Design and Simulation Fuzzy like PID controller

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Abstract

The aim of this work is to design a controller based on fuzzy logic control in order to improve the performance of the control system. A fuzzy like PID controller has been designed based on fuzzy like PI controller and fuzzy like PD controller; then applying these three controllers to a case study Ball and Beam control system, finally compare the simulation results among three controllers by using Matlab Toolbox, the concludes the superiority of the (FPID) over the others is to be considered.

Keywords: Fuzzy controller, PID controller, control systems

الخلاصة:

هدف البحث هو تصميم وبناء مسيطر على اساس استخدام المنطق المضبب (FLC)يتضمن ثلاثة انواع من المسيطرات وهي:- مسيطر المنطق المضبب التناسبي-التكاملي(FPI),مسيطر التناسبي-التفاضلي(FPD) ومسيطر المنطق التناسبي-التكاملي-التفاضلي(FPID). تم تطبيق المسيطرات الثلاث على نظام (Ball and Beam control system) تمت مقارنة النتائج باستخدام حقيبة ال-Simulink من برنامج ال-Matlab . اثبتت النتائج التفوق الكبير لاداء المسيطر المنطق التناسبي-التكاملي-التفاضلي(FPID) على بقية الانواع الاخرى من المسيطرات.

1. Introduction

Fuzzy logic has rapidly become one of the most successful today's technologies for developing sophisticated control systems. Fuzzy logic controller is more robust than conventional PID controller because it covers a much wider range of operating conditions than PID, and can operate with noise and disturbances of different natures. Given the dominance of conventional PID control in industrial applications, it is significant both in theory and in practice if a controller can be found that is capable of outperforming the PID controller with comparable ease of use. Some types of PID fuzzy controllers are able to satisfy these requirements [1].

Fuzzy controller provides mathematical framework for manipulating non precise and ill-defined concept. The control of a plant by a human operator is more successful than by any conventional PID. Since the strategy of the human operator is typically vague and can be best described qualitatively it is natural to employ fuzzy set theory to describe the strategy [2]. Fuzzy logic controllers are inherently nonlinear controllers, and hence fuzzy control technology can be viewed as a new practical way of developing nonlinear controllers. The major advantage of this technology over the traditional control technology is its capability of capturing and utilizing qualitative human experience and knowledge in quantitative manner through the use of fuzzy sets, fuzzy rules, and fuzzy logic [3]. The simplest and most used way to implement a fuzzy controller is to rely it as a computer program on general purpose computer [4]. Sensor measurements are used as scheduling variables that govern the change of the controller parameters, often by means of a look-up table [5].

Despite a lot of research and the huge number of different solutions proposed, most industrial control systems are still based on conventional PID regulators. Most of the classical industrial controllers have been provided with special procedures to automate the adjustment of their parameters (tuning and self-tuning). However, PID controllers cannot provide a general solution to all control problems. Fuzzy control constitutes one of the fastest-growing areas of control technology development, and have even better prospects for the future. The attraction of a fuzzy logic controller (FLC) from the process-control point of view can be explained by the fact that a FLC provides good support for translating both the heuristic knowledge about the process of a skilled operator, and control procedures into numerical algorithms [6].

The aim of this paper is to design and simulate fuzzy like PID controller based fuzzy like PI controller and fuzzy like PD controller, then applying these three designs to a case study Ball and Beam control system, finally compare the simulation results among three controllers by using Matlab Toolbox.

2. Transferring gains from PID to Fuzzy controller

The design procedure is to transfer the PID gains to the linear fuzzy controller [7].

The ideal continuous PID controller formula is:

$$u = K_p\left(e + \frac{1}{T_i}\int_0^t e.d\tau + T_d\frac{de}{dt}\right) \qquad (1)$$

u is the controller output. The constant K_p is the proportional gain, T_i is the integral time, T_d is the derivative time, and e is the error between the reference and the process output.

We are concerned with digital control, and for small sampling periods Ts, the equation may be approximated by a discrete approximation. Replacing the derivative term by a backward difference and the integral by a sum using rectangular integration, the approximation becomes:

$$u_n = K_p\left(e_n + \frac{1}{T_i}\sum_{j=1}^{n} e_j T_s + T_d\frac{e_n - e_{n-1}}{T_s}\right) \qquad (2)$$

Index n refers to the time instant. By tuning we shall mean the activity of adjusting the parameters K_p, T_i, and T_d.

