Mathematical modelling, simulation and experimental verification of a scara robot

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Abstract

A complete mathematical model of SCARA robot (Serpent 1) is developed including servo actuator dynamics and presented together with dynamic simulation in this paper. The equations of motion are derived by using Lagrangian mechanics. Dc servo motors driving each robot joint is studied with PD controller action. Serpent 1 robot is instructed to achieve pick and place operations of three different size cylindrical objects through assigned holes. The performance of robot-actuator-control system is examined with numerical simulation and experimentally verified. The results of experimentation are given with comments. An agreement between the model and the experiments is certainly obtained herein.

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Keywords: SCARA robot; Mathematical modelling; Simulation; Dc servomotors

1. Introduction

A robot’s manipulator arm can move within three major axes of x, y and z referring to base travel, vertical elevation and horizontal extension. Different manipulator configurations are available as rectangular, cylindrical, spherical, revolute and

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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 vertical axis is controlled pneumatically. The tasks performed can be classified as pick and place, non-contact tasks (welding, painting) and the contact tasks (peg-in-hole). SCARA designed at Japan, is generally suited for small parts insertion tasks for assembly lines like electronic component insertion [1–3].

Many different studies have been carried out on SCARA robot. Bhatia et al. [4] have implemented an expert system based approach for the design of a SCARA robot. Ge et al. [5] have presented dynamic modelling and controller design for a SCARA/Cartesian smart materials robot with piezoelectric actuators and sensors. Omodei et al. [6] have presented and compared three algorithms for the geometric parameter identification of industrial robots. Experimental results were obtained for a SCARA IBM 7535 robot. A CRS A 251 robot was simulated with TELEGRIP software. Er et al. [7] have then studied on the design, development and implementation of a Hybrid Adaptive Fuzzy Controller (HAFC) suitable for real-time industrial applications. The SEIKO D-TRAN 3000 series SCARA robot was controlled and analysed. Hong et al. [8] have investigated a modular and object oriented

### Nomenclature

- $e$: error signal
- $I_{a1}, I_{a2}$: armature current for motor 1 and 2 (A)
- $J_1, J_2$: moment of inertias of the main and the fore arm (kg m$^2$)
- $J_{m}, J_{m1}, J_{m2}$: motor and equivalent inertias (kg m$^2$)
- $J_{g1}, J_{g2}$: inertias of the gearbox 1 and 2 (kg m$^2$)
- $L_{a1}, L_{a2}$: armature inductances for motor 1 and 2 (H)
- $K_{a1}, K_{a2}$: back emf constants for motor 1 and 2 (V/rad/s)
- $K_{t1}, K_{t2}$: torque constants for motor 1 and 2 (N m/A)
- $m_1, m_2$: masses of the main and the fore arm (kg)
- $N_1, N_2$: gearbox ratios for motor 1 and 2
- $r_1, r_2$: lengths of the main arm and the fore arm (m)
- $R_{a1}, R_{a2}$: armature resistances for motor 1 and 2 (Ω)
- $T_{1}, T_{2}$: motor torques (Nm)
- $T$: kinetic energy of the system (J)
- $V_{a1}, V_{a2}$: armature control voltages (V)
- $x_B, y_B$: coordinates of point B (m)
- $\theta_1, \dot{\theta}_1, \ddot{\theta}_1$: angular disp., vel. and acceleration of the main arm (rad, rad/s, rad/s$^2$)
- $\theta_2, \dot{\theta}_2, \ddot{\theta}_2$: angular disp., vel. and acceleration of the fore arm (rad, rad/s, rad/s$^2$)
- $\theta_{m1}, \dot{\theta}_{m1}, \ddot{\theta}_{m1}$: angular disp., vel. and acceleration of the main arm motor (rad, rad/s, rad/s$^2$)
- $\theta_{m2}, \dot{\theta}_{m2}, \ddot{\theta}_{m2}$: angular disp., vel. and acceleration of the fore arm motor (rad, rad/s, rad/s$^2$)
approach for the PC-based open robot control (PC–ORC) system. The proposed control system was applied to a SCARA robot. Nagchoudhuri et al. [9] have demonstrated imaging and motion of a SCARA robot in a robotics course in the field of mechatronics. Later Mino and White [10] have presented modelling and simulation of an industrial manipulator (CRS A 251, 5 axis robot) as a case study. A complete model was provided with its mechanical and electrical equations of motion.

