

The Design Process of a 2-DOF PID Controller Applying the Salp Swarm Algorithm for Position Control of a Linear DC Motor

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Abstract

Conventional single-degree-of-freedom PI and PID controllers face a trade-off between fast tracking and low overshoot in precision position control. This paper investigates the design of a two-degree-of-freedom proportional-integral-derivative (2-DOF PID) controller for position control of a Linear DC Motor. The Salp Swarm Algorithm (SSA) is employed to tune the controller parameters, including the proportional gain, integral gain, derivative gain, proportional set-point weight, and derivative set-point weight. To provide a fair controller-structure comparison, the same SSA procedure is also applied to conventional PID and PI controllers under identical simulation conditions. The controller performance is evaluated in MATLAB/Simulink using a step reference input and a load disturbance of 0.10 N applied at $t = 10$ s over 30 independent runs. Two objective functions are considered: the integral of time-weighted absolute error (ITAE) and the integral of absolute error (IAE). The results show that the SSA-tuned 2-DOF PID controller provides the lowest objective function values for both tuning criteria. Under ITAE-based tuning, the proposed controller achieves an ITAE value of 1.5341, which is 53.02% lower than the PID controller and 54.34% lower than the PI controller. Under IAE-based tuning, it achieves an IAE value of 0.3096, which is 70.17% lower than the PID controller and 77.37% lower than the PI controller. The mean values over all runs are also the lowest among the three controllers. In addition, the proposed controller reduces overshoot (to 1.15% and 1.50% under ITAE and IAE, respectively) and undershoot compared with the SSA-tuned PID and PI controllers, with a fast rise time of 0.73 s and 0.30 s. These results demonstrate that the additional set-point weighting parameters of the 2-DOF PID structure improve the tracking performance of the Linear DC Motor position control system.

Keywords: 2-DOF PID controller; Controller optimization; Linear DC motor; Position control; Salp swarm algorithm

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1. Introduction

Linear DC Motors are widely used in precision motion control applications because they can provide direct linear motion with high controllability [1, 2]. They are commonly found in automation systems [3], servo mechanisms [4], machine tools [5], and transportation equipment where accurate position tracking is required [6]. In such applications, the controller must achieve fast response, low overshoot, small undershoot, and low steady-state error [7, 8]. Previous work has also emphasized that DC motor control requires accurate and stable controller design to improve position-control performance under practical operating conditions [9, 10]. Excessive overshoot in these applications not only degrades positioning accuracy but can also impose mechanical stress on the moving element and the driven load, which is unacceptable in precision equipment such as machine tools and automated positioning stages. The controller for a Linear DC Motor must therefore suppress overshoot without sacrificing tracking speed, a requirement that is difficult to satisfy with a single-degree-of-freedom structure.

Conventional PI and PID controllers are widely used because of their simple structure and ease of implementation [11, 12]. However, their single-degree-of-freedom structure may lead to a trade-off between fast tracking response and overshoot reduction. A 2-DOF PID controller provides additional flexibility by introducing the proportional set-point weighting parameter P_w and derivative set-point weighting parameter D_w [13–15]. These parameters allow the reference response to be shaped more effectively than a conventional PID controller. Specifically, P_w and D_w scale the contribution of the reference signal to the proportional and derivative terms, as expressed in Eq. (7), so that the reference-tracking path can be shaped independently of the feedback path. Reducing the reference contribution to the proportional and derivative actions attenuates the sudden control effort produced at a step change in the set-point, which is the main source of overshoot, while the feedback path retains full gain for disturbance rejection. Therefore, the 2-DOF PID controller is considered in this study to improve the position response of a Linear DC Motor.

Metaheuristic optimization has been widely adopted for controller tuning in motor drive and motion control systems, since it does not require an analytical tuning rule and can handle non-convex, multi-parameter search spaces. Particle swarm optimization has been applied to the decoupling control of bearingless brushless DC motors through a neural network inverse system [9], and intelligent approaches such as neural-network-based fuzzy PID control have been developed for brushless DC motor drives [10]. The firefly algorithm has been used to optimize PID parameters in BLDC motor drive systems supplied by solar panels [12], while the Harris Hawks optimization algorithm has been employed for optimal DC motor control [8]. Metaheuristic tuning has likewise been extended to two-degree-of-freedom structures, as in the Dwarf Mongoose algorithm applied to classical and 2-DOF controllers for fuel-cell-powered nanogrids [14]. However, most of these studies focus on demonstrating the capability of a particular optimizer, while the controller structure is kept fixed. As a result, the specific contribution of the 2-DOF structure itself remains difficult to isolate, since differences in reported performance may originate from the optimizer rather than from the controller structure. A controlled comparison in which PI, PID, and 2-DOF PID controllers are tuned by the same optimizer, under identical bounds, search settings, and simulation conditions, is therefore needed, particularly for the Linear DC Motor, for which such a structural comparison has received limited attention.

