World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:12, No:2, 2018

Scorbot-ER 4U Using Forward Kinematics Modelling and Analysis

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Abstract**—**Robotic arm manipulators are widely used to accomplish many kinds of tasks. SCORBOT-ER 4u is a 5-degree of freedom (DOF) vertical articulated educational robotic arm, and all joints are revolute. It is specifically designed to perform pick and place task with its gripper. The pick and place task consists of consideration of the end effector coordinate of the robotic arm and the desired position coordinate in its workspace. This paper describes about forward kinematics modeling and analysis of the robotic end effector motion through joint space. The kinematics problems are defined by the transformation from the Cartesian space to the joint space. Denavit-Hartenberg (D-H) model is used in order to model the robotic links and joints with 4x4 homogeneous matrix. The forward kinematics model is also developed and simulated in MATLAB. The mathematical model is validated by using robotic toolbox in MATLAB. By using this method, it may be applicable to get the end effector coordinate of this robotic arm and other similar types to this arm. The software development of SCORBOT-ER 4u is also described here. PC-and EtherCAT based control technology from BECKHOFF is used to control the arm to express the pick and place task.

Keywords**—**Forward kinematics, D-H model, robotic toolbox, PC-and EtherCAT based control.

I. INTRODUCTION

OVER the past decades, industries are moving toward automation. The reason behind this is the requirements of accuracy, efficiency in repetitive tasks, high productivity and budgeting for industrial processes. Robotics manipulators are designed to work in the automation system of the industrial processes. The robotic manipulators perform many major applications such as welding, painting, assembly, packing, labelling product inspection, and testing. Especially, picking and placing tasks are also among well-known the manipulators' applications. According to the desired tasks of the manipulators in the manufacturing processes, robotic manipulators are designed with similar functions to human arm. They have many links connected by joints allowing either rotation motion or translational (linear) displacement. The links of the manipulator can be considered to form a kinematic chain. The terminus of the kinematic chain of the manipulator is called the end effector and it is analogous to the human hand. Therefore, manipulator modelling consists of study of its kinematics behaviour [1]. Kinematics is related to manipulator motion without considering forces producing motions. And it also consists of how various links move with respect to one another and in time. Kinematics problems are usually categorized into two sub-problems, i.e. forward kinematics and inverse kinematics.

Forward kinematics is determining the Cartesian position and orientation of a mechanism, given the joint coordinates. Inverse kinematics is computing the joint variables given the manipulator end-effector position and orientation. For serial robotic manipulators, inverse kinematics problem is more complex than forward kinematics problem [1].

Manipulator kinematics analysis and modelling are very complex and difficult due to the multi DOF and multilink space mechanisms. A lot of research technologies are developed with some improvements in robotics manipulators [3]. Iqbal et al. modeled a 6-DOF robotic arm manipulator, ED7220C with modelling and analysis of its workspace. This manipulator is used for pick and place applications [4]. Dechrit et al. developed of 4-DOF (PRRP) SCARA robot arm and analysed its kinematics problems. PRRP is developed from SCARA robot by adding a linear sliding actuator in order to increase its workspace for pick and place task [5]. Khan and Quan modeled and analysed forward kinematics of 6-DOF underwear manipulator.

This paper focuses on the forward kinematics of Scorbot-ER 4U in Section I. By using MATLAB robotics toolbox, the forward kinematics model is validated in Section II. Section III presents the control system of Scorbot-ER 4U for pick and place task with PC-and EtherCAT based control technology from Beckhoff, Experiments are presented in Section IV, and Section V discusses about conclusion.

II. KINEMATICS MODEL

Scorbot-ER 4U is a vertical articulated robot, with five revolute joints. With gripper attached, the robot has six degrees of freedom [6]. Fig. 1 identifies the joints and links of mechanical arm. The movements of the joints are given in Table I.

Kinematics is the science of motion that treats the subject without regarding the forces that cause it [2]. In this paper, the forward kinematics was implied in the principal role to analyse the motion of Scorbot-ER 4U. The forward kinematics is process of determination the position and orientation of end effector giver values for joints variable of the manipulators [2]. For studying this problem, method based on Denavit-Hartenberg (DH) convention is used to determine modelling robot links and joints.