2.1 Proportional Control

The basic structure of a P controller is shown in eq.(1)[8].

$$u_n = K_p e_n \qquad (3)$$

The input to the fuzzy proportional (FP) controller is error, and the output is the control signal u, the block diagram is in Fig. (4). This is the simplest fuzzy controller. It is relevant for state- or output- feedback in a state space controller, compared to crisp proportional control the fuzzy P controller has two gains, GE and GU instead of just one. As a convention, signals are written in lower case before gains and upper case after gains, for instance, E= GE* e.

The gains are mainly for tuning the response, but since there are two gains, they can also be used for scaling the input signal onto the input universe to exploit it better. The controller output is the control signal Un, a nonlinear function

$$U_n = f(GE * e_n) * GU \qquad (4)$$

The function f is the fuzzy input-output map for the fuzzy controller. Using the linear approximation f (GE* en)= GE* en, then

$$U_n = GE * e_n * GU = GE * GU * e_n \qquad (5)$$

The product of the gain vectors is equivalent to the proportional gain.

$$GE * GU = K_p \qquad (6)$$

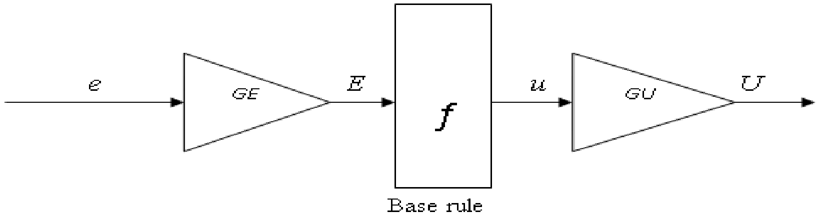

Figure (4): Fuzzy Proportional Control

2.2 Fuzzy Proportional and Derivative Control

Derivative action helps to predict the error and proportional-derivative controller uses the derivative action to improve closed-loop stability [9]. The basic structure of a PD controller is

$$U_n = K_p(e_n + T_d \frac{e_n - e_{n-1}}{Ts}) \qquad (7)$$

The control signal is thus proportional to an estimate obtained by linear extrapolation. For Td= 0 the control is purely proportional, and as Td is gradually increased, it will dampen the oscillations.

If Td becomes too large, the system becomes over-damped and it will not start to oscillate again. The inputs to the fuzzy proportional-derivative (FPD) controller is the error and change error as shown in Fig. (5). In fuzzy control the term is usually called change in error.

$$ce_n = \frac{e_n - e_{n-1}}{Ts} \quad (8)$$

This is a discrete approximation to the differential quotient using a backward difference. Other approximations are possible, as in crisp PD controllers. The controller output is a nonlinear function of error and change in error.

$$U_n = f(GE * e_n, GCE * ce_n) * GU \quad (9)$$

Again the function f is the input-output map of the fuzzy controller, only this time it is a surface. Using the linear approximation GE* e_n+ GCE* ce_n, then

$$U_n = (GE * e_n + GCE * ce_n) * GU \quad (10)$$

$$U_n = GE * GU * (e_n + \frac{GCE}{GE} * ce_n) \quad (11)$$

By comparison, the gains in eq. (11) with eq.(7) and eq.(6)

$$\frac{GCE}{GE} = T_d \quad (12)$$

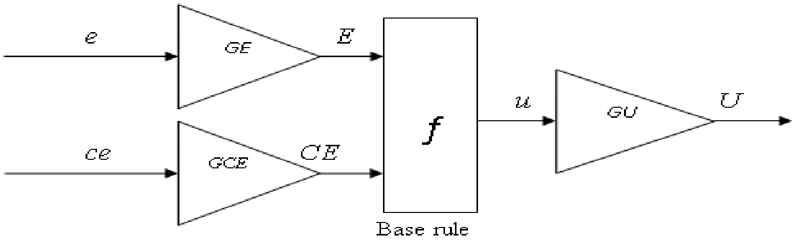

Figure (5): Fuzzy PD Control (FPD)

