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Design of Fuzzy Logic Controller for a Spherical tank system and its Real time implementation

G.Sakthivel*
Lecturer (Selection Grade)

T.S.Anandhi*
Reader

S.P.Natarajan*
Professor & Head

*Dept of Instrumentation Engineering, Annamalai University, Chidambaram, INDIA

ABSTRACT

A real time implementation of Fuzzy logic controller (FLC) for a spherical tank to control liquid level is studied. Control of liquid level in a spherical tank is highly non linear due to variation in the area of cross section of level system with change in shape .System identification of spherical tank system is done using black box model which is identified to be non linear and approximated to be a First order plus dead time model .Here the conventional PI controller parameters are designed based on Ziegler-Nicholas method and its servo & regulatory responses are compared with Fuzzy logic controller based on mamdani model. The real time implementation of the process is designed and implemented in MATLAB using VMAT-01 Data Acquisition Module .It is observed from the results of Fuzzy Logic controller out performs in no overshoot, faster settling time, better set point tracking and produces lower performances indices like Integral square error(ISE*)* .

Keywords: Fuzzy controller**,** PI controller, spherical tank, system identification

1. Introduction

As PID is regarded as the standard control structures of the classical control theory and fuzzy controllers have positioned themselves as a counterpart of classical PID controllers on the same dominant role at the knowledge rich spectrum. PID controllers are designed for linear systems and they provide a preferable cost/benefit ratio. However, the presences of nonlinear effects limit their performances. Fuzzy controllers are successful applied to non-linear system because of their knowledge based nonlinear structural characteristics. Hybridization of these two controller structures comes to ones mind immediately to exploit the beneficial sides of both categories[1]. Chemical process present many challenging control problems due to their nonlinear dynamic behavior, uncertain and time varying parameters, constraints on manipulated variable, interaction between manipulated and controlled variables, unmeasured and frequent disturbances , dead time on input and measurements. Because of the inherent nonlinearity, most of the chemical process industries are in need of traditional control techniques. Spherical tanks find wide application in gas plants and process industries. Control of a level in a spherical tank is important, because the change in shape gives rise to the nonlinearity. The most basic and pervasive control algorithm used in feedback control is PID control algorithm[2]. The Fuzzy Logic Controller is well suited for the level control of spherical tank system for which conventional controller is not giving satisfactory result.

A fuzzy system can be shown to be a non-linear, which is useful for designing the controller for a non-linear process. After the industrial application of the first fuzzy controller by Mamdani (1974) fuzzy systems have obtained a major role in engineering systems and consumer products in the 1980s and 1990s. Takagi and Sugeno (1985) have discussed the main features of fuzzy models like the input space is decomposed into subspaces, then, within each subspace (i.e., fuzzy regions in the input space), the system model can be approximated by simpler models, in particular linear ones, then it is possible to use conventional controller development techniques for controlling these relatively simple local models and finally, the global fuzzy model in the state-space is derived by blending the subsystems` models in terms of the weighted average of rule contributions.

Procyk and Mamdani (1979) have suggested the advantage of FLC which can be applied to plants that are difficult to get the mathematical model. Recently, fuzzy logic and conventional control design methods have been combined to design a Proportional-Integral Fuzzy Logic Controller (PI-FLC). Hybriding the fuzzy and PI are to have a better control of non-linear. Qin and Borders (1994) have developed a PI-type fuzzy controller that uses information from the fuzzy regions of a non-linear process such as continuous stirred tank reactor for pH titration. Anganathan et al. (2002) have designed a fuzzy predictive PI control for processes with large time delay. Anandanatarajan et al. (2005) have designed the globally linearized controller for a first order non-linear system with dead time for a conical tank level process based on simulation. Anandanatarajan and Chidambaram (2005) have discussed the evaluation of a controller using variable transformation on a hemi-spherical tank which shows a better response than PI controller.

