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Superb Fairy-Wing Algorithm for PID Tuning: A Comparison with Meta-heuristics

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Abstract: Controlling today's engineering systems has become an indispensable part of life. By controlling systems, we ensure that the structure fulfills its purposes in a healthy manner. Although the PID (Proportional–Integral–Derivative) controller dates back to the 1950s, it is still the most preferred controller for controlling systems in many engineering fields. Although the internal structure of the PID controller is simple and understandable, it has been proven to deliver successful results in many studies in the literature. The use of PID controllers in today's systems is becoming increasingly widespread. The Fairy Wren, a small bird species native to Australia with striking plumage, has inspired scientists through the development of the Superb Fairy Wren Optimization Algorithm (SFOA). SFOA offers advantages in situations requiring high accuracy, in which classical algorithms become trapped in local minima. This study marks the first time that the SFOA algorithm has been used to determine the parameters of a PID controller. The Particle Swarm Optimization (PSO) and Artificial Bee Colony (ABC) algorithms, which are well-established meta-heuristic optimization algorithms, were compared with SFOA. The study aimed to determine the K_p , K_i and K_d parameters that best matched the step response within a specific system. Performance evaluations of the meta-heuristic optimization algorithms used in the study were compared using error metrics such as root mean square error (RMSE), which are calculated based on the system's response to the reference signal. The results show that, while classical meta-heuristic optimization methods (PSO and ABC) produce acceptable solutions for adjusting the PID controller parameters, the new-generation meta-heuristic algorithm (SFOA) obtains more accurate and stable PID controller parameters. The success of the SFOA optimization algorithm has been proven using the specified error criteria. This enables its use in setting the parameters of PID controllers, which are also employed in complex systems.

Keywords: PID controller, Optimization systems, Automatic Control, Meta heuristic Algorithm

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1. INTRODUCTION

Controllers are a fundamental requirement for system behavior in many areas of our lives, including industrial systems. PID controllers are widely preferred in today's controller-requiring applications. The main reasons for this are their simple structure and effective feedback system. Today, they are used in HVAC systems, motor speed and position controls, robotic control systems, aviation, automotive, temperature-sensing, manufacturing systems, and servo motors. They are preferred in these systems, particularly due to their low cost and high accuracy (Bansal, et al., 2012; Kushwah & Patra, 2014; Joseph, et al., 2022).

The PID controller essentially generates the control signal by evaluating the error signal using three different evaluators. These are the Proportional (P), Integral (I), and Derivative (D) components. Proportional control responds directly to the instantaneous error. As the error increases, the output becomes stronger. Integral control minimizes long-term errors by accumulating past errors. The integral controller minimizes steady-state error. The derivative controller responds to the rate of change of the error, ensuring system control against sudden changes. The derivative controller minimizes oscillations (Vatansever & Şen, 2013; Izci et al., 2022; Müftü, 2023; Müftü & Gökçe, 2024; Güven & Mengi, 2025).

$$u(t) = K_p e(t) + K_p \int e(t)dt + K_d \frac{de(t)}{dt} \quad (1)$$

In determining the parameters of PID controllers, different structures are being preferred every day. In traditional methods, the Ziegler-Nichols method stands out as a classic technique. As the complexity of the systems used increases, different methods are being preferred. Meta-heuristic algorithms, which have proven themselves in many areas today, can be categorized as inspired by swarm intelligence, evolution, animal behavior, physical and chemical processes, social behavior and interaction, and artificial intelligence-based structures.

Meta-heuristic algorithms have become one of most effective methods for solving complex and non-linear problems in scientific and engineering applications in recent years. Classic methods sometimes fail to reach the desired global solution due to problems such as getting stuck at local minima. Meta-heuristic algorithms do not get stuck in local minima within the solution space because they treat the problem as a whole. One of the fundamental problems addressed by optimization methods, and one of the greatest successes of meta-heuristic algorithms, has been the determination of controller parameter values. (Gandomi et al., 2013; Abdel-Basset, Abdel-Fatah, & Sangaiah, 2018; Çelik, et al., 2019; Almufti et al., 2023; Ortatepe, 2023).

In this study, SFOA, one of the newest methods in today's metaheuristic optimization algorithms, was used to determine the parameters of the PID controller, which is used for many different purposes in the literature. PSO and ABC, which have proven themselves in terms of usability, stability, and success, were used to compare with SFOA (Eberhart & Kennedy, 1995; Karaboga & Akay, 2009). The results obtained scientifically demonstrate that SFOA can be used to determine the K_p , K_i and K_d parameters of the PID controller using RMSE error criteria.

