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Kinematic Modeling and Simulation of a SCARA Robot by Using Solid Dynamics and Verification by MATLAB/Simulink

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Abstract

Simulation of robot systems which is getting very popular, especially with the lowering cost of computers, can be used for layout evaluation, feasibility studies, presentations with animation and off-line programming [1].

In this research, a complete mathematical model of SCARA robot was developed including servomotor dynamics and presented together with dynamic simulation. The equations of kinematics are derived by using D-H notation. Dc servomotor driving each robot joint is studied and modeled. SCARA robot is constructed to achieve drilling operation using solid dynamic software. The performance of robot-actuator system is examined with solid dynamic simulation and verified with MATLAB/simulink. The results of simulations were discussed. An agreement between the two softwares is certainly obtained herein. The facilities of the programs used for kinematic simulation of robot systems were emphasized

Keywords: SCARA robot; Mathematical modeling; kinematics solutions; Simulation; Dc servomotors; MATLAB/simulink and solid dynamics softwares.

Nomenclature

J_1, J_2	moment of inertias of the main and the fore arm (kg m^2)
J_m	motor inertia (kg m^2)
J_{g1},J_{g2}	inertias of the gearbox 1 and 2 (kg m^2)
V_a	armature voltage
L_{a1},L_{a2}	armature inductances of motor 1 and 2 (H)
R	armature circuit resistance (Ω)
φ	the flux per pole,
T	electromagnetic torque developed by the motor (Nm)
B	damping ratio of the mechanical system
ke	electromotive force constant
k_T	torque constant (Nm/amp)
k_ω	speed constant (v\rad\s)
m_1,m_2	masses of the main and the fore arms (kg)
L_1,L_2	lengths of the main and the fore arms (m)
p_x,p_y	horizontal robot coordinates (m)
$\theta_1, \dot{\theta}_1, \ddot{\theta}_1$	angular displacement, velocity and acceleration of the main arm (rad,rad/s,rad/s^2)
$\theta_2, \dot{\theta}_2, \ddot{\theta}_2$	angular displacement, velocity and acceleration of the fore arm (rad,rad/s,rad/s^2)
$d_3, \dot{d}_3, \ddot{d}_3$	translational displacement velocity and acceleration of the quill
g_r	gearreduction ratio
η	efficiency of the system
θ_m	angular position of the motor (rad)
D	warm wheel diameter
θ_L	load angular position

1. Introduction

Robotics is a special engineering science which deals with designing, modeling, controlling and robots' utilization. Nowadays robots accompany people in everyday life and take over their daily routine procedures. The range of robots' utilization is very wide, from toys through office and industrial robots finally to very sophisticated ones needed for space exploration.

A large family of manufacturing equipment among the variety, which exists, is the one which supplies the motion required by a manufacturing process, such as: arc-welding, spray painting, assembly, cutting, polishing, milling, drilling etc. Of this class of equipment, an increasingly popular type is the industrial robot. Different manipulator configurations are available as rectangular, cylindrical, spherical, revolute and horizontal jointed. A horizontal revolute configuration robot, selective compliance articulated robot arm (SCARA) has four degrees of freedom in which two or three horizontal servo controlled joints are shoulder, elbow and wrist. Last. SCARA designed at Japan, is generally suited for small parts insertion tasks for assembly lines like electronic component insertion [2]. Although the final aim is real robotics, it is often very useful to perform simulations prior to investigations with real robots. This is because simulations are easier to setup, less expensive, faster and more convenient to use. Building up new robot models and setting up experiments only takes a few hours. A simulated robotics setup is less expensive than real robots and real world setups, thus allowing a better design exploration. Simulation often runs faster than real robots while all the parameters are easily displayed on screen [3].

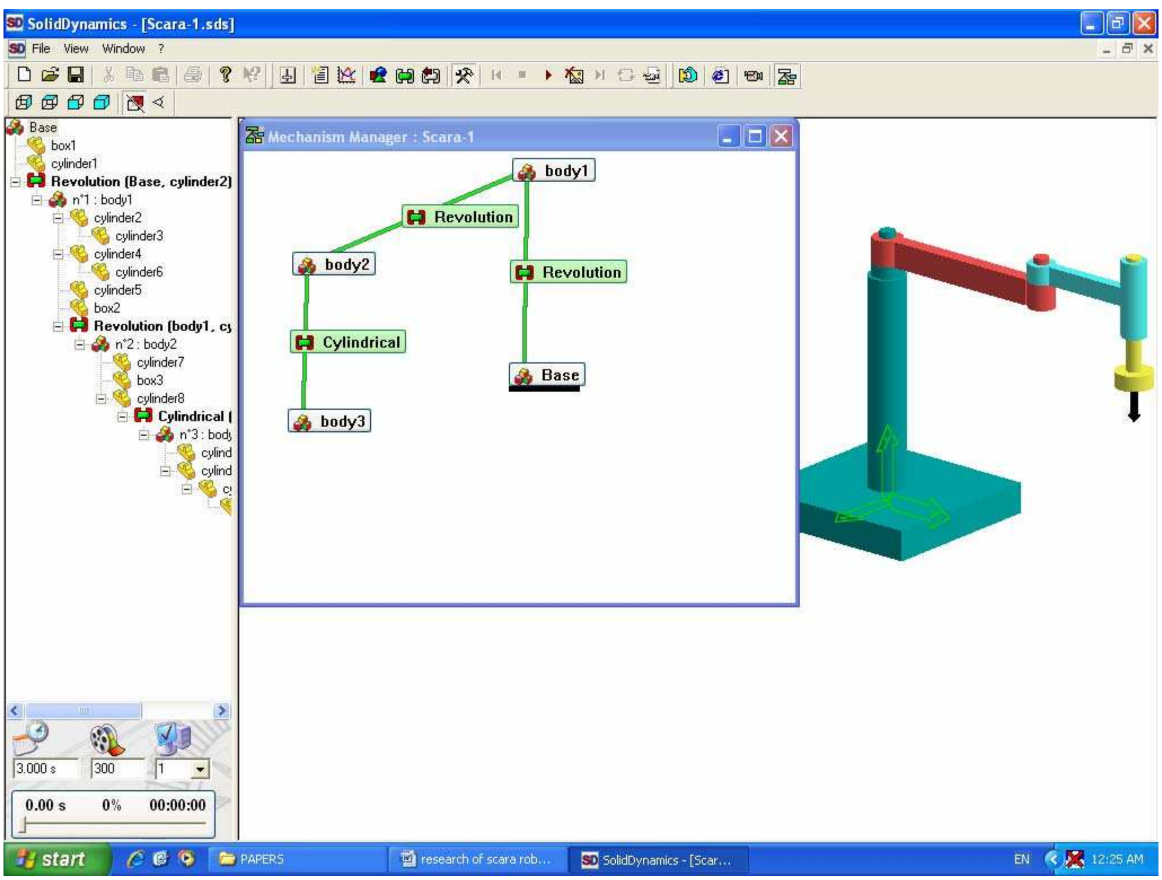
The possibility to perform real-time simulations becomes particularly important in the later stages of the design process. The final design can be verified before one embarks on the costly and time consuming process of building a prototype [4].