Fuzzy Logic controllers can generally be divided in to two types, Mamdani type controllers and Sugeno type controllers. The rule base of Fuzzy controllers consists of rules of the form *If x is A then Y is B where x* *is an input variable ,Y is the output variable* and A & B are fuzzy sets for the input variable and output variable respectively. In Mamdani type fuzzy controllers both antecedent and consequent of the rules (A&B) are Fuzzy sets[8] .In the case of Sugeno type fuzzy controllers, the antecedent parts of the rules (A) are Fuzzy while the consequent portions (B) are crisp. The present study deals with development of Mamdani type Fuzzy Controllers

In this work, real time fuzzy logic controller based on Mamdani type model is designed for controlling the liquid level in a spherical tank. Since the process is non-linear, the model is designed at three different operating regions (at level 30cm, 45cm, 60cm).The process model is experimentally determined from step response analysis and is interfaced to spherical tank in real time using VAMT-01 module through MATLAB. The Digital PI controller parameters are obtained from Ziegler-Nicholas method. The Digital Fuzzy Logic Controller is designed based on Mamdani model and the performances are compared with conventional controller based on time domain specifications like rise time, peak time settling time and Integral Square Error (ISE)

2 Experimental setup

A real time experimental setup for highly nonlinear spherical tank is constructed. The process control system is interfacing VMAT-01 module to the Personal Computer (PC). The laboratory set up for this system is shown in Figure 1,it consists of a spherical tank, a water reservoir, pump, rotameter, a differential pressure transmitter, an electro pneumatic converter (I/P converter), a pneumatic control valve, an interfacing VMAT-1 module and a Personal Computer (PC). The differential pressure transmitter output is interfaced with computer using VMAT-01 module in the RS-232 port of the PC.

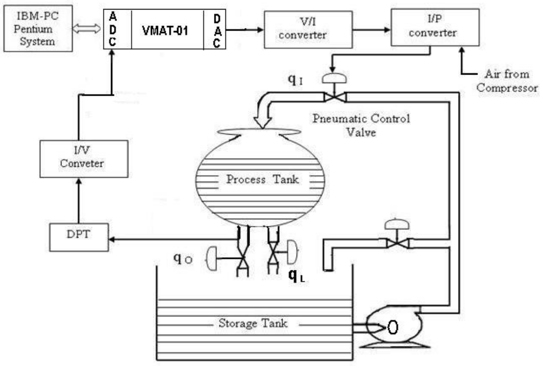

Figure 1: Experimental setup for liquid level control of a Spherical tank

This module supports 1 analog input and 1 analog output channels with the voltage range of ±5 volt and two Pulse Width Modulation (PWM). The sampling rate of the module is 0.1 sec and baud rate is 38400 bytes per sec with 8-bit resolution.

The model is developed using Simulink blockset in MATLAB software and is then linked via this VMAT-1 module with the sampling time of 0.1second. Figure 2 shows the real time experimental setup of a spherical tank. The pneumatic control valve is air to close, adjusts the flow of the water pumped to the spherical tank from the water reservoir. The level of the water in the tank is measured by means of the differential pressure transmitter and is transmitted in the form of (4-20) mA to the interfacing VMAT-01 module to the Personal Computer (PC). After computing the control algorithm in the PC control signal is transmitted to the I/P converter in the form of current signal (4-20) mA, which passes the air signal to the pneumatic control valve. The pneumatic control valve is actuated by this signal to produce the required flow of water in and out of the tank. There is a continuous flow of water in and out of the tank. Table 1 shows the various technical specifications of experimental setup. Figure 3 shows the system interfaced with VMAT-01 module.

Figure 2 Experimental set up for a spherical tank

Figures 3 Real time interfacing of VMAT-1 module with Spherical Tank

3. Modeling of a spherical tank system

The spherical tank system is highly nonlinear system in order to control this, the most basic and pervasive control algorithm used in the feedback control is the Proportional Integral and Derivative (PID) control algorithm. PID control is a widely used control strategy to control most of the industrial automation .The system identification problem deals with the determination of a mathematical model for a system or a process by observing the input-output data[5]. Historically, system identification has been needed in designing a suitable control process for an unknown system (black box problem) or an incompletely known system (gray box problem). In most practical systems, such as industrial processes, the actual parameter values within a known model structure are unknown[3]. This type of problems, which are examples of the gray box variety, are more accurately called as system parameter identification problems. The need for more accurate knowledge of system parameters has increased with recent advances in adaptive and optimal control.

