Design and Implementation of Controller for a Nonlinear Spherical Tank System using Soft computing Techniques

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Abstract -- In this work, Particle Swarm Optimization (PSO) based intelligent controller design technique is attempted for a nonlinear spherical tank process. The search process is guided by an objective function, which considers the minimization of some key parameters such as Integral Square Error (ISE), Integral Absolute Error (IAE), and settling time (t_s) of the process under study. The proposed controller tuning procedure is initially tested on the mathematical model of the spherical tank system with a chosen operating region. A detailed simulation study is also performed with the chosen operating regions in order to validate the performance of proposed controller design technique and the results are validated with fuzzy controller. The simulation results evident that, the PSO based PI controller offers better steady state response and performance indices for the considered operating region. Finally, the PSO tuned PI controller is implemented and tested on a laboratory scale real time nonlinear spherical tank system. The real-time responses evident that, proposed controller offers enhanced result for both reference tracking and disturbance rejection operations with an improved performance measure values..

Keywords: Spherical tank, PI controller, PSO, Optimization, ISE, IAE.

I. INTRODUCTION

Most of the real time industrial process loops and chemical process are nonlinear in nature and designing an optimal controller for such system is really a challenging job compared to linear processes. Despite of the significant developments in advanced process control schemes, classical and modified structured PID (Proportional + Integral + Derivative) controllers are still widely used in most of the industrial control applications because of its simple structure, robust performance and easy implementation [1]. Designing the PID controller with the existing classical methods are model dependent and time consuming, particularly for a nonlinear system, the PID controller design becomes complicated. Hence it is necessary to implement soft computing approaches in controller design procedure for nonlinear process.

Fuzzy Logic Control (FLC) is one of the most popular soft computing methods discussed by most of the researchers in the last two decades. Fuzzy control theory usually provides non-linear controllers that are capable of performing different complex non-linear control action.

The major consideration in FLCs is to determine fuzzy rule base, membership functions (MFs) of input/output variables, and input/output scaling factors [5]. The drawback of FLC is difficult to derive of fuzzy control rules which are often time-consuming and needs process expertise [6]. To overcome this drawback evolutionary algorithms are used to estimate the optimal controller parameters.

Heuristic approach based PID tuning has attracted many researchers due to its ability to find optimized controller parameters with a minimized computation time, computing accuracy, and memory size compared with other methods. Recently particle swarm optimization (PSO) algorithm is one of such computing method which is applied for controller design.

Nithya et al. proposed Mamdani and Takagi-Sugeno based FLC for spherical tank control [3]. Debnath et al. designed an adaptive FLC for a nonlinear inverted pendulum system [5]. Further, the work also proved that PSO algorithm has stable convergence with good computational efficiency while comparing the Symbiotic, Adaptive Neuro-Evolution for the same process. Chiou et al. proposed a method for determining the optimal fuzzy PID -controller parameters for active automobile suspension system based on PSO [6]. The study reduces the effect of suspension deflection and sprung mass acceleration. Bouallegue et al. [7] introduced PSO based PID type FLC structures to an electrical DC drive speed control and proved its efficiency when compared with genetic algorithm (GA).

Kumar et al. presented determination of PID controller parameters using PSO for a three tank liquid level process to reduce the error and compared its performances with GA and conventional controller [8]. Latha et al. presented PID controller tuning for unstable systems using heuristic algorithm and improved the time domain performances when compared with conventional and GA controller [10]. Hassen et al. proposed PSO based optimal fuzzy PID Controllers for the two-coupled distillation column process to minimize sum square error [11, 12]. Ko and Wu proposed PSO based fuzzy PID controller for a multivariable seesaw system and proved its performance to be better than a fixed-gain PID controller [13]. Gaing determined the optimal PID controller parameters of an AVR system using PSO algorithm and improved its time-domain performance criterion compared with GA [14]. Dineshkumar and Meenakshipriya designed gain scheduled PI controller for a interacting spherical two tank system to regulate the level as per requirement [16]. Suresh et.al proposed feed forward controller for a nonlinear thermal process to improve transient performance than conventional controller [17, 18]. The fuzzy based controllers are widely discussed in the literature by the most of the researchers [19, 21]. Sivagurunathan and Jayanthi [23] proposed fuzzy logic based self-tuning of PI controller for a liquid level process to improve dynamic characteristics and compare its performances with Internal Model Controller (IMC). Kotteeswaran and Sivakumar [24] discussed PSO based baseline PI controller for ALSTOM gasifier to improve performance indices.

