On the Mentor Arm Position Placement Problem: A forward Kinematics Analysis

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Abstract **This paper presents a forward kinematics model predicated on Denavit Hartenberg's (DH) analytical scheme for robot arm position analysis. The developed model aims at predicting and recovering the end-effecter's position of a real robot nomenclatured "Mentor arm" for different joint variables. The Mentor arm is an articulated robot arm characterized with five rotary joint axes. It is basically a serial manipulator whose geometrical configuration consists of a waist, shoulder, elbow, left wrist axle, right wrist axle and an end-effecter gripping mechanism. The basic challenge associated with the Mentor arm is the limited information available on its governing control model for position placement. Two ways by which control can be effected on the Mentor arm include: the use of a simulator and the Workcell Amalgamated Logical Linguistic Instructions (WALLI) software. The non-versatility of this control software is seen in the non-availability of a programmable environment by users. The user interface of WALLI allows for numeric keyboard inputs such that each input results in the orientation of a specific joint by a margin equivalent to the input. The relationship between the keyboard inputs and joint motion of the arm is not feasible to the users. The proposed DH scheme as presented herein has successfully reproduced the end-effecter position of the Mentor arm with marginal differences for different experimental trials.**

Keywords: Forward Kinematics, D-H Concept, Mentor arm, Walli Software

I. INTRODUCTION

The Mentor arm is an articulated robot arm characterized with five rotary joint axes. It is basically a serial manipulator whose geometrical configuration consists of a waist, shoulder, elbow, left wrist axle, right wrist axle and an end-effecter gripping mechanism. Two ways by which control could be effected on the Mentor arm are namely: the use of a simulator or the use of the Workcell Amalgamated Logical Linguistic Instructions (WALLI) software interface via the keyboard. The governing analytical control scheme upon which the WALLI software works is not readily available. The fundamental challenge is to develop a kinematic model based on an analytical scheme that can reproduce a similar result as the WALLI software or the simulator in respect of the Mentor arm end-effecter position.

The kinematics of manipulators involves the study of the geometric and time based properties of the motion and in particular how the various links move with respect to one another and with time. Also, it is an analytical description of the spatial movement of the robot like a function of time and a relationship between the position and the orientation (localization) of the robot's final link and the values of their joint coordinates. Forward kinematics is the problem of solving the cartesian position and orientation of a mechanism given the knowledge of the kinematic structure and the joint coordinates. It involves placing the robot's final link (position and orientation), with respect to a reference system of coordinates, resolving the values of each link and the geometric parameters of the robot's elements.

This paper presents a forward kinematics model predicated on Denavit Hartenberg's (DH) analytical scheme for robot arm position placement. The developed model aims at predicting and recovering the end-effecter position of a real robot (Mentor arm) for different joint variables. The basic challenge associated with the use of the Mentor arm as shown in Figure 1 is the limited information on the governing model for the arm position placement problem.

Popovic et al. [1], developed a procedure for the analysis of upper extremity movement of the arm while Clothier and Shang [2], presented a geometric approach to solving the unknown joint angles required for the autonomous positioning of a robotic arm. Sahu et al. [3], proposed a new method known as quaternion algebra to solve the forward kinematics problem while Man et al. [4], proposed a mathematical and theoretical foundation for the design of the configuration and kinematic analysis of a novel humanoid robot. Also, Wang et al. [5], reviewed full body kinematics of a radial symmetrical six-legged robot with statically stable movements while Cubero [6], described a general purpose

Inverse Kinematics (IK) method for solving all the joint variables for any type of serial-link robotic manipulator using its Forward Kinematic (FK) solution. A Virtual model robot was developed by Kuma [7], in the MATLAB environment. The virtual system performs forward kinematics and inverse kinematics in addition to providing a simulation of the robot teach box. Cho et al. [8] presented a forward and inverse kinematics novel static deflection compensation algorithm for LCD glass-handling robot. Rodriguez-Donate et al. [9], proposed a fused smart sensor network to estimate the forward kinematics of an industrial robot using Kalman filters. Parasuraman [10] presented a new approach to control the manipulators for Humanoid robot using the Denavit Hardenberg (D-H) concept while Izadbakhsh and Fateh [11] presented a model-free robust control (MFRC) approach for position control of robot manipulators in the state space. Sivaraman et al. [12] applied the robot kinematic theory to agriculture.

