Variations and Hybridizations of Genetic Algorithms Enhance Performance in Automated Route Planning

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Abstract. This article delves into the challenges of automated route planning in robotics and logistics, emphasizing the genetic algorithm (GA) as a significant approach. The study conducts a thorough investigation of GA's capabilities in resolving route planning problems for mobile robots, encompassing both static and dynamic scenarios, as well as multi-robot coordination. The analysis, based on recent literature, highlights that modifying the genetic algorithm can effectively enhance its performance. Notable improvements were observed in convergence speed and the ability to avoid local minima, essential for achieving optimal or near-optimal solutions in complex route planning problems. This research contributes to advancing knowledge in route planning for mobile robots and offers valuable insights for researchers and practitioners interested in utilizing the genetic algorithm as a powerful tool to address optimization challenges in dynamic and multi-robot environments.

Keywords. genetic algorithm, path planning, one or multiple robots, static and dynamic environment, variation and hybridization.

1. Introduction

The text provides an overview of the importance of path planning for mobile robots, emphasizing its relevance in various applications, including autonomous delivery systems and manufacturing facilities [1]. The quality of the planned path directly affects optimization criteria such as distance traveled, processing time, and energy consumption, with a specific focus on the distance traveled metric.

Path planning in robotics is described in terms of two main factors: the nature of the environment (static or dynamic) and the level of knowledge the robot has about the environment (complete or incomplete) [1]. Static environments have unchanging conditions, while dynamic ones involve moving obstacles. Complete knowledge implies a known environment, while incomplete knowledge means the environment may be unknown to the robot. Planning for a single robot differs significantly from planning for multiple robots, where interactions and coordinated movements become crucial [1].

Classical and heuristic methods are introduced as approaches to path planning [4]. Classical methods offer accuracy and determinism but suffer from limited scalability. Heuristic methods, on the other hand, employ intelligent strategies, reducing execution time but not guaranteeing optimality. Genetic algorithms are highlighted as an increasingly popular heuristic approach for path planning, leveraging natural selection processes for optimizing trajectories in large workspaces [2].

Genetic algorithms are described as stochastic search techniques that encode possible solutions as chromosomes within a population. Evaluation through a fitness function and genetic operations such as reproduction, crossover, and mutation lead to population evolution, converging to high-quality solutions over generations [5].

However, genetic algorithms are criticized for their slower convergence rate in the context of path planning [4], prompting the exploration of adaptations to improve their performance in static and dynamic environments, including scenarios with single or multiple robots.

The article outlines its structure, including methodology for obtaining genetic algorithms, details about modified or hybridized algorithms, results, and discussion, concluding with potential directions for future work [4].

2. Methodology

This research aims to investigate the performance of various adaptations and hybridizations of genetic algorithms (GAs) in the context of path planning for mobile robots [4][6]. The study addresses challenges inherent to GAs, such as slow convergence rates and susceptibility to local/global minima/maxima, by making GA more efficient.

The research considers two categories of GA adaptations:

- Genetic Algorithm Variations: These modifications focus on improving specific GA performance characteristics. For instance, changes to the mutation operator have been proposed to accelerate convergence [7].

- Hybridizations with Other Algorithms: In addition to internal variations, the study explores hybrid approaches where GA is combined with other algorithms like fuzzy-genetic, genetic-neural-fuzzy, and genetic-PSO [7].

To evaluate the performance of these GA adaptations, the research examines a range of path planning scenarios for mobile robots, including static and dynamic environments, as well as single-robot and multi-robot path planning situations. The selection of scenarios aims to represent the diversity of challenges encountered in real-world applications.

The literature review, conducted from 2010 onwards, identifies relevant academic materials that have tested GAs in various path planning scenarios. Studies included in the review are selected based on relevance and methodological quality.

Performance evaluation metrics include convergence time, solution quality, computational efficiency, and other relevant criteria. These metrics facilitate a comprehensive analysis of the impact of adaptations in different scenarios.

The analysis of results will involve comparing different GA approaches across the selected scenarios and identifying trends and patterns. The research has no significant ethical considerations, as it involves the analysis of previously published results. However, limitations may arise from variations in the quality of the reviewed studies and differences in the implementations of GA adaptations in individual studies.

