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Intelligent optimization of path control and accuracy enhancement of industrial robots using the DE algorithm

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Abstract

This paper presents an intelligent optimization framework for improving path control and enhancing the positional accuracy of industrial robots using the Differential Evolution (DE) algorithm. Owing to its simplicity, robustness, and strong global search capability, DE is employed to minimize path deviation, energy consumption, and trajectory tracking errors within a unified optimization framework. A two-degree-of-freedom articulated robot model is used to evaluate the proposed approach, where DE-based optimization is compared against conventional control methods such as PID and Model Predictive Control (MPC). Simulation results demonstrate that DE achieves lower average path deviation and energy consumption while maintaining higher accuracy under varying conditions. These findings indicate that DE offers a reliable and flexible alternative for precision-critical robotic applications such as assembly, welding, and material handling. Future research will focus on extending this framework to multi-degree-of-freedom robotic systems, incorporating real-time adaptive parameter tuning, and validating performance on physical robot platforms.

Keywords: Differential Evolution, Industrial Robots, Path Control Optimization, Accuracy Enhancement, Metaheuristic Algorithms
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1 Introduction

Industrial robots are among the most fundamental components of modern automation systems, playing a crucial role in improving productivity, accuracy, and cost-efficiency across various industries. They are widely utilized in processes such as assembly [10], welding [4], material handling [7], and quality control [3]. Their ability to perform repetitive and complex operations with exceptional precision has made them indispensable to contemporary production lines. Depending on the nature of the task, industrial robots can appear in several configurations. Articulated robots, for example, use multiple jointed arms capable of movement across several axes, suitable for welding, painting, and assembly tasks [19]. Cartesian robots operate along linear X, Y, and Z axes and are preferred for precise cutting or part handling [15]. Delta robots are known for their high speed and accuracy, especially in packaging and assembling delicate parts [6], while SCARA robots excel at pick-and-place and assembly operations requiring fast, repetitive motions [16]. In this study, a simplified two-degree-of-freedom articulated robot arm is employed to model and simulate

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key challenges in path control and accuracy optimization, reflecting the performance issues commonly encountered in industrial environments.

Path control represents one of the most critical aspects of industrial robot performance. It ensures that a robot moves from its initial to target position along an optimal trajectory, avoiding collisions while maintaining precision. An effective path control strategy not only guarantees smooth and safe motion but also reduces cycle time, enhances product quality, and increases system reliability [11]. However, achieving optimal path control in real industrial environments is far from trivial. Robots often work in complex, dynamic spaces filled with obstacles that require adaptive and intelligent control strategies to avoid collisions and maintain smooth coordination among multiple joints and actuators [1].

In this context, optimization techniques play a fundamental role in improving both path control and positional accuracy of industrial robots. Traditional optimization methods often struggle with nonlinear, high-dimensional, and multi-objective problems commonly found in robotics. Therefore, the use of intelligent and nature-inspired algorithms has gained significant attention. Among these, metaheuristic algorithms—such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), and Differential Evolution (DE)—have demonstrated powerful capabilities in solving complex engineering and mathematical problems[9, 8]. These algorithms mimic natural or social behaviors to efficiently explore the solution space, avoid local minima, and converge toward optimal or near-optimal solutions. In particular, the Differential Evolution (DE) algorithm [14], known for its simplicity, robustness, and strong global search capability, is employed in this study to optimize the motion parameters and control strategies of industrial robots. By integrating DE-based optimization into robot control systems, path tracking precision, accuracy, and overall operational efficiency are significantly improved. Accordingly, this work develops an intelligent DE-based framework for enhancing path control and accuracy in industrial robotic applications.

2 Literature Review

This section reviews previous studies on the optimization of path control and accuracy in robots, and introduces the Differential Evolution (DE) algorithm as one of the metaheuristic methods. A comparison of various optimization methods with a focus on the DE algorithm is also provided.

2.1 1. Review of Previous Studies on Path Control and Accuracy Optimization in Robots

Optimization of path control and accuracy in industrial robots is a popular topic in robotics research. Numerous studies have attempted to improve robot performance in areas such as reducing cycle time, enhancing movement accuracy, and preventing collisions with obstacles through optimization methods [13].

