NPID DOUBLE HYPERBOLIC CONTROLLER WITH PARTICLE SWARM OPTIMIZATION (PSO) TECHNIQUE FOR XY TABLE BALLSCREW DRIVE SYSTEM

L. Abdullah[1], S.C.K. Junoh[1], Z. Retas[1], S.N.S. Salim[2] and M.H. Nordin[3]

[1]Faculty of Manufacturing Engineering,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

[2]Faculty of Electrical and Electronic Engineering Technology,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya,
76100 Durian Tunggal, Melaka, Malaysia.

[3]London South Bank University, 103 Borough Road,
SE1 0AA London, United Kingdom.

Corresponding Author's Email: [1]lokman@utem.edu.my

Article History: Received 15 October 2019; Revised 13 March 2020; Accepted 16 October 2020

ABSTRACT: The difficulty in determining the parameters of NPID Double Hyperbolic controller tends to apply an optimization technique. In this study the optimization technique named as Particle Swarm Optimization (PSO) technique is applied on the NPID Double Hyperbolic controller for XY Table Ballscrew drive system. The inspiration of the PSO is based on the behavior of bird flock in which all particles are placed at random position and supposed to move randomly in a defined direction in the search space. Eventually, each particle moves along the direction of its best previous positions to discover a new better position with respect to some error measures. In addition, the PSO technique is able to obtain the optimum parameters in order to produce a better performance of a system based on an error function obtained from tracking error. The PSO using NPID Double Hyperbolic controller scheme is designed via MATLAB/Simulink software and the PSO is run for 10 times in obtaining a better RMSE result. For future work, it is recommended to explore the superiority features offered in another optimization for better judgment in improving a better convergence of optimization process.

KEYWORDS: *Machine Tools; NPID Double Hyperbolic Controller; Particle Swarm Optimization*

1.0 INTRODUCTION

Recently, optimization techniques are widely uttered by many researchers in the area of controller design. There are quite a number of optimization techniques were introduced by researchers especially for the purpose of obtaining optimum parameters of the controller which affect the performance of the system [1-5]. One example of optimization method is Particle Swarm Optimization (PSO) technique. The PSO was established in 1995 in which the PSO technique was successfully computerized using the bird flocking behavior [12]. Owing to this advantage, PSO technique was widely applied on the controller design in obtaining the optimum parameters. For instance, three different tuning methods namely Ziegler-Nicholas (ZN) method, PSO, and Firefly Algorithm (FA) in obtaining the parameters of PID controller as shown in [6]. The simulation results showed that the ZN method produced smallest rise time, while the PSO produced better transient response; smallest settling time, smallest overshoot and smallest steady state error. These tuning methods were also evaluated in term of absolute position error. The PSO produced smallest error of 0.4898, while the ZN and the FA produced error of 0.7000 and 0.5641, respectively. Furthermore, Kumar et al. [7] proposed a cuckoo PID controller for three different mathematical models of nonlinear systems such as inverted pendulum, ship roll dynamics and Van der Pol oscillator. The simulation with sinusoidal input for inverted pendulum showed that cuckoo PID produced better performance compared to PSO-PID controller.