In this paper, the PSO algorithm based PI controller design for a nonlinear spherical tank system is proposed. The operating points for the non-linear spherical tank system is chosen as 11cm, 20cm and 30cm and corresponding mathematical models are derived using the black box modelling technique. For the developed model, PI values are computed using the PSO algorithm. Initially a simulation study is performed using Matlab software and later a real time implementation of the proposed work is carried using a laboratory scale spherical tank process loop. The performance of the PSO tuned PI controller is compared with the fuzzy controller and the result are presented.

The remainder of this article 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 fuzzy logic control, the PSO-tuning method and proposals for defining the fitness function. Section 5 presents simulated results and real time implementation. Conclusion of the present work is given in section 6.

II. EXPERIMENTAL SETUP

Fig.1 shows the experimental setup of a spherical tank. The laboratory set up for this system consists of a spherical tank, water reservoir, pump, rotameter, differential pressure transmitter, electro pneumatic converter (I/P converter), 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.

III. SYSTEM IDENTIFICATION

A. Mathematical Model of Spherical Tank System

The development of mathematical model for a nonlinear spherical tank system is considered in this work. The nonlinear dynamics of a spherical tank system is described by the first order differential equation

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

where V represents volume of tank, F_{in}, F_{out} are the inflow and outflow rate respectively.

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

where h is the total height of the tank in cm.

Applying the steady state values and solving 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.

B. Block Box Modeling

This section presents a method considered to develop approximated reduced order model of the spherical tank system for the operating regions 11cm, 20cm, and 30 cm respectively.

A general first order process with dead time is represented by

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

Fig. 1. Experimental Setup of Spherical Tank

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 measure 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 [4]. Also the time delay is the amount of time, after the input change, before a significant output response is observed. Here two point method [4], [22] 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 from Equation 7 and Equation 8

$$\tau = 1.5(t63.2\% - t28.3\%) \tag{7}$$

$$t_d = t63.2\% - \tau \tag{8}$$

The model is subjected to the formulated controller and tested in a real time environment. The process dynamics are analyzed in three operating points so as to obtain their corresponding suitable model. The obtained model parameters of three operating points are shown in Table 1.

TABLE 1
Calculated Values of K, τ and τ d for Different Operating Regions

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

IV. CONTROLLER DESIGN

A. *Fuzzy Logic Controller*

Fuzzy control uses a list of rules than complicated mathematical expressions. These rules are modeled after decision previously made by human through the process control systems. The fuzzy logic controller consists of fuzzification, inference engine and defuzzification stages.

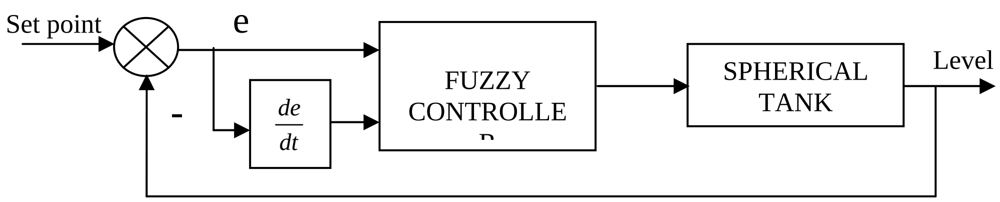

Fig. 2. Fuzzy control scheme

The fuzzification which converts each element of input data to degrees of membership by a lookup in one or more membership functions. The rule base and inference engine basically decides the rules to be fired for particular inputs. The defuzzification is the process of converting fuzzy signal into a crisp control signal. The triangular membership function with seven linguistic values of seven different ranges has been used for error and change of error. The general closed loop diagram of fuzzy controller is shown in figure 2.

In the considered liquid level process, fuzzy controller is designed with two input and one output variable. To design the controller, error (e(t)) and change in error (Δe(t)) are considered as input. The output variable of fuzzy controller serves as input for control valve. For the system under study, the universe of discourse for both e(t) and Δe(t) may be normalized from -1 to 1. The linguistic labels of inputs and outputs are Negative Maximum (Nmax), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM) and Positive Maximum (Pmax). The fuzzy rules are shown in table 2.