3. Searched algorithms

Each subsequent subsection will address a distinct genetic algorithm that has undergone modifications or hybridizations with other algorithms. The titles of these subsections correspond to the titles of the academic papers used as references. For each academic work, we will highlight the modifications made, the simulation scenarios used, and the results obtained. This will provide a deeper and clearer understanding of the results of our research.

3.1 An improved genetic algorithm with co-evolutionary strategy for global path planning of multiple mobile robots

In this article, the authors introduce two genetic algorithms: the Improved Genetic Algorithm and the Co-evolutionary Genetic Algorithm (CIGA). CIGA builds upon the former algorithm and both were designed for handling static environments. The Improved Genetic Algorithm was created for route planning of a single mobile robot, while CIGA was tested in route planning for multiple mobile robots. These experiments were conducted in a Microsoft Visual C++ 6.0 programming environment.

The key differences between these algorithms and conventional genetic approaches involve modifications to the fitness function, selector operator, and an innovative modification operator. Additionally, some genetic operators like crossover and mutation underwent minor adjustments. The results of the experiments showed that both algorithms effectively guided robots along near-optimal trajectories from the starting point to the destination, while avoiding collisions with obstacles in the environment [8].

3.2 Matrix-Binary Codes based Genetic Algorithm (MGA) for path planning of mobile robot

In this article, the authors introduce the Matrix-Binary Codes based Genetic Algorithm (MGA) [7], a modified genetic algorithm designed for iterative nonlinear search. MGA uses sensor measurements, including left obstacle distance (LOD), front obstacle distance (FOD), and right obstacle distance (ROD), to compute the heading angle (HA) as its output.

To evaluate MGA's performance, experiments were conducted in both real environments using the Khepera-II robot with 8 infrared sensors programmed in C++, and in MATLAB simulations. Remarkably, the comparison between real experiments and simulations showed minimal differences, not exceeding 5.82%, indicating consistent results between the two settings.

MGA outperformed other heuristic methods such as fuzzy logic (FL), artificial neural networks (ANN), and ant colony optimization (ACO) in terms of route planning and execution time. It proved effective in static and dynamic environments, even when the destination point was moving. These findings suggest that MGA holds promise for a wide range of route planning applications.

3.3 Multi-AGV path planning with double-path constraints by using an improved genetic algorithm

In this article, the authors aimed to improve route planning for multiple autonomous guided vehicles (multi-AGV) using a genetic algorithm [9]. They introduced heuristic three-exchange crossover operators, replacing the traditional two-exchange crossover operators, to enhance the algorithm's performance. This modification aimed to generate more optimal offspring, gather additional information, and potentially inherit superior characteristics from parent solutions, ultimately increasing the search speed of the algorithm. Additionally, they applied double-path constraints to minimize both the total distance traveled by all AGVs and the individual distances traveled by each AGV, with the goal of achieving the shortest and most optimized total distance.

Simulation results showed that the enhanced genetic algorithm successfully reduced the distances traveled by all AGVs, including the maximum distance traveled by a single AGV. This indicates that the modified genetic algorithm significantly improved the efficiency of route optimization for autonomous vehicles, resulting in shorter and more efficient paths.

3.4 Dynamic Path Planning for Mobile Robot Based on Genetic Algorithm in Unknown Environment

In this article, the authors developed a dynamic route planning system for unknown environments based on a genetic algorithm [2]. The genetic algorithm's fitness function considered three crucial factors: collision avoidance route, shortest distance, and path smoothness. Specific genetic operators were selected to enhance the algorithm's effectiveness.

The simulations were performed in a Visual C++ 6.0 programming environment, with the goal of assessing the system's performance in complex dynamic environments. The results indicated that the system was highly effective in avoiding collisions with moving obstacles, showcasing its efficiency in dynamic and intricate environments.

3.5 Coordination in Navigation of Multiple Mobile Robots

In this article, the authors addressed a problem in two parts: first, they focused on generating optimal trajectories for a single robot, and then they extended their approach to coordinate multiple robots by modifying these optimal trajectories [10]. Two types of multi-robot coordination approaches were considered: centralized and decentralized. Centralized methods create a joint configuration space for all robots in a static environment, offering optimality but requiring significant computation. Decentralized approaches, in contrast, plan the trajectories of individual robots separately and are computationally lighter.

The algorithm has two main components: generating the initial path and coordinating that path. The initial path generation is relatively independent of the specific mechanism used. The coordination phase fine-tunes trajectories, primarily through the mutation operator, with other operators used to create points near collision-prone areas.