2.3 Fuzzy Proportional and Integral Control

If there is a sustained error in steady state, integral action is necessary. The integral action will increase the control signal if there is a small positive error, no matter how small positive error is; the integral action will decrease it if the error is negative. A controller with integral action will always return to zero in steady state. An increment controller adds a change in control signal Δu to the current control signal,

$$u_n = u_{n-1} + \Delta u \quad (13)$$

$$\Delta u = K_p (e_n - e_{n-1} + \frac{1}{T_i} e_n T_s) \quad (14)$$

The fuzzy Proportional and Integral (FPI) controller [10] in Fig.(6) is almost the same configuration as the FPD controller except for integrator on the output. The output from the rule base is therefore called change in output(CU_n) and the gain on the output has changed name accordingly to GCU.The control signal Un is the sum of all previous increments,

$$U_n = \sum_i (cu_i * GCU * T_s) \tag{15}$$

The linear approximation to this controller is:

$$U_n = GCE * GCU * (\frac{GE}{GCE} \sum_{i=1}^{n} e_i * T_s + e_n) \tag{16}$$

By comparing equations (2) and (16) it is clear that the gains are related in the following way,

$$\frac{GE}{GCE} = \frac{1}{T_i} \tag{17}$$

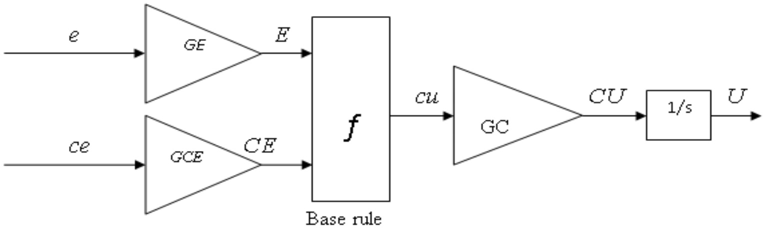

Figure (6): Fuzzy PI Control (FPI)

2.4 Fuzzy like PID control

The general type of this structure of fuzzy PID-control is shown in Fig. (7). The feature of this structure is the avoidance of the complexity of the rule-base and membership function design [11]. Both-the fuzzy-PI and fuzzy PD-controllers can use the same membership functions, and the same rule-base. Only the gains for the input and output signals have to be tuned with appropriate coefficients. The final control action can be expressed as a sum of both control actions.

$$u(n) = u_{PI}(n) + u_{PD}(n) = u(n-1) + \Delta u(n) + u_{PD}(n) \tag{18}$$

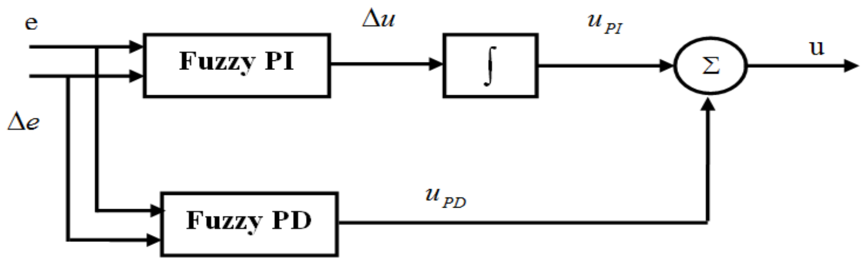

Figure (7): Fuzzy PI control with fuzzy PD control

3. Position control of Ball and Beam modeling

A ball is placed on a beam, as shown in Fig. (8), where it is allowed to roll with one degree of freedom along the length of the beam. A lever arm is attached to the beam at one end and a servo gear at the other. As the servo gear turns by an angle theta, the lever changes the angle of the beam by alpha. When the angle is changed from the vertical position, gravity causes the ball to roll along the beam. A controller will be designed for this system so that the ball's position can be manipulated [12].

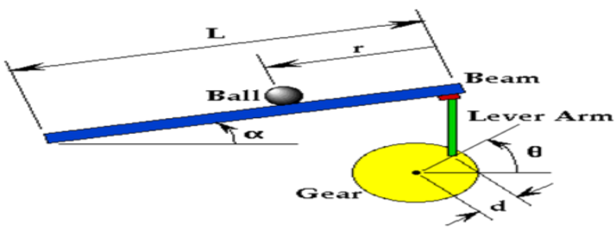

Figure (8): The ball and beam modeling

The constants and variables for this problem are defined as shown in table (1).

