CLEI electronic journal, Volume 26, Number 2, Paper 7 , September 2023

Mathematical Modeling of coupled tank interacting system for controlling water level using GWO and PSO optimization

Hafiz M. Shaikh, Neelima R. Kulkarni
PES Modern College of Engineering,
Pune, Maharashtra State, India.
hafizshaikh815@gmail.com, nrkmcoe@gmail.com

and

Mayuresh V. Bakshi
Vishwakarma Institute of Information and Technology,
Pune, Maharashtra State, India.
bakshi.mayuresh@gmail.com

Abstract

In bulk drug production industries maintaining the water level at a precise point is a major challenge. Loss in production at the initial stage is observed until the water level reaches desired level. Pharmaceutical industries can however earn more profit if they could maintain precise water level control at the initial stage of production. Industries using Proportional-Integral-Derivative (PID) controller for water level control in coupled tank interacting system, many a times, fails to provide the desired response in an optimized manner. To synchronize the water level precisely with best performance parameters, the work presented in this paper introduces the implementation of Particle Swarm Optimization (PSO) and Grey Wolf Optimization (GWO). By determining the mathematical model, the method for water level control in the coupled tank MIMO system may be accomplished. The prior step for implementing any control strategy is system identification. This can be processed by analyzing the actual parameters of the coupled tank. State-space analysis of coupled tanks is explained in detail along with its conversion into transfer function. In this paper, the inherent parameters required for the calculation are discussed. MATLAB is used as the platform for observing the responses. Observations from the literature review on PID controller articulate that, there is a need for a better controller to enhance the performance using the optimization techniques. Performance analysis of PSO and GWO for water level control in coupled tank interacting system based on the simulation and hardware results is conferred in this paper.

Keywords: Arithmetic Model, Coupled Tank, GWO, Optimization, PSO, PID Controller.

1 Introduction

The elucidation or explanation of physical systems is critical in the study of certain chemical or pharmaceutical procedures. According to a survey, many pharmaceutical industries use manual methods for observing and controlling water levels in the tanks. It is desirable in case of boilers and reactors to maintain the water level as closely as possible to the set value. In case of the applications such as production of hypochlorite, requirement of an adequate amount of water is very important which can be ensured by maintaining the appropriate level in the tank.

The level control systems normally consist 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]. The mathematical modelling is the first step in developing a suitable control for the tank system, which includes the transfer function of bridged tank interacting system. A first order transfer function is used in the single container level control system. It is observed that a transfer function as that of bridged tank interacting system is not the result of two first order transfer functions as it is in the case of non-interacting system. Further, 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 [4], [19]. However, rectangular shaped tanks are not predominantly considered in interactive tank systems [2]. An ARM7TDMI microprocessor manages the level in the non-interacting bridged tank system [5]. Genetic algorithm and Ant colony optimization makes lot of iterations, and the system becomes a bit slow [3]. Meta heuristic techniques are used for process control application [21].

Particle swarm optimization (PSO) is used for optimization of PID parameters to control water level in coupled tank interactive system [28]. PSO has some demerits when it comes to global optimization as it gets trapped into the local minima and does not reach global optimum value. Grey wolf optimization (GWO) is another meta heuristic algorithm which behaves aggressively based on the hunting behaviour of grey wolves [24]. GWO tries to eliminate to demerits of PSO and provides the global optimization in the early iterations.

1.1 Research gaps with key observations based on literature review

Research gaps along with the key observations are presented in this subsection. From the literature survey, it is suggested to optimize the conventional PID controller such that the responses are more precise [6]. For a fixed set point control , a conventional PID controller can attain the level precisely but in the systems, where the set point changes at diverse levels some other type of controller is required.[7].

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 flow in the tank [8] that can change the level in the tank. Further, it is required that the human observation for level measurement must be replaced with a suitably designed controller for which an arithmetic model of the interactive container system is available [9].

Once an arithmetic prototype of the system is ready, different control strategies can be applied[10]. From the literature it can be found that, most of the coupled tank liquid level systems predominantly utilize a linear mathematical prototype to outline controllers of various types such as a PID controller. The PID controllers are commonly found in pharmaceutical and chemical industries [11]. Fuzzy logic controller is also found to be used for water level control in a single input single output (SISO) tank system [12], [13], [14]. For a constant set point of water level, fuzzy logic controller gives satisfactory response but for the applications where the variation in set point is required, fuzzy logic controller fails to provide appropriate results. Range of membership functions and fuzzy rules need to be perfectly defined for achieving a fair degree of accuracy [15], [16], [17]. Furthermore, PID controller may not be able to provide the enhanced performance in most instances when employed in coupled tank interacting type systems thus necessitating the use of meta heuristic tuning methods through application of various optimization techniques.

1.2 Main contribution and organisation of the paper

The main contribution of this paper is the development of GWO and PSO for optimization of PID parameters in order to achieve better response from the coupled tank system. The performance of the system is analysed through the simulation. The implementation of GWO algorithm for optimizing the PID parameters for coupled tank interactive system is the novelty of this paper. A comprehensive performance analysis of both the optimization techniques is presented which helps in deciding the particular optimization technique based on the application.

The organisation of this paper is as follows. Section 2 depicts the schematic as well as the actual hardware of bridged containers along with the development of its arithmetic model. The description of experimental setup and hardware configuration about the system can be found in section 3. GWO algorithm methodology and its working along with responses is illustrated in section 4. Implementation of PSO algorithm with its responses is presented in section 5. Section 6 explains about overall performance analysis of all the optimization techniques used followed by the conclusion in Section 7.

