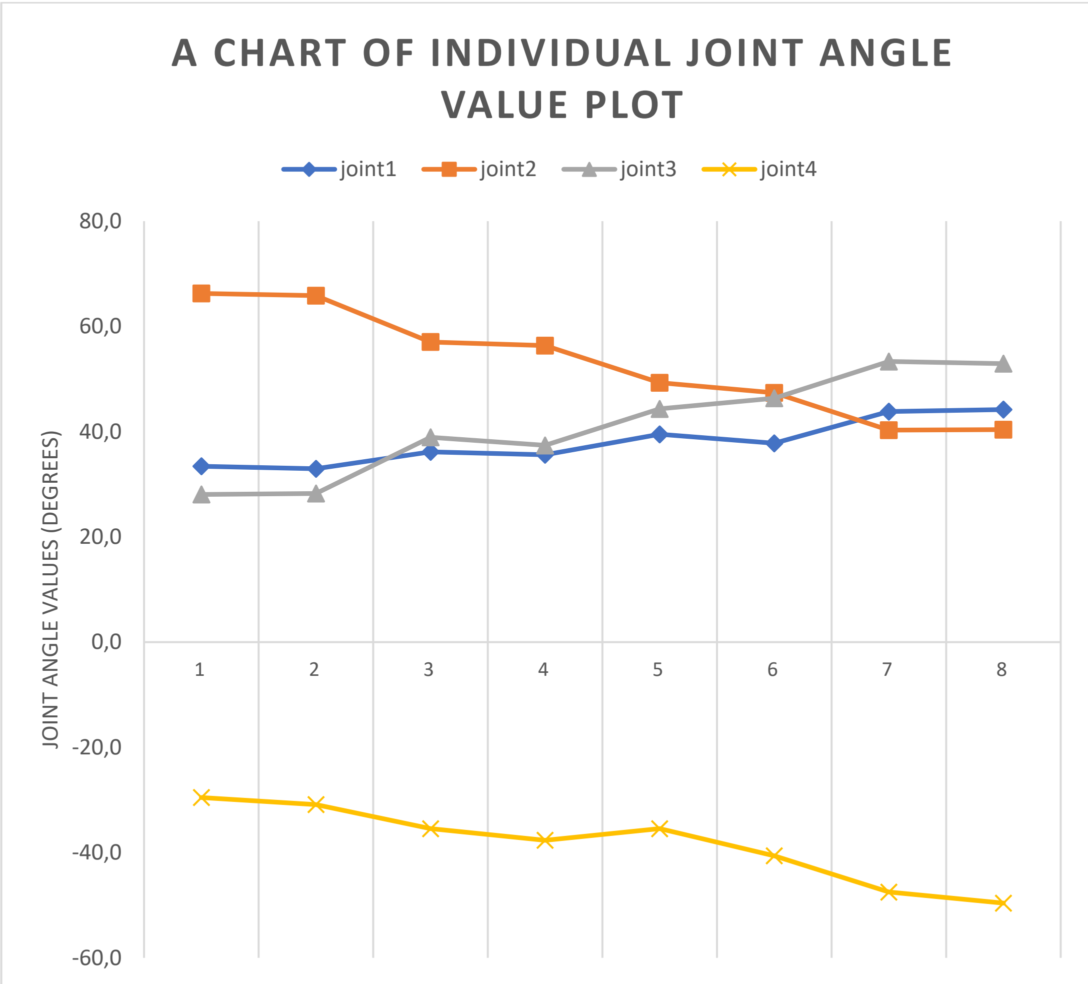

Fig. 8. Line Plot of Individual Joint Angle Value

From Fig. 7, a close comparison between the joint positions obtained using the DKT to those obtained using the structured texts (Control) were either close in value or slightly apart, showing the usefulness of the DKT approach to determining the joint values, especially to users with few skills in text-based programming approach of robots.

From Fig. 8, it was seen that due to the position of pick point (A) for the various levels concerning the origin, the joint 1 value had positive joint angle values and negative joint angle values as indicative of the place point (B) for both the DKT approach and the Control method. Joint 4 values were negative values for the pick point (A) and positive joint angle values for the place point (B). The joint 2 and 3 angle values were all positive, irrespective of the position of points A or B. The joint angle value means for joint 1 (1.7, 1.5), joint 2 (51.25, 51.01), joint 3 (42.71, 42.55) and joint 4 (-5.3, -5.7) for the Control and DKT approaches respectively. Histogram plots of the individual joint angle values were as shown in Fig. 9.

