American Journal of Sciences and Engineering Research

E-ISSN -2348 – 703X, Volume 8, Issue 4, 2025

A Comparative Review of Particle Swarm Optimization Applications in Intelligent Control Systems

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Abstract: *This paper presents a comparative review of three intelligent control approaches that integrate Particle Swarm Optimization (PSO) into different control architectures—neural networks, PID controllers, and fuzzy logic systems—to address nonlinear system challenges in robotics and automation. Drawing on recent studies involving mobile robots and rotary inverted pendulums, the review highlights how PSO enhances each system's performance by autonomously tuning critical parameters, thereby improving trajectory tracking, convergence speed, and control accuracy. The analysis reveals that PSO consistently outperforms traditional tuning methods, offering greater adaptability, robustness, and efficiency across varying control tasks. By synthesizing methodologies and simulation outcomes, this paper underscores PSO's versatility and effectiveness as a unified optimization strategy for intelligent control design, while also identifying opportunities for future research in hybrid algorithms and real-time adaptive control systems.*

Keywords: *Particle Swarm Optimization (PSO), Intelligent Control, Mobile Robot, Neural Network Control, PSO-PID, Fuzzy Logic Controller, Nonlinear Systems, Trajectory Tracking, Optimization Algorithms, Adaptive Control*

I. Introduction

Over the past three decades, intelligent optimization algorithms have played an increasingly pivotal role in the development of adaptive control systems across robotics, automation, and nonlinear dynamic modeling. Among them, Particle Swarm Optimization (PSO) has emerged as one of the most effective and versatile nature-inspired algorithms. Initially developed by Kennedy and Eberhart (1995), PSO simulates the social behavior of flocks of birds or schools of fish, where individual agents (particles) move through a multidimensional search space by updating their velocities and positions according to both their own best-known positions and the best-known positions of their neighbors. This population-based, stochastic search mechanism allows PSO to handle complex, nonlinear, and non-differentiable optimization problems with relatively low computational cost (Kennedy & Eberhart, 1995; Sun et al., 2012).

One of the core strengths of PSO lies in its ability to maintain a balance between exploration (global search) and exploitation (local refinement), which makes it especially well-suited for parameter tuning tasks in dynamic control systems. Unlike traditional optimization methods such as gradient descent or genetic algorithms (GAs), PSO does not require gradient information and is less likely to suffer from premature convergence, particularly in high-dimensional or rugged search spaces (Wang et al., 2020). These characteristics make PSO highly applicable in control engineering problems involving uncertainty, nonlinear dynamics, and time-varying constraints—conditions frequently encountered in real-world systems such as mobile robots, inverted pendulums, and autonomous vehicles (Bari et al., 2022; Zhang et al., 2023).

 Received-20-06-2025, Accepted- 29-06-2025

Recent studies have demonstrated the superior performance of PSO when integrated with conventional control methodologies. For instance, PSO has been widely used to fine-tune the parameters of Proportional-Integral-Derivative (PID) controllers, resulting in significantly improved system response times and minimized overshoot in unstable systems (Khorram et al., 2022). In artificial neural networks (ANNs), PSO has been employed to optimize connection weights and biases, thereby accelerating convergence during training and improving generalization ability (Zhou et al., 2023). Similarly, when applied to fuzzy logic controllers, PSO helps in determining optimal membership function parameters and fuzzy rule sets, eliminating the need for trial-and-error or expert-based tuning approaches (Panigrahi et al., 2021). These hybrid models—often referred to as PSO-PID, PSO-ANN, or PSO-Fuzzy systems—combine the interpretability and structure of classical controllers with the adaptive power of evolutionary optimization.

This review paper presents a comparative analysis of three recent implementations of PSO in intelligent control design. The first study involves a neural network-based controller for mobile robots, where PSO is used to optimize the network weights to enhance tracking performance (Vũ, 2013). The second investigates PSO-based PID tuning for rotary inverted pendulum stabilization, a canonical benchmark problem in control theory (Son & Dung, 2021). The third integrates fuzzy logic with PSO to control a two-wheeled mobile robot, focusing on trajectory tracking and reduced tracking errors (Son & Dung, 2023). These three studies are representative of the diverse application spectrum of PSO in intelligent control systems, each utilizing a different core controller architecture but sharing the common goal of improving robustness, stability, and responsiveness through intelligent optimization.