2 Coupled Tank System representation

Coupled tank interacting system consists of 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' inlets. A valve regulates the output flow from each of the two tanks. Figure 1 shows a schematic representation of the system.

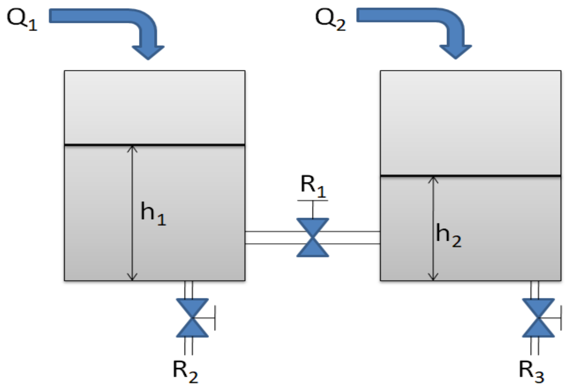

Figure 1: Coupled tanks are depicted schematically.

The system is made up of two rectangular-shaped tanks that are connected to each other. Table 1 lists the specifications for these two tanks.

Table 1: Physical Specifications of Coupled Tanks

Parameter	Quantity
Volume of each tank	6 lit
Length of tank	0.13m
Width of tank	0.13m
Height of tank	0.35m
Hydraulic Resistance of valve	$15552 sec/m^2$

The water flow into tanks 1 and 2 is depicted respectively by Q_1 and Q_2. The level of water in the two tanks is displayed by h_1 and h_2 respectively. The discharge coefficients of the exit valves for the two tanks are represented by R_2 and R_3. R_1 is the discharge coefficient which corresponds to the course of water along the two coupled tanks. Due to the link connecting them, the coupled tanks function in an interactive way. This interacting link is controlled by valve R_1.

2.1 Arithmetic model derivation

Mathematical modelling of the two tank interactive liquid level control system can be found in the literature [1]and [4]. Determination and domineering of water level in coupled tank interacting system has many complexities. A mathematical model aids in regulation of water level in the two tanks by suitably designing a controller. The dynamics involved in the coupled tank MIMO system can be expressed by constructing differential equations for both of these tanks and the further analysis is then carried out.

Bernoulli's mass balance theory facilitates to write the differential equation representing the system dynamics. The basic concept behind this theory is inflow minus outflow during a small interval of time 'dt' is same compared with the amount saved inside the tank. According to the above theory, the differential equations are given by equations 1 and 2 as below.
For Tank 1:

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

For Tank 2:

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

Where,
a_1 = Area of tank 1 (m^2)
a_2 = Area of tank 2 (m^2)
h_1 = Height of water level in tank 1 (m)
h_2 = Height of water level in tank 2 (m)
Q_1 = Water flow in tank 1 (m^3/sec)

Q_2 = Water flow in tank 2 (m^3/sec)
R_3 = Discharge coefficient of interaction link (sec/m^2)

3 Experimental Setup and Hardware configuration

Manual observation of the water level by observing flow through the rota-meter is practiced in pharmaceutical industries. This results in generation of error while water level control which ultimately results in loss of production. To resolve this problem, a suitable sensor along with a controller is essential. A prototype of such a system is used here for experimentation consisting of coupled tanks each of 6 litres.

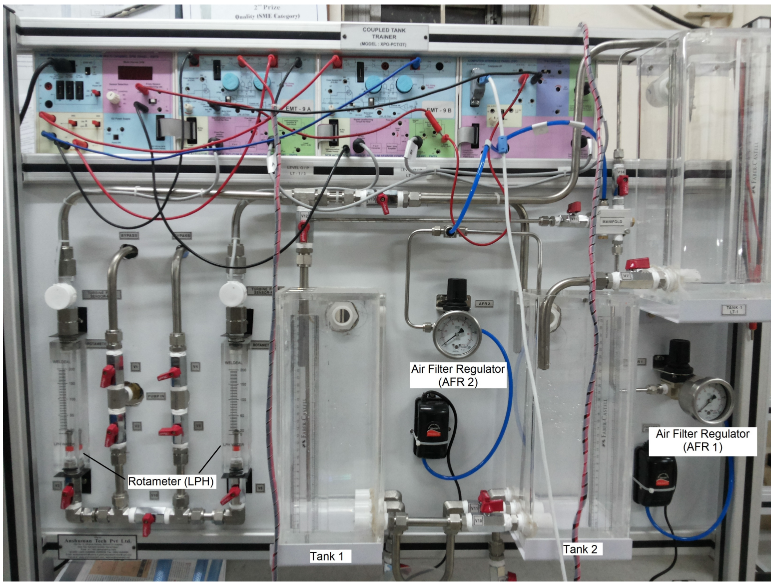

Figure 2: Actual hardware image of coupled tanks.

Figure 2 displays the photograph of a coupled tank system showing the hardware details. Three tanks are positioned on the panel, of which the lower two are connected together and are used for the experiments. An interacting link is present between these two tanks. The water level inside the tank is gauged by the bubbler method. In this method, an air bubble is lodged inside water and pressure of air bubble over the surface of water is calibrated in terms of voltage ranging from 0 to 2.5 V. Air filter Regulators are mounted to maintain air pressure up to 1 psi.