The need for accurate and computationally efficient manipulator dynamics has been extensively emphasized in recent years. Modeling and simulation of robot systems by using various program softwares will facilitate the process of designing, constructing and inspecting the robots in the real world. Simulation is important for robot programmers to evaluate, predict the behavior of robot, in addition to verify and optimize the path planning of the process [5]. Moreover, this will save time and money and play important role in the evaluation of manufacturing automation [6]. Being able to simulate opens a wide range of options for solving many problems creatively. You can investigate, design, visualize, and test an object or even if it does not exists [7].

In this work, 4 axis SCARA robot system for drilling task will be designed and developed using SD program as shown in figure 1. The structure will be built depending on the principles of solid bodies modeling with SD technology [8, 9].To emphasize the obtained results in SD program, simulation by using MATLAB/Simulink software will be carried out. The Results of both sofwares will be presented and discussed. In the paper, the equations of kinematics for SCARA robot with the robot dynamics and the actuators-dc servomotors for each joint were developed with D-H formulation. Actuator characteristics; dc servo motors were studied in detail.

The paper is organized as follows: First, an introduction to robotics, robot kinematics is presented in section 2. In section 3, the inverse kinematics of the robot is presented. Fourthly, the dynamics is presented in section 4. Sections 5 and 6 give the actuator equations (actuator modeling) and the transmission equations respectively for the developed robot. In section 7, the simulation and results are presented followed by the conclusions and the references.

Figure 1: General screen of the SD program with (from the left to the right) menus, tool bars, tree structure, 3D window for the constructed SCARA robot at zero position



2. Robot kinematics

The Denavit-Hartenberg (D-H) parameters for SCARA robot specified in figure 2 are defined in table 1:

Figure 2: D-H Parameters for four- joint SCARA Robot

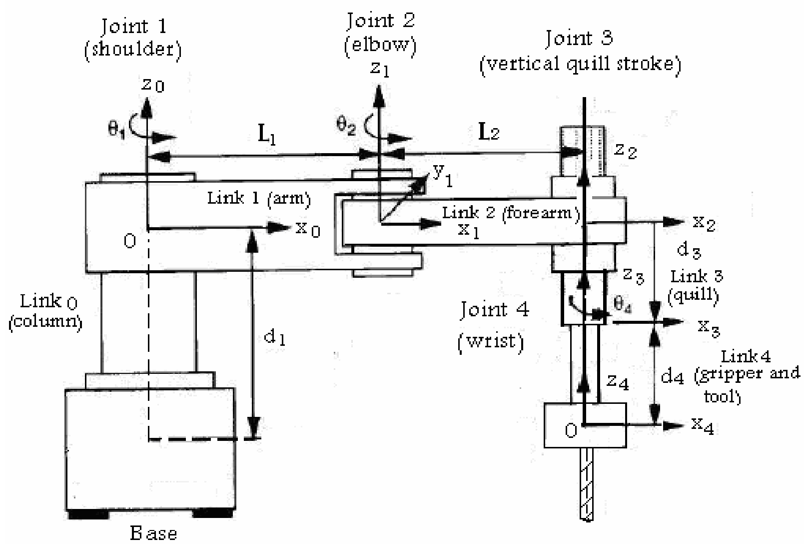


Table1: D-H parameters of the robot

i	**θ_i**	**d_i**	**a_i**	**α_i**
1	θ_1	0	L_1	0
2	θ_2	0	L_2	0
3	0	d_3	0	0
4	θ_4	d_4	0	0

By using (D-H) convention [10], the transformation matrices result in:

$$T_1^0 = A_1 = \begin{bmatrix} c_1 & -s_1 & 0 & L_1c_1 \\ s_1 & c_1 & 0 & L_1s_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$T_2^1 = A_2 = \begin{bmatrix} c_2 & -s_2 & 0 & L_2c_2 \\ s_2 & c_2 & 0 & L_2s_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$T_3^2 = A_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$T_4^3 = A_4 = \begin{bmatrix} c_4 & -s_4 & 0 & 0 \\ s_4 & c_4 & 0 & 0 \\ 0 & 0 & 1 & -d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

After multiplication and use of addition matrices, one gets the total transformation matrix:

$$T_4^0 = \begin{bmatrix} c_{124} & -s_{124} & 0 & L_2 c_{12} + L_1 c_1 \\ s_{124} & c_{124} & 0 & L_2 s_{12} + L_1 s_1 \\ 0 & 0 & 1 & -d_3 - d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

3. Inverse Kinematics of the Robot

3.1. Inverse solution for position:

Desired location of the SCARA robot

$$T_H^R = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

The final equation representing the robot is:

$$T_H^R = A_1 A_2 A_3 A_4 = T_4^0 \tag{7}$$

To solve for the angle θ_4, both sides of equation (7) are successively premultiplied with $A_3^{-1} A_2^{-1} A_1^{-1}$ matrices, such that:

$$A_3^{-1} A_2^{-1} A_1^{-1} T_H^R = A_4 \tag{8}$$

The left side of the equation (8) ($A_3^{-1} A_2^{-1} A_1^{-1} T_H^R$) is:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} c_2 & s_2 & 0 & -L_2 \\ -s_2 & c_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} c_1 & s_1 & 0 & -L_1 \\ -s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & -d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times$$

$$\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} =$$

$$\begin{bmatrix} n_x c_{12} + n_y s_{12} & o_x c_{12} + o_y s_{12} & a_x c_{12} + a_y s_{12} & p_x c_{12} + p_y s_{12} - L_1 c_2 - L_2 \\ -n_x s_{12} + n_y c_{12} & -o_x s_{12} + o_y c_{12} & -a_x s_{12} + a_y c_{12} & -p_x s_{12} + p_y c_{12} - L_1 s_2 \\ n_z & o_z & a_z & p_z + d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

From 1,4 and 2,4 elements of the equations(5) and (6)

$$p_x = L_1 c_1 + L_2 c_{12} \tag{10}$$

$$p_y = L_1 s_1 + L_2 s_{12} \tag{11}$$

From equation10 and equation11,

$$c_2 = \frac{1}{2L_1 L_2}(p_x^2 + p_y^2 - L_1^2 - L_2^2) \tag{12}$$

$$s_2 = \pm\sqrt{1 - c_2^2} \tag{13}$$

$$\theta_2 = \tan^{-1}\frac{s_2}{c_2} \tag{14}$$

Rearranging equation (10) and equation (11) yields:

$$p_x = (L_1 + L_2 c_2)c_1 - L_2 s_2 s_1 \tag{15}$$

$$p_y = L_2 s_2 c_1 + (L_1 + L_2 c_2)s_1 \tag{16}$$

Solving equations (15) and (16) by Kramer's rule:

$$\Delta = \begin{bmatrix} L_1 + L_2 c_2 & -L_2 s_2 \\ L_2 s_2 & L_1 + L_2 c_2 \end{bmatrix} = (L_1 + L_2 c_2)^2 + (L_2 s_2)^2 \tag{17}$$

