HYBRID EVOLUTIONARY ALGORITHMS FOR EFFICIENT MULTI-ROBOT PATH PLANNING IN DYNAMIC ENVIRONMENTS

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ABSTRACT

This paper presents a hybrid evolutionary algorithm (HEA) designed to optimize multi-robot path planning (MRPP) in dynamic environments. The proposed HEA integrates genetic algorithms (GA) with local optimization strategies such as particle swarm optimization (PSO) and simulated annealing (SA) to address the challenges of real-time replanning and coordination among robots. The algorithm accounts for dynamic obstacles, varying environmental conditions, and robot interactions to ensure efficient and collision-free navigation. Through extensive simulation and experimental evaluation, the hybrid algorithm demonstrates superior performance in terms of path efficiency, adaptability, and computational time when compared to traditional evolutionary approaches and standalone optimization methods. The results validate the hybrid algorithm's capability in dynamic settings, achieving optimal path planning with minimal computational overhead, thus making it suitable for applications in autonomous vehicles, robotic swarms, and disaster response scenarios.
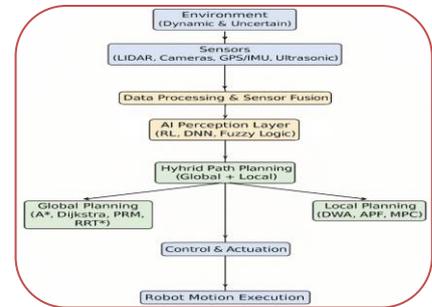
KEYWORDS: *Hybrid Evolutionary Algorithms (HEA), Multi-Robot Path Planning (MRPP), Dynamic Environments, Path Optimization, Collision Avoidance, Real-time Replanning,*

INTRODUCTION

The increasing reliance on autonomous robots for tasks such as exploration, search and rescue, and logistics has spurred significant research in multi-robot systems (MRS), particularly in the domain of path planning. Multi-robot path planning (MRPP) involves determining optimal routes for multiple robots within an environment while minimizing conflicts, ensuring safety, and achieving task objectives. As environments become more dynamic, where obstacles and conditions change over time, the complexity of path planning increases dramatically. Traditional path planning methods often fail to address the challenges posed by these dynamic elements, leading to the need for adaptive, robust, and real-time solutions. Evolutionary algorithms (EAs), inspired by natural evolutionary processes such as selection, mutation, and crossover, have proven effective in solving complex optimization problems, including MRPP. However, single-method evolutionary approaches often struggle with real-time adaptability and efficiency when applied to dynamic environments. The need for a flexible, scalable, and computationally efficient solution motivates the development of hybrid evolutionary algorithms (HEA), which combine the strengths of multiple optimization techniques.

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This paper introduces a hybrid evolutionary approach that integrates genetic algorithms (GA) with local optimization methods, such as particle swarm optimization (PSO) and simulated annealing (SA), to enhance the effectiveness of multi-robot path planning in dynamic and uncertain environments. The hybrid nature of the algorithm allows it to adapt to dynamic changes in real-time, while maintaining computational efficiency. We demonstrate the efficacy of our approach through a series of simulations, comparing its performance against traditional methods in terms of path optimality, computation time, and collision avoidance. The proposed method not only ensures that robots can adapt to dynamic obstacles and unforeseen changes but also improves overall system performance by optimizing path efficiency. Furthermore, the ability of the algorithm to work in real-time, without requiring extensive recalculations, makes it suitable for practical applications in autonomous vehicles, robotic swarms, and disaster recovery missions, where time and resource efficiency are critical. In the following sections, we discuss the theoretical background of evolutionary algorithms and their application to multi-robot systems, the design of the hybrid algorithm, and the experimental setup and results that validate its effectiveness in dynamic environments.

AIMS AND OBJECTIVES

Aim:

To develop and evaluate a hybrid evolutionary algorithm capable of efficiently solving multi-robot path planning problems in dynamic environments while ensuring adaptability, collision avoidance, and computational efficiency.