Figure 1: A Pictorial View of the Mentor Robot Arm

II. Kinematic Analysis of the Mentor Robot Arm

Table 1: Mentor Robot Arm Kinematic Structure and Design Specifications

AXIS	**ANGULAR MOVEMENT(degrees)**	**AXLE CENTRE LENGTH(mm)**
Axis 0 (waist)	210	185
Axis 1 (Shoulder)	180	165
Axis 2 (Elbow)	230	150
Axis 3 (Left Wrist Axle)	320	0
Axis 4 (Right Wrist Axle)	320	0
Wrist Pitch	140^0	_
Wrist Roll:	320^0	_

PROPERTIES	**SPECIFICATION**
Repeatability	2mm
Lifting (Payload)	1000gm at full reach
Reach	428mm from 1 axle centre
Base	320 x 270 x 189 (mm)
Control System	8 bit (0.4%)
Gripper	Jaw opening 45mm and Jaw pressure 10N

A. Generalized Denavit-Hartenberg (D-H) Convention

The study of position analysis problem of a robot arm can be carried out by different methods. Two commonly used methods are Denavit-Hartenberg's (D-H) method and method of successive screw displacement. Both methods are systematic in nature and more suitable for the kinematic analysis of complex serial manipulator architecture. Also used frequently by some scientists and researchers for the serial manipulators of relatively simple geometry and for the analysis of parallel manipulators is the geometric method Tsai [13]. Denavit-Hartenberg's method (D-H) was used to perform the kinematic study of the mentor robot arm in this paper as a result of its associated merits such as versatility and general acceptability for modeling of n joints and links of serial link manipulator regardless of arm complexity.

The D-H technique works with the quadruple $\{a_i, \alpha_i, \theta_i, d_i\}$ which represents link length, twist angle, joint angle and link offset distance respectively. It also labels an orthonormal (x, y, z) coordinate system to each robot joint. Following Denavit-Hartenberg's [14] convention, a cartesian coordinate system is attached to each link of a manipulator, except for the base and end-effector link. The following parameters as listed below are uniquely determined by the geometry of the axes:

a_i: represents the length of the ith link or offset distance between two adjacent joint axes where

d_i: represents the translational distance between two incident normals of a joint axis.

α_i: represents the twist angle between two adjacent joint axes.

θ_i: represents the joint angle between two incident normals of a joint axis.

The four basic transformation matrices about the moving coordinate axes of the respective joints are given as:

$$T_{(z,d)} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad T_{(z,\theta)} = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & 0 \\ s\theta_i & c\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{(x,a)} = \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad T_{(x,\alpha_i)} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c\alpha_i & -s\alpha_i & 0 \\ 0 & s\alpha_i & c\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^{i-1}T_i = T(z,d)T(z,\theta)T(x,a)T(x,\alpha)$$

Expanding the expression for ${}^{i-1}T_i$, we obtain

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

which is the Denavit-Hartenberg (D-H) transformation matrix. The trailing subscript $_{(i)}$ and the leading superscript $^{(i-1)}$ denote that the transformation takes place from the i^{th} coordinate system to the $(i-1)^{th}$ coordinate system.

B. DH Modeling of the Mentor Arm

Figures 2 and 3 respectively show a diagrammatic and plain view of the DH representation of the mentor robot arm. This is an anthropomorphic five-jointed manipulator consisting of five revolute joints and no prismatic joints. The first three joints are used to move the tool point to its desired position while the last two joints adjust the orientation of end-effector. The D-H parameters were found by assigning a local frame reference at every joint as shown below. Anticlockwise rotation is taken to be positive for the joint axis direction convention.