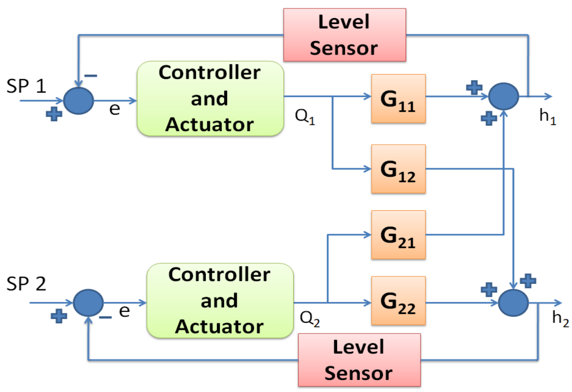

Figure 3: Block diagram representation of two tank interactive liquid level control system

To understand the actual working of water level control in coupled tank system, a block diagram is shown in figure 3. The area of tank 1 and tank 2 is same denoted by a_1 and a_2 and its value is 0.0169 m^2. The value of discharge coefficient R_2 and R_3 is 15552 sec/m^2 while that of R_1 is 7776 sec/m^2.

Programming and the use of MATLAB commands can be used to get the transfer function of coupled tank from the state-space equation. MATLAB programming makes it convenient to compute the complex transfer function matrix easily. The four transfer functions are represented in equations 3, 4, 5 and 6

$$G_{11} = \frac{59.17s + 0.6754}{s^2 + 0.02283s + 0.00007238} \tag{3}$$

$$G_{12} = \frac{0.4503}{s^2 + 0.02283s + 0.00007238} \tag{4}$$

$$G_{21} = \frac{0.4503}{s^2 + 0.02283s + 0.00007238} \tag{5}$$

$$G_{22} = \frac{59.17s + 0.6754}{s^2 + 0.02283s + 0.00007238} \tag{6}$$

Transfer functions calculated are used further for designing the control mechanism based on optimization technique. Water level (h_1) and (h_2) is obtained from the four transfer functions which is further sensed calculation error and generating control signal.

3.1 Interfacing of software and hardware using Arduino UNO

The coupled tank hardware configuration is connected to the MATLAB software by interfacing it through Arduino UNO 328P. The circuit diagram of the connection is given in the figure 4. Ground signal for the

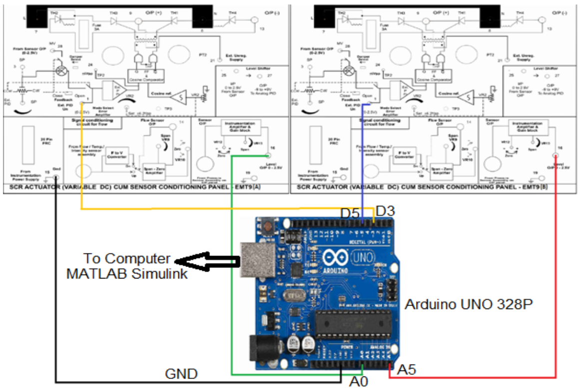

Figure 4: Arduino UNO 328P interfacing with Hardware and Software

Arduino UNO is taken from the EMT 9 (A) panel. Green and yellow lines connected to the EMT 9 (A) panel are used for tank 1 whereas blue and red lines are connected to EMT 9 (B) panel are used for tank 2. Simulink model above shows interfacing of Arduino UNO with the coupled tank system. Two analog input blocks A0 and A5 are used which collect the measured value of level from pin number 16 on EMT 9 (A) and (B) panel. Two PWM digital output blocks D3 and D5 are used which sends the control signal generated by the GWO-PID controller to pin number 1 on EMT 9 (A) and (B) panel.

4 Grey Wolf Optimization (GWO)

GWO is implemented with respect to hunting behaviour of the grey wolves in a pack [18]. Leader in pack dominates the group and finds the most optimized path for hunting the prey. It is a meta heuristic technique which can be used for optimization of PID parameters [19]. Exploration ability of GWO is excellent and it finds the optimal level of the objective function during the earlier search. The objective function can be the performance index which is the main control objective also. Integral square error (ISE) is selected as the performance index which is considered as the objective function in GWO algorithm. Four number of search agents and five iterations gives the desired response for water level control.

4.1 PID tuning based on Grey Wolf Optimization (GWO-PID)

Alpha is a leader of the pack as per the hierarchy shown in figure 5. The best possible path is enlightened by the alpha wolf. The next commander after alpha wolf is beta wolf, which holds the command. Delta and omega wolves are the subordinates in the pack. Without getting stuck in an early convergence, GWO algorithm conspicuously finds the optimal solution. GWO algorithm is explained using a flowchart in figure 6.

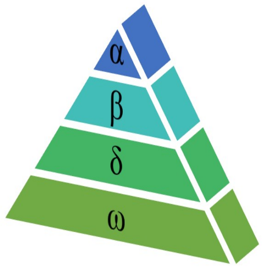

Figure 5: Hierarchical order of Grey Wolves Pack

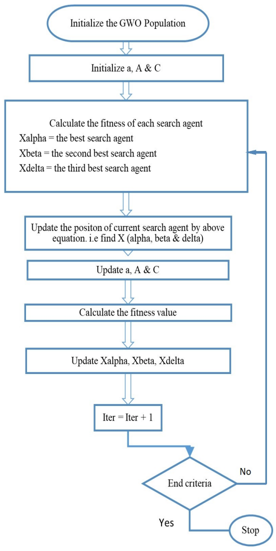

Figure 6: Flowchart showing working of algorithm of GWO

4.2 Arithmetic Model of GWO

Encircling and hunting behaviour of the grey wolves can be arithmetically derived in order to optimize PID controller parameters. The distance or the optimized path between the prey and wolf is found utilizing the following expression:

$$\vec{D} = \left| \vec{C}\vec{X_p}(t) - \vec{X(t)} \right| \tag{7}$$

$$\vec{X}(t+1) = \vec{X_p}(t) - \vec{A}\vec{D} \tag{8}$$

$$\vec{A} = 2\vec{a}.\vec{r_1} - \vec{a} \tag{9}$$

$$\vec{C} = 2\vec{r_2} \tag{10}$$

Grey wolves identify the prey's location for hunting after encircling it. Alpha being the leader of the pack, takes the initiative and commands the pack for hunting. Alpha has the best solution about the position of the prey. Beta and delta also contribute to transferring their best solution for better hunting. These three wolves update their positions and indulge other search agents (containing omega) to revise their own positions. Mathematical expressions for the same are given below:

$$\vec{D_\alpha} = \left| \vec{C_1}\vec{X_\alpha} - \vec{X} \right| \tag{11}$$

$$\vec{D_\beta} = \left| \vec{C_2}\vec{X_\beta} - \vec{X} \right| \tag{12}$$

$$\vec{D_\delta} = \left| \vec{C_3}\vec{X_\delta} - \vec{X} \right| \tag{13}$$

$$\vec{X_1} = \vec{X_\alpha} - \vec{A_1}.(\vec{D}\alpha) \tag{14}$$

$$\vec{X_2} = \vec{X_\beta} - \vec{A_2}.(\vec{D}\beta) \tag{15}$$

$$\vec{X_3} = \vec{X_\delta} - \vec{A_3}.(\vec{D}\delta) \tag{16}$$

$$\vec{X}(t+1) = \frac{\vec{X_1} + \vec{X_2} + \vec{X_3}}{3} \tag{17}$$

Nomenclature used in the mathematical expressions for GWO are shown in table 2

Table 2: GWO Nomenclature used in the expressions

GWO Variables	Terminology
$\vec{D}$	Distance between prey and wolf
$\vec{C}$,$\vec{A}$	Coefficient vectors
$\vec{X_p}(t)$	Current position of the prey
$\vec{X(t)}$	Current position of the wolf
T	Current number of iterations
$\vec{a}$	Linearly decreasing (2 to 0) coefficient vector
$\vec{r_1}$, $\vec{r_2}$	Random vectors in range [1,0]
X_α, X_β, X_δ	Current position of α, β, δ
X_1, X_2, X_3	Updated location of wolves
$\vec{X}(t+1)$	Mean of the updated position

The GWO variables and terminologies shown in table 2 are used in GWO algorithm code written in MATLAB script. MATLAB simulink is embedded with GWO code script which comprises of all the GWO parameters are set and their values are shown in table 3. Upper bound and lower bound values shown in

Table 3: GWO parameters and their values

GWO parameters	Values
Number of search agents	4
Upper bound	[5 0.05 1.5 4 0.035 1.515]
Lower bound	[0.1 0.01 0.001 0.1 0.01 0.001]
Maximum iteration value	5

table 3 are derived after experimenting the conventional PID controller independently on the coupled tank system. As compared with genetic algorithm which requires lot of iterations [20], GWO gives optimized results in five iterations.

4.3 Simulation of PID controller using GWO for coupled tank system

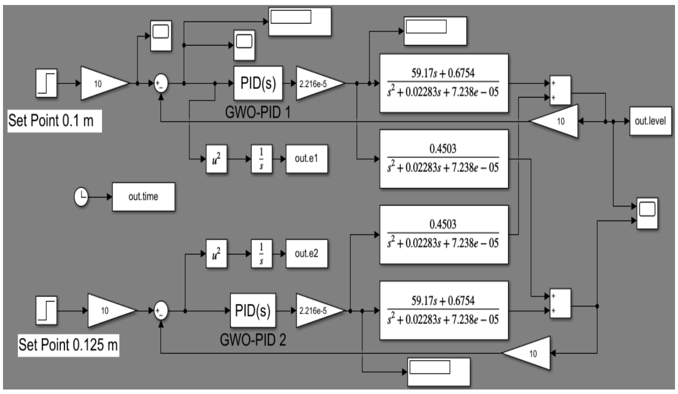

Figure 7: Simulink model for water level control in coupled tanks using GWO-PID controller

With reference to Simulink model shown in figure 7, (ISE) integral square error is computed and given as the input signal to the PID controller whose PID parameters are optimized by GWO. Performance index is ISE. ISE is the prey ($\vec{X_p}$) which needs to be minimized or killed. Every PID parameter has 4 search agents which update their positions (Kp, Ki and Kd values) 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 proportion in the tanks.

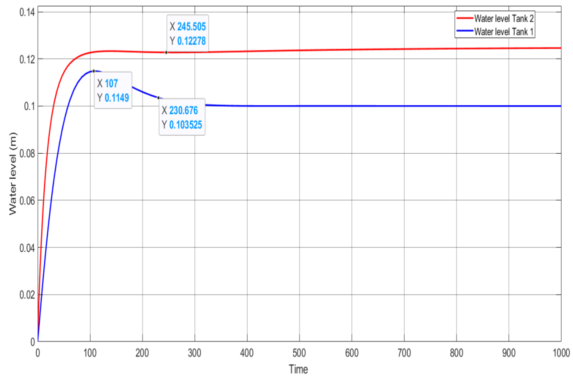

Figure 8: Simulation Response for water level control in coupled tanks using GWO-PID controller

The simulation response shown in the figure 8 illustrates water level using GWO-PID optimization technique. The %Overshoot for tank 1 level is noticeable. The settling time is however reduced.

