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RESEARCH ARTICLE

# Design and Performance Analysis of a Nonlinear Magnetic Levitation System Using PID Controller Optimized With COOT Algorithm

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**ABSTRACT** Recent growth in magnetic levitation can be attributed to its ability to minimize friction and disturbance in industries, transportation, aerospace, biomedicine, and magnetic bearings. Due to the magnetic levitation system's nonlinear and unstable nature, control engineers found it exceedingly challenging to design a stabilizing controller. The magnetic levitation system is abbreviated as a maglev system. Using the integral square error criterion, a newly developed metaheuristic algorithm named the COOT algorithm is used to optimize the PID controller parameters. The performance of the proposed algorithm is evaluated using simulation and hardware with several kinds of reference trajectories and compared to the performance of other algorithms, such as the genetic algorithm and the whale optimization algorithm. Based on simulation and hardware results, it was determined that the proposed algorithm performed well with less settling time, rise time, and integral square error.

**INDEX TERMS** Maglev, PID controller, COOT algorithm, time domain, frequency domain.

## I. INTRODUCTION

An American inventor, Emile Bachelet presented a demonstration model of his concept for a magnetically levitated vehicle. An electromagnetic field will develop when an electric current flows through a solenoid, and ferromagnetic objects attract toward created electromagnetic field [1] in this paper authors used a digital Fractional Order Proportional Integral Derivative (FOPID) controller for a magnetic levitation system to improve the position accuracy. The maglev system is nonlinear and unstable. The absence of friction and noise is a benefit of maglev technology [2], [3], [4], [5]. The control mechanism and energy need to lift the object with the aid of a magnetic field are quite sophisticated. For such a system, it is necessary to provide a controller that will use a magnetic field to lift the ferromagnetic ball into the air. Swain et al. [6] designed a FOPID controller based on the dominant pole placement method and concluded that FOPID is better than the Integer Order Proportional Integral Derivative (IOPID) controller to track reference trajectory. Yadav et al. suggested an improved PID controller for a maglev system in 2016 [7] and in 2018 teaching learning-based optimization algorithm is used to tune the Proportional Integral Derivative (PID) controller algorithm, improving the time domain and frequency domain specification by reducing the integral time square error and integral time absolute error, [8]. Gao et al. maglev system is used for measuring the densities of samples and also separating the poly methyl methacrylate particles [9]. In the year 2021, Dey et al. tuned the FOPID controller using the grey wolf algorithm and achieved the best transient and steady-state response [10]. Opposition-based Artificial Electric Field is used to tune [11] FOPID controller for an unstable magnetic ball suspension system, it achieved good performance criteria like peak overshoot, settling time, rise time, gain margin, and phase margin. In 2017, Dhanya et al. implemented a Fractional stabilizing controller for a maglev system and reduces the steady-state error and peak overshoot [12]. A hardware maglev system was created in 2018 by Yaseen et al. used the SIMLAB platform and achieved 14.6%, 0.199, and 0.064 for maximum overshoot, settling time, and

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rise time respectively [13]. Sain et al. suggested an I-PD controller for the maglev system utilizing the Jaya algorithm in the same year 2018 and performed a robustness analysis [14]. In the year 2021, Dey et al. designed and analyzed the performance of the maglev system using the FOPID controller [10]. Qin et al. developed a new control technique for a maglev system using a state-dependent ARX model [15]. In the year 2023, Xu et al. used only input and output data for developing a new optimization algorithm for the maglev system [16]. Bauer et al. implemented a FOPID controller for the maglev system with SoftFRAC in the year 2020 [17]. LQR-PID controller was developed for the linearized maglev system by Anurag et al. in the year 2018 achieving transient performance and stability at a time [18]. Abdullah Mughees and Syed Ali Mohsin used a FOPID controller for the design and control of the maglev system, the controller is optimized by Ant colony optimization Algorithm in the year 2020 [19] efficiency of the settling time increased to 95.99% compared to the IOPID-ZN controller.

Several methods were recently developed to enhance control in maglev technology. Designing a PID controller is quite an easy task for control engineers for practical applications. PID controller's internal structure is very simple and easily implemented in many practical applications. PID control can also offer reliable regulation of constant references for nonlinear systems while rejecting constant disruptions [20], [21]. In 1991, Yaguang et al. optimized the PID controller using Powell's and simplex methods. Based on their simulations' results, they concluded that Powell's technique is excellent to the simplex method because the choice of initial values does not affect the computation time [22]. Reference [23] uses the LQR technique for PID tuning. For the maglev system, In 2011, Lin et al. created a fuzzy compensating controller and an adaptive PID controller [24]. In the year 2014 Bin Fang, proposed three theorems to evaluate stabilizing PID controller for a fixed delay interval plant [25]. A discontinuous integral PID controller was introduced by Jaime A. Moreno in the year 2020 for tracking any time-varying reference. By using the discontinuous integral PID controller asymptotic tracking and rejection of disturbance problems can be achieved [26]. Saurabh Srivastava and V.S. Pandit proposed a graphical optimizing approach for PI/PID controller using a dominating pole placement strategy with an ensured gain margin (GM) and phase margin for the first-order and second-order plus time delay systems (PM) [27]. For an industrial biological fermentation process, Khan et al. proposed a PID controller [28], effectively removing dissolved oxygen oscillations and improving the response and settling times. To attain the required phase margin, Mikhalevich et al. developed a new tuning technique for the PID controller [29].

For complex systems like uncertain spacecraft systems, servo mechanical systems, nonlinear systems, etc., many autotuning PID control techniques have been developed [30], [31]. Fuzzy control, genetic algorithms (GA), robust control, and adaptive nonlinear control are some recent techniques that have been used with PID control [24]. Natural phenomenon-derived optimization techniques have become increasingly popular among algorithms for tackling optimization problems [32]. The following groups are used to categorize the techniques. (i) mechanisms for evolution based on competencies, such as GA [33] and Differential Evaluation [34]. (ii) Techniques for iterating based on physical laws, such as gravitational search algorithm [35] and simulated annealing [36]. (iii) Particle swarm optimization (PSO) and grey wolf optimization (GWO) are two examples of swarm-based techniques (iv) Human-based simulation techniques, including teaching-learning-based optimization [37] and social engineering optimizer [38] (v) biological immune-based techniques, such as the immune algorithm [39] and the neural network algorithm [40]. Reference [41] proposes a hardware PSO algorithm-based PID controller. The GA-based PID controller was implemented for the maglev system [42]. Extreme seeking optimized decentralized PID controller proposed in [43].

A GA was created in 1975 and depends on Charles Darwin's theory of natural selection. It was created by John Holland and others. The genetic operators that are essential to the GA for problem-solving include crossover and recombination, mutation, and selection [44]. The Procedure followed by GA: (a) Encoding cost function (b) defining a fitness function (c) creating individuals' population (d) carrying out iterations by evaluating the fitness of individuals (e) decoding the results to access the solution for the problem [45], [46], [47], [48]. Under certain conditions, a GA faces two problems first is premature convergence and the second is random behavior [49]. To be highly adaptable for issue formulation and performance time, GA is capable of providing semi-consistent good solutions [50], [51]. In 2022, Bruno Mota, Pedro Faria, and Zita Vale suggested using GA to manage power demand for residential load scheduling. Achieved a 15% reduction in bills by implementing the GA [52]. Bégin-Drolet et al. proposed the GA for the single input single output systems in the year 2018 validated it on the cardiac bioreactor, and confirmed GA can be used for optimal and adaptive control effectively [53].

The Whale optimization algorithm (WOA) was a metaheuristic algorithm that Seyedali Mirjalili and Andrew Lewis proposed in 2016. The largest mammal, whales are highly intelligent and empathetic creatures. The social behavior of whales is an interesting point, they live either alone or in groups. However, we will usually watch in groups. The three operators of the whale optimization algorithm are the foraging behaviors of humpback whales using bubble nets, encircling prey, and searching for prey [54]. In 2022, Liu et al. proposed whale optimization-based point cloud data for inspecting sewer pipelines [55]. Using a whale optimization algorithm, 2022 Guanghui Zhao presented a multi-stage charging technique that is health conscious. Battery power loss and charging time are both factors in the multi-charge technique [56].

The COOT bird optimization method was a brand-new metaheuristic algorithm that Iraj Naruei and Farshid Keynia proposed in 2021. Swarms of coot birds served as the inspiration for this algorithm. Coot birds travel in two different ways on the water's surface: first, they move irregularly, and then, second, they move regularly. The coot algorithm imitates the movements of coots as they move across the water. The final bird in the swarm travels like a chain of coots as it goes toward the group leader to obtain the food [57]. For the best placement of photovoltaic generators in a distribution system with varying loads and solar radiation, Le Chin Kien et al. suggested the coot algorithm. They also compared the coot algorithm to the transient search and crystal structure algorithms. Out of the two, the coot algorithm finds a good voltage of up to 4.5 percent and a good energy loss of up to 60.96 percent. The response of the coot algorithm is three times faster than the crystal structure algorithm and two times faster than the transient search algorithm [58]. The proposed method is utilized to optimize the PID controller's settings to reduce the maglev system's integral square error (ISE). Analysis of time response graphs is used to judge how well the PID controller is working with the magnetic levitation system. The results of the simulation and practical tests show how effective the suggested approach is.