2. MATERIAL AND METHOD

2.1 PID controller

One of the most commonly used controllers in feedback control systems is the PID controller. Occupying a large place in industrial systems, PID produces successful results in the control field by bringing the system behavior closer to the desired reference value (Borase et al., 2021; Tandan & Swarnkar, 2015). The system in which the study was conducted is shown in Figure 1.

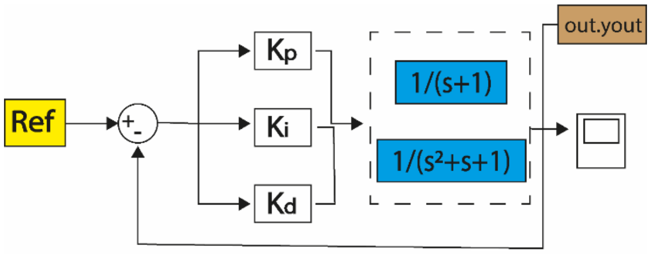

Figure 1. Block diagram of the system under control

Two different transfer functions were used to increase the complexity level of the applied control system. The transfer function given in Equation 2 has a simple first-order structure. It does not require damping and has real negative roots. The transfer function specified in Equation 3, on the other hand, has a complex second-order structure. It is an oscillatory and damped system in terms of time response.

$$G(s) = \frac{1}{s+1} \qquad (2)$$

$$G(s) = \frac{1}{s^2+s+1} \qquad (3)$$

2.2 Meta Heuristic Optimization

There are many methods available for solving optimization problems encountered in scientific research. Meta-heuristic algorithms are structures inspired by successful situations in nature. Meta-heuristic algorithms are influenced by structures such as coefficients and problem constraints within their internal structures. In this study, for the problem of determining the parameters of the PID controller, the K_p , K_i and K_d values were set to min [0,1, 0,1, 0,1] and max [100, 100, 10] for each algorithm, respectively.

2.2.1. The Superb Fairy--Wren Optimization Algorithm

There are algorithms available for optimization problems used in many areas of our lives (Kızıloluk & Can, 2021). There are even many methods for classifying these algorithms. Among the classifications made within meta-heuristics, SFOA is a heuristic method developed based on swarm logic, inspired by the coordinated movements of birds, exploration, and exploitation balance, as shown in Figure 2 (Zhong et al., 2025). A large number of candidate solutions are identified, and new solutions are generated based on income and expenses. SFOA is flexible in terms of applicability and can be used for many problems (Zhong et al., 2025; Jia et al., 2025).

Figure 2. Display of Superb fairy-wren bird (Jia et al., 2025)

In the most general sense, it is designed for use in areas such as numerical optimization, engineering design, and high-dimensional feature selection. It is inspired by three natural phenomena: the development of superb fairy sparrows, their feeding behavior after reproduction, and their avoidance strategies against predators. By mathematically deriving their responses to these events, it has demonstrated the success of SFOA in the IEEE CEC2017 and IEEE CEC2022 benchmark functions. The mathematical equations related to the operation of SFOA are provided below.

$$[X] = \begin{bmatrix} x_{1,1} & \cdots & x_{1,D} \\ \vdots & \ddots & \vdots \\ x_{N,1} & \cdots & x_{N,D} \end{bmatrix}_{N*D} \quad (4)$$

X Global matrix, x number of global members, N is the number of global members.

$$X = (ub - lb) * rand(0,1) + lb \quad (5)$$

Here, ub and lb are the upper and lower bounds of the decision variable D, respectively. rand is a random number between. SFOA will determine each member's position using the formula (5) to achieve a better objective function.

$$Xnew_{i,j} = X_{i,j}^{t} + (lb + (ub - lb) * rand), r > 0.5 \quad (6)$$

$$s = r_1 * 20 + r_2 * 20 \quad (7)$$

$$Xnew_{i,j} = X_G + \left(X_b X_{i,j}^{t}\right) * p \;\; , \; r < 0.5 \quad (8)$$

$$X_C = X_b * C \quad (9)$$

Here, X_b represents the current optimal position, and C is a constant with a value of 0.8.