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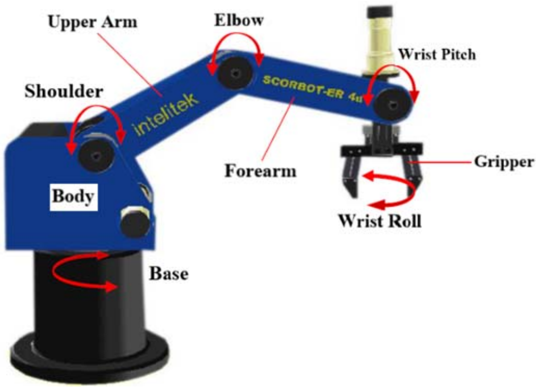


Fig. 1 Robot arm links and joints

TABLE I
MOVEMENT DESCRIPTION OF THE JOINTS

Axis No.	Joint Name	Motion
1	Base	Rotates the body.
2	Shoulder	Raises and lowers the upper arm.
3	Elbow	Raises and lowers the forearm.
4	Wrist Pitch	Raises and lowers the end effector (gripper)
5	Wrist Roll	Rotates the end effector (gripper)

To solve the kinematics problem, we have to assign frame to each link by starting from base frame to end-effector frame. The frame assignment is shown in Fig. 2. Then, we define the D-H parameters obtained in Table II.

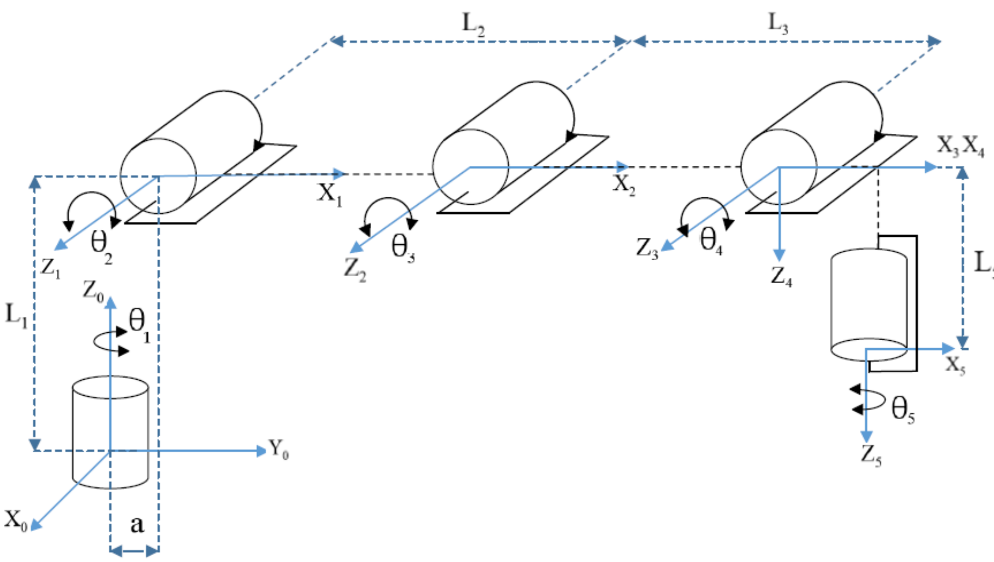


Fig. 2 Frame assignment to the Scorbot-ER 4U

TABLE II
DENAVIT-HARTENBERG PARAMETERS

Joint i	a_i (cm)	α_i (rad)	d_i (cm)	θ_i (rad)
1	a =1.2	$\pi/2$	L_1 =35	θ_1
2	L_2 =22	0	0	θ_2
3	L_3 =22	0	0	θ_3
4	0	$\pi/2$	0	θ_4
5	0	0	L_5 =15	θ_5

The D-H representation above depends on four link parameters, the following definitions of the four link parameters are valid:

- a_i (Link length) = the distance from Z_{i-1} to Z_i measured along X_i
- α_i (Link Twist) = the angle from Z_{i-1} to Z_i measured about X_i
- d_i (Joint Distance) = the distance from X_{i-1} to X_i measured along Z_{i-1}
- θ_i (Joint angle) = the angle from X_{i-1} to X_i measured about Z_{i-1}

The 4x4 homogeneous transformation matrix is used to determine the forward kinematics in this section. It can be easily developed by considering frame {i-1} and frame {i}. This transformation consists of four basic transformations.