This study compares the performance of the COOT-optimized PID controller with other algorithms (such as GA and WOA) on a nonlinear system (magnetic levitation system) and demonstrates that the COOT algorithm-based PID controller produces superior time domain analysis. Furthermore, hardware implementation enables validation of controller performance.

The motivation of the proposed work is as of now no one implemented the COOT algorithm for the maglev system and the performance of the maglev system is examined using only step response. The unique contribution of the proposed work for the maglev system performance is examined by the square response and servo response. The reason for using a servo response is in the future this technique can be used for rocket launching to reduce fuel consumption such that the height of the rocket can be increased stepwise.

The unique feature and advantage of the proposed work is COOT algorithm itself is a distinctive feature, it is a nature-inspired optimization algorithm that uses the collective intelligence and search strategies of the birds to solve the optimization problem [57]. Based on the system characteristics and requirements it can adjust search behavior dynamically. This adaptability permits the algorithm to locate optimal control parameters for sustained levitation and precise positioning of the object in an efficient manner. The collective intelligence behavior helps to share information among individuals and improves cooperation between individuals. This behavior permits optimizing the control strategy, minimizing errors, and enhancing the maglev system's stability and accuracy. Due to adaptive optimization and collective intelligence the proposed method helps to achieve precise and stable levitation control. The advantages of the proposed method are reducing the settling time, good disturbance rejection, robustness, and flexibility in handling nonlinear systems.

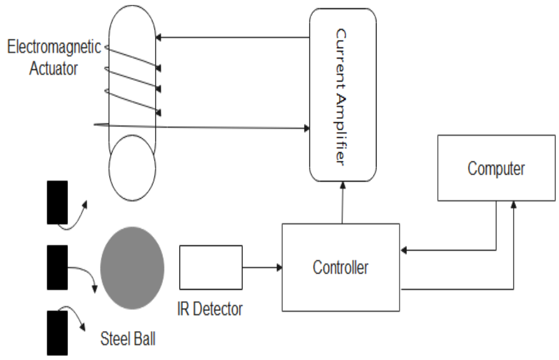


**FIGURE 1. Schematic diagram of magnetic levitation system.**

**TABLE 1. Magnetic levitation system parameters.**

| System Parameters | Symbols | Values |
|---|---|---|
| Mass of the steel ball | m | 0.02kg |
| Acceleration due to gravity | g | 9.81 m/s2 |
| The equilibrium value of the current | $i_0$ | 0.8 A |
| The Equilibrium value of a position | $x_0$ | -1.5 |
| Control voltage to coil current gain | $k_1$ | 1.05A/V |
| Sensor gain, offset | $k_2$, η | 143.48 V/m, -2.8 V |
| Control voltage input level | U | ±5 V |
| Sensor output voltage level | $x_v$ | 1.25 V to -3.75 V |

The document is organized in the manner described below: Section II provides an outline of the magnetic levitation system. Sections III and IV of this article each explain the PID controller and the COOT optimization technique. Sections V and VI explain the computational complexity and results and discussion respectively of the proposed work, followed by conclusion.

## II. DESCRIPTION OF MAGNETIC LEVITATION SYSTEM

The magnetic levitation setup works as a simple model of magnetic levitation trains and magnetic bearings. Magnetic levitation trains are becoming popular in recent decades and some of the lines are already available in Shanghai. Magnetic levitation is a concept that uses an electromagnetic field to suspend an object in the air without any mechanical assistance. Designing a controller for the nonlinearly unstable magnetic levitation system is necessary.

An electromagnetic coil, a ferromagnetic metal ball, and an infrared sensor make up the magnetic levitation system. To keep the metal ball in the desired position gravitational force and electromagnetic force have to be balanced which is the key factor of the magnetic levitation system. Between a personal computer and a magnetic levitation system, as well as from the magnetic levitation system to the computer, control signals have been sent via an analog control interface.

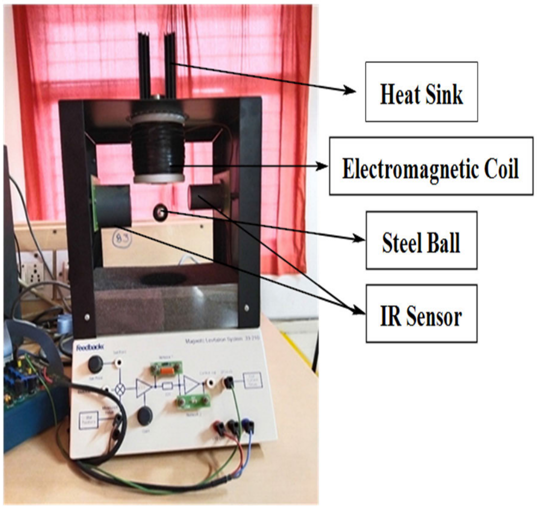


**FIGURE 2.** Hardware setup of the magnetic levitation system.

The magnetic levitation system is illustrated schematically in Figure. 1 while system parameters are listed in Table 1. Figure. 2 shows the hardware setup of the magnetic levitation system designed by Feedback Instruments.

When electricity passes through the coil, it becomes magnetic, drawing the ball upward while being repelled by gravity's pull in the other direction. Infrared sensors are used to continuously track the movement of the ball in the air. You can vary the ball's placement by adjusting the current that flows through the coil.

The magnetic levitation mechanism is determined by the location of the ball and the current flowing through the coil.

$$m.\ddot{x} = mg - k\frac{i^2}{x^2} \tag{1}$$

where m stands for the ball's mass, x for its location, i for the electromagnetic coil's current, g for the gravity, and k is affected by the coil's parameters. It is necessary to find equilibrium points for the linearization of the magnetic levitation system. By taking $x_0 = -1.5$V (position is expressed in volts), $i_0 = 0.8$A, linearization is performed.

$$\ddot{x} = g - f(x, i) \tag{2}$$

$$\text{f(x, i)} = \text{k}\frac{i^2}{mx^2} \tag{3}$$

linearization has been done using the Taylor series method

$$\ddot{x} = -\left(\frac{\partial f(i,x)}{\partial i}|_{i_{0},x_0}\Delta i + \frac{\partial f(i,x)}{\partial x}|_{i_{0},x_0}\Delta x\right) \tag{4}$$

$$s^2\Delta x = -(k_i\Delta i + k_x\Delta x) \tag{5}$$

$$s^2\Delta x + k_x\Delta x = -k_i\Delta i \tag{6}$$

$$\Delta x(s^2 + k_x) = -k_i\Delta i \tag{7}$$

$$\frac{\Delta x}{\Delta i} = \frac{-k_i}{s^2 + k_x} \tag{8}$$

where $k_i = 2\text{mg}/\text{i}_0$ and $k_x = -2\text{mg}/\text{x}_0$

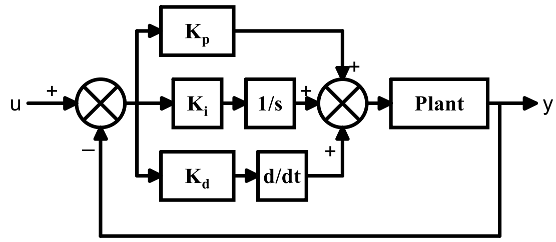


**FIGURE 3.** PID controller.

Above equation (8) is the transfer function of the magnetic levitation system where $\xi = 0$ therefore the system is an undamped unstable system and the poles are located on the imaginary axis of the s-plane. Due to the unstable nature of the system, it is necessary to design a controller to make the magnetic levitation system stable.

The constraint of this system is, that the maximum mass of the object levitated by the magnetic field is 0.02kg and the maximum current flowing through the coil is 0.8A. The assumption made to experiment is, that the effect of air on the levitated object is negligible.

## III. PID CONTROLLER

Due to its straightforward design and straightforward installation, PID controllers are extensively utilized in industrial applications. Nearly 90% of industrial feedback loops employ PID controls [59]. Even though the PID controller structure is straightforward, it has undergone numerous modifications and hybridizations over the years to improve performance. The Figure. 3 shows the PID controller's block diagram.

The PID controller consists of three parameters:

1. Proportional gain
2. Integral gain
3. Derivative gain

The PID controller's transfer function is

$$G(s) = k_p + \frac{k_i}{s} + k_d s \tag{9}$$

The PID controller's effectiveness depends upon the controller parameters' choice. The PID controller parameters are tuned by GA, WOA, and COOT algorithms using the integral square error method.

$$J_{ISE} = \int_0^\infty e^2 dt \tag{10}$$

Integral square error is the objective function of the system and is given in equation (10).