$$\Delta s_1 = \begin{bmatrix} L_1 + L_2 c_2 & p_x \\ L_2 s_2 & p_y \end{bmatrix} = (L_1 + L_2 c_2)p_y - (L_2 s_2)p_x \tag{18}$$

$$\Delta c_1 = \begin{bmatrix} p_x & -L_2 s_2 \\ p_y & L_1 + L_2 c_2 \end{bmatrix} = (L_1 + L_2 c_2)p_x + L_2 s_2 p_y \tag{19}$$

$$s_1 = \frac{\Delta s_1}{\Delta} = \frac{(L_1 + L_2 c_2)p_y - L_2 s_2 p_x}{(L_1 + L_2 c_2)^2 + (L_2 s_2)^2} = \frac{(L_1 + L_2 c_2)p_y - L_2 s_2 p_x}{p_x^2 + p_y^2} \tag{20}$$

$$c_1 = \frac{\Delta c_1}{\Delta} = \frac{(L_1 + L_2 c_2)p_x + L_2 s_2 p_y}{(L_1 + L_2 c_2)^2 + (L_2 s_2)^2} = \frac{(L_1 + L_2 c_2)p_x - L_2 s_2 p_y}{p_x^2 + p_y^2} \tag{21}$$

$$\theta_1 = \tan^{-1}\frac{s_1}{c_1} = \tan^{-1}\frac{(L_1 + L_2 c_2)p_y - L_2 s_2 p_x}{(L_1 + L_2 c_2)p_x + L_2 s_2 p_y} \tag{22}$$

From 4,4 elements of the equation (5) and(6):

$$d_3 = -p_z - d_4 \tag{23}$$

We have

$$\theta_3 = 0 \tag{24}$$

From1,1 and 2,1 elements of the equation (4) and (9):

$$c_4 = n_x c_{12} + n_y s_{12} \tag{25}$$

$$s_4 = -n_x s_{12} + n_y c_{12} \tag{26}$$

$$\theta_4 = \tan^{-1}\frac{-n_x \sin(\theta_1 + \theta_2) + n_y \cos(\theta_1 + \theta_2)}{n_x \cos(\theta_1 + \theta_2) + n_y \sin(\theta_1 + \theta_2)} \tag{27}$$

3.2. Inverse solution for velocity:

From equation (11) and equation (12):

$$\dot{p}_x = -L_1 s_1 \dot{\theta}_1 - L_2 s_{12}(\dot{\theta}_1 + \dot{\theta}_2) \tag{28}$$

$$\dot{p}_y = +L_1 c_1 \dot{\theta}_1 + L_2 c_{12}(\dot{\theta}_1 + \dot{\theta}_2) \tag{29}$$

So,

$$\dot{p}_x = -(L_1 s_1 + L_2 s_{12})\dot{\theta}_1 - L_2 s_{12}\dot{\theta}_2 \tag{30}$$

$$\dot{p}_y = (L_1 c_1 + L_2 c_{12})\dot{\theta}_1 + L_2 c_{12}\dot{\theta}_2 \tag{31}$$

Using Kramer's rule to solve equation (31) and equation(32):

$$\dot{\theta}_1 = \frac{\dot{p}_x c_{12} + \dot{p}_y s_{12}}{L_1 s_2} \tag{32}$$

$$\dot{\theta}_2 = \frac{-\dot{p}_y(L_1 s_1 + L_2 s_{12}) - \dot{p}_x(L_1 c_1 + L_2 c_{12})}{L_1 L_2 s_2} \tag{33}$$

Translational velocity:

$$\dot{d}_3 = -\dot{p}_z \tag{34}$$

By differentiating the equation (27):

$$c_4 d\theta_4 = -\left[dn_x s_{12} + n_x c_{12}(d\theta_1 + d\theta_2)\right] + d_{ny} c_{12} - n_y s_{12}(d\theta_1 + d\theta_2) \tag{35}$$

So,

$$d\theta_4 = -\frac{d\theta_1 + d\theta_2)}{c_4}(n_x c_{12} + n_y s_{12}) - \frac{s_{12}}{c_4} dn_x + \frac{c_{12}}{c_4} dn_y \tag{36}$$

and finally:

$$\dot{\theta}_4 = \frac{d\theta_4}{dt} = \frac{c_{12}\dot{n}_y - s_{12}\dot{n}_x - (n_x c_{12} + n_y s_{12})\dot{\theta}_{12}}{c_4} \tag{37}$$

3.3. Inverse solution for acceleration:

$$\ddot{\theta}_1 = \frac{(-\dot{p}_x s_{12} + \dot{p}_y c_{12})\dot{\theta}_{12} + (\ddot{p}_x c_{12} + \ddot{p}_y s_{12}) - L_1 c_2 \dot{\theta}_1 \dot{\theta}_2}{L_1 s_1} \tag{38}$$

$$\ddot{\theta}_2 = -\frac{\left[(\ddot{p}_y s_1 - \ddot{p}_x c_1)L_1 + (\ddot{p}_y s_{12} + \ddot{p}_x c_{12})L_2 + (\dot{p}_y c_1 - \dot{p}_x s_1)L_1\dot{\theta}_1 + (\dot{p}_y c_{12} + \dot{p}_x s_{12})L_2\dot{\theta}_{12} + L_1 L_2 c_2 \dot{\theta}_2^2\right]}{L_1 L_2 s_2} \tag{39}$$

$$\ddot{d}_3 = -\ddot{p}_z \tag{40}$$

$$\ddot{\theta}_4 = \frac{\ddot{n}_y c_{12} - \ddot{n}_x s_{12} - (2\dot{n}_y s_{12} + 2\dot{n}_x c_{12})\dot{\theta}_{12} - (n_y c_{12} - n_x s_{12})\dot{\theta}_{12}^2 - (n_x c_{12} + n_y s_{12})\ddot{\theta}_{12} + s_4 \dot{\theta}_4^2}{c_4} \tag{41}$$

4. Dynamics

For SCARA robot figure 3, torques exerted on the robot joints are [11]:

$$T_1 = b_{11}\ddot{\theta}_1 - b_{12}\ddot{\theta}_2 - b_{13}\ddot{d}_3 - b_{14}\dot{\theta}_1\dot{\theta}_2 + b_{15}\dot{\theta}_2^2 \tag{42}$$

$$T_2 = -b_{21}\ddot{\theta}_1 + b_{22}\ddot{\theta}_2 + b_{23}\ddot{d}_3 + b_{24}\dot{\theta}_1^2 \tag{43}$$

$$T_3 = -b_{31}\ddot{\theta}_1 + b_{32}\ddot{\theta}_2 + b_{33}\ddot{d}_3 - b_{34} \tag{44}$$