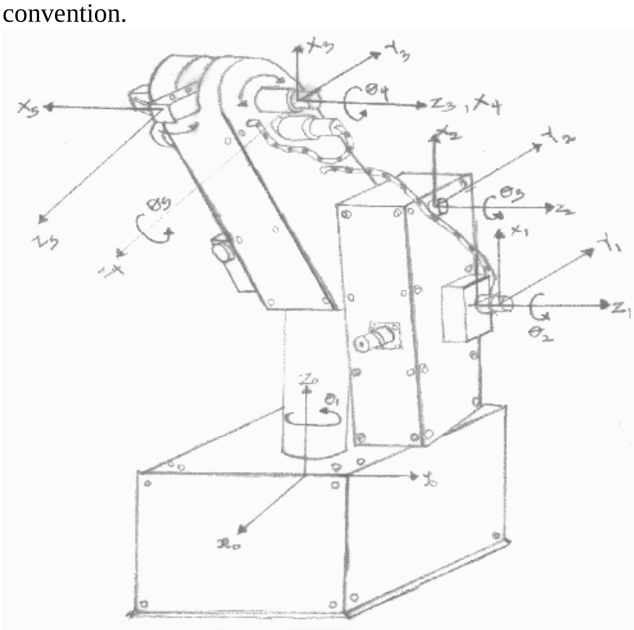

Figure 2: A diagrammatic view of DH Coordinate assignment for the Mentor arm

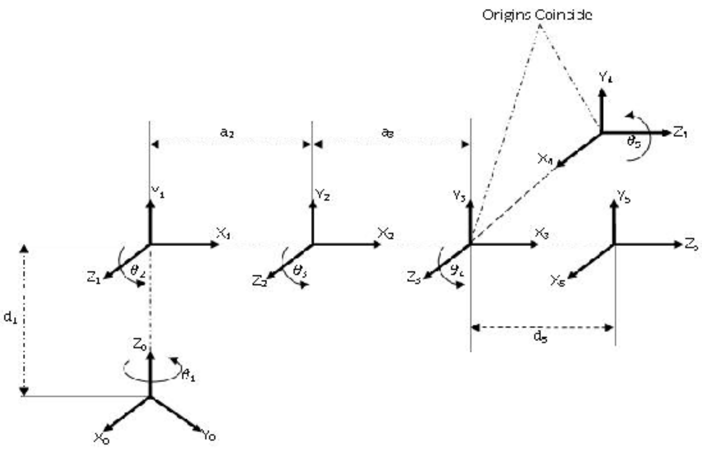

Figure 3: A plain view of D-H Coordinates for the Mentor robot arm

The D-H parameter table shows the four basic parameters considered for the D-H kinematic analysis and their corresponding values for each of the links that make up the robot arm. However, table 2 shows the D-H parameter table for the five jointed space robot arm.

TABLE 2: D-H PARAMETERS for the Mentor Robot Arm

Link i	**Joint angle, θi Degrees**	**Twist angle, αi degrees**	**Link length, a_i mm**	**Link offset, di mm**
1	θ_1	90	0	185
2	θ_2	0	165	0
3	θ_3	0	150	0
4	θ_4	90	0	0
5	θ_5	0	0	110

Using the DH convention, the forward kinematics of the Mentor arm can be obtained from the relationship:

as: $${}^{0}T_n = \prod_{i=1}^{n} {}^{i-1}T_i \qquad {}^{0}T_5 = \prod_{i=1}^{5} {}^{i-1}T_i$$