## IV. COOT OPTIMIZATION ALGORITHM

Coots are little waterfowl that belong to the rail family. On the water surface, the coot bird's behavior and movement are different. To develop the new optimization method coot bird behavior on water surfaces was taken as a reference [57]. The coot birds have four movements:

- Random movement

- Chain movement
- Changing the position of the group leader
- Directing the group leaders to the ideal location

### A. MATHEMATICAL MODEL

The algorithm starts with an initial random population $(\overrightarrow{x}) = \{\overrightarrow{x_1}, \overrightarrow{x_2}, \overrightarrow{x_3}, \ldots . \overrightarrow{x_n}\}$. The target function continuously evaluates the random population and target value determined by $(\overrightarrow{O}) = \{\overrightarrow{O_1}, \overrightarrow{O_2}, \overrightarrow{O_3}, \ldots, \overrightarrow{O_n}\}$. By using equation (11) population is randomly generated [54].

$$Cootposition\,(i) = rand\,(1,d)\,.*\,(ub - lb) + lb \tag{11}$$

The coot's location is Cootposition(i). The letters d stands for the problem dimension, lb for the lower search space boundary, and ub for the upper search space boundary.

The fitness of each solution should be determined using the objective function following the generation of the initial population and evaluation of each agent position $O_i = f(\vec{x})$.

As previously indicated, the four coot bird movements on the lake surface are now implemented.

### B. RANDOM MOVEMENT

To execute this movement, according to equation (12) random positions are considered.

$$Q = rand\,(1, d)\,.*\,(ub - lb) + lb \tag{12}$$

This movement of the coot explores several regions of the search space. This movement will assist the algorithm in escaping from the local optima if it becomes stuck there. The coots' new position is determined using the equation (13).

$$CootPosition_{new}\,(i) = CootPosition\,(i) + A \times R_2 \times (Q - CootPosition\,(i)) \tag{13}$$

where $R_2$ is a random number in the interval [0, 1]. A is calculated according to equation (14).

$$A = 1 - L \times \left(\frac{1}{Max_{iter}}\right) \tag{14}$$

where L is the current iteration, the maximum iteration is represented by $Max_{iter}$.

### C. CHAIN MOVEMENT

The chain movement can be achieved by using the average distance between two coots. The new position of the coot is calculated using equation (15).

$$CootPosition\,(i) = 0.5 \times (CootPosition\,(i-1) + CootPosition\,(i)) \tag{15}$$

### D. ADJUSTING THE POSITION BASED ON THE GROUP LEADER

A select few coots take charge of their flock, and the other coots must modify their positioning by the group leader. Coots will adjust their position based on the leaders' average positions after taking those positions into account. To implement this movement, we use equation (16).

$$K = 1 + (i\ MOD\ NL) \tag{16}$$

where NL is the leader number, K is the index number of the leader, and I is the index number of the present coot.

Based on the leader's K coot(i) must update its position. Based on the selected leader next position of the coot is calculated by equation (17)

$$Cootposition\,(i) = LeaderPosition\,(k) + 2 \times R_1 \times \cos\,(2R\pi) \times (LeaderPosition\,(k) - CootPosition\,(i)) \tag{17}$$

The selected leader is represented by *LeaderPosition(k)*. $R_1$ is the random number in the interval [0, 1], $\pi$ is 3.14, and R is the random number in the interval [−1,1].

### E. LEADING THE GROUP BY THE LEADERS TOWARDS OPTIMAL AREA

Leaders must update the group's position with the goal for it to move towards the goal (optimal area). Equation (18) is used to update the position of the leader. (18), as shown at the bottom of the next page, where gBest is the best position, $R_3$ & $R_4$ are the random numbers in the interval [0, 1], and B is calculated using equation (19).

$$B = 2 - L \times \frac{1}{Max_{iter}} \tag{19}$$

Initially, PID controller topology should be determined, in the next step controller parameters and the first population of coots are initialized randomly. In the next step, coot positions are found using equation (12). The fitness of the coot or the leader is calculated in the next step. If the coot gets struck in the local optima, the random movement behaviour of the coot will help to escape and the new coot position will be calculated by using equation (13). Coot birds start to form a chain movement by taking the average position of two coots and updating their position by using the equation (15). The coot birds start to follow the leader based on equation (16) and the coot's leader updates their position based on equation (17). To lead the coots towards optimal value, the leader will update their position based on the equation (18). If the iteration doesn't reach the maximum iteration or the coots don't reach the optimal value of the PID controller the coot bird movement will be repeated from equation (13).

Figure. 4. shows the flow chart of an implementation of the COOT algorithm for the PID controller. This flow chart helps to understand how the COOT algorithm optimizes the PID controller. Table. 2. Shows the input optimization parameter values, which helps to give the best controller parameter values. The COOT algorithm is considered for the magnetic levitation system due to fast convergence and ease of implementation moreover in various fields like frequency regulation of microgrid, optimal carbon-energy combined

**TABLE 2.** Coot optimization parameter values.

| Coot optimization parameters | Values |
|---|---|
| Number of search agents (N) | 50 |
| Maximum iteration | 100 |
| Lower boundary | 1 |
| Upper boundary | 10 |
| Dimension | 3 |

flow of power grid, parameter estimation of the photovoltaic model, etc coot algorithm gave the best results, so we tried coot algorithm for my application.

## V. COMPUTATIONAL COMPLEXITY OF CONTROLLER DESIGN

### A. COMPUTATIONAL COMPLEXITY OF CONTROLLER DESIGN USING GA

The population size, number of iterations, and objective value have the greatest impact on the computational complexity of a PID controller that employs a GA.

- Objective value evaluation: Evaluation of objective value requires calculating the ISE for each individual in the population. The complexity of calculating the ISE for a problem size of 1 is constant time complexity (O(1)).
- Selection: Typically, the complexity of GA selection operations is linear O(50), where 50 represents the population size.
- Crossover: Typically, linear O(50) is the complexity of the crossover operation.
- Mutation: The mutation operation's complexity is determined by the mutation rate and the size of the problem. The mutation operation can be considered constant time complexity O(1) for a problem size of 1 and a mutation rate of 0.1.

With a population size of 50 and a maximum number of 100 iterations, the overall computational complexity of the GA component can be approximated as O(50 × 100). Thus, the complexity in this instance is O(5000).

### B. COMPUTATIONAL COMPLEXITY OF CONTROLLER DESIGN USING WOA

For estimating the computational complexity of the PID controller using WOA with a problem size of 1, population size of 50, and maximum iteration of 100, we consider the following factors.

- WOA iteration: With the maximum iteration of 100, in each iteration, the positions of the 50 whales will be updated based on the objective value. Therefore, the computational complexity of the WOA iteration would be an order of O(100 × 50).
- Objective value evaluation: In each iteration ISE objective function needs to be evaluated for each search agent in the population. Since the population size is 50, the ISE value will be computed 50 times in each iteration.
- PID controller evaluation: Once the WOA converges and determines the optimal PID gains, the PID controller needs to be evaluated to measure its performance.

Considering these factors, the overall computational complexity can be estimated as O(50 × 100). Thus, the complexity is O(5000).

### C. COMPUTATIONAL COMPLEXITY OF CONTROLLER DESIGN USING COOT ALGORITHM

The computational complexity of the PID controller utilizing the COOT algorithm with an ISE objective function, a problem size of 1, a population size of 50, and a maximal iteration count of 100 can be evaluated as follows:

- Objective value evaluation: For each member of the population, the objective function ISE must be calculated. Given that the size of the problem is one, the time complexity of evaluating the objective function for each individual is O(1).
- Update velocities and positions: Individual coot velocities and positions are updated based on the objective value with a time complexity of O(1).
- Boundary constraints: The lower and upper limits of the PID controller gain are 1 and 10, and the algorithm applies these constraints. The complexity of applying boundary constraints in terms of time is O(1).
- Convergence: The algorithm verifies the termination criteria, such as attaining a maximum of 100 iterations. This operation has an O(1) time complexity.

Considering 100 as the maximum number of iterations, the total complexity of computation is O(1).

## VI. RESULTS & DISCUSSION

In this work, the COOT algorithm is proposed for tuning the PID controller which helps to control the magnetic levitation system. Figure. 5 displays the magnetic levitation system's open loop response of magnetic levitation system.

