

Optimization of PID Parameters Utilizing Variable Weight Grey-Taguchi Method and Particle Swarm Optimization

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Abstract. Controller that uses PID parameters requires a good tuning method in order to improve the control system performance. Tuning PID control method is divided into two namely the classical methods and the methods of artificial intelligence. Particle swarm optimization algorithm (PSO) is one of the artificial intelligence methods. Previously, researchers had integrated PSO algorithms in the PID parameter tuning process. This research aims to improve the PSO-PID tuning algorithms by integrating the tuning process with the Variable Weight Grey-Taguchi Design of Experiment (DOE) method. This is done by conducting the DOE on the two PSO optimizing parameters: the particle velocity limit and the weight distribution factor. Computer simulations and physical experiments were conducted by using the proposed PSO-PID with the Variable Weight Grey-Taguchi DOE and the classical Ziegler-Nichols methods. They are implemented on the hydraulic positioning system. Simulation results show that the proposed PSO-PID with the Variable Weight Grey-Taguchi DOE has reduced the rise time by 48.13% and settling time by 48.57% compared to the Ziegler-Nichols method. Furthermore, the physical experiment results also show that the proposed PSO-PID with the Variable Weight Grey-Taguchi DOE tuning method responds better than Ziegler-Nichols tuning. In conclusion, this research has improved the PSO-PID parameter by applying the PSO-PID algorithm together with the Variable Weight Grey-Taguchi DOE method as a tuning method in the hydraulic positioning system.

1. Introduction

Hydraulic positioning system has been used in modern industrial applications. This is due to the capabilities of the larger driving force, fast response and high power-to-weight ratio. Hydraulic positioning system is generally categorized in the stabilization and tracking control. This system will always be the driving force to reduce energy consumption and to improve the efficiency and accuracy of the motion control. However, the nonlinearity of the system causes the difficulty for accurate control. Recently, researchers have focused on dynamic characteristics of a hydraulic positioning system for the control purpose. Some of them designed and implemented a suitable controller proper operation with dynamic and nonlinear system [2].



Hydraulic positioning system uses proportional-integral-derivative controllers (PID). This controller is the most famous controller among industrial player because of the simplicity of PID structure and easy to implement in various industrial applications. However, PID controller deals have some issues that limit their application. The main issue is the difficulty to tune the PID controller. This is significant when the controlled system is highly dynamic. It will be hard for the system to achieve the desired performance when the system is nonlinear and time-varying.

Recently, particle swarm optimization (PSO) has been implemented in various applications. PSO algorithm is an evolutionary computational technique. This algorithm is designed to solve optimization problems and easy to be implemented [1]. The issue with PSO-PID algorithm is the random assignment of parameter values. For example, there is no clear guideline on the values of the particle velocity limit and the weight distribution factor implemented in the PSO-PID algorithm. Therefore, the goal of this study is to implement PSO-PID tuning algorithm together with the Variable Weight Grey-Taguchi Design of Experiment (DOE) so that an optimal performance of hydraulic positioning system is achieved. The role of the Variable Weight Grey-Taguchi DOE is to determine the proper values for the particle limit velocity and the weight distribution factor.

The paper is organized as follows: Section II describes the system dynamic model. Section III presents an overview of PSO-PID algorithm. Section IV reviews the Variable Weight Grey-Taguchi DOE method. Section V presents the system with PSO-PID tuning algorithm together with the Variable Weight Grey-Taguchi Design of Experiment (DOE) as well as the Ziegler Nichols tuning algorithm. Finally, the results of the PSO-PID tuning algorithm together with the Variable Weight Grey-Taguchi Design of Experiment (DOE) and Ziegler Nichols tuning algorithm are presented in Section V.

2. PSO-PID Algorithm

[5] suggested new performance criterion based on the time domain that is easier and simpler. This performance criterion is used as evaluation function in the PSO algorithm and he has named the algorithm as PSO-PID tuning algorithm. The evaluation function proposed by him is established in the following equation:

$$W(K) = [1 - e^{(-\beta)}](M_p + E_{ss}) + [e^{(-\beta)}](T_s - T_r) \quad (1)$$

A set of good control parameters K_p , K_i and K_d can produce a good system response by minimizing the evaluation function. The evaluation function includes the settling time (T_s), rise time (T_r), maximum overshoot (M_p) and steady-state error (E_{ss}). [5] applied PSO-PID algorithm to improve the step transient response of an AVR system. PSO algorithm is used to determine the three PID controller parameters: K_p , K_i and K_d . The controller parameters represent an individual K by $K \equiv [K_p, K_i, K_d]$; therefore there are three members in an individual. These members are allocated as real values. In the process of developing the PSO-PID tuning algorithm, [5] replaced few terms in the PSO algorithm developed by [7]. The term “individual” is used to replace the term “particle” and “population” replaces the term “group”. If there are n individuals in a population, then the dimension of a population is $n \times 3$. For the population number, [5] and [10] suggested to use 50 population ($n = 50$).