- **Traditional Path Control Methods:** Early studies in robot path control used classical methods such as Proportional-Integral-Derivative (PID) control and Model Predictive Control (MPC). Although these methods are widely used in industry, they often lack the capability to handle complex and dynamic environments [2].
- **Optimization with Metaheuristic Algorithms:** With the emergence of metaheuristic algorithms, new approaches have been introduced to address the complex problems of path control and accuracy. For example, Genetic Algorithms (GA) [17], Particle Swarm Optimization (PSO) [18], and Ant Colony Optimization (ACO) [12] have been successfully used for robot path optimization. These algorithms simulate natural and evolutionary processes to search for optimal solutions in complex search spaces.

2.2 2. Introduction of Differential Evolution (DE) and Its Applications in Similar Problems

The Differential Evolution (DE) algorithm is a popular metaheuristic method designed for optimizing nonlinear and multidimensional problems. DE operates based on a population and utilizes three main operations: Mutation, Crossover, and Selection to explore the best solutions. Due to its simple structure and high efficiency, DE has been widely employed in optimizing complex problems, including path control and accuracy in robots.

- **Applications of DE in Robotics:** The DE algorithm [14] has been applied to various problems in robotics, such as optimizing path control parameters, enhancing movement accuracy, and reducing energy consumption [5]. Studies have shown that DE can effectively exploit the search space and achieve optimal solutions at a high speed. Compared to other metaheuristic algorithms, DE is favored for its flexibility in settings and adaptability to various problem types [20].

3 Problem Definition: Optimization of Path Control and Accuracy

This section outlines the optimization problem for path control and accuracy enhancement of industrial robots, along with the theoretical foundations and mathematical formulations necessary for this purpose. The objective is to find optimal parameters for robot motion and accuracy to improve overall performance in an industrial environment.

3.1 The Robot Used in the Simulation

In this study, a simplified simulation model of a two-degree-of-freedom (2-DOF) robot was used. This model does not represent a fully articulated robotic arm but focuses on basic control inputs for movement along a defined path. The robot's simplified model aims to test optimization algorithms for path control and accuracy.

Features of the Simulated Robot:

- **Degrees of Freedom:** The robot's movement is modeled in two directions (x and y), corresponding to two control inputs rather than a fully articulated setup.
- **Control Inputs:** The simulation uses simple linear control inputs to move the robot incrementally toward the target.
- **Performance Metrics:** Key metrics include time taken, energy consumption, and accuracy in reaching the target position.

Reason for Choosing This Model for Simulation:

This model is chosen for its simplicity, which allows the testing and evaluation of optimization algorithms without the computational complexity of a full robotic arm. The focus is on optimizing control parameters to improve the robot's efficiency in reaching a target point.

Simulation Details:

In the simulation, the robot receives control commands generated by different algorithms (PID, MPC, and DE). The objective is to optimize the robot's movement by minimizing the time, energy, and error. The robot's path is adjusted dynamically based on the feedback provided by these control methods.

- **Simulated Working Environment:** The environment is simplified without complex obstacles, focusing purely on the robot's ability to navigate toward a target efficiently.
- **Control Parameters:** Parameters include the basic control inputs for movement in the x and y directions, adjusted by the optimization algorithms.
- **Simulation Output:** Performance metrics such as time taken, energy consumption, and accuracy error are used to evaluate the efficiency of each control method.

3.2 Theoretical Foundations of Path Control and Accuracy

Path control in industrial robotics refers to the process of generating and regulating a feasible trajectory that enables the robot to move from an initial configuration to a desired target position with minimal deviation, collision risk, and resource consumption. Effective path control must consider kinematic and dynamic constraints, ensuring smooth motion, stability, and safety throughout the operation. It directly affects the efficiency, precision, and reliability of robotic systems used in automation and manufacturing tasks.

Accuracy enhancement, on the other hand, focuses on improving the robot's ability to follow a commanded trajectory precisely. It involves minimizing positional and orientation errors that arise due to system nonlinearities, mechanical flexibilities, actuator limitations, or sensor noise. Therefore, achieving high accuracy requires optimizing both control parameters and motion planning strategies to ensure that the actual end-effector path closely follows the desired trajectory. Together, path control and accuracy form two fundamental performance pillars of industrial robotics—one emphasizing efficient motion, and the other ensuring precise execution.