This paper presents the design of a 2-DOF PID controller using the Salp Swarm Algorithm (SSA) [16] for Linear DC Motor position control. SSA is a swarm-based optimizer inspired by the chain movement of salps, where the population is divided into leader and follower salps and the best solution is used as the food source to guide the search process. SSA is selected in this study because it requires only a single main control coefficient, which reduces the risk that the comparison is affected by optimizer-specific parameter tuning, and because it has demonstrated competitive performance on constrained engineering design problems [16]. It should be emphasized that the objective of this work is not to claim the superiority of SSA over other optimizers; rather, SSA serves as a common and fixed tuning mechanism so that any observed performance difference can be attributed to the controller structure. In this work, SSA is therefore used as the common tuning method for all controllers, and the study compares controller structures, not optimization algorithms. The proposed SSA-tuned 2-DOF PID controller is compared with SSA-tuned PID and PI controllers using MATLAB/Simulink. Two objective functions, ITAE and IAE, are used to evaluate the controller performance in terms of rise time, settling time, overshoot, undershoot, objective function value, convergence behavior, and statistical results over independent runs.

The main contributions of this paper are summarized as follows:

- A 2-DOF PID controller tuned by the Salp Swarm Algorithm is designed for position control of a brushed Linear DC Motor, with the proportional and derivative set-point weights included as decision variables.
- A controlled structural comparison of the 2-DOF PID, PID, and PI controllers is conducted under an identical optimizer, identical parameter bounds, an identical number of search agents and iterations, and identical simulation conditions, so that the observed performance difference is attributable to the controller structure rather than to the optimization algorithm.
- The comparison is performed under two objective functions, ITAE and IAE, and is evaluated using both time-domain indices (overshoot, undershoot, rise time, and settling time) and error-integral criteria.
- Statistical results over 30 independent runs are reported for all controllers, and the effect of the search-bound setting on the tuned controller parameters is examined and discussed.

The remainder of this paper is organized as follows. Section 2 presents the Linear DC Motor model, the controller structures, the objective functions, the SSA-based tuning procedure, and the simulation setup. Section 3 presents and discusses the results obtained using the ITAE and IAE criteria, including time-domain performance, convergence behavior, and statistical results. Section 4 concludes the paper and outlines directions for future work.

2. Materials and Methods

2.1 Linear DC Motor Model

The plant used in this study is a brushed Linear DC Motor position control system [17]. The mathematical model consists of the electrical circuit, back-electromotive force, thrust force, and mechanical motion of the moving element. The armature voltage equation is expressed as shown in Eq. (1);

$$V_a(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + e_b(t) \quad (1)$$

where $V_a(t)$ is the input voltage, $i_a(t)$ is the armature current, R_a is the armature resistance, L_a is the armature inductance, and $e_b(t)$ is the back-electromotive force. The back-electromotive force is proportional to the mover velocity, as shown in Eq. (2);

$$e_b(t) = K_b \frac{dx(t)}{dt} \quad (2)$$

where K_b is the back-electromotive-force coefficient and $x(t)$ is the output position. The thrust force generated by the motor is proportional to the armature current, as shown in Eq. (3);

$$F_e(t) = K_t i_a(t) \quad (3)$$

where $F_e(t)$ is the electromagnetic thrust force and K_t is the thrust coefficient. The mechanical motion of the moving element is described as shown in Eq. (4);

$$M_t \frac{d^2x(t)}{dt^2} + F \frac{dx(t)}{dt} = F_e(t) \quad (4)$$

where M_t is the mass of the moving element and F is the linear viscous damping coefficient. From Eq. (1) – (4), the transfer function from the input voltage to the output position is obtained as shown in Eq. (5);

$$G(s) = \frac{X(s)}{V_a(s)} = \frac{K_t}{s[(L_a s + R_a)(M_t s + F) + K_b K_t]} \quad (5)$$

where $G(s)$ is the transfer function of the Linear DC Motor, $V_a(s)$ is the input voltage, and $X(s)$ is the output position. The parameters of the brushed Linear DC Motor used in the MATLAB/Simulink simulation are summarized in Table 1. All motor parameters are adopted from the permanent-magnet linear motor model reported in [17] and are used without modification.

Table 1. Parameters of the brushed Linear DC Motor used in simulation.