After that, Tomera [8] applied an ant colony optimization (ACO) in order to tune the PD controller for ship steering application by using MATLAB/Simulink. This ACO searched a shortest path starting from the ant's nest to the food position. The number of ants, maximum number of iterations, pheromone influence gain and indicator describing the evaporation rate were determined as 10, 20, 3 and 0.05, respectively. This ACO technique was compared to genetic algorithm (GA). The performance index in term of integral absolute error (IAE) showed that the ACO was assigned to reduce this error. The ACO produced a faster converging to determine the PD parameter compared to GA technique which both techniques were run for 10 times. This study concluded that the ACO was an effective technique to tune the PD controller and useful for further complex optimization problems. In a subsequent study, Ouyang and Pano [9] presented three different types of tuning position domain PID parameter for 3-DOF planar robotic manipulator. There are particle swarm optimizations (PSO), differential evolution (DE) and genetic algorithm (GA); also named as meta-heuristic optimization algorithms. These techniques enabled in optimizing the gains of the controller based on these algorithms as well as a good performance of the system for linear and nonlinear contour under various fitness functions such as ISE, IAE, and mean and standard deviation of absolute error (MSMAE). The results showed that the PSO-ISE produces smallest linear contour error, while DE-IAE produces smallest nonlinear contour error. Next, Sambariya et al. [10] developed a new meta-heuristic, namely Firefly algorithm (FFA) in order to optimize the PID parameter for standard single machine infinite-bus (SMIB). This FFA was inspired from firefly behavior in which they were attracted to a brighter light. The light intensity of this FFA was proportional to the inverse of the fitness value. This light intensity was reduced when the distance between the two fireflies was increased. The performance indices used were integral of the time-weighted absolute error (ITAE), integral square error (ISE), and integral of the absolute error (IAE). This study found that the FFA technique produced a more stable system compared to Many Optimizing Liaisons (MOL) and Ant Bee Colony (ABC). The reviews above showed that the optimization techniques were widely applied on PID controller in obtaining the optimum PID parameters.

Furthermore, the reviews above on the optimization method in obtaining the optimum parameters of PID controller showed that the PID controller was still used nowadays due to simple design and better performance. Owing to the simplicity design of PID controller, an improvement controller namely nonlinear PID or can be called as NPID controller was investigated in order to improve the PID's performance. In addition, the NPID controller successfully improved the performance of various applications compared to the PID controller as investigated by [24-26]. In recent years, the application of optimization technique on NPID controller started to be investigated. For example, Jin and Son [24] proposed a NPID controller based on tuning rules of first-order plus time delay model and tuning rules of a genetic algorithm. Regarding to the recent investigation on optimization technique for NPID controller, this study proposed an application of PSO – based NPID Double Hyperbolic controller. The NPID Double Hyperbolic controller consisted of two nonlinear components as adopted from previous work by Junoh et al. [11] for XY Table Ballscrew drive system. The parameters of this controller were difficult to determine due to the nonlinear gains consisted of five parameters and these parameters cannot be assumed as zero value at every calculation. Owing to this reason, the author proposes a PSO-NPID Double Hyperbolic controller scheme to address this issue.

2.0 METHODOLOGY

2.1 Experiment Setup

This study uses a XY Table Ballscrew drive system which is linked to a personal computer, Digital and Analog converter (DAC/ADC) board and amplifier board as illustrated in Figure 1. The personal computer is equipped with MATLAB/Simulink and dSPACE software in enabling to obtain a transfer function of the system which is used on the control system in performing some work of simulation of PSO – based NPID Double Hyperbolic controller scheme. The transfer function is determined from the input and output system data. It is also determined as a second order transfer function that is described as a mass-spring-damper system [11]. The detail of experimental setup and transfer function of the system are already adopted from previous work by Junoh et al. [11].

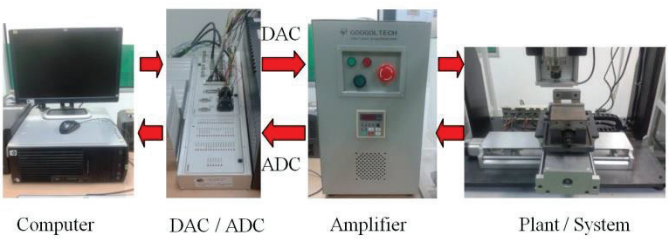

Figure 1: Four main components of experimental setup

2.2 PSO Algorithm

The PSO is an optimization technique which is inspired from behavior of a flock of birds. The PSO technique is introduced by Eberhart and Kennedy [12]. It starts with randomly movement of some particles at certain position and velocity. The position and velocity of particles are derived using MATLAB syntax in Equation (1) and Equation (2) such as