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

$$
{}^{0}T_1 = \begin{bmatrix} C\theta_1 & 0 & S\theta_1 & 0 \\ S\theta_1 & 0 & -C\theta_1 & 0 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^{1}T_2 = \begin{bmatrix} C\theta_2 & -S\theta_2 & 0 & a_2 C\theta_2 \\ S\theta_2 & C\theta_2 & 0 & a_2 S\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{2}T_3 = \begin{bmatrix} C\theta_3 & -S\theta_3 & 0 & a_3 C\theta_3 \\ S\theta_3 & C\theta_3 & 0 & a_3 S\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^{3}T_4 = \begin{bmatrix} C\theta_4 & 0 & S\theta_4 & 0 \\ S\theta_4 & 0 & -C\theta_4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{4}T_{5} = \begin{bmatrix} C\theta_5 & -S\theta_5 & 0 & 0 \\ S\theta_5 & C\theta_5 & 0 & 0 \\ 0 & 0 & 1 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

III. RESULTS AND DISCUSSION

The simulation results as presented are for the forward kinematic analysis of the mentor robot arm as modeled using the DH concept. Simulations were conducted using Matlab Robotics Toolbox on an Intel (R) Core (TM) Duo CPU T2400 @ 1.83GHz, 1.00GB Memory (RAM), 32bit Operating System. The Matlab Robotics Toolbox (version 7) was used to represent the primary functions of the serial link manipulator by description matrices. The variables θ1 θ2 θ3 θ4 and θ5 respectively represent the joint axes 0 through 4. The result of end effecter's position from Matlab simulation was then compared with experimental result generated from inbuilt mentor software (Wallis 4).

For different keyboard values entered on the WALLI software, the corresponding joint angles, experimental and simulation positions for the end-effecter are presented as shown in Figures 4-11.

A. Experiment 1

Joint 1: Axis 0 = 128 ➔ θ_1= 0;Joint 2: Axis 1 = 155 ➔ θ_2= 0
Joint 3: Axis 2 = 128 ➔ θ_3= 0; Joint 4: Axis 3 = 128 ➔ θ_3= 0
Joint 5: Axis 4 = 128 ➔ θ_5= 0
The forward kinematics matrix from the DH model is given as:

$$
T = \begin{bmatrix} -1.0000 & -0.0000 & 0.0000 & 0.0000 \\ 0.0000 & -1.0000 & 0 & 0.0000 \\ 0.0000 & 0 & 1.0000 & 0.8000 \\ 0 & 0 & 0 & 1.0000 \end{bmatrix}
$$

The resulting end-effecter's position as plotted on the Matlab Robotics Toolbox is as shown in figure 4. The variables P_x, P_y, and P_z as given by the WALLI software are; Px = 1, Py = 0, Pz =801 all in millimeters while the analytical values using DH model were given as: P_x = 0.000, P_y = 0.000, P_z = 0.800 in meters.

B. Experiment 2

Joint 1: Axis 0 = 255 ➔ θ_1= 105^0 ;Joint 2: Axis 1 = 155 ➔ θ_2= 0
Joint 3: Axis 2 = 128 ➔ θ_3= 0 ;Joint 4: Axis 3 = 128 ➔ θ_4= 0
Joint 5: Axis 4 = 128 ➔ θ_5= 0
The forward kinematics matrix from the DH model is given as:

$$
T = \begin{bmatrix} 0.2588 & 0.9659 & -0.0000 & -0.0000 \\ -0.9659 & 0.2588 & 0.0000 & 0.0000 \\ 0.0000 & 0 & 1.0000 & 0.8000 \\ 0 & 0 & 0 & 1.0000 \end{bmatrix}
$$

The resulting end-effecter's position as plotted on the Matlab Robotics Toolbox is as shown in figure 5. The variables P_x, P_y, and P_z as given by the WALLI software are; Px = -1, Py = 6, Pz = 801 all in millimeters while the analytical values using DH model were given as: P_x = 0.000, P_y = 0.000, P_z = 0.800 in meters.

