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Design of Non-Linear Controller for a Ball and Beam System

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Abstract: For any non linear system, designing and testing the behavior of a controller is a tedious task. The ball and beam system has typical features of a non-linear system, wherein the control of a rolling ball at a desired point on the beam is difficult. The main focus is to regulate the ball's position on the beam by changing the angle of the beam. Therefore by analyzing and modeling the system, a control technique for the system is designed with the help of Quanser Servo motor. Thus a fuzzy logic controller is developed and designed in the QUARC toolbox in MATLAB for effective and optimum response of the system. The simulation shows great progress and successful results.

Keywords: non-linear; ball and beam; fuzzy logic controller(FLC)

1. INTRODUCTION

Ball and beam system is a highly complex and non-linear system. It is often used as a benchmark problem in studying various control methods [8]. The model has a horizontal beam which pivots about one end; and a servo motor whose shaft is connected to the other end of the beam; with a ball that rolls freely on top of the beam [10].

The ultimate goal is to automatically control the position of the ball on the beam by controlling the beam's angle accordingly. The angle of the beam is controlled via a servo motor. Fuzzy logic controller doesn't require complex mathematical modeling and is known for handling uncertainties . By defining the accurate range of inputs and outputs, a fuzzy logic controller can be designed effectively. In order to find the experimental transfer function of the SRV02 an experimental set up is developed and is determined using Frequency domain method. The results obtained using this method is compared with the theoretical and the accurate transfer function of the Quanser servo plant is determined.

2. SYSTEM DESCRIPTION

The Ball and Beam system consists of a v-grooved steel bar and a free rolling ball. The output shaft of the servo motor is connected to one end of the beam through a gear mechanism to control the position of the ball on the beam while the other end of the beam is fixed. Thus the beam begins to tilt by when an electrical control signal is applied to the motor amplifier. By measuring the output voltage from the stainless steel bar, the position of the ball on the track is measured via a linear sensor. The main job is to control the angle of the lever arm with the parallel beam so that the Ball is positioned accordingly on the Beam. The Quanser servo plant is interfaced with the PC which consists of the Quarc software using the Q8-USB data acquisition board and Quanser VoltPAQ-X1 power amplifier. Since the system is used for control objective, accurate modeling of the system is mandatory.

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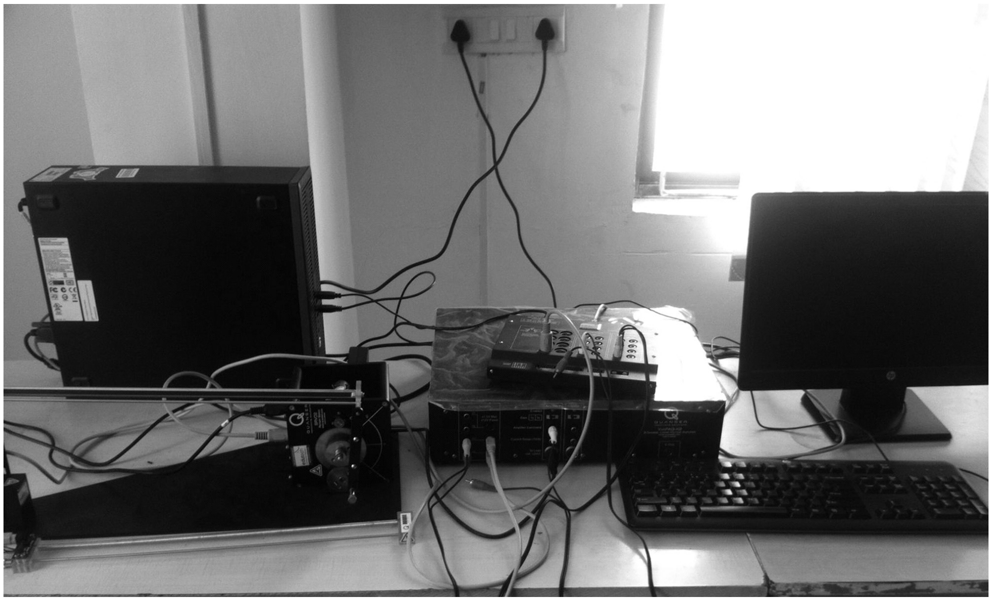

Figure 1: Quanser Ball and Beam setup

3. THEORITICAL TRANSFER FUNCTION OF QUANSER SERVO MOTOR

The transfer function that represents load shaft rate Ω_1 with respect to an applied motor voltage $\mathbf{V}_m$ is given by the first order transfer function, [11-13],

$$\frac{\Omega_1(s)}{V_m(s)} = \frac{1.53}{0.0254s + 1}$$

From the mechanical and electrical equations of the motor, the transfer function is derived analytically.

