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Modelling and control of 5DOF Robot Arm using Neuro-Fuzzy Controller

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Abstract: Modelling and control of 5 degree of freedom robot arm is the subject of this paper. The modelling consisting of forward and inverse kinematics is derived based on Denavit Harterberg (DH) representation. The main objective of this paper is to control the robot manipulator arm by traditional PID controller, Neuro Fuzzy logic controller, and to compare the results obtained by the two methods.

Keywords: 5 DOF Robot Arm, DenavitHarterberg representation, DC Servo motor, PID Controller, Neuro-Fuzzy Controller

1. Introduction: In this paper the controlled robot manipulator arm is of Lynx-6 robot. The number of joints present in the arm indicates the Degrees of Freedom. Here 5 DOF means robot arm contains 5 joints. The arm links are connected and moved with the help of D.C. Servo motors.

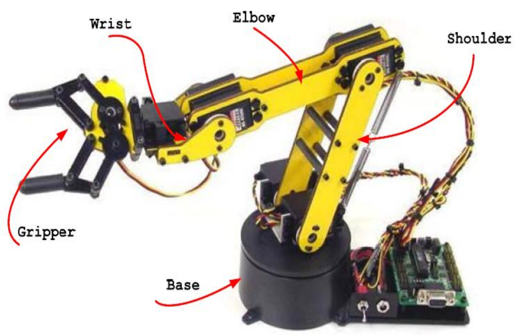

Fig 1.1 Lynx-6 Robot Arm

These joints are of two types revolute or rotatory (Human joints) and prismatic or sliding joints. The forward and inverse kinematics of robot arm manipulator are derived based on DenavitHarterberg (DH) representation [1] [2] [3]. Forward kinematics derives the angle of rotation of link if the position of the arm is defined. The inverse kinematics derives the position if the angle of link is defined. Further the D.C. Servo motor model is obtained. Now the position of robot manipulator arm is being controlled by the traditional PID Controller, NeuroFuzzy logic controller. The results obtained are comparedby the specifications like peak overshoot, rise time, steady state error. The typical 5 DOF Lynx-6 robot manipulator arm is shown in fig.1.1.

2.Kinematics and mathematical modelling of Robotmanipulator:

Robot manipulator is named according to number of DOF, which refers to the number of joints. The robot manipulator arm has 5 joints, which mean the robot has 5DOF. Each one of these joints has a motor allowing the motion to the commanded link. The motors have feedback sensors to measure the output (e.g. position, velocity, and torque) at each instant. Links and joints form a kinematic chain connected to ground from one side, and the other is free. At the end of the open side, the end-effector (e.g. gripper, welding tool, or another tool) is used to do some tasks. The kinematics robot manipulator is derived by using DenavitHarterberg (DH) representation. In determining the forward kinematic (FK) where the robot manipulator end-effector should be known. This means what rigid motion each joint effect on its link to obtain the desired configuration. The configuration space of the end-effector contains the transformation matrix T that relates the position and orientation of the end-effector.

The following equation explains the forward kinematic problem.

$$F(\theta_1, \theta_2, \theta_3 \ldots. \theta_n) = [x, y, z, R]$$

Where $\theta_1, \theta_2, \theta_3 \ldots. \theta_3$ are the input variables, [x, y, z] are the desired position and R_d the desired rotation. The second problem is determining the inverse kinematic (IK), which calculates the value of each joint variable if the desired position and orientation of end-effector are known. That means if the final link configuration is known, what is the possible configuration (e.g. solutions) of the robot manipulator to move the end effector of the robot arm to desired position and orientation in space. Inverse kinematic problem may express mathematically as follows:

$$F(x, y, z, R) = [\theta_1, \theta_2, \theta_3 \ldots. \theta_n]$$

For serial manipulators with revolute or prismatic joints the FK is derived using procedures such as the DH convention matrix, but in the parallel manipulator, the forward kinematic be not easy to be solved due to the complexity of the robot manipulator. Therefore, it may solved by using a set of nonlinear equations. On the other hand, solving the IK for parallel manipulator is easier than FK solution, and there are many solutions to achieve the desired task.

a) Obtain the DH parameters.

To describe the kinematics of any robot, four parameters are given for each link θ_i, α_i, d_i, α_i,where two of them described the link, and the others describe the connection with other links.

DH PARAMAETER REPRESENTATION

Link	Joint	α_i	α_i	d_i	θ_i
1	0-1	α_1	α_1	d_1	θ_1
2	1-2	α_2	α_2	d_2	θ_2
3	--	--	--	--	--
i	(i-1)-›i	α_i	α_i	d_i	θ_i

where α_i is the distance along $x\ i$ from $o\ i$ to the intersection of $X\ i$ and $Z\ i$- 1axes, $d\ i$ is the distance along $Z\ i$- 1from $o\ i$- 1to the intersection of $x\ i$ and $Z\ i$- 1axes,αi is the angle between $Z\ i$- 1and $Z\ i$ measured about X_i , and θ_i is the angle between $X\ i$- 1and $X\ i$ measured about $Z\ i$- 1.

b) Obtain link transformation matrices Ai (A matrices).

