Classical and Metaheuristic Optimizations Performance in an Electro-Hydraulic Control System

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***Abstract*—Electro-Hydraulic Actuator (EHA) system is a prevalent mechanism in industrial sectors. This system commonly involving works that required high force such as steel, automotive and aerospace industries. It is a challenging task to acquire precision when dealing with a system that can produce high force. Besides, since most of the mechanical actuator performance varies with time, it is even difficult to ensure its robustness characteristic towards time. Therefore, this paper proposed the industrial's well-known controller, which is the Proportional-Integral-Derivative (PID) controller that can improve the precision of the EHA system. Then, an enhanced PID controller, which is the fractional order PID (FOPID) controller will be applied. A classical and metaheuristic optimization methods, which are gradient descent (GD) and particle swarm optimization (PSO) algorithm are used to obtaining the optimal gains of both controllers. In addition, to examine the tracking performance of the designed controllers, the performance of the proposed optimization algorithms is analysed. As a result, in a practical point of view, it can be inferred that the PSO algorithm is capable to generate more practical sense of gains compared with GD, and the precision characteristic of the FOPID is greater than the PID controller.**

***Index Terms*—positioning tracking analysis, Electro-Hydraulic Actuator (EHA), robust control design, gradient descent optimization, particle swarm optimization**

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I. Introduction

Dynamics delivered to the Electro-Hydraulic Actuator (EHA) system are usually linear or rotary, which are also referred as the cylinder or motor. Due to its character that is capable to deliver high forces, widespread engineering applications dealing with these high-forces dynamics have been found in construction [1], agriculture [2], oil and gas [3], mining and material handling machinery [4]. Whereby, EHA system produces massive contributions in the engineering sector that impetus the world economy [5].

However, the existence of uncertainties, nonlinearities behaviour and disturbances in the EHA system normally causing tracking errors and phase lag during the position tracking process, which consequently increase the challenge of the controller design [6]. These existing drawbacks motivate researchers to further investigate the potential method that is capable to enhance the hydraulic actuator performance. Where control system emerged to be effectively improved the EHA system performance by reducing the effect of the existing drawbacks.

Owing to the fact of the proportional-integral-derivative (PID) controller, which is easy to be understood, it is a universal control strategy in the industrial sector, and a control strategy trademark for researchers to conduct their research. In a recent trend, researchers have intended to alter the structure of this controller so that enhancement can be achieved. Most

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common structures including gain-scheduling and fractional order that is evidence to be performed better than the conventional PID controller [7–10]. With the synthetization of computational optimization algorithms in these control strategies, great improvement has been obtained in the EHA system [11–13].

This paper addressing the tracking performance of the PID and FOPID controller in terms of error analysis implemented in the nonlinear EHA system. Both control parameters will be optimized using classical and metaheuristic algorithms, which are gradient descent (GD) and particle swarm optimization (PSO), respectively. Then, the controller performances are examined comprehensively in a simulation environment. The work will be implemented in hardware in a near future. The organizations of this paper are, the discussion of the system modelling, the optimization methods are first presented. Then, a comprehensive examination of the controller performances is carried out. Subsequently, the overall performances of both controllers implemented in the EHA system will be concluded.

II. Modelling and Optimization

A. Modelling of the Electro-Hydraulic Actuator System

In current work, proportional will be utilized in the experimental platform. The spool of the proportional valve is driven by the motor with a certain amount of torque as depicted in Fig. 1.

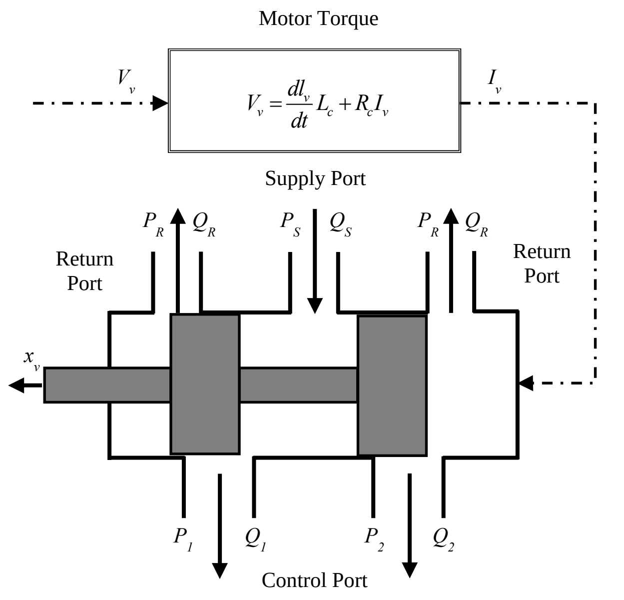

Figure 1. Common structure of EHA valve.