Thus steady state gain of the system is,

$$K = 1.53 \text{ dB}$$

Time constant is,

$$\tau = 0.0254s$$

4. MODELING OF QUANSER SERVO MOTOR EXPERIMENTALLY

A linear model of the system can also be determined purely experimentally. Basically, the idea is to observe how a system reacts to different inputs and change parameters of the model until a reasonable fit is obtained. The inputs can be selected in many different ways with the help of different methods. System modeling can be done either using Bumptest method or Frequency response method. This paper discusses about frequency response method.

A. Frequency Response Method

The frequency response method, a sine wave input with fixed amplitude and frequency is given to the servo motor. The output will be sinusoid with the same frequency but with different amplitudes. By varying the frequency of the sine wave and observing the outputs, a bode plot of the system can be obtained. In Frequency response method, the input offset voltage is kept as small as possible to minimize the error at output. In this experiment, input signal is the motor voltage and output signal is the motor speed. [11-13]

By keeping the amplitude of the input sine wave constant and varying frequency at each frequency setting, the amplitude of the output sine wave is recorded. To create a Bode magnitude plot the ratio of the output and input amplitudes for the given frequency can be used. Then, the transfer function for the system can be extracted from this plot.

1. Procedure

First, the steady-state gain of the system must be created, for that a constant input voltage i.e., 2V must be created. The following steps has to be carried out[9][11-13]:

1. In the Simulink diagram, click on the Signal Generator block and ensure that the parameters are set accordingly as follows:
   - Signal form: sine wave
   - Frequency: 0.0
   - Amplitude: 1.0
   - Units: Hertz
2. The Amplitude slider gain is set to 0.
3. The Offset block is set to 2.0 V.
4. Open the load shaft speed scope and the motor input voltage scopes.
5. Build the Simulink model toolbar button to compile the diagram.
6. Once the model code has been compiled, select the Connect To Target button. Start to run the controller. The SRV02 unit will begin rotating in one direction. From the scope, it is seen that the yellow trace is the measured speed and the purple trace is the simulated speed.
7. Measure the load shaft speed and enter the measurement in Table I below under the $f = 0$ Hz row.

   The measurement is read directly from the scope in order to find the maximum load speed.

2. Response of the System

By varying the frequency of the sine wave input the speed of the motor is recorded and the corresponding gain values are calculated [11-13].

Table 1
Obtained frequency response data

f(Hz)	*Amplitude(V)*	*Maximum Load Speed(rad/s)*	*Gain (rad/s/V)*	*Gain (rad/s/V,dB)*
0.0	2.0	3.31	1.66	4.40
1.0	2.0	3.23	1.61	4.13
2.0	2.0	3.15	1.57	3.91
3.0	2.0	2.96	1.47	3.34
4.0	2.0	2.77	1.38	2.79
5.0	2.0	2.54	1.29	2.21
6.0	2.0	2.43	1.22	1.72
7.0	2.0	2.34	1.17	1.36
8.0	2.0	2.22	1.11	0.90

3. Transfer Function

Magnitude of Frequency response of SRV02 plant transfer function [11-13]

$$| G_{wl,\,v}(\omega_j) | = \frac{\Omega_l(\omega_j)}{V_m(\omega_j)}$$

where, ω is the frequency of the motor input voltage. Thus for $f = 1$ Hz the maximum load speed is 0.3369 and the voltage is 0.2V. Therefore Gain is

$$| G_{wl,\,v}(0) | = 1.66 \text{ [rad/s]}$$

The Gain in dB is,

$$| G_{wl,\,v}(0) |_{dB} = 20 \log 10(1.66) = 4.40\text{dB}$$

The –3dB Gain is,

$$| G_{wl,\,v}(\omega_c) |_{dB} = 1.52 \text{ dB}$$

From the bode plot the cut-off frequency is $f_c = 6.6$ Hz.

