PID controller tuning performance evaluation based on integral time square error for coupled tank system

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ABSTRACT

This study presents a conclusive performance evaluation based on integral time between the conventional and optimization based proportional integral derivatives (PID) tuning method. The tuning method of interest are including trial and error, auto-tuning, Ziegler-Nichols (ZN), Cohen-Coon (CC), and particle swarm optimization (PSO). The coupled tank system (CTS) is used for the system under consideration as it's one of the popular technologies in industrial control application. Previous study had compared the tuning performance in terms of its transient response. The transient consists of several parameters such as rise time (Tr), settling time (Ts), peak time (Tp), steady state error, overshoot, and steady state error. Due to that, a conclusive performance comparison could not be achieved. Hence this study proposed integral time squared error evolution which is based on only one parameter which also reflects good overall transient response performance. The results show that of all tuning methods, PSO provide the smallest integral time square error (ITSE) value, while trial and error provide the highest with a value of 12.84 and 203.10, respectively. The ITSE also reflects the transient response performances.

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1. INTRODUCTION

The coupled tank system (CTS) is one of the most popular technologies in industrial control operations because it is used to study concepts of fluid flow, pressure, and level control. Several controllers have been used in CTS in past studies. These controllers include sliding mode control [1], [2], inverted decoupling controllers [3], internal model control (IMC) [3], proportional integral derivative (PID) [4], and LQR [4]. Additionally, the PID tuning technique is one of the most frequently applied tuning methods for CTS [5]-[7]. Moreover, the performance of CTS has been successfully enhanced through the implementation of optimization techniques, including modified-ant colony optimization (ACO) [8], particle swarm optimization (PSO) [4], [9], bat algorithms (BA) [10], and different evolution [11].

Proportional integral derivatives (PID) controllers serve as fundamental tools due to their simplicity, robustness against model errors, and ease of implementation. The controller regulates system behaviour by adjusting three key: parameters proportional gain, integral time, and derivative time. Achieving optimal PID controller performance is essential for maintaining stability and meeting control system requirements. Each term in PID controller plays a specific role in ensuring better system performance. The P-term reduces error but does not eliminate it, the I-term eliminates error but tend to make the system oscillate, and the D-term improves the speed of the responses [12].

Various techniques have been applied for PID tuning, which can be broadly classified as classical and computational or optimization techniques [13]. Traditionally, engineers have relied on analytical or empirical rules, such as Ziegler-Nichols (ZN), Cohen-Coon (CC), and trial-and-error methods. However, these classical techniques may fall short when dealing with complex, nonlinear systems or systems affected by uncertainties and disturbances. To address these limitations, metaheuristic optimization algorithms has gained prominence. These techniques enhance PID controller performance and robustness, allowing for the tuning PID controllers and simultaneous adjustments of multiple PID controllers.

By comparing optimization techniques with traditional tuning approaches, studies have demonstrated improved accuracy and efficiency. For instance, [9] compares PSO with ZN, CC, auto-tuning, and trial-and-error, [10] compares BA with ZN, and [14] compares genetic algorithm (GA) with ZN.

Previous literatures has evaluated the PID controller performance based on transient response and time-integral-based performance metrics [9]. Most conventional methods assess controller performance based on transient response characteristics such as percentage overshoot, rise time (Tr), and settling time (Ts). In contrast, optimization techniques often rely on time-domain metrics, specifically time-integral performance. Due to the varied characteristics of transient response evaluations, they may not provide a conclusive comparison.

This study aims to provide a conclusive comparison of PID tuning methods between conventional and optimization techniques. To achieve this objective, this study will implement a time-integral-based performance evaluation for the study of [9] and analyze the results based on its transient response characteristics.

2. METHOD

The summary of the methodology for this study is presented in Figure 1. The control of liquid levels in tanks and flow between them is a fundamental in the process industries. A CTS is a device consisting of two tanks connected by pipes, where each tank's liquid level is controlled by a pump or valve. The schematic diagram of CTS is shown in Figure 2. This study utilizes a second-order single-input single-output (SISO) model of the CTS, with its block diagram shown in Figure 3.