$$p = \sin\left((ub - lb) * 2 + (ub - lb) * m\right. \quad (10)$$

$$m = \left(\frac{FEs}{MaxFEs}\right) * 2 \quad (11)$$

Among these, FEs indicate the current number of evaluations, while $MaxFEs$ indicate the maximum number of evaluations.

$$Xnew_{i,j} = X_b + X_{i,j} * l * k \;\; ,r < 0.5 \qquad (12)$$

$$k = 0.2 * \sin\left(\frac{\pi}{2} - w\right) \qquad (13)$$

$$w = \frac{\pi}{2} * \frac{FEs}{MaxFEs} \qquad (14)$$

$$Xnew_{i,j} = \begin{cases} X_{i,j}^{t} + (lb + (ub - lb) * rand), \;\; r > 0.5 \\ X_b * C + \left(X_b - X_{i,j}^{t}\right) * p, \;\; r < 0.5 \; and \; s > 20 \\ X_b + X_{i,j} * l * k \;\;\; r < 0.5 \; and \; s > 20 \end{cases} \qquad (15)$$

In the mathematical structure of SFOA, r is a random number for decision, s is the hazard threshold, r_1 and r_2 are normally distributed random numbers, X_G is the global best solution position, p is the maturity factor (with a sine function), X_C is the optimum position scaled by a constant coefficient, and l is the Levy flight step size.

2.2.2 Particle Swarm Optimization Algorithm

The swarm behavior of living creatures in nature has been a source of inspiration in many areas of science. Developed in 1995, inspired by swarm behavior, PSO is a population-based optimization algorithm. The particles within it represent the possible solution, forming the population created by the swarm particles. Particles possess position and velocity within the solution space. Due to its fast convergence, applicability to continuous and discrete problems, and ease of parameter tuning, it is used for optimization problems encountered in many fields. In this study, the coefficients within the PSO algorithm's internal structure, w = 0.7, c_1= 1.5, c_2 = 1.5 were determined for the problem of determining the PID controller's parameters. (Kennedy & Eberhart, 1995; Wang, et al., 2018).

2.2.3 Artificial Bee Colony Algorithm

The miraculous behavior of honeybees has inspired ABC, a meta-heuristic optimization algorithm. ABC considers three basic types of bees: workers, observers, and explorers. Explorer bees search for new areas with high potential. Worker bees evaluate the error of existing solution points, while observer bees use the information obtained to achieve better solutions. By mathematically modeling these behaviors, ABC enables the attainment of global solutions without getting stuck in local minima. With advantages such as low computational cost and few internal parameters, ABC is particularly prevalent in engineering problems and many other fields (Karaboga, 2005; Karaboga & Basturk, 2007).

4. RESULTS AND DISCUSSION

In this study, two different transfer functions, first-order and second-order, were used in the control system implemented in the MATLAB Simulink environment. PSO, ABC, and the proposed meta-heuristic method SFOA were used to determine the PID controller parameter values K_p , K_i and K_d for each transfer function scenario. In the studies, variables such as the number of steps and population size were kept as close as possible. The reason for this was to create equal conditions between PSO, ABC, and SFOA while optimizing the controller parameters in the control system. The input reference value specified for each transfer function is set to 15. The output value obtained for the 15 input values for the first-order system is shown in Figure 3, while the reference value tracking of the algorithms is shown in Figure 4.