The magnetic levitation system is an undamped unsteady system. To make the system stable PID controller is used. The PID controller's parameters were optimized using the COOT algorithm. The performance of the COOT algorithm on the magnetic levitation system was compared with the GA and WOA.

$$LeaderPosition\,(i) = \begin{cases} B \times R_3 \times \cos(2R\pi) \times (gBest - LeaderPos\,(i)) \pm gBest & +for\ R_4 < 0.5 \\ & -for\ R_4 \geq 0.5 \end{cases} \tag{18}$$

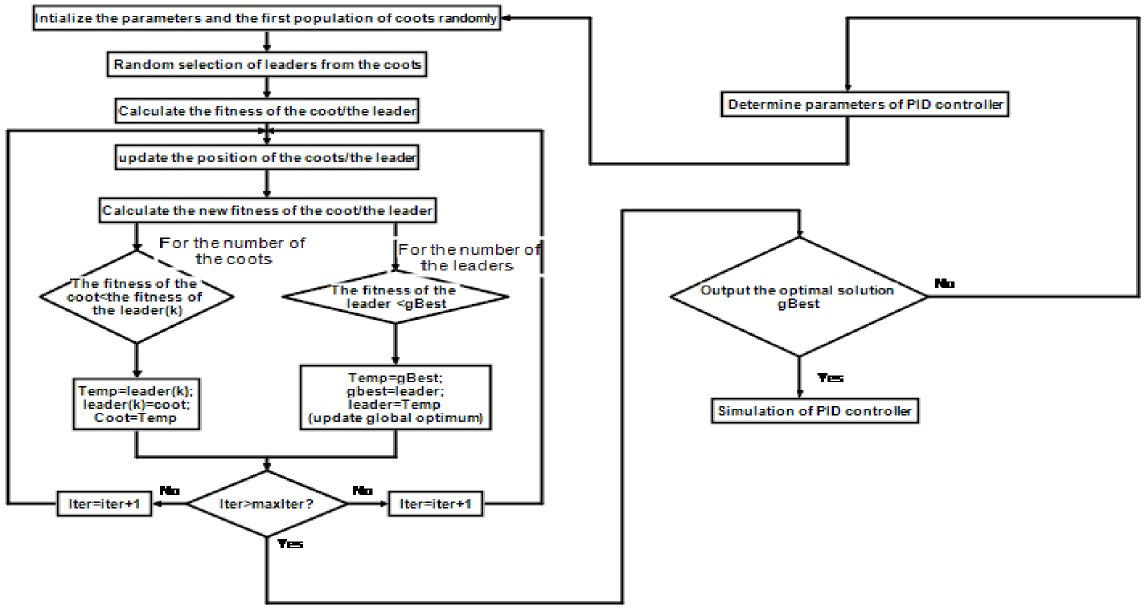


**FIGURE 4.** Flow chart of COOT algorithm.

**TABLE 3.** PID controller parameters using various algorithms.

| Algorithm | Kp | Ki | Kd | Performance Index |
|---|---|---|---|---|
| GA | 2.9908 | 1.0311 | 1.0002 | 0.148 |
| WOA | 5.0024 | 1.0015 | 1.0923 | 0.098 |
| COOT | 6.0040 | 1.0009 | 1.0105 | 0.083 |

**TABLE 4.** Time domain characteristics of magnetic levitation system with different algorithms.

| Algorithm | Maximum Overshoot (%) | Rise time (s) | Settling time (s) |
|---|---|---|---|
| GA | 57.613 | 0.8556 | 38.9507 |
| WOA | 61.4709 | 0.6811 | 23.5403 |
| COOT | 63.2753 | 0.6244 | 21.2753 |

The parameters of the COOT algorithm are mentioned in Table 2. The convergence curve of the algorithms is shown in Figure. 6. In the convergence curve performance index obtained by the COOT algorithm is less compared to the other two algorithms. The optimized PID controller parameters obtained using different algorithms are shown in Table 3.

Figure. 7 shows the time domain analysis of the magnetic levitation system using a PID controller optimized by different algorithms and the zoomed plot shows the settling time of magnetic levitation where the COOT algorithm helps to make the system settle at 21.27 seconds. Table 4. Shows the time domain characteristics of magnetic levitation systems using different algorithms. The settling time and rise time of the magnetic levitation system using the COOT algorithm are much less compared to the other algorithms.

### *A. SIMULATION RESULTS*

Figures 8 and 9 display the magnetic levitation system's servo response and square response with GA optimized PID controller. Figure 10 and 11 shows the servo response and square response of the magnetic levitation system using a WOA-based optimized PID controller. The servo response and square response of the COOT-based optimized PID controller of the magnetic levitation system are shown in Figures 12 and 13. Here blue color refers to the desired position and the red color refers to the ball position after levitation. From the simulation results of the COOT algorithm tunned controller magnetic levitation system's servo response, at the initial stage ball position has less peak, unlike WOA and GA tunned controller's servo response which is particularly important in practical applications. Similarly in square response ball reaches the desired position compared to other optimization algorithms both at the maximum and minimum position of square response. From Figures 12 & 13 we observed that the magnetic levitation system performed well with the COOT algorithm-based PID controller. Figure 14 & 15 shows a comparison of servo response and square response respectively of the magnetic levitation system using a PID controller tuned with GA, WOA, and COOT algorithms.

The hardware system response was examined after finding the simulation response of the magnetic levitation system, with the identical PID controller values obtained by GA, WOA, and COOT.

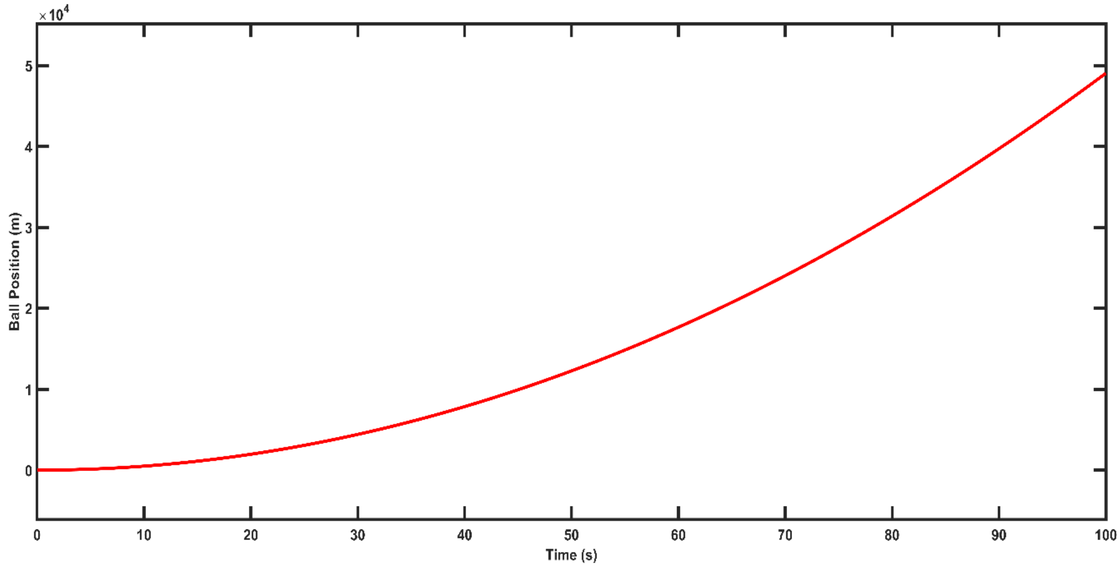


**FIGURE 5.** Open-loop response of magnetic levitation system.

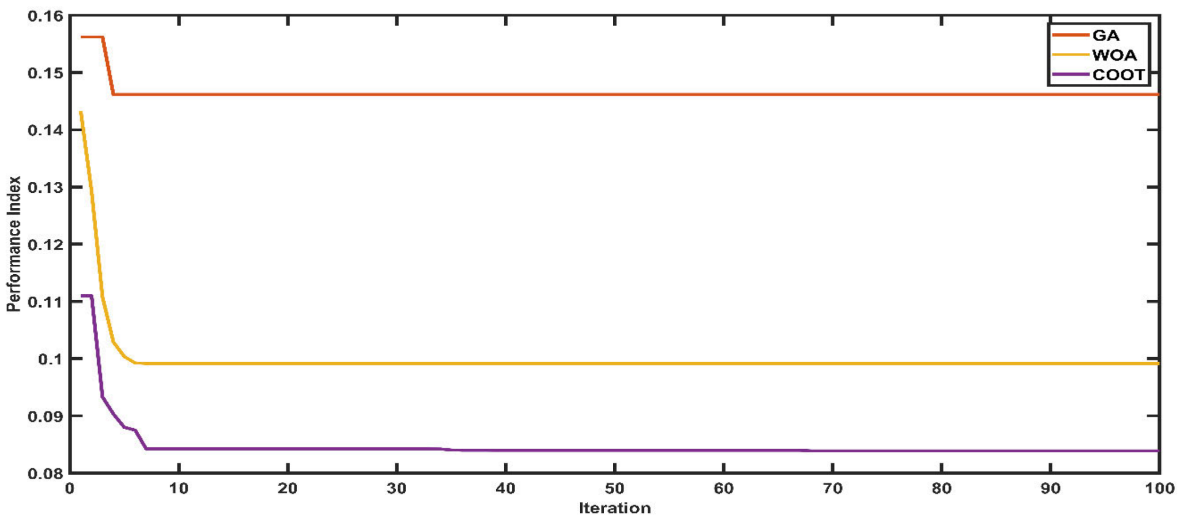


**FIGURE 6.** Convergence curve.

**TABLE 5.** Integral square error of magnetic levitation with different algorithms.

| Magnetic levitation System | Algorithm | Step reference | Square reference |
|---|---|---|---|
| Simulation | GA | 0.0873 | 1.46409 |
| | WOA | 0.0154 | 0.253 |
| | COOT | 0.0126 | 0.1912 |
| Hardware | GA | 0.7996 | 1.8145 |
| | WOA | 0.1756 | 0.1651 |
| | COOT | 0.1575 | 0.1078 |