Symbol	Description	Numerical value
R_a	Resistance of the armature winding	2.70 Ω
L_a	Inductance of the armature circuit	0.414 mH
M_t	Mass of the moving element	0.30 kg
K_b	Back-electromotive-force coefficient	0.732 V·s m ⁻¹
K_t	Electromagnetic thrust coefficient	0.732 N/A
F	Linear viscous damping coefficient	0.712 N·s m ⁻¹

2.2 Controller Design

Three controller structures are investigated in this study: the 2-DOF PID controller, the PID controller, and the PI controller [18 – 20]. The tracking error between the reference position and the output position is defined as shown in Eq. (6);

$$e(t)=r(t)-y(t) \quad (6)$$

where $e(t)$ is the tracking error, $r(t)$ is the reference position, and $y(t)$ is the output position of the Linear DC Motor. The 2-DOF PID controller is used as the proposed controller because it includes proportional and derivative set-point weighting parameters. The control signal of the 2-DOF PID controller is formulated as shown in Eq. (7);

$$u(t)=K_p[P_w r(t)-y(t)]+K_i \int_0^t e(\tau) d\tau+K_d \frac{d}{dt}[D_w r(t)-y(t)] \quad (7)$$

where $u(t)$ is the control signal. The parameters K_p , K_i , and K_d are the proportional gain, integral gain, and derivative gain, respectively. The parameters P_w and D_w are the proportional set-point weighting parameter and derivative set-point weighting parameter, respectively. The decision vector of the proposed 2-DOF PID controller is defined as shown in Eq. (8);

$$X_{2\text{DOF-PID}}=[K_p, K_i, K_d, P_w, D_w] \quad (8)$$

For the conventional PID controller, the decision vector is defined as shown in Eq. (9);

$$X_{\text{PID}}=[K_p, K_i, K_d] \quad (9)$$

For the PI controller, the decision vector is defined as shown in Eq. (10);

$$X_{\text{PI}}=[K_p, K_i] \quad (10)$$

In the MATLAB/Simulink implementation, the same controller structure is used for all cases. For the PID controller, $P_w = 1$ and $D_w = 1$ are fixed. For the PI controller, $K_d = 0$, $P_w = 1$, and $D_w = 1$ are fixed.

In this study, the derivative action in Eq. (7) is implemented in its ideal form, without a derivative filter coefficient. In addition, the control signal is not limited by an actuator saturation block, and no anti-windup compensation is applied. These conditions are applied identically to all three controllers, so that the comparison reflects the controller structures themselves rather than differences in derivative filtering or saturation handling. It should also be noted that the simulation model does not include measurement noise, so the noise amplification normally associated with an ideal derivative term does not affect the reported results. Nevertheless, the inclusion of a derivative filter, actuator saturation limits, and anti-windup compensation is necessary for physical implementation, and these aspects are addressed as part of the future work toward experimental validation.

2.3 Objective Functions

The controller parameters are tuned by minimizing the position tracking error. In this study, two objective functions are used: the integral of time-weighted absolute error (ITAE) [21] and the integral of absolute error (IAE) [22]. The ITAE objective function is expressed as shown in Eq. (11);

$$J_{\text{ITAE}}=\int_0^T t|e(t)|dt \quad (11)$$

The IAE objective function is expressed as shown in Eq. (12);

$$J_{\text{IAE}}=\int_0^T |e(t)|dt \quad (12)$$

where T is the simulation time and $e(t)$ is the position tracking error. In each tuning case, SSA searches for the controller parameter set that gives the minimum objective function value.