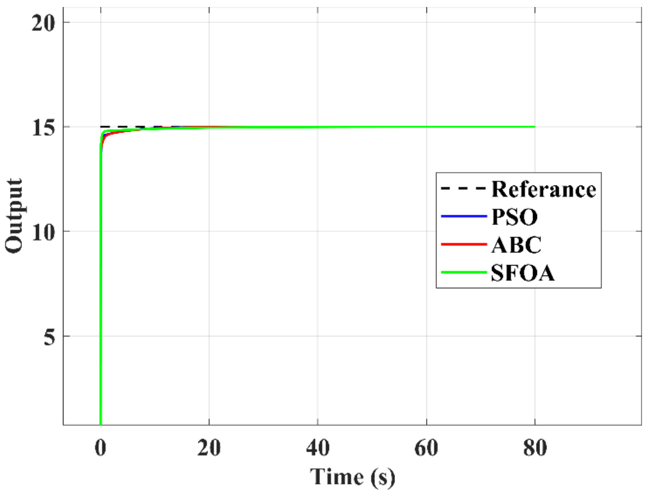

Figure 3. Reference tracking for first-order systems

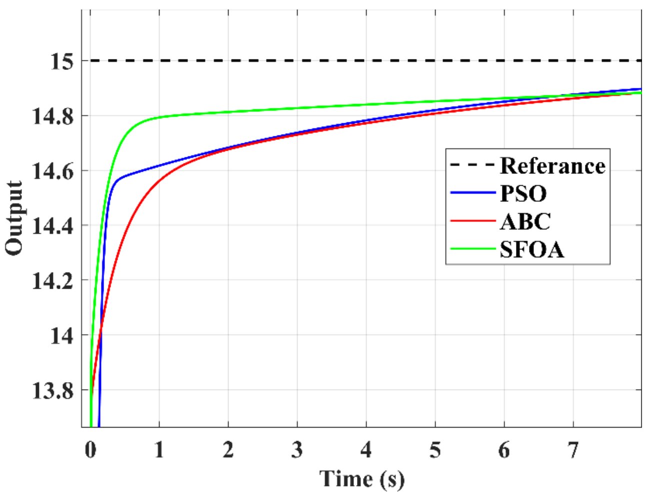

Figure 4. Closed-loop reference tracking for first-order systems

In the study conducted for the first-order system, it is clearly seen in Figures 3 and 4 that the values found by each algorithm yield results close to the input reference value. When the successful algorithms are ranked, SFOA, ABC, and PSO are seen to yield more successful results. However, nothing definite can be said about PSO and ABC. For such uncertain situations, mathematical error criteria should be examined. The controller parameters found by the meta-heuristic algorithms used for the first-order system and the RMSE error criterion are given in Table 1.

Table 1. Control parameters and error criterion for a first-order system

	K_p	K_i	K_d	RMSE
PSO	25.88	5.00	0.34	0.2631
ABC	30.72	5.00	10.00	0.2008
SFOA	63.97	5.00	10.00	0.1839

When the obtained results are examined, according to the RMSE error criterion, the success values of meta-heuristic algorithms for the first-order system can be ranked as follows: SFOA, ABC, and then PSO. The convergence curves of meta-heuristic algorithms for the first-order system are shown in Fig. 5.

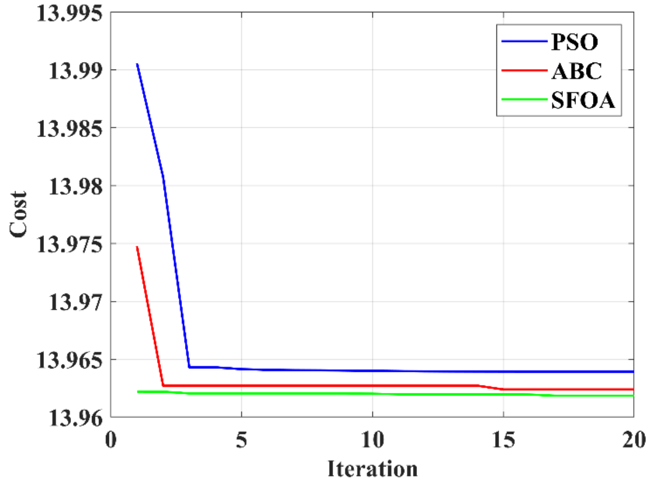

Figure 5. Convergence curves of metaheuristic algorithms for first-order systems

Second-order systems within control systems have a more complex structure than first-order systems. In this study, SFOA was also tested in two different systems. For the second-order system, the parameters obtained by metaheuristic algorithms in the problem of determining the parameters of the PID controller resulted in reference tracking, as shown in Fig. 6 and enlarged in Fig. 7.