**TABLE 6.** Comparison of integral square error.

| Controller | ISE |
|---|---|
| GA-PID | 1.8145 |
| WOA-PID | 0.1651 |
| COOT-PID | 0.1078 |
| dPSO-PID[1] | 2.488 |

### *B. HARDWARE RESULTS*

Figures 16 and 17 depict the magnetic levitation system's servo response and square response with a GA-optimized PID controller. The servo response and square response of the magnetic levitation system with a WOA-based optimized PID controller are shown in Figures 18 and 19. The servo response and square response of the COOT-based optimized PID controller in the magnetic levitation system are shown in Figures 20 and 21. A comparison of the servo response

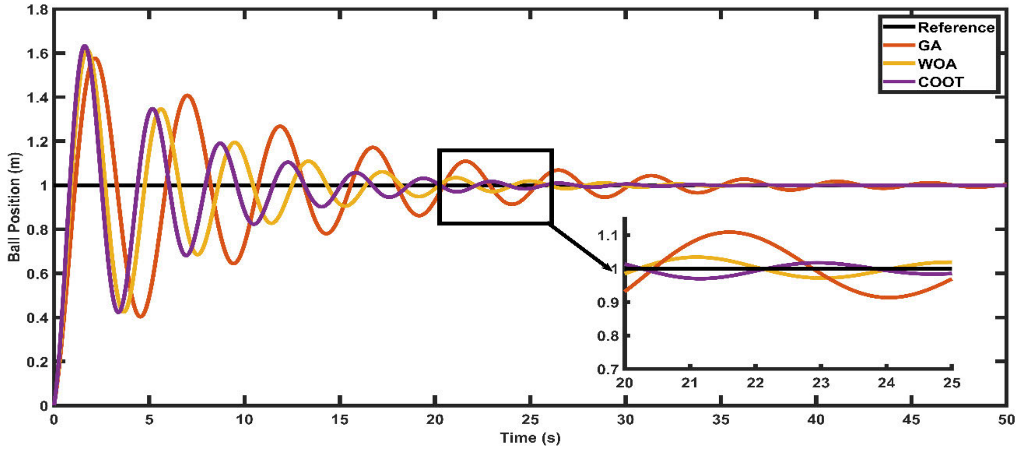


**FIGURE 7.** Time domain response analysis of magnetic levitation system using different algorithms.

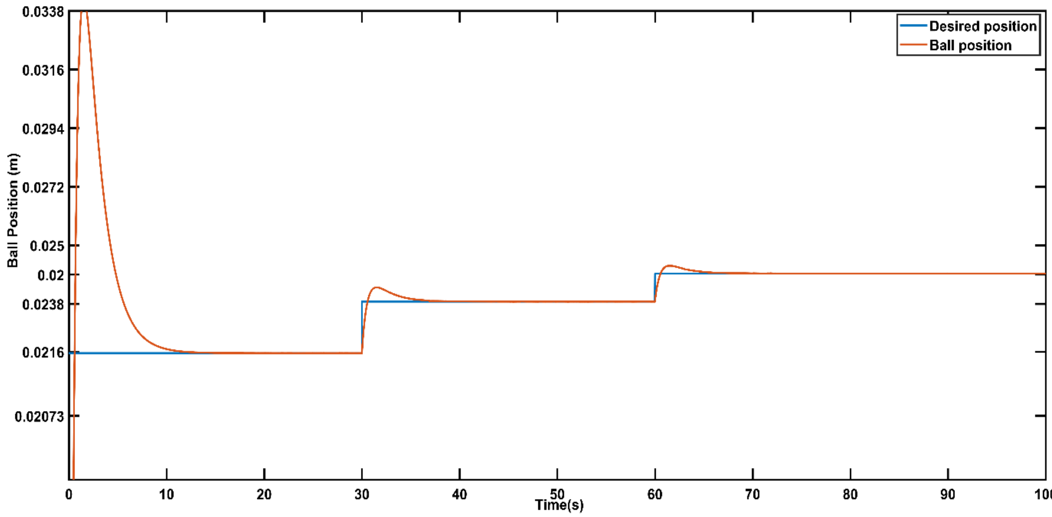


**FIGURE 8.** Servo response of the magnetic levitation system with GA tuned controller.

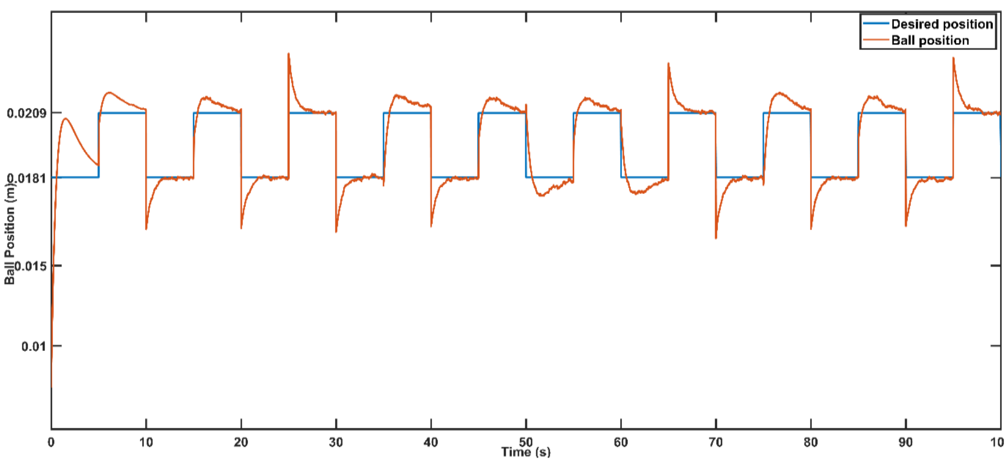


**FIGURE 9.** Square response of the magnetic levitation system with GA tuned controller.

and square response of the magnetic levitation system using a PID controller tuned with GA, WOA, and COOT algorithms is shown in Figures 22 & 23 respectively. Figure 2 shows the hardware setup of the magnetic levitation system which is not an autonomous system, where we have to keep the ball in the magnetic field with the help of hand. In every hardware results plot after 15 seconds ball reaches the reference trajectory because the integral action in the magnetic levitation

