Journal of Innovative Research in Engineering and Sciences 2(5), September, 2011.
ISSN : 2141-8225. http://www.grpjournal.org. Printed in Nigeria.

Modelling and Real Time Implementation of Digital Pi Controller for a Non Linear Process *(pp. 274-290)*

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Abstract: In Process industries, control of process parameters for a nonlinear process is one of the important issues identified in literature. The nonlinear process considered for modeling is spherical tank liquid level system. Control of liquid level in a spherical tank is nonlinear due to the variation in the area of cross section of the level system with change in shape. System identification of this nonlinear process is done using black box model, which is identified to be nonlinear and approximated to be first order plus dead time model. Here the Digital PI controller is designed using Ziegler Nicholas Tuning rule. The real time implementation of the process is designed and implemented in MATLAB using VMAT-01 Data Acquisition Module.

Key words: PI controller, nonlinear process, spherical tank, system identification.

1 INTRODUCTION

There are many nonlinear systems in process industries. 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 this inherent nonlinearity, most of the chemical process industries are in need of traditional control techniques. Control of a level in a spherical tank is important, because the change in shape gives rise to the nonlinearity

The spherical tank system is a 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. Spherical tanks find wide application in gas plants (Tarajan, Chidambaram and Jayasingh, 2005). PID control is a widely used control strategy to control most of the industrial automation processes because of its remarkable efficacy, simplicity of approximated by a first-order time-delayed model and suggested frequency domain approach based on normalized open loop transfer function to evaluate the effects of uncertainties in the process parameters and thus, control system robustness (Chidambaram, 1998). In principle, the action of the controller is calculated by multiplying a constant factor with the error, the integral of the error and the derivative of the error. Ziegler- Nichols has developed a well known design methods to provide a closed-loop response with a quarter-decay ratio. The real time model is designed for controlling the liquid level in a spherical tank. The process model is experimentally determined from step response analysis and is interfaced to real time with MATLAB using simple cost effective VMAT-01 module.

2 EXPERIMENTAL METHOD

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-01 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.

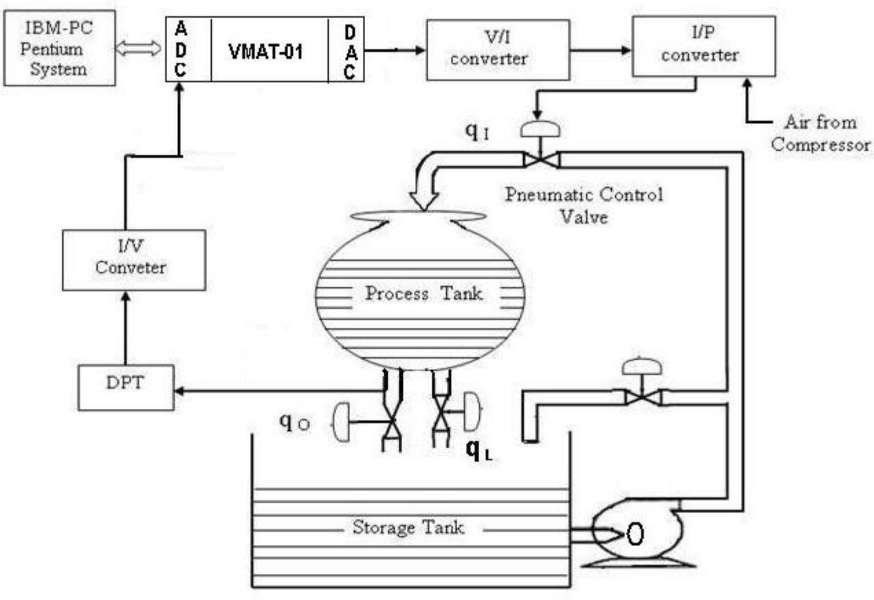

Figure 1: Experimental setup for liquid level control of a Spherical tank

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.