Table 1: Technical Specifications of Experimental Setup

Part Name	**Details**
Spherical Tank	Material :Stainless Steel Diameter - 50 cm, Volume : 102 liters
Storage Tank	Material :Stainless Steel , Volume : 48 liters
Differential Pressure Transmitter	Type Capacitance, Range (2.5 - 250)mbar, Output (4 - 20)mA
Pump	Centrifugal 0.5 HP
Control valve	Size ¼“ Pneumatic actuated” Type: Air to close Input (3 - 15) psi
Rotameter	Range (0 - 18) lpm
Air regulator	Size 1/4" BSP Range (0 - 2.2)bar
I/P converter	Input (4 - 20) mA Output (0.2 - 1) bar
Pressure gauge	Range (0 - 30) psi Range (0 - 100)psi

4.Mathematical Modeling

The Spherical tank system shown in Figure 4 is essentially a system with nonlinear dynamics. The spherical tank setup has a maximum, height of H cm Maximum radius of r m[5]. The level in the tank at any instant is obtained by making mass balance as indicated below

Let :

q_I – Inlet flow rate to the tank (m^3/min)
q_O– Outlet flow rate to the tank (m^3/min)
q_L – Load applied to the tank (m^3/min)
H – Height of the Spherical tank (m)
H - Height of the liquid level in the tank at any time‘t’(m)
R- Top radius of the Spherical tank (m)
r – Radius of the spherical vessels at a particular level of height h (m)

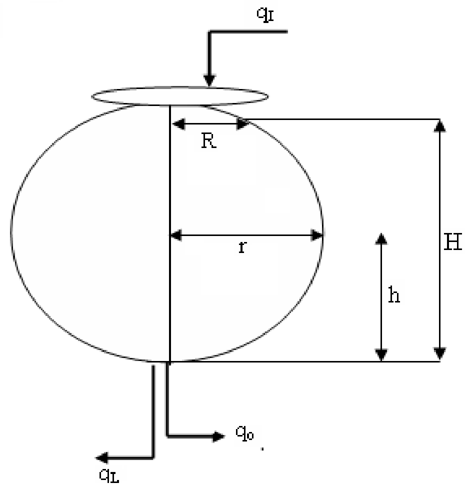

Figure 4 Spherical Tank Liquid level system

Rate of accumulation of mass in the tank = Rate of Mass flow in - rate of mass flow out

Its nonlinear dynamics described by the first – order differential equation.

$$\frac{dV}{dt} = q_1 - q_2 \qquad (1)$$

Where V is the Volume of the tank, q_1 is the Inlet flow rate and q_2 is the outlet flow rate.

$$V = \frac{4}{3}\pi h^3 \qquad (2)$$

Where h is the total height of the tank in cm. Applying the steady state values, and solving the equations (1)&(2), for linearzing the non - linearity in the spherical tank,

$$\frac{H(s)}{Q_1(s)} = \frac{R_t}{\tau s + 1} \qquad (3)$$

Where $\tau = 4\pi R_t h_s$ and $R_t = \frac{2h_s}{Q_2(s)}$

5 Black box modeling

Consider the first order system with dead time represented by the following transfer function

$$y(s) = \frac{K_p e^{-\theta s}}{\tau_p s + 1} u(s) \qquad (4)$$

The output response to a step input change

$$y(t) = \begin{cases} 0 & \text{for } t < \theta \\ K_p \Delta u\{1 - \exp(-(t-\theta)/\tau_p)\} & \text{for } t \geq \theta \end{cases} \qquad (5)$$

