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Computational analysis of hybrid grey wolf and particle swarm optimization for water level control in coupled tank

Hafiz Minhajuddin Shaikh[1], Neelima R. Kulkarni[1], Mayuresh V. Bakshi[2]
[1]Department of Electrical Engineering, PES Modern College of Engineering (PESMCOE), Savitribai Phule Pune University, Pune, India
[2]Department of Engineering and Applied Science, Vishwakarma Institute of Information Technology, Pune, India

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ABSTRACT

Water level control at a precise set point is a major concern in process control systems such as bulk drug production industries. Loss in production at the initial stage is observed until the water level reaches desired level. Pharmaceutical industries can however be benefited if they could maintain the precise water level control at the initial stage of production with the help of the performance optimization using various techniques. To achieve optimized value of the selected performance index, a hybrid of particle swarm optimization (PSO) and grey wolf optimization (GWO) is found to provide the desired performance in the best possible manner. The mathematical model of the coupled tanks is first developed using the state space analysis which can then be converted to transfer function form so as to accomplish the simulation. In this paper, integral square error (ISE) is selected as the performance index for the minimization to improve overall performance of the system. Observations from the hybrid GWO-PSO optimization articulate that overshoot and settling time can be improved as per the industry needs. Performance evaluation of different optimization techniques is discussed in this paper.

Corresponding Author:

Hafiz Minhajuddin Shaikh
Department of Electrical Engineering, PES Modern College of Engineering (PESMCOE)
Savitribai Phule Pune University
Pune, India
Email: hafizshaikh815@gmail.com

1. INTRODUCTION

According to a survey, many pharmaceutical industries use manual methods for observing and controlling water levels in the tank. It is desirable in case of boilers and reactors to maintain the water level as closely as possible to the set point. In case of the applications such as production of hypochlorite, requirement of an adequate amount of water is very important. Such level control system normally consists of coupled tanks which are interacting with each other. The behaviour of the interacting coupled tank system is different and somewhat complex from that of the non-interacting system which is comparatively simpler from the control point of view [1]. It can be seen from the literature that in most of the systems, the shape of the tank is spherical and heuristic control strategies have been designed to control the liquid level [2]. However, rectangular shaped tanks are not predominantly considered in interactive tank systems [3]. This paper takes into account the interacting coupled tanks which are rectangular in shape. Most of the published literature considers non-interacting coupled tank system wherein an ARM7TDMI microprocessor manages the fluid level in the [4], [5]. There are various optimization techniques of which genetic algorithm (GA) and ant colony optimization (ACO) use large number of iterations, and the system becomes a bit slow [5]. Artificial neural network (ANN) makes the control system complex hence it is discarded for water level control experimentation.

The research problem can be found through the literature survey and hence the key findings can be derived. From the literature survey it is suggested to optimize the parameters of conventional controller such that the responses are more precise [6]. For a fixed set point control system, a conventional proportional integral derivative (PID) controller is used for coarse tuning but for fine tuning we require optimization techniques along with it. It is observed that in most of the liquid level systems which are controlled manually, rotameters are traditionally used to keep a track and govern the water level inside tank. Coupled tank liquid level system predominantly utilize a linear mathematical prototype to outline controllers such as PID controller which is commonly found in pharmaceutical and chemical industries [7]. Hybridization of optimization tools like grey wolf optimization (GWO) and particle swarm optimization (PSO) for fine tuning of PID has rarely been found to be implemented for controlling the water level in coupled tank multiple-input multiple-output (MIMO) system.

The main objective and contribution of this paper is the development of hybrid GWO-PSO based optimization for the selection of parameters of PID controller for fine tuning. Deriving mathematical model of the coupled tank system and simulating it in MATLAB is the second objective of the proposed work. Interfacing circuit for connecting hardware setup with the computer (MATLAB) is done through the Arduino. Realization of simulation results for hybrid GWO-PSO optimization of PID parameters by implementing the same in hardware is the other objective and novelty of this paper.

Methodology of the system can be explained in steps. The first step is to develop the mathematical model by formulating the mathematical equations in state space form with the application of Bernoulli's mass balance equation for the coupled tank. Transfer functions are then obtained by converting the state space model. The second step is to carry out the simulation using these transfer functions in MATLAB/Simulink platform. Conventional PID controller is used initially for obtaining the level response. The third step involves applying the optimization tools like PSO and GWO for the PID controller and record the simulation and hardware experimentation results. After analyzing, transient response can be further improved by hybridization of PSO and GWO. The fourth step involves implementation of hybrid combination of optimization tools on the actual hardware using Arduino UNO 328P by interfacing with MATLAB/Simulink. All the hardware observations were noted and represented in tabular format later in this paper for better understanding.