Figure 2: Real time interfacing of VMAT-1 module with Spherical Tank

Table 1: Technical Specifications of Experimental Setup

Part Name	**Details**
Spherical Tank	Material :Stainless Steel Diameter - 50 cm, Volume : 102 liters
Stroage Tank	Material :Stainless Steel , Volume : 48 liters
Differential Pressure Transmitter	Type Capacitance, Range (2.5 - 250)mbar,

	Output (4 - 20)mA Siemens make
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

3 SYSTEM IDENTIFICATION

The system identification problem deals with the determination of a mathematical model for a system or a process by observing the input-output data. 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) (Bequtte, 2006). In most practical systems, such as industrial processes, the actual parameter values within a known model structure are unknown. 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.

3.1 Black box modeling

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

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

The output response to a step input change

$$y(t)=\begin{cases}0 & \text{for } t<\theta \\ K_p\Delta u\{1-\exp(-(t-\theta)/\tau_p)\} & \text{for } t\geq\theta\end{cases} \tag{2}$$

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 (Dale, Thomas and Duncan, 2004). 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 Figure 3.

The process gain is calculated by

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

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. (Tarajan, Chidambaram and Jayasingh, 2005) 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

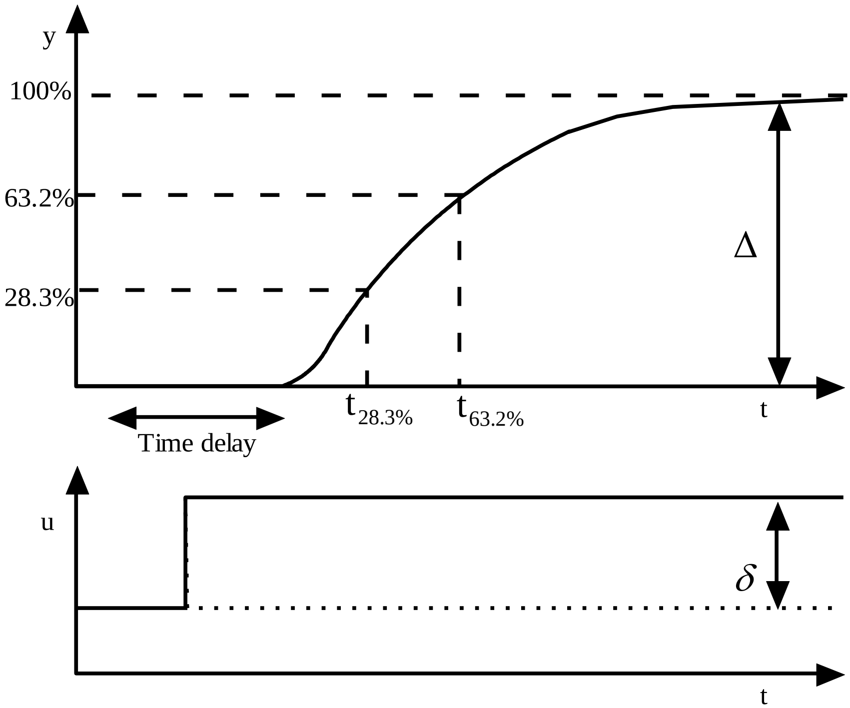

Figure 3: Two point method for estimating process parameters

3.2 Two 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. The time constant and time delay can be estimated from equation 3 and equation 4

$$\tau_p = 1.5(t_{63.2\%} - t_{28.3\%}) \quad (3)$$

$$\theta = t_{63.2\%} - \tau_p \quad (4)$$

The proposed works objective is to find the three different models at various operating regions. The obtained parameters are reported in table 2.The open loop response of spherical tank process around operating point of 30cm, are shown in figure 4,Similarily open loop response of operating point at 45, 60 are obtained.

Open Loop Models

In the spherical tank process, the model has been taken at three different operating points of level around 30 cm, 45 cm and 60 cm at lower, middle and upper level of the tank.