$$\omega_c = 2\pi f_c$$

$$\omega_c = 41.469\text{[rad/s]}$$

Time constant is,

$$\tau = \left(\frac{1}{\omega_c}\right) = 0.0226 \text{ s}$$

Thus the transfer function of the system is,

$$\frac{\Omega_l(s)}{V_m(s)} = \frac{1.66}{0.0226\,s + 1}$$

5. DESIGN METHODOLOGY OF FUZZY LOGIC CONTROLLER

Although PID control is the practiced technique for the handling of non-linear systems the system modeling is often troublesome and sometimes impossible. Alternatively, Fuzzy Logic Control is useful when the existing sources of information are interpreted or when the processes are too complex for analysis. In fuzzy control the main focus is on gaining an intuitive knowledge of how to control the process in an efficient way, this information is then directly loaded into the fuzzy controller. Therefore, the control technique founded on fuzzy logic not only simplifies the design, but reduces the tedious task of solving complex mathematical equations for nonlinear systems. As a result, fuzzy controller delivers an enhanced performance in comparison to the conventional controller which fails to cope with the non-linearity of a process under control.

The design procedure employs the MATLAB Fuzzy Logic toolbox version 7.1. The Fuzzy Logic toolbox has the ability to take fuzzy systems into the SIMULINK platform directly and can test them out in a simulation environment which makes it highly valuable. To an extent a better controller is designed with the aid of the simple fuzzy rules defined. For fuzzification process, the triangular membership functions are used for both input as well as output and for defuzzification, the centroid method is used.

The universe of discourse is given as follows:

- $e = [-1, 1]$
- $de = [-1, 1]$
- $Z = [-2, +2]$

A. Membership Functions

The system is designed using two types of input to observe the result for two cases and where the fuzzy rules are same in both cases. Each fuzzy set has seven membership functions, which is given as negative big (NB), negative medium (NM), negative small (NS), positive small (PS), positive medium (PM), positive big (PB) and zero (ZE)[1-3][12-13].

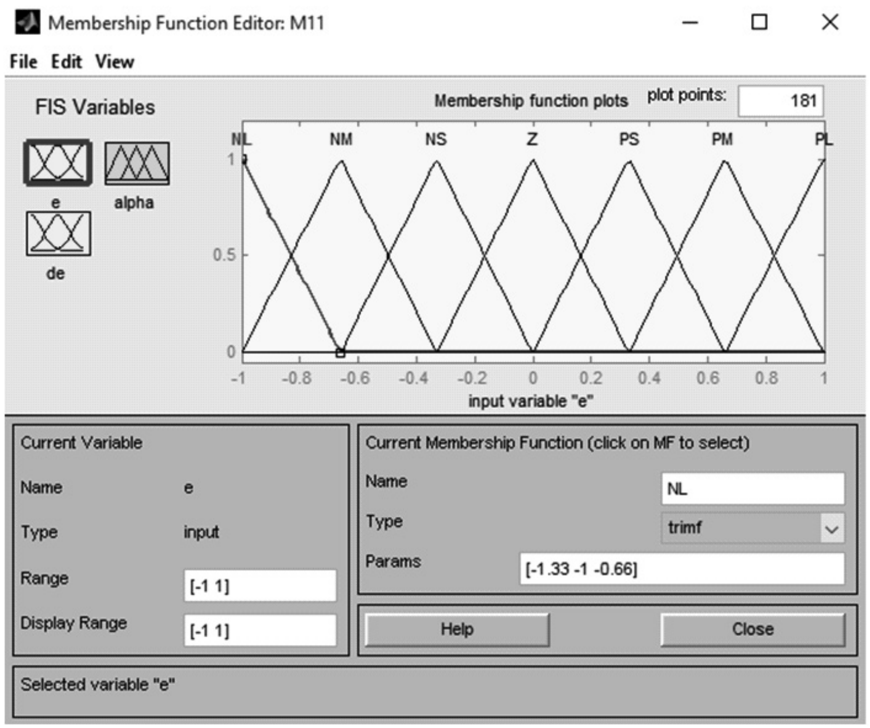

Figure 2: Inputs "error e" and "change of error de"