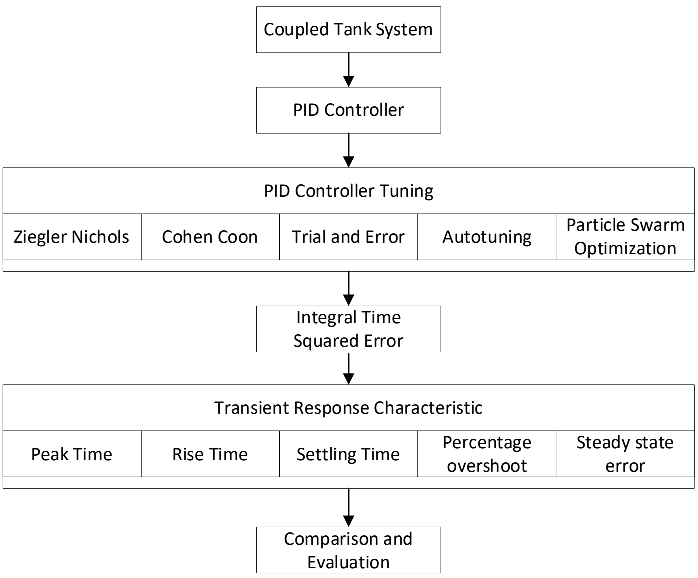

Figure 1. Summary of the methodology

The CTS system is presented in (1). The parameter values listed in Table 1 are substituted into the equation, yielding the overall transfer shown in (2).

$$\frac{h_2(s)}{q_1(s)} = \frac{k_1 k_2}{(T_1 s+1)(T_2 s+1)-k_{12}k_{21}} \quad (1)$$

$$G_p(s) = \frac{h_2(s)}{q_1(s)} = \frac{0.0361}{36.9406s^2+12.1565s+0.4514} \quad (2)$$

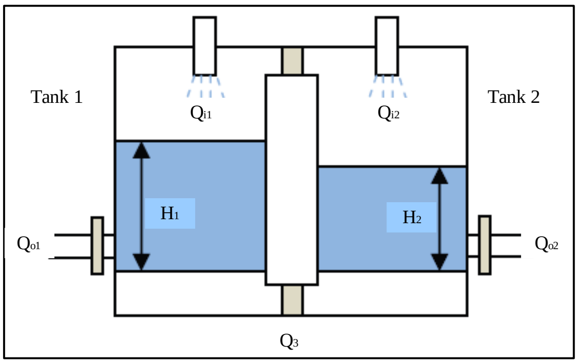

Figure 2. Schematic diagram of CTS

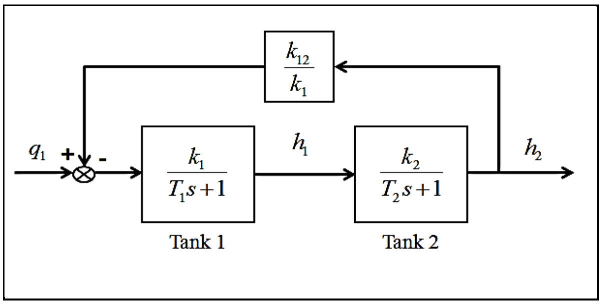

Figure 3. Second order single input single output CTS

Table 1. Parameter of PID controller according to the tuning methods

Variable	Value
h_2	15 cm
α_1	10.78 $cm^{3/2}$/sec
α_2	11.03 $cm^{3/2}$/sec
α_3	11.03 $cm^{3/2}$/sec
A_1	32 cm^2
A_2	32 cm^2

A PID controller is a type of feedback controller that adjusts the input signal based on the difference between the intended and actual output signal. PID stands for proportional, integral, and derivative—the three components that form the basis of the controller's equation [9]. The equation for the PID parameters is shown in (3):

$$G_c(s) = K_p + \frac{K_i}{s} + K_i s \quad (3)$$

Where Kp is proportional gain, Ki is integral gain, and Kd is derivative gain.