The torque of the motor is producing from the voltage, V_v and generating the current, I_v that produced mechanical motion of the spool valve, which can be expressed in equation (1).

$$V_v = \frac{dl_v}{dt} L_c + R_c I_v \tag{1}$$

where L_c and R_c denote the inductance and the resistance, respectively.

A second-order differential equation is formed through the derivative of the electrical equation as indicated in equation (2).

$$\frac{d^2 x_v}{dt^2} + 2\xi_v \omega_v \frac{dx_v}{dt} + \omega_v^2 x_v = I_v \omega_v{}^2 \tag{2}$$

where ξ and ω represent the damping ratio and the natural frequency of the spool valve.

The position of the proportional valve is considering to be centred that control the flow of the fluid, Q of the chamber. The equation of flow rate, Q in equation (3) consists of the proportional valve gain, K_v and the pressure difference, P_v that affecting the position of the spool valve, x_v.

$$Q = K_v x_v \sqrt{\Delta P_v} \tag{3}$$

In each chamber, the characteristic of the fluid flow is denoted in (4) and (5) by neglecting the leakage effect that is uncertain to be occurred [14].

$$Q_1 = \begin{cases} K_{v1} x_v \sqrt{P_s - P_1} & ; x_v \geq 0, \\ K_{v1} x_v \sqrt{P_1 - P_r} & ; x_v < 0, \end{cases} \tag{4}$$

$$Q_2 = \begin{cases} -K_{v2} x_v \sqrt{P_2 - P_r} & ; x_v \geq 0, \\ -K_{v2} x_v \sqrt{P_s - P_2} & ; x_v < 0, \end{cases} \tag{5}$$

In the evolution of the EHA system, the pressure regulator is commonly equipped on the power pack. The operating pressure is thus can be limited by the regulator. The dynamics of the pump and the proportional valve forming the pressure as expressed in (6).

$$P_s = \frac{\beta_e}{V_t} (Q_{pump} - Q_L) dt \tag{6}$$

where β_e is the bulk modulus of the fluid, V_t is the piping volume, which is connected between the pump and the proportional valve, Q_{pump} is the constant flow rate from the pump volume, Q_L is the flow rate from the proportional valve volume.

It is well-known that most mechanical systems are highly nonlinear in nature, thus, an appropriate control strategy is necessary to compensate for the existing drawback. The discussion of the controller design has been done in [15]. By implementing an appropriate optimization approach, the prominent performance of the system is believed to be achieved.

B. Gradient Descent Tuning Method

Gradient Descent (GD) is a classical deterministic optimization algorithm, which is commonly executed by following the command, for instance starting conditions, path, procedures, and function. Randomness usually does not exist in deterministic algorithms [16].

Gradient ascent or descent is both implemented for maximization and minimization of such as financial profit, and error function, respectively. By comply with user command, GD executed and searching from the initial to the final nearest point of a particular function, with the different paths that consist of different step sizes as illustrated in Fig. 2.

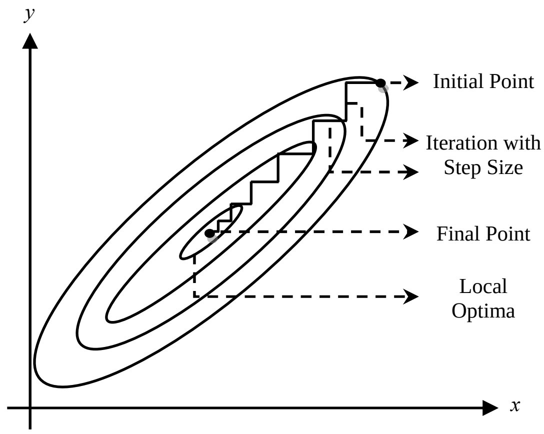

Figure 2. Common process of the gradient descent classical deterministic optimization algorithm.