C. Experiment 3

Joint 1: Axis 0 = 128 ➔ θ_1= 0^0 ; Joint 2: Axis 1 = 0 ➔ θ_2= 70 ;
Joint 3: Axis 2 = 128 ➔ θ_3= 0 ; Joint 4: Axis 3 = 128 ➔θ_4= 0 ;
Joint 5: Axis 4 = 128 ➔ θ_5= 0
The forward kinematics matrix from the DH model is given as:

$$
T = \begin{bmatrix} -0.3420 & 0.0000 & -0.9397 & -0.3994 \\ -0.0000 & -1.0000 & -0.0000 & 0.0000 \\ -0.9397 & 0.0000 & 1.3420 & 0.5204 \\ 0 & 0 & 0 & 1.0000 \end{bmatrix}
$$

The resulting end-effecter's position as plotted on the Matlab Robotics Toolbox is as shown in figure 6. The variables P_x, P_y, and P_z as given by the WALLI software are; Px = -400, Py = 6, Pz = 524 all in millimeters while the analytical values using DH model were given as: P_x = -0.3994, P_y = 0.000, P_z = 0.5204 in meters.

D. Experiment 4

Joint 1: Axis 0 = 128 ➔ θ_1= 0^0 ;Joint 2: Axis 1 = 255 ➔ θ_6= -110
Joint 3: Axis 2 = 128 ➔ θ_3= 0 ; Joint 4: Axis 3 = 128 ➔ θ_4 = 0
Joint 5: Axis 4 = 128 ➔ θ_5= 0
The forward kinematics matrix from the DH model is given as:

$$
T = \begin{bmatrix} 0.3421 & -0.0000 & 0.9397 & 0.3994 \\ 0.0000 & -1.0000 & -0.0000 & -0.0000 \\ 0.9397 & 0.0000 & -0.3420 & 0.2296 \\ 0 & 0 & 0 & 1.0000 \end{bmatrix}
$$

The resulting end-effecter's position as plotted on the Matlab Robotics Toolbox is as shown in figure 7. The variables P_x, P_y, and P_z as given by the WALLI software are; Px = -, Py = 6, Pz = 524 all in millimeters while the analytical values using DH model were given as: P_x =-0.3994, P_y = -0.000, P_z = 0.2296 in meters.

E. Experiment 5

Assuming the following values are entered (for the mentor arm joint axes) on the WALLI software, the resulting joint angles are as stated below:
Joint 1: Axis 0 = 128 ➔ θ_1= 0^0 ; Joint 2: Axis 1 = 155 ➔ θ_2= 0
Joint 3: Axis 2 = 255 ➔ θ_3= 115; Joint 4: Axis 3 = 128 ➔ θ_4= 0
Joint 5: Axis 4 = 128 ➔ θ_5= 0
The forward kinematics matrix from the DH model is given as:

$$
T = \begin{bmatrix} 0.4226 & 0.0000 & -0.9063 & -0.2356 \\ -0.0000 & -1.0000 & -0.0000 & -0.0000 \\ -0.9063 & 0.0000 & -0.4226 & 0.4301 \\ 0 & 0 & 0 & 1.0000 \end{bmatrix}
$$

The resulting end-effecter's position as plotted on the Matlab Robotics Toolbox is as shown in figure 8. The variables P_x, P_y, and P_z as given by the WALLI software are; Px = -243, Py = 0, Pz = 436 all in millimeters while the analytical values using DH model were given as: P_x =-0.2356, P_y = -0.000, P_z = 0.4301 in meters.

F. Experiment 6

Assuming the following values are entered (for the mentor arm joint axes) on the WALLI software, the resulting joint angles are as stated below:
Joint 1: Axis 0 = 128 ➔ $\theta_1 = 0^0$; Joint 2: Axis 1 = 155➔ $\theta_2 = 0$
Joint 3: Axis 2 = 0 ➔ $\theta_3 = -115$; Joint 4: Axis 3 = 128 ➔ $\theta_4 = 0$;
Joint 5: Axis 4 = 128 ➔ $\theta_4 = 0$
The forward kinematics matrix from the DH model is given as:

$$T = \begin{bmatrix} 0.4226 & -0.0000 & 0.9063 & 0.2356 \\ 0.0000 & -1.0000 & -0.0000 & -0.0000 \\ 0.9063 & 0.0000 & -0.4226 & 0.4301 \\ 0 & 0 & 0 & 1.0000 \end{bmatrix}$$

The resulting end-effecter's position as plotted on the Matlab Robotics Toolbox is as shown in figure 9. The variables P_x, P_y, and P_z as given by the WALLI software are; Px = 240, Py = 0, Pz = 432 all in millimeters while the analytical values using DH model were given as: P_x = -0.2356, P_y = -0.0000, P_z = 0.4301 in meters.