The organization of this paper is such that, section 2 depicts the schematic of coupled tank system as well as the actual hardware of the system and explains arithmetic model derivation of the system. Section 3 explains the conventional method of PID controller for controlling water level in coupled tanks. Section 4 elaborates arithmetic expressions and optimization of PID using GWO for tuning the parameters. Responses of coupled tank system by PID controller using GWO is also explained in section 4. In section 5 implementation of PSO-PID using MATLAB/Simulink is done. Section 6 explains the hybrid GWO-PSO-PID optimization and its algorithm in the form of flowchart. Section 7 explains about overall performance analysis of all the controllers used. Section 8 describes the conclusion of the paper.

2. COUPLED TANK INTERACTING SYSTEM

In coupled tank, interacting defines a system that has two similar or dissimilar tanks connected with each other via a link between them. There are two independent inputs and two independent outputs in the system. Two pumps deliver water to the tanks through inlets. A valves regulates the output of the tanks. Figure 1 shows a schematic of the system.

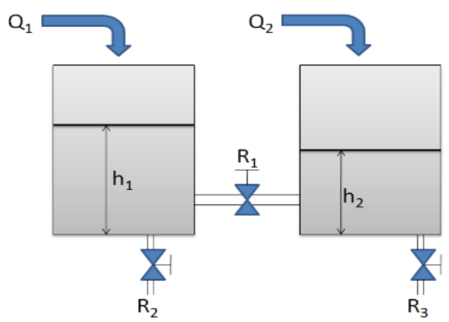


Figure 1. Schematic of coupled tanks

The system is made up of two rectangular shaped tanks that are connected to each other. The water flow into the tanks 1 and 2 is depicted respectively by Q_1 and Q_2. For making arithmetic calculations simple, all the units of different parameters are considered in SI system. Each tank has a capacity of 6 liters. Length and width of tank is 0.13 m while height is 0.35 m and hydraulic resistance of valve is 15,552 sec/m^2.

The height of the water level in tanks 1 and 2 is indicated by h_1 and h_2 respectively. The discharge coefficients for tanks 1 and 2 are represented by R_2 and R_3. R_1 is the discharge coefficient which corresponds to the flow of water along the two coupled tanks. The interacting link is controlled by valve R_1. Figure 2 displays the circuit diagram for interfacing of MATLAB software with the hardware using Arduino Uno 328P.

Pin numbers D3, D5, A0 and A5 are used for interfacing MATLAB with the hardware. Pin numbers A0 and A5 collect the analog signal of actual water levels from both tanks in the form of a voltage signal ranging from 0 to 5 V and then convert it into digital form to send it to the MATLAB. The digital control signals generated from the MATLAB are then sent to Arduino UNO board at pin numbers D3 and D5 which gets converted to analog signal and are sent to the hardware panel at test point 1 as shown in the Figure 2. The yellow line shows the connection from D3 pin on Arduino board to test point 1 at EMT 9(A) panel. The blue line shows the connection from D5 pin on Arduino board to test point 1 at EMT 9(B) panel. The green line shows connection from A0 pin on Arduino to test point 16 on EMT 9(A) panel. The red line shows connection from A5 pin on Arduino to test point 16 on EMT 9(B) panel.