The value of a particular function is reduced at a very fast rate in a slope direction. Based on the stopping criteria such as the cost function that usually refer to means square error reached lower bound, iteration reached the maximum value, the process is repeated by referring to the equation (7).

$$X_{i+1} = X_i - \lambda_i \nabla f(X_i) = X_i - \lambda_i g(X_i) \tag{7}$$

where for a particular function $f(X)$, the changes of the gradient operator ∇ is based on the step size of λ. λ is crucial that commonly varies over time to avoid the diverging phenomena. Commonly, the stable condition of λ leads to the following equation (8).

$$f(X_{i+1}) \leq f(X_i) \tag{8}$$

The zigzag or orthogonal form of directional derivative depicted in Fig. 2 is formed based on equation (9).

$$\frac{d}{d\lambda_i} f(X_{i+1})^T . \frac{d}{d\lambda_i} X_{i+1} = -\nabla f(X_{i+1})^T g(X_i) \tag{9}$$

The initial setting of the GD required further study and analysis before the implementation to any system. In this article, the initial value of Ziegler-Nicholes as in [17] was adopted. An appropriate setting is necessary based on the end function of a particular system. The end function in the electro-hydraulic system including lifting, pressing, and clamping. Some of the end functions required fast convergence of this optimization algorithm. Some might require high precision. The setting that has been made might work in a simulation environment, but further performance inspection in the experimental environment is needed.

C. Particle Swarm Optimization

Particle Swarm Optimization (PSO) is known to be uncomplicated and able to be applied to various applications [18]. Basically, the implementation of the PSO algorithm can be summarized as in Fig. 3.

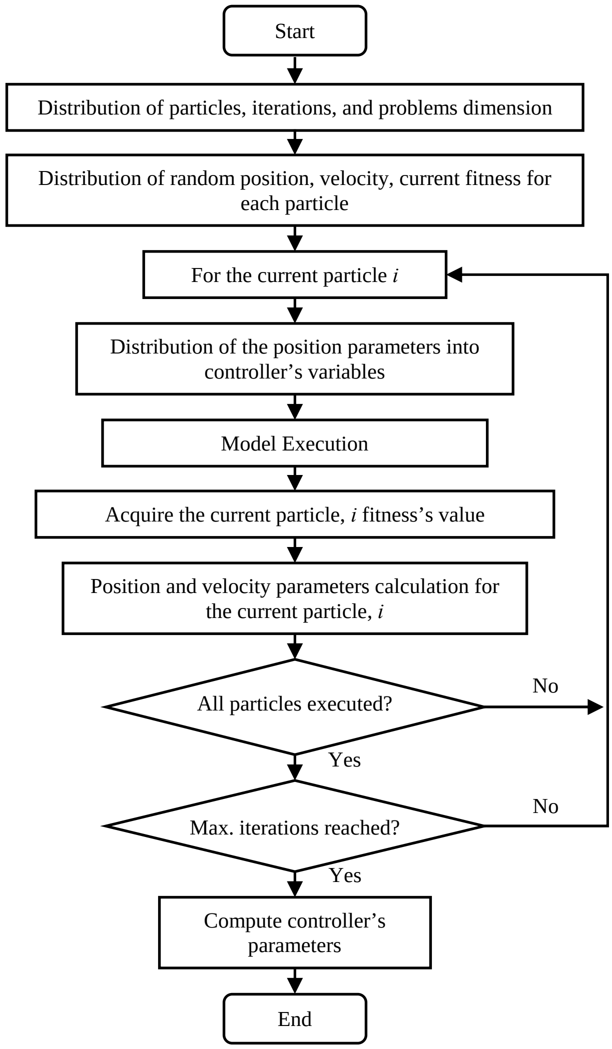

Figure 3. Common process of the gradient descent classical deterministic optimization algorithm.