$$AP(p,d) = lP(d) + (uP(d) - lP(d)) * rand() \tag{1}$$

$$AV(p,d) = rand() \tag{2}$$

where, AP(p,d) is particle position at particle and dimension, p is particle, d is dimension, lP(d) is dimension of lower limit of position, Up(d) is dimension of upper limit of position, and AV(p,d) is particle velocity at particle and dimension. These randomly particle's position and velocity will be updated towards the best position based on the personal best position and the global best position. The detail knowledge of these position and velocity algorithm are disclosed by many researchers such as [13-21]. The updated particle velocity and particle position are derived in Equation (3) and Equation (4), respectively. At that time, each particle produces the best value that is saved at every iteration. This process is continued until the particles find a target value with the best global value.

$$\begin{aligned} AV(p,d) &= iw * AV(p,d) + c * rand() * (PeP(p,d) - AP(p,d)) + \\ & s * rand() * (GP(i,d) - AP(p,d)) \end{aligned} \tag{3}$$

$$AP(p,d) = AP(p,d) + AV(p,d) \tag{4}$$

where, iw is inertia weight ranged from 0.4 to 0.9, c is cognitive coefficient ranged from 1.4 to 1.9, s is social coefficient ranged from 1.4 to 1.9, PeP(p,d) is personal best position at particle and dimension, GP(i,d) is global best position at iteration and dimension, rand1 and rand2 are random numbers in the range, and i = 1, 2, 3, 4,…, are the number of iterations [27-29].

2.3 PSO Using NPID Double Hyperbolic Scheme

The NPID Double Hyperbolic controller scheme was adopted from previous work in [11]. It consists of PID controller and two mathematical hyperbolic functions; namely, nonlinear proportional, NP, and nonlinear integral, NI of the controller. The PID controller consists of three parameters, namely proportional gain (KP =1.12 V/mm), integral gain (KI = 0.006 V.s-1/mm), and derivative gain (KD = 0.007 V.s/mm). In addition, the NP function is added before KP and the NI function is added before KI. The NP function is designed by increasing the NP value when the error is increased and by decreasing the NP value when the error is decreased. Meanwhile, the NI function is designed by increasing the NI value when the error is decreased and by decreasing the NI value when the error is increased. The detail of these functions is adopted from previous work [11]. These functions includes five parameters in which the NP includes two parameters; f and g, while the NI includes three parameters; m, q and r. These five parameters are needed to be determined in order to improve the tracking performance of the XY Table Ballscrew drive system. Therefore, these parameters are determined with the best global value of PSO algorithm in which the PSO code is written on the command window of MATLAB, while the NPID Double Hyperbolic controller scheme as shown in Figure 2 is designed on the Simulink/MATLAB software. In order to link both code and controller, the PSO code is written as shown in Equation (5) to call the Simulink filename of NPID Double Hyperbolic. After that, the error function is calculated to update particles' new position and velocity for each iteration of PSO run. The error function is obtained from tracking error and written by PSO code as calculated in Equation (6). The smallest error function produces an optimum controller parameters.