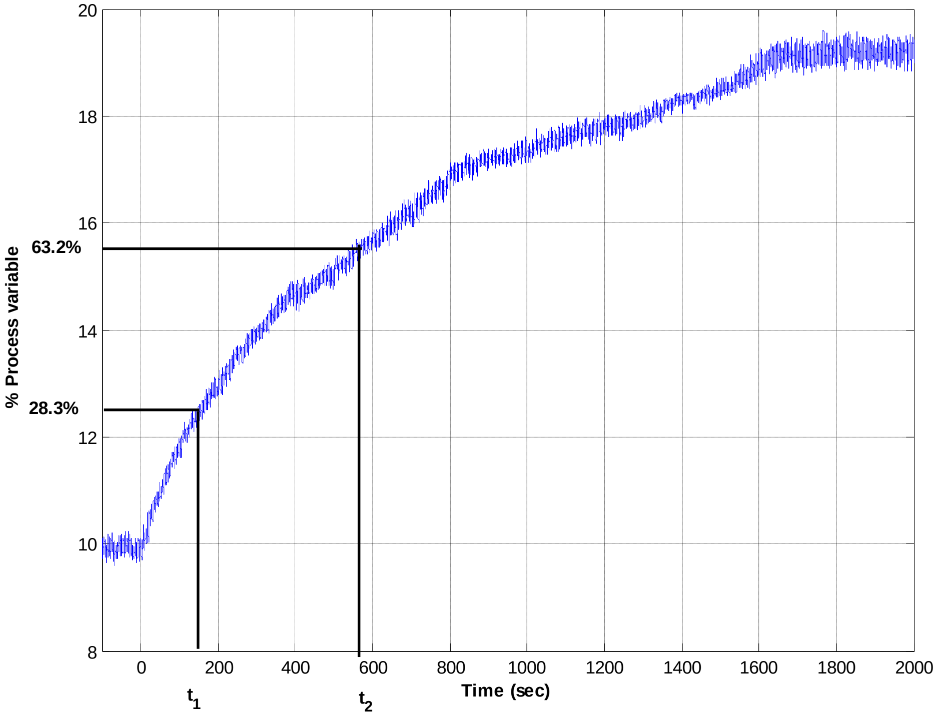

Figure 4 Open loop response of spherical tank process around 28 cm of level

Figure 4 gives the open loop response of the process by changing the manipulated variable from 40% to 42%. From the open loop response,

$$\text{Process gain } k = \frac{\text{change in output}}{\text{change in input}}; k = \frac{19-10}{2} = 4.5$$

Time constant $\tau = 1.5(t_2 - t_1)$

$$\tau = 1.5(560-120) = 440$$

Time delay $\theta = t_2 - \tau$

$$\theta = 560 - 440 = 120$$

There the process transfer function at this operating point is given as

$$G(s) = \frac{4.5e^{-120s}}{440s+1} \tag{5}$$

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 60 cm	2.75	1050	150

4 PID CONTROLLER DESIGN

PID controller design is based on a direct relationship between the parameters of the controller and the process mode (Dale, Thomas and Duncan, 2004). Several approaches have been applied in the past to evaluate design procedures for an optimal frequency response using the conception of unity gain approach and gain adjustment. But universally valid design equations were not found until now. Thus one of the most challenging issues in control engineering education and application is still controller design. It is considered that PID controller is the most common control technique that is extensively used in control applications. The PID controller has been used in daily life by a huge number of applications and control engineers. PID control offers an easy method of controlling a process by varying its parameters. Moreover, PID controllers are available at low cost. Consequently, if the parameters are tuned properly, it provides robust and reliable performance for most systems. PID variations (P, PD, and PI) are widely used in more than 90% to 95% of industrial control applications. However, there is own limitation of the PID controller; if the requirement is reasonable and the process parameters variation are limited, the PID performances can give only satisfactory performance (Seborg et al, 2004).

4.1 PID Characteristic Parameters

PID controller widely used in industrial control systems is composed of proportional control action, integral control action and derivative control action (Bequtte, 2006). There are many forms of PID controller implementations such as a stand-alone controller or Distributed Control System (DCS). Figure 5 is a simple diagram showing the schematic of the PID controller and it is known as non-interacting form or parallel form.

