

A Relative Analysis of PD based Fuzzy, Neural And ANFIS Controller for Balance Control of Inverted-Pendulum System

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Abstract—This paper elucidates a comparative study of highly non-linear and intricate Inverted Pendulum system using different soft computing methods. Primarily, a Fuzzy Logic controller was designed from Proportional-Derivative(PD) control. Furthermore, a Neural Networks(NN)controller was used to enhance the results obtained from Fuzzybased control system. Also, an Adaption basedNeuro Fuzzy Inference System(ANFIS) controller was proposed and evaluated in context to both controllers. The proposed controllers are developed in MATLAB-Simulink. Finally, the study exemplifies the impact of variation(disturbance) on performance parameters of Inverted Pendulum system. The outcomes show that ANFIS controller offers better control compared to rest controllers.

Keywords—Inverted Pendulum, P-D control, Fuzzy Logic control, Neural Network control, ANFIS control, Matlab-Simulink

I. INTRODUCTION

A distinctive highly challenging Inverted Pendulum or single pendulum system is frequently recommended as a standard nonlinear system to compare various control methods in engineering and used by many researchers [1, 7]. A control system must control the balancing mechanism of the system. As known, Fuzzy Logic Control system consist of a process of defining diverse set of rules to acquire best control for non-linear process. Fuzzy Logic provides forthright and easy path to demonstrate specific results from ambiguous and inaccurate information [2]. The best technique for identifying neural networks is forward modelling. While training, same inputs

and outputs for process and Artificial Neural Networks are compared. The error obtained is then used to upgrade weights of Neural Network. Target values for Neural Network are provided by Inverted Pendulum system [3].

ANFIS is a different class of controller that chains both Fuzzy Logic Control and Neural Networks to acquire best control of Inverted Pendulum system. ANFIS uses different models like SUGENO-Inference model, MAMADANI-Inference models, where output of each triggered rule is linear algebraic combination of sets of input Variables and constants. Also, ANFIS applies backward propagation to optimize input data sets[4].

This paper firstly, presents the schematic design of Proportional-Derivative(PD) control of Rotary Arm of pendulum. Based on the data collected in workspace of PD control a Fuzzy Logic controller was developed in MATLAB Simulink. Secondly, A Neural Network was designed based on Fuzzy Logic Control and compared.

Finally, An Adaptive Neuro Fuzzy Inference system was formed, which is a combination of Fuzzy Logic and Neural Networks. The outcome of this practice concludes that ANFIS gives the best result in controlling such non-linear control systems.

II. INVERTED PENDULUM MODELLING

A. Model Convention

QUBE Servo 2 kit is used to implement the various soft computing based control algorithms. In actual, the rotary arm pivot attached to QUBE servo 2 is activated. Where, arm has a length of L_r , inertia of J_r , and its angle of Θ , increase negatively when it rotates clockwise. When control voltage (u) is negative, the servo and thus the rotary arm should move in clockwise direction and viceversa[5].

The pendulum link and rotary arm are connected with total length of L_p , and located at the centre of mass. The inertia around its centre of mass is J_p . The inverted pendulum angle, $L_p/2$, is around "0" when it is perfectly upright in the vertical position and increases directly when rotated anti-clockwise. The model of rotary inverted pendulum is as shown in Figure 1.1.

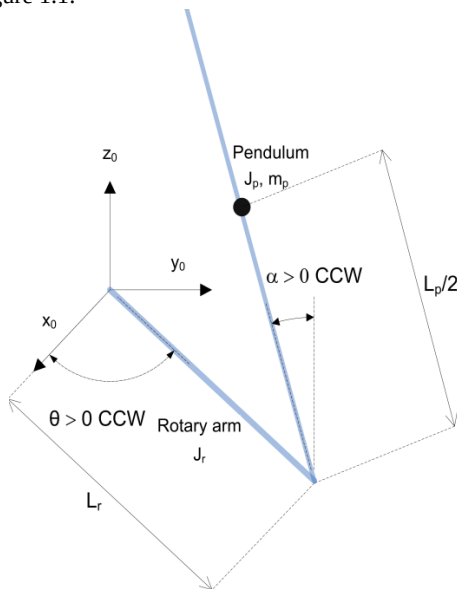


Figure 1.1., Rotary Inverted Pendulum conventions.