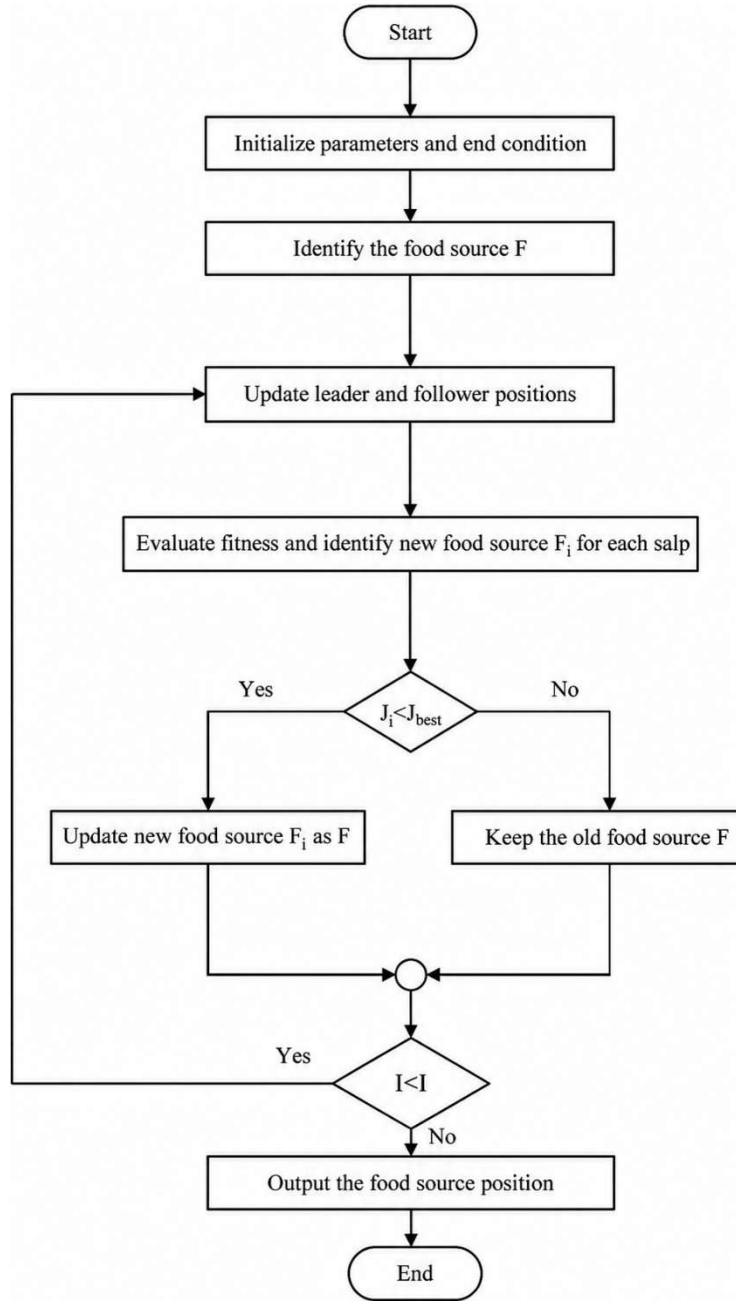


Fig. 1 Flowchart of the SSA-based controller parameter tuning process.

2.4 Salp Swarm Algorithm-Based Tuning

The Salp Swarm Algorithm (SSA) is applied to tune the parameters of the 2-DOF PID, PID, and PI controllers. In SSA, the population is divided into a leader salp and follower salps. The leader salp moves toward the food source, which represents the best solution obtained so far, while the follower salps update their positions according to the salp in front of them. The leader position is updated as shown in Eq. (13);

$$x_j^l = \begin{cases} F_j + c_1[(ub_j - lb_j)c_2 + lb_j], & c_3 \geq 0 \\ F_j - c_1[(ub_j - lb_j)c_2 + lb_j], & c_3 < 0 \end{cases} \quad (13)$$

where x_j^l is the position of the leader salp in the j -th dimension, F_j is the position of the food source, ub_j and lb_j are the upper and lower bounds, and c_1 , c_2 , and c_3 are SSA coefficients. The coefficient c_1 is calculated as shown in Eq. (14);

$$c_1 = 2e^{\left(\frac{4l}{L}\right)^2} \quad (14)$$

where l is the current iteration and L is the maximum number of iterations. The follower salps update their positions as shown in Eq. (15);

$$x_j^i = \frac{1}{2}(x_j^i + x_j^{i-1}), i \geq 2 \quad (15)$$

where x_j^i is the position of the i -th follower salp in the j -th dimension. In this work, each salp represents one candidate controller parameter set. For each candidate solution, the parameters are assigned to the MATLAB/Simulink model, and the position response of the Linear DC Motor is simulated. Then, the selected objective function is calculated from the tracking error. Boundary checking is applied to keep all parameters within the specified search range.

The overall SSA-based tuning procedure is summarized in Fig. 1. The process starts with parameter initialization, followed by food source identification, salp position updating, fitness evaluation, and food source updating. These steps are repeated until the maximum number of iterations is reached, and the best food source is selected as the optimal controller parameter set.

2.5 Simulation Setup

The proposed control system is implemented in MATLAB/Simulink, as shown in Fig. 2. A step input is used as the reference position, and the output position of the Linear DC Motor is measured for performance evaluation. To evaluate the disturbance rejection capability, a load disturbance with an amplitude of 0.1 N is applied at $t = 10$ s at the mechanical force summation point of the Linear DC Motor model. The same motor model, reference input, simulation time, disturbance condition, parameter bounds, number of search agents, maximum iteration, and number of independent runs are used for all controllers. Therefore, the comparison focuses only on controller structures.

The simulation is executed using a variable-step ode45 solver with a maximum step size of 1×10^{-3} s, a relative tolerance of 1×10^{-3} , and an absolute tolerance of 1×10^{-6} . The same solver configuration is applied to every objective function evaluation and to every controller, so that all candidate solutions are assessed under numerically identical conditions. The simulation and SSA parameter settings are summarized in Table 2.