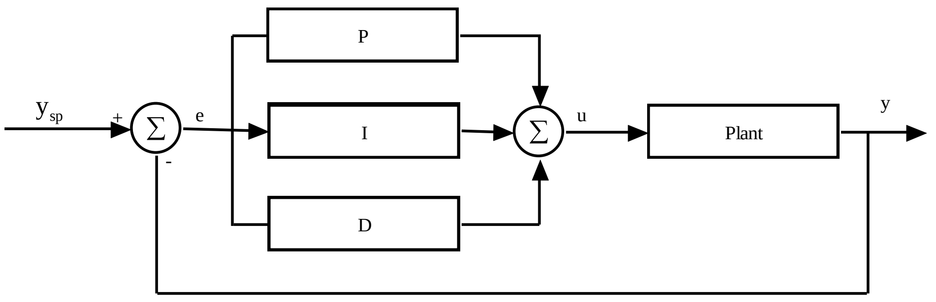

Figure 5: Block Diagram of a PID controller

The parallel controllers are mostly preferred for higher order systems. The transfer function of continuous PID controller in Laplace transform is defined for a continuous system as

$$G_c(s) = K_P + \frac{K_I}{s} + K_D s \tag{8}$$

The proportional controller response is proportional to the control error. The controller error is defined as the difference between the set point and the process output. The proportional controller output is the multiplication of the system error signal and the proportional gain. Proportional term can be mathematically expressed as

$$P_{term} = K_p e \tag{9}$$

The integral control applies a control signal to the system which is proportional to the integral of the error. The offset introduced by the proportional control is removed by the integral action but a phase lag is added into the system. Integral term can be mathematically expressed as

$$I_{term} = K_I \int e\,dt \tag{10}$$

There is a proportion between the derivative controller output and the rate of change of the error. Derivative control is used to decrease and eliminate overshoot of system response and introduce a phase lead action that removes the phase lag introduced by the integral action.

$$D_{term} = K_D \frac{de}{dt} \tag{11}$$

Combining these three types of control together, transfer function of continuous PID controller is formed as

$$G_c(s) = \frac{K_D s^2 + K_p s + K_I}{s} \tag{12}$$

where K_p, K_I and K_D are the proportional, integral and derivative gains, respectively. The control signal to the plant is given by

$$u(t) = K_p e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt} \tag{13}$$

To convert equation 13 to discrete form edt is approximated by summation of rectangles $\sum e_i T$, where T is the sampling interval and e_i is the value of the error at sample time i..If the sampling interval T is small enough, the diffential term de/dt can be approximated by

$$\frac{de}{dt} = \frac{e(n) - e(n-1)}{T} \tag{14}$$

Where e(n) and e(n-1)are he values of the error signal e at time interval n and n-1.Now the Digital form of the PID controller is given by

$$u(n) = u(n-2) + k_1 e(n) + k_2 e(n-1) + k_3 e(n-2) \tag{15}$$

Where

$$k_1 = k_p + \frac{k_d}{T} + k_i T$$

$$k_2 = k_i T + 2k_d T$$

$$k_3 = \frac{k_d}{T} - k_p$$

The digital PI controller to control the liquid level of spherical tank is shown in figure 6. Proportional action K_p improves the system rising time, and reduces the steady state error. However, the higher value of K_p produces large overshoot and the system may be oscillating; therefore, integral action K_I is used to eliminate the steady state error. Despite the integral control, reducing the steady state error, it may make the transient response worse. Therefore, derivative gain K_D will have the effect of increasing the damping in system, reducing the overshoot, and improving the transient response.