The measured output is in deviation variable form. The three process parameters K_p, τ_p, θ can be estimated by performing a single step test on process input. The process gain is found as simply the long term change in process output divided by the change in process input[3]. Also the time delay is the amount of time , after the input change, before a significant output response is observed .There are several ways to estimate time constant for this model. Two point method for estimating the process parameters are shown in Figure5

The process gain is calculated by

$$K_p = \frac{\Delta}{\delta} = \frac{\text{Change in process output}}{\text{Change in process input}}$$

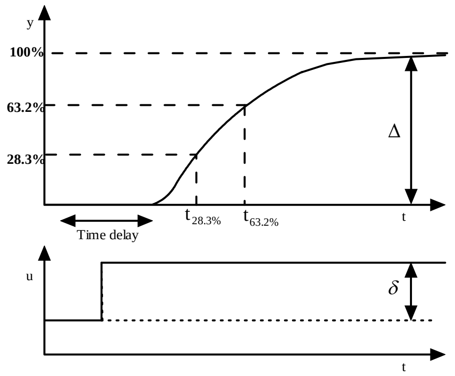

Figure 5: Two point method for estimating process parameters

System identification for the spherical tank system is done using black box modeling in real time. For fixed input flow rate and output flow rate ,the Spherical tank is allowed to fill with water from (0-50) cm height. At each sample time the data from differential pressure transmitter i.e. between (4-20) mA is being collected and fed to the system through the serial port RS - 232 using VMAT-1 interfacing module. Thereby the data is scaled up in terms of level .Using the open loop method, for a given change in the input variable; the output response for the system is recorded. Ziegler and Nichols [3] have obtained the time constant and time delay of a First Order Plus Time Delay (FOPTD) model by constructing a tangent to the experimental open loop step response at its point of inflection. The tangent intersection with the time axis at the step origin provides a time delay estimate; the time constant is estimated by calculating the tangent intersection with the steady state output value divided by the model gain.

5.1Two point method for estimating time constant

Simth have obtained the parameters of FOPTD transfer function model by letting the response of the actual system and that of the model to meet at two points which describe the two parameters τ and θ. Here the time required for the process output to make 28.3% and 63.2% respectively[3]. The time constant and time delay can be estimated from equation 6 and equation 7

$$\tau_p = 1.5(t_{63.2\%} - t_{28.3\%}) \qquad (6)$$

$$\theta = t_{63.2\%} - \tau_p \qquad (7)$$

The proposed works objective is to find the three different models at various operating regions. The obtained parameters are reported in table 2.

Table 2: Process gain, Time constant and Time delay at different operating points

Operating Point	K_p	τ_p	**θ**
at 30 cm	4.5	440	120
at 45 cm	6	1200	130
at 65 cm	2.75	1050	150

5.1 Ziegler-Nichols (ZN)method

If a mathematical model of the plant can be obtained, Then it is possible to apply different design techniques to define controllers parameters .On the other hand if the system is complicated and getting the mathematical model is difficult ,then experimental approaches must be used to tune the PID parameters[6]. Ziegler and Nichols developed the rules based on the transient response characteristics of the systems and determined the values of PID controller. Ziegler and Nichols present tuning rules based on process models that have been obtained through the open loop step tests. Ziegler and Nichols proposed tuning parameters for a process that has been identified as first order with dead time based on open loop step response . Their recommended tuning parameter are shown in Table 3.

Table 3 :PI controllers parameters at different operating points

Operating Point	**Controller gain $Kp_{,i}$**	**Integral Gain $K_{c,i}$**
at 30 cm	0.7330	0.0018
at 45 cm	1.3846	0.0032
at 65cm	2.2900	0.0046

6 Design of Fuzzy Logic Controller

The design of FLC using Mamdani model for a spherical tank in real time is attempted using cost effective data acquisition system[9]. The design of the fuzzy logic control system consists of several steps. First, the variables for the fuzzy control system are determined[9]. The universe of Discourse for all the variables involved are then set.Here, the fuzzy controller is designed with two input variables, level, error in level and one output variable, valve opening. Figure 6 shows the fuzzy logic controller to controller the level in spherical tank with error and level as input.