Table: 1 The Ball and Beam constants and variables

symbol	description	value
M	mass of the ball	0.11 kg
R	radius of the ball	0.015 m
d	lever arm offset	0.03 m
g	gravitational acceleration	9.8 m/s^2
L	length of the beam	1.0 m
J	ball's moment of inertia	9.99e-6 kgm^2

The second derivative of the input angle α(beam angle coordinate) actually affects the second derivative of r (ball position coordinate). However, we will ignore this contribution. The Lagrangian equation of motion for the ball is then given by the following:

$$0=\left(\frac{J}{R^2}+m\right)\ddot{r}+mg\sin\alpha-mr(\dot{\alpha})^2 \qquad (19)$$

Linearization of this equation about the beam angle, alpha = 0, gives the following linear approximation of the system:

$$\left(\frac{J}{R^2}+m\right)\ddot{r}=-mg\alpha \qquad (20)$$

The equation which relates the beam angle to the servo angle of the gear (θ) can be approximated as linear by the equation below:

$$\alpha=\frac{d}{L}\theta \qquad (21)$$

Substituting this into the previous equation, will get:

$$\left(\frac{J}{R^2}+m\right)\ddot{r}=-mg\frac{d}{L}\theta \tag{22}$$

Taking the Laplace transform of the equation (22), the following equation is found:

$$\left(\frac{J}{R^2}+m\right)R(s)s^2=-\frac{mgd}{L}\Theta(s) \tag{23}$$

Finally the transfer function of (θ(s)) gear angle to (R(s)) ball position will has the following form:

$$\frac{R(s)}{\Theta(s)}=-\frac{mgd}{L\left(\frac{J}{R^2}+m\right)}\frac{1}{s^2} \tag{24}$$

4. Simulation of designed controllers

The simulation of the three controller performed by using Matlab toolbox. A block diagram of the fuzzy like PD system controller is shown in Fig. (9). The FLC has two inputs, the error (e) and change of error (ce). All membership functions of the FLC inputs, e and are defined on the common normalized domain [-1,1], and the output as shown in Fig.(10), u, is defined on the common normalized domain [-2,2] as shown in Fig.(11). The characters NB, NM, NS, ZE, PS, PM, and PB stand for negative big, negative medium, negative small, zero, positive small, positive medium, and positive big, respectively. Here triangular MFs are chosen. The rule-base for computing the output u is shown in Table (2).

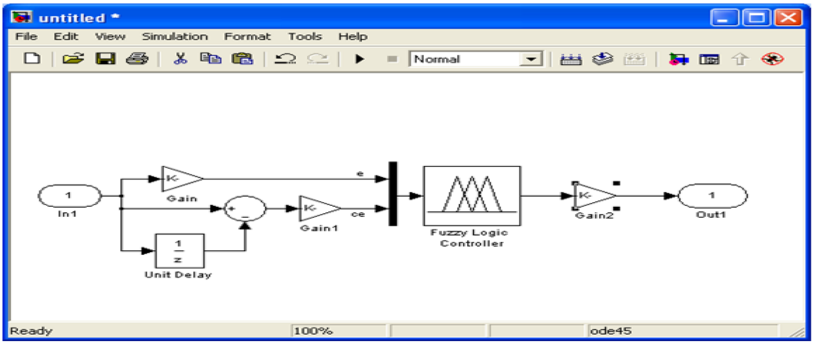

Figure (9): Block Diagram of the Fuzzy like PD Control System

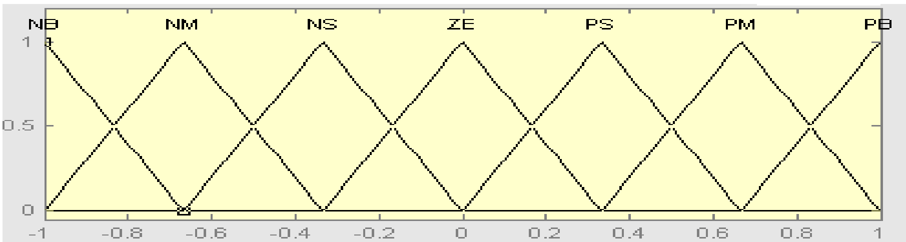

Figure (10): Fuzzy like PD Control membership functions for (e)and (ce)

