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Evolutionary Algorithms based Controller Optimization for a Real Time Spherical Tank System

[1]Ganapathy Sivagurunathan and [2]Kaliannan Saravanan

[1]*Department of Electronics and Instrumentation Engg, St.Joseph's College of Engineering,Chennai – 600 119, Tamilnadu, India.*
[2]*Department of Chemical Engg,Kongu Engineering College, Perundura,Erode – 638 052, Tamilnadu, India.*

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ABSTRACT

Background: PID controllers are used in the process industries because of its simple structure and minimum cost. Conventional controller is not effective for nonlinear process and selection of controller parameters is also a difficult task. The properties of heuristic algorithm such as faster convergence, learning rate and easy implementation can alleviate the aforesaid drawback of conventional controllers. **Objective:** In this work an attempt is made to implement suitable controller for nonlinear spherical tank to control level using Particle Swam Optimization (PSO). To compare the performance of the implemented controller with conventional and Genetic Algorithms based controller. **Results:** The servo and regulatory responses of PSO based PI controller results in minimal peak overshoot, less settling time and reduced Integral Absolute Error (IAE) when compared to other methods. **Conclusion:** The PSO based PI controller and Ziegler and Nichols (ZN) controller for a real time spherical tank system to control the level process is implemented. The proposed PI parameter estimation using PSO has improved the system characteristics in terms of better time domain specifications, set point tracking, disturbance rejection, and error minimization.

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INTRODUCTION

Proportional + Integral + Derivative (PID) controller is widely used in most of the chemical process industries such as pharmaceutical, oil and gas, petrochemical, food and beverage due to its simple structure, low cost, flexibility, robust performance for a wide range of operating conditions and efficiency. Many process industries present challenging control problem due to its nonlinear dynamic behavior. Control of liquid level in processes such as spherical and conical tank is a tedious task since the physical parameters vary significantly. The performance of the PID controller mainly depends on three controller parameters such as proportional gain (K_p), integral gain (K_I), and derivative gain (K_d). To determine the tuning parameter of the conventional PID controller for the linear and nonlinear processes require an approximated first or second order transfer-function model with a time delay. The tuning procedure predicted for one particular process model will not provide the suitable response for other process models (Rajinikanth and Latha, 2012). Hence, finding new methods to automatically estimate PID parameters was the interest of researches.

To enhance the capabilities of traditional PID tuning techniques, several artificial intelligent techniques such as simulated annealing, genetic algorithms, fuzzy logic, neural network and PSO are being developed to tune the parameters of the PID controllers. Genetic Algorithm (GA) is a stochastic algorithm based on principles of natural selection and evolutionary genetics. GA is a stochastic global search method that mimics the process of natural evolution (Nikhileshwar *et al*., 2012).

Even though, GA methods have been used to solve complex optimization problems, the search has identified some deficiencies in its performance. The main disadvantages of GAs are degradation of searching capability in some cases and premature convergence. Hence, alternate methods are required to overcome these disadvantages. Recently, heuristic algorithms are used to alleviate this difficulty. PSO is one such method which can be used to overcome the drawbacks of GA (Mohammad Ahmadi *et al*., 2013).

PSO is a population based stochastic optimization technique inspired by social behavior of bird flocking or fish schooling (Kennedy and Eberhart 1995). The PSO can provide stable convergence to the optimum values much faster than the GA. Further, the optimum values which are found by PSO have shorter calculation time and easy implementation when compared to the other optimization methods (Mohammad Ahmadi *et al*., 2013).

Corresponding Author: Ganapathy Sivagurunathan, Department of Electronics and Instrumentation Engg, St.Joseph's College of Engineering, Chennai – 600 119, Tamilnadu, India.
E-mail: gsgnathan@gmail.com.

It has been recently reported that GA provides better performance when compared to classical approach (MohdSazliSaad *et al*., 2012, Eissa *et al*., 2013, MeghaJaiswal and Mohna Phadnis, 2013, Neenu Thomas and Poongodi, 2009).