Where:

$$b_{11} = r_1^2 m_1 + j_1 + g_{r1}^2 j_{m1} + (L_1^2 + r_2^2 + 2L_1 r_2 c_2)m_2 + L_1^2 m_{m2} + j_2 + j_{m2} +$$
$$(L_1^2 + L_2^2 + 2L_1 L_2 c_2)(m_3 + m_{m3}) + j_3 + j_{m3}$$

$$b_{12} = (r_2^2 + L_1 r_2 c_2)m_2 + j_2 + g_{r2} j_{m2} + (L_1^2 + L_1 L_2 c_2)(m_3 + m_{m3}) + j_3 + j_{m3}$$

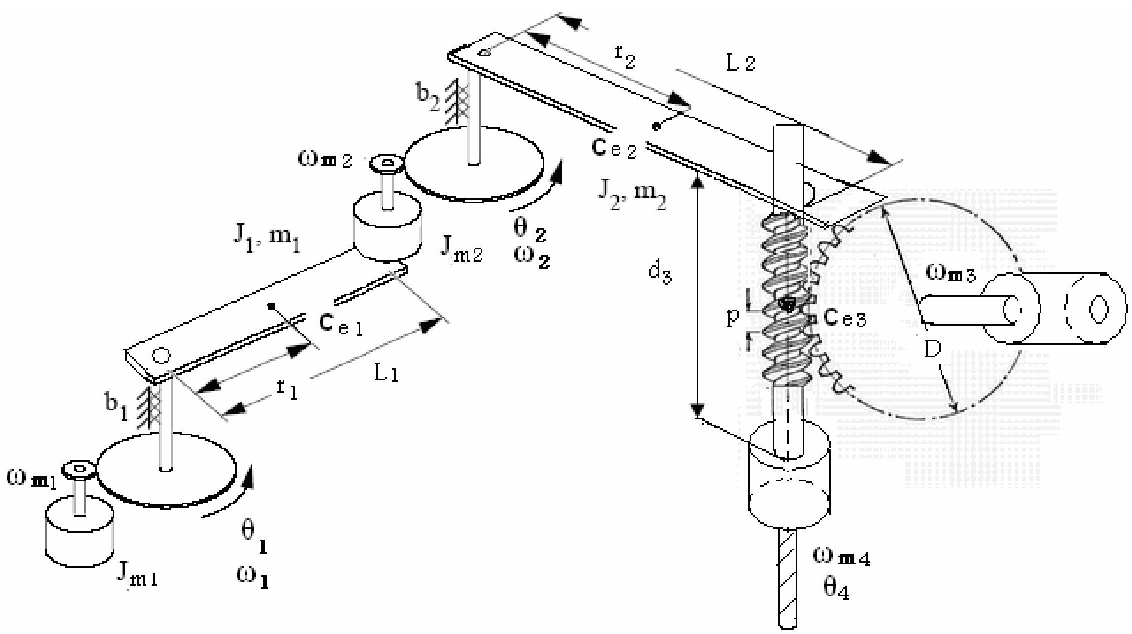
$$b_{13} = g_{r3} j_{m3}$$

$$b_{14} = 2L_1 s_2\left[m_2 r_2 + (m_3 + m_{m3})L_2\right]$$

$$b_{15} = L_1 s_2\left[m_2 r_2 + (m_3 + m_{m3})L_2\right]$$

$$b_{21} = m_2(r_2^2 + L_1 r_2 c_2) + j_2 + g_{r2} j_{m2} + (L_1^2 + L_1 L_2 c_2)(m_3 + m_{m3}) + j_3 + j_{m3}$$
$$b_{22} = r_2^2 m_2 + j_2 + g_{r2}^2 j_{m2} + L_2^2 (m_3 + m_{m3}) + j_3 + j_{m3}$$
$$b_{23} = g_{r3} j_{m3}$$
$$b_{24} = L_1 s_2 \left[m_2 r_2 + (m_3 + m_{m3}) L_2\right]$$
$$b_{31} = b_{32} = g_{r3} j_{m3}$$
$$b_{33} = m_3 + g_{r3}^2 j_{m3}$$
$$b_{34} = m_3 g$$

Figure 3: Model of the SCARA robot-Joint connections and Geometry of segments and joint positions



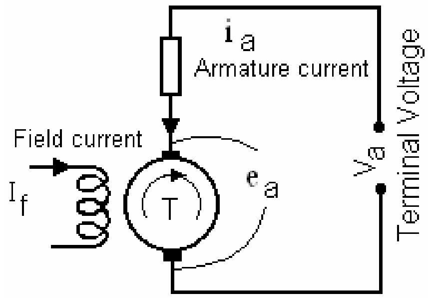
5. Actuator Equations (Actuator Modeling)

Actuators are the devices used to move robots. Many types of such devices are used such as pneumatic pistons, hydraulic pistons, DC motors, and stepper motors to satisfy this function. Since most of the present robots employ DC motors, a detailed model for this type of actuator will be derived and used through out this research. The control of the motor drive system will use PWM method to supply the motor with the controlled voltage. Microcontrollers are often used to achieve this task because of the following advantages:

1) smaller size and reduced weight
2) fewer inputs and outputs, and
3) remote operation using
4) it is possible to change the armature voltage with minimum losses

The equations which govern the operation of permanent magnet, separately or shunt wound DC motors- figure 4 when the flux is constant are [12]:

Figure 4: Separately dc motor



$$V_a = R i_a + e_a + L\frac{di_a}{dt} \quad (45)$$

$$e_a = k_e \phi \omega_m = k_\omega \omega_m \quad (46)$$

$$T = k_e\, \phi\, i_a = k_T\, i_a \quad (47)$$

$$T = T_L + J_m \frac{d\omega_m}{dt} + b\omega_m \quad (48)$$

6. Transmission Equations

Many types of transmission elements are in use in robot design. The purpose of the transmission is to transmit mechanical power from actuator to the load. Gears are the most common transmission elements in robot designs. A common revolute-joint transmission element in robots is the harmonic drive [13]. These drives feature in-line parallel shafts and very high transmission ratio in compact packages. Transmitted torque to the motor shaft (T) can be calculated from figure5 as:

$$T = T_L / g_r \eta \Rightarrow T \frac{\omega_m}{\omega_L}\ \eta = T\frac{\theta_m}{\theta_L}\ \eta = T_L \quad (49)$$

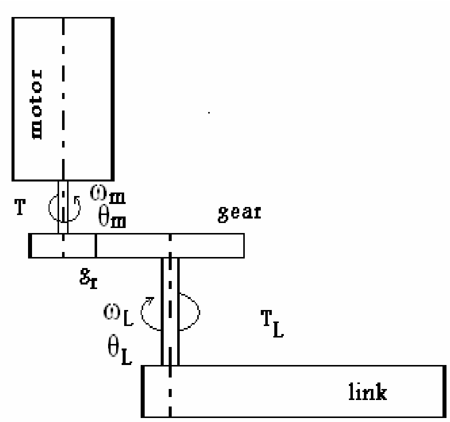
Also, the transmitted inertia is

$$J = J_m + J_L / g_r^{\ 2} \quad (50)$$

For the third joint, the translational variable (linear velocity) can be derived as:

$$\omega_m \frac{D}{2} = \dot{d}_3 \quad (51)$$

Figure 5: Schematic model of a robot revolute joint



7. Simulation and Results

Simulations are carried out for the constructed SCARA robot by SD program (figure1) with the specification listed in table 2, in addition to these specifications, the length of the main arm (shoulder), the fore arm (elbow) and the quill are L_1 = 0.25 m, L_2= 0.15m and d_3=0.075 m respectively.