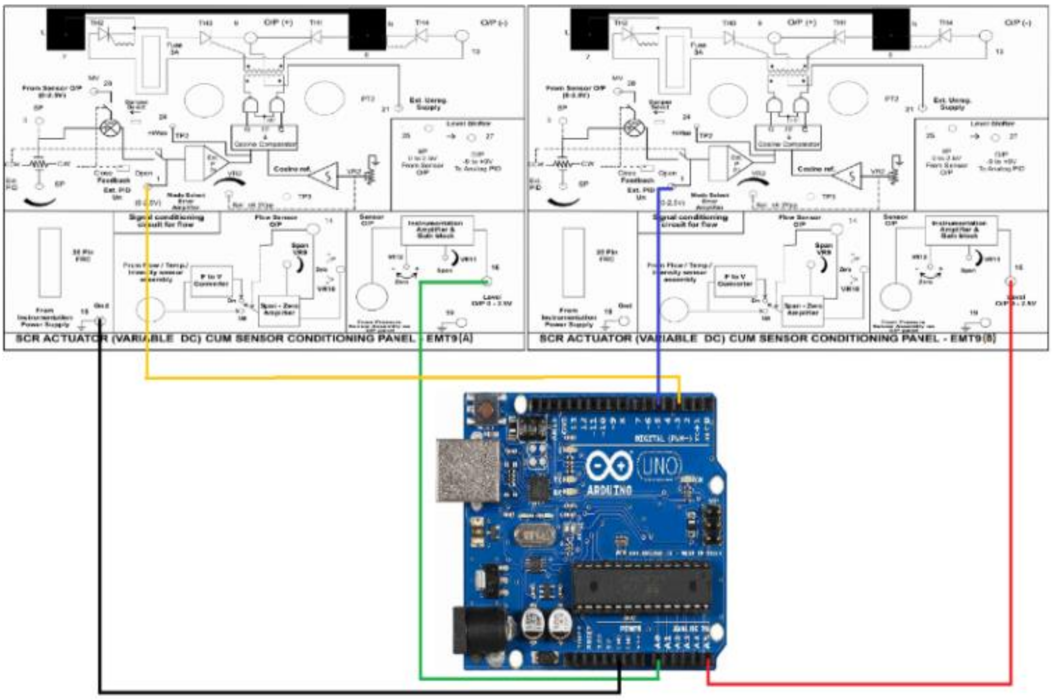


Figure 2. Circuit diagram for interfacing of controller kit with Arduino Uno

2.1. Mathematical model derivation

Mathematical modelling of two tank interactive liquid level control system can be found in the literature [8]. A mathematical model is required for water level control in coupled tanks which needs a suitable controller [9]. Bernoulli's mass balance theory facilitates to find the differential equation of the system. The basic concept is inflow minus outflow for a small interval of time 'dt' is same compared with the amount accumulated inside the tank. According to the above theory, differential equations for the tanks are as shown in (1) and (2):

For tank 1:

$$a_1 \frac{dh_1}{dt} = Q_1 - \left(\frac{h_1 - h_2}{R_1}\right) - \frac{h_1}{R_2} \quad (1)$$

For tank 2:

$$a_2 \frac{dh_2}{dt} = Q_2 - \frac{h_2}{R_3} - \left(\frac{h_2 - h_1}{R_1}\right) \quad (2)$$

where,

a_1, a_2 = Area of tank 1 and 2 (m^2), h_1, h_2=Height of water level in tank 1 and 2 (m),
Q_1, Q_2 = Water flow in tank 1 and 2 (m^3/sec), R_1=Discharge coefficient of interaction link (sec/m^2).

The value of R_1 is 7,776 sec/m^2 while value of R_2 and R_3 is 15,552 sec/m^2. MATLAB programming makes it convenient to compute the complex transfer function matrix easily. The block diagram representation for the system is shown in Figure 3. Error (e) is generated by comparing set point 1 (SP1) or set point 2 (SP2) with actual level in tank 1 (h_1) or actual level in tank 2 (h_2). This error signal is given to the controller and actuator which then allow the flow (Q) of water to the tanks. The state space model gets converted into 4 transfer functions as follows:

$$G11 = \frac{59.17s+0.6754}{s^2+0.02283s+7.238e^{-5}} \qquad G12 = \frac{0.4503}{s^2+0.02283s+7.238e^{-5}}$$

$$G21 = \frac{0.4503}{s^2+0.02283s+7.238e^{-5}} \qquad G22 = \frac{59.17s+0.6754}{s^2+0.02283s+7.238e^{-5}}$$

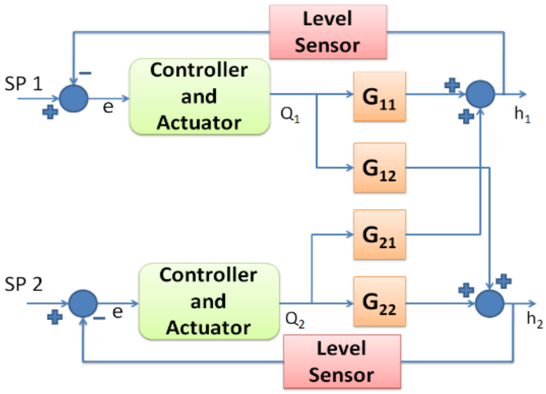
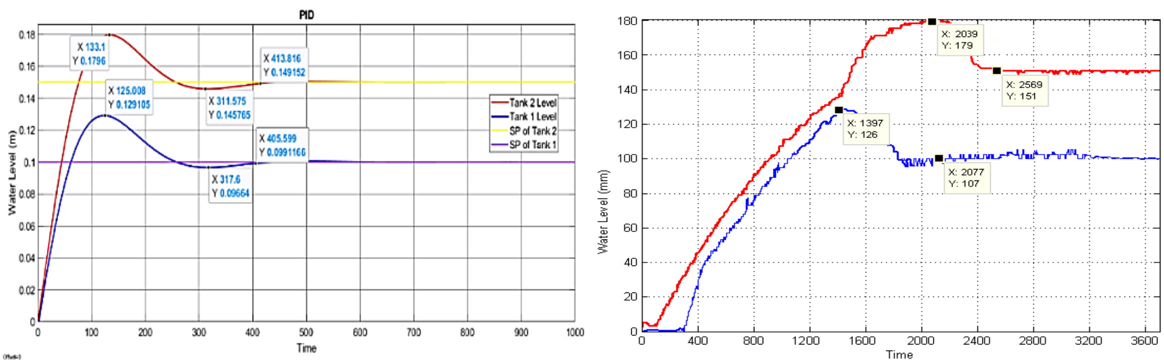