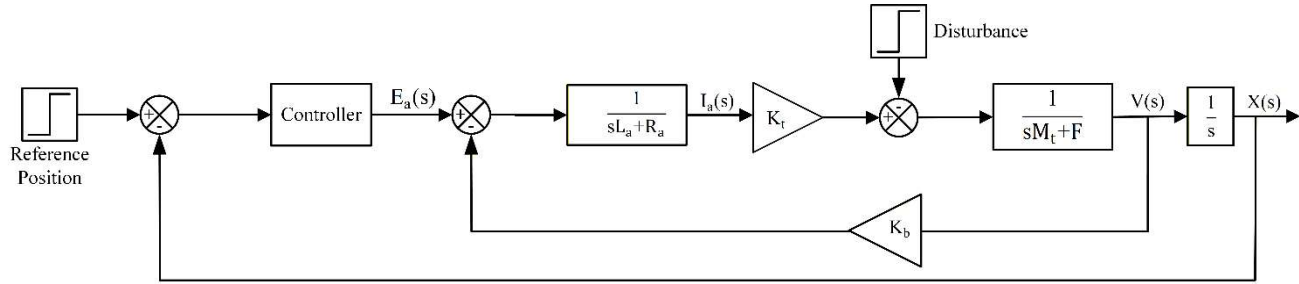


Fig. 2 Block diagram of the Linear DC Motor position control system.

The same search bound $[0, 5]$ is applied to every optimized parameter of every controller. Although the set-point weighting parameters of a 2-DOF PID controller are frequently restricted to the range $[0, 1]$, they are treated here as generalized weighting parameters and are allowed to search over the same range as the controller gains. This choice is made so that no controller is given a wider or narrower search space than another, which preserves the fairness of the structural comparison. The influence of this bound setting on the resulting parameters is examined in Section 3.

The performance of the controllers is evaluated using rise time, settling time, overshoot, undershoot, objective function value, convergence curve, and statistical results over independent runs. The rise time is defined as the time required for the response to rise from 10% to 90% of the final reference value. The settling time is defined as the time after which the response enters and permanently remains within a $\pm 2\%$ band around the final reference value; because this criterion is evaluated over the entire 20 s simulation, the reported settling time includes the recovery period following the load disturbance applied

at $t = 10$ s. The overshoot is measured as the maximum positive deviation from the reference value during the initial transient, and the undershoot is measured as the maximum negative deviation observed after the load disturbance is applied.

Table 2 Simulation and SSA parameter settings.

Parameter	Value
Search agents	50
Maximum iteration	50
Independent runs	30
Parameter bounds (K_p , K_i , K_d , P_w and D_w)	[0, 5]
Simulation time	20 s
Reference input	Unit step
Load disturbance	0.1 N at $t = 10$ s
Solver	ode45, variable-step
Maximum step size	1×10^{-3} s

3. Results and Discussions

3.1 Results Using ITAE as Objective Function

In the first case, ITAE was used as the objective function for tuning the controller parameters. The optimized parameters of the SSA-tuned 2-DOF PID, PID, and PI controllers are shown in Table 3.

Table 3 Optimized controller parameters using ITAE.

Controller	K_p	K_i	K_d	P_w	D_w
SSA-2DOF-PID	4.9973	4.9365	1.1535	0.6741	2.9290
SSA-PID	4.9999	2.9114	0.0004	-	-
SSA-PI	4.9277	2.8530	-	-	-

It should be noted that, under the ITAE criterion, the derivative gain of the SSA-tuned PID controller converged to a near-zero value ($K_d = 0.0004$). This indicates that, for this plant and this objective function, the optimizer found no benefit in using derivative action, so the tuned PID controller effectively reduces to PI action. This behaviour is a property of the ITAE cost landscape rather than a constraint imposed by the controller structure, and it should be considered when interpreting the comparison between the PID and PI controllers in this case.

Table 4 Time-domain performance using ITAE.

Controller	Overshoot (%)	Undershoot (%)	Rise time (s)	Settling time (s)	ITAE
SSA-2DOF-PID	1.1532	4.9235	0.7317	12.6131	1.5341
SSA-PID	36.2940	6.1928	0.7440	12.9568	3.2656
SSA-PI	36.1522	6.2640	0.7481	12.9904	3.3595

The time-domain performance values are summarized in Table 4. The SSA-tuned 2-DOF PID controller achieved the lowest overshoot of 1.1532%, compared with 36.2940% for the PID controller and 36.1522% for the PI controller. The proposed controller also produced the lowest undershoot of 4.9235% and the shortest settling time of 12.6131 s. The final ITAE value of the 2-DOF PID controller was 1.5341, which was lower than those of the PID and PI controllers.

The position responses of the Linear DC Motor using ITAE-based tuning are shown in Fig. 3. The SSA-tuned 2-DOF PID controller provided a smoother tracking response with a much smaller overshoot than the SSA-tuned PID and PI controllers. The PID and PI controllers reached the reference position with large transient overshoots, while the proposed 2-DOF PID controller closely followed the reference with a limited peak response.