The equations of motion for Serpent 1, SCARA robot with the robot dynamics and the actuators-dc servo motors for each joint are developed with Lagrangian formulation in this paper. Actuator characteristics; dc servo motors are studied in detail. Serpent 1-actuator equations are solved by numerical integration and different pick and place experiments are performed, and simulations are carried out together with experiments. With the simplifying assumptions taken, a compromise between the model and experiments are provided.

2. Experimental set-up

The experimental set up consists of a Serpent 1 type robot, a rigid platform, a PC, a driver unit for servo and pneumatic system (Control box), a motion control card, a compressor for pneumatic action and a software provided. Fig. 1 shows the Serpent 1 robot at University of Gaziantep, Department of Mechanical Engineering Dynamic Systems and Control Laboratory.
SCARA type Serpent 1 robot system and its control structure is shown in Fig. 2. Serpent 1 is connected to the control box via a combined electrical and pneumatic connector. Walli-2.5 (Workcell Amalgamated Logical Linguistic Instructions), a joint control programming language is used for main programming. Teach programming is performed by Serpent control program-Charmer [11].

Serpent 1 is controlled by three servo amplifiers, a solenoid driver, an interface board built in computer. Two articulated joints of the arm and the wrist rotation are actuated by dc servo motors (24 V). It operates on the $XY$ plane where $\theta_1$ and $\theta_2$ represent the shoulder and the elbow, respectively. The third rotary axis, roll is given as the wrist. Vertical movement is performed in the $z$ direction. The gripper has powered pneumatically. Most of the software is written in Basic. Closed loop position control for each rotary axis is performed by rotary potentiometers. Picking up a cylindrical object from a hole and replaced it into another hole on the same surface is described the task for robot.

Working envelope and photograph of the located objects of Serpent 1 are given in Fig. 3(a) and (b). Specifications of Serpent 1 and the located objects are given in Tables 1 and 2.

2.1. Serpent 1 configuration

In the application, the gripper is positioned in $x$-$y$ plane. It is not always required to rotate about a vertical axis. So this dof is neglected while deriving the equations of
motion. The gripper also works at a constant vertical displacement which is not taken during modeling. The robot kinematics is described by referring to Fig. 4. Motion control is implemented only for axes $h_1$ and $h_2$.

The inverse kinematics transforms the output position into the joint coordinate. The position of the arm end refers to the tip of the manipulator. Coordinates of point B, $x_B$ and $y_B$ can be written as

$$x_B = r_1 \cos \theta_1 + r_2 \cos(\theta_1 + \theta_2)$$

(1)

$$y_B = r_1 \sin \theta_1 + r_2 \sin(\theta_1 + \theta_2)$$

(2)

Table 1
Specifications of Serpent 1

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Main arm length ($r_1$)</td>
<td>250 mm</td>
</tr>
<tr>
<td>Fore arm length ($r_2$)</td>
<td>150 mm</td>
</tr>
<tr>
<td>Shoulder movement ($\theta_1$ axis)</td>
<td>200°</td>
</tr>
<tr>
<td>Elbow movement ($\theta_2$ axis)</td>
<td>250°</td>
</tr>
<tr>
<td>Wrist rotation (roll axis)</td>
<td>450°</td>
</tr>
<tr>
<td>Up and down (z axis)</td>
<td>75 mm</td>
</tr>
<tr>
<td>Maximum tip velocity</td>
<td>550 mm/s</td>
</tr>
<tr>
<td>Capacity</td>
<td>2.0 kg</td>
</tr>
</tbody>
</table>