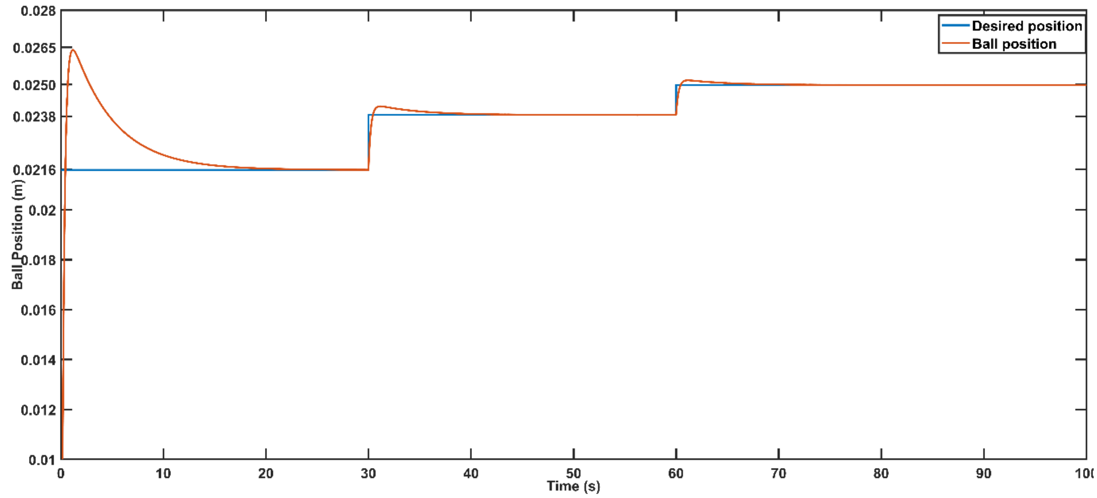


**FIGURE 10.** Servo response of the magnetic levitation system with WOA tuned controller.

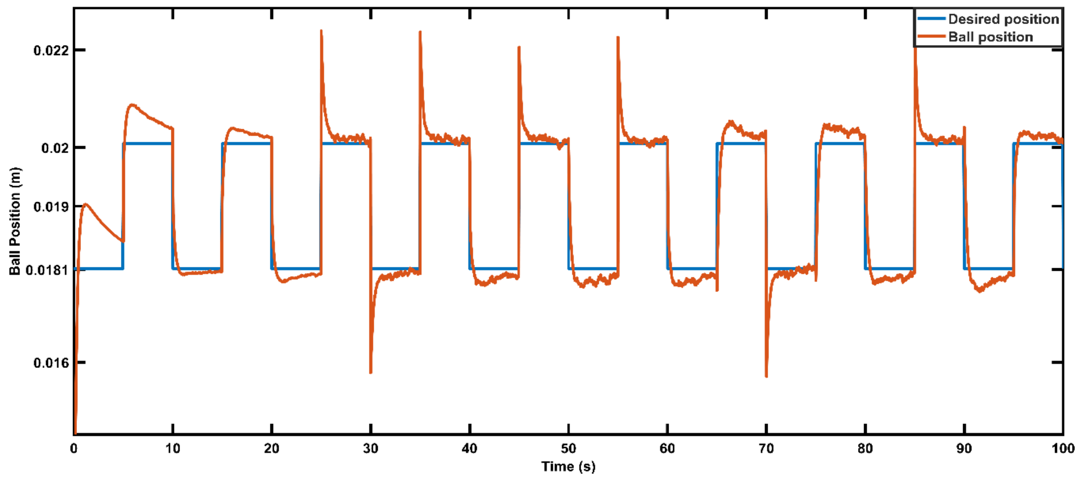


**FIGURE 11.** Square response of the magnetic levitation system with WOA tuned controller.

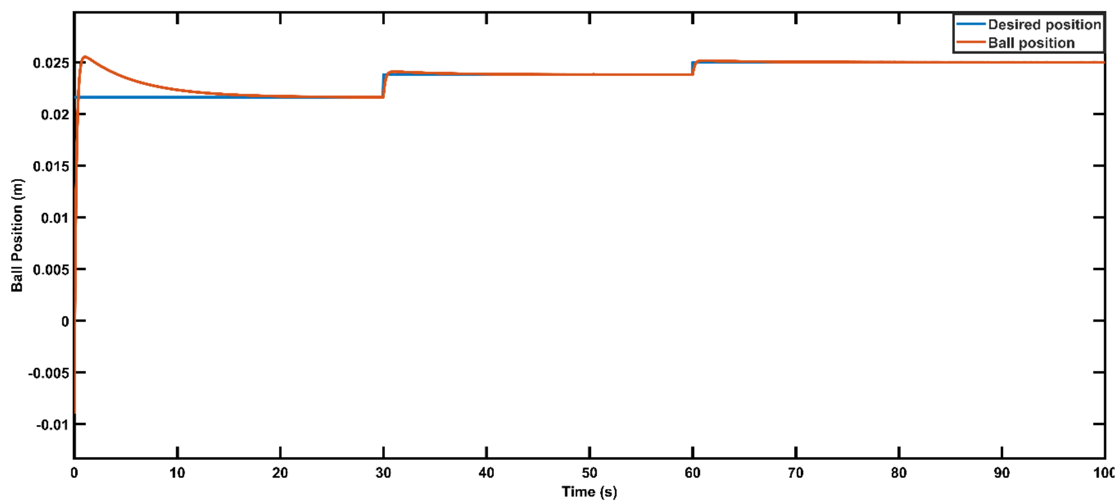


**FIGURE 12.** Servo response of the magnetic levitation system with COOT tuned controller.

system can improve the system performance in terms of error minimization, however, the system is not an autonomous system the integral action has to be turned on when the ball is already stabilized by the PD controller otherwise huge error of ball position would be integrated by the controller resulting in unrealistic control values. This would cause system

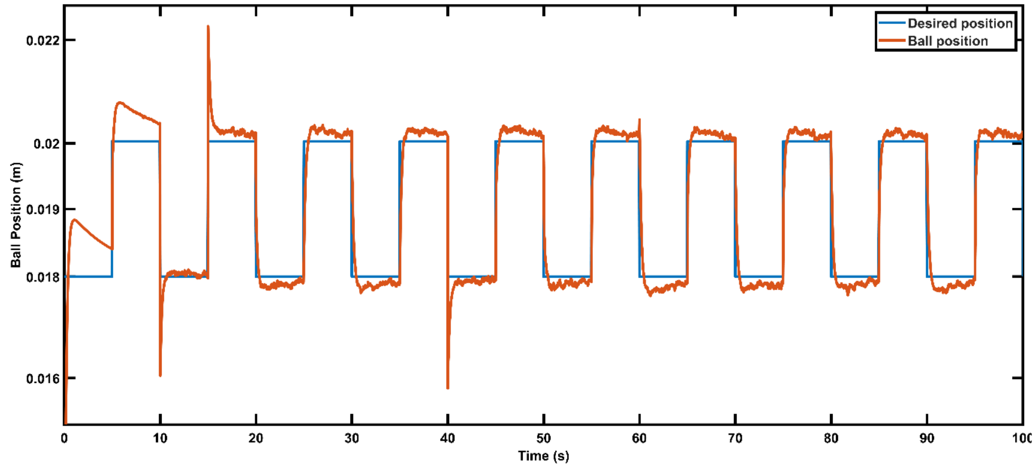


**FIGURE 13.** Square response of the magnetic levitation system with COOT tuned controller.

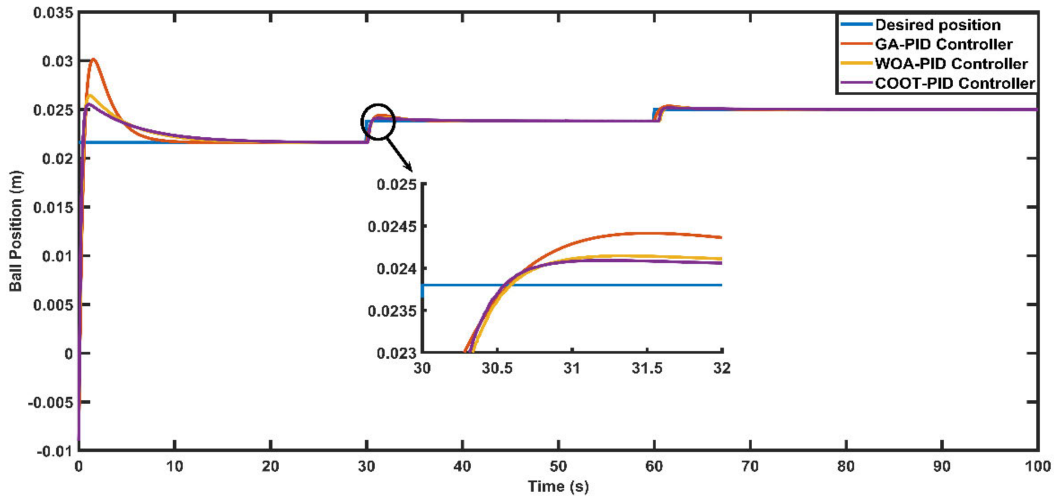


**FIGURE 14.** Comparative analysis of PID controller using GA, WOA, and COOT algorithm of an servo response.

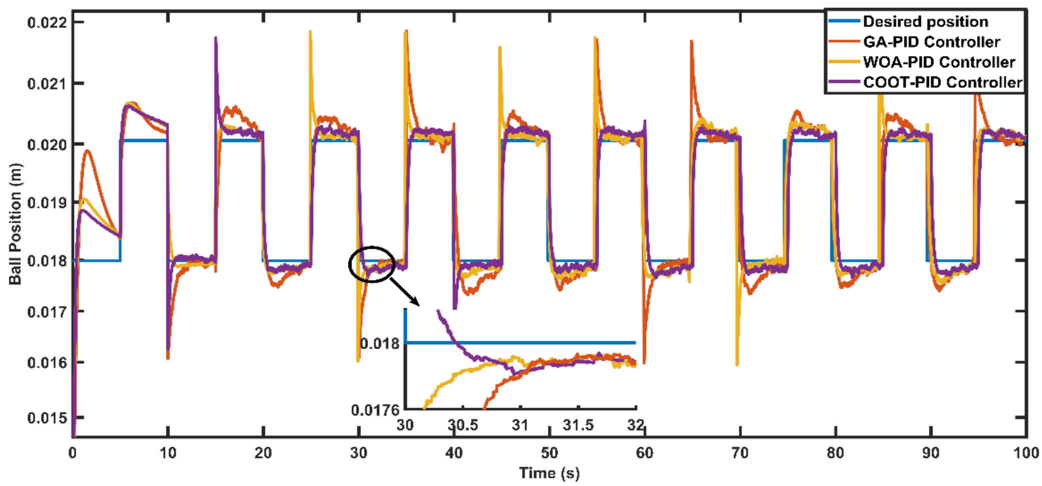


**FIGURE 15.** Comparative analysis of PID controller using GA, WOA, and COOT algorithm of a square response.

destabilization. Using a COOT-based controller in a magnetic levitation system ball reaches the reference trajectory with less deviation compared to the GA, WOA-based controller.