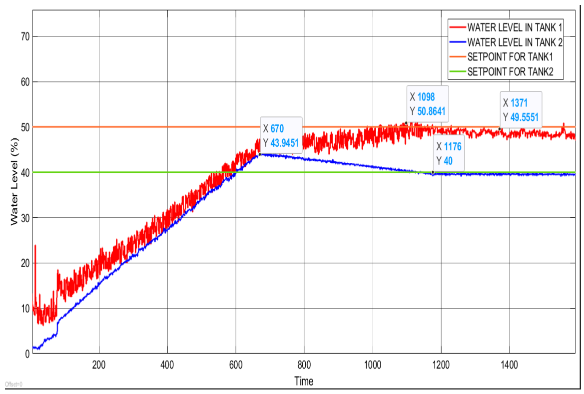

Figure 9: Hardware Response for water level control in coupled tanks using GWO-PID controller

The hardware response for water level control using GWO-PID optimization is shown in figure 9. The %Overshoot more than that of the PSO-PID optimization. Settling time is observed to be minimized as compared with PSO-PID water level response.

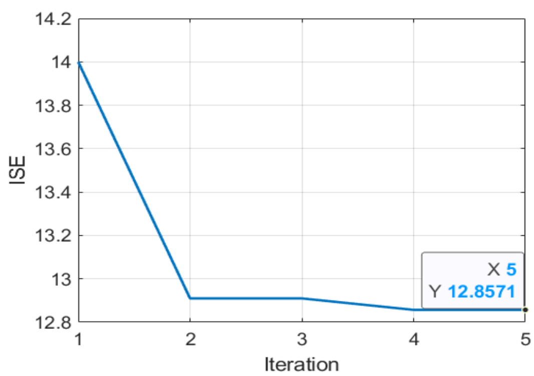

Figure 10: ISE response across iterations for GWO

The value of ISE decreases as the iteration increases. The value for fifth iteration is 12.85 which is less than that obtained in PSO-PID optimization. The response for ISE vs Iteration is given in figure 10.

5 Particle swarm optimization

In optimization problem search space, each particle will have position. 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.

For particle 'i' the location of particle is depicted by 'x'_i. This vector belongs to the search space indicated by 'x'. Time index is included to this place, denoted by x(i), in order to differentiate between time steps (t). "i" provides the particle index, while "x" gives the location vector. Every particle has a velocity in contrast to a location, which is indicated by the symbol "vi(t)". The motion of particle "i" is expressed by its velocity in terms of its direction, distance, and step size. 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. Every particle's location and velocity are changed using this straightforward process during each PSO iteration. In tank 1, the set point is 0.125m whereas for tank 2 it is 0.1m.

5.1 Particle Swarm Optimization: Parameters and values

Initial parameters of PSO include number of variables, upper bound value, lower bound value, defining objective function, settling number of particles, maximum iteration value, maximum and minimum values of weight and acceleration coefficient. The table 4 displays all the values utilised in the PSO algorithm:

Table 4: PSO Parameters and their values

PSO parameters	Values (before optimization)	Values (after optimization)
Number of variables	3	6
Upper bound	[2.5 0.014 0]	[3.6 0.023 0.00035 1.2 0.007 0.003]
Lower bound	[0 0 -3.5]	[0 0 -3.5 0 0 -0.556
Number of particles	30	30
Maximum iteration value	20	5
Maximum value of weight	0.9	0.9
Minimum value of weight	0.2	0.2
Acceleration coefficient	2	2

Initially number of particles are decided first before starting with the PSO optimization. Around 30 particles for each parameter are selected. There are 3 PID parameters which are to be manipulated to optimize the objective function. The objective function to be optimized here is Integral square error (ISE). To achieve the desired result, the integral square error must be reduced. ISE is selected because it reduces the maximum as well as minimal valued error and focus on it. After testing the system using conventional PID controller, the upper bound and lower bound parameters of the PID parameters are chosen. The values of PID parameters get updated based on the PSO process. For the first experiment maximum iteration value was selected as 20, which can be changed as per the accuracy and time span is desired. Maximum and minimum of weight is 0.9 and 0.2 respectively. Acceleration coefficient is 2.

5.2 Implementation of PSO-PID in simulation

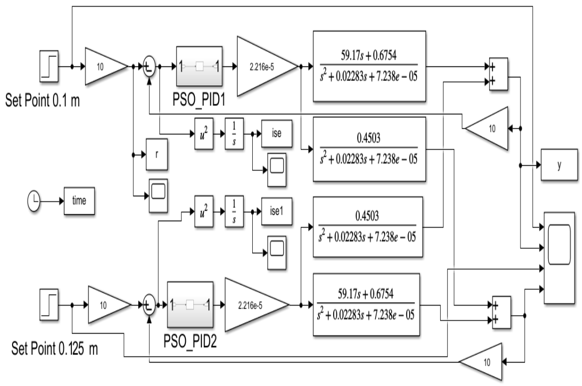

Figure 11: PSO-PID controller model for coupled tank systems in Simulink

As shown in figure 11, coupled tank water level control utilising a PSO-PID controller is simulated. The algorithm for PSO is embedded in PSO-PID block which gets executed after running the model. The simulation runs for 20 number of iterations and then it stops. Reference input and water level output signals are sent to the workspace as time series variables ‘r’ and ‘y’ respectively. (ISE) Integral square error is computed inside the algorithm and set as the objective function. Pbest and Gbest continuously get updated according to the present value of ISE reported. PID parameters get tuned automatically till 20 iterations are completed.