(Nithya *et al*., 2008) proposed fuzzy logic controller tuned by GA to effectively control the liquid level in spherical tank than the conventional approach. (Sivagurunathan and Jayanthi, 2012) proposed a design of fuzzy logic based self-tuning of PI controller for a liquid level process to improve dynamic characteristics and compared its performances with Internal Model Controller(IMC).The PSO based controllers are widely discussed in the literature by the most of the researchers (Panduro *et al*., 2009, Sidhartha Panda and Padhy 2007, Bijay Kumar and RohtashDhiman 2011, Tushar Jain and M. J. Nigam 2008, Zwe-Lee Gaing 2004, Nagaraj *et al*., 2008) to improve transient and steady state characteristics. (Rajinikanth and Latha 2012, Rajinikanth and Latha 2013) designed PSO and BFO (Bacterial Foraging Algorithm) based controllers for various nonlinear and unstable systems and proved its performances to be better than the conventional approach. Various researches (Ali Marzoughi *et al*., 2012, Kotteeswaran and Sivakumar 2014) were carried out to design the controller using PSO to improve the overall performances than the classical approaches.(Giriraj Kumar *et al*., 2008) proved PSO based controller for liquid level process in a conical tank system to improve time domain specifications. Further its performance criteria were compared with IMC.

In this work, an estimation of optimal PI controller using PSO is proposed for level control in a spherical tank system. The estimated controller parameters are tested in simulated environment and also implemented in real time process. The performance of PSO based PI controller is compared with GA based PI controller and classically tuned (ZN) system. The simulation results show that PSO based controller has an improved performance index against other methods.

The remainder of this paper is organized as follows. The real time experimental setup is presented in section 2. The mathematical model of the level process is described in section 3. Section 4 describes conventional approach for level control. Section 5 and 6 overviews and concept of GA and PSO tuning methods and proposals for defining the fitness function respectively. Section 7 presents simulated results and real time implementation. Conclusion of the present work is given in section 8.

Experimental Setup:

Figure 1 shows the real time experimental setup of a spherical tank. The system 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 with positioner, an interfacing module (DAQ) and a Personal Computer (PC). The differential pressure transmitter output is interfaced with computer using data acquisition RS-232 port of the PC. The programs written in script code using MATLAB software is then linked via the interface module.

The pneumatic control valve 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 level transmitter and is transmitted to the interfacing module and hence to the PC. After computing the control algorithm in the PC control signal is transmitted to the I/P converter which passes the air signal to the pneumatic control valve. The control signal used is in the range of 4-20 mA. 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.

Fig. 1: Experimental setup of spherical tank

System Identification:

Mathematical Model of Spherical Tank System:

A model derived from a real –time spherical tank system which exhibits the property of non-linearity is considered in this work. The nonlinear dynamics of spherical tank system is described by the first order differential equation

$$\frac{dV}{dt} = F_{in} - F_{out} \tag{1}$$

Where V is the volume of tank, F_{in}, F_{out} are the inflow and outflow rate.

$$V = \frac{4}{3}\pi h^3 \tag{2}$$

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

$$\frac{H(s)}{Q(s)} = \frac{R_t}{\tau s + 1} \tag{3}$$

Where $R_t = \frac{2h_s}{F_{out}}$, $\tau = 4\pi R_t h_s$

h_s -height of the tank at steady state

Block Box Modeling:

The general first order process with dead time is represented by

$$y(s) = \frac{k_p e^{-t_{ds}}}{\tau s + 1} u(s) \tag{4}$$

The output response to a step change input

$$y(t) = 0 \text{ for } t < t_d \tag{5}$$

$$y(t) = k_p \Delta u\{1 - \exp(-(t - t_d)/\tau)\} \text{ for } t \geq t_d \tag{6}$$

The measured output is in deviation variable form. The three process parameters can be estimated by performing single step test on the process input.The process gain is found as simply the long term change in process output divided by the change in process input (WayneBequtte 2006). Also, the time delay in output response for corresponding change in input is observed. Here two point method (WayneBequtte 2006,Sakthivel *et al*., 2011) is used for estimating the process parameters.