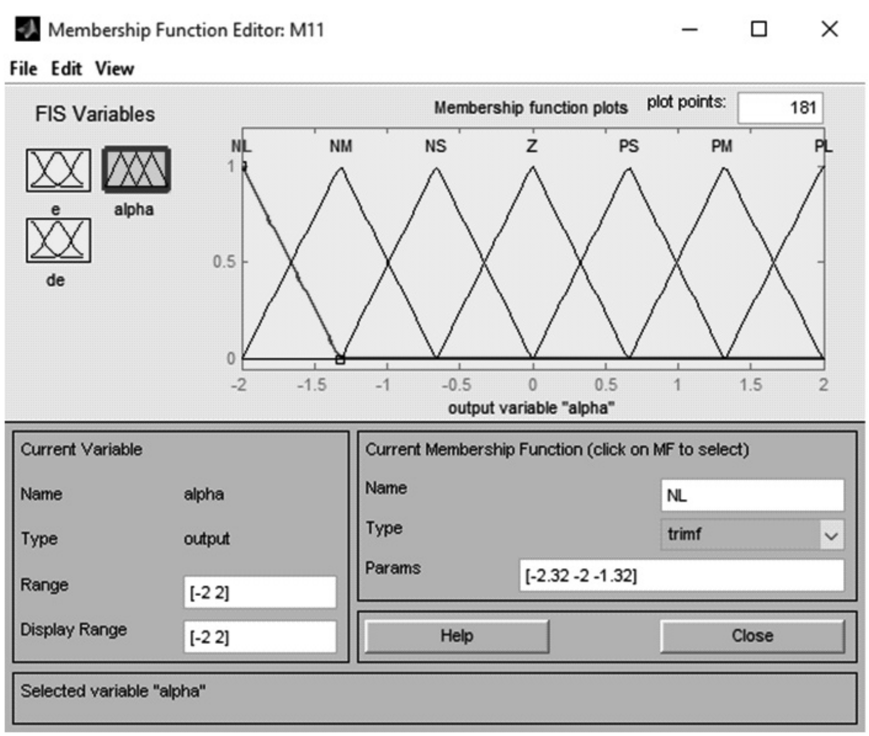

Figure 3: The output(Z) of the fuzzy control

B. Rule Base

Fuzzy control rules is vital for a fuzzy controller. In general, the two methods to generate fuzzy rules: one is summarized based on practical experience and knowledge of operators or experts; the other is summarized through the analysis of the input and output data from experiments.

The rule base used in the design closely follows the one mentioned in the given Table 2. [3][12-13].

Table 2
Fuzzy Rules

e/ė	*PL*	*PM*	*PS*	*Z*	*NS*	*NM*	*NL*
NL	Z	NS	NM	NL	NL	NL	NL
NM	PS	Z	NS	NM	NL	NL	NL
NS	PM	PS	Z	NS	NM	NL	NL
Z	PL	PM	PS	Z	NS	NM	NL
PS	PL	PL	PM	PS	Z	NS	NM
PM	PL	PL	PL	PM	PS	Z	NS
PL	PL	PL	PL	PL	PM	PS	Z

C. Simulink

Simulation Model of the ball and beam system is shown in Figure 4 and in MATLAB 2013b the model is simulated and controlled [12].