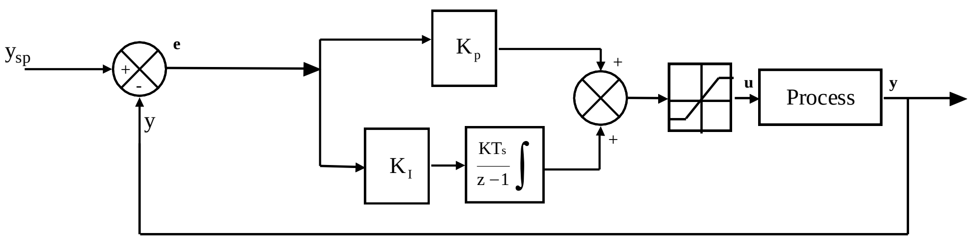

Figure 6: PI controller to control the level in spherical tank

4.2 Controller Design Methods

Although PID controllers are widely used in industry, the tuning of these parameters can be very challenging (Tarajan , Chidambaram and Jayasingh, 2005). Tuning of a PID controller refers to the tuning of its various parameters (P, I and D) to achieve an optimized value of the desired response. The basic requirements of the output will be the stability, desired rise time, peak time and overshoot. Different processes have different requirements of these parameters which can be achieved by meaningful tuning of the PID par ammeters. When a mathematical model of a system is available, the parameters of the controller can be explicitly determined. However, when a mathematical model is unavailable, the parameters must be determined experimentally. Controller tuning is the process of determining the controller parameters which produce the desired output. Controller tuning allows for optimization of a process and minimizes the error between the variable of the process and its set point (Gustavsson, Ljung and Soderstorm, 1977). Types of controller tuning methods include the trial and error method, and process reaction curve methods. The most common classical controller tuning methods are the Ziegler-Nichols and Cohen-Coon methods.. The Ziegler-Nichols method can be used for both closed and open loop systems, while Cohen-Coon is typically used for open loop systems.

4.3 Ziegler-Nichols (ZN) method

If a mathematical model of the plant can be obtained (Dale, Thomas and Duncan, 2004) 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. 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 parameters are shown in table 4.

Table 3: Ziegler –Nichols open loop tuning parameters

Controller type	K_c	τ_I	τ_D
P- only	$\frac{\tau_p}{k_p\theta}$	—	—
PI	$\frac{0.9\tau_p}{k_p\theta}$	3.3θ	—
PID	$\frac{1.2\tau_p}{k_p\theta}$	2 θ	0.5θ

It should be noted that using the model parameters reported in table 3. PI controller parameters are obtained. The PI parameters at 3 different operating points are reported in Table 4.

Table 4: PI Controller Parameters at different Operating Points

Operating Point	Controller gain Kp,i	Integral Gain Kc,i
at 30 cm	0.7330	0.0018
at 45 cm	1.3846	0.0032
at 60 cm	2.2900	0.0046

5 RESULTS AND DISCUSSIONS

The Digital PI controller is designed and obtained controller parameters are applied in real time to control the liquid level in spherical tank process. The spherical tank is tested closed loop mode under the closeness between reference and controlled variables brings out the accuracy of the proposed algorithm and usefulness of the scheme for practical application .The Digital PI controller is run for a sequence of set points 30, 45,65cm .The servo and regulatory responses of PI controller are shown in figure 7, 8, 9 and their corresponding controller output are shown in figure 7a, 8a, 9a. The performance indices of Digital PI controller for three operating conditions are shown in Table 5.

Table 5: Performance indices of PI controller

LEVEL(cm)	**30cm**	**45cm**	**65cm**
Rise time(secs)	1900	2000	4200
Settling time(secs)	7600	9500	14500
% overshoot	14	11.5	17.1
ISE	2855	3966	4125