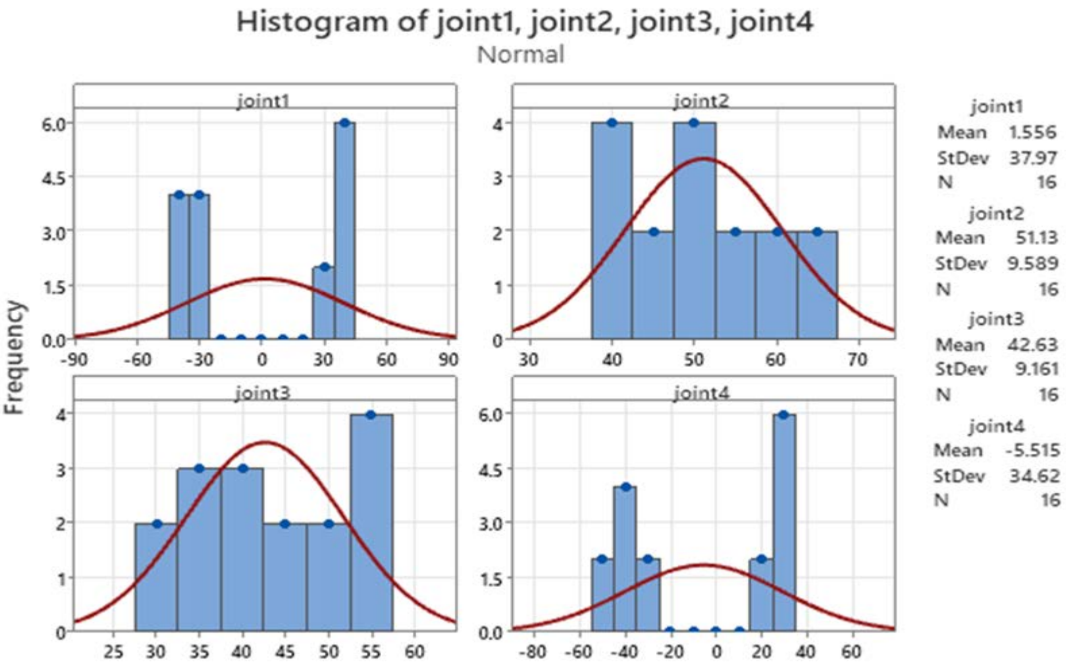

Fig. 9. Histograms of Individual Joint Angle Values

From Fig. 9, the joint 1 and 4 angle values showed a unimodal distribution with a bell curve of the angle values obtained using the DKT and Control. The joint 2 angle values were relatively symmetric in the distribution, the same as those of joint 3 angle values. The joint values obtained using the Control and DKT technique showed that it is possible to get the joint angle values as such with other geometric solutions and algebraic solutions; thus, the inverse kinematic solutions were determined.

The robotic manipulator calculates the joint configurations for every slight movement of the robotic arm at every instance the lock arm button is pressed and released and using the *getpose ()* command in the control platform in Fig. 4, returns the joint values. The arm uses the analytical equations as presented by Mohammed and Sunar [32] to find the inverse solutions. Using the DKT approach, the robotic arm performed the palletizing experiment by picking the wooden block from pick point A and placing it at place point B for the four levels tested. Points far out of the work envelope or close to the joint limits were not viable for the experiment's success as the arm would display alarms and lock it to avoid damage to the arm.

4 CONCLUSIONS

Kinesthetic teaching (KT) as a paradigm of programming by demonstration (PbD) provides an opportunity for learner robots to be programmed via onboard sensors, thus dealing with the correspondence problem. DKT provides room for the intuitive programming of industrial robots, especially for users with fewer skills in robotic programming, given the dynamic nature of consumer needs. This study proposed using DKT and structured texts to program a robot manipulator and determine the inverse kinematics of the arm. The robotic arm was programmed to perform palletizing tasks using the DKT and structured texts to validate the study. The control platform created was vendor-specific to the Dobot Magician arm. The individual joint angle values obtained using the DKT were within justifiable margins from those obtained using the control experiment. The robotic arm performed palletizing as programmed using DKT and structured texts. Future works aimed at creating a platform accommodative of other arms, such as KUKA, for deployment and conducting contour path welding using DKT.

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