Simulations in MATLAB were conducted to evaluate the algorithm's performance. A simulation agent and the algorithm were developed for this purpose. The simulations involved reading predefined scenarios and generating travel plans using the algorithm, followed by moving individual robots based on these plans, displayed in the user interface.

Results highlighted that planning collision-free trajectories for multiple robots is a challenging task. The algorithm proved to be more time-efficient than centralized approaches and was probabilistically complete, unlike reactive approaches. Moreover, it treated all robots equally, in contrast to prioritized methods. Experimental findings demonstrated that the algorithm outperformed both centralized and prioritized genetic algorithms in terms of performance [10].

3.6 Optimal Robot Path Planning for Multiple Goals Visiting Based on Tailored Genetic Algorithm

In this article, the authors tackled the task of guiding a robot to multiple destinations and introduced a custom genetic algorithm for optimal path planning, aiming to cover as many objectives as possible while minimizing periods of inactivity to save energy [11]. They modified the Tailored Genetic Algorithm to adapt it to this problem:

- Nodes were combined to represent chromosomes.
- Fitness functions were split into two parts: one for energy consumption and one for evaluating idle time.
- Three new operators were introduced alongside the standard genetic operators: Repair, Cutting, and Deletion.

The experimental results yielded several key findings:

- The algorithm's solution may not always be the globally optimal one, suggesting opportunities for future enhancements.
- The convergence rate varied across three test cases, indicating the influence of specific problem settings.
- Simulations demonstrated efficient computational performance, although the test environment contained only 17 nodes.

These results provide insights into the effectiveness of the custom genetic algorithm for multi-destination path planning, with implications for energy savings and idle time optimization in practical applications [11].

Other algorithms from various bibliographic sources were subjected to investigation, namely:

"Global Path Planning for Mobile Robots in Large-Scale Grid Environments using Genetic Algorithms", "Applying genetic algorithm and ant colony optimization algorithm into marine investigation path planning model", "Hybrid PSO-HSA and PSO-GA algorithm for 3D path planning in autonomous UAVs", among others.

Based on the analysis of the aforementioned algorithms, Tab. 1 was compiled, summarizing the underlying objectives of these algorithms and providing a concise overview of the main adaptations implemented, along with the achieved results. In the table, column headers are described as follows: "SE" refers to Static Environment, "DE" denotes Dynamic Environment, "SR" corresponds to Single Robot, and "MR" designates Multiple Robots. These columns outline the fundamental characteristics of the referenced algorithms. For each algorithm, we employ "T" (for True) or "F" (for False) in each of these columns to indicate the presence or absence of a specific feature in the algorithm under study.

4. Results and Discussion

This study examined the effectiveness of the genetic algorithm for route planning in both static and dynamic environments, considering scenarios involving single and multiple mobile robots [1]. Through a literature review, the study found that variations and hybridizations of the genetic algorithm often produced positive results in both static and dynamic settings.

Most studies primarily focused on route planning for individual mobile robots, with fewer addressing the complexities of planning routes for multiple robots simultaneously [1]. Nonetheless, some modifications proved effective even in multi-robot scenarios.

A significant observation was that the genetic algorithm can be adapted to improve various aspects of route planning, including convergence time and avoidance of local minima. Comparative studies indicated that modified genetic algorithms frequently outperformed traditional heuristic methods like Fuzzy Logic (FL), Artificial Neural Networks (ANN), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Invasive Weed Optimization (IWO).

It's worth noting that while the genetic algorithm may not always find the optimal solution, it often approximates a near-optimal one. Challenges remain in adapting it for real-time applications due to its relatively slower search process, especially as the search space grows. However, the algorithm's potential applicability in dynamic environments has been demonstrated.

In summary, in static environments, the genetic algorithm consistently demonstrated good performance in most tests, even though the majority of research focused on individual robot route planning. Algorithms designed for multi-robot route planning also showed promise. Route planning is a critical task in intelligent robotic systems, and ongoing research aims to address challenges in both static and dynamic environments, ensuring its continued relevance [2].

It's important to note that the study didn't delve into the analysis of specific factors in route planning, such as the type of scenario in the experiments or the objective function used.

Tab. 1 - Summary of algorithm results.