These three components influence the overall performance of the system as follows: i) the proportional term –provides an overall control action proportional to the error signal, determined by the all-pass gain factor, ii) the integral term – reducing steady state errors through low-frequency compensation using an integrator, and iii) the derivative term – enhances transient response through high-frequency compensation using a differentiator [15]. The PID control structure for CTS is shown in Figure 4.

PID control tuning is the process of determining ideal PID parameter values (Kp, Ki, and Kd) to minimize errors and enhance system performance. This tuning can be performed using several ways and remains significant research topic [16]. Some implemented tuning method for coupled tanks systems include conventional techniques such as automatic tuning, ZN, CC, and optimization techniques like

PSO [4], [9], [11], [17], BA [10], Firefly algorithm [18], differential evolution (DE) [11], and ACO [8]. Additionally, [19] analyzed the applications of ACO, grey wolf optimizer (GWO), and flower pollination algorithm (FPA) for nonlinear interconnected tanks. Each technique offers unique benefits and drawbacks depending on the system's requirements and characteristics [10].

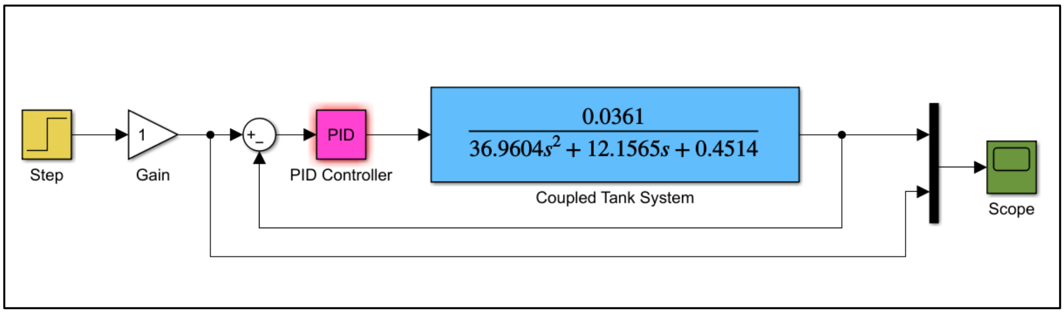

Figure 4. PID control structure with CTS

The ZN method is the most widely used conventional tuning technique for PID controllers. It was developed in the 1940s by John G. Ziegler and Nathaniel B. Nichols. The CC tuning method, published in 1953 by Cohen and Coon, is the second most popular. CC offers an advantage over ZN when dealing with systems that have a larger operating range. Another method for determining PID parameter values is trial and error. This is one of the simplest approaches as it does not require mathematical calculations, but it relies on an experienced practitioner to find the optimal parameter values. In this method, the Ki and Kd initially set to zero, and then Kp is gradually increased [20]. Autotuning, on the other hand, leverages MATLAB applications for parameter tuning.

Optimization techniques, however, require a cost function to be minimized or maximized. According to Joseph *et al.* [21], six cost functions are defined, but the four most commonly used are integrated absolute error (IAE), integral of squared error (ISE), integral time square error (ITSE), and integral time absolute error (ITAE). While the mostly used are four [13], [22], which are IAE, ISE, ITSE, and ITAE. The equations for ISE, IAE, ITAE, and ITSE are provided in (4)-(7). Each performance index has its own advantages and disadvantages. As noted by Chen and Chang [23], ISE achieves faster error tracking but is prone to oscillations, while IAE provides good response characteristics but lacks effective selection performance. ITSE delivers better dynamic performance with improved Ts. Iruthayarajan and Baskar [24] summarize that ISE are suitable for analytical and computational purposes, IAE useful for computer simulation studies and ITAE can reduce large initial error with emphasize error occurring later in response.