The time required for the process output to make 28.3% and 63.2% of the long term change is denoted by $t_{28.3\%}$ and $t_{63.2\%}$, respectively. The time constant and time delay can be estimated using equation 7 and equation 8

$$\tau = 1.5(t_{63.2\%} - t_{28.3\%}) \tag{7}$$

$$t_d = t_{63.2\%} - \tau \tag{8}$$

The model is subjected to the formulated controller and tested in a real time environment. The process dynamics are analyzed in three operating regions so as to obtain their corresponding suitable model. The obtained model parameters of four operating regions are shown in Table1.

Table 1: Calculated values of k, τ and τ_d for different operating regions

Operating point (cm)	Model parameters		
	K	τ(sec)	τ_d(sec)
11	2.275	157.5	77.5
20	3.42	486	94
30	4.5	465	85

Tuning of PID Controllers using conventional approach:

(Ziegler and Nichols 1942) presented 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. From the open loop response the estimated tuning parameters for three operating points of a spherical tank system are shown in Table 2.

Table 2: PI Controller gain values for different operating points

Operating point (cm)	Controller values	
	K_p	K_i
11	0.804	0.003115
20	1.360	0.004346
30	1.094	0.003865

Genetic Algorithm approach for PID tuning:

GAs is a stochastic global adaptive search method that mimics the process of natural evolution. In recent times GA has been recognized as an effective and efficient technique to solve optimization problems compared with other optimization techniques (MeghaJaiswal and MohnaPhadnis 2013). The powerful capability of genetic algorithm in locating the global optimal solution is used in the design of controllers. GAs exhibits considerable robustness in problem domains that are not conducive to formal and classical analysis. The various steps in GA based optimization are discussed in this section in detailed.

A Initialization:

The initial population few individual solutions are generated. The population is generated randomly, covering the entire range of possible solutions (Nikhileshwar *et al*., 2012).

B Selection:

The entire chromosome will go through the selection process based on their fitness value. Higher the fitness value, the more chance an individual in the population will be selected (MohdSazliSaad *et al*., 2012).

C Reproduction:

This process involve crossover and mutation after the selection process has been completed. The crossover operator is used to create new solutions from the existing solutions available in the mating pool after applying selection operator. This operator exchanges the gene information between the solutions in the mating pool. Mutation changes the structure of the string by changing the value of a bit chosen at random. Mutation prevents the algorithm to be trapped in local minima and maintain diversity in the population. Commonly, lower mutation rate should be chosen. Higher mutation rate may probably cause the searching process become random search. After crossover and mutation process have been completed replace the current population with the new population (MohdSazliSaad *et al*., 2012).

D Termination:

The process of optimization is halted once a termination condition is achieved. The termination condition can be either the number of generations or the solution satisfying an optimum criterion (Nikhileshwar *et al*., 2012).

Implementation of GA based PI controller:

GA can be applied to tune the gain of PI controller to ensure optimal control performance for a liquid level process. GA parameters chosen for the optimization are shown in table 3.

Table 3: GA Parameters

Parameter	Value
Population size	20
Number of generations	100
Selection method	Stochastic Universal sampling
Crossover method	Scattered
Cross over rate	0.8
Mutation probability	0.2

PSO approach for PID tuning:

PSO is one of the most powerful computational algorithm technique based on swarm intelligence and it was developed by (Eberhart and Kennedy 1995). It was inspired by social behaviour of bird flocks and fish swarms. It is widely applied in various engineering problems due to its high computational efficiency and easy implementation (Rajinikanth and Latha 2012). In PSO, a group of birds are initialized with arbitrary positions 'S_i' and their velocities 'V_i'. At early searching stage, each bird in the swarm is scattered randomly throughout the search space of dimension D. With the supervision of the Objective Function (OF), own flying experience and their companions flying experience, each particle in the swarm dynamically adjust their flying position and velocity. During the optimization search, each particle remembers its best position attained so far (i.e. pbest – (P^t_i,D)), and also obtains the global best information achieved by any particle in the population (ie. gbest – (G^t_i,D))(Rajinikanth and Latha 2012).