After obtaining the table of DH convention, a series of homogeneous matrices can be derived depending on the number of the DOF. The transformation matrix for each joint from joint 1 to the joint i can be calculated as:

Ai= Rot(z, θ_i)Trans (z, d_i)Trans(x, α_i) Rot(x, α_i)

Or in terms of the full matrices

$$Ai = \begin{bmatrix} C\theta i & -S\theta i & 0 & 0 \\ S\theta i & C\theta i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & di \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C\alpha i & -S\alpha i & 0 \\ 0 & S\alpha i & C\alpha i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

i.e.

$$Ai = \begin{bmatrix} C\theta i & -S\theta iC\alpha i & S\theta S\alpha i & aiC\theta i \\ S\theta i & C\theta iC\alpha i & -C\theta iS\alpha i & aiS\theta i \\ 0 & S\alpha i & C\alpha i & di \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

c) Obtain the manipulator transformation matrixH^{o}i(H matrix).

After the homogeneous matrix has been defined for each link of the robot manipulator, simple solution to find the total homogeneous matrix for robot manipulator with *i-links* is accomplished by multiplying all the transformation matrices from A1to $A\ i$ as follows:

H^{o}i = A1,A2,A3…Ai

The matrices from A1to Ai are the transformation matrices from joint 1 to joint I and H^{o}iis the location of the *ith* coordinate frame with respect to the base coordinate.

d) Calculate the position and orientation of the end-effector.

The general homogeneous matrix for the desired position and orientation of the end-effector that obtained from as follows:

$$H^{o}i = \begin{bmatrix} r11 & r12 & r13 & x \\ r21 & r22 & r23 & y \\ r31 & r32 & r33 & z \\ 0 & 0\,0 & & 1 \end{bmatrix} = A1,A2...Ai$$

Where the rotation matrix and the position vector of endeffecter is as follows:

$$Rd=\begin{bmatrix} r11 & r12 & r13 \\ r21 & r22 & r23 \\ r31 & r32 & r33 \end{bmatrix}$$

$$P=\begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

3. DC Motor Modelling

Generally, modelling refers to system (e.g. plant) description in mathematical terms, which characterizes the input-output relationship [39]. Direct current (DC) motor is a common actuator found in many mechanical systems and industrial applications such as industrial and educational robots. DC motor converts the electrical energy to mechanical energy. The motor directly has a rotary motion, and when combined with mechanical part it can provide translation motion for the desired link. The fig.3.1 shows the schematic diagram of D.C. Motor is shown.

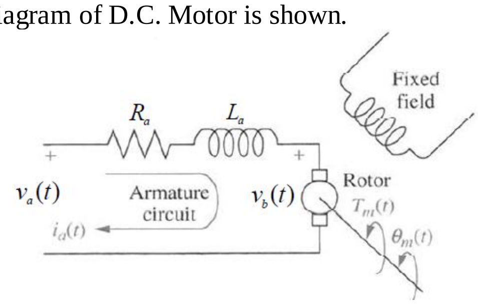

Figure 3.1: Schematic of DC motor system

The transfer function of motor speed is derived as

$$G_{speed}(s) = \frac{\dot{\theta}(s)}{V(s)} = \frac{K_t}{J_m L_a s^2 + (L_a B_m + R_a J_a)s + K_t K_b}$$

In addition, the transfer function of the motor position is determined by multiplying the transfer function of the motor speed by the term 1/*s*.

$$G_{position}(s) = \frac{\theta(s)}{V(s)} = \frac{K_t}{s[J_m L_a s^2 + (L_a B_m + J_m R_a)s + K_t K_b]}$$

Fig.3.2 shows the block diagram of D.C. motor.

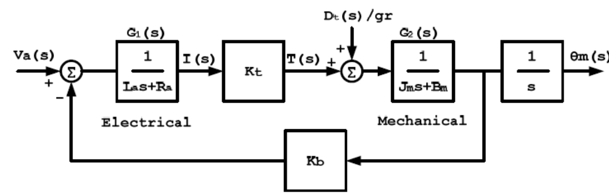

Fig. 3.2

The state space model of DC motor could be expressed as follows:

$$X\ dot\ (t) = \begin{bmatrix} -Ra/La & 0 & -Kb/La \\ 0 & 0 & 1 \\ Kt/Jm & 0 & -Bm/Jm \end{bmatrix} \begin{bmatrix} x1(t) \\ x2(t) \\ x3(t) \end{bmatrix} + \begin{bmatrix} 1/La \\ 0 \\ 0 \end{bmatrix} Va(t)$$

$$Y(t) = [0\ 1\ 0] \begin{bmatrix} x1(t) \\ x2(t) \\ x3(t) \end{bmatrix}$$

The following table shows DC motor parameters and values chosen for motor simulation.