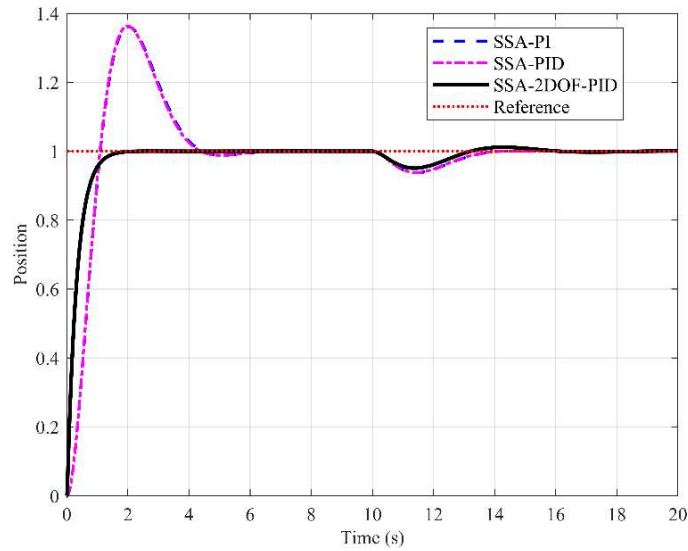


Fig. 3 ITAE-based position responses.

The convergence curves of the SSA-tuned controllers using ITAE are shown in Fig. 4. The SSA-tuned 2-DOF PID controller showed a continuous reduction in the fitness value and reached the lowest final ITAE value. In contrast, the PID and PI controllers converged to higher objective function values.

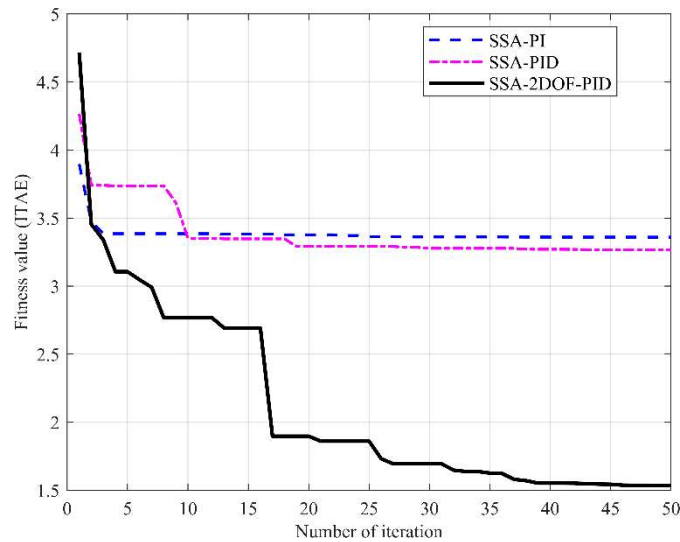


Fig. 4 ITAE-based convergence curves.

The statistical results over 30 independent runs are shown in Table 5. The SSA-tuned 2-DOF PID controller obtained the lowest best and mean ITAE values. The best ITAE value of the proposed controller was 53.02% lower than that of the PID controller and 54.34% lower than that of the PI controller. In terms of mean performance over the 30 runs, the proposed controller achieved a mean ITAE value that was 45.68% lower than that of the PID controller and 46.94% lower than that of the PI controller, indicating that the improvement is not limited to the best-case run. However, the standard deviation of the 2-DOF PID controller was higher than those of the PID and PI controllers, indicating greater variation among independent runs. It should be noted, nevertheless, that the worst ITAE value obtained by the 2-DOF PID controller (2.4075) remained lower than the best values obtained by the PID (3.2656) and PI (3.3595) controllers. The higher variation therefore reflects a wider spread within a consistently superior performance range, rather than any run in which the proposed controller was outperformed.

Table 5 Statistical results over independent runs using ITAE.

Controller	Best	Mean	Worst	Std
SSA-2DOF-PID	1.5341	1.7827	2.4075	0.3197
SSA-PID	3.2656	3.2819	3.7157	0.0819
SSA-PI	3.3595	3.3595	3.3595	1.9021×10^{-5}

3.2 Results Using IAE as Objective Function

In the second case, IAE was used as the objective function for tuning the controller parameters. The optimized parameters of the three SSA-tuned controllers are shown in Table 6. The optimized parameter sets for all three controllers were obtained under the same search bounds and simulation conditions.

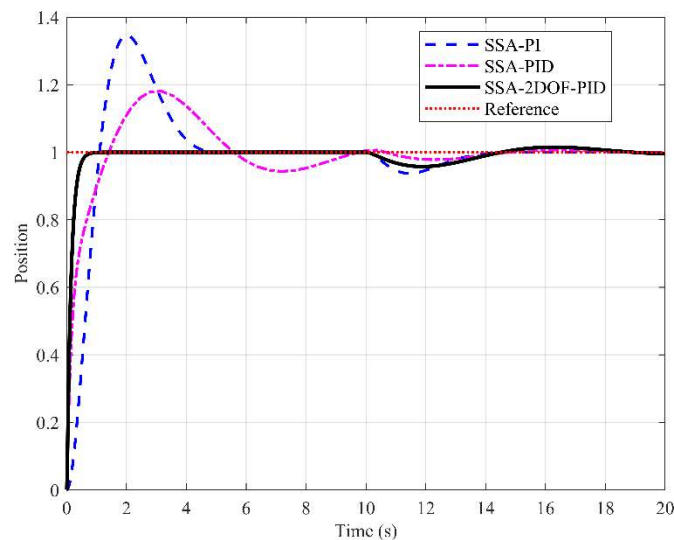
Table 6 Optimized controller parameters using IAE.