Three identical dc servo motors are used for actuating arm joints and electrical data for dc servo motors are listed as [2]:

V_s =24v, $J_m = 3.3 \times 10^{-6}$ kg m^2, K_e = 0.047 V/rad/s, K_T = 0.047 Nm/A, R = 3.5 Ω, L = 1.3 mH, g_{r1} = 90, g_{r2} = 220.D= 0.030m.

The developed model is studied with three different possible simulations [2]. The solutions can show each possible case behaving differently in the response. In SD, initially, the main arm is tried to be held constant (θ_1= 1.6493 rad) and the motion of the fore arm is observed (θ_2= 1.475- 2.6178rad) as shown in figure 6a. Whole trajectory is shown and animated in figs. 6b and 6c, where both axes are given in meters representing the horizontal coordinates of the end effector as P_x and P_y.

Secondly, the motion of the main arm is observed (θ_1= 3.0142-0.794125rad) and the fore arm is tried to be kept constant (θ_2= 2.4495696 rad) as shown in figure 7a. Whole trajectory is shown and animated in figs.7b and 7c, where both axes are given in meters representing the horizontal coordinates of the end effector as P_x and P_y.

Finally, the motions of the main arm and the fore arm are observed (θ_1= 0.232-2.4695rad) and (θ_2= 1.3521- 2.0944rad) as shown in figure8a. Whole trajectory is shown and animated in figs.8b and 8c, where both axes are given in meters representing the horizontal coordinates of the end effector as P_x and P_y

Table 2: Data given by SD program for the constructed SCARA robot

Mass Parameters

Body	Name	Mass	G Center	Ixx,Iyy,Izz	Ixy,Ixz,Iyz
1	body1	1.9874	0.11511 0.0 -0.00048086	0.000481037 0.0179453 0.0176861	0.0 -0.000756924 0.0
2	body2	0.917789	0.102257 0.0 0.0	0.000472827 0.00348701 0.0031443	0.0 0.0 0.0
3	body3	0.703604	0.0 0.0 -0.0420267	0.00215244 0.00215244 0.000114505	0.0 0.0 0.0

Figure 6a: Graph of the input angles

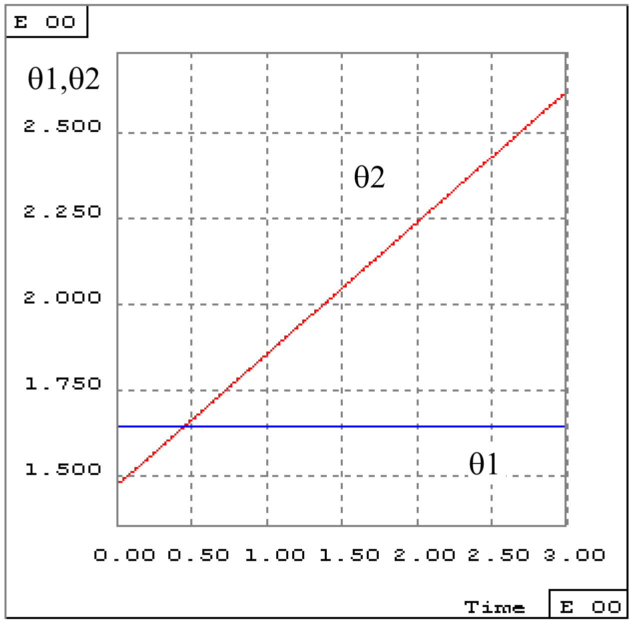


Figure 6b: the output variables (final position)

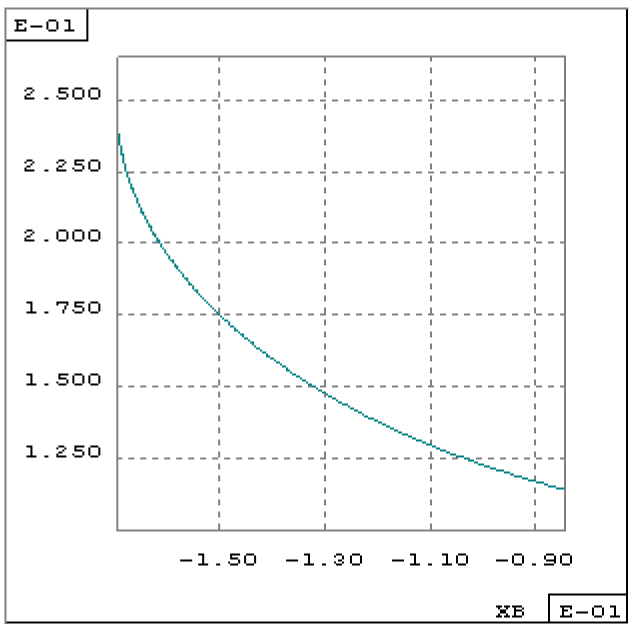


Figure 6c: the output variables (final position) X_B=f(t), Y_B=f(t) and 3D window accompanied by animation