Below table. 5 represents the ISE value of the magnetic levitation system with various algorithms. The ISE values of servo response and square response of COOT

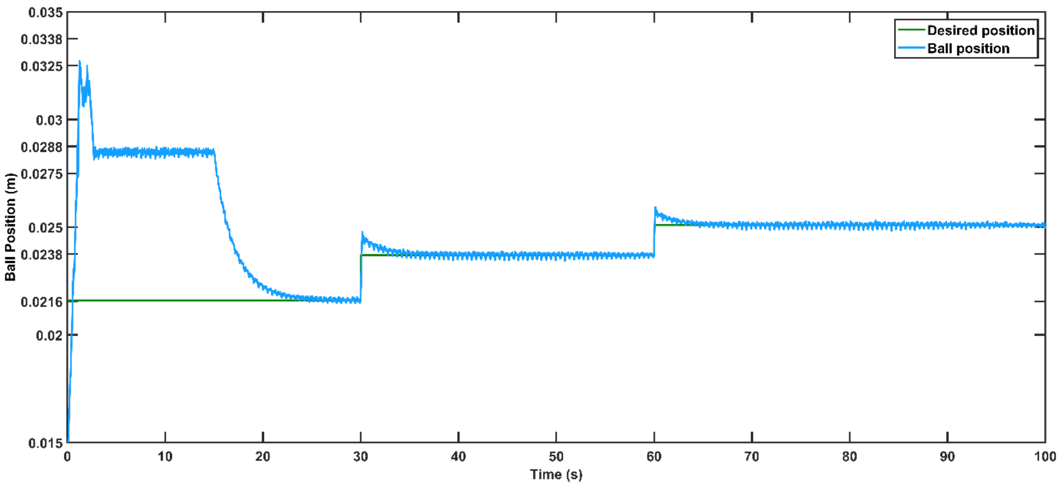


**FIGURE 16.** Servo response of the magnetic levitation system with GA based controller in hardware.

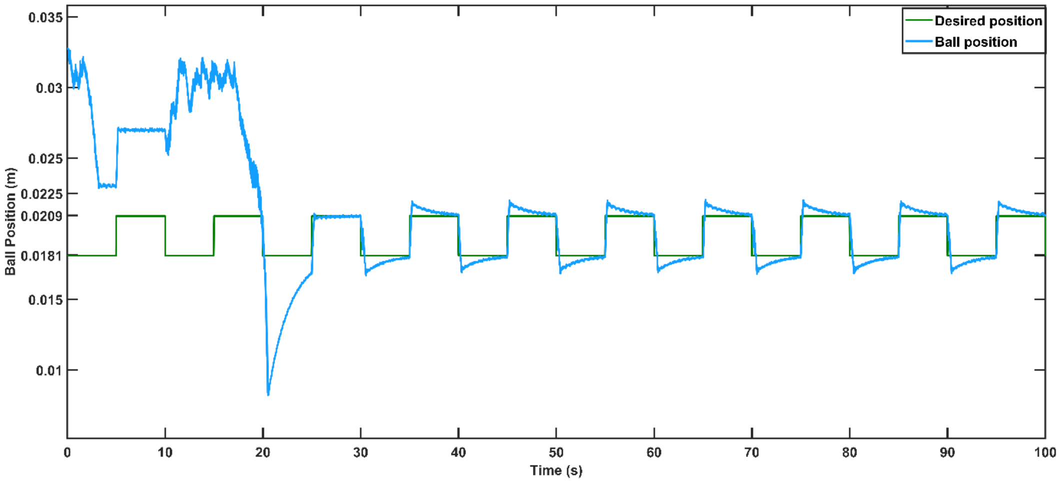


**FIGURE 17.** Square response of the magnetic levitation system with GA based controller in hardware.

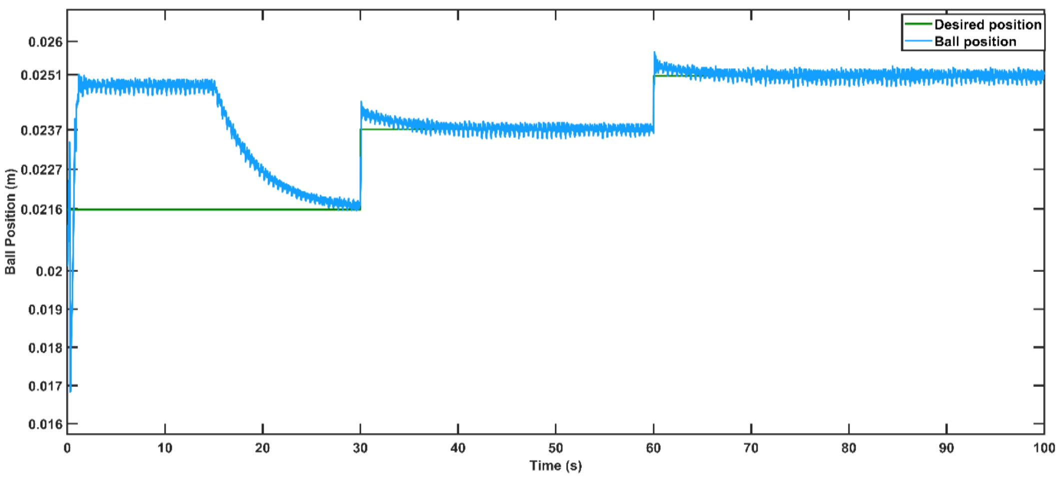


**FIGURE 18.** Servo response of the magnetic levitation system with WOA based controller in hardware.

algorithm-based optimized controller of magnetic levitation system is very less compared to the other algorithms both in simulation and hardware. Hence the proposed COOT algorithm performed well in both simulation and hardware and reaches the reference trajectory. The obtained ISE value shown in table 5 is less compared to the ISE