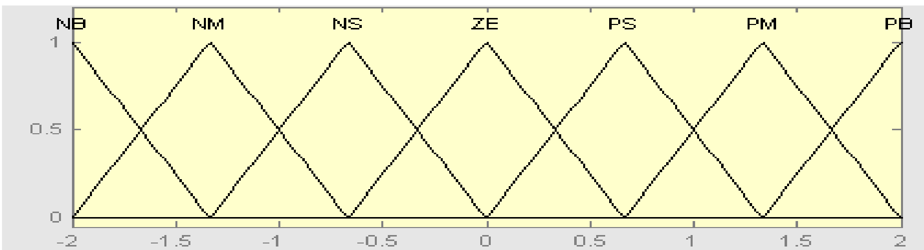

Figure (11): Fuzzy like PD Control membership functions for Δu

Table (2): Fuzzy-PD Rules for Computation of Δu

Δe / e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB

A block diagram of the fuzzy like PI system controller is shown in Fig.(12). The FLC has two inputs, the error e(k) and change of error Δe(k). All membership functions of the FLC inputs are (e, Δe), and the output (Δu) are defined on the common normalized domain [-1,1] as shown in Fig.(13). The characters NB, NM, NS, ZE, PS, PM, and PB stand for negative big, negative medium, negative small, zero, positive small, positive medium, and positive big, respectively. Here triangular MFs are chosen. The rule-base for computing the output Δu is shown in Table (3).

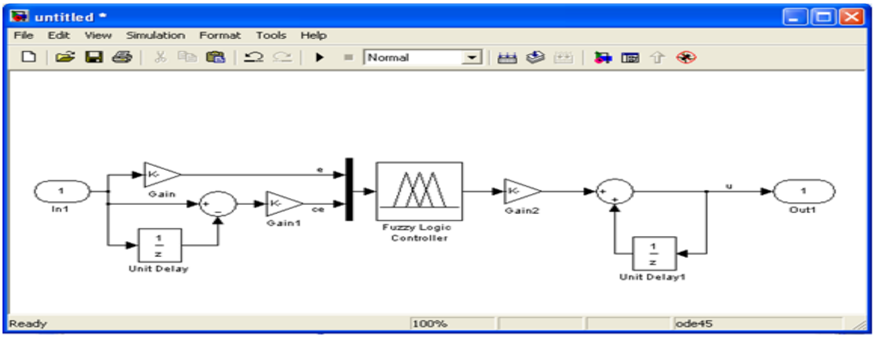

Figure (12): Block Diagram of the Fuzzy like PI Control System

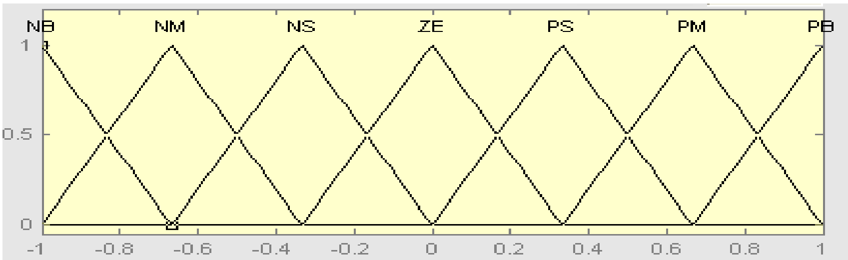

Figure (13): Fuzzy like PI Control membership functions

Table (3): Fuzzy-PI Rules for Computation of Δ u

Δe / e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PM	PB	PB	PB

The tuning the fuzzy PI+PD control it is recommended to tune the fuzzy PI-controller first without using the fuzzy PD-controller. Then keep the gains for input signals unchanged after adding fuzzy PD-control and adjust the gains for output signals to obtain an appropriate result. This type of controller is the one adopted in this work. A block diagram of the fuzzy like PID system controller is shown in Fig.(14). It is represent the combination of fuzzy like PI and fuzzy like PD controllers.

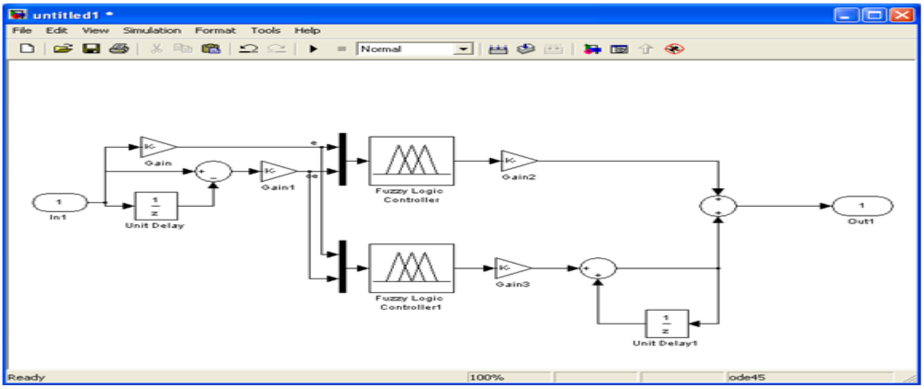

Figure (14): Block Diagram of the Fuzzy like PID Control System

5. Results and discussion

The simulation of designed controllers were applied to ball and beam control system as a case study by using Simulink Matlab toolbox.