Table 2
Specifications of three located objects

<table>
<thead>
<tr>
<th></th>
<th>Dimension (mm)</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>$\varnothing 20 \times 30$</td>
<td>100</td>
</tr>
<tr>
<td>Medium</td>
<td>$\varnothing 38 \times 40$</td>
<td>380</td>
</tr>
<tr>
<td>Big</td>
<td>$\varnothing 58 \times 50$</td>
<td>820</td>
</tr>
</tbody>
</table>
Inverse mapping of linkage coordinates to joint coordinates to be performed. So a known inverse problem appears to be solved by using Eqs. (1) and (2). Solution can be found in many text books [1,2]. Joint angles $\theta_1$ and $\theta_2$ can be expressed in terms of tip position as

$$
\cos \theta_2 = \frac{(x_B^2 + y_B^2) - (r_1^2 + r_2^2)}{2r_1r_2}
$$

$$
\tan \theta_1 = \frac{-(r_2 \sin \theta_2)x_B + (r_1 + r_2 \cos \theta_2)y_B}{(r_2 \sin \theta_2)y_B + (r_1 + r_2 \cos \theta_2)x_B}
$$

By using Eqs. (3) and (4), joint velocities and accelerations can be calculated.

3. System modelling

The equations of motion relating joint torques, positions, velocities and accelerations are derived here. Actuator dynamics is also included by considering a model for pm dc servomotors and its control structure together with the robot dynamics. Some simplifying assumptions like; no gear and transmission losses and friction in joints are taken while deriving equations of motion.

3.1. DC Servo motor modelling

A dynamic model for a pm dc servo motor has an armature equation and a dynamic equation which must be considered together with robot equations [12–15]. Loads are driven by pm dc servo motors through reduction gearboxes and timing belts. A circuit model includes a pm armature controlled dc motor, gearbox, belt-pulley component and a mechanical load.

Kirchhoff's voltage law is applied around the armature windings. The motor armature equation is given as
\[ L_{an} \frac{dI_{an}}{dt} + R_{an} I_{an} + K_{re} \dot{\theta}_{mn} = V_{an} \]  
(5)

where subscripts \( n = 1, 2 \) referring to the main arm and the fore arm movements, respectively. The motor current \( I_n \) produces a torque \( T_n \), proportional as
\[ T_n = K_T I_n \]  
(6)

The main arm, shoulder movement is performed by a gearbox and belt-pulley arrangement. A gear train introduces a relation
\[ N_n = \frac{\theta_{mn}}{\theta_n} \]  
(7)

where \( N_n \) is the coupling ratio introduced by gearbox 1 and 2 and \( \theta_{mn} \) is the angular displacement of the motor. Equivalent moment of inertias are taken as
\[ J_{m1} = J_m + J_{g1} \quad \text{and} \quad J_{m2} = J_m + J_{g2} \]

Two identical dc servo motors are used for actuating arm joints and electrical data for dc servo motors are listed as

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( J_1 )</td>
<td>0.0980 kg m(^2)</td>
</tr>
<tr>
<td>( J_2 )</td>
<td>0.0115 kg m(^2)</td>
</tr>
<tr>
<td>( m_1 )</td>
<td>1.90 kg</td>
</tr>
<tr>
<td>( m_2 )</td>
<td>0.93 kg</td>
</tr>
<tr>
<td>( J_m )</td>
<td>3.3 \times 10^{-6} \text{kg m}^2</td>
</tr>
<tr>
<td>( K_{e1} = K_{e2} )</td>
<td>0.047 V/\text{rad/s}</td>
</tr>
<tr>
<td>( K_{t1} = K_{t2} )</td>
<td>0.047 Nm/A</td>
</tr>
<tr>
<td>( R_{a1} = R_{a2} )</td>
<td>3.5 \Omega</td>
</tr>
<tr>
<td>( L_{a1} = L_{a2} )</td>
<td>1.3 mH</td>
</tr>
<tr>
<td>( N_1 = 90, N_2 = 220 )</td>
<td></td>
</tr>
<tr>
<td>( J_{g1} )</td>
<td>0.0002 kg m(^2)</td>
</tr>
<tr>
<td>( J_{g2} )</td>
<td>0.0005 kg m(^2)</td>
</tr>
</tbody>
</table>

3.2. Controller action

Many types of controller schemes; PD, PI, PID can possibly be employed. A lot of studies can be found on applications of PD and PID controllers on servo systems [15,16]. In the study presented, PD action is chosen with the control software available. A PD controller is used for calculating the armature control voltage as
\[ V_{an}(t) = K_{pe} e_n(t) + K_{de} \frac{de_n(t)}{dt} \]  
(8)

where the error signal
\[ e_n(t) = \theta_{mn}(t) - \theta_{na}(t) \]  
(9)
\[ \dot{e}_n(t) = \theta_n(t) - \dot{\theta}_n \]  

(10)

\( K_{pp} \) and \( K_{dp} \) represent proportional and derivative control gains. Motor reference point is given by subindex \( n_c \). Subscript \( n \) becomes 1 and 2 while describing the main arm and the fore arm joints.