G. Experiment 7

Assuming the following values are entered (for the mentor arm joint axes) on the WALLI software, the resulting joint angles are as stated below:
Joint 1: Axis 0 = 128 ➔$\theta_1 = 0$;Joint 2: Axis 1 = 155➔ $\theta_2 = 0$
Joint 3: Axis 2 = 128 ➔$\theta_3 = 0$;Joint 4: Axis 3 = 242 ➔ $\theta_4 = 70$
Joint 5: Axis 4 = 128 ➔ $\theta_5 = 0$

The forward kinematics matrix from the DH model is given as:

$$T = \begin{bmatrix} -0.3420 & 0.0000 & -0.9397 & -0.1034 \\ -0.0000 & -1.0000 & -0.0000 & 0.0000 \\ -0.9063 & 0.0000 & 0.3420 & 0.7276 \\ 0 & 0 & 0 & 1.0000 \end{bmatrix}$$

The resulting end-effecter's position as plotted on the Matlab Robotics Toolbox is as shown in figure 10. The variables P_x, P_y, and P_z as given by the WALLI software are; Px = -101, Py = 0, Pz = 730 all in millimeters while the analytical values using DH model were given as: P_x = -.1034, P_y = 0.0000, P_z = 0.7276 in meters.

H. Experiment 8

Assuming the following values are entered (for the mentor arm joint axes) on the WALLI software, the resulting joint angles are as stated below:
Joint 1: Axis 0 = 0 ➔ $\theta_1 = 0^0$; Joint 2: Axis 1 = 155➔ $\theta_2 = 0$
Joint 3: Axis 2 = 255 ➔ $\theta_3 = -70$; Joint 4: Axis 3 = 128 ➔ $\theta_4 = 0$
Joint 5: Axis 4 = 128 ➔ $\theta_5 = 0$
The forward kinematics matrix from the DH model is given as:

$$T = \begin{bmatrix} -0.3420 & -0.0000 & 0.9397 & 0.1034 \\ 0.0000 & -1.0000 & -0.0000 & 0.0000 \\ 0.9063 & 0.0000 & 0.3420 & 0.7276 \\ 0 & 0 & 0 & 1.0000 \end{bmatrix}$$

The resulting end-effecter's position as plotted on the Matlab Robotics Toolbox is as shown in figure 11. The variables P_x, P_y, and P_z as given by the WALLI software are; Px = 103, Py = 0, Pz = 732 all in millimeters while the analytical values using DH model were given as: P_x = -.1034, P_y = 0.0000, P_z = 0.7276 in meters.