Controller	Kp	Ki	Kd	Pw	Dw
SSA-2DOF-PID	4.1981	4.3098	4.7159	0.8456	1.5975
SSA-PID	4.9997	4.9747	4.9993	-	-
SSA-PI	5.0000	2.7199	-	-	-

It is observed that, under the IAE criterion, the optimized gains of the PID controller ($K_p = 4.9997$, $K_i = 4.9747$, $K_d = 4.9993$) and the proportional gain of the PI controller ($K_p = 5.0000$) lie at or very close to the upper search bound. This indicates that the performance of these two controllers was limited by the specified search range rather than having converged to an interior optimum, which is also consistent with the very small standard deviations reported for these controllers in Table 8. Since the identical bound $[0, 5]$ was applied to every optimized parameter of every controller, no controller was given a search-space advantage, and the comparison therefore remains valid under this common bound. Nevertheless, the reported performance margins between the 2-DOF PID controller and the single-degree-of-freedom controllers should be interpreted with respect to this bound, and a comparison using wider search bounds is identified as future work.

Table 7 Time-domain performance using IAE.

Controller	Overshoot (%)	Undershoot (%)	Rise time (s)	Settling time (s)	IAE
SSA-2DOF-PID	1.4982	4.2434	0.3049	13.5230	0.3096
SSA-PID	18.0864	5.6677	1.0255	13.0725	1.0379
SSA-PI	34.6093	6.2513	0.7594	13.0638	1.3679

**Fig. 5** IAE-based position responses.

The time-domain performance results are listed in Table 7. The SSA-tuned 2-DOF PID controller achieved the lowest overshoot of 1.4982% and the lowest undershoot of 4.2434%. It also provided the fastest rise time of 0.3049 s. Although the PID and PI controllers had slightly shorter settling times, their overshoot values were much higher than that of the proposed controller. The final IAE value of the 2-DOF PID controller was 0.3096, which was lower than those of the PID and PI controllers.

The position responses obtained using IAE-based tuning are shown in Fig. 5. The SSA-tuned 2-DOF PID controller reached the reference position rapidly with a small overshoot. In contrast, the PID and PI controllers produced larger transient peaks. The PI controller showed the largest overshoot, while the 2-DOF PID controller provided the most balanced response.

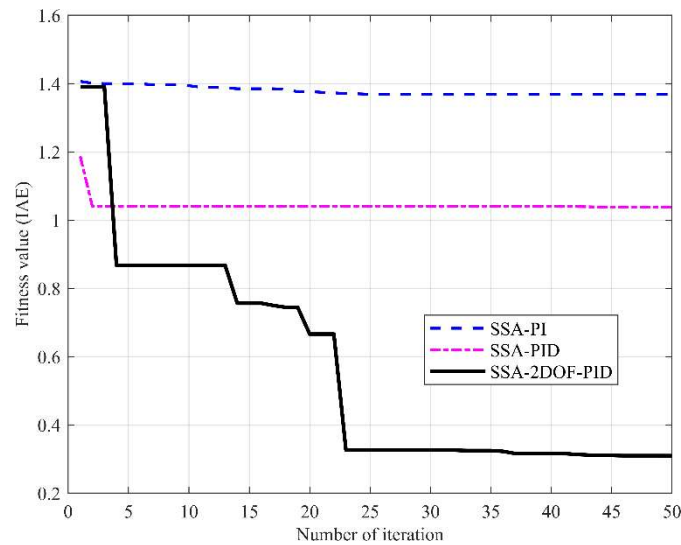


Fig. 6 IAE-based convergence curves.

The convergence curves using IAE are shown in Fig. 6. The SSA-tuned 2-DOF PID controller showed the largest reduction in fitness value during the optimization process and achieved the lowest final IAE value. The PID and PI controllers converged at higher objective function values.

Table 8 shows the statistical results over 30 independent runs. The SSA-tuned 2-DOF PID controller achieved the lowest best, mean, and worst IAE values. The best IAE value of the proposed controller was 70.17% lower than that of the PID controller and 77.37% lower than that of the PI controller. The corresponding mean IAE value of the proposed controller was 57.23% lower than that of the PID controller and 67.53% lower than that of the PI controller. As in the ITAE case, the standard deviation of the 2-DOF PID controller was higher than those of the PID and PI controllers, which converged to almost identical solutions in every run. However, the worst IAE value obtained by the 2-DOF PID controller (0.6293) remained lower than the best values obtained by the PID (1.0379) and PI (1.3679) controllers, so the wider spread occurred entirely within a superior performance range. These results indicate that the 2-DOF PID structure improved the tracking-error performance under the IAE criterion.

