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# Optimizing Three-Tank Liquid Level Control: Insights from Prairie Dog Optimization

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ABSTRACT

The management of chemical process liquid levels poses a significant challenge in industrial process control, affecting the efficiency and stability of various sectors such as food processing, nuclear power generation, and pharmaceutical industries. While Proportional-Integral-Derivative (PID) control is a widely-used technique for maintaining liquid levels in tanks, its efficacy in optimizing complex and nonlinear systems has limitations. To overcome this, researchers are exploring the potential of metaheuristic algorithms, which offer robust optimization capabilities. This study introduces a novel approach to liquid level control using the Prairie Dog Optimization (PDO) algorithm, a metaheuristic algorithm inspired by prairie dog behavior. The primary objective is to design and implement a PID-controlled three-tank liquid level system that leverages PDO to regulate liquid levels effectively, ensuring enhanced stability and performance. The performance of the proposed system is evaluated using the ZLG criterion, a time domain metric-based objective function that quantifies the system's efficiency in maintaining desired liquid levels. Several analysis techniques are employed to understand the behavior of the system. Convergence curve analysis assesses the PDO-controlled system's convergence characteristics, providing insights into its efficiency and stability. Statistical analysis determines the algorithm's reliability and robustness across multiple runs. Stability analysis from both time and frequency response perspectives further validates the system's performance. A comprehensive comparison study with state-of-the-art metaheuristic algorithms, including AOA-HHO, CMA-ES, PSO, and ALC-PSODE, is conducted to benchmark the performance of PDO. The results highlight PDO's superior convergence, stability, and optimization capabilities, establishing its efficacy in real-world industrial applications. The research findings underscore the potential of PDO in PID control applications for three-tank liquid level systems. By outperforming benchmark algorithms, PDO demonstrates its value in industrial control scenarios, contributing to the advancement of metaheuristic-based control techniques and process optimization. This study opens avenues for engineers and practitioners to harness advanced control solutions, thereby enhancing industrial processes and automation.

## 1. Introduction

Chemical process liquid level management is a typical issue in industrial process control. Many businesses rely on liquid-level controllers to keep their plants running smoothly [1]. Liquid level control is crucial in various industrial applications, such as food processing, nuclear power generation plants, industrial chemical processing, and pharmaceutical industries. Therefore, in the realm of industrial process control, the precise regulation of liquid levels in tanks is of utmost significance to ensure efficient and stable operations [2]–[4]. One of the most widely employed control techniques is the proportional-integral-derivative (PID) control system [5]–[7], which leverages a feedback loop to maintain desired liquid levels within the tanks [8]–[10]. However, despite its popularity, the traditional PID control may face challenges when it comes to optimizing complex and nonlinear systems.

To address this issue, researchers have been actively exploring the potential of metaheuristic algorithms, which offer robust and adaptive optimization capabilities in tackling complex control problems [11]–[14]. Among these algorithms, a promising contender is the particle swarm optimization [15], modified grey wolf optimization [16], cuckoo search algorithm [17], [18], and improved genetic algorithm [19], along with non-dominated sorting genetic algorithm and multi-objective particle swarm optimization [20]. The primary objective in the context of this study is to design and implement a PID controlled three-tank liquid level system using the prairie dog optimization (PDO) [21] as a novel metaheuristic algorithm in this specific field of research. The proposed system aims to effectively regulate the liquid levels in the tanks to desired setpoints, ensuring enhanced stability and performance. The performance evaluation of the PDO-controlled system is conducted through the application of a time domain metrics-based objective function known as ZLG criterion [22]. The ZLG is a key indicator that quantifies the system's efficiency in maintaining the desired liquid levels, and it forms the basis for comparison with other state-of-the-art metaheuristic algorithms [23]–[25].