The search operation is mathematically described by the following equations;

$$V^{t+1}_{i,D} = W\left[V^t_{i,D} + C_1.R_1.(P^t_{i,D} - S^t_{i,D}) + C_2.R_2.(G^t_{i,D} - S^t_{i,D})\right] \tag{9}$$

$$S^{t+1}_{i,D} = S^t_{i,D} + V^{t+1}_{i,D} \tag{10}$$

Where: W = inertia weight; $V^t_{i,D}$ = current velocity of the particle; $S^t_{i,D}$ = current position of the particle; R_1, R_2 are the random numbers in the range 0-1; C_1, C_2 are the cognitive and global learning rate respectively, $V^{t+1}_{i,D}$ = updated velocity; $S^{t+1}_{i,D}$ - updated position.

In order to design an optimal controller the following algorithm parameters are considered; dimension of search space is two (i.e., K_p,K_i), number of swarm and bird step is considered as 20, the assigned value of cognitive parameter C_1 is 2.0 and global search parameter is C_2 is 1.5, the inertia weight "W" is set as 0.6.

Objective Function:

Optimization accuracy of soft computing technique mainly depend on the Objective Function (OF) which guides the algorithm. In this work, OF is chosen as a minimization problem. The main objective of the controller is to reduce the rise time, peak overshoot, peak overshoot, settling time and final steady state error. In this work, the following OF with three parameters such as IAE, peak overshoot and t_s are considered as follows;

$$J(\theta)_{\min} = w_1 * IAE + w_2 * M_P + w_3 * t_s \tag{11}$$

Where θ = dimension of search (K_p, K_i), w_1 – w_3 are the weighting function used to assign the priority for the individual cost functions (w_1=w_2= w_3=10),M_p- peak overshoot and t_s- settling time

$$IAE = \int_O^t |e(t)|dt = \int_O^t |r(t) - y(t)|dt \tag{12}$$

$$M_P = y(t) - r(t)$$

Where e(t) – Error, y(t) – Output, r(t) – Input and t – Time considered for error calculation.

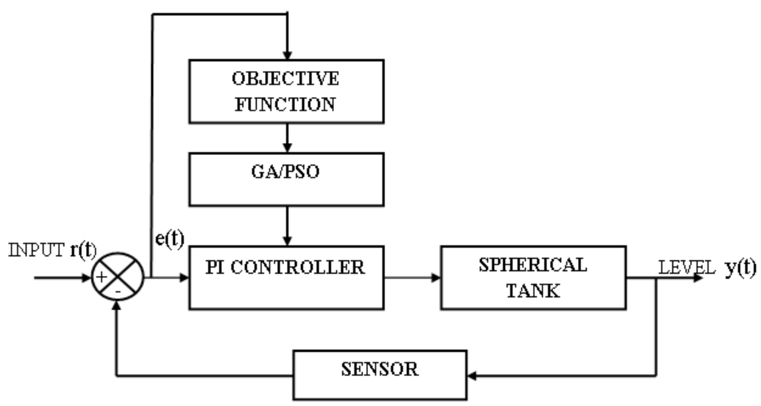

Fig. 4: Block diagram of GA/PSO based controller

The block diagram of GA and PSO based controller design procedure considered in this work is shown in figure 4. The PSO algorithm continuously adjust Kp, K_i until J(θ) is minimized.