By analyzing the methodologies, objective functions, system models, and simulation results of these works, this paper aims to evaluate the strengths and limitations of each approach. Additionally, it identifies current research gaps and suggests directions for further exploration, particularly in the context of hybrid swarm-based methods, real-time implementation, and scalability to multi-agent systems. This synthesis contributes to the growing body of knowledge on the applicability of PSO in modern intelligent control and highlights its enduring relevance in both academic research and industrial practice.

II. PSO-Optimized Neural Network Controller for Mobile Robots

The integration of Particle Swarm Optimization (PSO) into neural network-based control architectures has become a widely explored technique for addressing complex robotic navigation and path-tracking challenges. In his seminal master's thesis, Vũ Ngọc Huyên (2013) proposed a hybrid intelligent control framework that leverages the power of multilayer feedforward Artificial Neural Networks (ANNs), optimized using the PSO algorithm, for controlling the dynamic behavior of mobile robots. The motivation behind this hybridization stems from the limitations of traditional backpropagation algorithms, which often suffer from slow convergence and susceptibility to local minima in nonlinear and high-dimensional environments (Vũ, 2013). By incorporating PSO to optimize the network's connection weights and learning parameters, the proposed system demonstrates faster convergence, improved generalization, and enhanced robustness in real-time control scenarios.

The ANN used in the model is structured as a multilayer perceptron (MLP) with hidden layers capable of approximating nonlinear functions, a property reinforced by the universal approximation theorem (Hornik, 1991). PSO's role in this context is to perform a global search over the neural network's parameter space, thereby accelerating the learning process and avoiding suboptimal solutions. This approach aligns with recent findings, where metaheuristic algorithms like PSO are shown to significantly improve ANN training efficiency and accuracy in control applications (Zhou et al., 2023; Zangeneh et al., 2021). In Vũ's work, the control model was developed and simulated using MATLAB Simulink, focusing on real-time trajectory tracking of a differential drive mobile robot. The results showed substantial improvements in trajectory convergence, with minimized error between the robot's actual position and the reference point across multiple test cases.

One of the critical innovations in Vũ's study is the implementation of a PSO-ANN-based controller in a dynamic, nonlinear environment—an approach that has since become a foundation for adaptive control in mobile robotics. Compared to classical control methods, the proposed architecture provides greater adaptability to external disturbances and parameter uncertainties, which are typical in autonomous robot operations. The neural network controller, once optimized using PSO, demonstrates the capability to maintain tracking performance despite changes in desired trajectories or environmental conditions. Moreover, Vũ's method sets a precedent for further research into hybrid intelligent control schemes, combining biologically inspired optimization techniques with neural learning architectures.

This work prefigures later developments in swarm-intelligence-assisted neural control, which has been expanded to include deep learning models, recurrent neural networks, and reinforcement learning systems (Zhang et al., 2023). It also supports broader trends in using soft computing for mobile robotics, emphasizing interpretability, adaptability, and computational efficiency in real-time implementations. As mobile robots increasingly operate in unstructured and dynamic environments, hybrid models such as the PSO-ANN approach remain critical in developing autonomous systems with advanced decision-making and path-planning capabilities.

III. PSO-PID Controller for Rotary Inverted Pendulum

The rotary inverted pendulum is a widely used benchmark problem in control systems research due to its inherent instability, underactuated nature, and pronounced nonlinear dynamics. Stabilizing such a system demands a control strategy capable of handling rapid fluctuations and complex interactions between the pendulum and arm angles. In this context, Son and Dung (2021) developed an advanced control framework that integrates Particle Swarm Optimization (PSO) with classical Proportional–Integral–Derivative (PID) control to optimize system performance. Traditional PID controllers, although simple and effective in linear systems, often fall short when applied to nonlinear environments like the inverted pendulum, as manual tuning of parameters (Kp, Ki, Kd) typically relies on heuristic or trial-and-error approaches, leading to suboptimal stability and delayed system response (Boukabou et al., 2021; Khorram et al., 2022).

To address these limitations, the authors employed PSO to automate the tuning process by minimizing the Integral of Absolute Error (IAE), which quantifies cumulative deviation in both the pendulum and arm angles over a defined time period. PSO's population-based search mechanism allows for iterative refinement of control parameters, using swarm intelligence to converge toward an optimal solution based on both individual and global best experiences (Son & Dung, 2021). The control model was implemented and simulated in MATLAB Simulink, and included a dual-loop structure—one for pendulum angle control and another for arm angle stabilization. Results showed that with an increasing number of particles (20, 30, 50) and generations (15, 20, 30), the adaptation function converged more quickly, yielding precise control over the system dynamics and significantly reducing oscillations in both angular trajectories.