In the context of CTS tuning using optimization techniques, ACO uses ISE and IAE [8], BA employs IAE, ISE, and ITSE [10], PSO applies ISE and IAE [8], and ITSE [4], DE uses IAE, ISE, and ITSE [11] as cost function. Among these indices, ITSE is often preferred due to its ability to provide better dynamic performance and improved Ts. Maghfiroh *et al.* [25] have demonstrated that ITSE delivers superior performance compared to other integral methods. The ITSE equation is shown in (7). ITSE is defined as weighting the squared error by time, emphasizing errors occurring later in the response. It can be described as the area under the graph between the desired response and the actual response.

$$\mathrm{ISE} = \int_0^t (e_i(t))^2 dt \tag{4}$$

$$\mathrm{IAE} = \int_0^t |e_i(t)| dt \tag{5}$$

$$\mathrm{ITAE} = \int_0^t |e_i(t)| t dt \tag{6}$$

$$\mathrm{ITSE} = \int_0^t (e_i(t))^2 t dt \tag{7}$$

Where e is an error, and t is the respective time of the error.

The value of PID controller Kp, Ki, and Kd for ZN, CC, trial and error, and autotuning is obtain based on [20], while PSO based on [9]. Based on the PID value, the ITSE will then be evaluated for each tuning method by using (7). Then the transient response for each method will be analyzed.

3. RESULTS AND DISCUSSION

PID control tuning is the process of determining ideal PID parameter. The value of PID parameter of Kp, Ki, and Kd, based on respective tuning method of trial and error, ZN, CC, autotuning and PSO is shown in Table 2. Figure 5 illustrates the control structure corresponding to each tuning method. Based on the PID value, the transient response of the closed loop CTS with PID controller are obtained and shown in Figure 6. The ITSE was then calculated, and all transient response characteristics were evaluated.

Table 2. Parameter of PID controller according to the tuning methods

Tuning method	Parameter		
	Kp	Ki	Kd
Trial and error	15.00	1.00	8.00
ZN	168.00	35.00	201.60
CC	235.88	33.92	203.21
Autotuning	53.40	1.54	-2.98
PSO	250.99	4.35	171.64