B. Non-Linear Equations of Motions

Lagrange's method has been used to find motion equations, instead of using classical approach. This system is particularly used for complicated systems with multiple joints. For generalized co-ordinated defined, Euler-Lagrange equations can be described as,

$$\frac{\partial^2 L}{\partial t \partial \theta} - \frac{\partial L}{\partial \theta} = Q1 \quad (1)$$

$$\frac{\partial^2 L}{\partial t \partial \dot{\theta}} - \frac{\partial L}{\partial \dot{\alpha}} = Q2 \quad (2)$$

The LaGrange of the system is described as,

$$L = T - V(3)$$

Where, T and V are kinetic energy and potential energy of the system accordingly. Thus, the LaGrange is the difference between a system's kinetic and potential energies. The load generated by servo motor to the pendulum arm is expressed precisely as,

$$\tau = \frac{\eta_g k_g \eta_{m k_t} (v_m - k_{m k_t} \dot{\theta})}{R_m} \quad (4)$$

On Linearizing these non-linear equation, the linear state model can be obtained is,

$$\dot{X} = Ax(t) + Bu \quad (5)$$

$$y = Cx(t) + Du(6)$$

In Inverted Pendulum, the state and output are defined as,

$$X = [\theta \ \dot{\theta} \ \alpha \ \dot{\alpha}]^T \quad (7)$$

$$Y = [x_1 \ x_2]^T \quad (8)$$

Where, $\dot{\theta}$ is derivative of θ and $\dot{\alpha}$ is derivative of α . In the equation of output, only the servo link position and link angles are measured. Based on this, the C and D matrices can be written as,

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, D = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

The speed of the servo and pendulum can be calculated by differentiating and filtering position and angle [5].

III. MODEL BASED CONTROLLER DESIGN

A. Proportional-Derivative (PD) Control

The Integral term was sacrificed for the balance control of Inverted Pendulum. Instead, a combination of Proportional-Derivative (PD) control is used. The closed-loop transfer function is denoted as,

$$T(s) = \Theta_m(s) / \Theta_d(s) \quad (9)$$

Solving for $Y(s)/R(s)$, we obtain the closed-loop expression,

$$T(s) = \frac{K k_p}{Ts^2 + (1 + K k_d)s + K k_p} \quad (10)$$

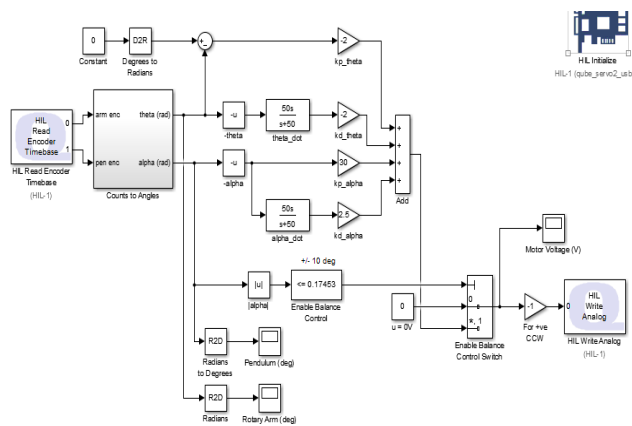
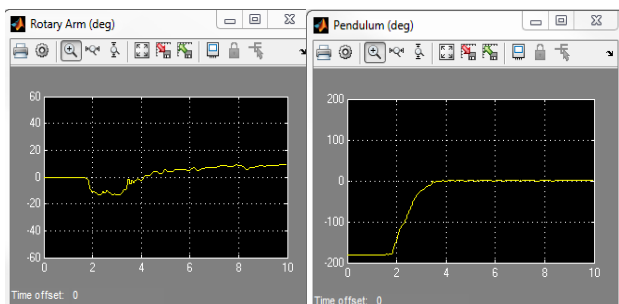


Figure 1.2, Simulink model for Balance(PD) control

Balancing of the pendulum arm is a common control objective. In this way, we will develop the control strategies to balance the pendulum in the upright position with maintaining the position of the arm. During the balancing control of the pendulum system, the pendulum angle is kept smaller and balancing can be accomplished with a simple proportional-derivative controller which is as shown in Figure 1.2. The output position tracking graph of PD control is as shown,



(a) Rotary arm. (b) Pendulum.