To gain a comprehensive understanding of the system's behavior, several analysis techniques are employed in this study. First, the convergence curve analysis is utilized to assess the convergence characteristics of the PDO-controlled system. The convergence curve reveals the rate at which the algorithm converges to the optimal solution, providing insights into its efficiency and stability. Additionally, statistical analysis is conducted to evaluate the reliability and robustness of the PDO algorithm across multiple runs. This analysis enables the determination of the PDO's consistency in producing superior results under various scenarios, strengthening the confidence in its performance. Furthermore, stability analysis of the PDO based and PID controlled system is conducted from both time and frequency response perspectives. The time response analysis measures the system's response to step inputs, shedding light on its dynamic behavior and transient characteristics. On the other hand, the frequency response analysis unveils the system's performance in the frequency domain, offering valuable insights into its stability and resonance behavior. To benchmark the performance of the PDO against other state-of-the-art metaheuristic algorithms, namely arithmetic optimization algorithm with Harris hawks optimization (AOA-HHO) [26], covariance matrix adaptation evolution strategy (CMA-ES) [26], particle swarm optimization (PSO) [27] and hybrid differential evolution PSO with an aging leader and challengers (ALC-PSODE) [27], a comprehensive comparison study is undertaken. The results of each algorithm are thoroughly analyzed and contrasted to establish the supremacy of the PDO based and PID controlled system.

The outcomes of this research endeavor demonstrate the remarkable performance and efficacy of the PDO in PID control applications for three-tank liquid level systems. By surpassing the benchmark algorithms in terms of convergence, stability, and optimization, PDO exhibits its potential as a valuable tool in real-world industrial applications, empowering engineers and practitioners with advanced control solutions. The findings of this study contribute to the burgeoning field of metaheuristic-based control techniques, fostering advancements in process optimization and automation.

## 2. Prairie Dog Optimization (PDO) Algorithm

PDO a recent optimization method presented to simulate the foraging and burrow building behaviors of the prairie dogs [28]–[30]. It starts with a random pattern of search to attain the promising region of interest. Three mathematical phases (initialization and evaluation, exploration, exploitation) are provided to perform the iterative process in PDO. In initialization and evaluation phase, PDO considers colony of $Q$ coteries with $N$ prairie dogs (PDs) for each coterie. The colony of $Q$ coteries is represented by a matrix of the possible positions of these coteries and colony ($C$) using (1) where $C_{ij}$ stands for the $i^{th}$ coterie of the $j^{th}$ element within the colony where each coterie is represented by the matrix ($PA$) that contains the possible positions of $N$ prairie dogs.

$$C = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1d} \\ \vdots & \vdots & C_{ij} & \vdots \\ C_{Q1} & C_{Q2} & \cdots & C_{Qd} \end{bmatrix} \tag{1}$$

$$PA = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1d} \\ \vdots & \vdots & P_{ij} & \vdots \\ P_{N1} & P_{N2} & \cdots & P_{Nd} \end{bmatrix} \tag{2}$$

In (2), $P_{ij}$ denotes the $i^{th}$ PD of the $j^{th}$ element and $N \leq$ Q. After initialization process, the fitness of prairie dog' position is evaluated based on the objective or target function that reflects the quality of found food source. In terms of minimization objective, minimum fitness value among the colony denotes the best solution so far. In exploration phase, PDs forage to dig new burrows in the vicinity of a plentiful food source as part of their exploration behavior. The PDO performs the exploration search using two criteria. The first criterion employs Levy flight [31] to provide the prairie dogs with a long jumping movement aiming to explore more fresh food sources. The second criterion aims to assess the effectiveness of the digging and the quality of the available food sources. The renewed position for the burrow building is modeled as follows where $P_{best,j}$ denotes the coined global best solution, $\rho$ specifies the food source alert parameter which is set to 0.1 kHz [32].

$$P_{i+1,j+1} = P_{best,j} \times P_{r,j} \times DS \times Levy(N) \qquad \forall\ T_{max}/4 \leq t < T_{max}/2 \tag{3}$$

$C_{best,i,j}$, presented in (4), analyzes the effects of the most effective solution so far, $P_{r,j}$ denotes a randomly created solution, $Z_{i,j}$, presented in (5), specifies the random cumulative influence of each prairie dog inside the colony and $Ds$, presented in (6), represents the coterie's strength in digging. $Levy(N)$ defines the Levy distribution function [33] for offering more exploration using its diverse jumping steps.

$$C_{best,i,j} = P_{best,j} \times \delta + \frac{P_{i,j} \times mean\ (P_{N,Q})}{P_{best,j} \times \left(x_j^{Lb} - x_j^{Ub}\right) + \delta} \tag{4}$$

$$Z_{i,j} = \frac{P_{best,j} - Pr}{P_{best,j} + \delta} \tag{5}$$

$$Ds = 1.5 \times a \times (1 - t/T_{max})^{(2 \times t/T_{max})} \tag{6}$$

In here, $a$ denotes a stochastic number to ensure exploration ability and it uses a value of 1 for an even iteration and $-1$ for an odd one, $\delta$ denotes a small number, $t$ and $T_{max}$ signify the present iteration and the maximum size of iterations, respectively. In exploitation phase, the exploitative search of PDO simulates the unique communication of prairie dogs using their sounds or signals when they find an abundant food source or observe the predators. In this phase two skills are used which are mathematically modeled as follows where $\varepsilon$ denotes a small number to illustrate the goodness of food source, and $Pe$, presented in (9), describes the effects of the predator and $rand$ is a random value between 0 and 1 generated by the uniform distribution.