Figure 3. Block diagram representation of two tank interactive liquid level control system

3. CONVENTIONAL PID CONTROLLER

The main purpose of a PID controller is to regulate a process or system to a setpoint (desired value) by continuously calculating and adjusting its control output. PID parameters are tuned using Zeigler Nichols technique. Figure 4 explains the simulation and hardware responses of water level using PID controller. There is a considerable overshoot and undershoot present in the response as shown in Figure 4(a). Settling time for both the tanks is also found to be comparatively higher.

The hardware response shown in Figure 4(b) consists of a high level of overshoot and settling time with negligible undershoot. Large settling time and overshoot may result in the production loss of pharmaceutical industries. This necessitates the application of an optimization technique to be implemented for achieving the enhanced performance.



(a) (b)

Figure 4. Response of water level in coupled tanks using PID controller for (a) simulation and (b) hardware

4. PID CONTROLLER BASED ON GWO

GWO is implemented with respect to hunting behaviour of the grey wolves in a pack. The orders given to the pack are determined by the grey wolf social structure [9]. Leader in pack dominates the group and finds the most optimized path for hunting the prey. The position of each wolf corresponds to a candidate solution, and the objective function determines the fitness of each wolf. The algorithm iteratively updates the positions of the wolves in search of the optimal solution. Without getting stuck in an early convergence, GWO algorithm conspicuously finds the optimal solution. GWO algorithm is explained using a flowchart in Figure 5.

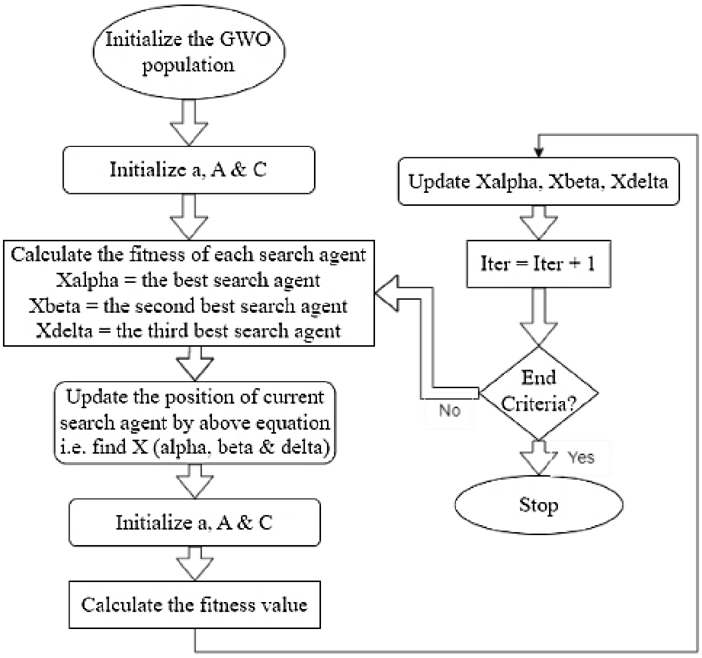


Figure 5. Flowchart showing the working of algorithm for GWO

4.1. Arithmetic model of GWO

The parameters of PID controller can be optimized by analyzing the encircling and hunting behavior of grey wolves using arithmetic methods [10], [11]. Let the current position of the prey be denoted by $\overrightarrow{X_p}(t)$ while that of the wolf is denoted by $\vec{X}(t)$. Coefficient vectors are denoted by $\vec{C}$, $\vec{A}$. The following expression is used to determine the distance $\vec{D}$ or optimized path between the prey and the wolf as shown in (3).

$$\vec{D} = \left|\vec{C}\overrightarrow{X_p}(t) - \vec{X}(t)\right| \quad (3)$$

After circling the prey, grey wolves identify its location for hunting. The position of the prey is best shown by alpha. Beta and delta work together to transfer their most effective solution for better hunting [12], [13]. Other search agents (including omega) are encouraged to revise their own positions by these three wolves who update their positions $(\overrightarrow{X_1}, \overrightarrow{X_2}, \overrightarrow{X_3})$. Mean of the updated position is denoted by $\vec{X}(t+1)$. Mathematical expressions for the same are shown in (4).