RESULTS AND DISCUSSION

In this section, the results from the proposed PSO based PI controller is applied to the level process of the spherical tank system are presented and discussed.Initially, ZN,GA and PSO tuned PI controller is tested in a simulation environment using the model of the nonlinear spherical tank system at three operating points(11cm,20 cm, and 30 cm). The GA and PSO based controller tuning is attempted as discussed in section 5 and 6 of this paper and the obtained optimal controller parameters are presented in table 4.The estimated optimal PI (K_p,K_I) parameters will minimize the IAE value when the process is in steady state. In order to prove the efficiency of PSO based PI controller, the performance is compared with other two PI controllers which are tuned by ZN and GA.

Table 4: Estimated Controller parameters

Setpoint (cm)	Controllers	K_p	K_i
11	ZN	0.804	0.003115
	GA	0.6926	0.003
	PSO	0.6010	0.0030
20	ZN	1.360	0.004346
	GA	1.0954	0.00175
	PSO	0.9218	0.0017
30	ZN	1.094	0.003865
	GA	0.8731	0.0016
	PSO	0.7371	0.00155

Servo Response:

After finding the optimal controller values, the proposed controller settings are applied in simulation mode to study the controller performance on the spherical tank with different operating regions. The simulation is also performed with ZN and GA controllers and the results are compared. The simulated responses of the three controllers for the two operating points are shown in figures 5 to 6.

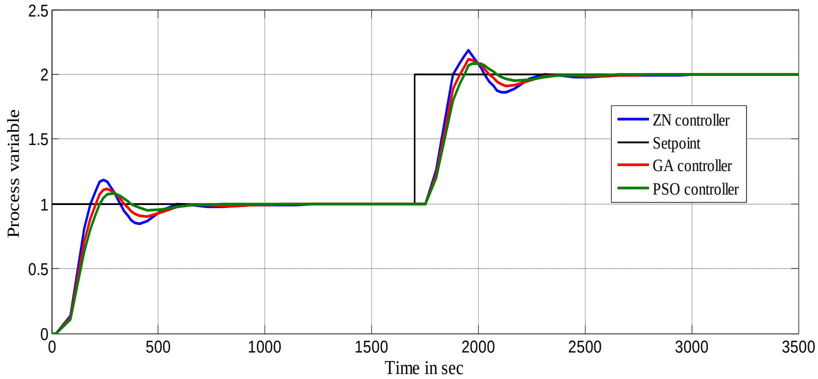

Fig. 5: Servo responses of ZN, GA and PSO based PI controller at the operating point of 11cm

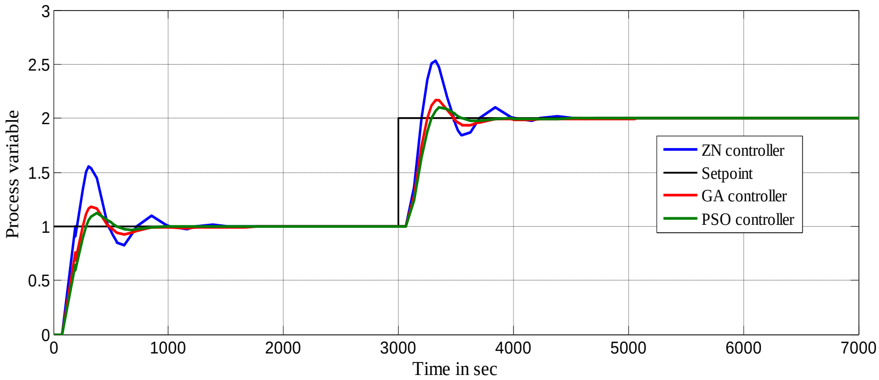

Fig. 6: Servo responses of ZN, GA and PSO based PI controller at the operating point of 20cm

Figures 5-6 show the setpoint tracking performance of the model (11 cm) for multiple set points. The performances of controllers are analyzed by considering rise time, peak time, settling time and percentage peak overshoot and the performance evaluation is presented in table 5-7. From the figure 5-6 it is observed that the

PSO based controller will follow the changes of set point with small overshoot at initial position when compare to ZN and GA based controllers and also requires less settling time.