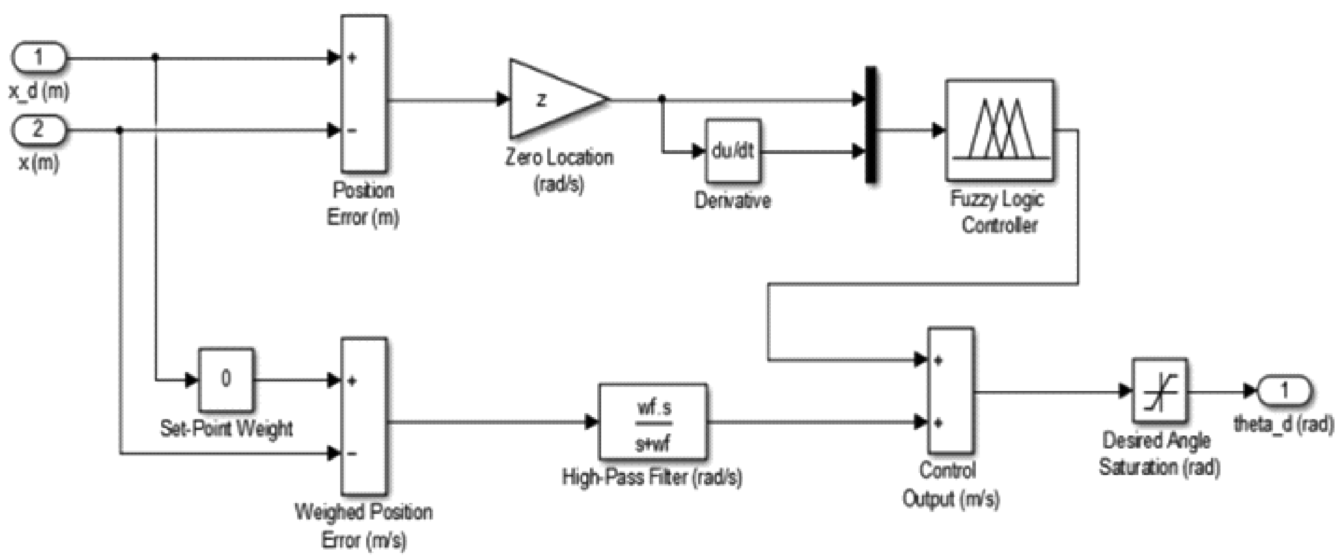

Figure 4: Subsystem Block diagram of Ball and Beam setup using FLC

6. RESULTS AND DISCUSSION

The simulation results of the ball position and angle position response is plotted and illustrated. Figure 5, *x*(*m*) scope demonstrates the ball position set point and the simulated response. We observe a steady settling of the response which is similar to the desired output is acquired having a peak overshoot of 0.619% with a settling time of 3.34 sec. Similarly Figure 6, the theta l (deg) scope, demonstrates the desired servo angle position, which is acquired by the outer-loop control, and the simulated servo response. And Figure 7 is the SRVO2 Motor input voltage scope V_m(V)[12].

Table 3
Output Response of FLC

S.No	PARAMETERS	FLC
1.	Peak time	4.33 s
2.	Percentage overshoot	0.619 %
3.	Settling time	3.34 s
4.	Steady state error	7.2×10^{-6}

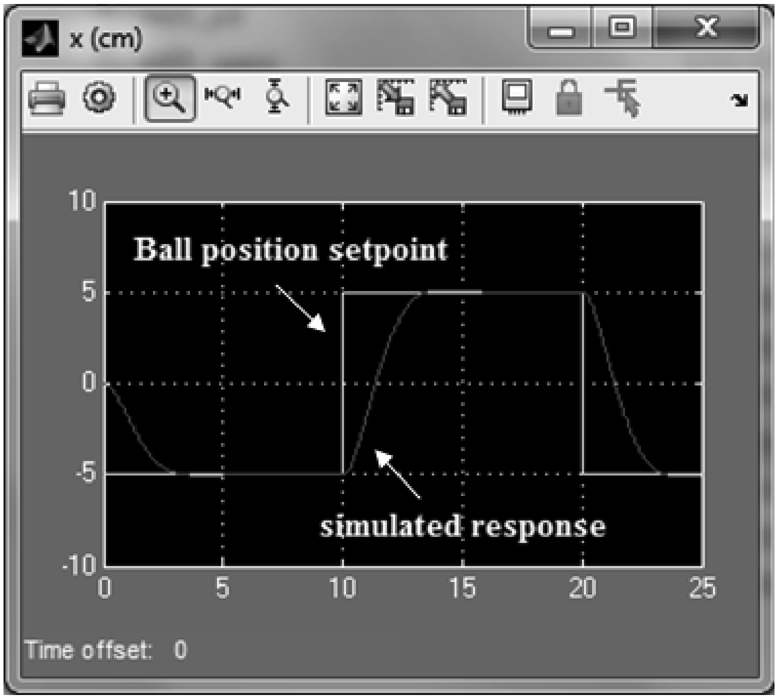

Figure 5: Fuzzy control ball position scope *x*(*m*)