DC Motor parameters and values	
Parameter	Value
Moment of inertia	Jm=0.000052 Kg.m2
Friction coefficient	Bm=0.01 N.ms
Back EMF constant	Kb=0.235 Nm/A
Torque constant	Kt=0.235 Nm/A
Electric resistance	Ra=2.0 ohm
Electric inductance	La=0.23 H
Gear ratio	gr
Load torque	Tl(t)
Angular speed	Wm rad/sec

On substituting the parameter values in the transfer function we get

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$$G(s) = \frac{19649}{s^3 + 201s^2 + 6290s}$$

4. PID controller design

PID controller is considered the most control technique that is widely used in control applications. A huge number of applications and control engineers had used the PID controller in daily life. PID control offers an easy method of controlling a process by varying its parameters. Since the invention of PID control in 1910, and Ziegler-Nichols' (ZN) tuning method in 1942 [7] and [38], PID controllers became dominant and popular issues in control theory due to simplicity of implementation, simplicity of design, and the ability to be used in a wide range of applications [40]. Moreover, they are available at low cost. Finally, it provides robust and reliable performance for most systems if the parameters are tuned properly. According to different sources like JEMIMA2, PID controllers or PID variations (P, PD, and PI) are widely used in more than 90% to 95% of control applications. However, the PID controller has its own limitation; the PID performances can give only satisfactory performance if the requirement is reasonable and the process parameters variation are limited. The general form of the PID controller in continuous time formula given as:

$$u(t) = K_P e(t) + K_I \int_0^t e(t)dt + K_D \frac{de(t)}{dt}$$

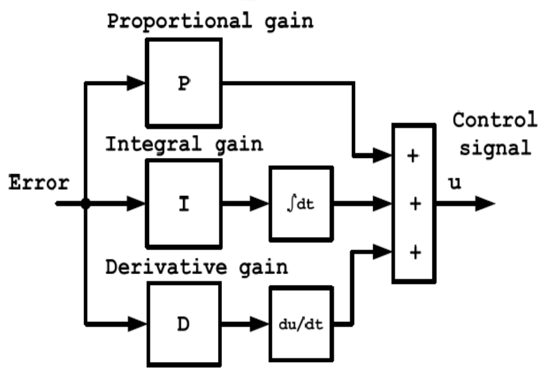


Fig. 4.1 PID controller structure

The transfer function of the PID controller in parallel is:

$$G_{PID\_Paralle}(s) = K_P + \frac{K_I}{s} + K_D s = \frac{K_D s^2 + K_P s + K_I}{s}$$

For the robot manipulator if the PID controller is used as controller plant, the final transfer function of the disturbance compensator, *G cd* (*s*), is given by:

$$G_{cd}(s) = \frac{L_a s^2 + R_a s}{K_t (K_D s^2 + K_P s + K_I)}$$

Using SIMULINK, the DC motor model with disturbance rejection control using PID controller is created as shown in Figure 5. This model includes all transfer functions that are derived previously. The feed forward transfer function is also added to this model.Fig. Block diagram of PID controller The following simulated model represents IJC for N joint robot manipulator (e.g. revolute or prismatic) joints is accomplished by using N block diagrams with respect to the number of the independent joints. Designing these controllers accomplished using SIMULINK. The main system consists of several levels. As a case study, the independent joint control is implemented to 5DOF robot arm. For each individual motor the angle and load disturbance are given and position each motor is observed. The following plots show the positions of each individual motor for step input with various values of disturbances. We can also observe the specifications like the overshoot, rise time, steady state error etc.

5. Design of Neuro-Fuzzy logic controller

Recently, the combination of neural networks and fuzzy logic has received attention. Neural networks bring into this union the ability to learn, but also require an excessive number of iterations for training of complex systems. Fuzzy logic offers a system model based on membership functions and a rule base, but requires an explicit stating of the IF/THEN rules. Several methods for combining neural networks and fuzzy logic have been studied (Khan, 1993) (Lin and Song, 1994) (Nauck, et. al., 1993). In this paper we implement the inference stage of a fuzzy system using a neural network. The given figure illustrates the system architecture for the described combination of neural networks and fuzzy logic. By replacing the rule base of a fuzzy system with a trainable neural network, complex input-output relationships can be achieved which cannot be easily specified by IF/THEN rules. With fuzzification and defuzzification stages augmenting a neural network, significant improvements in the training time, in the ability to generalize, and in the ability to find minimizing weights can be realized. Furthermore, the fuzzy membership functions give the designer more control over the neural network inputs and outputs.It should be noted that NN contributes to determination of constructing the fuzzy rules