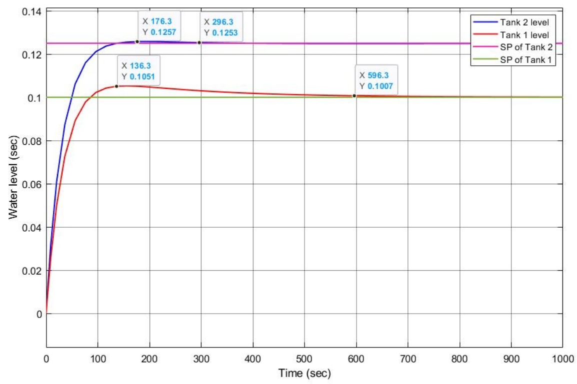

Figure 12: Initial Step response of the water level in coupled tanks using a PSO-PID controller

Water level response of coupled tanks utilizing PSO- PID controller has been displayed figure 12. 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 present which is very less. The amount of weights and cycles can be increased in order to further reduce this overshoot. Increasing number of iterations will however result in making the system slow. After certain number of experimentation, 5 iterations were found to be optimal for the system. Interaction effect is seen in the response of tank 2.

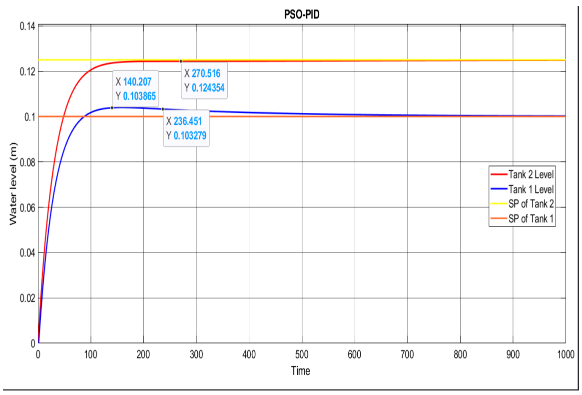

Figure 13: Optimised response of water level in coupled tanks using PSO-PID controller

Improvement in the response can be observed in figure 13, it is the consequence of optimization in PSO algorithm. Number of iterations are also reduced as a result. PID range for both controllers should be properly implemented to get best response. Inside tank 2, water level shows some overshoot, but it is little bit reduced as compared to the response shown in figure 12.

Hardware responses for water level control using PSO PID controller is shown in figure 14. This response is almost equivalent to the simulation response shown in figure 13. The time in hardware response is in samples. For conversion of this sampled time into seconds it should be multiplied with 0.2. As 5 samples are collected in 1 sec hence the sampled time is multiplied with 1/5 (that is 0.2 sec).

The objective function used in optimization algorithm is integral square error (ISE). The value of ISE decreases as the iteration increases. The value for fifth iteration is 17.7 which is more than that obtained in GWO-PID optimization. The response for ISE vs Iteration is given in figure 15.

6 Performance analysis and discussion

The optimization techniques are implemented on the actual hardware setup and responses are recorded. The comparison of both simulation and hardware results can be done based on the analysis of its performance

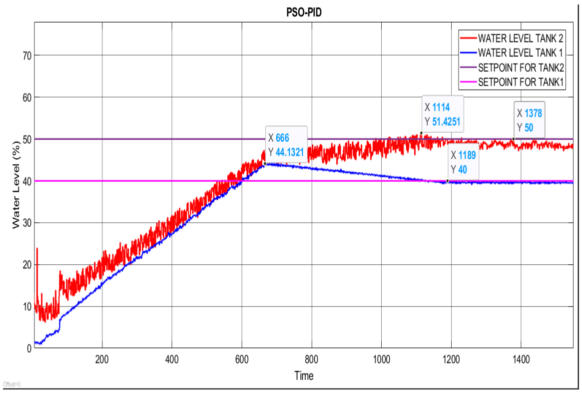

Figure 14: Hardware response of water level in coupled tanks using PSO-PID controller

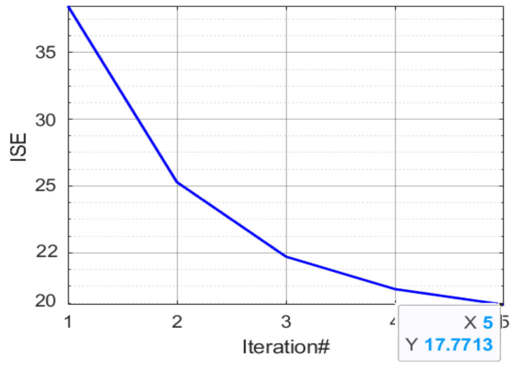

Figure 15: ISE response across iterations for PSO

parameters like % Overshoot, %Undershoot, Settling time (sec) and Offset (m). Validation of simulation software results and hardware results is done in table 5 and 6.