[5] also proposed the Routh-Hurwitz criterion to limit the evaluation value for each individual in the population within a suitable range. According [5], the Routh-Hurwitz test shows the closed-loop control system stability and each individual is suitable to be implemented. It will produce a small value of $W(K)$. The evaluation function f in (2) is the result of the reciprocal of the Eq.(1).

$$f = \frac{1}{W(K)} \quad (2)$$

This evaluation function will be used in the PSO-PID algorithms as the performance evaluation function. In addition, [5] used inertia weight ω as proposed by [12] to provide a balance between global and local

exploration. Inertia weight can reduce the average iterations number and can adequately obtain optimal results. Thus, [5] agreed with [3] and [8] that the most appropriate inertia weight value is in the range of 0.9 to 0.4. [5] introduces Eq.(3) in his research to allow a balance between global and local exploration. The equation involves inertia weight maximum and minimum values $(\omega_{\max}, \omega_{\min})$ the maximum iteration number $(iter_{\max})$ and the current iteration number $(iter)$. The equation is:

$$\omega = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{iter_{\max}} \times iter \quad (3)$$

Next, there are nine steps used by Gaing in the PSO-PID tuning algorithm. In order to find the best value of K_p , K_i and K_d , He used the following nine steps.

3. Variable Weight Grey-Taguchi DOE method

The proposed tuning algorithm includes the Variable Weight Grey-Taguchi method in the process of determining the optimum setting of maximum velocities for each parameter in order to obtain optimum values of K_p , K_i and K_d .

Step 1: Determine the Factors

First step is the definition of the problem. In this step, the control factors and response factors are identified and selected. The control factors are based on parameters that give significant effect to the output. This study focuses to manipulate two PSO parameters: Limit of change in velocity ($V_{\max}$) and weighting factor (β).

$V_{\max}$ works as a constraint to control the global exploration ability of a particle swarm. It determines the resolution, or fineness, with which regions between the present position and the target position are explored. If $V_{\max}$ is too high, particles might fly past good solutions. However, if $V_{\max}$ is too small, on the other hand, particles may not explore sufficiently beyond locally good areas. The weighting factor β on the evaluation function $W(K)$ can be adjusted to meet specific requirements. The settings of β can also be considered as the manipulated variable to determine the optimal parameter values. Therefore, Variable Weight Grey-Taguchi method is applied to determine the best value of $V_{\max}$ for each particle and the weighting factor, β . $V_{\max}$ and β are set as the control factors in the Variable Weight Grey-Taguchi method.

Step 2: Identify the Level

Second step is designing and identifying the level of Orthogonal Arrays (OA) to determine the suitable number of experiments. By using OA, the number of experiments can be reduced and the calculation is presented in a few steps. The first step is to determine the Degree of Freedom (DOF) using Eq.(4) below.

$$DOF = L_i - 1 \quad (4)$$

whereby L_i is the number of levels. Second step is to design the suitable OA using Eq.(5) below.

$$OA = (DOF \times N) + 1 \quad (5)$$

N is the number of factors. For the same number of factors and levels using OA required at least nine experiments. However, this study needs larger OA because L_9 may not fulfil the requirement for higher resolution. Then, the selection of L_{27} with 27 experiments is appropriate for higher resolution.

Step 3: Conduct the PSO Tuning Algorithm

In this step, the nine steps of PSO algorithm are applied to determine the response factors. The simulation process will be conducted by referring to the rows of selected OA. The control factors combine with levels respectively in each row.

Step 4: Analyse the Data

The next step is to analyse the data based on the Grey-Taguchi algorithm. The normalized raw data and GRC values in each factor are then calculated. This transformation is called Grey Relational Grade (GRG). Using this GRG values the optimal parameter value is determined by the highest values.