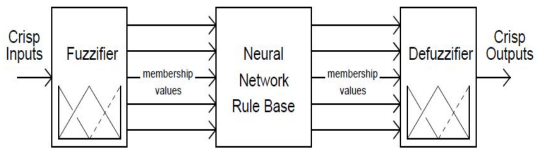


Fig. 5.1 A Fuzzy system with Neural network rule base

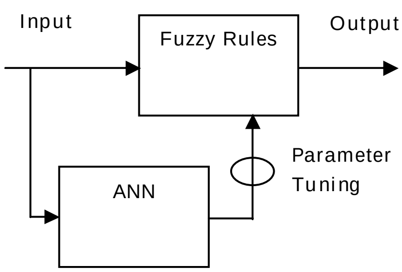


Fig. 5.2 Model of Neuro-Fuzzy controller

INPUTS TO THE NEURO-FUZZY CONTROLLERS

Input	**Description**
θ1	Joint angle of link1 to the base
θ2	Joint angle of link2 from link1's axis
θ3	Joint angle of link3 from link2's axis
θ4	Joint angle of link4 from link3's axis
θ5	Joint angle of link5 from link4's axis

OUTPUTS TO THE NEURO-FUZZY CONTROLLERS

Input	Description
Δ θ1	a small change in the angle between link1 and the base
Δ θ2	a small change in the angle between link2 and the link1 axis
Δ θ3	a small change in the angle between link3 and the link2 axis
Δ θ4	a small change in the angle between link4 and the link3 axis
Δ θ5	a small change in the angle between link5 and the link4 axis

6. Results and Discussions

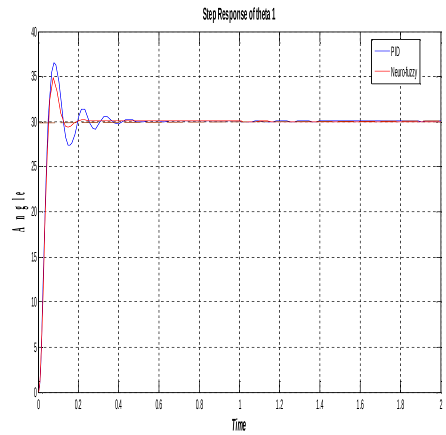
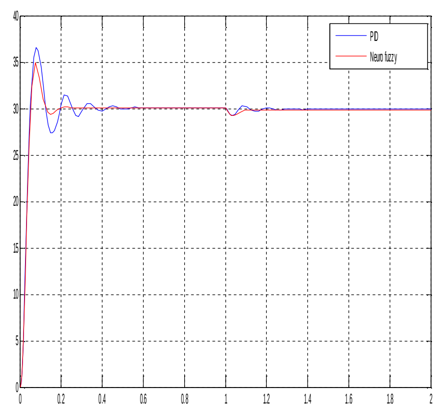


Fig.6.1 PID&Neuro-Fuzzy controllers Step response without disturbance.



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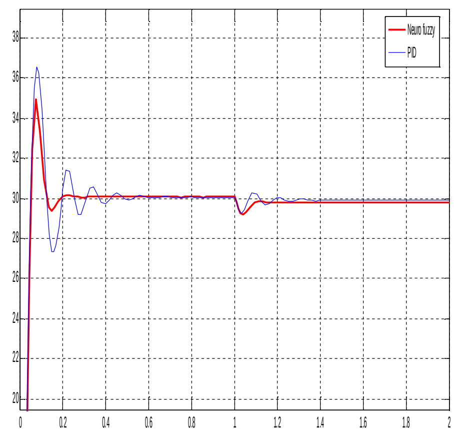

Fig.6.2 PID&Neuro-Fuzzy controllers Step response with disturbance of 0.5 N-m.

7. Conclusion:

Robotics has become recently an interesting area of research. The objective of this paper is to control the 5DOF Lynx6 robot arm to reach the specified location with minimum error while meeting certain specification In this paper, we study the robot manipulator from two sides: modelling and control. Modelling process includes kinematic analysis and DC motor modelling. The desired tasks were accomplished using three stages: the first stage was to provide systematic rules for analysing forward and inverse kinematics solutions for the robot manipulator with revolute or prismatic joints using DH parameters, then analysing the mathematical model of the DC motor in both frequency and time domains. In the second stage, we discussed the problem of control techniques. PID controller was applied, to control the robot manipulator, then the Neuro-Fuzzy controller is applied to robot manipulator . In the third stage, we compared the results of using the two controllers for controlling the robot manipulator. All simulations were presented using MATLAB and SIMULINK, which are used widely in control applications.

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