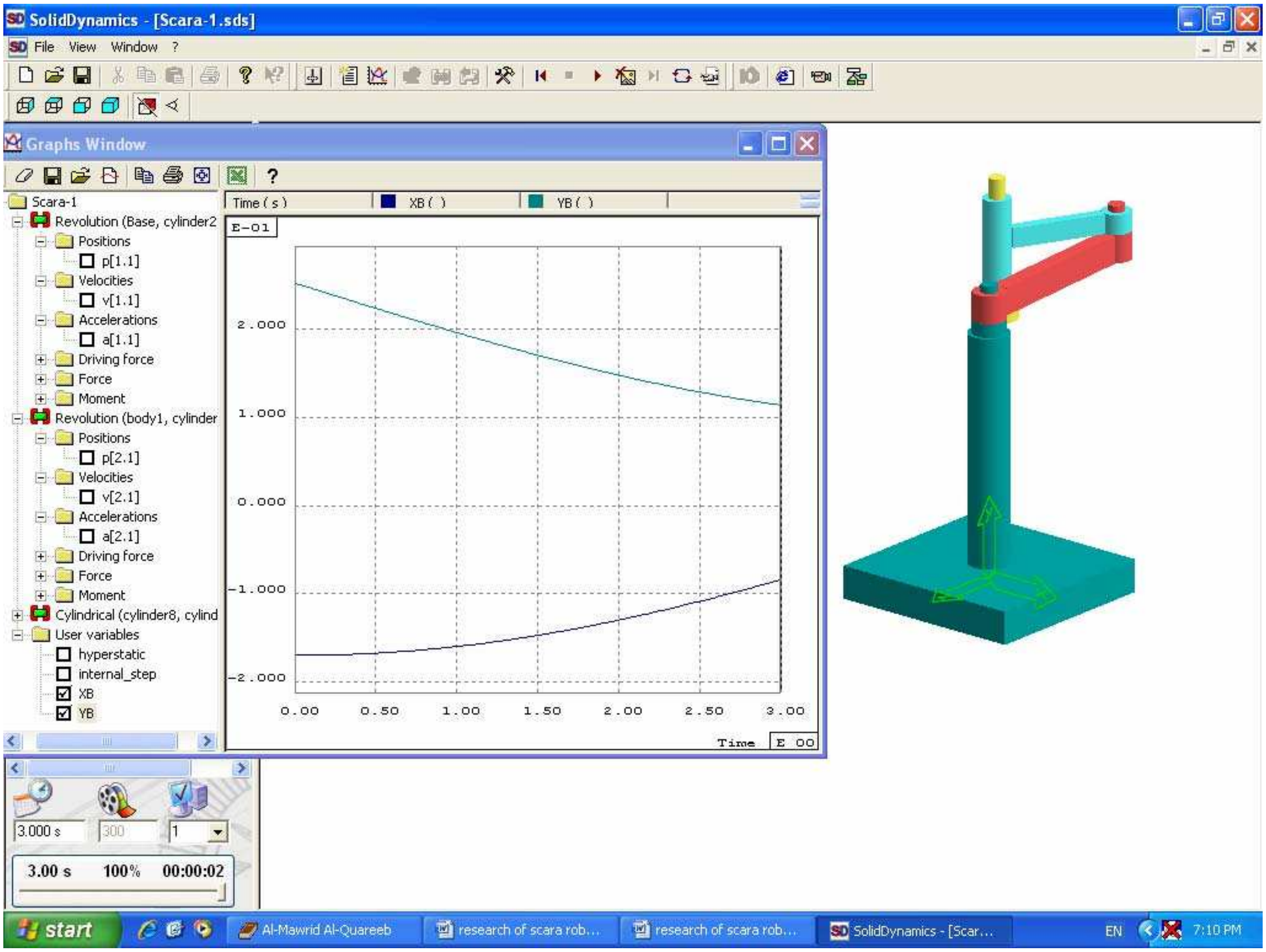


Figure 7a: Graph of the input angles

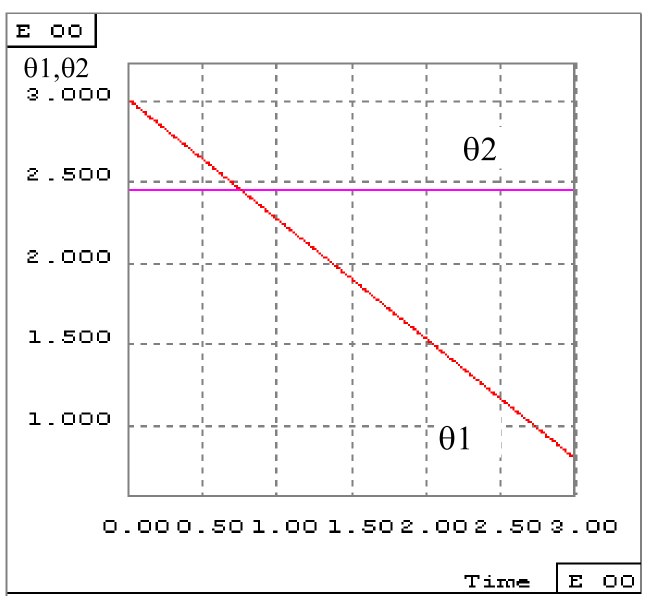


Figure 7b: The output variables (final position**)** $Y_B=f(X_B)$

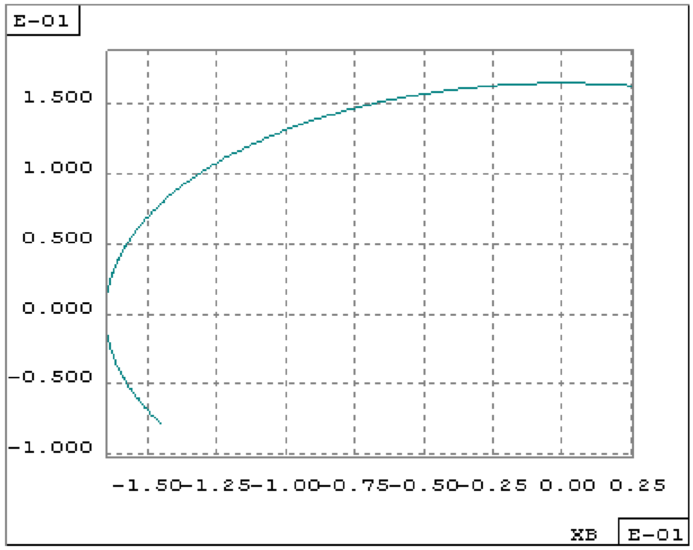


Figure 7c: The output variables (final position) $X_B=f(t)$, $Y_B=f(t)$ and 3D window accompanied by animation