$$\text{sim('NPID\_Double\_Hyperbolic')} \tag{5}$$

$$\text{result} = \text{open('Tracking\_Error.mat')} \tag{6}$$

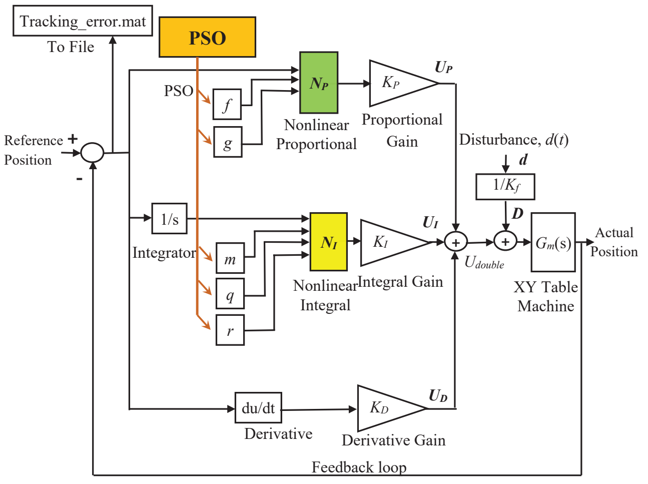

Figure 2: PSO technique using NPID Double Hyperbolic controller

3.0 RESULTS AND DISCUSSION

In this case, 10 PSO runs are conducted to observe the optimum value of nonlinear parameters of NPID Double Hyperbolic controller. Based on previous researchers [3, 14, 18, 22-23], 10 until 30 PSO run should be accomplished. Hence, the 10 PSO run is acceptable for this case. Next, the 10 PSO runs with the best global value for five parameters of nonlinear functions of the NPID Double Hyperbolic controller are performed via simulation test. The simulation test for each PSO run is conducted to demonstrate the validity of PSO – based NPID Double Hyperbolic controller. The performance evaluation for these simulations are conducted in term of Root Mean Square Error (RMSE) for each PSO run. The smallest RMSE value indicates that the nonlinear parameters produced the optimum values.

In addition, the RMSE value is also influenced by cutting force effect. This work uses a cutting force with spindle speed of 1500 rpm and this cutting force is injected on the control scheme. The maximum value of the cutting force is 24.86 Newton. The sinusoidal of input signal is used at frequency of 0.2 Hz and amplitude of 15 mm. The cutting force and input signal with a transfer function of XY table ball screw drive system are injected on the NPID Double Hyperbolic controller as shown in Figure 2 in Section 2.3.

The results of the 10 PSO runs for five parameters of nonlinear functions of the NPID Double Hyperbolic controller are shown in Figure 3 for the case of the NP and Figure 4 for the case of NI. The results show that the value of g is obtained to be larger than the value of f for the case of NP. Meanwhile, for the case of the NI, the value of m is obtained to be much smaller than q and r. The optimum parameters for each PSO run and RMSE result are tabulated in Table 1. The result showed that the PSO run at 2 until 5 produced the smallest RMSE value compared to the other PSO run. Figure 5 shows RMSE result for 10 PSO runs and Figure 6 shows the error results of XY Table Ballscrew drive system for 10 PSO runs.

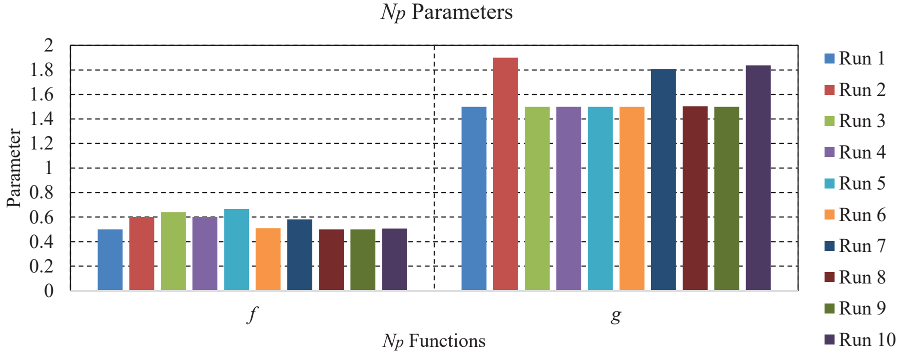

Figure 3: N_P parameter (f and g)

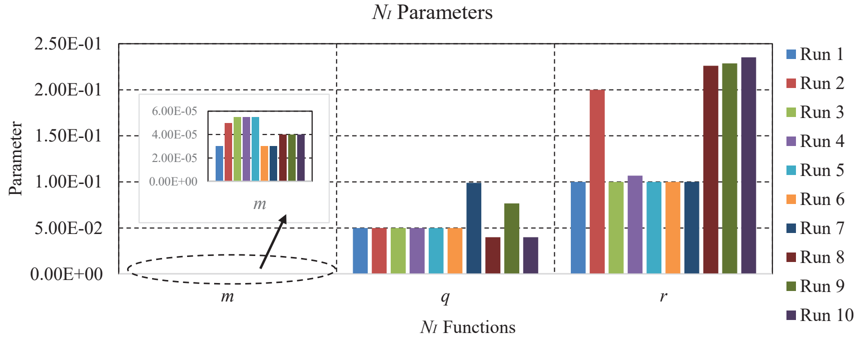

Figure 4: N_I parameter (m, q and r)