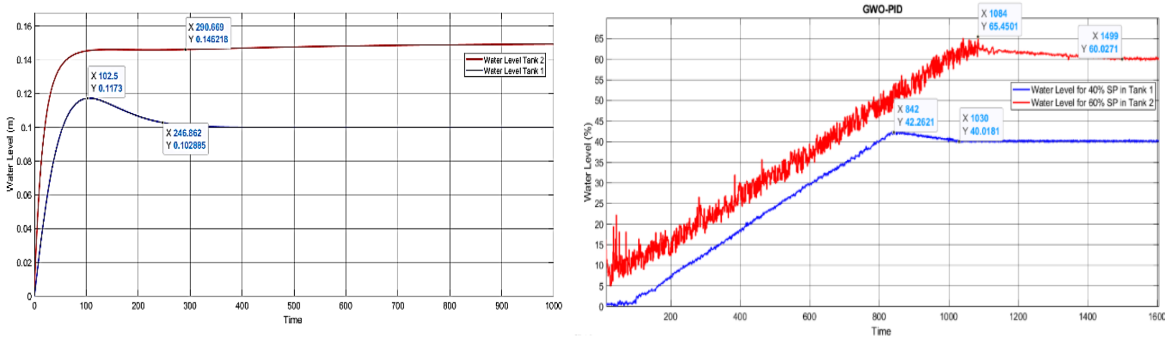
$$\vec{X}(t+1) = \frac{\overrightarrow{X_1}+\overrightarrow{X_2}+\overrightarrow{X_3}}{3} \quad (4)$$

These mathematical expressions are coded in the MATLAB script and are fetched into the Simulink model. For every iteration, the global best value of the performance index is determined which helps in converging to the optimized value. To get the optimized results within less time, the range of PID (upper bound and lower bound) should be kept properly. The number of iterations required should be as minimum as possible so that the controlling action can be fast.

4.2. Simulation of coupled tank system by PID controller using GWO

The performance index selected is integral square error (ISE) is computed and applied as the input signal to the PID controller of which the parameters are optimized by GWO. In context of GWO, ISE is the prey ($\vec{X}_p$) which needs to be minimized. Every PID parameter has a total number of four search agents which update their positions (values of Kp, Ki and Kd respectively) as per the estimated prey position (ISE value). GWO algorithm works accordingly to find the optimum value of PID parameters which indeed regulate the water level in the coupled tanks. The GWO algorithm involves several parameters, such as the search agent positions, the search range, and the exploration and exploitation rates. Figure 6 depicts the simulation and hardware responses for water level using GWO-PID optimization. Simulation responses for water level in coupled tanks using GWO-PID is shown in Figure 6(a). It is observed that the overshoot is present in the second tank which is set at lower level.

Adjusting these parameters, such as reducing the step size or adjusting the exploration and exploitation rates can potentially reduce the overshoot. The settling time is found to be much improved than PSO. Implementation of GWO-PID on hardware gives responses which are shown in Figure 6(b).



(a) (b)

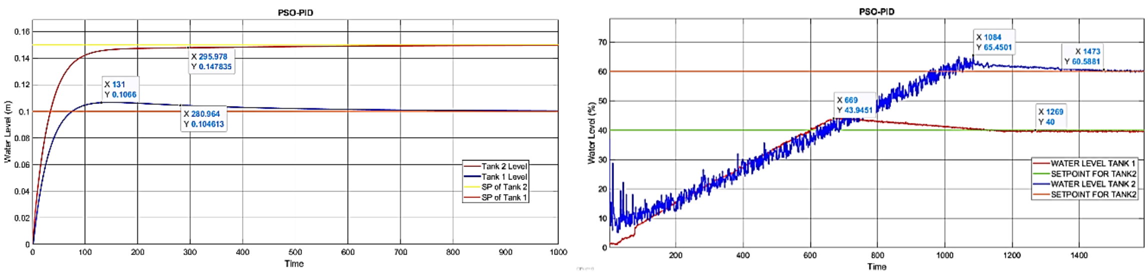
Figure 6. Response for water level control in coupled tanks using GWO-PID controller for (a) simulation and (b) hardware

5. PID CONTROLLER BASED ON PSO

In search space of an optimization problem, each particle will have a position [14]. The optimization problem's search space is a collection of all potential solutions, and our goal is to select the optimal one from this collection [15]. Each particle remembers its perfect location and greatest experience, which are signified by personal best, in contrast to its position and velocity (Pbest). There is also a global best (Gbest) or common best amongst the member of swarm which is the greatest occurrence of every particle in the swarm [16]. Every particle's location and velocity are changed using this straightforward process during each PSO iteration.