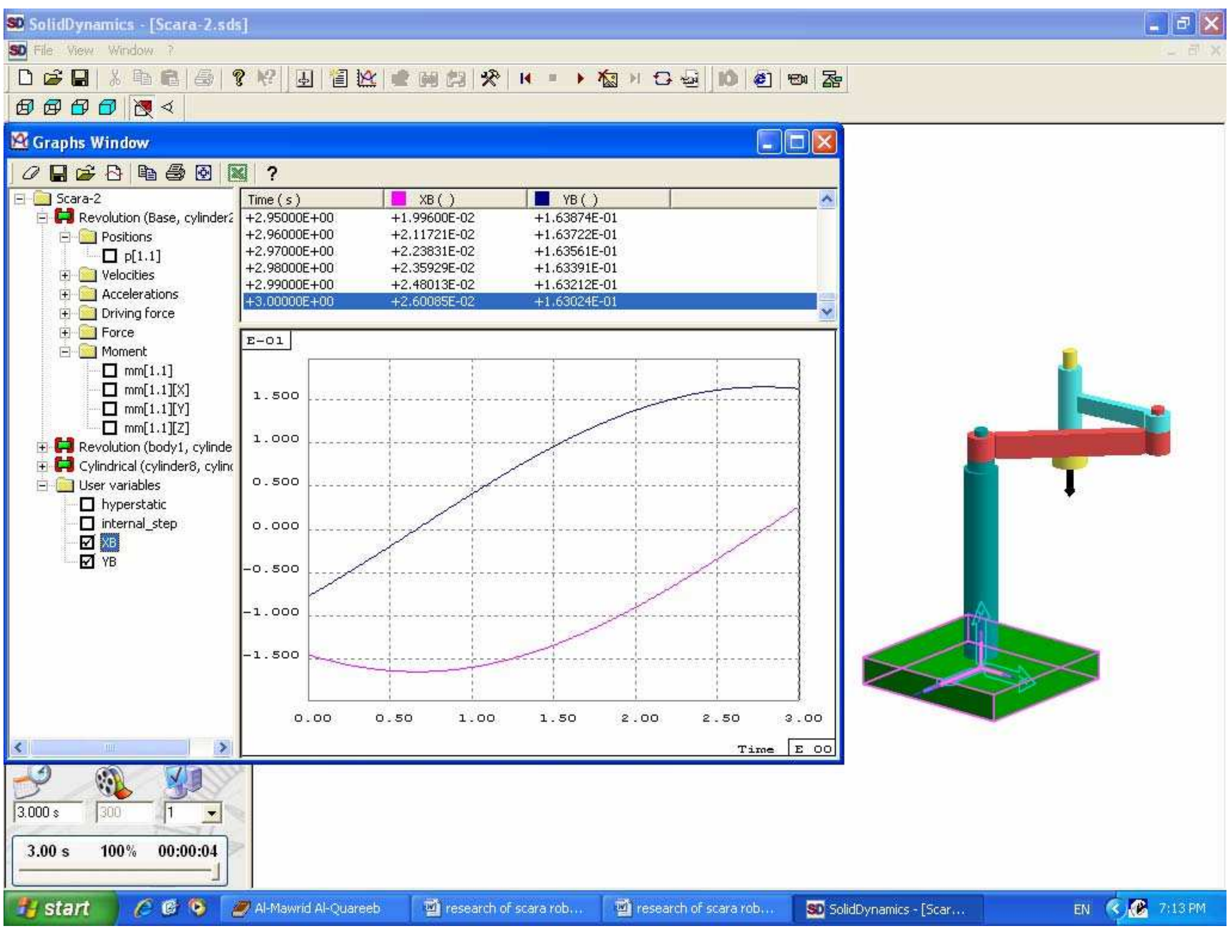


Figure 8a: Graph of the input angles

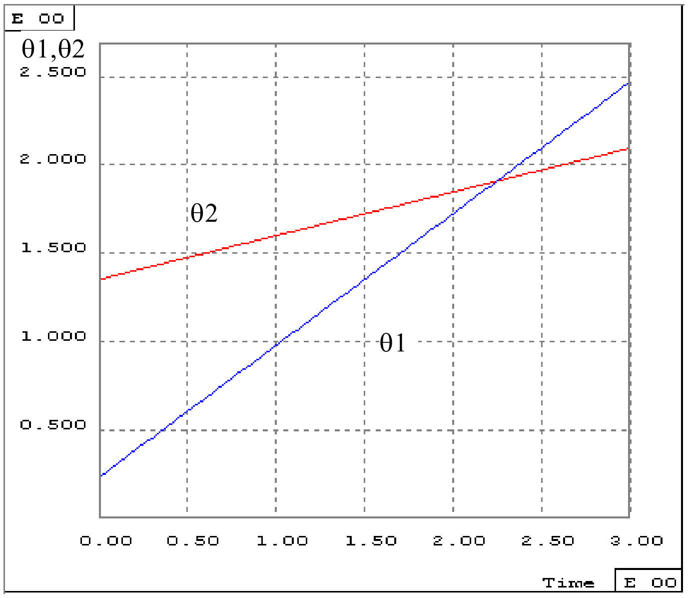


Figure 8b: the output variables (final position) $Y_B=f(X_B)$

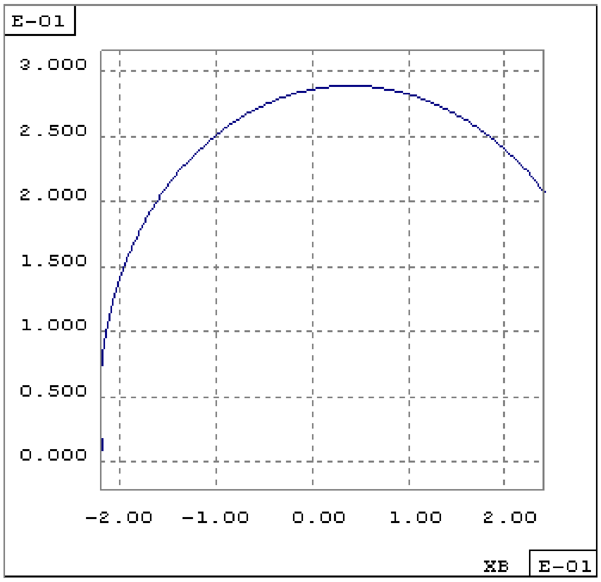
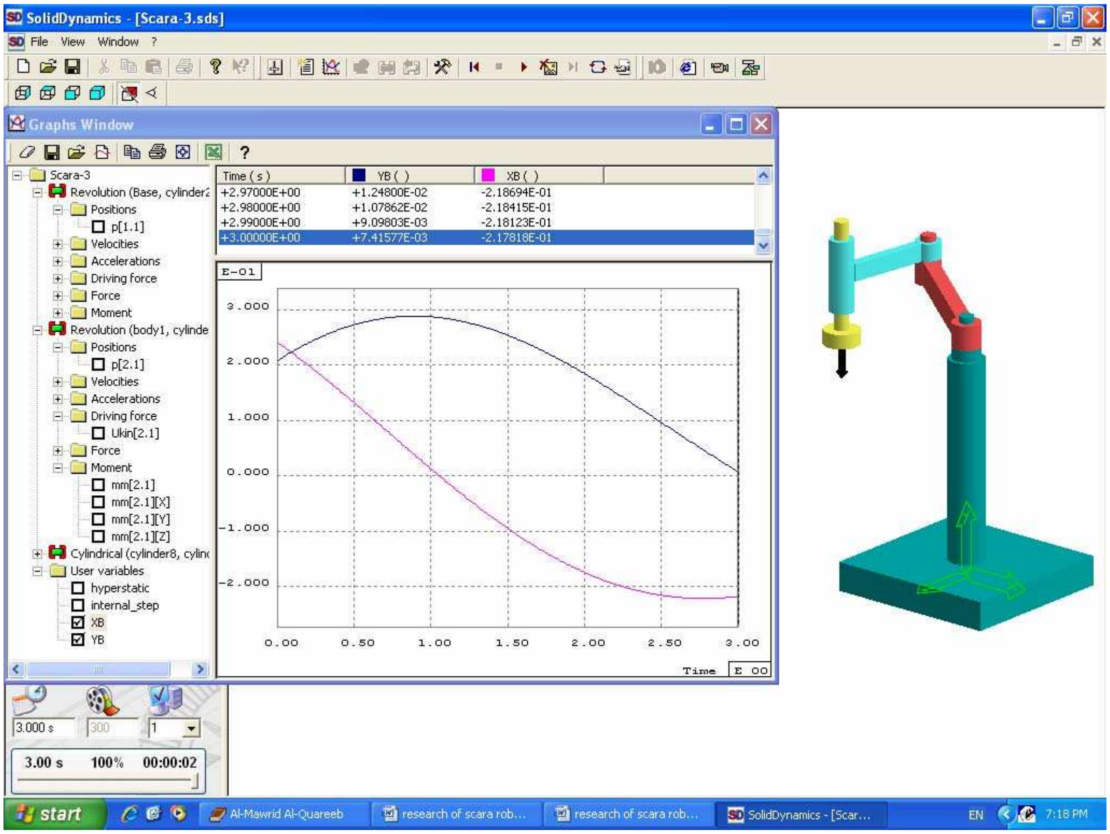


Figure 8c: the output variables (final position) X_B=f(t), Y_B=f(t) and 3D window accompanied by animation



By MATLAB/Simulink, simulation was carried out using block diagram of the robot system in figure9. The block diagram was built by using Laplace transformation [14], The same results for the three above cases were verified in figs.10a, 10b and 10c. From these figures, it is obviously seen that the trajectory coordinates can be investigated for known angles of the joints (forward kinematics). Also, investigating can be done for joint angles by inverse kinematics.