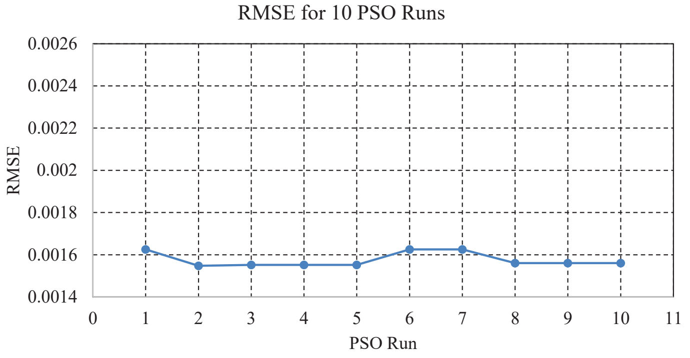

Figure 5: RMSE result for 10 PSO runs

Table 1: N_P and N_I parameters for 10 PSO runs with RMSE result

PSO Run	N_P and N_I Parameters					RMSE (μm)
	f	g	m	q	r	
1	0.5000	1.5000	3.00e-5	0.0500	0.1000	1.63
2	0.6000	1.9000	5.00e-5	0.0500	0.2000	1.55
3	0.6403	1.5000	5.50e-5	0.0500	0.1000	1.55
4	0.6000	1.5000	5.50e-5	0.0500	0.1067	1.55
5	0.6658	1.5000	5.50e-5	0.0500	0.1000	1.55
6	0.5098	1.5000	3.00e-5	0.0500	0.1000	1.63
7	0.5821	1.8066	3.00e-5	0.0990	0.1000	1.63
8	0.5000	1.5033	4.00e-5	0.0400	0.2260	1.56
9	0.5000	1.5000	4.00e-5	0.0767	0.2286	1.56
10	0.5056	1.8372	4.00e-5	0.0400	0.2353	1.56