Figure 1.3 QUBE-Servo 2 rotary pendulum response

The rotary arm and pendulum angles are both stabilized about angle zero. Also, notice that the rotary arm tends to rotate back-and-forth about the set point or reference angle.

B. Fuzzy Controller

Fuzzy Logic implementation has an advantage of experiment based information helps to solve it in a simpler manner. Here we used the output data of PD controller as an input for fuzzy block. Fuzzy logic inputs, angular position and velocity which contain necessary information are conveyed to rule base. Membership functions of input and output are chosen to be triangular. Rule base is a set of different IF-THEN expressions as shown below

IF x is small AND y is big THEN z is medium.

IF x is big AND y is medium THEN z is big.

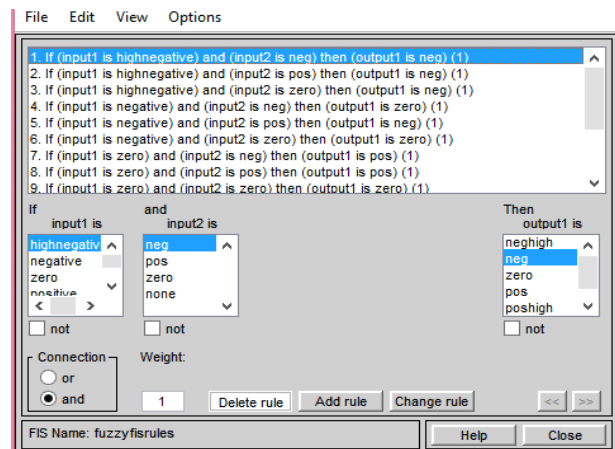


Figure 1.4 Fuzzy rule base

Above Figure 1.4, shows the rule editor for Fuzzy Logic System. Total Fifteen rules are generated for Five Inputs and Three Output Triangular membership functions. Once generated FIS file is exported to Fuzzy Logic Block and trained according to defined rules. The output response of fuzzy logic compared to PD control is as shown in figure 1.5.

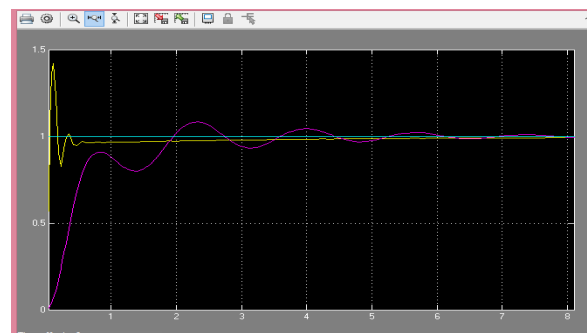


Figure 1.5 PD vs Fuzzy output response

From the graph shown in Figure 1.5, It gets clear that the output of PD has higher peak overshoot compared to fuzzy output i.e., the proportional error does persist in the PD system, while the response of fuzzy almost tracks around the set point and has least overshoot. Also, the settling time for fuzzy system and PD system is almost similar.

C. NN Controller

According to control law developed in section 2(B), a feed forward Neural Network was constructed to imitate the controller. Network has three hidden layers and 5, 4 and 1 neurons in each hidden layer. With output layer as linear

function, the activation functions are tag-sigmoid. Figure 1.6 shows the Simulink model of Neural Network.