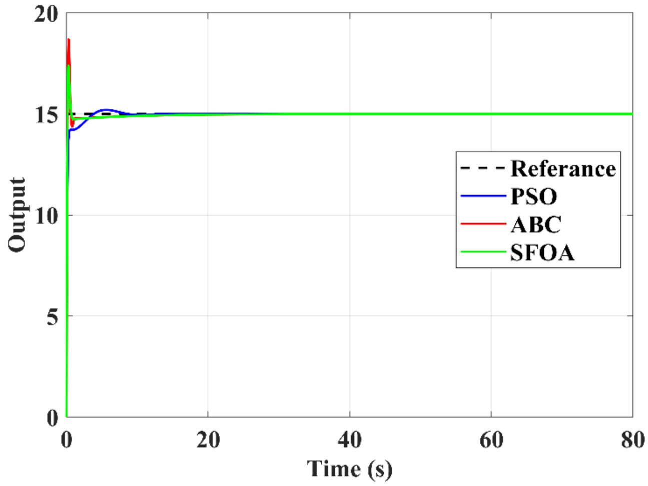

Figure 6. Reference tracking for second-order systems

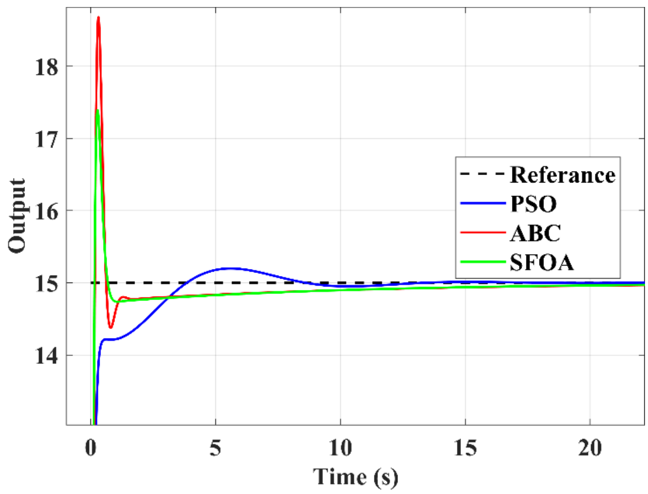

Figure 7. Closed-loop reference tracking for a second-order system

When examining the results obtained for the second-order system, it has yielded successful results in each meta-heuristic for 80 seconds, similar to the first-order system. However, upon examining Figure 7, it can be concluded that PSO, which exhibits overshoot in SFOA and ABC, lags behind ABC and SFOA in terms of convergence time. Figure 7 shows that SFOA is more successful than ABC. To make a clear statement about PSO, mathematical error criteria are needed. The controller parameters and RMSE error criteria values for the second-order system are specified in Table 2.

Table 2. Control parameters and error criterion for the second-order system

	K_p	K_i	K_d	RMSE
PSO	5.00	5.00	9.10	0.4648
ABC	52.34	5.00	7.18	0.4661
SFOA	48.49	5.00	10.00	0.4164

When examining the RMSE results for the second-order system, if metaheuristic algorithms are ranked by success, SFOA, PSO, and ABC can be ranked as the most successful. The results for the convergence curves of the algorithms for the second-order system are shown in Fig. 8.

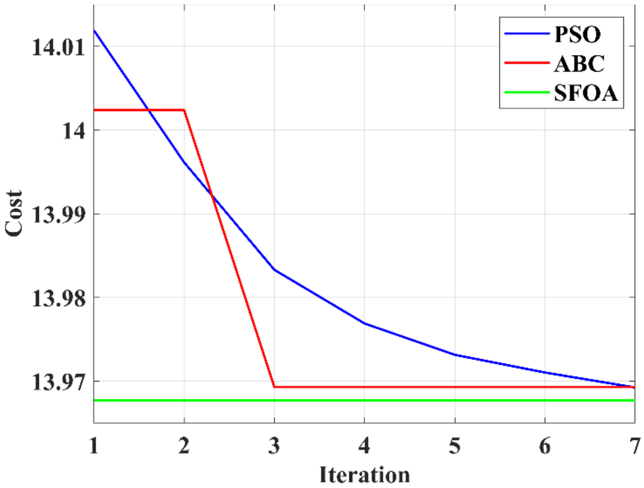

Figure 8. Convergence curves of metaheuristic algorithms for second-order systems

5. CONCLUSION

• As a result of the study, the SFOA algorithm was used for the first time to determine PID controller parameters.

• PSO and ABC algorithms are proven algorithms in many areas such as control systems. Although PSO and ABC algorithms produced acceptable results when compared to the SFOA algorithm in this study, SFOA stood out with a lower RMSE.

• The SFOA's ability to avoid getting stuck in local minima resulted in a more accurate outcome relative to the system's reference signal.

• Based on the results obtained, it is believed that the SFOA algorithm can be successfully applied not only to this specific topic but also to more complex control problems.

• By using SFOA to determine the parameters of the PID controller, it has been demonstrated that it can be used in different problem structures in the future.

Conflict of Interest
The authors have no conflicts of interest to declare.

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