$$P_{i+1,j+1} = P_{best,j} - C_{best,i,j} \times \varepsilon - Z_{i,j} \times rand;\ \forall\ T_{max}/2 \leq t < 3\,T_{max}/4 \tag{7}$$

$$P_{i+1,j+1} = P_{best,j} \times Pe \times rand;\ \forall\ 3\,T_{max}/4 \le t < T_{max} \tag{8}$$

$$Pe = 1.5 \times (1 - t/T_{max})^{(2\times t/T_{max})} \tag{9}$$

## 3. Proportional Integral Derivative (PID) Controller

For the control of a three-tank system, this paper adopts a PID controller which has the form presented in (10) where the gains known as proportional, integral, and derivative are denoted by $K_P$, $K_I$, and $K_D$, respectively [34]–[36]. The Laplace form of a PID controller is presented in (11).

$$u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt} \tag{10}$$

$$PID(s) = K_P + \frac{K_I}{s} + K_D s \tag{11}$$

The block diagram illustrated in Fig. 1 shows the block diagram of a PID controller adopted in a feedback control system for a three-tank system in order to be used in industrial processes.

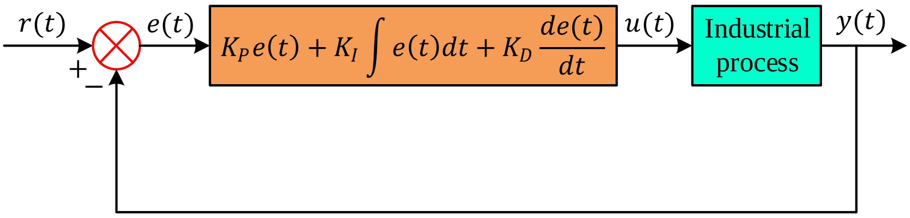


**Fig. 1.** Block diagram of a PID controlled three-tank system for industrial processes

## 4. Liquid Level System with PID Controller

The system for controlling liquid levels consists of three interconnected tanks: Tank 1, Tank 2, and Tank 3 [4]. Its primary goal is to manage and stabilize the liquid levels within each tank using a control setup. To formulate a mathematical description of this arrangement, the following assumptions and simplifications are taken into account: The tanks possess open upper sections, enabling the liquid surface to be in contact with the surrounding atmosphere. The liquid is treated as incompressible with a consistent density. Liquid movement between the tanks happens unidirectionally, flowing from higher-level tanks to those at lower levels. No leakage exists within the system, and the rate of liquid flow between tanks is proportionate to the difference in liquid levels between any two given tanks. Based on these assumptions, the behavior of the liquid levels in each tank can be expressed using a system of interconnected differential equations. Let $H1$, $H2$, and $H3$ represent the liquid levels in Tank 1, Tank 2, and Tank 3, respectively. The system's dynamics can be described as $dH1/dt = qin - q12 - q13$, $dH2/dt = q12 - q23$ and $dH3/dt = q13 + q23 - qout$ where $qin$ is the flow rate into Tank 1, $qout$ is the flow rate out of Tank 3, and $q12$, $q13$, and $q23$ are the flow rates between the tanks. The flow rates are proportional to the difference in liquid levels between the tanks, therefore, the followings can be written: $q12 = k12(H1 - H2)$, $q13 = k13(H1 - H3)$ and $q23 = k23(H2 - H3)$ where $k12$, $k13$, and $k23$ are the proportionality constants that depend on the geometry of the system and the properties of the liquid. With these equations, the behavior of the system for different flow rates and control strategies can be simulated. Considering the above explanation, the transfer function control theory techniques can also be used to design a control system that regulates the liquid levels in each tank by adjusting the flow rates. The design of such a control system will depend on the specific requirements and constraints of the application. Fig. 1 visualizes a simple structure of a tank that is used in a three-tank system. In the simplified structure given by Fig. 2, $q_1$ and $q_2$ represent the liquid flow rates towards in and out of the tank, respectively. $h$ represents the height and $A$ is the cross-sectional area of the related tank. The transfer function in (12) is used in this study for a three-tanks liquid level system [26], [27]. The system with the PID controller then can be represented with the model in (13) using the block diagram in Fig. 1.