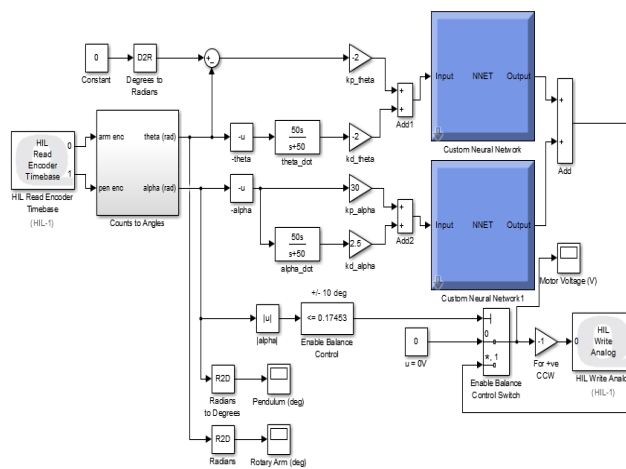


Figure 1.6 Simulink Model of Neural Network

In this figure two custom Neural Network blocks are used to control two different quantities, Alpha and Theta angles. Alpha along with its derivative was used as an input to first Neural Network. While, Theta with its derivative was used as an input to second Neural Network. NN tool was used in Simulink to generate custom Neural blocks which were used in Simulink model.

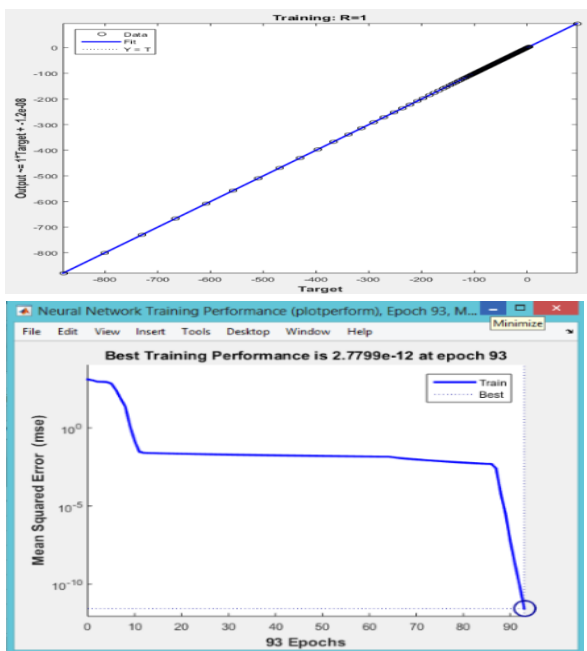


Figure 1.7 Output training tracking of Neural Network

The command used to generate actual the Neural Network is as shown,

```
x=-pi:(error data):pi;
```

```
y=-pi:(output data):pi;
```

```
t=y;
```

```
net=newff(x,y,5);
```

```
net=train(net,x,y);
```

```
y1=sim(net,x);
```

```
plot(y,y1,'r');plot(y);hold on
```

Above figure 1.7, shows the training state of Neural Network. outputvs target graph depicts that output tracks target data successfully. Also, best training performance was achieved at 93rd epoch.

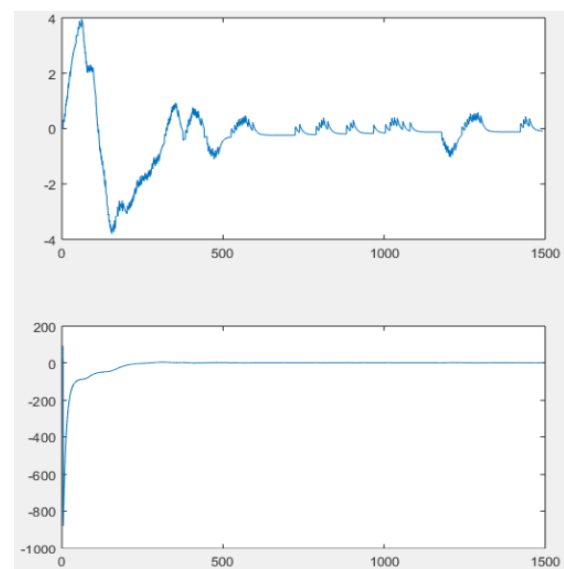


Figure 1.8 Actual tracking output

Above Figure 1.8 shows the actual tracking output, where the set point is achieved successfully.