Experimental data points are measured while performing three different experiments on Serpent 1; two axes positioning (\( \theta_1 \) and \( \theta_2 \) are changing), one axis movement where \( \theta_1 \) is constant, one axis movement where \( \theta_2 \) is constant. The numerical methods are used for curve fitting for the trajectories followed by Serpent 1 [17,18]. The experimental data for \( \theta_1 \) and \( \theta_2 \) are correlated with analytical expressions between time variable. The overall data are fit by using least-squares regression. The best function is found to be 2nd order polynomials for both axis. Thus having found the best fit, the angular velocity points are calculated, and used in Eq. (10) for utilizing feedback information in the velocity error during simulation.

4. Equations of motion

The dynamic equations of Serpent 1 are derived by using Lagrange’s equations described as [12,13]. The system equations of motion include two second order ODEs. The two generalized coordinates are defined as \( \theta_m \) and \( \dot{\theta}_m \).

\[
\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = Q_i \quad \text{for} \quad i = 1, 2, \ldots, n \tag{11}
\]

where \( L \) is the Lagrangian function (\( L = T - V \)) refers to system’s total kinetic and potential energies. \( Q_i \) represent generalized torques for the main arm and the fore arm, and \( q_i \) is the generalized coordinate.

Serpent 1’s total kinetic energy, \( T \) can be given by

\[
T = \frac{1}{2} J_{m1} \dot{\theta}_{m1}^2 + \frac{1}{2} m_1 \left( \frac{r_1^2}{4} \right) \dot{\theta}_1^2 + \frac{1}{2} J_{m2} \dot{\theta}_{m2}^2 + \frac{1}{2} J_2 (\dot{\theta}_1^2 + 2 \dot{\theta}_1 \dot{\theta}_2 + \dot{\theta}_2^2) \\
+ \frac{1}{2} m_2 \left\{ r_2^2 \dot{\theta}_1^2 + \left( \frac{r_2^2}{4} \right) (\dot{\theta}_1 + \dot{\theta}_2)^2 + r_1 r_2 (\dot{\theta}_1^2 + \dot{\theta}_1 \dot{\theta}_2) \\
\times \left[ \cos(\theta_1 + \theta_2) \cos \theta_1 + \sin(\theta_1 + \theta_2) \sin \theta_1 \right] \right\} \tag{12}
\]

Taking time derivatives of Eq. (12) and replacing them into Eq. (11), the following equations are obtained. The equations of motion of Serpent 1 are given by including the dynamics of dc servo motor as:

- For the main arm (shoulder) movement,
For the fore arm (elbow) movement;

\[ L_{a1} \frac{dI_{a1}}{dt} + R_{a1}I_{a1} + K_{e1} \dot{\theta}_{m1} = V_{a1} \]  

\[
\left[ J_{m1} + \frac{(J_1 + J_2)}{N_1^2} + \frac{(m_1r_1^2 + m_2r_2^2 + 4m_2r_2^2)}{4N_1^2} \right] \ddot{\theta}_{m1} + \left[ \frac{m_2r_1r_2}{N_1^2} \left( \cos \left( \frac{\theta_{m1}}{N_1} + \frac{\theta_{m2}}{N_2} \right) \cos \left( \frac{\theta_{m1}}{N_1} \right) \right) \right] \dot{\theta}_{m1} + \left[ \frac{J_2}{N_1^2} + \frac{m_2r_2^2}{2N_1^2N_2} \left( \cos \left( \frac{\theta_{m1}}{N_1} + \frac{\theta_{m2}}{N_2} \right) \right) \right] \dot{\theta}_{m2} + \frac{m_2r_1r_2}{N_1^2} \left( \frac{\theta_{m1} \dot{\theta}_{m2}}{N_1} + \frac{\dot{\theta}_{m2}^2}{2N_2} \right) \right.
\]