TABLE 2
Rule Base for Fuzzy Controller for Level Process

Δe(t) / e(t)	N_{max}	*NM*	*NS*	*ZE*	*PS*	*PM*	P_{max}
N_{max}	N_{max}	N_{max}	NM	NS	NM	NM	NS
NM	N_{max}	NM	NM	NS	NM	NS	NS
NS	NM	NM	NS	Z	NS	Z	Z
ZE	Z	Z	Z	Z	Z	Z	Z
PS	PM	PS	PS	Z	Z	Z	Z
PM	P_{max}	PM	PM	Z	PM	PS	PS
P_{max}	P_{max}	P_{max}	PM	PS	PM	PM	PS

B. Particle Swarm Optimization (PSO)

(PSO) developed by Kennedy and Eberhart [9], is a swarm intelligence based on stochastic and population-based optimization. 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 [1], [10], [23], [25, 26, 27]. In this, 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, and also obtains the global best information achieved by any particle in the population.

The search operation is mathematically described by the following equations;

$$V_{i,D}^{t+1} = W\left[V_{i,D}^{t} + C_1.R_1.(P_{i,D}^{t} - S_{i,D}^{t}) + C_2.R_2.(G_{i,D}^{t} - S_{i,D}^{t})\right] \qquad (9)$$

$$S_{i,D}^{t+1} = S_{i,D}^{t} + V_{i,D}^{t+1} \qquad (10)$$

where: W = inertia weight; $V_{i,D}^{t}$ = current velocity of the particle; $S_{i,D}^{t}$ = 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; $V_{i,D}^{t+1}$ = updated velocity; $S_{i,D}^{t+1}$ - 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 1.5 and global search parameter is C_2 is 2, the inertia weight "*W*" is set as 0.6.

C. Objective Function

Optimization accuracy of soft computing technique mainly relies on the Objective Function (OF) which guides the algorithm. In this work, OF is chosen as a minimization problem. In the literature, there exist a number of weighted sum-based objective functions [15], we considered the following with three parameters such as ISE, IAE, and t_s as follows;

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

Where p = dimension of search (K_p, K_i), and $w_1 - w_3$ are the weighting function used to assign the priority for the individual cost functions (w_1=w_2=1; w_3=0.5).

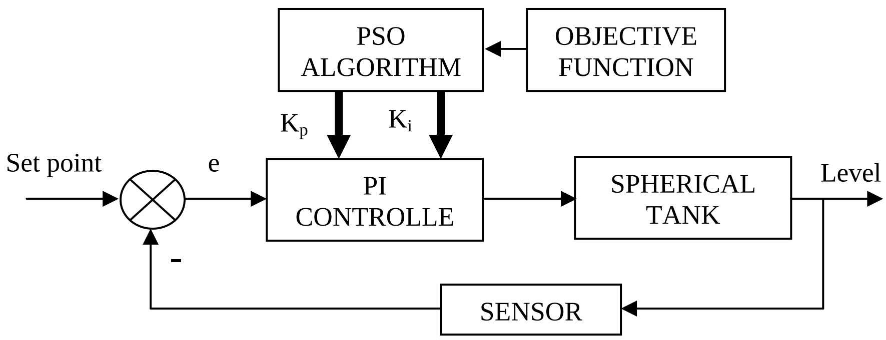

Fig. 3. Block diagram of PSO based controller

The block diagram of PSO based controller design procedure considered in this work is depicted in figure 3. The PSO algorithm continuously adjust Kp, K_i until J(p) is minimized.

V. RESULTS AND DISCUSSION

Initially, the PSO tuned PI controller is tested in a simulation environment using the model of the nonlinear spherical tank system for three operating points. The PSO based controller tuning is attempted as discussed in section 4 and the obtained optimal controller parameters are presented in table 3.

TABLE 3
PI Tuning Values for Different Operating Points

Operating point (in cm)	Tuning parameters	
	K_P	K_I
11	0.45	0.0031
20	0.72	0.0015
30	0.60	0.0013

A.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 (11cm, 20cm and 30cm). The simulation is also performed with fuzzy controller and the results are compared. The simulated response of proposed controller and fuzzy controller for the three operating points are shown in figures 4 to 6.