D. ANFIS Controller

ANFIS in Simulink is simulated by generating ANFIS file by commands as shown below,once command execution is done it will create FIS file in workspace.Training this file in fuzzy inference system would generate Fuzzy Logic controller which acts as Adaptive Neural Fuzzy Inference system.It trains the data by using Fuzzy Logic and generates the output

using Neural Networks and this makes the ANFIS controller more promising for non-linear systems.

MATLAB command for generating the ANFIS file is written as below:

```
Training data = [e u];
No. of MFs = 2;
Membership function type = 'triangular membership fun. ';
epoch n = 20;
infis = genfis(training data, no. of MFs, Mf type);
outfis = anfis(training data, in fis, 20);
plot(e,u,e,evalfis(e,out fis));
legend('Training Data','ANFIS Output');
```

The block diagram of ANFIS controller in Simulink is as shown in figure 1.9.

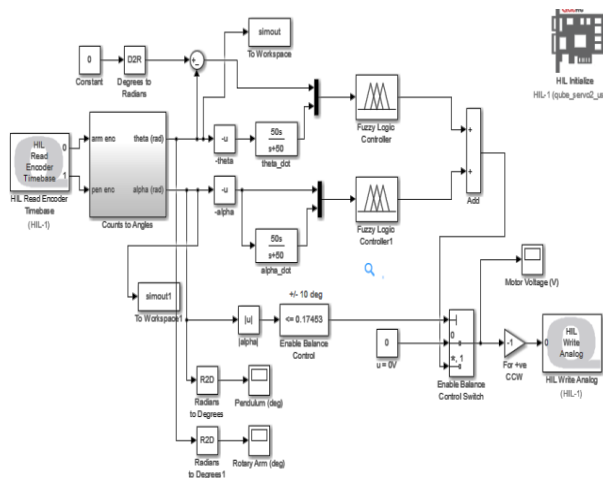


Figure 1.9 Simulink model of ANFIS controller

E. Comparative Analysis

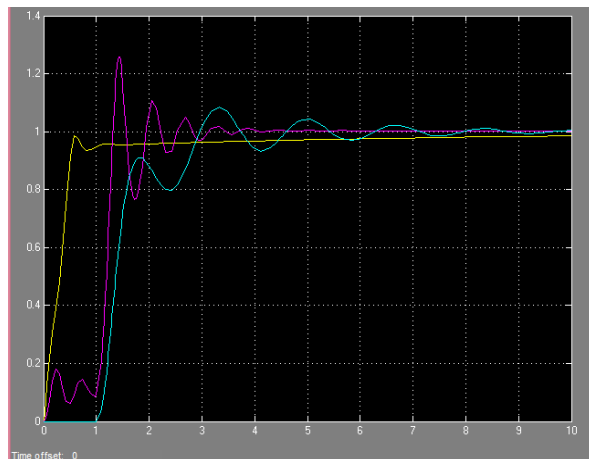


Figure 1.10 Simulink based comparison of controller response

Comparative analysis has been shown in figure 1.10. Figureshows the comparison of responses of fuzzy logic system with neural networks and adaptive neuro fuzzy inference system. Due to advantages of both fuzzy and neural network based system, ANFIS giving best performance. It has least peak overshoot and least settling time compared to both fuzzy and neural network.

Detailed transient specifications of control systems described in this paper are as follows:

Controller	Settling Time	Peak Overshoot
PD	8.81 Second	1.38 Amplitude
Fuzzy	8.34 Second	1.15 Amplitude
Neural	7.22 Second	1.22 Amplitude
ANFIS	7.19 Second	0.98 Amplitude

IV. CONCLUSIONS

In this paper, PD, Fuzzy, Neural Network and ANFIS algorithm is implemented on inverted pendulum system. All algorithms are used to design controller for the balancing the pendulum. As understood the fuzzy based system is better decision making system and Neural Network having a very good function approximation capability. Fuzzy and NN based algorithms gives better result compared to conventional PD controller based system. Since, ANFIS having hybrid structure of both Fuzzy and NN, it has advantages of both. All the proposed algorithms are compared in figure 1.10 and with values of transient response data. Results proved the superiority of ANFIS algorithm compared to other algorithms.

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