Initial parameters of PSO include number of variables such as, upper bound, lower bound, defining the objective function, settling number of particles, maximum iteration value, maximum and minimum values of weight and acceleration coefficient [17], [18]. The objective function to be optimized is ISE [19]. ISE is selected as a performance index because it reduces the minimal value of error and focus on it [20]. After experimenting on the system using PID controller, the upper bound and lower bound parameters of the PID are fixed. The values of PID parameters are updated based on the PSO algorithm [21], [22]. This includes initialization of the population of search agents followed by the evaluation of fitness based on the performance index [23], [24]. The loop continues such that the present fitness is better than the previous fitness [25]. Pbest and Gbest continuously get updated according to the present value of ISE reported. PID parameters get tuned automatically till five iterations are complete.

Figure 7 illustrates water level response of simulation and hardware using PSO-PID optimization. The water level response of coupled tanks utilizing PSO-PID controller for simulation has been displayed in Figure 7(a). In case of tank 1, water level perfectly settles without any overshoot but, for tank 2 it can be observed that there is some overshoot in the response. The PID range for both the controllers should be properly implemented to get the best response. Experimental response for water level control in coupled tanks using PSO-PID controller is shown in Figure 7(b). The disturbance present in the response is because of the natural water turbulence effect.



(a) (b)

Figure 7. Response for water level control in coupled tanks using PSO-PID controller for (a) simulation and (b) hardware

6. PID CONTROLLER BASED ON HYBRIDIZATION OF GWO-PSO OPTIMIZATION

PSO provides best results when it comes to exploitation of the search agents, but exploration technique is poor. Minimization of a performance index occurs at the last iteration, which shows that global minima is not obtained rather it gets trapped into local minima. GWO has four search agents which gives a best minimization at global level. GWO tries to find the best optimal value for ISE at the very first instance. The response of ISE for hybrid GWO-PSO shows the minimized value at second iteration itself and also shows a steady graph which depicts benefits of both GWO and PSO getting implemented. Optimization in positioning is taken care by GWO whereas velocity is improvised by the PSO algorithm.

The working of hybrid GWO-PSO can very well be understood by studying the flowchart shown in Figure 8. Validation of proposed hybrid GWO-PSO methodology can be carried out by modeling it in MATLAB/Simulink. Algorithm of hybrid GWO-PSO is written in MATLAB script. The real time ISE value is fetched from the Simulink model. The PID parameters kp_1, ki_1, kd_1 and kp_2, ki_2, kd_2 are selected from the hybrid GWO-PSO algorithm. The simulation time for running the model is kept as 1,000 sec so that we can observe the complete response till the water level reaches to steady state.