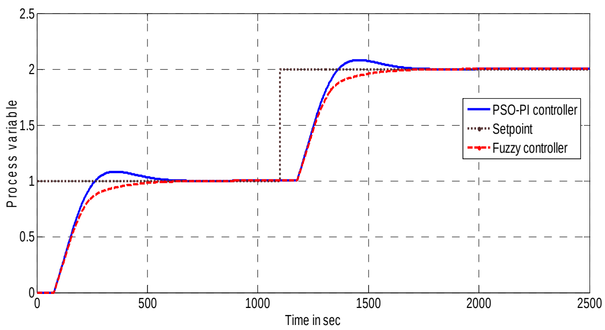

Fig. 4. Servo response of fuzzy and PSO based PI controller at the operating point of 11cm

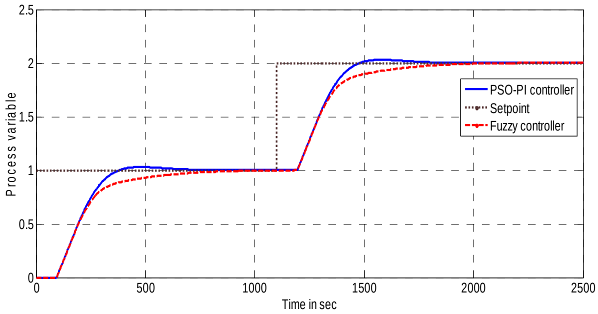

Fig. 5. Servo response of fuzzy and PSO based PI controller at the operating point of 20cm

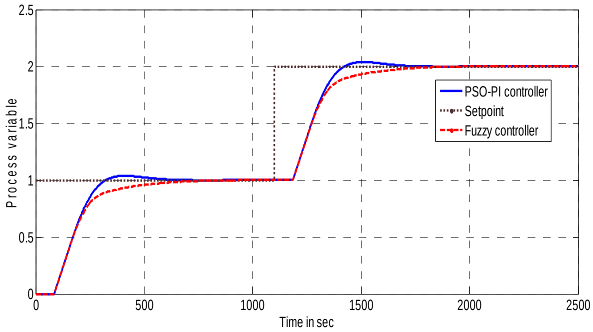

Fig . 6. Servo response of fuzzy and PSO based PI controller at the operating point of 30cm

Fig 4 depicts the reference tracking performance of the model (11 cm) for multiple set points. From the figure it is observed that the PSO based controller will follow the changes of set point with small overshoot at initial position. The fuzzy based controller shows a sluggish response. The performance evaluation is presented in Table 4-6.

TABLE 4
Time Domain Comparison of Fuzzy and PSO Based PI Control

Specifications	Setpoint (cm)	Fuzzy	PSO
Rise Time (sec)	11	750	265
	20	1050	380
	30	900	325
Peak Time (sec)	11	780	360
	20	1100	480
	30	940	400
Settling Time (sec)	11	780	650
	20	1100	840
	30	940	710
% Overshoot	11	--	8
	20	--	3
	30	--	3

TABLE 5
Performance Indices Comparison

Set point (cm)	Controller	ISE	IAE
11	Fuzzy	134.2	181.7
	PSO	129.4	173.3
20	Fuzzy	166.9	238
	PSO	161.3	209
30	Fuzzy	147.8	204.6
	PSO	141.0	185.6

TABLE 6
Performance Indices Comparison (Servo Response)

Set point (cm)	Controller	ISE	IAE
11	Fuzzy	268.8	363.2
	PSO	259.6	346.5
20	Fuzzy	334	475
	PSO	323.5	418.1
30	Fuzzy	294.3	409.2
	PSO	287	371.2

The PSO tuned PI offers a smooth response with improved rise time (t_r) peak time (t_p), settling time (t_s). The ISE and IAE value for PSO tuned PI controller is less compared to fuzzy controller in all the operating regions. From Fig. 5, Fig. 6, and Table 4-6, it is noted that, similar results are obtained for other considered models.

Fig. 7 shows the regulatory response of the process for the developed model of 11cm. Initially, the system is allowed to track an unity set point value and a load disturbance of 20% is applied at 1100 sec.

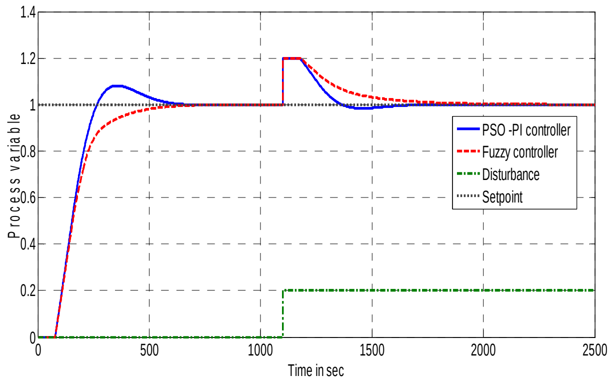

Fig. 7 Regulatory response of fuzzy and PSO based PI controller at the operating point of 11 cm with 20% disturbance