Table 5: Comparison of time domain specification obtained using ZN, GA and PSO based PI controllers

Setpoint (cm)	Controller	Rise time(t_r) (sec)	Peak time(t_p) (sec)	Settling time(t_s) (sec)	Peak overshoot (%)
11	ZN	183	250	1620	18
	GA	200	255	1440	11
	PSO	230	280	1200	7
20	ZN	200	315	3000	52
	GA	240	330	2600	18
	PSO	280	350	2000	10
30	ZN	178	280	2800	52
	GA	218	315	2000	19
	PSO	250	310	850	11

Table 6: Performance indices comparison

Setpoint (cm)	Controller	ISE	IAE
11	ZN	112.6	171.4
	GA	114.9	164.8
	PSO	118.7	160.2
20	ZN	171	283
	GA	143	214.3
	PSO	148.5	203.6
30	ZN	156.4	259.9
	GA	129.3	189.1
	PSO	134.2	180.9

Table 7: Performance Indices comparison (Servo response)

Setpoint (cm)	Controller	ISE	IAE
11	ZN	229.4	343.3
	GA	233.8	332.7
	PSO	241.4	325.5
20	ZN	344.6	568.5
	GA	289.6	426.3
	PSO	299.5	408.0
30	ZN	316.4	523.4
	GA	263	379.8
	PSO	272.7	367.5

Table 5 clearly indicates that the settling time and peak overshoot are less but rise time and peak time are slightly more when compared with other two controllers in all operating regions. From table 6 and 7, IAE values are low but ISE values are high for PSO tuned PI controller compared with ZN and GA based PI controller.

Real Time Implementation:

The performance of ZN and PSO tuned PI controller is validated in real time on a nonlinear spherical tank system. The hardware details of the considered experimental setup are given in section 2. The reference tracking performance of the system for multiple set points for various operating regions are shown in Fig 9-12.

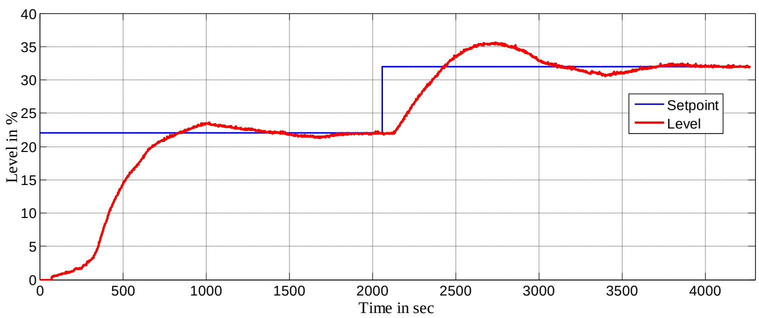

Fig. 9: Real time servo response of ZN controller at the operating point of 11 cm

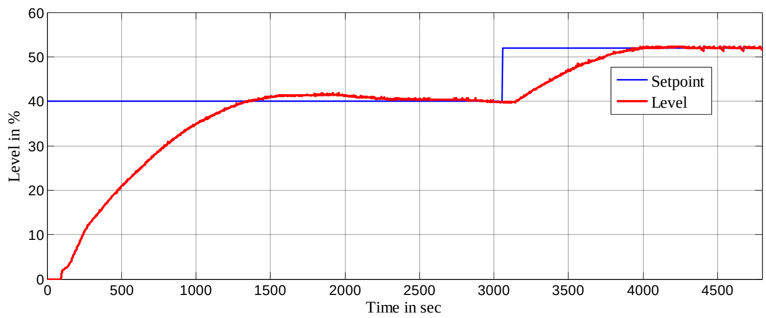

Fig. 10: Real time servo response of ZN controller at the operating point of 20 cm