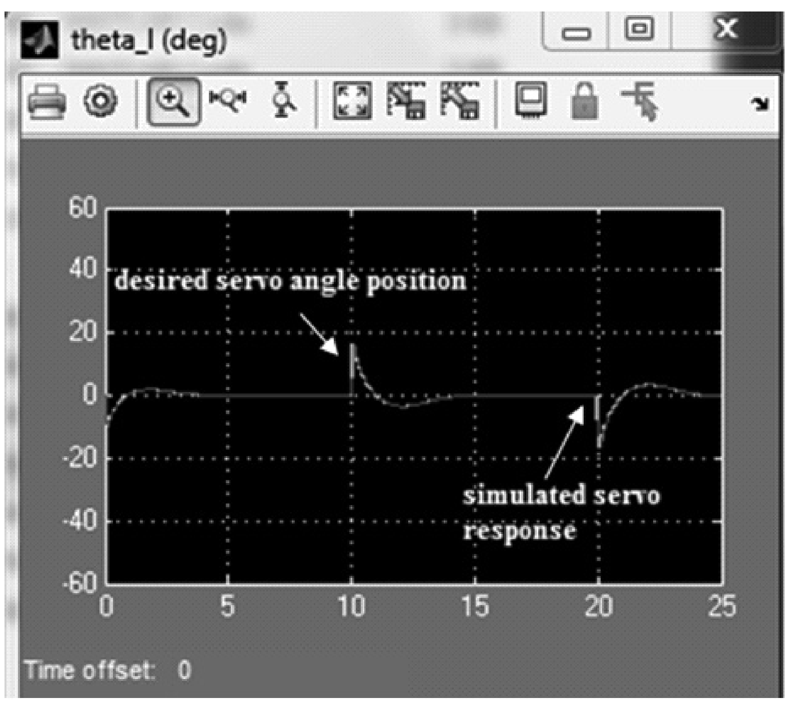

Figure 6: Fuzzy control servo angle scope theta l (deg)

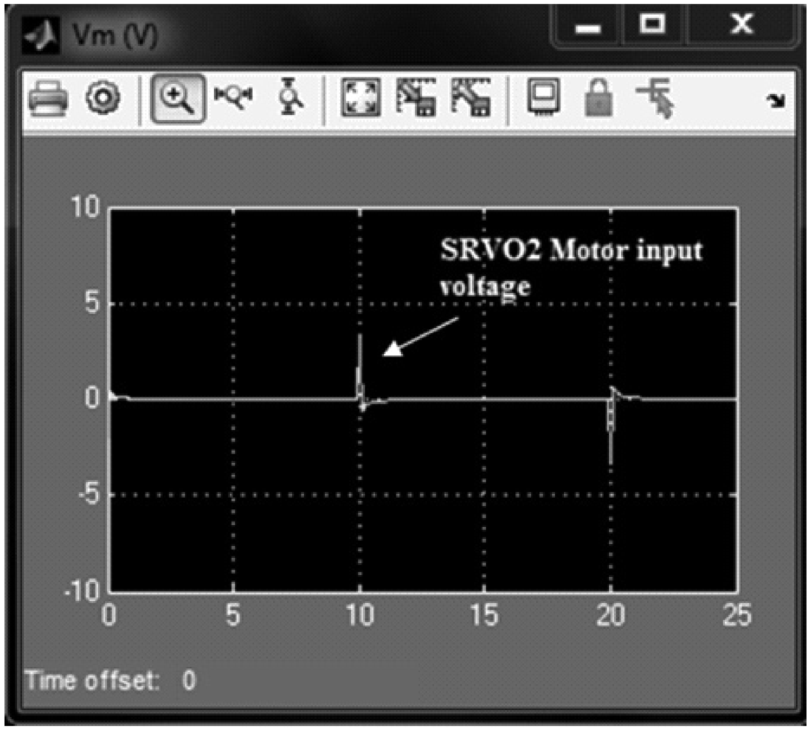

Figure 7: SRVO2 Motor input voltage scope V_m(V)

7. CONCLUSION

To obtain robust control of non-linear system determination of transfer function in real time is necessary. Modeling and control of the system using frequency response method is presented in this paper. By applying this technique, the Transfer function of the servomotor is derived which is essential for the robust control of a non-linear system. Fuzzy logic controller design for challenging nonlinear systems such as the ball and beam system increases the accuracy of the control action. Table III summarizes the behaviour of the FLC parameters. Thus the fuzzy algorithm is successfully applied to the system and from the simulation results it is inferred that fuzzy controller stabilizes the system efficiently and that the ball is controlled steadily.

The future work could be including advanced algorithms such as simulated annealing etc or Fuzzy with PID wherein an improved Fuzzy controller can be achieved.

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