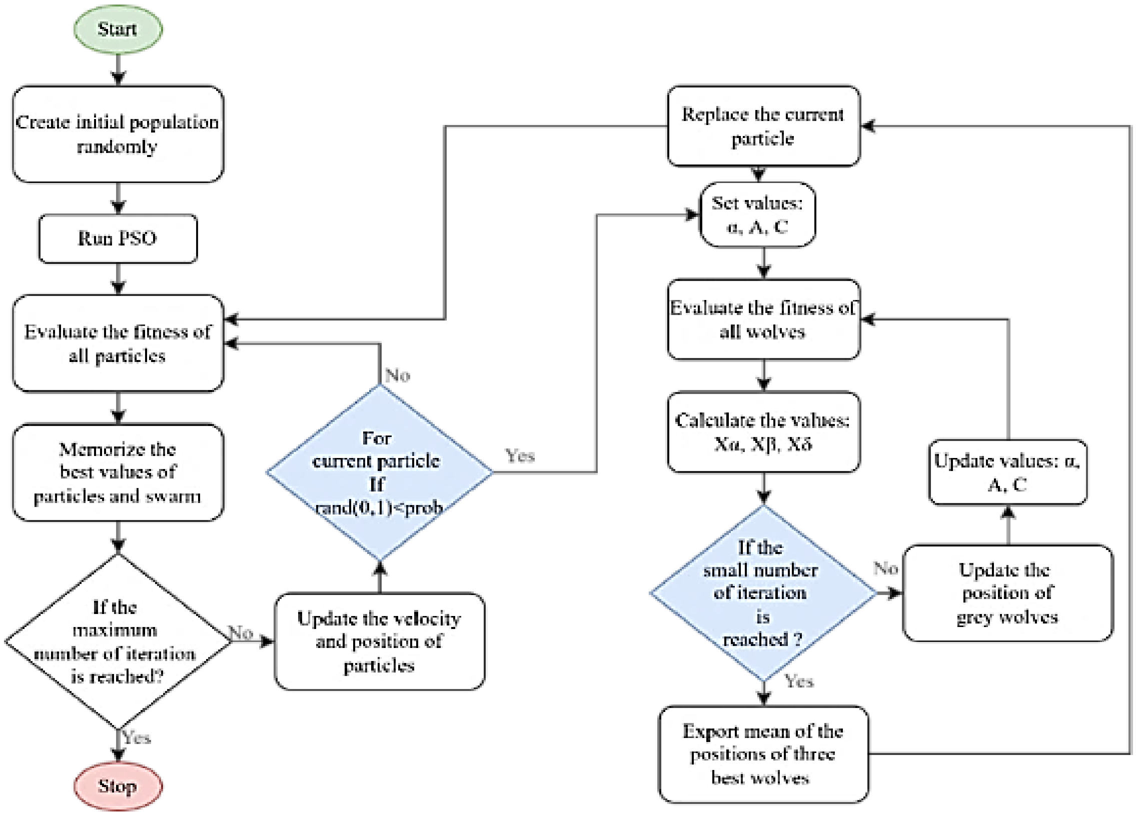
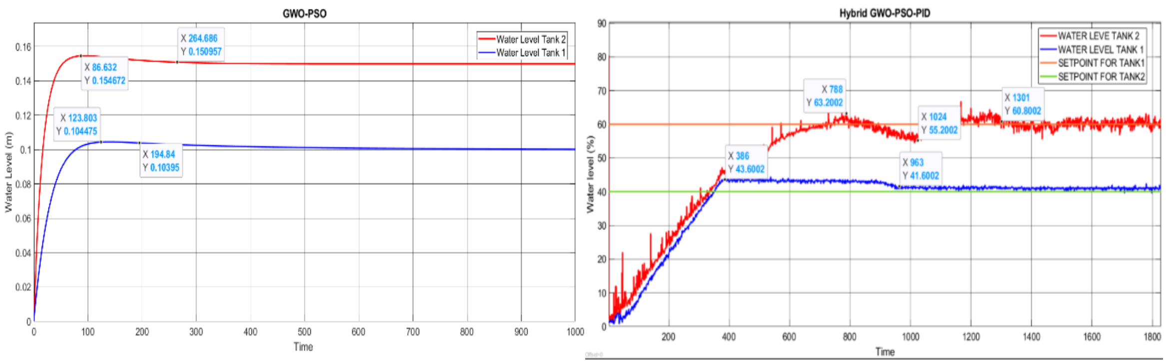


Figure 8. Flowchart for the working of hybrid GWO-PSO algorithm

Water level response for simulation and hardware using hybrid GWO-PSO optimization is shown in Figure 9. The water level response for hybrid GWO-PSO optimization using simulation is shown in Figure 9(a). The set level for tank 1 is 0.1 m which is 40% while that for tank 2 is 0.15 m which is 60%. The overshoot can be observed in water level response of both the tanks. Improved settling time in both the tanks can be observed. The performance comparison using various optimization techniques through simulation and experimentation can be found in the next section.

Hardware responses of hybrid GWO-PSO-PID optimization are shown in Figure 9(b). Overshoot is reduced and settling time is also improved. The number of search agents in GWO are increased for exploring the global minimum value for ISE and velocity of particles to reach has been updated by PSO which is depicted in the response. Hybridization algorithm is however easy to implement but the running time for process is increased.



(a) (b)

Figure 9. Response for water level control in coupled tanks using hybrid GWO-PSO-PID controller for (a) simulation and (b) hardware

7. PERFORMANCE ANALYSIS AND DISCUSSION

Performance analysis of optimization tools typically involves assessing several key aspects to evaluate their effectiveness and efficiency. The performance analysis is carried out based on some physical parameters like % overshoot, settling time and offset. To make an informed choice, it's essential to compare the performance of different optimization tools. This comparison can involve benchmarking against other well-established tools or using standard test problems to assess their relative strengths and weaknesses.