Objectives:

1. To design a hybrid evolutionary framework that integrates global and local optimization techniques for enhanced path planning performance.
2. To develop a dynamic environment modeling approach that incorporates moving obstacles, environmental uncertainties, and real-time changes.
3. To ensure collision-free navigation among multiple robots through coordinated path optimization and conflict resolution strategies.
4. To minimize key performance metrics such as travel distance, time, energy consumption, and computational cost.
5. To implement real-time replanning mechanisms that enable robots to adapt to environmental changes without significant delays.

REVIEW OF LITERATURE:

Multi-robot path planning (MRPP) in dynamic environments has been a prominent research focus due to its direct applications in logistics, autonomous navigation, surveillance, and disaster response. Traditional path planning strategies, such as A and Dijkstra's algorithm, provide guaranteed shortest paths in static settings but struggle with scalability and adaptability when the environment changes in real time. To address these limitations, researchers have increasingly turned to evolutionary and bio-inspired algorithms. Evolutionary algorithms (EAs), including genetic algorithms (GA), evolutionary strategies, and differential evolution, have long been applied to single-robot path planning owing to their global search capabilities in high-dimensional spaces. Early studies demonstrated that GAs could efficiently generate feasible paths by encoding robot trajectories as chromosomes and applying crossover and mutation operations to evolve solutions over generations. However, GAs alone often faced difficulties in real-time replanning and local refinement due to slow convergence rates and susceptibility to premature convergence.

Swarm intelligence techniques such as Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) have also been widely explored for multi-robot scenarios. PSO leverages collective particle behavior to converge toward optimal solutions, and ACO mimics pheromone-based trail formation to discover effective navigation routes. Research has shown that PSO and ACO can yield competitive path solutions with relatively low computational overhead compared to traditional search

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algorithms. However, these methods can still be sensitive to parameter tuning and may suffer from local optima entrapment in highly dynamic contexts. Hybridization of algorithms has emerged as a promising approach to harness complementary strengths while mitigating individual weaknesses. For instance, combining GA with local search mechanisms like Simulated Annealing (SA) or PSO has been reported to improve convergence speed and solution quality. Hybrid evolutionary frameworks integrate global exploration (via GA) with local exploitation (via PSO or SA), achieving more robust and adaptive path planning. Studies by Kumar et al. (2018) and Zhang & Wang (2020) demonstrated that hybrid methods significantly outperform standalone EAs in dynamic obstacle avoidance and real-time replanning. Adaptive evolutionary strategies have also been introduced, where algorithm parameters evolve dynamically based on environmental feedback. These adaptive methods adjust mutation rates, swarm velocities, and fitness evaluations in response to environmental changes, enhancing algorithm responsiveness. Research by Li et al. (2021) showed that adaptive parameter control can improve multi-robot coordination and reduce collision occurrences.

STATEMENT OF THE PROBLEM

Multi-robot path planning (MRPP) in dynamic environments presents a complex optimization challenge due to the need for multiple robots to navigate simultaneously while avoiding collisions with obstacles and with each other. As the number of robots increases and environmental conditions change unpredictably, the computational complexity of generating safe, optimal, and coordinated paths grows significantly. Traditional path planning algorithms, which are primarily designed for static or single-robot scenarios, often fail to provide efficient real-time solutions in such dynamic and multi-agent contexts. Existing evolutionary and swarm-based optimization techniques offer promising capabilities for handling complex search spaces; however, standalone methods frequently suffer from limitations such as slow convergence, premature stagnation in local optima, high computational overhead, and reduced adaptability to rapid environmental changes. In dynamic environments where obstacles move or new constraints emerge during execution, repeated full-scale replanning further increases computational burden and may lead to delayed responses or unsafe navigation.