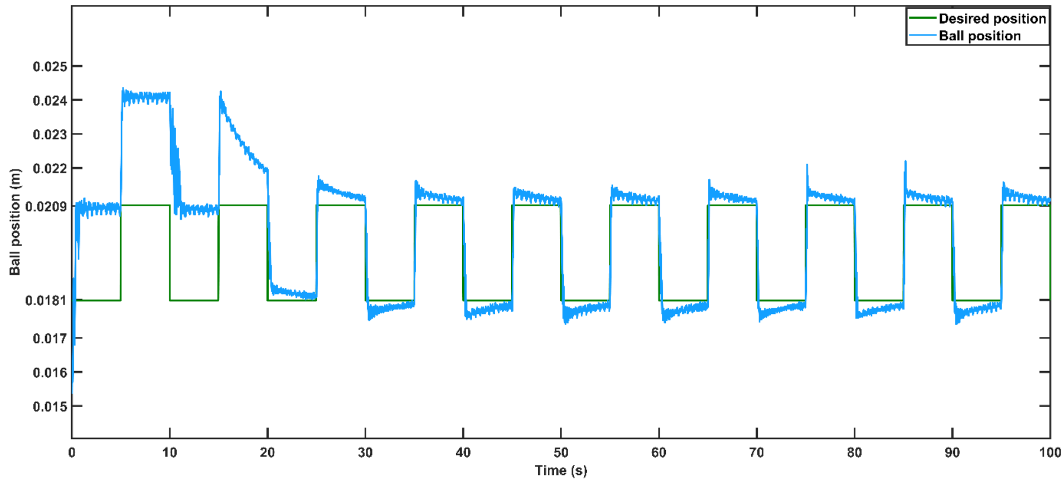


**FIGURE 19.** Square response of the magnetic levitation system with WOA based controller in hardware.

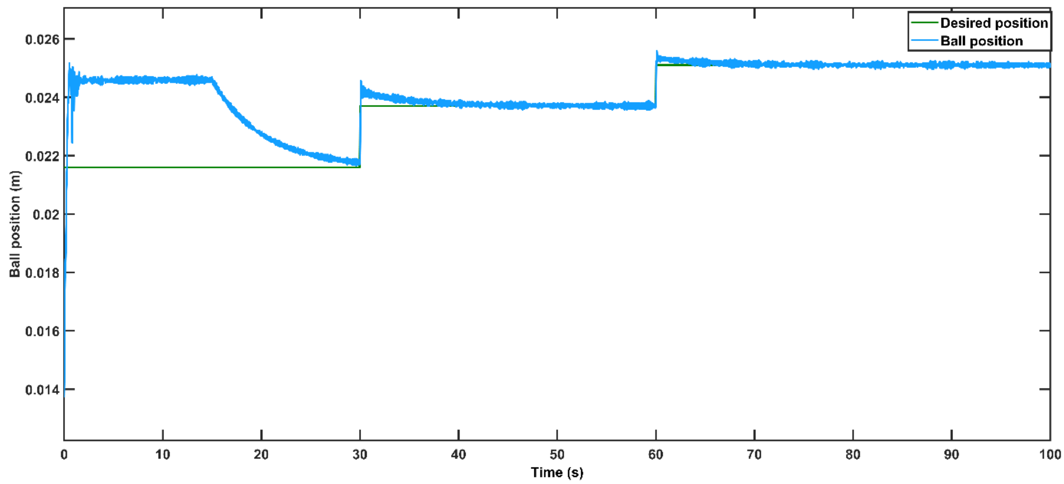


**FIGURE 20.** Servo response of the magnetic levitation system with COOT based controller in hardware.

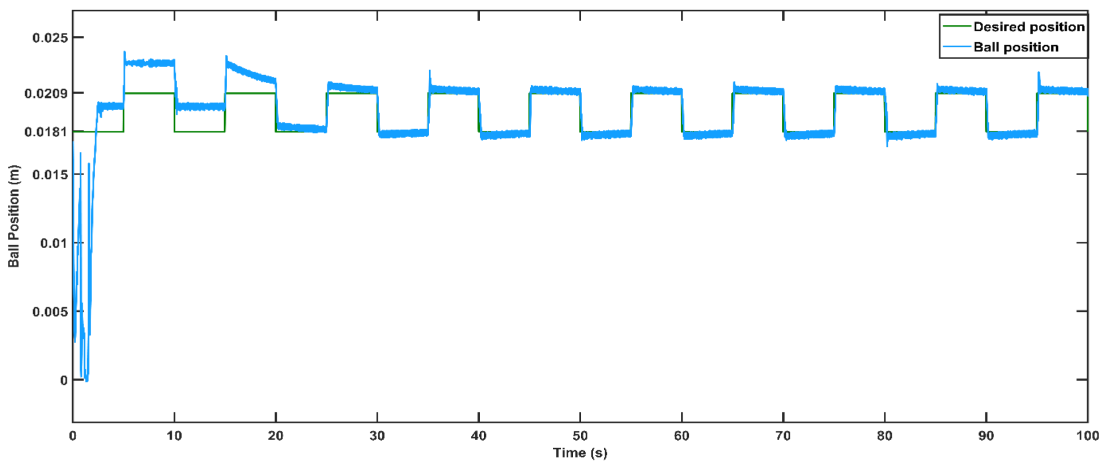


**FIGURE 21.** Square response of the magnetic levitation system with COOT-based controller in hardware.

value obtained in [1] where they used a FOPID controller and it is optimized using a dynamic PSO (dPSO) algorithm. Table 6 shows the comparison of the obtained ISE value from the proposed work with the ISE value obtained from [1].

Figure 24 shows the response of the maglev system after introducing the external disturbance. Compared to the GA-PID controller and WOA-PID controller, the COOT-PID controller performed well on the system in terms of reaching the desired position. The maglev system reaches the desired

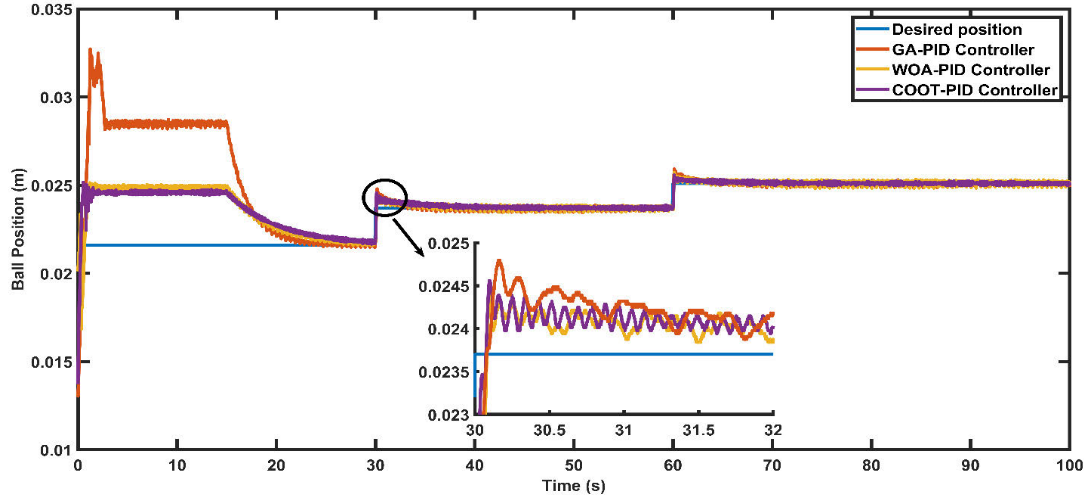


**FIGURE 22.** Comparative analysis of PID controller using GA, WOA and COOT algorithm.

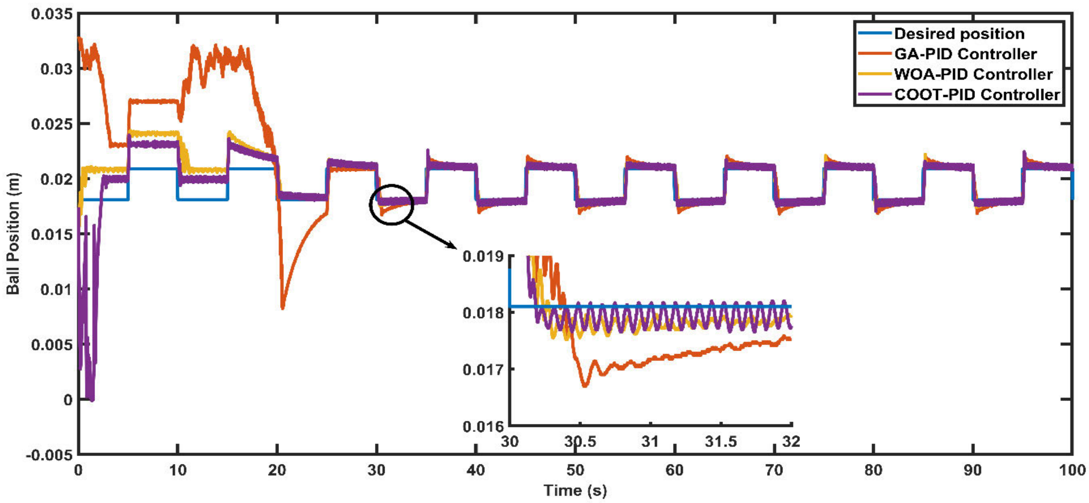


**FIGURE 23.** Comparative analysis of PID controller using GA, WOA and COOT algorithm.

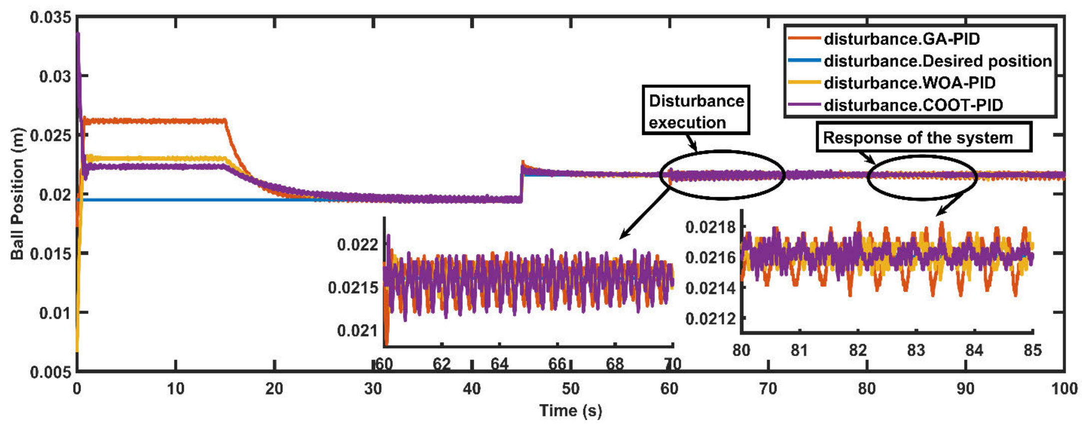


**FIGURE 24.** Response of maglev system after executing the disturbance.

position at 80 seconds by using the COOT-PID controller after introducing the disturbances. The reason for adding the disturbance at 60 seconds is, that the system is in steady state condition. In this system mainly disturbance will occur by the air, this can be avoided by completely closing the air entries.

## VII. CONCLUSION

In this paper, for both simulation and hardware, a PID controller is used to control the magnetic levitation system. The novelty of the work is COOT algorithm is recommended for tuning the PID controller parameters and finding the performance of the COOT algorithm on the magnetic levitation system. The COOT-based optimal controller's effectiveness has been compared to the GA-based and WOA-based optimal controllers. ISE and time domain analysis are used to find the performance of the system. Using the COOT algorithm ball reaches the reference trajectory with less integral square error compared to the other algorithms. From the results, it was concluded that the COOT algorithm performed well compared to the other algorithms both in simulation and hardware. More settling time is a drawback of the proposed method.

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