Set points selected for tank 1 and tank 2 are 40% and 60% respectively for comparison and validation purpose. Table 1 shows the observations noted during simulation and hardware experimentation of the system for the various optimization tools. PID controller without optimization shows higher % overshoot along with the settling time [26]. The settling time is also more. As discussed earlier, PSO shows overshoot of 6.6% in tank 1 which is less but the settling time is 280 sec which is little high. GWO has a settling time of 246 sec in tank 1 which is the best amongst all the optimization tools, but the overshoot is 17.3% which is better than the other optimization techniques. Hybrid GWO-PSO based PID has an overshoot of 4.4% and settling time is 194 sec which is good and desirable. Hardware experimentation results are in close agreement with the simulation results. Thus, hybrid GWO-PSO based PID performs better as compared to the PID controller using the other optimization tools.

Table 1. Performance analysis of simulation and hardware results

Controller with the Optimization tool	Tank no.	Simulation results						Hardware results			
		SP		Overshoot		Settling time (sec)	Offset (m)	Overshoot		Settling time (sec)	Offset (m)
		%	m	m	%			m	%		
PID	Tank 1	40	0.1	0.0291	29.1	405	0	0.0290	29.0	415.4	0
	Tank 2	60	0.150	0.0296	19.7	413	0	0.0260	17.3	513.2	0
PSO-PID	Tank 1	40	0.1	0.0066	6.6	280	0	0.0098	9.8	253.8	0
	Tank 2	60	0.150	0.0000	0.0	295	0	0.0136	9.1	294.6	0.0038
GWO-PID	Tank 1	40	0.1	0.0173	17.3	246	0	0.0056	5.6	206.2	0
	Tank 2	60	0.150	0.0000	0.0	290	0	0.0136	9.1	299.8	0
Hybrid GWO-PSO-PID	Tank 1	40	0.1	0.0044	4.4	194	0	0.0090	9.0	192.6	0
	Tank 2	60	0.150	0.0046	3.1	264	0	0.0080	5.3	260.2	0

8. CONCLUSION

In this paper, hybrid GWO-PSO based algorithm is found to be implemented for optimization of PID controller to control level of water in the coupled tanks. The simulation is carried out using the mathematical model developed for the coupled tanks using MATLAB. The hardware experimentation is carried out with the help of Arduino Uno as the interfacing medium between the MATLAB and hardware and the responses are observed. ISE is chosen as a performance index because of its tendency to focus on large errors giving the optimized results. Various optimization techniques such as genetic algorithm, ant colony, PSO, and GWO. are available and found in the literature. However, as per the literature survey, PSO and GWO are best suited for process control system and hence used in this paper. PSO is selected for the optimization purpose because it performs better in reducing the overshoot and GWO shows better results in improving the settling time. Since PSO is found to be trapped into the local minimum, hybridization of GWO and PSO is carried out so as to gain the advantages of both PSO and GWO. The experimental results demonstrate the validation of the proposed optimization techniques.

Performance index ISE is found to be minimized considerably when PID parameters are perfectly tuned using PSO and GWO, which can also be seen in the responses as well. Number of iterations, number of particles (in PSO) and number of search agents (in GWO) are updated frequently for obtaining the optimal solution. Proposed methodology is beneficial in pharmaceutical and chemical industries that require water level control in coupled tank reactors for processing hypochlorite solution and dichlorobenzene.

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BIOGRAPHIES OF AUTHORS

Hafiz Shaikh received M.E. degree in electrical engineering from Savitribai Phule Pune University, Maharashtra, India, in 2008. Currently pursuing Ph.D. in electrical engineering (Control Systems) in Savitribai Phule Pune University, Maharashtra, India. His research interests include fuzzy logic controller, and optimization of PID. He has published research papers in international conferences. He can be contacted at email: hafizshaikh815@gmail.com.

Neelima R. Kulkarni graduated in Electrical Engineering from Walchand College of Engineering, Sangli, Maharashtra, India in 1985. Post graduated from COEP, Pune in 1998. She completed her Ph.D. in Electrical Engineering in 2011. She has total teaching Experience of 38 years. Her area of interest is control system, renewable energy and power electronics and drives. She has published total 73 research papers out of which 33 International Journals, 11 International Conferences and 29 National Conferences and Journals are in her contribution. She can be contacted at email: nrkmcoe@gmail.com.

Mayuresh V. Bakshi completed Ph.D. from IIT Bombay in 2017. He is presently working as an assistant professor in Electrical Engineering at Vishwakarma Institute of Information Technology, Pune. He has a teaching experience of around 23 years. He has authored books on control system, power system and Electrical machines for various universities across India. His research interests include robust stabilization and H-infinity control applicable to electrical circuits and networks. He has presented and published papers in reputed international conferences and journals. He can be contacted at email: bakshi.mayuresh@gmail.com.