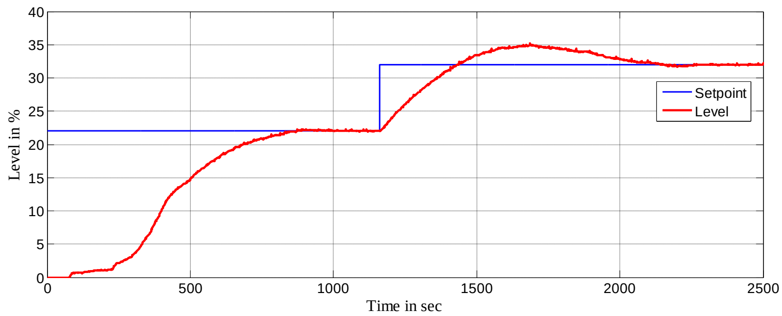

Fig. 11: Real time servo response of PSO based PI controller at the operating point of 11 cm

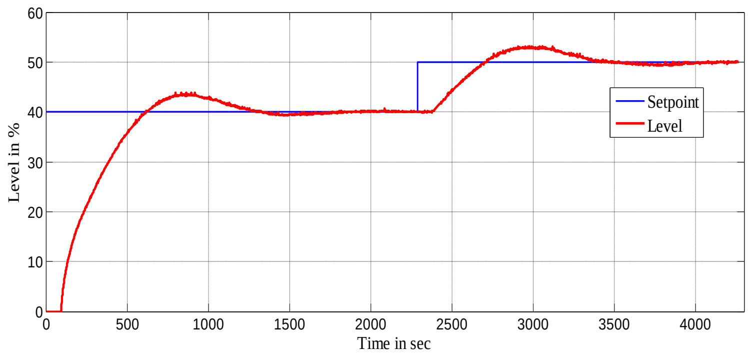

Fig. 12: Real time servo response of PSO based PI controller at the operating point of 20 cm

Fig. 9 depicts the reference tracking performance of ZN controller for a set point of 11cm (22% for a tank diameter of 50cm). Initially, the reference tracking is studied with a single reference input. Later, 10% change is added with the initial set point at 2100 sec and the set point is increased from 11cm to 16 cm. From this figure, it is noted that, initially, the ZN controller track the set point with small initial overshoot but when we apply change in set point the controller track the change in set point with increase in overshoot at initial position. Similar set point tracking performance of ZN controller is also validated at the operating point of 20cm (40% for a tank diameter of 50cm). The real time response is shown in figure 10. It is observed that the controller track the given set point with small initial overshoot but when we apply 10% change of set point at 3100 sec the controller immediately follow the change of set point without any overshoot.

Further the proposed PSO based PI controller is also implemented in real time to control the liquid level of nonlinear spherical tank system for a set point of 11cm and 20cm. The responses are shown in figure 11 and 12. It is noted that the controller track the set point without any overshoot, when we apply 10% changes of set point (5cm) at 1200 sec the controller follow the changes of set point with small overshoot is shown in figure 11. Similarly the proposed controller also validated for a set point of 20cm (40% for a tank diameter of 50cm). The response of the controller at 20cm operating point is depicted in figure 12. From the figure it is observed that the controller tracks the given set point and the change in set point with small overshoot. The proposed PSO tuned PI controller quickly settles the desired level compared with ZN controller.

Regulatory Response:

After identifying the controller parameters, the controller is tested in simulation and real time environment with 20% load changes at the operating point of 20cm. The responses of simulated and real time are recorded in figure 13 and 14.