Table 8 Statistical results over independent runs using IAE.

Controller	Best	Mean	Worst	Std
SSA-2DOF-PID	0.3096	0.4442	0.6293	0.0827
SSA-PID	1.0379	1.0386	1.0396	4.4025×10^{-4}
SSA-PI	1.3679	1.3679	1.3681	3.6272×10^{-5}

3.3 Comparative Discussion

The results from both ITAE- and IAE-based tuning show that the SSA-tuned 2-DOF PID controller provided better tracking performance than the SSA-tuned PID and PI controllers. The main improvement was observed in the transient

response, where the proposed controller produced lower overshoot and lower undershoot after the load disturbance was applied. This indicates that the proportional and derivative set-point weighting parameters, P_w and D_w , helped improve the reference tracking response and disturbance response of the Linear DC Motor position control system.

Although the PID and PI controllers showed smaller variation in some statistical results, their objective function values and transient deviations were higher than those of the 2-DOF PID controller. Therefore, the comparative results confirm that, under the same SSA tuning conditions and within the specified search bounds, the 2-DOF PID controller provided the most suitable controller structure among the controllers investigated in this study.

The statistical results reported in Tables 5 and 8 are based on the best, mean, worst, and standard-deviation values obtained over 30 independent runs. Although these statistics consistently favour the proposed controller, a formal non-parametric significance test, such as the Wilcoxon rank-sum test, would provide stronger statistical evidence for the observed differences and is identified as an item for future work.

4. Conclusion

This paper presented an SSA-tuned 2-DOF PID controller for position control of a Linear DC Motor. The proposed controller was evaluated and compared with SSA-tuned PID and PI controllers under identical MATLAB/Simulink simulation conditions. Since the Salp Swarm Algorithm was used as the common tuning method for all controllers, the comparison focused on controller structures rather than optimization algorithms. Two objective functions, ITAE and IAE, were considered to evaluate the tracking performance of the control system. A load disturbance with an amplitude of 0.1 N was also applied at $t=10$ s to examine the disturbance rejection response of each controller.

The simulation results showed that the SSA-tuned 2-DOF PID controller provided superior overall performance compared with the SSA-tuned PID and PI controllers. Under ITAE-based tuning, the proposed controller achieved an ITAE value of 1.5341, which was 53.02% lower than that of the PID controller and 54.34% lower than that of the PI controller. Under IAE-based tuning, the proposed controller achieved an IAE value of 0.3096, which was 70.17% lower than that of the PID controller and 77.37% lower than that of the PI controller. In terms of mean performance over 30 independent runs, the corresponding reductions were 45.68% and 46.94% under the ITAE criterion, and 57.23% and 67.53% under the IAE criterion, confirming that the improvement was not limited to the best-case run. Although the standard deviation of the proposed controller was higher than those of the PID and PI controllers, its worst-case values under both criteria remained lower than the best values obtained by the other two controllers. In addition, after the load disturbance was introduced, the proposed controller produced lower undershoot than the PID and PI controllers. These results indicate that the proportional and derivative set-point weighting parameters of the 2-DOF PID structure provide additional flexibility for improving both reference tracking and disturbance response of the Linear DC Motor position control system.

Several limitations of this study should be acknowledged. First, under the ITAE criterion the derivative gain of the SSA-tuned PID controller converged to a near-zero value, so the tuned PID controller effectively reduced to PI action, which limits the interpretation of the three-structure comparison in that particular case. Second, under the IAE criterion several optimized gains of the PID and PI controllers were located at the upper search bound, indicating that their performance was constrained by the specified search range rather than by an interior optimum; the reported performance margins should therefore be interpreted with respect to the common bound $[0, 5]$ applied to all controllers. Third, the comparison was based on best, mean, worst, and standard-deviation statistics without a formal non-parametric significance test.

Although the proposed controller showed promising performance in MATLAB/Simulink simulation, further investigation is still required for practical implementation. Future work should include comparison with other metaheuristic optimization algorithms under the same controller structures, evaluation using wider parameter search bounds, the application of non-parametric statistical significance testing such as the Wilcoxon rank-sum test, real-time experimental validation, robustness analysis under motor parameter variations, further disturbance rejection tests, and validation using nonlinear motor models, together with the inclusion of a derivative filter, actuator saturation limits, and anti-windup compensation for physical implementation. In addition, multi-objective controller tuning may be considered to simultaneously optimize tracking accuracy, transient response, disturbance rejection, and control effort for practical Linear DC Motor position control applications. From a practical perspective, the substantial reduction in overshoot achieved by the 2-DOF PID structure is directly relevant to precision industrial applications such as machine tools, automated positioning stages, and servo mechanisms, where excessive overshoot degrades positioning accuracy and imposes unnecessary mechanical stress on the driven load.

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