The universe of Discourse for these parameters are 0 to 100cm, -37 to 59 cm and -24 to 98% for level, error , and valve opening respectively .Both input variables are designed with five fuzzy sets having triangular membership functions(shown in figure 7 and figure 8). The Linguistic terms associated with the variables are NB(negative Big),N(Negative), Z(Zero),P(Positive),PB(Positive Big), for level and error in level. The membership function of the output variable are triangular ,But there are nine fuzzy sets defined by the Linguistic variables(shown in figure 9) C(Closed),VVS(very very small),VS(very small), S(small), M(Medium),L(Large), VL(VeryLarge), VVL(Very Very large),O(Open).

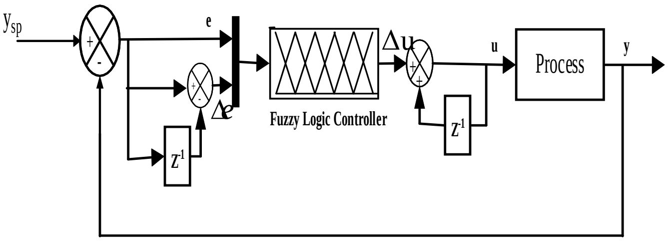

Figure 6 Fuzzy logic controller to control the level in spherical tank

The fuzzy sets are designed such that the starting point of a particular fuzzy set is summit of the previous set and ending point is set to the summit of the next fuzzy set. this is done for the sake of simplicity . Next Rule based is developed .The rule base is usually developed based on expert knowledge is developed by an understanding of the system and some trial and error manipulations. The rule base developed for this system is shown in table 4. MAXMIN inference is used .That is MIN is used for the 'and' conjunction and MAX for the 'OR' conjunction. The choice of the operators for inference us purely a matter of preference for the particular system ..The center of gravity method is used here , as there is no loss of information when using this method.

7 Results and Discussion

The Fuzzy Logic Controller is designed and applied to real time control of spherical tank liquid level system. The Performance of the Fuzzy Logic Controller is compared to Digital PI controller . The fuzzy logic controller is run for a sequence of set points, that is, 30, 45 and 65 cm is compared with a PI controller for the same sequence of set point changes. The servo and regulatory responses of PI controller are shown in figure 10,12,14. Figure11,13,15 shows the servo and regulatory

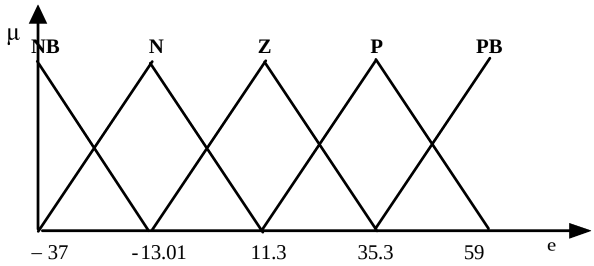

Figure 7 Membership function for error (e)