$$^{i-1}T_i = \begin{bmatrix} C\theta_i & -S\theta_i C\alpha_i & S\theta_i S\alpha_i & a_i C\theta_i \\ S\theta_i & C\theta_i & -C\theta_i S\alpha_i & a_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where $S\theta_i = \sin\theta_i$, $C\theta_i = \cos\theta_i$, $S\alpha_i = \sin\alpha_i$, $C\alpha_i = \cos\alpha_i$

Then, we substitute the D-H parameters from Table II into (1), the transform matrix of each link is as follows:

$$^{0}T_1 = \begin{bmatrix} C_1 & 0 & S_1 & aC_1 \\ S_1 & 0 & -C_1 & aS_1 \\ 0 & 1 & C\alpha_i & L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$^{1}T_2 = \begin{bmatrix} C_2 & -S_2 & 0 & L_2 C_2 \\ S_1 & C_2 & -C_1 & L_2 S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$^{2}T_3 = \begin{bmatrix} C_3 & -S_3 & 0 & L_3C_3 \\ S_3 & C_3 & 0 & L_3S_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$^{3}T_5 = \begin{bmatrix} C_4 & 0 & S_4 & 0 \\ S_4 & 0 & -C_4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

$$^{4}T_5 = \begin{bmatrix} C_5 & -S_5 & 0 & 0 \\ S_1 & C_5 & 0 & 0 \\ 0 & 0 & 1 & L_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

To determine the end effector transformation matrix T_e, where $T_e = {}^{0}T_5$, we multiply (2)-(6) together as the following:

$$^{0}T_5 = {}^{0}T_1 * {}^{1}T_2 * {}^{2}T_3 * {}^{3}T_4 * {}^{4}T_5 \quad (7)$$

$$^{0}T_5 = \begin{bmatrix} K_1 & K_4 & K_7 & p_x \\ K_2 & K_5 & K_8 & p_y \\ K_3 & K_6 & K_9 & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

where

$$K_1 = C_1C_5C_{234} + S_1S_5$$

$$K_2 = -C_1S_5 + S_1C_{234}C_5$$

$$K_3 = C_5S_{234}$$

$$K_4 = S_1C_5 + C_1C_{234}S_5$$

$$K_5 = -C_1C_5 - S_1C_{234}S_5$$

$$K_6 = -S_{234}S_5$$

$$K_7 = C_1S_{234}$$

$$K_8 = S_1S_{234}$$

$$K_9 = -C_{234}$$

we can get the value of the end-effector coordinate in cartesian space of the Scorbot-ER 4 U as:

$$\begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} C_1(a + L_3C_{23} + L_5S_{234} + L_2C_2) \\ S_1(a + L_3S_{23} + L_5C_{234} + L_2C_2) \\ L_1 + L_3S_{23} - L_5C_{234} + L_2S_2 \end{bmatrix} \quad (9)$$

where also $S_x = \sin\theta_x$, $C_x = \cos\theta_x$, $S_{xy} = \sin(\theta_x + \theta_z)$, $C_{xy} = \cos(\theta_x + \theta_y)$, $S_{xyz} = \sin(\theta_x + \theta_y + \theta_z)$, $C_{xyz} = \cos(\theta_x + \theta_y + \theta_z)$.

III. Validation of Forward Kinematics Model

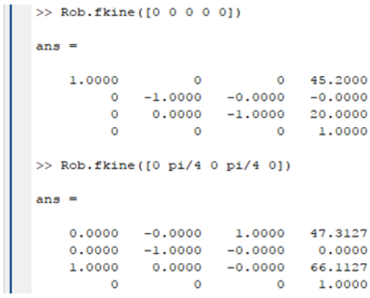
The forward kinematics model of Scorbot-ER 4U has been validated by using robotics toolbox in MATLAB. To examine the accuracy of the mathematics model in (8), we have made the comparison between the results from (8) and MATLAB. Given the various angle set as input to the developed forward kinematics model (8) and MATLAB toolbox, the corresponding results have been compared and plotted.