The searching will always start with randomly distributed position and velocity values on the wide range of searching area. All the particles will then share their velocity and position information obtained in every iteration. The particle will be updated with new velocity and position information based on the formula as stated below [19].

$$\begin{aligned} v_{id}^{k+1} = v_{id}^{k} + c_1 rand_1^k (pbest_{id}^k - s_{id}^k) \cdots \\ + c_2 rand_2^k (gbest_{id}^k - s_{id}^k) \end{aligned} \tag{10}$$

$$s_{id}^{k+1} = s_{id}^{k} + v_{id}^{k+1} \tag{11}$$

Searching will be ended when one of the criteria is fulfilled. The criteria are such as achievement of the minimum error, and maximum iterations are reached. Descriptions for formulas 10 and 11 are summarized in Table I [20].

TABLE I. DESCRIPTION OF THE PSO FORMULA

Terms	Description
v	Particle's velocity
k+1	Particle's future iteration
I	Particle's value, where i = 1, 2, 3, …, n
d	Problem dimension of a particular system, where d = 1, 2, 3, …, n
k	Particle's iteration, where k = 1, 2, 3, …, n
$c_{1/2}$	c_1 = self-coefficient c_2 = group / swarm-coefficient
$rand_{1/2}$	$rand$ = random value ranged from 0 to 1 $rand_1$ = random value of self-coefficient $rand_2$ = random value of group-coefficient
pbest	Particle's personal or self-best value
gbest	Particle's group / swarm or global best value

III. RESULTS AND DISCUSSION

In the control system, conventional tuning methods such as try and error, common Ziegler-Nichols tuning method for PID controller might hardly maximize the performance of a controller. Optimization methods are therefore compensating for this circumstance by obtaining the optimal gains of a controller. Countless optimization methods have been introduced over time through different device approach with a similar objective, which is to obtain an optimal result.

In this paper, MATLAB/Simulink 2021a software will be fully used to conduct the controller design and optimization process. By using a step response, the performance of the designed controllers, which are proportional-integral-derivative (PID) and fractional-order proportional-integral-derivative (FOPID) have been observed. By using the classical and metaheuristics optimization methods, which are Gradient Descent (GD) and Particle Swarm Optimization (PSO), the performance of the obtained gains, implemented into the PID and FOPID controller have been evaluated.

Table II listed the parameters or gains acquired from both GD and PSO optimization methods. Fig. 4 is the output result with a specific line or waveform representation as indicated in the legend. Based on the result on the figure, and the numerical data in Table III, the PID and FOPID controllers, which optimized using GD showing slightly different performances compared with the PSO. While the FOPID controller that optimized using the PSO algorithm is far better than the PID controller.

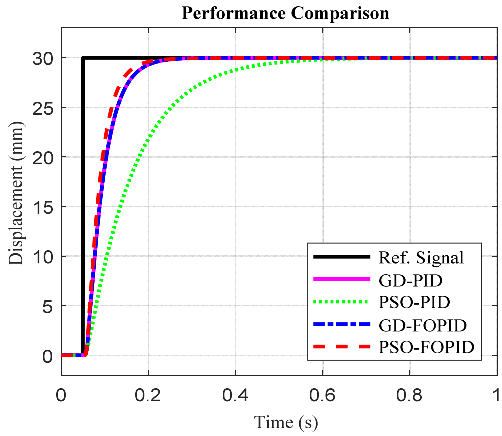

Figure 4. Output performance of PID and FOPID with GD and PSO optimization algorithms.

In this work, the PSO algorithm implemented to search for the PID and FOPID gains was using random values as its initial value. While GD algorithm has using Ziegler-Nicholes parameters as emphasized in the earlier section as its initial value, which cannot be executed in a random parameter. Since the GD toolbox has been well-developed in MATLAB, thus the toolbox will be used, where fix initial gains are necessary before the execution. Instead of fix initial gains, PSO required only random or simply said any initial value to searching for the optimal gains.

Thus, in this situation, the performance measurement matric as tabulated in Table III is necessary to be involved. Since PSO is much more user friendly than the GD, which is like plug and play execution, thus the performance in terms of accuracy and precision might be degraded. However, as shown in the numerical data in the table, the overall performance in terms of overshot percentages, rise time, settling time and the root means square error analyses of the FOPID controller that optimized using PSO algorithm has outperformed the other three strategies.