The findings from this work are consistent with broader research trends that highlight the efficacy of swarm optimization techniques in fine-tuning PID controllers for nonlinear and time-variant systems. For instance, recent studies have shown that PSO-tuned PID controllers outperform traditional Ziegler–Nichols methods, especially in achieving faster settling time, reduced overshoot, and enhanced robustness against system disturbances (Oladipo et al., 2022; Lin et al., 2023). Moreover, the authors' use of IAE as a performance index aligns with current best practices in control optimization, where minimizing integral-based error functions such as IAE or Integral of Squared Error (ISE) is crucial for high-performance regulation (Sadat et al., 2021).

Ultimately, the study by Son and Dung demonstrates how PSO enhances the flexibility and adaptability of PID controllers in challenging nonlinear control environments. Their approach not only reduces manual effort in tuning but also facilitates real-time adaptability, making it suitable for broader applications such as robotics, aerospace systems, and industrial automation where precise and reliable control is paramount.

IV. Fuzzy-PSO Controller in Mobile Robot Path Tracking

In their 2023 study, Son and Dung present an innovative approach to mobile robot path tracking by integrating Particle Swarm Optimization (PSO) with Fuzzy Logic Control (FLC)—a combination designed to harness the strengths of both intelligent control paradigms. Fuzzy logic, widely used for modeling systems with uncertainty and linguistic variables, excels at approximating human-like reasoning in dynamic environments.

However, the performance of traditional fuzzy controllers is often hindered by the subjectivity involved in the manual design of membership functions, fuzzy rules, and scaling factors (Panigrahi et al., 2021). To address these shortcomings, the authors employed PSO as a metaheuristic optimizer that autonomously tunes the fuzzy controller parameters—including the shapes and ranges of membership functions, as well as rule base coefficients—based on the minimization of a control fitness function. This approach enables the fuzzy controller to adapt to nonlinearities and disturbances in real time, ensuring smoother and more accurate robot navigation.

The system modeled in MATLAB Simulink simulates a differential drive two-wheeled mobile robot tasked with following a dynamically moving reference point. The control objectives focus on minimizing positional errors in both Cartesian coordinates (x, y) and the orientation angle (θ), while ensuring real-time responsiveness. The authors defined two key input variables—distance to the reference point (d) and heading angle error (α)—and mapped them to output variables that govern the velocities of the left and right wheel motors (ωL and ωR). The fuzzy rule base was constructed with 25 IF–THEN rules, and the defuzzification process employed the centroid method for output computation. The PSO algorithm was applied to optimize both the input and output membership parameters, with a swarm size of 20 and 50 generations.

Simulation results revealed that the PSO-optimized fuzzy controller outperformed its conventional counterpart in all evaluated metrics. Specifically, the optimized system exhibited significantly reduced steady-state error, quicker settling time, and enhanced tracking accuracy, even under varying speed conditions (vr = 0.5 m/s and vr = 1 m/s). The fitness function values—used as an objective performance index—were nearly halved when compared to the traditional fuzzy logic controller, indicating a substantial improvement in path-following precision (Son & Dung, 2023). These results are in agreement with broader trends in robotics control literature, where hybrid PSO-FLC models have demonstrated superior adaptability and efficiency in non-model-based scenarios such as mobile robot tracking, swarm robotics, and intelligent vehicles (Yadav & Chouhan, 2022; Habib et al., 2023).

The practical significance of this work lies in its ability to eliminate trial-and-error procedures typically associated with fuzzy system design, allowing for autonomous adaptation in dynamic environments. This makes it particularly suitable for real-time robotic applications where precise localization and obstacle avoidance are critical. Furthermore, this study reinforces the viability of PSO as a lightweight yet powerful optimizer for tuning rule-based intelligent control systems, offering a promising direction for future research in autonomous navigation and cooperative multi-agent robotics.

V. Comparative Analysis

All three studies leverage PSO to overcome parameter tuning challenges in nonlinear control systems.