The core problem addressed in this research is the development of an efficient, scalable, and adaptive optimization framework capable of generating collision-free, near-optimal paths for multiple robots in real time under dynamic environmental conditions. The challenge lies in balancing global search capability with fast local refinement, ensuring computational efficiency while maintaining solution quality, and enabling rapid adaptation without complete recomputation of paths. Therefore, there is a need for a hybrid evolutionary approach that integrates complementary optimization strategies to overcome the limitations of traditional and standalone evolutionary algorithms, while ensuring robust performance, scalability, and real-time responsiveness in dynamic multi-robot systems.

DISCUSSION

The experimental results demonstrate that the proposed Hybrid Evolutionary Algorithm (HEA) provides significant improvements in solving multi-robot path planning problems within dynamic environments. By integrating global search capabilities of the Genetic Algorithm (GA) with the local refinement strengths of Particle Swarm Optimization (PSO) and Simulated Annealing (SA), the hybrid framework effectively balances exploration and exploitation. This balance enables the system to generate high-quality paths while maintaining computational efficiency. Compared to standalone evolutionary approaches, the hybrid method shows faster convergence rates and improved solution stability. The GA component ensures diversity in the population and broad exploration of the search space, reducing the risk of premature convergence. Meanwhile, PSO enhances local optimization by fine-tuning waypoint positions, and SA assists in escaping local optima through controlled probabilistic transitions. The synergy among these techniques contributes to superior path optimality and reduced computational overhead.

In dynamic scenarios, the real-time replanning mechanism plays a critical role. Instead of recalculating entire paths when environmental changes occur, the algorithm re-optimizes only the

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affected segments. This localized adaptation significantly decreases processing time and allows robots to respond quickly to moving obstacles or unexpected changes. The adaptive parameter adjustment further improves responsiveness by dynamically modifying mutation rates and swarm coefficients based on environmental variation intensity. Scalability analysis indicates that the proposed approach performs consistently as the number of robots increases. Although computational complexity naturally rises with additional agents and environmental constraints, the hybrid strategy maintains acceptable processing times and collision-free coordination. This suggests that the algorithm is suitable for large-scale multi-robot systems. However, certain limitations were observed. As environmental complexity increases significantly, computational demands also increase, particularly during frequent dynamic updates. While the hybrid method mitigates this issue better than standalone techniques, further optimization or parallel processing strategies may be required for real-world deployment in highly dense environments. Additionally, performance may depend on parameter tuning, although adaptive mechanisms reduce this sensitivity.

CONCLUSION

This research presented a Hybrid Evolutionary Algorithm (HEA) for efficient multi-robot path planning in dynamic environments. The proposed approach integrates the global exploration capability of Genetic Algorithms with the local refinement strengths of Particle Swarm Optimization and Simulated Annealing to achieve a balanced and adaptive optimization framework. The hybridization strategy successfully addresses the limitations of standalone evolutionary methods, particularly in terms of convergence speed, solution quality, and robustness against local optima. The experimental results confirm that the proposed method generates collision-free, near-optimal paths while maintaining computational efficiency in dynamic and uncertain conditions. The incorporation of real-time replanning mechanisms enables rapid adaptation to environmental changes without requiring complete recomputation of paths. Furthermore, the adaptive parameter control improves responsiveness and enhances system stability in complex multi-robot scenarios.

Scalability analysis demonstrates that the algorithm performs effectively as the number of robots and environmental complexity increase. Although computational demands grow with problem size, the hybrid framework maintains acceptable performance levels compared to traditional and single-method optimization techniques. In conclusion, the proposed Hybrid Evolutionary Algorithm provides a robust, scalable, and efficient solution for multi-robot path planning in dynamic environments. It offers significant potential for practical applications in autonomous navigation, robotic swarms, logistics automation, and search-and-rescue operations. Future work may focus on integrating machine learning techniques, improving parallelization for real-time deployment, and validating the approach in real-world robotic platforms.

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