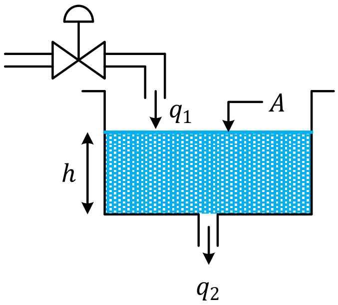


**Fig. 2.** Simplified structure of a tank

$$G_{plant}(s) = \frac{1}{(4s+0.2)^3} = \frac{1}{64s^3 + 9.6s^2 + 0.48s + 0.008} \tag{12}$$

$$W(s) = \frac{PID(s) \times G_{plant}(s)}{1 + PID(s) \times G_{plant}(s)} \tag{13}$$

## 5. Application of PDO Algorithm and Comparative Simulation Results

### 5.1. Objective Function and Recommended PDO-based PID Controller Design

The PDO parameters, for the application of the three-tank system, are set as presented in Table 1. For the implementation, the application of the three-tank system is represented as a minimization problem. In this regard, the $F$ objective function (ZLG) presented in (14) is adopted as a time domain metrics-based minimization tool [37]–[39]:

$$F = \left(1 - e^{-\beta}\right) \times \left(E_{ss} + \frac{OS}{100}\right) + e^{-\beta} \times (T_{st} - T_{rt}) \tag{14}$$

where $\beta$ is a balancing factor equals to 1 [40], $E_{ss}$ is the steady state error, $OS$ is percent overshoot, $T_{st}$ is the settling time and $T_{rt}$ is the rise time. The implementation procedure showing the PID controlled three-tank system using $F$ objective function is depicted in Fig. 3.

**Table 1.** Parameters of PDO algorithm

| Parameter | Used value |
|---|---|
| Food source alarm ($\rho$) | 0.1 |
| Food source quality ($\varepsilon$) | 2.2204E−16 |
| Individual $PD$ difference $\delta$ | 0.005 |
| Bounds of $K_P$ | [0.0001, 0.1] |
| Bounds of $K_I$ | [0.0001, 0.1] |
| Bounds of $K_D$ | [0.01, 2] |
| Maximum number of iterations | 50 |
| Population size | 30 |
| Independent run number | 25 |

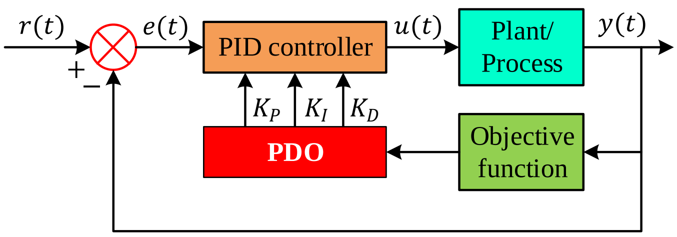


**Fig. 3.** Implementation procedure showing the minimization with PDO and $F$ objective function

### 5.2. Statistical Analysis and Evolution of Convergence Curve

The PDO is initially assessed for its performance of minimizing the $F$ objective function for the three-tank liquid level system. Table 2 presents the statistical metrics obtained from the minimization of $F$ objective function. As seen from the data in the table, the PDO has a consistent minimization ability within a narrow band indicating its good performance characteristics. Fig. 4 demonstrates the PDO based $F$ objective function minimization. The related figure highlights the efficacy of the PDO in terms of consistent minimization through iterations, further indicating its capability for three-tank liquid level system.

**Table 2.** Statistical results of objective function minimized by PDO

| Metric | Value |
|---|---|
| Best | 5.1608 |
| Worst | 5.9473 |
| Median | 5.2542 |
| Average | 5.3420 |
| Standard deviation | 0.2057 |
| Variance | 0.0423 |