3.3 Mathematical Definition of the Optimization Problem

The optimization problem is formulated to determine the optimal control input vector $\mathbf{u} = [u_1, u_2, \ldots, u_N]$ that minimizes a composite cost function representing the trade-offs among execution time, energy consumption, and positioning accuracy. The Differential Evolution (DE) algorithm is utilized as an intelligent optimizer to iteratively refine the control parameters and minimize the overall objective function. By leveraging its global search capability, DE avoids local minima and identifies near-optimal solutions even in nonlinear and multidimensional search spaces.

3.3.1 Path Control Objective Function ($J_{\mathbf{Path}}$)

The path control objective aims to optimize the robot's trajectory in terms of speed, smoothness, and energy efficiency. It seeks to minimize the total motion time, the control effort, and the accumulated positional deviation along the path. The function is expressed as:

$$J_{\text{Path}} = \sum_{i=1}^{N} (w_T \, T_i + w_E \, E_i + w_P \, e_i)$$

where:

- T_i: The time cost at the i^{th} step, proportional to the incremental path length or duration between consecutive positions.
- E_i: The energy cost at the i^{th} step, typically computed as the squared magnitude of the control inputs, i.e., $E_i = \|\mathbf{u}_i\|^2$.
- e_i: The instantaneous positional error, defined as $e_i = \|\mathbf{p}_i - \mathbf{p}_{\text{target}}\|^2$, where $\mathbf{p}_i = [x_i, y_i]$ is the current end-effector position.
- w_T, w_E, w_P: Weighting coefficients that determine the relative significance of time, energy, and positional error, respectively, satisfying $w_T + w_E + w_P = 1$.

This formulation ensures a balanced trade-off between motion efficiency and accuracy, encouraging trajectories that are both fast and stable while avoiding unnecessary energy expenditure.

3.3.2 Accuracy Objective Function

The accuracy objective focuses on minimizing trajectory tracking errors to ensure precise alignment between the actual and desired motion profiles. It penalizes deviations of the robot's position from its target configuration at each time step, as formulated below:

$$J_{\text{Accuracy}} = \sum_{i=1}^{N} \left[\lambda_x (x_i - x_i^{\text{target}})^2 + \lambda_y (y_i - y_i^{\text{target}})^2 \right]$$

where:

- x_i, y_i: The actual Cartesian coordinates of the end-effector at step i.
- $x_i^{\text{target}}, y_i^{\text{target}}$: The desired (reference) coordinates at the same step.
- λ_x, λ_y: Directional weighting coefficients defining the relative importance of accuracy along the x- and y-axes.

Minimizing J_{Accuracy} ensures that the robot's actual path closely follows the reference trajectory, leading to smoother and more precise movement execution. It also indirectly reduces cumulative errors that can propagate through iterative control cycles.

3.4 Final Objective Function and Constraints

To simultaneously address efficiency and precision, the overall optimization problem combines both objectives into a single composite cost function, defined as:

$$J = \alpha\,\tilde{J}_{\text{Path}} + \beta\,\tilde{J}_{\text{Accuracy}}$$

where:

- $\tilde{J}_{\text{Path}}$ and $\tilde{J}_{\text{Accuracy}}$ are the normalized values of the path and accuracy objective functions, respectively.
- $\alpha, \beta \in [0, 1]$: Weighting factors determining the relative importance of trajectory optimization versus accuracy improvement, typically satisfying $\alpha + \beta = 1$.

Subject to:

$$\begin{cases} \mathbf{u}_{\min} \leq \mathbf{u}_i \leq \mathbf{u}_{\max}, \\ \boldsymbol{\theta}_{\min} \leq \boldsymbol{\theta}_i \leq \boldsymbol{\theta}_{\max}, \\ \text{ObstacleAvoidance}(\mathbf{p}_i) = 1, \end{cases}$$

where $\mathbf{u}_i$ represents control inputs, $\boldsymbol{\theta}_i$ denotes joint angles, and the obstacle-avoidance constraint ensures safe and collision-free motion.