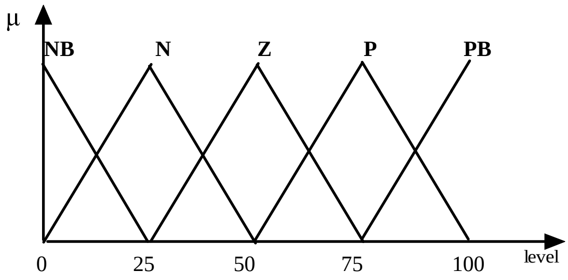

Figure 8 Membership function for level

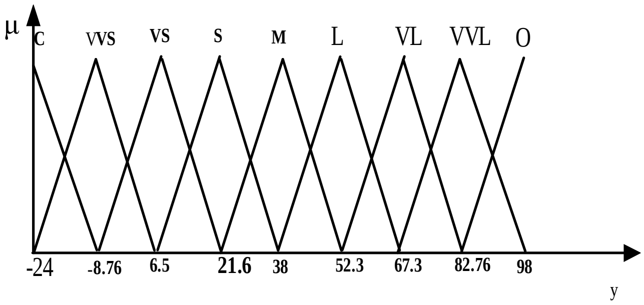

Figure 9 Membership function for change in controller output

Table 4 Rule table for Fuzzy Logic Controller

		LEVEL				
		NB	**N**	**Z**	**P**	**B**
ERROR	**NB**	C	C	C	C	C
	N	C	VS	C	C	C
	Z	VL	M	L	M	L
	P	O	M	M	VVS	VL
	B	O	O	O	O	VL

responses of Fuzzy Logic Controller. It is observed the level oscillates very much high for PI and where as oscillation is very much less in fuzzy logic controller. Also it is observed that in fuzzy logic controller tracks the given set point in less time compared to PI controller. It is also seen from Figure 11,13,15 there is no overshoot in fuzzy logic controller when compared to PI controller. Also it is observed that in fuzzy logic controller follows the smooth tracking towards the given set point. The performance indices comparison of controllers are shown in Table 5.The designed digital FLC controller gives faster response in terms of rise time, settling time and minimum % overshoot.

Changes in Load: The Fuzzy Logic Controller is used to control the spherical level system while applying a load change of 15% is recorded. The system is also run with a PI controller while applying the same load changes. It is clearly observed from the figures that for a sudden load change Fuzzy Logic Controller returns to the given set point immediate. Also it is observed the fuzzy controller follows without any overshoot for a load change compared to PI controller. The fuzzy controller is able to compensate for the load changes considerably better than PI controller.

8 Conclusion

For non-linear processes an Fuzzy Logic Controller is designed. Its performance is tested in real time by using the VMAT-01 module for a Spherical tank level process.. Comparison with a fuzzy logic and conventional PI controller gives testimony to the effectiveness of the fuzzy logic based PI control technique in the non-linear system. Experimental results prove that the response is smooth for both servo and regulatory changes for Fuzzy Logic Controller compared to PI controller. The settling time, rise time and overshoot in the Fuzzy Logic Controller shows the better response than PI controller .This is also validated by IAE values. It is concluded that for a nonlinear system the Fuzzy Logic Controller outperforms well when compared to conventional controller in real time using cost effective data acquisition system. The developed approach will go a long way in exploring innovative applications to meet state of art requirements

Table 5 . Performance indices comparison

LEVEL		**30 cm**	**45cm**	**65cm**
Rise time(secs)	PI	240	280	820
	FLC	210	263	381
Settling time(secs)	PI	1050	650	2900
	FLC	380	450	490
% overshoot	PI	10	13	6
	FLC	0	0	0
ISE	PI	4051	5998	5822
	FLC	1094	1122	1800

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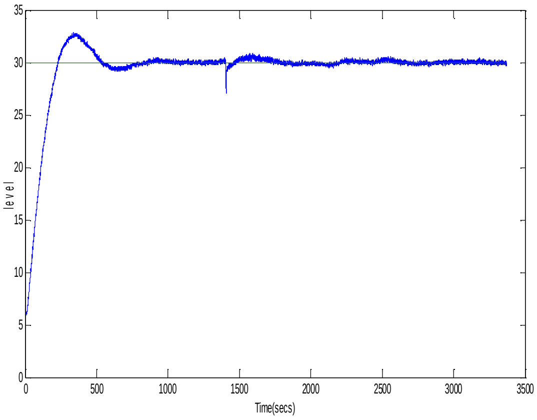