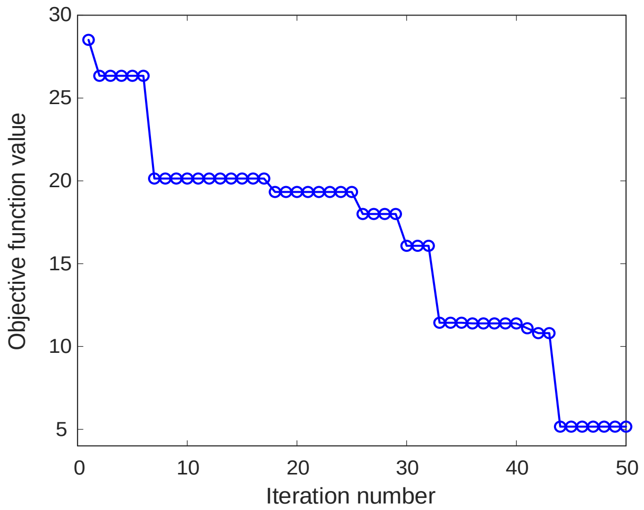


**Fig. 4.** Convergence curve showing the PDO based objective function minimization

### 5.3. Stability Analysis

The stability analysis is performed in this study to demonstrate the PDO's ability from time and frequency domain perspectives. For comparisons, arithmetic optimization algorithm with Harris hawks optimization (AOA-HHO) [26], covariance matrix adaptation evolution strategy (CMA-ES) [26], particle swarm optimization (PSO) [27] and hybrid differential evolution and PSO with an aging leader and challengers (ALC-PSODE) [27] are used in this study. Table 3 demonstrates the controller parameters obtained via each method and their corresponding transfer functions.

**Table 3.** Controller parameters and related transfer functions obtained via different algorithms

| Tuning method | $K_P$ | $K_I$ | $K_D$ | $W(s)$ |
|---|---|---|---|---|
| PDO | 0.021027 | 0.00044012 | 0.37871 | $\frac{0.3787s^2+0.02103s+0.0004401}{64s^4+9.6s^3+0.8587s^2+0.02903s+0.0004401}$ |
| AOA-HHO [26] | 0.040 | 0.0005 | 0.4269 | $\frac{0.4269s^2+0.04s+0.0005}{64s^4+9.6s^3+0.9069s^2+0.048s+0.0005}$ |
| CMA-ES [26] | 0.051 | 0.0013 | 0.3914 | $\frac{0.3914s^2+0.051s+0.0013}{64s^4+9.6s^3+0.8714s^2+0.059s+0.0013}$ |
| PSO [27] | 0.0528 | 0.0003 | 1 | $\frac{s^2+0.0528s+0.0003}{64s^4+9.6s^3+1.48s^2+0.0608s+0.0003}$ |
| ALC-PSODE [27] | 0.0419 | 0.0009 | 1 | $\frac{s^2+0.0419s+0.0009}{64s^4+9.6s^3+1.48s^2+0.0499s+0.0009}$ |

Fig. 5 illustrates the comparative step responses of PDO, AOA-HHO, CMA-ES, PSO and ALC-PSODE algorithms for three-tank liquid level system control. As seen from the respective figure, the PDO is capable of demonstrating a more desirable response in terms of overshoot ($M_{overshoot}$), and settling time ($T_{settling}$), making it the best approach that can be used to reach more desirable time domain stability for a three-tank liquid level system. Fig. 6 illustrates the comparative Bode plots of PDO, AOA-HHO, CMA-ES, PSO and ALC-PSODE algorithms for three-tank liquid level system control. As seen from the respective figure, the PDO is capable of demonstrating a more desirable response in terms of phase margin ($P_{margin}$) and gain margin ($G_{margin}$), making it the best approach that can be used to reach more desirable frequency domain stability for a three-tank liquid level system. The related illustrations in Fig. 5 and Fig. 6 are also supported by the numerical values presented in Table 4.