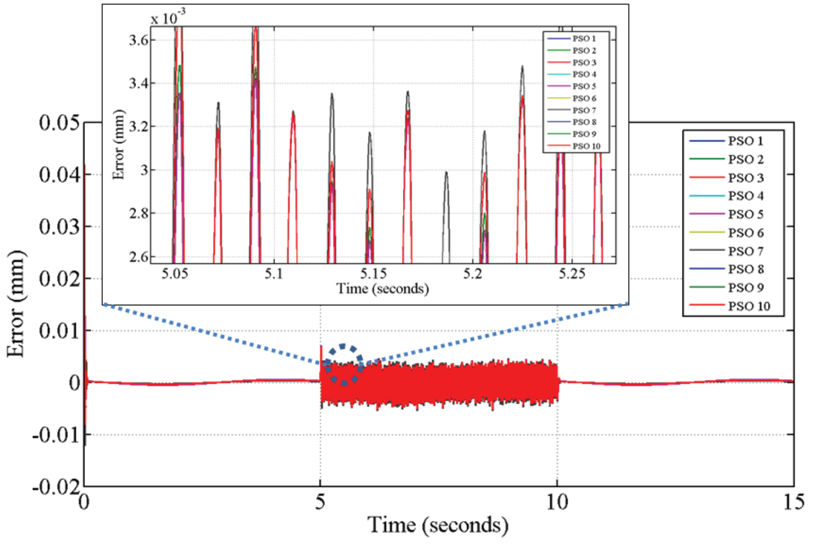

Figure 6: Error results of XY table ballscrew drive system for 10 PSO runs

4.0 CONCLUSION

In conclusion, this study emphasizes that the effectiveness of the proposed PSO using NPID Double Hyperbolic controller to obtain the parameters of the controller. The optimum parameters are expected to improve the tracking performance of the machine tool. The advantage of implementing the PSO technique for this controller is easily tuning the parameters of the controller at optimum values by using the MATLAB software. Thus, the PSO using NPID Double Hyperbolic controller is successfully validated in which the PSO run at 2 until 5 produced the smallest RMSE value compared to the other PSO run. At each PSO run, five parameters of nonlinear hyperbolic functions of the controller are determined to achieve a better tracking performance of XY Table Ballscrew drive system. The result from the 10 PSO runs show that the nonlinear proportional for the parameter of g should be larger than the value of f. Meanwhile, for the nonlinear integral, the parameter m is obtained to be much smaller than parameter q and parameter r. For future work, it is recommended to explore for another optimization technique in order to improve the converging of optimization process that minimize the time computations.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support by Universiti Teknikal Malaysia Melaka (UTeM) and Centre of Smart System and Innovative Design (COSSID) Faculty of Manufacturing Engineering.

REFERENCES

[1] K. Eltag, M.S. Aslamx, and R. Ullah, “Dynamic Stability Enhancement Using Fuzzy PID Control Technology for Power System”, *International Journal of Control, Automation and Systems*, vol. 17, no. 1, pp. 234-242, 2019.

[2] S. S. Kumar, C. Shreesha, and N. K. Philip, "Robust PID controller design for rigid uncertain spacecraft using Kharitonov theorem and vectored particle swarm optimization." *International Journal of Engineering and Technology*, vol. 7, no. 2, pp. 9-14, 2018.

[3] B. Mohanty, and P.K. Hota, “A hybrid chemical reaction-particle swarm optimisation technique for automatic generation control”, *Journal of Electrical Systems and Information Technology*, vol. 5, no. 2, pp. 229-244, 2018.

[4] J. A. Ramirez, J. M. Lopez-Lezama and N. Munoz-Galeano, “Particle swarm metaheuristic applied to the optimization of a PID controller”, *Contemporary Engineering Sciences*, vol. 11, no. 67, pp. 3333-3342, 2018.

[5] Y. Zhou, J. Zhang, X. Yang and Y. Ling, “Optimization of PID Controller Based on Water Wave Optimization for an Automatic Voltage Regulator System”,*Information Technology and Control*, vol. 48, no. 1, pp. 160-171, 2019.

[6] M.A. Abdullah, M.R. Ridzuan, F. Ahmad and M. Ibrahim, “Vehicle active suspension control using multi-order PID approach”, *Journal of Advanced Manufacturing Technology*, vol. 11, no. 1, pp. 1-14, 2017.

[7] P. Kumar, S. Nema and P. K. Padhy, "PID controller for nonlinear system using cuckoo optimization," in International Conference on Control, Instrumentation, Communication and Computational Technologies, Kanyakumari, India, 2014, pp. 711-716.

[8] M. Tomera, “Ant colony optimization algorithm applied to ship steering control”, *Procedia Computer Science*, vol. 35, pp. 83-92, 2014.

[9] P. Ouyang and V. Pano, “Comparative Study of DE, PSO and GA for Position Domain PID Controller Tuning”, *Algorithms*, vol. 8, no. 3, pp. 697–711, 2015.

[10] D. K. Sambariya, R. Prasad and D. Birla, "Design and performance analysis of PID based controller for SMIB power system using Firefly algorithm," in International Conference on Recent Advances in Engineering & Computational Sciences, Chandigarh, India, 2015, pp. 1-8.

[11] S. C. K. Junoh, L. Abdullah, Z. Jamaludin, N. A. Anang, T. H. Chiew, S. N. S. Salim and Z. Retas, "Evaluation of tracking performance of NPID double hyperbolic controller design for XY table ball-screw drive system," in 11th Asian Control Conference (ASCC), Gold Coast, Australia, 2017, pp. 665-670.

[12] R. Eberhart and J. Kennedy, "A new optimizer using particle swarm theory," in International Symposium on Micro Machine and Human Science, Nagoya, Japan, 1995, pp. 39-43.