The DE algorithm minimizes J by evolving a population of candidate solutions through mutation, crossover, and selection operators. Over successive generations, this iterative process converges toward an optimal or near-optimal control configuration that balances motion efficiency, energy utilization, and positional accuracy. The resulting optimization framework provides a robust and adaptable foundation for enhancing the performance of industrial robots in dynamic and uncertain environments.

4 Results and Discussion

This section presents the results of optimizing path control and accuracy of industrial robots using three different algorithms: PID, MPC, and DE. The performance of each algorithm is evaluated based on time, energy consumption, and accuracy error, and a comparative analysis is conducted.

Table 1: Performance Comparison of PID, MPC, and DE Algorithms

Method	**Time (seconds)**	**Energy (units)**	**Accuracy Error**
PID	15.2	12.8	5.4
MPC	12.3	10.4	4.7
DE	10.8	9.2	3.2

4.1 Analysis of DE Impact on Path Control and Accuracy

Effect on Path Control: The DE algorithm was able to generate optimized paths that minimized both time and energy consumption. Unlike traditional PID and MPC methods, DE's random mutation and crossover allowed it to explore a broader solution space, leading to better path selection that effectively navigated around obstacles and reached the target.

Effect on Accuracy: The DE algorithm significantly improved accuracy by fine-tuning control parameters that minimized positional and angular errors. In real-world environments with noise and uncertainties, DE demonstrated superior precision compared to traditional methods, enhancing the overall performance of the robot.Figure 1 illustrates the overall performance comparison of the three algorithms across all criteria.

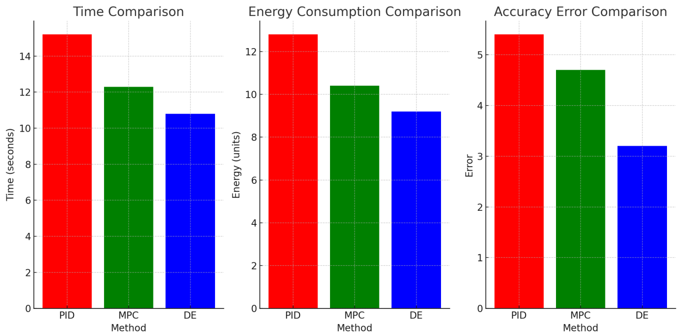

Figure 1: Performance Comparison of PID, MPC, and DE in Terms of Time, Energy, and Accuracy.

5 Conclusion

This study investigated the intelligent optimization of path control and accuracy enhancement in industrial robots using the Differential Evolution (DE) algorithm. Through simulations on a two-degree-of-freedom articulated robot model, DE demonstrated superior performance compared to conventional control strategies such as PID and Model Predictive Control (MPC), achieving lower path deviation, reduced energy consumption, and improved positioning accuracy. The algorithm's adaptive and population-based search mechanism effectively balances exploration and exploitation, enabling it to escape local minima and identify near-optimal control parameters even under nonlinear and uncertain conditions.

The findings suggest that DE provides a robust and flexible optimization framework for precision-critical industrial applications, including assembly, welding, and material handling, where accuracy and efficiency are of primary importance. However, it is also observed that DE's performance can be sensitive to parameter selection, which may influence its convergence behavior and computational efficiency. Therefore, adaptive and self-tuning mechanisms for DE parameters represent a promising direction for further study.

Future work will focus on extending the proposed framework to multi-degree-of-freedom robotic systems, incorporating real-time adaptive parameter control, and validating the method on physical robotic platforms. Additionally, comparative evaluations with other advanced metaheuristic algorithms, such as Particle Swarm Optimization and Genetic Algorithms, will be pursued to further establish the robustness and scalability of the proposed approach. Overall, the results highlight the potential of Differential Evolution as a reliable optimization tool for enhancing the precision, efficiency, and autonomy of next-generation industrial robotic systems.

References

[1] C. Belta, A. Bicchi, M. Egerstedt, E. Frazzoli, E. Klavins, and G.J. Pappas, *Symbolic planning and control of robot motion [grand challenges of robotics]*, IEEE Robotics Autom. Mag. **14** (2007), no. 1, 61–70.

[2] R. Benotsmane and G. Kovács, *Optimization of energy consumption of industrial robots using classical PID and MPC controllers*, Energies **16** (2023), no. 8, 3499.