\[
\times \cos \left( \frac{\theta_{m1}}{N_1} \right) - \cos \left( \frac{\theta_{m1}}{N_1} + \frac{\theta_{m2}}{N_2} \right) \left( \frac{\theta_{m1}}{N_1} \right) \right] = T_1(t, \theta_{m1}, \dot{\theta}_{m1})
\]

\[ (14) \]

\[ L_{a2} \frac{dI_{a2}}{dt} + R_{a2}I_{a2} + K_{e2} \dot{\theta}_{m2} = V_{a2} \]  

\[
\left[ J_{m2} + \frac{J_2}{N_2^2} + \frac{m_2r_2^2}{4N_2^2} \right] \ddot{\theta}_{m2} + \left[ \frac{J_2}{N_1^2N_2^2} + \frac{m_2r_2^2}{4N_1^2N_2^2} + \frac{m_1r_1^2r_2}{2N_1^2N_2^2} \right] \left( \cos \left( \frac{\theta_{m1}}{N_1} + \frac{\theta_{m2}}{N_2} \right) \cos \left( \frac{\theta_{m1}}{N_1} \right) \right) \dot{\theta}_{m1} + \left[ \frac{m_2r_1r_2}{2N_1^2N_2} \left( \frac{\theta_{m1}}{N_1} \right) \right] \left( \sin \left( \frac{\theta_{m1}}{N_1} + \frac{\theta_{m2}}{N_2} \right) \right) \right]
\]

\[
\times \cos \left( \frac{\theta_{m1}}{N_1} \right) - \cos \left( \frac{\theta_{m1}}{N_1} + \frac{\theta_{m2}}{N_2} \right) \left( \frac{\theta_{m1}}{N_1} \right) \right] = T_2(t, \theta_{m2}, \dot{\theta}_{m2})
\]

where the torque functions to be applied to the actuation system of the robot for each joint.

4.1. Numerical integration

Eqs. (13) through (16) represent the systems equations, and four equations are written for the whole system. A set of state variables are introduced, and Eqs. (13) and (16) are expressed as state-variable equations of nonlinear character. Six first order equations are resulted by taking dynamics of dc servo motor for the main arm and the fore arm. The ordinary differential equations are solved by 4th order Runge Kutta method to perform a numerical simulation of Serpent 1 [12,13,17]. The mechanical and electrical system equations are coupled together with the motors.
torque equation. So the movement of the arm in a desired position requires simultaneous solutions of the motor and the dynamic system equations for each simulation interval.

A computer program is written in Pascal for simulation. To obtain solutions for system ODEs available with numerical integration, the system constants; Serpent 1 link lengths, link masses, link moment of inertias and the initial conditions for the angular displacement, velocity and the motor currents are to be specified. Thus, the initial values; motor currents, motor angular displacements and velocities are set as inputs. The addition of the controller is improved the transient and steady-state responses during simulation. The proportional control \( K_p \) is very effective on the overall system stiffness and the derivative control \( K_d \) effects the overall system damping. The decay of oscillations are controlled easily by proper settings of \( K_p \) and \( K_d \). The performance of integration scheme depends on the nature of the functions being applied. Whole motion (picking and placing) is performed in 3 s. Integration step size \( \Delta t \) is taken 7.31 milli seconds herein.

5. Simulation and experimental results

Simulations are carried out together with experiments. Experimental data points are taken as motion reference points for angular positions of the main arm and the fore arm. The developed model is studied with three different possible simulations. The solutions can show each possible case behaving differently in the responses. All angular position values measured are converted into the assigned angular orientation by referring to the working envelope of Serpent 1 (Fig. 3 (a) and (b)) during simulation.

Initially, the main arm is tried to be held constant and the motion of the fore arm is observed. Fig. 5 represent the simulated and the experimental displacement results for this case. Fig. 5(a) and (b) give the experimental and simulated results for the main arm and the fore arm respectively. Whole trajectory is shown in Fig. 5(c). Experimental and simulated trajectories are given in thick and dotted lines. The vertical axis is given in radians and the horizontal axis in seconds for Fig. 5(a) and (b). In Fig. 5(c), both axes are given in meters representing the coordinates of the end effector as \( x_B \) and \( y_B \).