Assuming joint angle configuration $[\theta_1\ \theta_2\ \theta_3\ \theta_4\ \theta_5]$ as [0 0 0 0 0]; the position and orientation of the end-effector as computed from using (8) is as the following:

$$\begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} 45.2 \\ 0 \\ 20 \end{bmatrix}$$

Assuming joint angle configuration $[\theta_1\ \theta_2\ \theta_3\ \theta_4\ \theta_5]$ as [0 45° 0 45° 0], the position and orientation of the end-effector also computed from using (8) is as the following:

$$\begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} 47.31270 \\ 0 \\ 66.11270 \end{bmatrix}$$



```
>> Rob.fkine([0 0 0 0 0])

ans =

    1.0000         0         0   45.2000
         0   -1.0000   -0.0000   -0.0000
         0    0.0000   -1.0000   20.0000
         0         0         0    1.0000

>> Rob.fkine([0 pi/4 0 pi/4 0])

ans =

    0.0000   -0.0000    1.0000   47.3127
    0.0000   -1.0000   -0.0000    0.0000
    1.0000    0.0000   -0.0000   66.1127
         0         0         0    1.0000
```

Fig. 3 Using command 'Rob.fkine' in Matlab

By using the command 'Rob.fkine' in MATLAB, we obtained the same result, as shown in Fig. 3. Figs. 4 and 5 show MATLAB plot for these joint configurations.

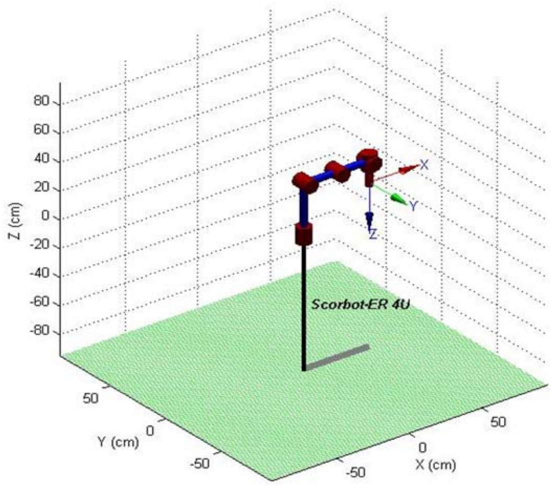


Fig. 4 Plot for joint angle configuration [0 0 0 0 0]

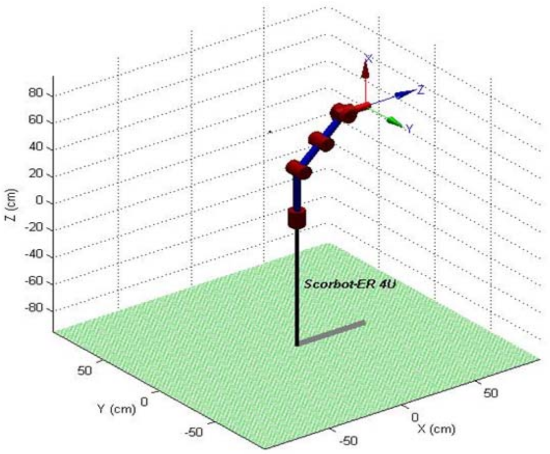


Fig. 5 Plot for joint angle configuration [0 45º 0 45º 0]

IV. Control System

The control method in this research is called PC-and EtherCAT based control. Ethernet for Control Automation Technoloy (EtherCAT) is an Ethernet-Based field bus system invented by Beckhoff Automation.

The PC-and EtherCAT based control in this research requires a personal computer (PC) running a 32-bit windows operating system to install the TwinCAT NC PTP software that supports IEC61131-3 programming language standard for coding and controlling the Scorbot-ER 4U robotics arm.

Fig. 6 shows the configuration of the control method. It mainly contains a personal computer running a 32-bit windows XP, a Ethernet PCI network card FC9011 which is installed in PCI slot of the computer, an EtherCAT coupler BK9011 that is connected with the Ethernet PCI network card via Ethernet cable, a digital input bus terminal card KL1408 that is used to get the signal from each limit switch of the robot, three bus terminal cards KL2552 that can enable direct operation of all DC motors with their optical encoders of Scorbot-ER 4U and a bus end terminal card KL9010. The installation of these components is shown in Fig. 7.