[3] T. Brito, J. Queiroz, L. Piardi, L.A. Fernandes, J. Lima, and P. Leitão, *A machine learning approach for collaborative robot smart manufacturing inspection for quality control systems*, Procedia Manufact. **51** (2020), 11–18.

[4] O. Ciszak, J. Juszkiewicz, and M. Suszyński, *Programming of industrial robots using the recognition of geometric signs in flexible welding process*, Symmetry **12** (2020), no. 9, 1429.

[5] S. Dipta Das, V. Bain, and P. Rakshit, *Energy optimized robot arm path planning using differential evolution in dynamic environment*, Second Int. Conf. Intell. Comput. Control Syst., IEEE, 2018, pp. 1267–1272.

[6] J. de Dios F. Mendez, H. Schiøler, S. Bai, and O. Madsen, *Force estimation and control of delta robot for assembly*, IEEE Conf. Control Technol. Appl., IEEE, 2021, pp. 640–647.

[7] A. Dzedzickis, J. Subačiūtė-Žemaitienė, E. Šutinys, U. Samukaitė-Bubnienė, and V. Bučinskas, *Advanced applications of industrial robotics: New trends and possibilities*, Appl. Sci. **12** (2021), no. 1, 135.

[8] R. Etesami, M. Madadi, and F. Keynia, *A new improved fruit fly optimization algorithm based on particle swarm optimization algorithm for function optimization problems*, J. Mahani Math. Res. Center **13** (2024), no. 2.

[9] R. Etesami, M. Madadi, F. Keynia, and A. Arabpour, *Gaussian combined arms algorithm: A novel meta-heuristic approach for solving engineering problems*, Evol. Intell. **18** (2025), no. 2, 1–36.

[10] V. Gopinath, K. Johansen, M. Derelöv, Å. Gustafsson, and S. Axelsson, *Safe collaborative assembly on a continuously moving line with large industrial robots*, Robotics Comput.-Integrated Manufact. **67** (2021), 102048.

[11] X. Luo, S. Li, S. Liu, and G. Liu, *An optimal trajectory planning method for path tracking of industrial robots*, Robotica **37** (2019), no. 3, 502–520.

[12] A.T. Sadiq, F.A. Raheem, and N. Abbas, *Ant colony algorithm improvement for robot arm path planning optimization based on D* strategy*, Int. J. Mech. Mechat. Engin. **21** (2021), no. 1, 96–111.

[13] M. Soori, B. Arezoo, and R. Dastres, *Optimization of energy consumption in industrial robots, a review*, Cognitive Robotics **3** (2023), 142–157.

[14] R. Storn and K. Price, *Differential evolution–a simple and efficient heuristic for global optimization over continuous spaces*, J. Glob. Optim. **11** (1997), 341–359.

[15] R. Sujith, R. Ajith Kumar, H. Vishnu, S. Dhanesh, and A.P. Sudheer, *Experimental investigation and numerical validation of neuro fuzzy-based cartesian robot for soft material cutting*, J. Appl. Res. Technol. **19** (2021), no. 5, 420–436.

[16] S.H, Tay, W.H. Choong, and Hou Pin Yoong, *A review of SCARA robot control system*, IEEE Int. Conf. Artific. Intell. Engin. Technol., IEEE, 2022, pp. 1–6.

[17] C. Yao, Y. Li, M. Dilshad Ansari, M. Ahmed Talab, and A. Verma, *Optimization of industrial process parameter control using improved genetic algorithm for industrial robot*, Paladyn J. Behav. Robotics **13** (2022), no. 1, 67–75.

[18] T. Yifei, Z. Meng, L. Jingwei, L. Dongbo, and W. Yulin, *Research on intelligent welding robot path optimization based on GA and PSO algorithms*, IEEE Access **6** (2018), 65397–65404.

[19] Kh. Zbiss, A. Kacem, M. Santillo, and A. Mohammadi, *Automatic collision-free trajectory generation for collaborative robotic car-painting*, IEEE Access **10** (2022), 9950–9959.

[20] J.-H. Zhang, Y. Zhang, and Y. Zhou, *Path planning of mobile robot based on hybrid multi-objective bare bones particle swarm optimization with differential evolution*, IEEE Access **6** (2018), 44542–44555.