TABLE 7
Performance indices comparison (Regulatory response)

Set point (cm)	Controller	ISE	IAE
11	Fuzzy	141	234.1
	PSO	135	207.9
20	Fuzzy	175.2	304.3
	PSO	168.4	250.9
30	Fuzzy	154.8	262.7
	PSO	149.9	222.8

The FLC offers sluggish response for both the reference tracking and disturbance operations. From Fig. 7 and Table 7, it is noted that, PSO tuned PI controller outperforms FLC

B. Real time Implementation

The performance of PSO tuned PI controller is validated in real time on a nonlinear spherical tank system. The hardware detail of the considered system is presented in section 2. The reference tracking performance of the system for multiple set points for various operating regions are shown in Fig 8 and 9.

Fig. 8 depicts the reference tracking performance 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 1150 sec and the set point is increased from 11cm to 16 cm. From this figure, it is noted that, initially, the proposed controller track the set point without any overshoot but when we apply change in set point the controller track the change in set point with small overshoot at initial position.

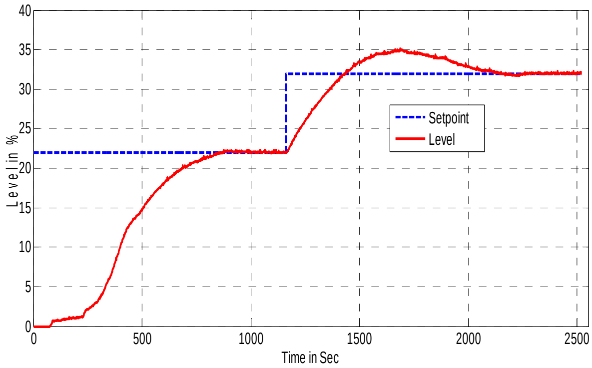

Fig. 8 Real time Servo response of PSO based PI controller at the operating point of 11cm

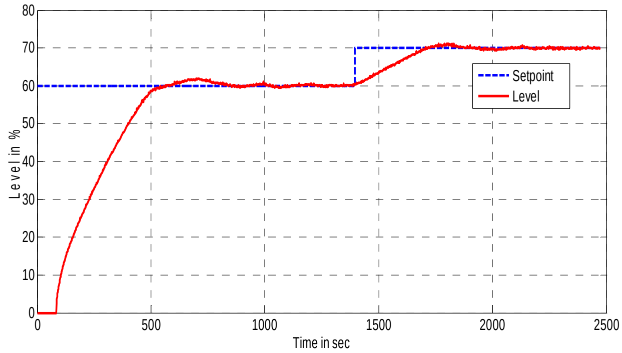

Fig. 9 Real time Servo response of PSO based PI controller at the operating point of 30cm

Fig. 9 shows the set point tracking performance of PI controller for setpoint of 30cm (60%) and an increment of 10% at 1400sec. The PI controller offered smooth response with negligible overshoot.

C. Regulatory response

The regulatory response of the controller is tested using the set point 11cm (22%). A load disturbance of 20% is applied at 1400sec and the recorded response is presented in Fig. 10. The figure evident that, the designed PI controller works well for both the reference tracking and disturbance rejection operations on the real time nonlinear spherical tank system.

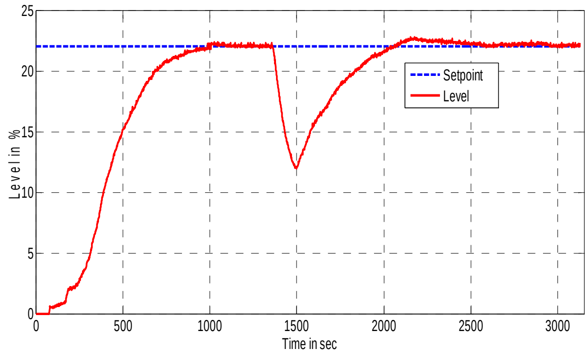

Fig.10 Real time regulatory response of PSO based PI controller at the operating point of 11cm

VI. CONCLUSIONS

This paper presents PSO algorithm based design and implementation of optimal PI controller for a nonlinear spherical tank system. A simulation study is carried to test the performance of FLC 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 specification in terms rise time, peak time and settling time are greatly improved. Further, the performance indices of the optimized controller are less than the fuzzy controller. FLC shows sluggish response compared to PSO based PI on all the operating regions. The performance of PSO tuned PI controller is then validated 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.

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