Figure 10 Servo Regulatory response of PI controller for a set point 30 cm

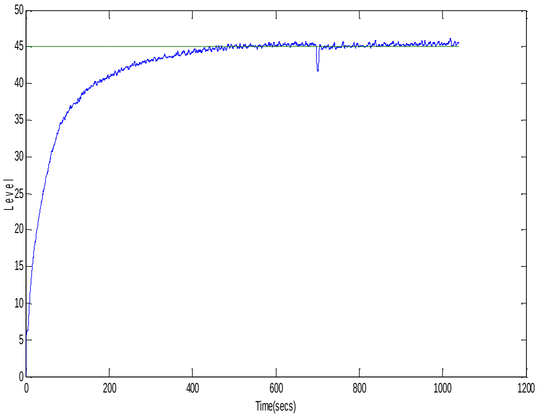

Figure 11 Servo Regulatory response of FLC for a set point 45cm

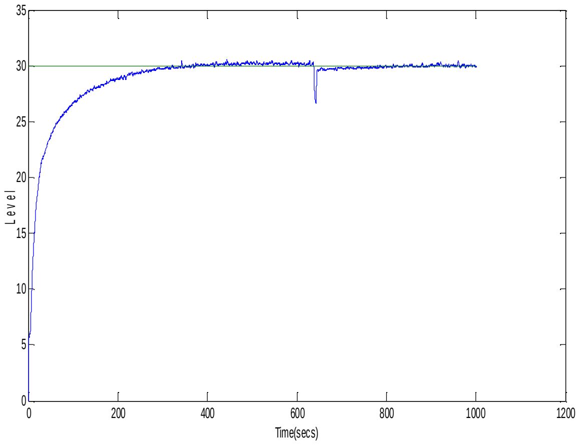

Figure 12 Servo Regulatory response of FLC for a set point 30 cm

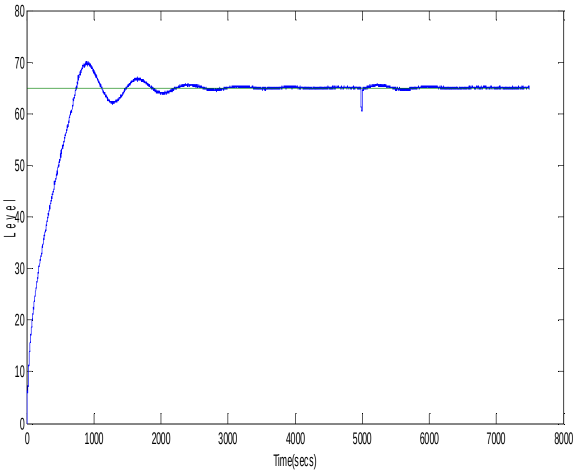

Figure 13 Servo Regulatory response of PI controller for a 65 set point

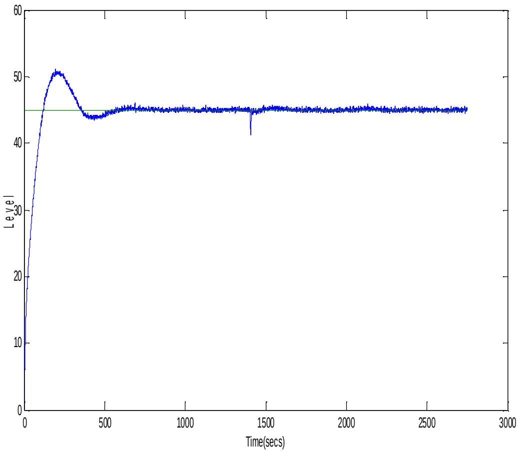

Figure 14 Servo Regulatory response of PI controller for a set point 45cm

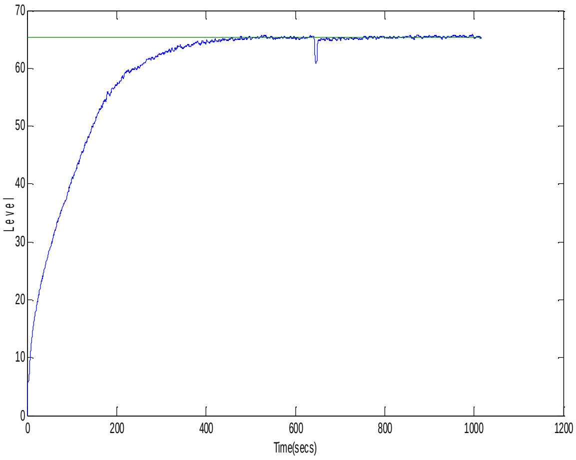

Figure 15 Servo Regulatory response of FLC for a set point 65cm