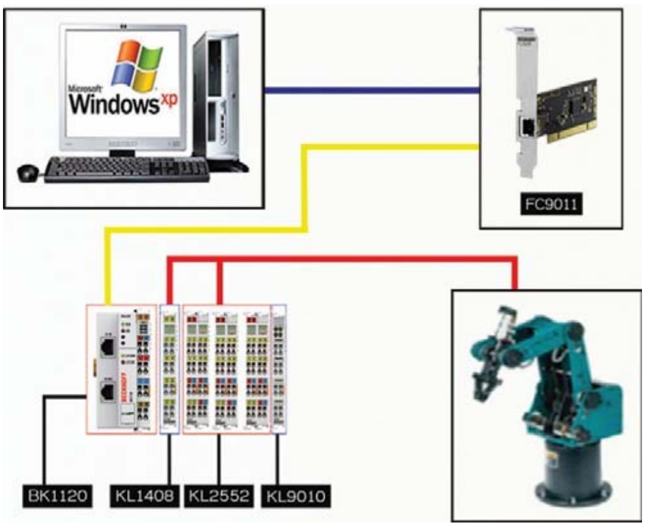


Fig. 6 Control system configuration

V. Experiments

In the experiment, the Scorbot-ER 4U robot arm is tested to express pick and place task by using PC-and EtherCAT based control method described in Section III.

Besides coding the robot arm on the TwinCAT software, the researchers designed a control displayed screen on personal computer as shown in Fig. 8 to facilitate for the users to control the robotic arm. On the displayed control screen, the users can jog each axis of the robotic arm, and also run the full program for expressing the pick and place task; moreover, the users can be aware of its all encoder values that are shown on the screen.

To perform the pick and place task, the robotic arm is controlled to move a small cylinder shape object from its located position to a new desired position in the robotic arm workspace. Fig. 9 demonstrates the arm moving from its home position (with all encoder values as zero) to the located position of the object and then the arm's gripper closes to pick the object up as shown in Fig. 10. Fig. 11 shows the motion of the robot with picking the object in its gripper toward destination point to place the object, after reaching the target, the gripper opens to drop the object. After that, the robotic arm continuous to move to its initial position as shown in Fig. 13.

Fig. 7 Control system and robotics arm installation

In this section, the researchers also tested on the accuracy of movement of each axis of the robotic arm. The researchers coded to move each axis to the desired position and make comparison between the position that determined in the code with the position of its encoder value where each axis reached. By this way, the researchers tested each axis for 100 times, and observed that there were error values occurred in the 100 times test. These error values are shown in Figs. 13-17.