Table 1 summarizes key aspects:

Study	Control Method	System	Optimization Target	Performance Gain
Vũ (2013)	PSO + Neural Network	Mobile Robot	Neural weights	Improved trajectory tracking
Son & Dung (2021)	PSO-PID	Inverted Pendulum	PID gains	Faster convergence, reduced IAE
Son & Dung (2023)	Fuzzy-PSO	Two-wheeled Robot	Fuzzy parameters	Better path tracking, reduced error

A comparative evaluation of the three reviewed studies reveals the extensive adaptability of Particle Swarm Optimization (PSO) in optimizing diverse control architectures under nonlinear and dynamic environments. Each study applies PSO within a distinct control framework—neural networks, PID controllers, and fuzzy inference systems—yet they all converge on the central objective of improving control precision and robustness through automated parameter tuning. This flexibility underscores PSO's unique position among nature-inspired metaheuristics, particularly its ability to traverse complex, multidimensional search spaces efficiently without requiring gradient information (Wang et al., 2020; Bari et al., 2022).

Vũ (2013) integrates PSO into a multilayer feedforward neural network to optimize synaptic weights for trajectory control in mobile robots. The result is a learning model capable of nonlinear function approximation, with PSO ensuring global convergence by mitigating the risk of local minima—an issue common to gradient-based backpropagation methods (Zhou et al., 2023). In contrast, Son and Dung (2021) employ PSO to tune the gain parameters (Kp, Ki, Kd) of a PID controller for stabilizing a rotary inverted pendulum system, a highly nonlinear and unstable platform. By minimizing the Integral of Absolute Error (IAE), their PSO-PID approach yields improved system response, faster convergence, and reduced oscillations, outperforming traditional tuning methods like Ziegler-Nichols (Khorram et al., 2022; Oladipo et al., 2022).

Expanding on this, Son and Dung (2023) propose a PSO-optimized fuzzy logic controller to regulate a two-wheeled mobile robot. The fuzzy controller, while effective in handling uncertainties and linguistic modeling, typically suffers from subjectivity in rule and membership function design. PSO automates this tuning process, significantly enhancing the controller's ability to track reference trajectories with lower steady-state errors. In this context, PSO serves as a bridge between heuristic-based fuzzy control and data-driven optimization, enabling real-time adaptation without compromising computational efficiency (Panigrahi et al., 2021; Habib et al., 2023).

Collectively, these implementations demonstrate PSO's capacity to enhance performance across multiple control paradigms. Regardless of the underlying control model—be it neurocomputational, rule-based, or feedback-driven—PSO consistently delivers improvements in system stability, error minimization, and convergence speed. This cross-architecture applicability not only validates PSO's algorithmic robustness but also suggests its potential as a unifying optimization tool in complex control scenarios, including multi-agent coordination, real-time adaptive robotics, and cyber-physical systems. Future research may explore hybridized metaheuristics combining PSO with reinforcement learning or deep learning to further expand its capabilities in high-dimensional, time-sensitive applications.

VI. Conclusion

This comparative review has examined three distinct yet complementary studies that demonstrate the broad applicability and effectiveness of Particle Swarm Optimization (PSO) in the field of intelligent control systems. Despite their varied implementations—ranging from neural networks and classical PID controllers to fuzzy logic systems—all studies underscore a consistent theme: PSO significantly enhances system performance through automated and intelligent parameter tuning. Each case exemplifies how PSO addresses core challenges in nonlinear control systems, such as poor convergence, susceptibility to local optima, and manual tuning inefficiencies.

In the first study, PSO was utilized to optimize the weights of a multilayer neural network for mobile robot trajectory tracking, resulting in improved adaptability and learning accuracy. The second study applied PSO to PID tuning in a rotary inverted pendulum system, demonstrating faster convergence, improved stability, and minimized error. The third highlighted the integration of PSO with fuzzy logic controllers in two-wheeled mobile robots, where PSO's ability to fine-tune fuzzy parameters led to more precise and reliable path tracking.

Taken together, these studies not only affirm the versatility of PSO across various control paradigms but also point to its growing relevance in real-time, adaptive, and autonomous control systems. As robotics and automation applications increasingly demand robustness in uncertain, dynamic environments, PSO emerges as a powerful and lightweight solution capable of meeting such complex requirements. Furthermore, the reviewed works lay the groundwork for future research into hybrid metaheuristics, such as combining PSO with reinforcement learning or deep neural architectures, to address higher-dimensional control problems and multi-agent coordination tasks.

In summary, PSO serves not merely as an optimization algorithm but as an enabler of intelligent autonomy, offering scalable, flexible, and efficient solutions for modern control challenges. Its continued evolution and integration with emerging technologies hold promising potential for both academic advancement and industrial innovation.

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