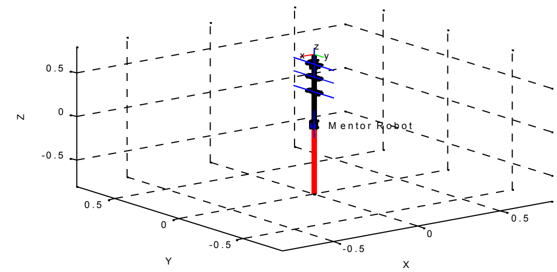

Figure 4: Simulation Plot for Experiment One

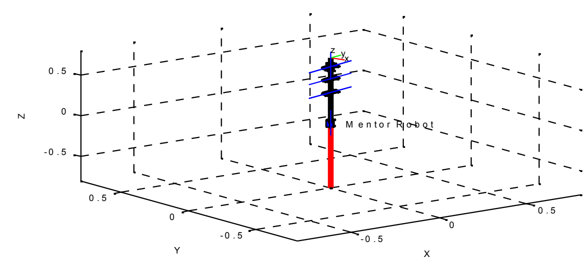

Figure 5: Simulation Plot for Experiment Two

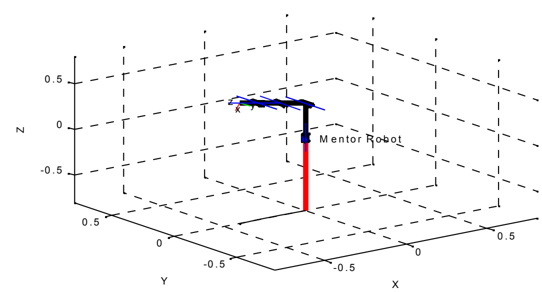

Figure 6: Simulation Plot for Experiment Three

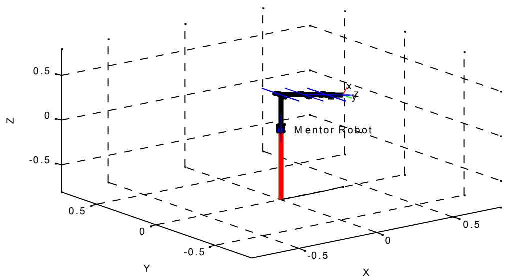

Figure 7: Simulation Plot for Experiment Four

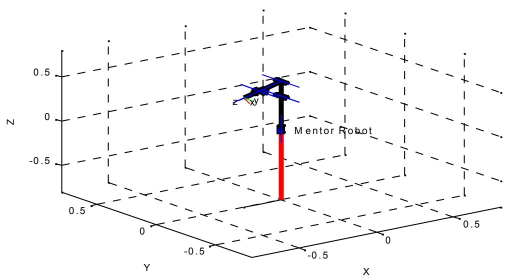

Figure 8: Simulation Plot for Experiment Five

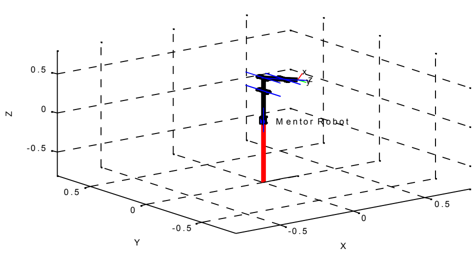

Figure 9: Simulation Plot for Experiment Six

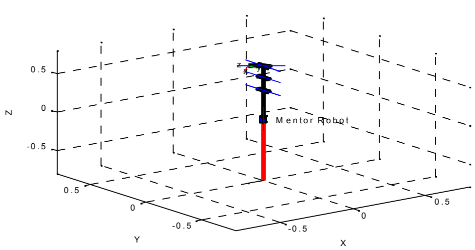

Figure 10: Simulation Plot for Experiment Seven

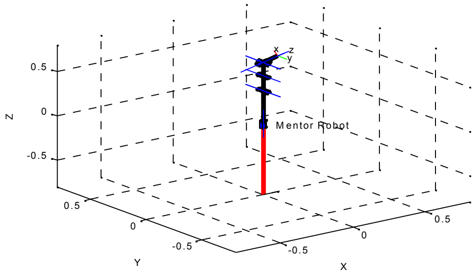

Figure 11: Simulation Plot for Experiment Eight

CONCLUSION

There is a reasonable correlation between the experimental readings obtained from the Mentor arm position analysis software (Walli 3) and the results obtained from the analytical modeling process. There is a high indication that our utmost goal of building a robot arm with a position placement scheme predicated on the DH concept would be realistic. Currently an on going research focused at building a prototype robot arm with position placement scheme hinged on the DH position analysis technique is on going. Further results on the Mentor arm which includes the inverse kinematics analysis and gripper prediction model would be presented in subsequent publication.

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