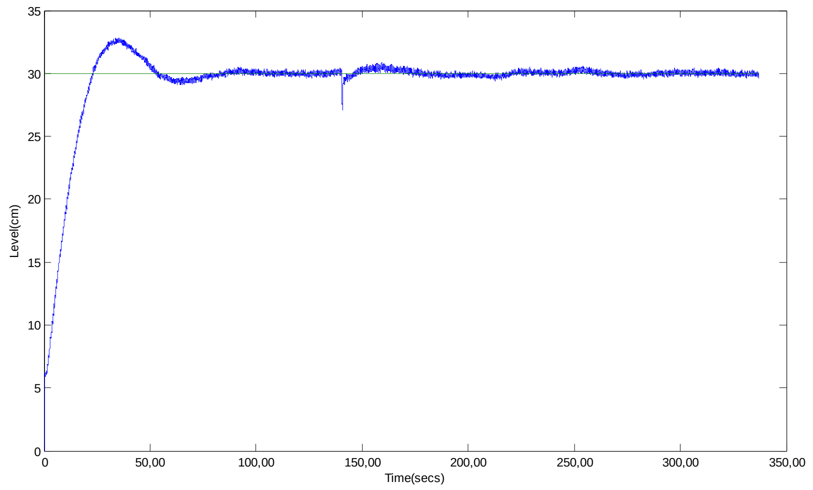

Figure 7: Servo Regulatory response of Spherical tank for a set point 30 cm

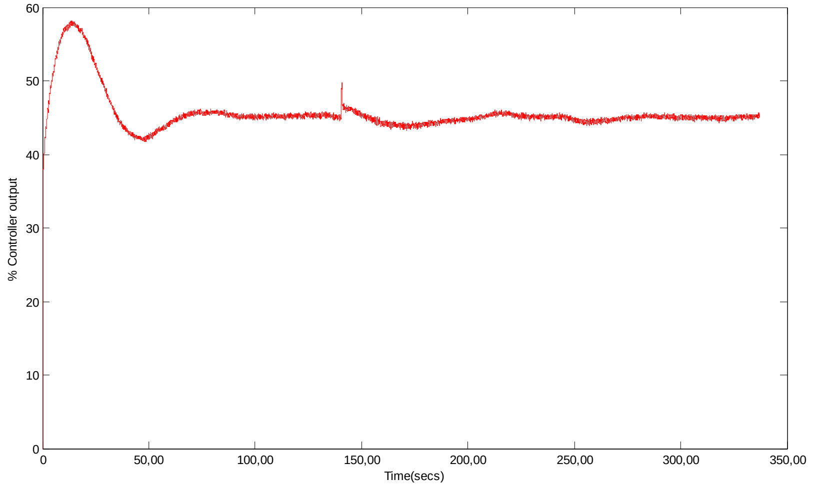

Figure 7a: Response of PI controller output

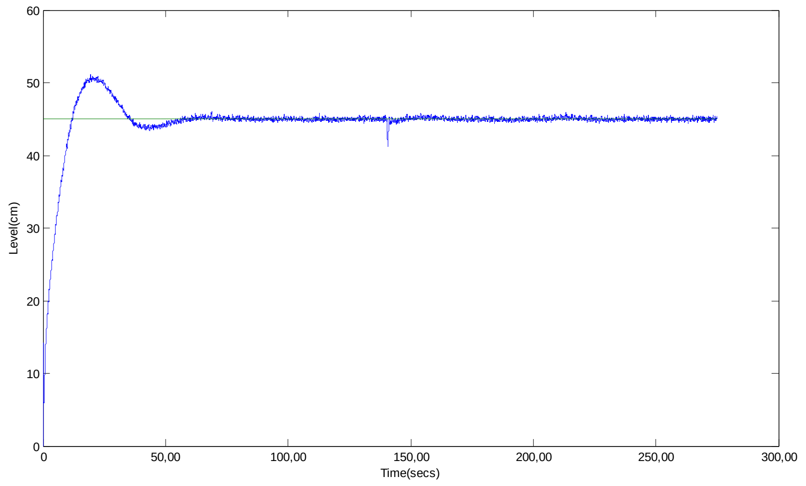

Figure 8: Servo Regulatory response of Spherical tank for a   set point 45cm

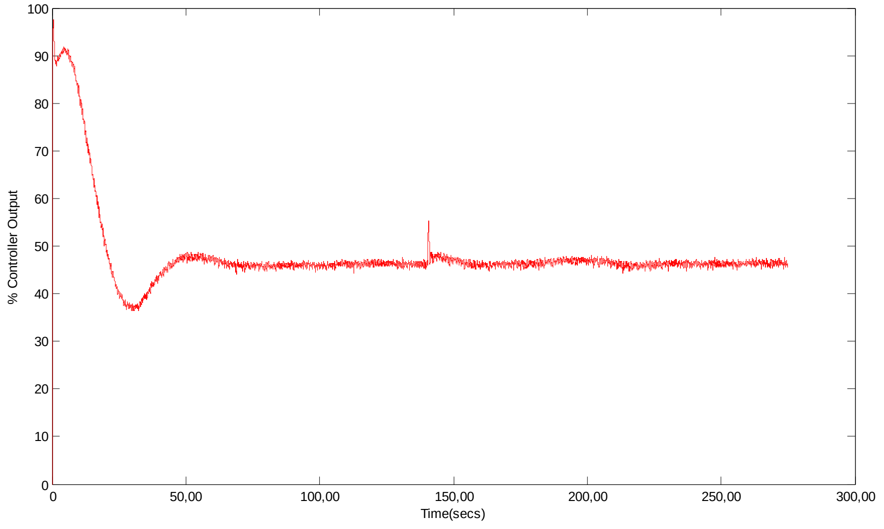

Figure 8a: Response of PI controller output

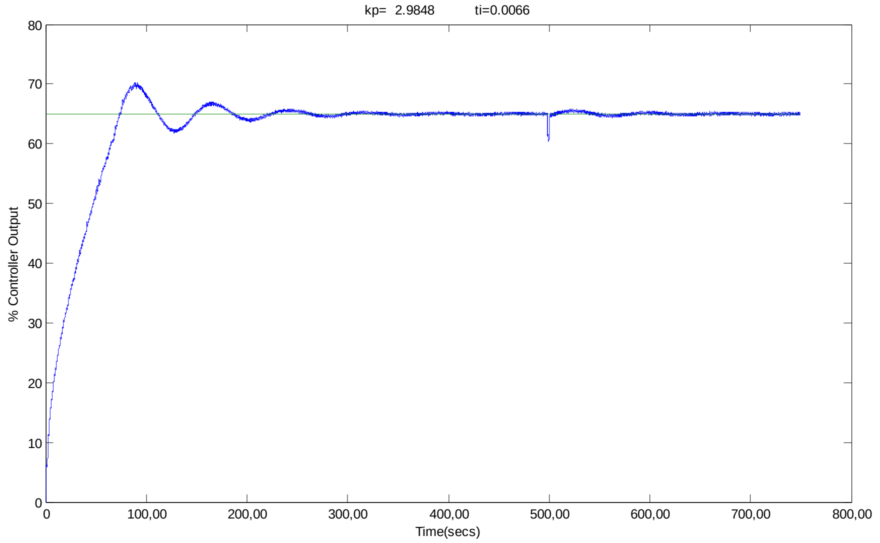

Figure 9: Servo Regulatory response of Spherical tank for a 65 set point

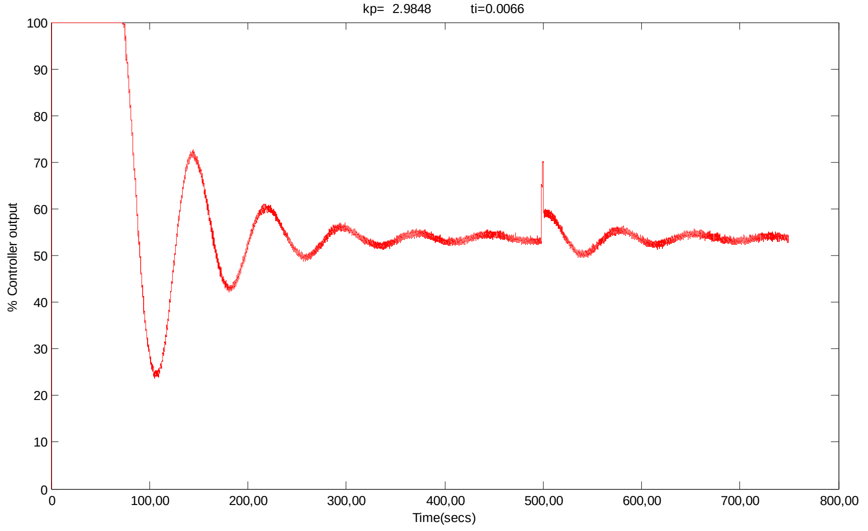

Figure 9a: Response of PI controller output

6 CONCLUSION

The digital PI controller is designed in real time using VMAT-01 module for a Spherical tank level process. Identification of the Spherical tank level process is done using Black box model and controller parameters are obtained by Ziegler –Nichols tuning rule**.** Experimental results show that the responses of PI digital controller for both set point and load changes.Results shows that the above method is effective in using the low cost data acquisition system.The developed approach will go a long way in exploring innovative applications to meet state of art requirements.

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