Table 5: Software Performance parameters of PSO-PID and GWO-PID

	PSO-PID		GWO-PID	
Performance Parameters	Tank 1	Tank 2	Tank 1	Tank 2
%Overshoot	3.8	0	14.9	0
%Undershoot	0	0	0	0
Settling time (sec)	236	270	230	245
Offset (m)	0	0	0	0

The simulation results are shown in table 5. %Overshoot using PSO-PID optimization is less as compared to GWO-PID optimization. %Undershoot and offset are zero. Settling time in case of PSO-PID optimization is more than GWO-PID optimization.

The hardware results shown in table 6 are similar to that of simulation results shown in table 5. %Overshoot can be reduced by using PSO-PID optimization but the settling time gets affected. Whereas in GWO-PID optimization settling time seems to be improved but % overshoot is more. PSO algorithm gets trapped in to the local minima and does not reach global best values in terms of performance index which is the reason for not getting settling time improved.

GWO algorithm on the other hand has the best exploration ability to reach global best value for performance index and gives improved result in terms of settling time. The comparative analysis of ISE for PSO-PID and GWO-PID is shown in table 7.

Table 6: Hardware Performance parameters of PSO-PID and GWO-PID

	PSO-PID		GWO-PID	
Performance Parameters	Tank 1	Tank 2	Tank 1	Tank 2
%Overshoot	10	2.8	9.8	1.7
%Undershoot	0	0	0	0
Settling time (sec)	237.8	275.6	235.2	274.2
Offset (m)	0	0	0	0

Table 7: Comparative analysis of Performance Indices

Performance Index	PSO-PID	GWO-PID
Integral Square Error (ISE)	17.77	12.85

7 Conclusion

Production loss in pharmaceutical industries could be overcome by implementation of optimization tools to the conventional systems incorporating PID controller. Minimization of objective function (ISE) was experimented by implementing PSO and GWO on PID controller. Performance Index ISE was minimized considerably when PID parameters were perfectly manipulated using PSO and GWO, which can be seen in the responses as well. Number of iterations, number of particles (in PSO) and number of search agents (in GWO) were updated frequently for obtaining the optimal solution. The simulation results and hardware results obtained after experimentation are similar and hence it can be claimed that PSO and GWO can be used for real time applications in industries where PID controller are conventionally used. The applications where overshoot is not permitted should go with PSO and application who require fast settling time should go with GWO. The constraints considered for finding optimal solution are overshoot, undershoot and settling time. A hybrid combination of PSO with GWO for tuning PID parameters can be experimented for getting benefits of both PSO and GWO which may result in possible improvement of water level response.

References

[1] Mircea Dulau and Tudor-Mircea Dulau *Multivariable System with Level Control*, 9th International Conference Interdisciplinarity in Engineering, INTER-ENG 2015.

[2] Meenakshi Sharma, Pallavi Varma and Lini Mathew *Design and Intelligent controller for a process control system*, ICICCS, 2016.

[3] Evelia Lizárraga Olivas, et.al. *Ant Colony Optimization for Membership function Design for a water tank fuzzy logic controller*, IEEE Workshop on Hybrid Intelligent Models and Applications (HIMA), 2013.

[4] Deepa P. and Sivakumar R *Synthesis of Heuristic control Strategies for liquid level control in spherical tank*, IEEE 2017.

[5] Ronnapop Jaisue, Jutarut Chaoraingern, Vittaya Tipsuwanporn and Arjin Numsomran, Phayupp Pholkeaw *A Design of Fuzzy PID Controller based on ARM7TDMI for coupled-tank Process*, 12th International conference on control, Automation and Systems 2012.

[6] X. Fang, T. Shen, X. Wang, and Z. Zhou, "Application and research of fuzzy PID in tank systems," Proc. - 4th Int. Conf. Nat. Comput. ICNC 2008, vol. 4, pp. 326–330, 2008, doi: 10.1109/ICNC.2008.293.

[7] M. Dulău and T.-M. Dulău, "Multivariable System with Level Control," Procedia Technol., vol. 22, no. October 2015, pp. 614–622, 2016, doi: 10.1016/j.protcy.2016.01.128.

[8] E. L. Olivas, O. Castillo, F. Valdez, and J. Soria, "Ant colony optimization for membership function design for a water tank fuzzy logic controller," Proc. 2013 IEEE Work. Hybrid Intell. Model. Appl. HIMA 2013 - 2013 IEEE Symp. Ser. Comput. Intell. SSCI 2013, pp. 27–

[9] P. Deepa and R. Sivakumar, "Synthesis of heuristic control strategies for liquid level control in spherical tank," Proc. 3rd IEEE Int. Conf. Adv. Electr. Electron. Information, Commun. Bio-Informatics, AEEICB 2017, no. 10, pp. 316–319, 2017, doi: 10.1109/AEEICB.2017.7972323.

[10] R. Jaisue, J. Chaoraingern, V. Tipsuwanporn, A. Numsomran, and P. Pholkeaw, A design of fuzzy PID controller based on ARM7TDMI for coupled-tanks process. 2012.

[11] C. Pornpatkul and T. Suksri, "Decentralized fuzzy logic controller for TITO coupled-tank process," ICCAS-SICE 2009 - ICROS-SICE Int. Jt. Conf. 2009, Proc., vol. 2, pp. 2862–2866, 2009.

[12] S. Krivić, M. Hujdur, A. Mrzić, and S. Konjicija, "Design and implementation of fuzzy controller on embedded computer for water level control," MIPRO 2012 - 35th Int. Conv. Inf. Commun. Technol. Electron. Microelectron. - Proc., pp. 1747–1751, 2012.