The normalized value lies between zero and one whereby better performance is reached when the normalized value is larger. The ideal value is equal to one. The grey relational coefficient (GRC) is used to determine the relationship between ideal and actual normalized response. The average calculation of GRC for each factor called Grey Relational Grade (GRG). Eq.(6) shows the average calculation of GRC.

$$GRG = \frac{GRC}{i} \quad (6)$$

whereby, i is the number of response factors.

Step 5: Select the Optimum Parameters

Then, optimum control factors are obtained from the average GRG at each parameter. The higher values of average GRG yield a better combination of parameters. So, the GRG values which are closer to 1.0, is closer to the ideal response.

Step 6: Determine the System Response

The next step is to verify the results obtained from an optimum set of factors. All the obtained parameters of maximum velocities will be run in PSO-PID tuning algorithm to get the PID parameters and system response values. The following nine steps of PSO algorithm will be repeated in this procedure.

Step 7: Verify the Result

The last step is to validate the obtained PID parameter values by comparing both simulation and physical experiment. Comparison between both results are conducted based on the system responses: transient response and steady-state response.

4. Simulation of the system

The DOE data set is implemented using the Variable Weight Grey-Taguchi in MATLAB program. The calculation of normalized value, GRC and GRG for 20%, 2% and 0.2% of the variable dynamic range on each dimension using Variable Weight Grey-Taguchi algorithm are recorded.

Therefore, the optimum set of PSO parameters is determined by picking the highest values of average GRG at each particle. The levels and values selected as an optimum set of PSO parameters are shown in Table 1.

Table 1. PSO parameters from optimum PSO parameters

PSO Parameters	Level	Value
V_{max}, K_p	3	2.00
V_{max}, K_i	3	0.20
V_{max}, K_d	2	0.02
Weighting factor, β	1	1.00

Then, the optimum sample is investigated using the PSO algorithm to determine the value for the performance characteristics. Table 2 shows the performance characteristic of the optimum PSO parameters.

Table 2. Performance characteristics of the optimum PSO parameters

Performance Characteristics	Weight	Value
Rise time, T_r (s)	0.01	0.083000
Settling time, T_s (s)	0.01	0.144000
Maximum overshoot, M_p	0.90	-1.188.E-12
Evaluation value, f	0.80	44.56200

The PID controller parameters are tuned by two methods. The first method is the proposed optimization method. For confirmation, the classical method (Ziegler-Nichols method) is used to compare the performance response for both methods [6]. Table 3 shows the PID parameters values for both methods and performance criteria of both methods.

Table 3. PID parameters values

Methods	Ziegler-Nichols	PSO-PID DOE
K_p	6.34156	8.77385000
K_i	0.20000	0.00861000
K_d	0.05000	0.13136500
T_r (s)	0.16000	8.3000.E-02
T_s (s)	0.28000	1.4400.E-01
M_p	0.23720	1.188.E-012

Table 4. Performance response for different set point of step response

Set Point (cm)	Ziegler-Nichols tuning algorithm			The proposed PSO-PID tuning algorithm		
	T_r (s)	T_s (s)	M_p	T_r (s)	T_s (s)	M_p
10	0.3865	0.5287	1.3514	0.3723	0.5093	0.4886
9	0.3477	0.4652	0.4190	0.3215	0.4587	1.3651
8	0.3100	0.4266	0.4857	0.3128	0.5125	1.4821
7	0.2738	0.3762	0.8082	0.2677	0.4990	1.5306

Table 4 shows performance results at different set points for both methods. The performance of both methods clearly shows that the modified algorithm improves the rise time, settling time and maximum overshoot.

5. Discussion

The purpose of this paper is to model and to improve the system performance of hydraulic positioning system. The paper proposed a system model using a mathematical transfer function to simulate actual system behaviours. This paper also proposed a PSO-PID tuning algorithm in combination with the Variable Weight Grey-Taguchi DOE in order to determine the optimum PID parameters.

6. Conclusion

In conclusion, the PSO-PID tuning algorithm with the Variable Weight Grey-Taguchi DOE successfully obtained the optimum PID parameters. The simulation results verified that the proposed tuning algorithm improved transient response compared to Ziegler-Nichols tuning algorithm. The transient response results from the modified PSO-PID tuning algorithm improved 48.13% of rise time and 48.57% of settling time. The physical experiment results verified that the proposed PSO-PID tuning algorithm improved the system performance.

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