The main arm is kept constant at \( \theta_1 = 94.5^\circ \) by sending a constant armature voltage. The fore arm, \( \theta_2 \) is continuously changing. Initial and final positions of the fore arm are measured as \( \theta_{2i} = 151.84^\circ \) and \( \theta_{2f} = 384.84^\circ \) during experiments. The proportional and derivative control gains are found \( K_{p1} = 300, K_{d1} = 50 \) for the main arm, and \( K_{p2} = 30, K_{d2} = 15 \) for the fore arm, respectively. Different simulation runs are performed by changing the controller settings \( K_p \) and \( K_d \) for both motors. Since simplifying assumptions are taken, quite good following characteristics are obtained at the end. This can be considered as a swinging arm example.

Secondly, the motion of the main arm is observed, and the fore arm is tried to be kept constant. Fig. 6 represent the simulated and the experimental results for this case. Fig. 6(a) and (b) give the experimental and simulated results for the main
arm and the fore arm, respectively. Whole trajectory performed for this example is shown in Fig. 6(c). Thick and dotted lines represent the experimental and the simulated results, respectively. The vertical axis is given in radians and the horizontal axis in seconds for Fig. 6(a) and (b). In Fig. 6(c), both axes are given in meters representing the coordinates of the end effector as $x_B$ and $y_B$.

The main arm is continuously changing and the fore arm is kept constant at $\theta_2 = 140.35^\circ$ by sending a constant armature voltage. Initial and final angles measured for the main arm are $\theta_{1i} = 172.70^\circ$ and $\theta_{1f} = 45.50^\circ$ during experiments. These

Fig. 5. Experimental and simulated results (first example).
values are converted into the original positioning values by using the working envelope. In this example, having given initial conditions, nearly 1/3 of the whole motion oscillatory behavior is observed during simulation. By increasing the gain values, respectively, transients are settled down. This is especially given to show transients in the response. Steady-state behavior is seen nearly in 1 s representing more difficult case compared to the first example. The proportional and derivative control gains are found $K_{p1} = 300$, $K_{d1} = 50$ for the main arm, and $K_{p2} = 170$, $K_{d2} = 30$ for the fore arm, respectively.

Finally, the motions of the main arm and the fore arm are observed, exemplifying the case when Serpent 1 works during an assembly operation. This is considered
when Serpent 1 to be used while picking and placing a large object referred during experiments, also performing two axis positioning. Fig. 7 represent the experimental and the simulated results for this case. Fig. 7(a) and (b) give the experimental and the simulated results for the main arm and the fore arm respectively. Whole trajectory performed is shown in Fig. 7(c). Experimental and simulated trajectories are given in thick and dotted lines. The vertical and the horizontal axes are given in radians.
and seconds in Fig. 7(a) and (b), respectively. In Fig. 7(c), both axes are given in meters representing the coordinates of the end effector as \( x_B \) and \( y_B \).

Initial and final positions for the main arm and the fore arm are; \( \theta_{1i} = 13.28^\circ, \theta_{1f} = 141.47^\circ \) and \( \theta_{2i} = 77.47^\circ, \theta_{2f} = 185.99^\circ \) during experiments. A conversion is performed for the correct angular positioning before simulation. The proportional and derivative control settings are found \( K_{p1} = 400, K_{d1} = 25 \) for the main arm, and \( K_{p2} = 60, K_{d2} = 15 \) for the fore arm, respectively. The positions for pick and place points are satisfactorily provided.

6. Conclusions

This paper has introduced a mathematical model for SCARA type, Serpent 1 pick and place robot system with its actuator dynamics. A procedure to illustrate how a system to be modelled was given. Simulation studies were performed by referring to the experimental data available. Here the manipulator parameters were fixed specifying Serpent 1 robot system, and the controller settings were tuned by looking at dynamic behavior of the robot-actuator system. Some assumptions were made while dealing with the actuator dynamics. The results obtained by the experiments and simulations were presented graphically.

Both simulation and experimental responses of Serpent 1 match reasonably good by considering highly nonlinear characteristics of the robot arm. The actual system behaves like predicted by simulation. The difference between both results is simply caused by assumptions made while developing the mathematical model, and also numerical calculations carried out (integration scheme). Here the coordinates of pick and place points are very important for exact positioning. This is certainly performed within the tolerances given for the operation.

References