[13] A. Belkadi, H. Oulhadj, Y. Touati, S. A. Khan and B. Daachi, "On the robust PID adaptive controller for exoskeletons: A particle swarm optimization based approach." *Applied Soft Computing*, vol. 60, pp. 87-100, 2017.

[14] A. M. Jadhav and K. Vadirajacharya, “Performance verification of PID controller in an interconnected power system using particle swarm optimization,” *Energy Procedia*, vol. 14, pp. 2075–2080, 2012.

[15] C. C. Soon, R. Ghazali, H. I. Jaafar, and S. Y. S. Hussien, "Sliding mode controller design with optimized PID sliding surface using particle swarm algorithm," *Procedia Computer Science*, vol. 105, pp. 235–239, 2017.

[16] A. Sungthong and W. Assawinchaichote, "Particle swam optimization based optimal PID parameters for air heater temperature control system," *Procedia Computer Science*, vol. 86, pp. 108–111, 2016.

[17] S. Bouallègue, J. Haggège, M. Ayadi, and M. Benrejeb, "PID-type fuzzy logic controller tuning based on particle swarm optimization," *Engineering Applications of Artificial Intelligence*, vol. 25, no. 3, pp. 484–493, 2012.

[18] Y. Lu, D. Yan, J. Zhang, and D. Levy, "A variant with a time varying PID controller of particle swarm optimizers," *Information Sciences*, vol. 297, pp. 21–49, 2015.

[19] C. Copot, T. M. Thi, and C. Ionescu, "PID based particle swarm optimization in offices light control," *IFAC-PapersOnLine*, vol. 51, no. 4, pp. 382–387, 2018.

[20] P. D. M. Oliveira, "Design of digital PID controllers using particle swarm optimization: A video based teaching experiment," *IFAC-PapersOnLine*, vol. 51, no. 4, pp. 298–303, 2018.

[21] S. M. H. Mousakazemi, N. Ayoobian, and G. R. Ansarifar, "Control of the pressurized water nuclear reactors power using optimized proportional–integral–derivative controller with particle swarm optimization algorithm," *Nuclear Engineering and Technology*, vol. 50, no. 6, pp. 877–885, 2018.

[22] M. M. El-Sherbiny, "Particle swarm inspired optimization algorithm without velocity equation," *Egyptian Informatics Journal*, vol. 12, no. 1, pp. 1–8, 2011.

[23] J. Zhang and S. Yang, "An incremental-PID-controlled particle swarm optimization algorithm for EEG-data-based estimation of operator functional state," *Biomedical Signal Processing and Control*, vol. 14, pp. 272–284, 2014.

[24] G.-G. Jin and Y.-D. Son, "Design of a nonlinear PID controller and tuning rules for first-order plus time delay models," *Studies in Informatics and Control*, vol. 28, no. 2, pp. 157-166, 2019.

[25] G.-B. So, "EA-based design of a nonlinear PID controller using an error scaling technique," *Studies in Informatics and Control*, vol. 28, no. 3, pp. 279–288, 2019.

[26] S. A. Rashad, M. Sallam, A. M. Bassiuny, and A. M. A. Ghany, "Control of master slave robotics system using optimal control schemes," *IOP Conference Series: Materials Science and Engineering*, vol. 610, pp. 1-12, 2019.

[27] R. Poli, J. Kennedy, and T. Blackwell, "Particle swarm optimization," *Swarm Intelligence*, vol. 1, no. 1, pp. 33–57, 2007.

[28] S. Sengupta, S. Basak, and R. Peters, "Particle warm optimization: a survey of historical and recent developments with hybridization perspectives," *Machine Learning and Knowledge Extraction*, vol. 1, no. 1, pp. 157–191, 2018.

[29] Y. He, W. J. Ma, and J. P. Zhang, "The parameters selection of PSO algorithm influencing on performance of fault diagnosis," *MATEC Web of Conferences*, vol. 63, pp. 1-5, 2016.