Name	SE	DE	SR	MR	Key features	Results
An improved genetic algorithm with co-evolutionary strategy for global path planning of multiple mobile robots [8]	T	F	T	T	Fitness function, selection operator, crossover operator, mutation operator, modification operator	Guided the robot's trajectory without colliding with obstacles.
Matrix-Binary Codes based Genetic Algorithm for path planning of mobile robot [7]	T	T	T	T	Matrices for manipulation	Better and less time-consuming route planning compared to FL, ANN, ACO.
Multi-AGV path planning with double-path constraints by using an improved genetic algorithm [9]	T	F	F	T	Heuristic operator, double-path constraints	All AGVs had their path shortened on the route.
Dynamic Path Planning for Mobile Robot Based on Genetic Algorithm in Unknown Environment [2]	F	T	T	F	Fitness function, selection operator, crossover operator, mutation operator	Avoided collisions with moving obstacles in complex dynamic environments.

Coordination in Navigation of Multiple Mobile Robots [10]	T	F	F	T	Mutation operator	It is better than centralized GA as it takes less time. It is better than prioritized GA as it treats robots the same.
Optimal Robot Path Planning for Multiple Goals Visiting Based on Tailored Genetic Algorithm [11]	T	F	T	F	Fitness function, chromosome representation, repair operator, cutting operator, deletion operator	The solution may not be the global optimum. Variation in the convergence rate. Efficiency in computational time.
Global Path Planning for Mobile Robots in Large-Scale Grid Environments using Genetic Algorithms [1]	T	F	T	F	Crossover operator	Finds optimal routes in spacious environments equal to A* in almost all situations.
Applying genetic algorithm and ant colony optimization algorithm into marine investigation path planning model [6]	T	F	T	F	ACOA-GA hybridization	Better performance and efficiency. Greater convergence speed.
Hybrid PSO-HSA and PSO-GA algorithm for 3D path planning in autonomous UAVs [12]	T	F	T	F	PSO-HSA hybridization, PSO-GA hybridization	Convergence to global min/max is fast. Avoided obstacles. He helped direct the ship. Better when compared with PSO and IWO.
Optimal Path Planning and Execution for Mobile Robots using Genetic Algorithm and Adaptive Fuzzy Logic Control [13]	T	F	T	F	GA-FL hybridization	Minimum path length. Collision-free path. Shorter route execution time.
Design of a hybrid controller using genetic algorithm and neural network for path planning of a humanoid robot [14]	T	F	T	F	GA-NN hybridization	Minimum error limits.
Dynamic path planning of mobile robots with improved genetic algorithm [15]	F	T	T	F	Mutation operator	Finds the ideal path much more often than other methods. Faster convergence.
Path Planning of Mobile Robots Based on a Multi-Population Migration Genetic Algorithm [3]	T	T	T	F	Crossover operator, mutation operator, selection operator	It has superior performance for route planning compared to standard GA. Good performance in static and dynamic route planning. Good convergence speed.
Double global optimum genetic algorithm particle swarm optimization-based welding robot path planning [16]	T	F	T	F	GA-PSO hybridization	Achieves the shortest, collision-free welding path. Better than GA and PSO for robot route planning.

5. Conclusion

The article investigates the efficiency of genetic algorithms (GAs) in the context of route planning, a crucial problem in robotics. The primary objective was to summarize and detail GAs' capabilities in automated route planning, emphasizing common modifications and hybridizations of these algorithms.

Initially, it was observed that the original form of genetic algorithms was not particularly useful for automated route planning due to their relatively slow convergence time. However, by making modifications to key parameters like mutation operators, objective functions, and fitness functions, GAs demonstrated adaptability and the ability to produce satisfactory results within reasonable timeframes. The study sets the stage for future research to explore GAs' capabilities in various aspects of route planning, including:

- Validation types: Whether through computer simulations or real-world experiments.
- Scenario types: Ranging from two-dimensional (2D) to three-dimensional (3D) configurations.
- Objective functions: Addressing both single-objective and multi-objective optimization problems.
- Consideration of dynamic robot constraints: Incorporating more complex dynamics and interactions in constantly changing environments.

In summary, the study highlights that with appropriate modifications, genetic algorithms can become a valuable tool in automated route planning. Future research in robotics is expected to continue exploring these capabilities to tackle increasingly complex challenges in both static and dynamic environments [2].

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