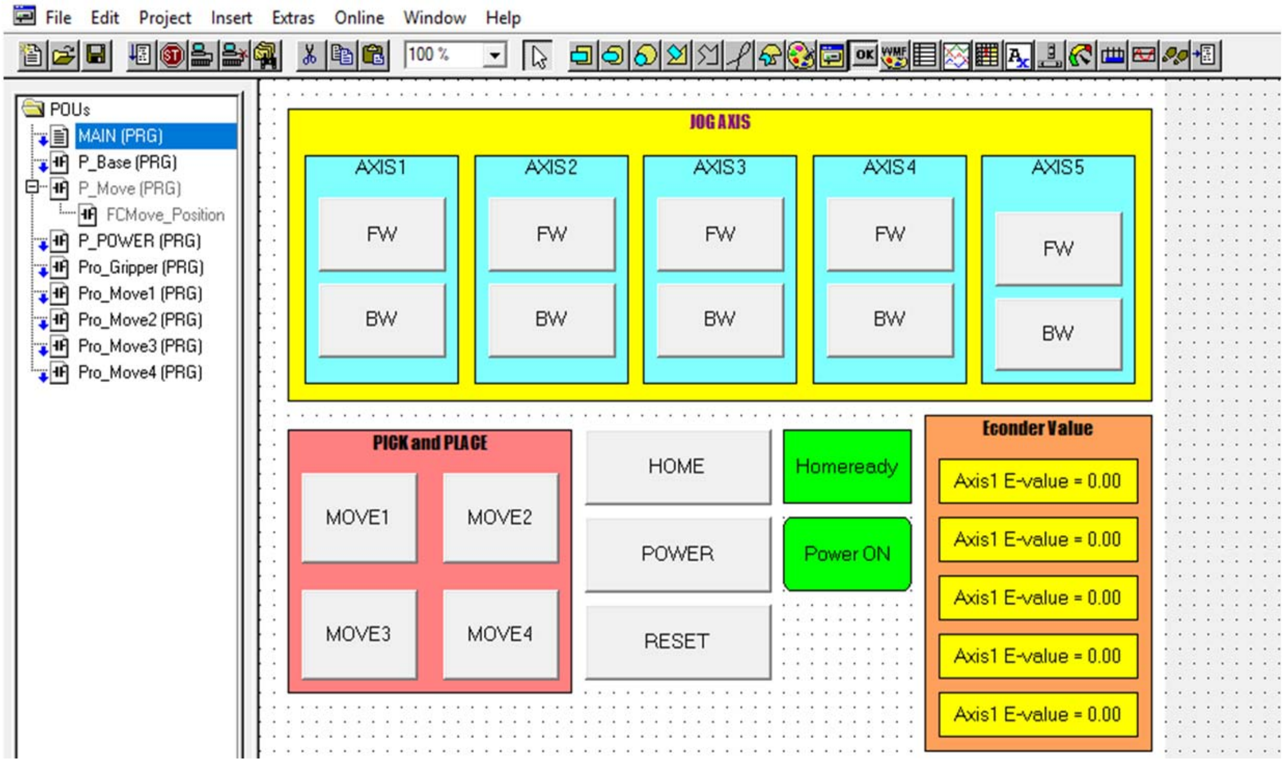


Fig. 8 Displayed control screen

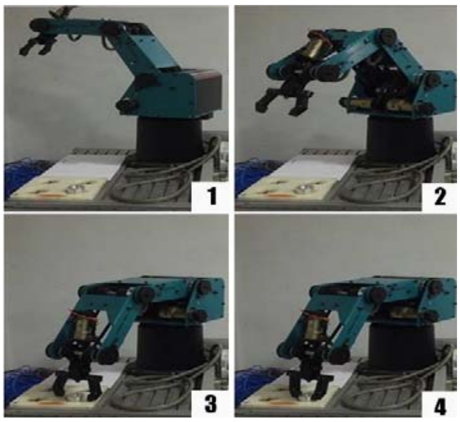


Fig. 9 Arm moving from home toward the object

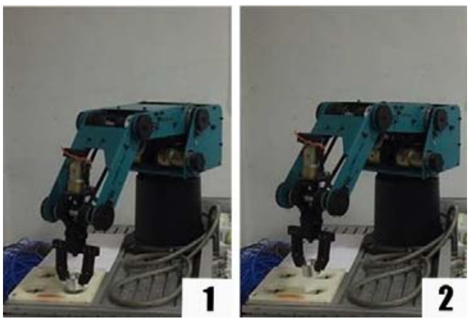


Fig. 10 Arm picking up the object

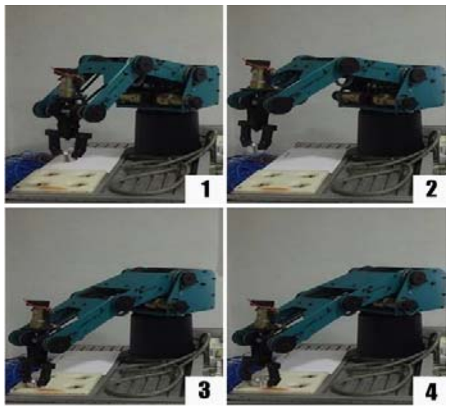


Fig. 11 Arm moving to drop the object

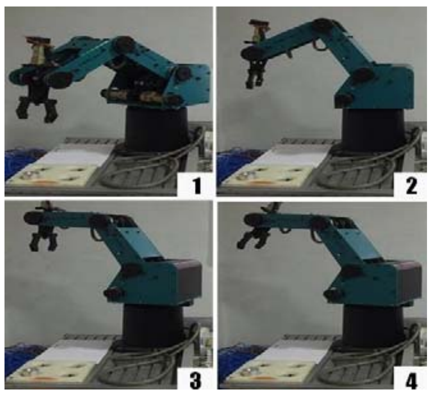


Fig. 12 Arm moving back to home

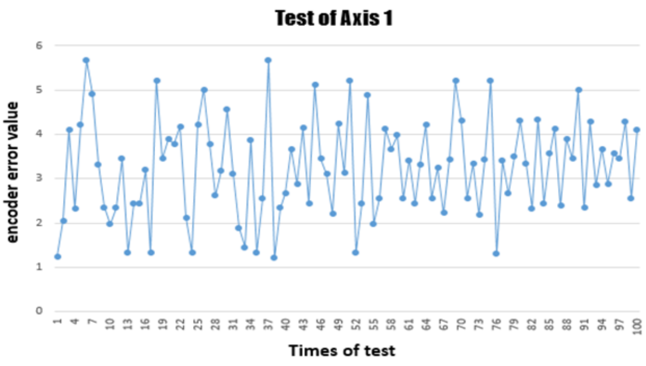


Fig. 13 Error values of Axis 1

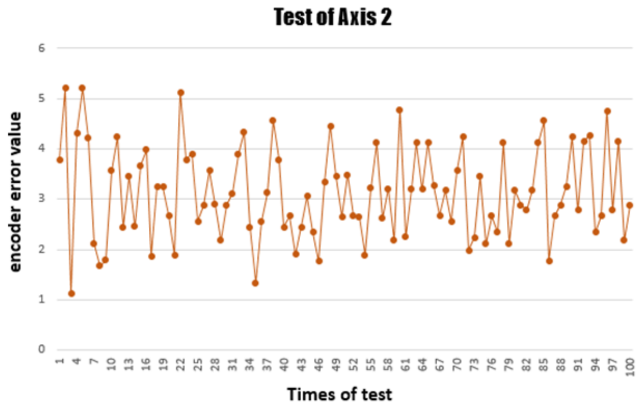


Fig. 14 Error values of Axis 2

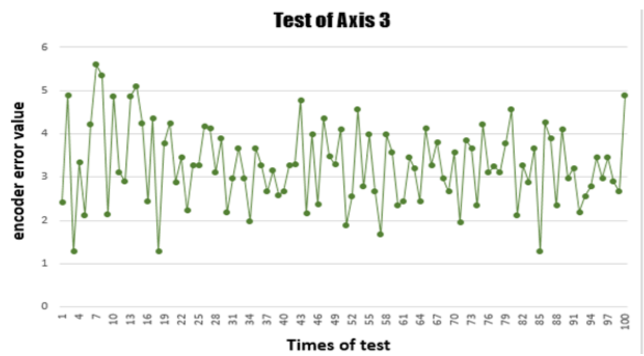


Fig. 15 Error values of Axis 3

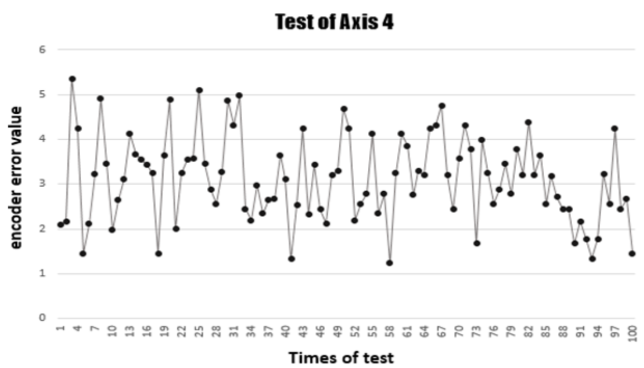


Fig. 16 Error values of Axis 4

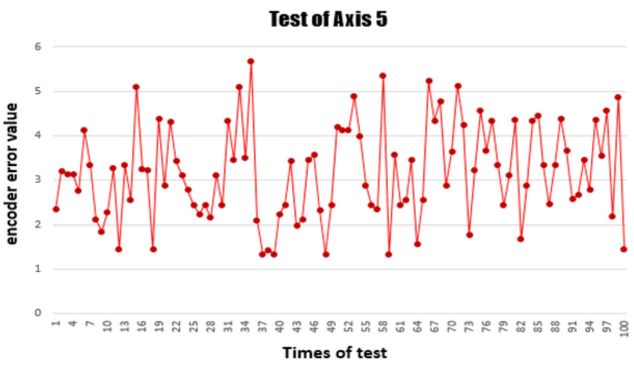


Fig. 17 Error values of Axis 5

VI. Conclusions

This paper described about forward kinematics analysis of the Scorbot-ER 4 U arm by using Denavit-Hartenberg model. Forward kinematics model has been validated in MATLAB by using the robotics toolbox, and the results that we got from MATLAB match exactly with that from using Denavit-Hartenberg model. The paper also presented about PC-and EtherCAT based control which is the technology invented by Beckhoff automation. This control method was used to control the robotic arm to express pick and place task. With this control method, the authors have tested the accuracy of each axis of the robotic arm 100 times, then made the comparison between the encoder values from code with the values that the robot arm reached. In the 100-time test, we got the different average error values of each axis. The average values of axis1 is ±3.2451 mm, ±3.123 mm for axis2, ±3.2754 mm for axis3, ±3.1094 mm for axis4 and ±3.171 mm for axis5. The average error values of each axis are very optimal that we can run the robotic arm to pick and place the object effectively.

Acknowledgments

This research was supported by department of Mechatronics Engineering, Rajamangala University of Technology Thanyaburi.

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