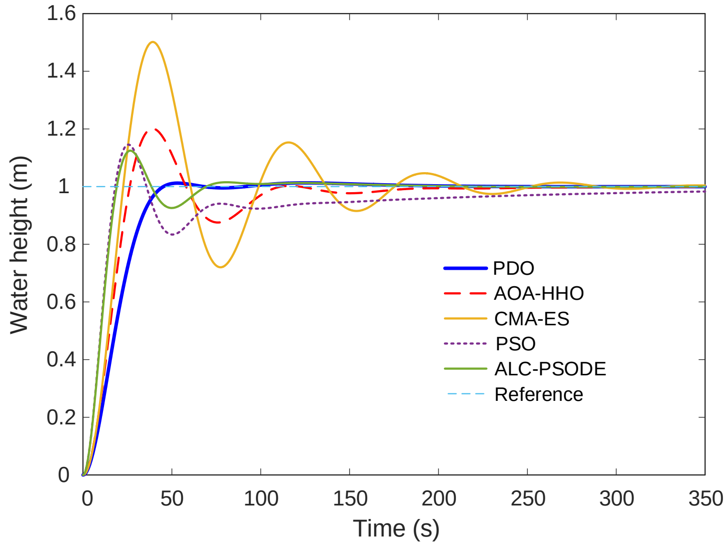


**Fig. 5.** Step response of different optimizers-based controller designs for water height

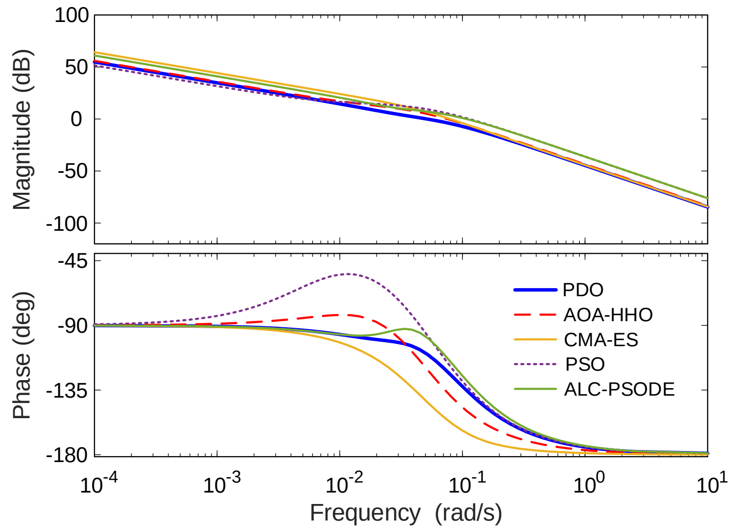


**Fig. 6.** Comparative Bode plot analysis

**Table 4.** Stability metrics for various tuning methods

| Tuning method | $T_{settling}$ (sec) | $M_{overshoot}$ (%) | $G_{margin}$ (dB) | $P_{margin}$ (°) |
|---|---|---|---|---|
| PDO | **41.2549** | **1.2934** | **Inf** | **69.9389** |
| AOA-HHO [26] | 160.1051 | 20.1160 | **Inf** | 43.1866 |
| CMA-ES [26] | 238.6552 | 49.9912 | **Inf** | 22.6244 |
| PSO [27] | 320.5526 | 14.4337 | **Inf** | 45.7205 |
| ALC-PSODE [27] | 64.2188 | 12.4585 | **Inf** | 51.6652 |

## 6. Conclusion

This study delved into the crucial realm of chemical process liquid level management within industrial process control. The intricate nature of this challenge, spanning various industries including nuclear power, food processing, and pharmaceuticals, underscores the need for robust control techniques. While traditional PID control has been a staple, its limitations in optimizing complex and nonlinear systems have steered researchers towards exploring alternative avenues. The introduction of the PDO as a novel metaheuristic solution marks a significant advancement in the field. Through the design and implementation of a PID-controlled three-tank liquid level system, the study demonstrated the potential of PDO to regulate liquid levels efficiently, thereby enhancing stability and performance. The application of the ZLG criterion as an objective function facilitated a comprehensive evaluation of the system's proficiency in maintaining desired liquid levels. The array of analysis techniques employed in this study shed light on the PDO based PID controlled system's behavior. Convergence curve analysis provided insights into the algorithm's convergence characteristics, highlighting its efficiency and stability. Statistical analysis further validated the algorithm's robustness and reliability across various scenarios. Stability analysis from both time and frequency response perspectives lent credence to the system's performance. The comparison study with state-of-the-art metaheuristic algorithms solidified PDO's standing as a superior choice for complex control problems. Outperforming benchmark algorithms in convergence, stability, and optimization, PDO demonstrated its prowess as a valuable tool for real-world industrial applications. This research serves as a cornerstone for engineers and practitioners seeking advanced control solutions to optimize their industrial processes.

In a rapidly evolving landscape of process optimization and automation, the findings of this study contribute substantially to the burgeoning field of metaheuristic-based control techniques. By highlighting the efficacy of PDO in regulating liquid levels, this research sets the stage for further exploration and application of innovative algorithms in industrial control scenarios. As industries continue to seek ways to enhance efficiency and stability, the insights gained from this study can be leveraged to develop robust solutions that redefine the boundaries of industrial process control.

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