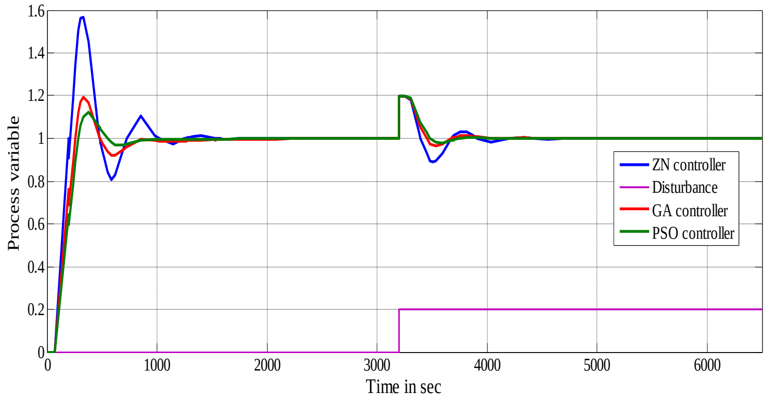

Fig. 13: Regulatory response of ZN, GA and PSO based PI controller at the operating point of 20 cm with 20% disturbance

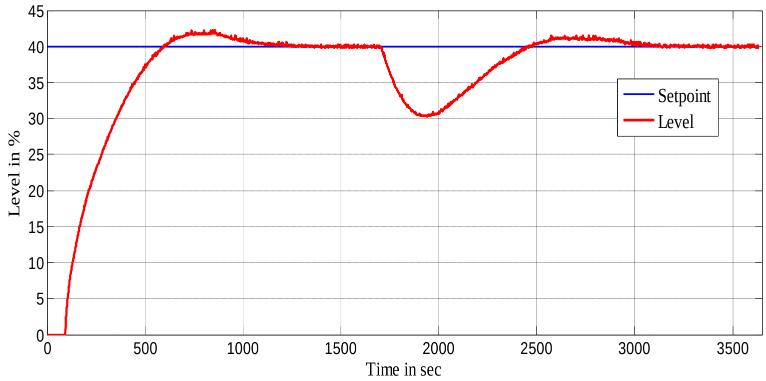

Fig. 14: Real time regulatory response of PSO based PI controller at the operating point of 20 cm with 20% disturbance

Figure 13 indicates that for a sudden load change at 3200 sec, the PSO based PI controller returns to the set point with negligible overshoot when compared with ZN and GA based PI controller. The PSO tuned PI based controller is capable to compensate for the load changes considerably better than conventional and GA -PI controller. From table 8 it is also noted that IAE values are considerably low but ISE values are high when compared with other two controllers. Further, the proposed PSO based PI controller implemented in real time liquid level process at the operating stage of 20cm with 20% load change. The recorded response is shown in figure 14. From the figure it is observed that the designed controller eliminates the given disturbances within 1350 sec.

Table 8: Performance indices comparison of ZN and GA and PSO based PI controller (Regulatory response)

Setpoint (cm)	Controller	ISE	IAE
11	ZN	117.2	205.7
	GA	119.6	198
	PSO	123.6	192.9
20	ZN	180.4	344.9
	GA	149.9	264.2
	PSO	156	252.7
30	ZN	166.2	323.7
	GA	136.3	232
	PSO	141.1	222.4

Conclusions:

This paper presents evolutionary algorithms such as GA and PSO based design and implementation of optimal PI controller for a nonlinear spherical tank system. A simulation study is carried to test the performance of ZN, GA and PSO tuned PI controller on the developed model for both the reference tracking and disturbance rejection operations. Through the simulation responses it is observed that, the time domain specifications such as peak over shoot and settling time of PSO based PI controller are greatly improved but rise time, peak time is slightly higher than the ZN and GA based PI controller. Further, the performance indices of the optimized controller are analyzed; IAE value is less when compared with other two controllers. The PSO tuned PI controller shows smooth response in servo and regulatory operations compared to ZN and GA based PI controller on all the operating regions. The performance of PSO tuned PI controller is then implemented on real time spherical tank process. The real time responses show that PSO tuned PI controller gives smooth response for set point tracking and disturbance rejection. It is concluded that PSO based controller is effective in optimal tuning for a liquid level process.

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