TABLE II. GAINS OBTAINED USING GRADIENT DESCENT AND PARTICLE SWARM OPTIMIZATION METHODS

Controller	Parameter				
	K_p	K_i	K_d	λ	δ
PID-GD	123.2469	0.0150	0.0038	1	1
PID-PSO	49.8454	0.0149	0.0471	1	1
FOPID-GD	123.2799	0.0150	0.0038	1	1.0053
FOPID-PSO	49.8377	44.1156	0.0584	49.5288	0.0664

TABLE III. ROOT MEANS SQUARE ERROR, TRANSIENT RESPONSE AND STEADY-STATE ERROR ANALYSES

Controller	Transient Response			Steady-State Error (e_{ss})	RMSE
	OS (%)	T_r *(s)*	T_s *(s)*		
PID-GD	6.4480x10^{-07}	0.0841	0.2054	1.7607x10^{-04}	1.6362
PID-PSO	7.9940x10^{-06}	0.2350	0.4755	1.0469 x10^{-03}	2.4027
FOPID-GD	1.9990x10^{-06}	0.0840	0.2053	1.7600 x10^{-04}	1.6360
FOPID-PSO	0	0.0687	0.1842	3.0375 x10^{-04}	1.5310

Furthermore, from a practical standpoint, in terms of the gain's feasibilities for both GD and PSO algorithms, the value of the gains for the PSO is more reasonable than the GD that has very high gains. However, this statement required further analyses in the experiment environment. Thus, both GD and PSO optimization methods have their pros and cons. The knowledge for a proper setting is necessary so that the algorithm can perform optimally.

Refer to Fig. 5, the yellow boundary on the right side was formed based on the setting that has been made before the execution. In this paper, the default setting has been adopted by only changing the reference response value. The setting can still be adjusted to minimize the error obtained in the result. However, further examination in a practical experimental environment is necessary to examine the performance of the obtained gains. Damage or instability might be occurred due to the very high gains.

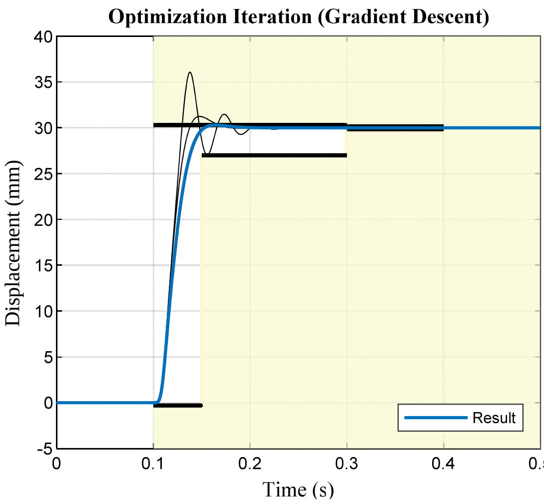

Figure 5. Optimization iteration for classical GD optimization method.

IV. CONCLUSION

A research based on two different control strategies with two different optimization algorithms is conducted. The simple and industrial's favourite controller, which is the PID controller is first designed under the nonlinear and uncertain characteristics of the EHA system. Followed by the enhanced PID controller with the so-called FOPID controller is designed. The controller's gains are obtained using GD and PSO algorithms. Based on the result, the PID and FOPID controllers, which were optimized using GD capable to acquire better performance compared with the PSO. However, most of the classical optimization algorithms are known to be having issues in dealing with multimodal or discontinuity functions. Therefore, most of the optimization methods, including classical and metaheuristic optimization methods existed with the trade-off to satisfy all the performance matrixes including precision, accuracy, and feasibility in the practical environment. Hence, researchers are encouraged to develop a method that is capable to covered-up most of the performance matrixes.

CONFLICT OF INTEREST

Authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

C. C. Soon and R. Ghazali conducted the research, analyzed the data, and wrote the paper. S. H. Chong, M. F. Ghani, Y. Md. Sam, Zulfatman review the manuscript. All authors had approved the final version manuscript.

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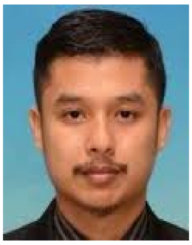

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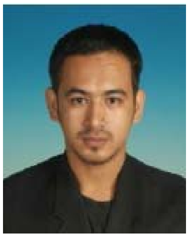

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