Graphs obtained by SD program show the motor angles given to the first and second joint of the robot to satisfy the specified positions (trajectory) of the end effecter.

The facilities of the SD program used for kinematic and dynamic simulation of robot systems were emphasized which means that we can use this powerful and useful tool confidently in visualization, predicting, analyzing and improving of robot systems.

Figure 9: SCARA robot modeled in MATLAB/Simulink with negative feedback of robot position

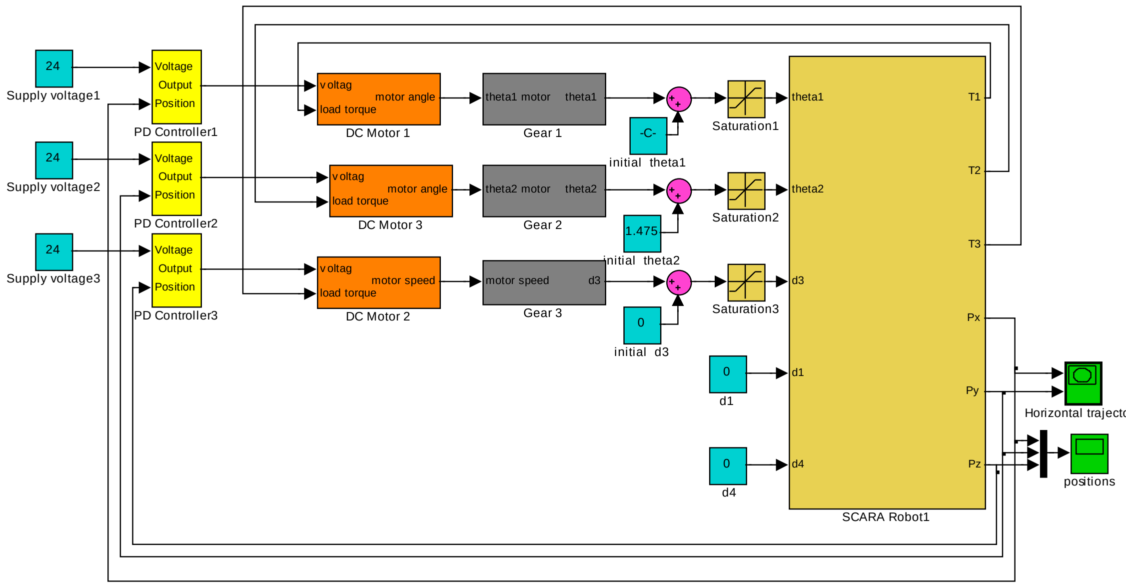


Figure 10a: Graphs of the output variables (final position) using MATLAB/Simulink for input variables θ_1= (1.6493) rad. and θ_2= (1.475- 2.6178) rad.

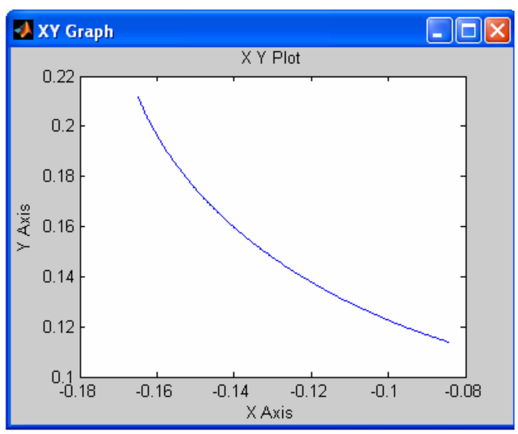


Figure 10b: Graphs of the output variables (final position) using MATLAB/Simulink for input variables θ_1= (3.0142-0.794125) rad. and θ_2= (2.4495696) rad.

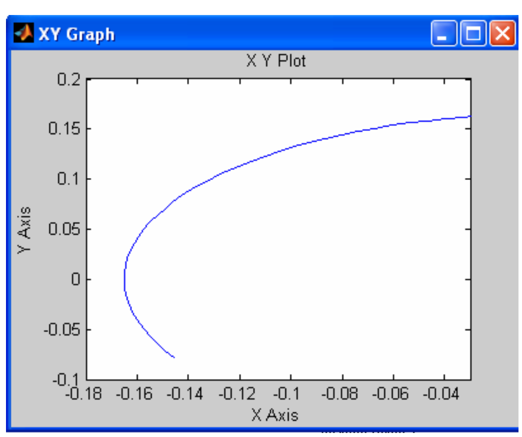
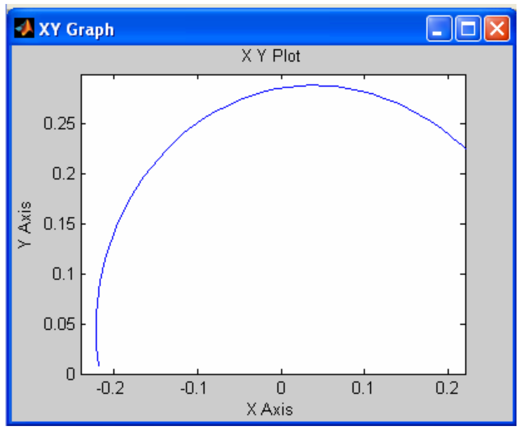


Figure 10c: Graph of the output variables (final position) using MATLAB/Simulink for input variables θ_1= (0.232-2.4695) rad. and θ_2= (1.3521- 2.0944) rad.



8. Conclusion

A complete mathematical model of SCARA robot is developed including servo actuator dynamics and presented together with dynamic simulation in this project. Forward and inverse kinematics equations were derived by using Denavit-Hartenberg notation. Simulation studies were performed by using both SD and MATLAB softwares. By using SD program, structure for the SCARA robot was built which enables the researchers to investigate robot parameters using both forward and inverse kinematics and in turn, this will facilitate the process of designing, constructing and inspecting on the robots in the real world. An agreement between the SD and the Matlab softwares is certainly obtained herein.

So, in the window of this calculation tool (by using SD software), one can manually enter the joint angles of the robot. The tool will then calculate the corresponding end effector position. The results are displayed in a graphical format and the motion of all joints and end effector can be observed.

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