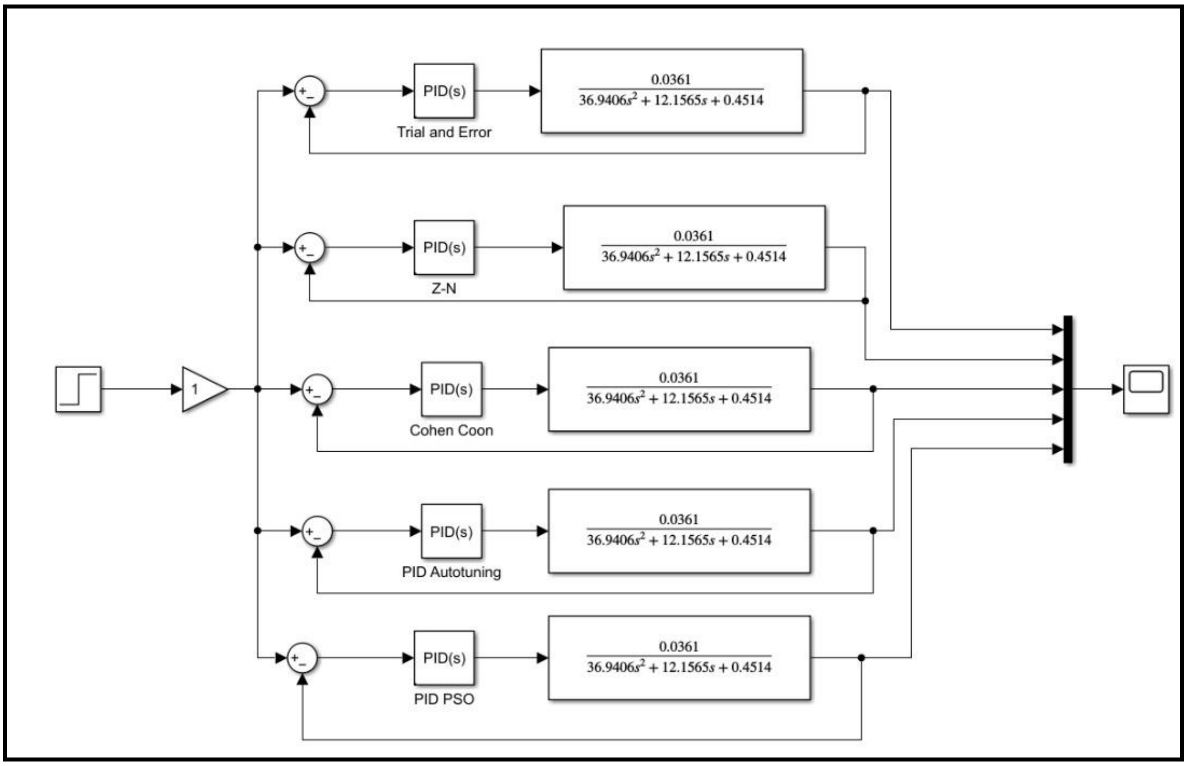

Figure 5. Control structure with different types of tuning method

Based on the computed results, PSO yields the smallest ITSE followed by autotuning, ZN, CC, and trial and error method, with the value of 12.84, 17.36, 22.03, 46.70, and 203.10, respectively. The transient response characteristics, including peak time (Tp), Ts, Tr, and percentage of overshoot, are summarized in Table 3. From the observations, as the PSO not only produces the smallest ITSE but also results in the lowest transient response values for Tp and Ts among all the methods. Conversely, the trial-and-error method, which has the highest ITSE value, reflects the longest transient response times (Tp, Ts, and Tr) and poorer performance. The CC method, with a moderate ITSE value, contributes to intermediate transient response values for Tp and Ts compared to the other methods. For a clearer comparison, the performance characteristic values and their corresponding ITSE are also presented in the form of a bar graph, as shown in Figure 7.

To validate the proposed method, two studies, [10] and [11] were considered. Katal *et al.* [10] implemented tuning methods using ZN and the BA techniques, optimized with the ITSE and ISE. Based Puralachetty and Pamula [11], four tuning methods were evaluated: PSO, DE, PSO with two-stage initialization (TSI), and DE with TSI. The tuning methods in [11] were assessed based on the minimum function value (MFV), which incorporates various time response criteria such as Tr, Ts, percentage peak overshoot, and steady-state error.

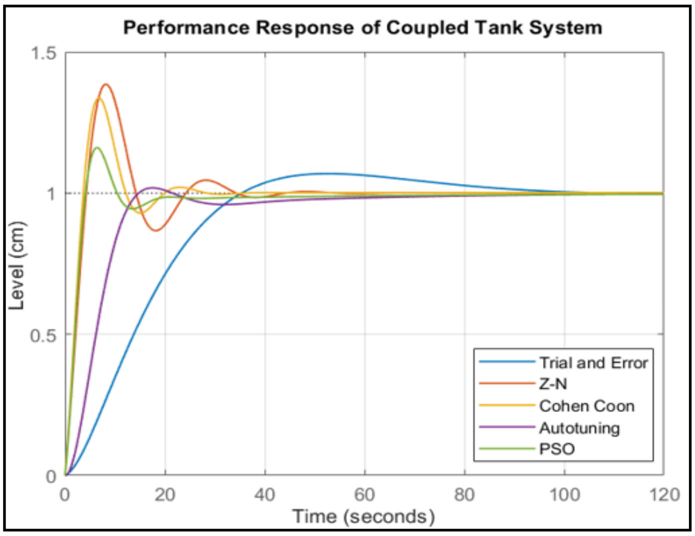

Figure 6. Transient response of the corresponding tuning methods

Table 3. Performance of CTS based its ITSE and its corresponding transient response characteristics

Tuning method	Performance					
	ITSE	T_P (s)	T_S (s)	T_R (s)	OS (%)	SSE
Trial and error	203.10	52.70	84.40	24.00	6.86	0.00
ZN	22.03	7.90	32.10	3.29	38.50	0.00
CC	17.36	6.70	23.59	**2.81**	33.70	0.00
Autotuning	46.70	17.70	53.40	9.14	**1.81**	0.00
PSO	12.84	**6.40**	**17.75**	3.27	16.19	0.00