[13] S. B. Prusty, U. C. Pati, and K. Mahapatra, "Implementation of fuzzy-PID controller to liquid level system using LabVIEW," Int. Conf. Control. Instrumentation, Energy Commun. CIEC 2014, pp. 36–40, 2014, doi: 10.1109/CIEC.2014.6959045.

[14] L. Mastacan and C. C. Dosoftei, "Level fuzzy control of three-tank system," Proc. - 19th Int. Conf. Control Syst. Comput. Sci. CSCS 2013, no. 1, pp. 30–35, 2013, doi: 10.1109/CSCS.2013.36.

[15] P. Manikandan, M. Geetha, T. K. Vijaya, K. S. Elamurugan, and V. Silambarasan, "Real-time implementation and performance analysis of an intelligent fuzzy logic controller for level process," 2013 4th Int. Conf. Comput. Commun. Netw. Technol. ICCCNT 2013, pp. 2–7, 2013, doi: 10.1109/ICCCNT.2013.6726640.

[16] S. W. He, C. Liu, Z. Song, and Z. Wang, "Real-time intelligent control of liquid level system based on MCGS and MATLAB," Proc. - Int. Conf. Mach. Learn. Cybern., vol. 1, pp. 131–136, 2014, doi: 10.1109/ICMLC.2014.7009105.

[17] Y. Zhao, "Research on application of fuzzy PID controller in two-container water tank system control," 2010 Int. Conf. Mach. Vis. Human-Machine Interface, MVHI 2010, pp. 679–682, 2010, doi: 10.1109/MVHI.2010.96.

[18] Q. Li, Y. Fang, J. Song, and J. Wang, "The application of fuzzy control in liquid level system," 2010 Int. Conf. Meas. Technol. Mechatronics Autom. ICMTMA 2010, vol. 3, pp. 776–778, 2010, doi: 10.1109/ICMTMA.2010.200.

[19] A. Jegatheesh and C. Agees Kumar, "Novel fuzzy fractional order PID controller for non linear interacting coupled spherical tank system for level process," Microprocess. Microsyst., vol. 72, p. 102948, 2020, doi: 10.1016/j.micpro.2019.102948.

[20] H. Yi and Q. Zhang, "An Optimal Fuzzy Control Method for Nonlinear Time-Delayed Batch Processes," IEEE Access, vol. 8, pp. 42608–42618, 2020, doi: 10.1109/ACCESS.2020.2976869.

[21] D. Wu and X. Tan, "Multitasking Genetic Algorithm (MTGA) for Fuzzy System Optimization," IEEE Trans. Fuzzy Syst., vol. 28, no. 6, pp. 1050–1061, 2020, doi: 10.1109/TFUZZ.2020.2968863.

[22] L. Li and W. Ding, "Optimization control strategy of boiler water level based on fuzzy PID," Proc. 28th Chinese Control Decis. Conf. CCDC 2016, pp. 5893–5896, 2016, doi: 10.1109/CCDC.2016.7532052.

[23] R. K. Singh and S. Yadav, "Optimized PI controller for an interacting spherical tank system," 2017 1st Int. Conf. Electron. Mater. Eng. Nano-Technology, IEMENTech 2017, 2017, doi: 10.1109/IEMENTECH.2017.8076977.

[24] K. Zhou, B. Yan, Y. Jiang, and J. Huang, "Double-tank liquid level control based on genetic algorithm," Proc. 2012 4th Int. Conf. Intell. Human-Machine Syst. Cybern. IHMSC 2012, vol. 2, no. 1, pp. 354–357, 2012, doi: 10.1109/IHMSC.2012.180.

[25] H. Shaikh and N. Kulkarni, "Fuzzy-PID based liquid level control for coupled tank (MIMO) interacting system," Commun. Comput. Inf. Sci., vol. 628 CCIS, pp. 188–195, 2016, doi: 10.1007/978-981-10-3433-6-23.

[26] H. Shaikh, "Computational Analysis of Water level Control using Fuzzy-PID for Coupled tank (MIMO) Interacting system," vol. 5, no. 6, pp. 1–6, 2016, doi: 10.15693/ijaist/2016.v5i6.1-6.

[27] M. Sharma, P. Verma, and L. Mathew, "Design an intelligent controller for a process control system," 2016 1st Int. Conf. Innov. Challenges Cyber Secur. ICICCS 2016, no. Iciccs, pp. 217–223, 2016, doi: 10.1109/ICICCS.2016.7542302.

[28] H. Shaikh, N. Kulkarni, and M. Bakshi, Computational Analysis of PID and PSO-PID Optimization for MIMO Process Control System. Springer Nature Singapore, 2023. doi: 10.1007/978-981-19-7346-8-57.

[29] R. Sehab, "Fuzzy PID supervision for a nonlinear system: Design and implementation," Annu. Conf. North Am. Fuzzy Inf. Process. Soc. - NAFIPS, pp. 36–41, 2007, doi: 10.1109/NAFIPS.2007.383807.

[30] A. Taneva, N. Muskinja, M. Petrov, and B. Tovornik, "FPID controller: Real time application," 2004 2nd Int. IEEE Conf. 'Intelligent Syst. - Proc., vol. 3, no. June, pp. 39–42, 2004, doi: 10.1109/is.2004.1344848.

[31] D. S. Bhandare, H. Shaikh, and N. R. Kulkarni, "Design and Implementation of Self-Tuning Fuzzy-PID Controller for Process Liquid Level Control," Int. J. Recent Adv. Eng. Technol., vol. 4, no. 7, pp. 131–135, 2016.