The step response of the system is unstable and causing the ball to roll right off the end of the beam because the system is non-linear system, as shown in fig.(15).

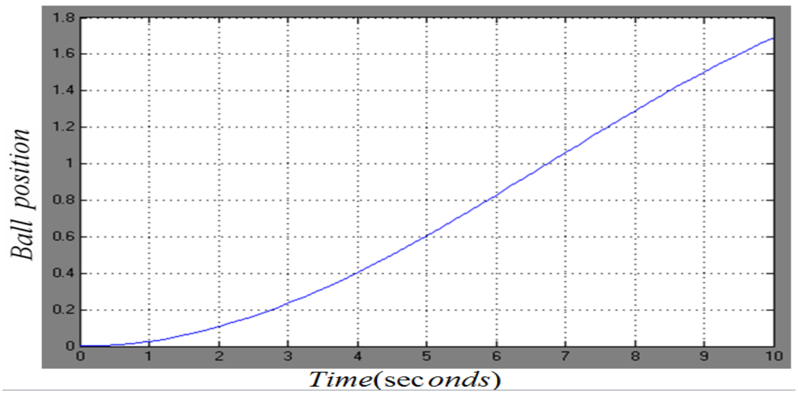

Figure (15): Step response for closed loop Ball and Beam controller

When applying fuzzy like PI controller shows in Fig.(16) for step input, the addition a controller doesn’t make the system stable because The integral term tends to increase the oscillatory or rolling behavior of the process response.

When applying fuzzy like PD controller as shown in Fig.(16) for step input, the system become stable but with high over shoot and long settling time.

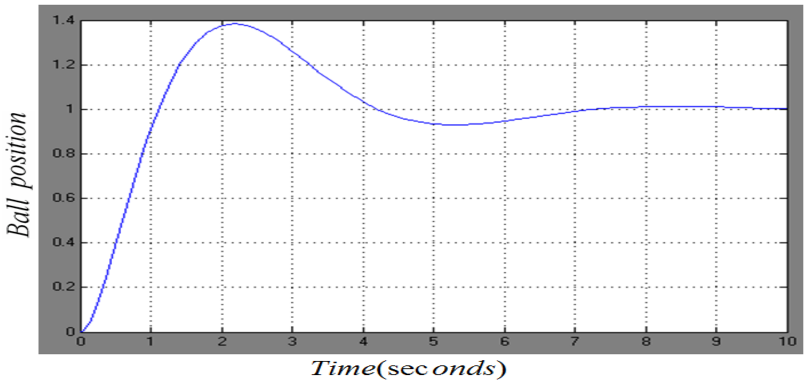

Figure (16): Step response of FPD controller for Ball and Beam controller

When applying fuzzy like PID controller as shown in Fig.(17) for step input, the system become stable without over shoot and less than 4 seconds settling time.

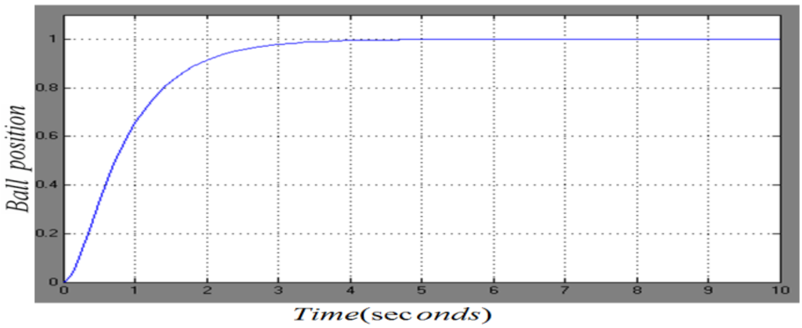

Figure (17): Step response of FPID controller for Ball and Beam controller

5. Conclusions

In this work there are three fuzzy logic based controller (fuzzy like PI, fuzzy like PD, and fuzzy like PID) were studied, also apllied these controllers to ball and beam control system as a case study by using Simulink Matlab toolbox. Results are showed fuzzy like PI controller doesn’t make the system stable, while the fuzzy like PD controller makes the plant stable but with overshoot, and long settling time. When applied fuzzy like PID controller to the plant makes the system stable with out over shoot, and reduce the settling time.

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