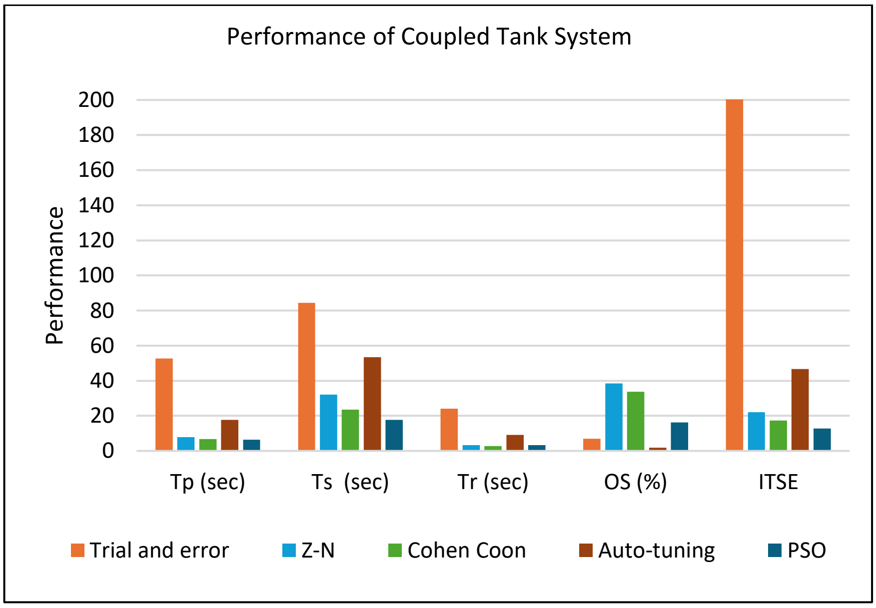

Figure 7. Comparison of the performance of CTS based on its ITSE and its corresponding transient response characteristics

The validation was performed by comparing the ITSE values obtained for each tuning method from studies [10] and [11], as shown in Table 4. The DE-TSI method from [11] produced the smallest ITSE value, validating the objective function of MFV, which was also minimized by DE-TSI. This method demonstrated generally smaller transient response. Similarly, [10] showed that a lower ITSE is associated with improved transient response performance.

Table 4. Comparable ITSE based tuning method on other literatures

Ref.	Tuning method	Objective function	Performance			
			ITSE	T_s (s)	T_R (s)	OS (%)
[11]	PSO	MFV: 16.8036	5.6423	10.2972	1.5196	21.7902
	DE	MFV: 6.9272	4.9479	8.1855	2.9039	2.7644
	PSO-TSI	MFV: 6.2929	5.0469	7.4481	2.9879	2.1479
	DE-TSI	MFV: 4.6456	3.8950	5.1489	3.3298	0.8122
[10]	ZN		43.2308	62.8387	5.0003	46.4433
	BA (ISE)		0.3526	0.5858	0.0864	16.24
	BA (ITSE)		0.0369	0.0268	0.0149	0.00

4. CONCLUSION

This study investigates the performance of various PID controller tuning methods for the CTS using the ITSE as a performance evaluation metric. Unlike previous studies that relied solely on transient response characteristics (e.g., peak time, settling time, rise time, and percentage overshoot), this study demonstrates that ITSE provides a more comprehensive and summative comparison of tuning methods that's trial and error, ZN, CC, autotuning, and PSO. The results reveal that PSO achieves the smallest ITSE value, indicating superior transient response performance, while autotuning produces the highest ITSE, reflecting less favorable results. The study also validates its findings by referencing prior works that used ITSE and other performance metrics, highlighting the importance of ITSE in comparing both conventional and optimization-based tuning techniques.

The study concludes that ITSE is an effective cost function for optimization techniques and a reliable evaluation metric for comparing the performance of conventional tuning methods. It provides a clearer and more comprehensive assessment of overall system performance.

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AUTHOR CONTRIBUTIONS STATEMENT

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Syahar Azalia Ab Shukor						✓			✓					
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Fardila M. Zaihidee				✓	✓					✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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